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Small-scale ion flux and magnetic field fluctuations in solar wind, foreshock and magnetosheath*

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We have continued investigation of waves in the regions of undisturbed solar wind, foreshock and magnetosheath. The analysis of ion flux and magnetic field variations with the time interval 1–240s was performed in the regions above. Very large variation in such a time interval can be considered the common feature of the foreshock and magnetosheath. The results of case and statistical studies showed that the level of relative variations of ion flux and magnetic field magnitude in foreshock is about 3 times larger than in undisturbed solar wind. Variations of these parameters in the magnetosheath topologically connected with the quasi-parallel bow shock are about two times larger than those behind the quasi-perpendicular. We also compared the results from Interball-1 data analysis with those from statistical analysis of cluster magnetic field measurements. The magnetic field variations obtained from the different satellite data coincide with each other very well not only in quality but also in quantity.

Keywords: magnetosheath, foreshock, solar wind
PACC: 9430V, 9430S, 9430P

1. Introduction

Solar wind plasma parameters and interplanetary magnetic field (IMF) fluctuate in a wide range of time interval and amplitude. These fluctuations are formed due to various shocks, discontinuities, magnetohydrodynamic (MHD) waves, turbulence in plasma and their interactions with each other on their way from the Sun to the Earth. In foreshock and magnetosheath regions plasma and magnetic field parameters fluctuate much more intensively than in undisturbed solar wind and very often such fluctuations are nonlinear with amplitudes larger than 10%.[1] The foreshock region is formed by a fraction of the incoming solar wind particles which are reflected at the bow shock front or escape from magnetosheath and magnetosphere.[2] These particles move along magnetic field lines away from the bow shock and interact with the incoming solar wind flow. The interaction between reflected ions and solar wind results in the formation of ion foreshock region where fast magnetosonic waves are generated, characterized by high positive values of correlation $R_{(\mathrm{F/B})} > 0.7$ between the ion flux and the magnetic field magnitude variations.[3] The value of such correlation can serve as an effective indicator of whether a spacecraft is in the foreshock or in the undisturbed solar wind.

The magnetosheath is an interface between the solar wind plasma flow and Earth's magnetosphere. Complex kinetic and MHD processes, which take place at the bow shock, at the magnetopause, and within the magnetosheath itself, modify the features of the incident solar wind plasma flow and provide the sources of free energy for the generation of various types of wave modes, instabilities and nonlinear structures.[4] Variations of plasma and magnetic field in the magnetosheath are very great over a broad range of frequencies.[5−8] The magnetosheath is very sensitive to the upstream conditions. The orientation of the IMF with respect to the bow shock normal is a parameter which strongly affects the wave properties of the ion flux, the magnetic field fluctuations, and their distribution inside the magnetosheath.[1,9] The

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bow shock and the downstream magnetosheath are called quasi-parallel when the angle $\theta_{\boldsymbol{B}\mathrm{n}}$ between the IMF and the bow shock normal (at the point where the spacecraft is topologically connected to the bow shock along the streamline, see Fig.1) is less than 45°, and quasi-perpendicular when $\theta_{\boldsymbol{B}\mathrm{n}} > 45°$.

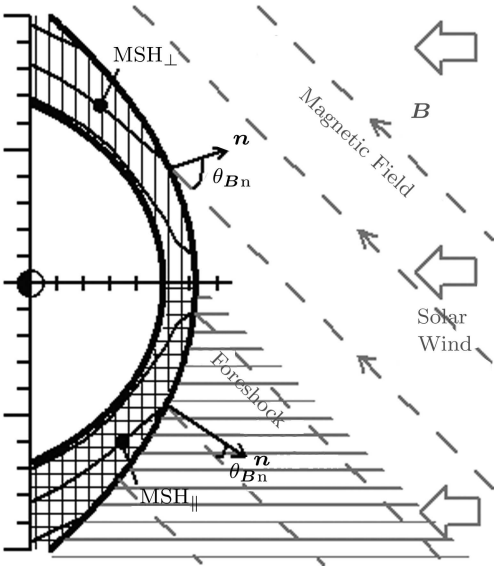


Fig.1. A schematic diagram for explaining various features of the solar wind and magnetosheath when the IMF is inclined 45° to the Sun–Earth line.

A preliminary investigation on some properties of the small-scale plasma turbulence in solar wind, foreshock and magnetosheath has been conducted.[1,10] Variations of ion flux in time interval 1–60s were mostly considered in Refs.[1] and [10] using the measurements of Interball-1 spacecraft. Statistical study showed that in the magnetosheath the amplitude of ion flux variations increases with the decrease of angle $\theta_{\boldsymbol{B}\mathrm{n}}$. Variations of ion flux in the foreshock region are much greater than in undisturbed solar wind, and exceed the variations in the magnetosheath. But in Ref.[1] a very rough method of foreshock selection was used and only data in the foreshock with intensive variations of ion flux were taken. In this work we will select all kinds of data in the foreshock region, no matter how strong the variations are there.

Some properties of magnetic field fluctuations in time interval 4–240s observed by cluster spacecraft in solar wind, foreshock and magnetosheath were investigated in Ref.[11]. The influence of IMF orientation with respect to upstream bow shock normal on properties of magnetic field turbulence in the magnetosheath was considered. In Ref.[11] Du *et al* showed that variations of the magnetic field magnitude and direction in the magnetosheath downstream of the quasi-parallel bow shock are more intensive than those in downstream of the quasi-perpendicular bow shock. Almost purely compressive waves were observed in the quasi-perpendicular magnetosheath.

In this paper we continue the investigation of plasma and magnetic field turbulence in the regions of undisturbed solar wind, foreshock, quasi-parallel and quasi-perpendicular magnetosheath. We will try to compare Interball-1 and cluster results and to define statistical characteristics of small-scale turbulence in the regions considered.

2. Observations and data analysis

The study is based on the analysis of ion flux[12,13] and magnetic field measurements[14] obtained during 01.1997–10.1998 onboard Interball-1 spacecraft. Such systematic measurements with very high time resolution (1s) made it possible to investigate and compare the statistical properties of the small-scale turbulence in solar wind (SW), foreshock (FSH) and in the magnetosheath (MSH) regions. The total statistics of the measurements considered in this study includes about 670 hours of observations in solar wind and about 500 hours (85 crossings) of observations in the magnetosheath. The positions of Interball-1 spacecraft in magnetosheath and solar wind during the selected intervals are presented in Fig.2. Interball-1 magnetosheath data are generally selected on its flanks and they do not cover the subsolar regions.

Systematic measurements of magnetic field on cluster spacecraft during 01.2001–01.2003 with time resolution (4s) are also considered in this study. Small-scale (4–240 s) magnetic field variations in solar wind, foreshock and magnetosheath are investigated. The total statistics includes 545 hours of measurements in solar wind and 598 hours of observations in the magnetosheath.

To calculate angle $\theta_{\boldsymbol{B}\mathrm{n}}$ when the spacecraft is located inside the magnetosheath we use the following procedure: the gas-dynamic model in Ref.[15] provides the bow shock orientation, the distribution of streamlines, and plasma parameters inside the magnetosheath normalized by solar wind parameters. Coordinates are also normalized by the distance D_s from the Earth to the subsolar point of the magnetopause. Given the undisturbed solar wind parameters, such as density, velocity and IMF B_z-component, D_s values

can be calculated at each moment using the model in Ref.[16]. Then we normalized Interball-1 coordinates by D_s to present them in the gas-dynamic model of Ref.[15]. As this model provides the distribution of streamlines inside the magnetosheath, we could trace at each moment the spacecraft positions along streamlines up to the bow shock and find the bow shock normal vectors. IMF measurements allow us to obtain the time dependence of angle $\theta_{\boldsymbol{B}n}$ along Interball-1 trajectory. More detailed description of this method has been given in Ref.[1].

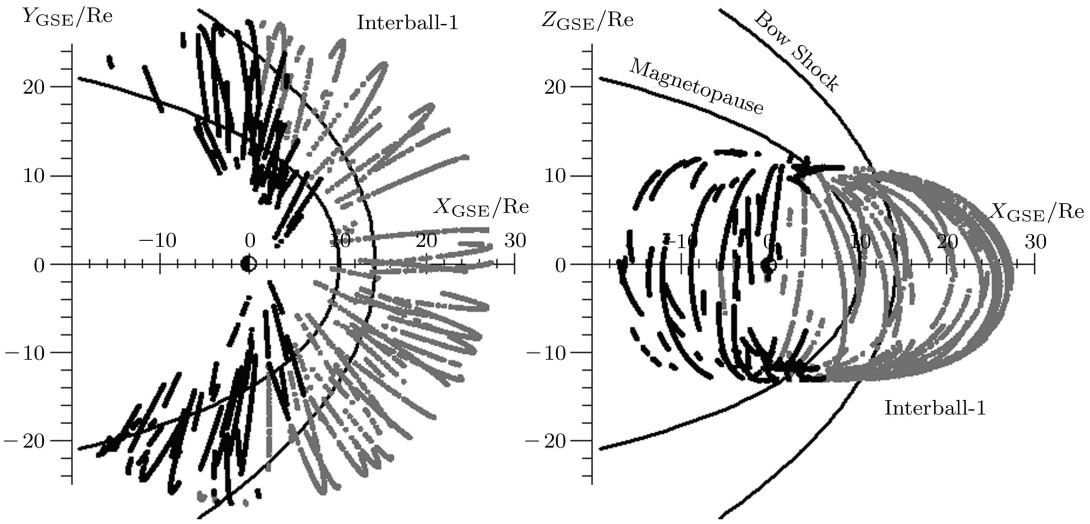


Fig.2. Positions of Interball-1 spacecraft in the time interval selected for the study. Grey points show the positions of the spacecraft when it is in undisturbed solar wind and foreshock, black points indicate magnetosheath crossings.

As a measure of intensity of fluctuations observed we use the value of the relative standard deviation (RSD) calculated as the ratio of standard deviation to the average value of a parameter in the particular interval. In this paper we analyse the value of a parameter in a 4-min long interval to investigate its small-scale variations. The behaviour of RSD gives the quantitative information about the relative amplitude of variations in such a time interval in different regions.

Magnetic field fluctuates not only in magnitude, but also in direction. We use R-parameter[11,17] to estimate the disturbance of magnetic field direction.

$$R = 1 - (1/n)\left|\sum_{i=1}^{n} B_i/|B_i|\right| = 1 - (1/n)\left[\left(\sum X_i\right)^2 + \left(\sum Y_i\right)^2 + \left(\sum Z_i\right)^2\right]^{1/2}, \qquad (0 \le R \le 1)$$

Here n is the number of measurements of the vector $\boldsymbol{B}$ in a time interval; X_i, Y_i and Z_i are the direction cosines of each vector. If the magnetic field vectors are clustered tightly around a common direction, then parameter R will approach 0. If all vectors point toward the same direction, R will be equal to 0. When the vectors are scattered, R becomes large. For uniformly distributed vectors, R is equal to 1. Accordingly, parameter R is a measure of variations of the field direction, and does not include changes in the field magnitude. A period of predominantly compressional oscillations will give R values close to 0.

3. Case study

Figure 3 shows the Interball-1 ion flux and magnetic field measurements on June 14, 1999. In the

beginning of the time interval Interball-1 is in the solar wind, then after multiple bow shock crossings at 14:37, 14:51, and 14:58 UT the spacecraft is moving across the magnetosheath, and at 20:44 UT it crosses the magnetopause and enters into magnetosphere.

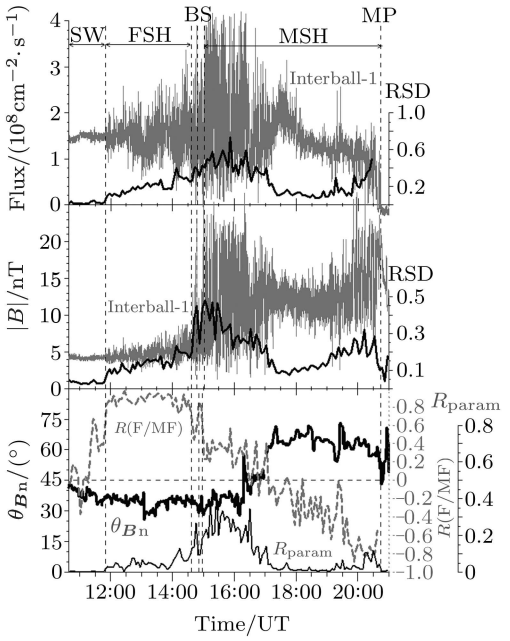


Fig.3. Interball-1 ion flux (top panel) and magnetic field magnitude (middle panel) observations in solar wind, foreshock and magnetosheath on June 14, 1999 (grey lines). Bold curves show RSD values of variations of these parameters in 4-min intervals. Vertical dashed lines indicate the positions of bow shock (BS) and magnetopause (MP) and foreshock boundary. The lower panel shows the angle $\theta_{\boldsymbol{B}\mathrm{n}}$ behaviour (thick solid curve), R-parameter (thin solid curve) and correlation coefficient R(F/B) (dashed curve) of the ion flux and magnetic field magnitude variations.

One can easily determine two distinctive regions in the solar wind as well as in the magnetosheath, which strongly differ by the level of variations. Up to 11:50 UT Interball-1 observed the quiet solar wind without substantial variations in the range 0.008–1 Hz. At 11:50 UT a sudden increase in RSD value is recorded and the intensity of variations grows while approaching the bow shock. After the bow shock crossing, variations of both parameters are even more amplified with RSD∼0.5 and they suddenly decrease at about 17:05 UT. So, RSD values allow us to separate more- and less-disturbed states of plasma and magnetic field in solar wind and magnetosheath. The transition from undisturbed solar wind to foreshock is accompanied by an abrupt change in fluctuation level, and the transition between the more- and less-disturbed magnetosheath regions is also characterized by an abrupt decrease in fluctuation level (see Fig.3). Investigations in Ref.[1] showed that this process is generally controlled by changes in orientation of the interplanetary magnetic field with respect to the bow shock normal, which is defined by angle $\theta_{\boldsymbol{B}\mathrm{n}}$. The results of calculation of the angle $\theta_{\boldsymbol{B}\mathrm{n}}$, R-parameter and R(F/B) values of correlation coefficient of the ion flux and magnetic field magnitude variations calculated in 4-min intervals are presented at the bottom panel in Fig.3.

The behaviours of angle $\theta_{\boldsymbol{B}\mathrm{n}}$, R-parameter and correlation coefficient R(F/B) are in good agreement with those of RSD(F) and RSD(B). From the beginning of the interval considered and up to 14:37 UT the bow shock is quasi-parallel with $\theta_{\boldsymbol{B}\mathrm{n}}$∼35–40°. The sudden increase of RSD(F) and RSD(B) at 11:50 UT is accompanied by the increase of the correlation coefficient up to the value R(F/B)∼0.9, indicating the ion foreshock region.[3] Although angle $\theta_{\boldsymbol{B}\mathrm{n}} < 45°$ even before 11:50 UT, no foreshock wave activity is observed there. This is probably because the ion foreshock outer boundary does not coincide exactly with the magnetic field line tangent to the bow shock. It is inclined downstream due to the $\boldsymbol{E} \times \boldsymbol{B}$ drift in the solar wind electric field.[18]

In the magnetosheath, for the time interval 14:58–16:20 UT, the bow shock orientation is still quasi-parallel. Very intensive variations of the ion flux (RSD(F) = 0.5) and magnetic field magnitude (RSD(B) = 0.3) and small positive values of correlation R(F/B) = 0.35 are observed there. At 16:20 UT angle $\theta_{\boldsymbol{B}\mathrm{n}}$ suddenly changes to 45°. Between 16:20 and 17:05 UT, the values of RSD(F) and RSD(B) remain large, but the correlation value drops to zero; one can see that both ion flux and magnetic field variations have changed their features, some kind of transient process takes place. At 17:05 UT the angle $\theta_{\boldsymbol{B}\mathrm{n}}$ changes to the value about 60–70°, and the upstream bow shock becomes quasi-perpendicular. At this moment variations of both parameters become small and do not correlate with each other or have negative correlation. Magnetic field direction is mostly disturbed in the quasi-parallel magnetosheath and the foreshock (see the behaviour of R-parameter at the bottom panel of Fig.3), while in the quasi-perpendicular region fluctuations have a compressive nature. In undisturbed solar wind variations of magnetic field magnitude and direction are very small.

An interesting region has been observed near the magnetopause during 19:50–20:40 UT. Values of

RSD(F) and RSD(B) increase in this region and their correlation drops to about $R(\mathrm{F/B}) = -0.8$. This may indicate the presence of the mirror mode waves that are typically observed near the subsolar part of the magnetopause downstream of the quasi-perpendicular bow shock.[19]

The interval of observations considered allows to define some general characteristics of small-scale turbulence in undisturbed solar wind, foreshock and magnetosheath at different $\theta_{\boldsymbol{B}\mathrm{n}}$ values. In undisturbed solar wind the ion flux and magnetic field variations are small and have negative or zero correlation. In foreshock variations are several times more intensive, and they grow toward the bow shock and have high positive correlation. In quasi-parallel magnetosheath variations are also very intensive and have small positive correlation, while in quasi-perpendicular magnetosheath variations are less intensive (except the regions filled with mirror mode waves, where the magnitude of magnetic field is strongly disturbed) and have negative or zero correlation.

4. Statistical study

One of the major problems of such an analysis is the data selection. To identify different solar wind regions with different properties of turbulence and wave activity one needs a number of plasma and magnetic field parameters which could define the state of the system. In this study we are restricted to the ion flux and magnetic field measured on Interball-1. To calculate angle $\theta_{\boldsymbol{B}\mathrm{n}}$ we use solar wind plasma and magnetic field parameters measured on WIND spacecraft.

From Fig.3 one can see that $\theta_{\boldsymbol{B}\mathrm{n}}$ itself cannot exactly define the boundary between undisturbed solar wind and foreshock, but in combination with correlation coefficient $R(\mathrm{F/B})$ it can give rather well separation of these regions.

At the first step we separate Interball-1 solar wind observations (including both undisturbed solar wind and foreshock) from the observations in the magnetosheath. Ion flux measurements by VDP device[12] allow us to determine the moments of the bow shock crossing with an accuracy about 1 min.

For the whole set of measurements in solar wind (including foreshock) RSD values are calculated for 4-min intervals and for each such interval we also calculate the correlation coefficients between ion flux and magnetic field magnitudes and angle $\theta_{\boldsymbol{B}\mathrm{n}}$. Interball-1 solar wind observations in 1998 are considered here. The distribution of correlation coefficient $R(\mathrm{F/B})$ versus $\theta_{\boldsymbol{B}\mathrm{n}}$ is shown in Fig.4. The total number of points here is $N = 13450$. One can see that it is possible to separate all the points into two groups:

a) Those with high positive correlation and small $\theta_{\boldsymbol{B}\mathrm{n}}$, and b) those with small (or negative) correlation and high $\theta_{\boldsymbol{B}\mathrm{n}}$.

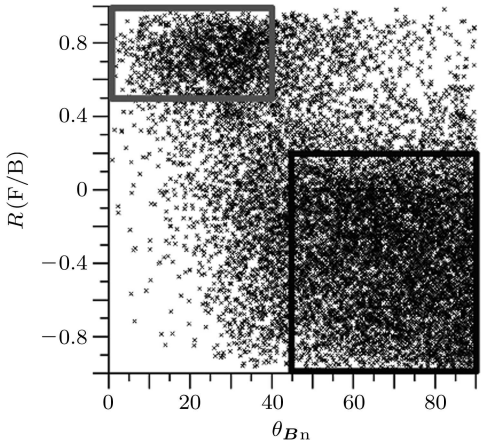


Fig.4. Distribution of correlation coefficients $R(\mathrm{F/B})$ versus $\theta_{\boldsymbol{B}\mathrm{n}}$ for the whole statistics in solar wind (including foreshock). The total number of points $N = 13450$.

The first group corresponds to the foreshock region which is connected with quasi-parallel bow shock and filled with fast magnetosonic waves[3] with high positive correlation coefficients $R(\mathrm{F/B})$. The second group corresponds to the undisturbed solar wind where correlation coefficient $R(\mathrm{F/B})$ is generally small or negative. In this paper we will define the general properties of plasma and magnetic field turbulence in different solar wind regions. To exclude the influence of points located in the transition region between the two groups on the final statistics, we make the following selection: for the undisturbed solar wind analysis we select only the intervals where $R(\mathrm{F/B}) < 0.2$ and $\theta_{\boldsymbol{B}\mathrm{n}} > 45°$; for the foreshock region we select the intervals with $R(\mathrm{F/B}) > 0.5$ and $\theta_{\boldsymbol{B}\mathrm{n}} < 40°$. These groups of points are shown in Fig.4 by rectangles. Such a selection is based on the general characteristics typical to the ion foreshock region and does not restrict the statistics of waves in the foreshock and undisturbed solar wind to their amplitude and frequency properties or location with respect to the bow shock.

The histograms of ion flux and magnetic field magnitude and of their RSD in the selected regions of foreshock and undisturbed solar wind are shown in Fig.5.

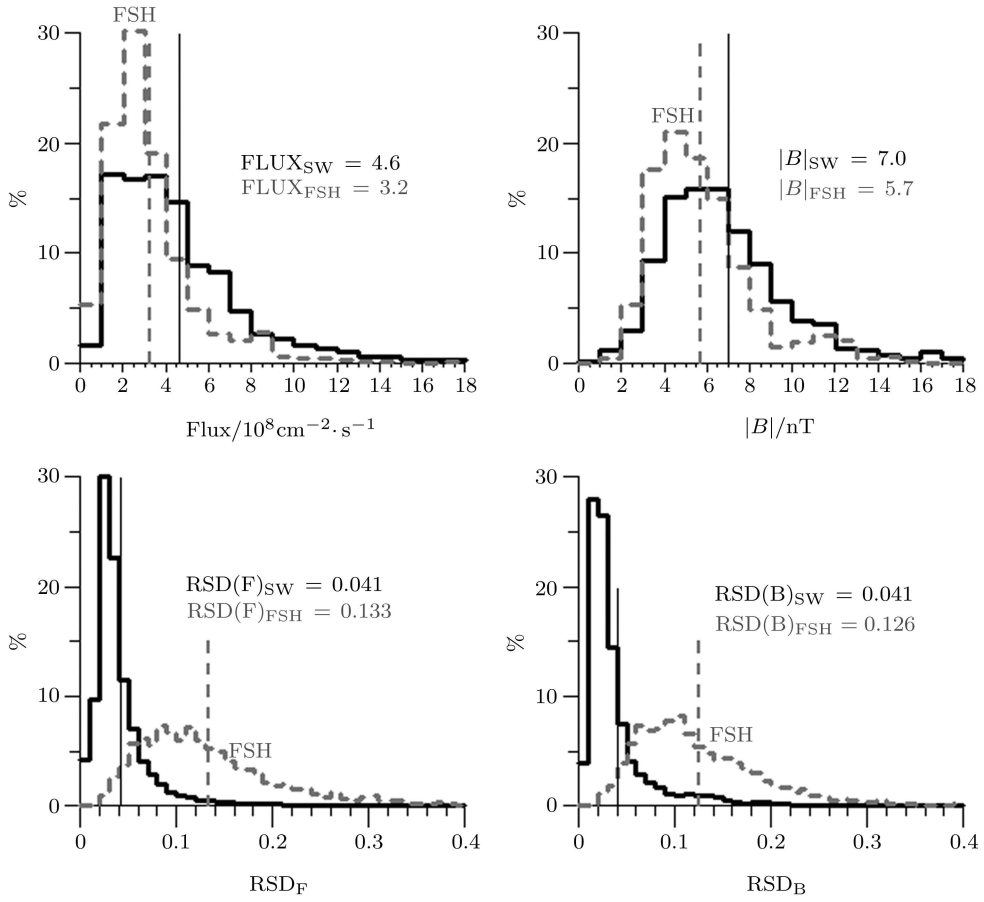


Fig.5. Histograms of ion flux and magnetic field and their RSD in solar wind and foreshock, plotted using Interball-1 data. Number of intervals in solar wind $N_{SW} = 10094$; in foreshock $N_{FSH} = 2012$.

One can see that both ion flux and magnetic field variations in foreshock are about 3 times larger than those in undisturbed solar wind. On the average, in solar wind RSD values of ion flux and magnetic field magnitude variations are nearly equal to each other with RSD = 0.04, while in foreshock they are both about 0.13. In undisturbed solar wind the distributions of RSD(F) and RSD(B) are very narrow and most part of points are located in the region with RSD$<$ 0.05. In foreshock their distributions are wider and up to the region with RSD$\sim$0.30. The distributions of ion flux and magnetic field themselves show that, on the average, both parameters in foreshock are about 20–30% less than in undisturbed solar wind.

As one can see from Fig.5 that there are no secondary peaks in the histograms of RSD(F) and RSD(B), which could be expected in the case of rough foreshock selection. So, our method provides very good ion foreshock identification.

The selection of quasi-parallel and quasi-perpendicular magnetosheath regions is a much more difficult task, because a mixture of various wave modes usually exists,[4] which cannot be identified only with the techniques mentioned above. Here we will base such selection only on estimation of $\theta_{\boldsymbol{B}n}$, and for quasi-parallel magnetosheath we will select the intervals with $\theta_{\boldsymbol{B}n} < 45°$, while for quasi-perpendicular magnetosheath with $\theta_{\boldsymbol{B}n} > 45°$.

Interball-1 observations during the period 01.1997–10.1998 have been considered for magnetosheath study. The histograms of ion flux and magnetic field magnitudes and of their RSD values in the quasi-parallel and quasi-perpendicular magnetosheath regions are presented in Fig.6. One can see that variations in quasi-parallel magnetosheath are more intensive than in quasi-perpendicular one. The distribution of variations of all the parameters stated in quasi-perpendicular magnetosheath is rather narrow and mostly located in the region with low RSD values, while in quasi-parallel magnetosheath it is widened to larger RSD values. Average values of parameters in quasi-parallel magnetosheath are smaller than in quasi-perpendicular one, which is in qualitative agreement with the MHD theory.

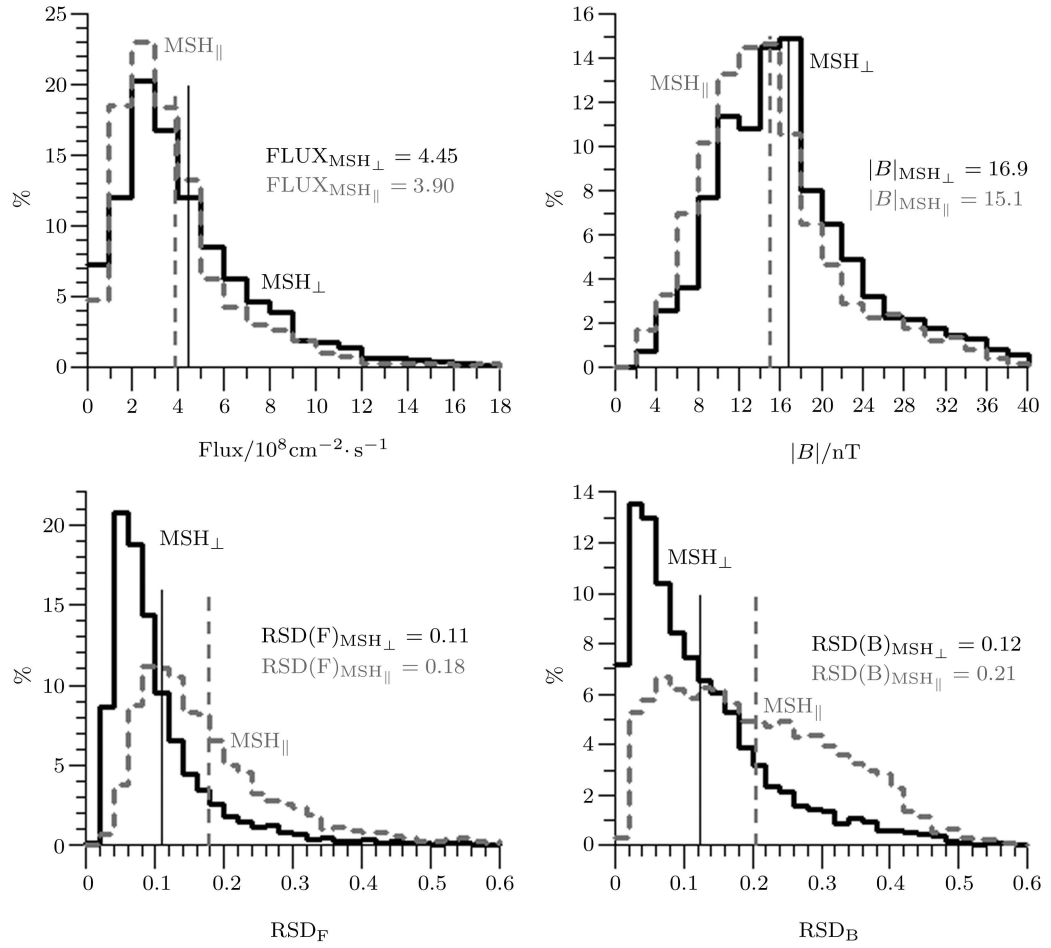


Fig.6. Histograms of ion flux and magnetic field and their RSD in quasi-perpendicular and quasi-parallel magnetosheath, plotted using Interball-1 data. Number of intervals in quasi-perpendicular magnetosheath $N_{\mathrm{PERP}} = 6077$; in quasi-parallel magnetosheath $N_{\mathrm{PAR}} = 3130$.

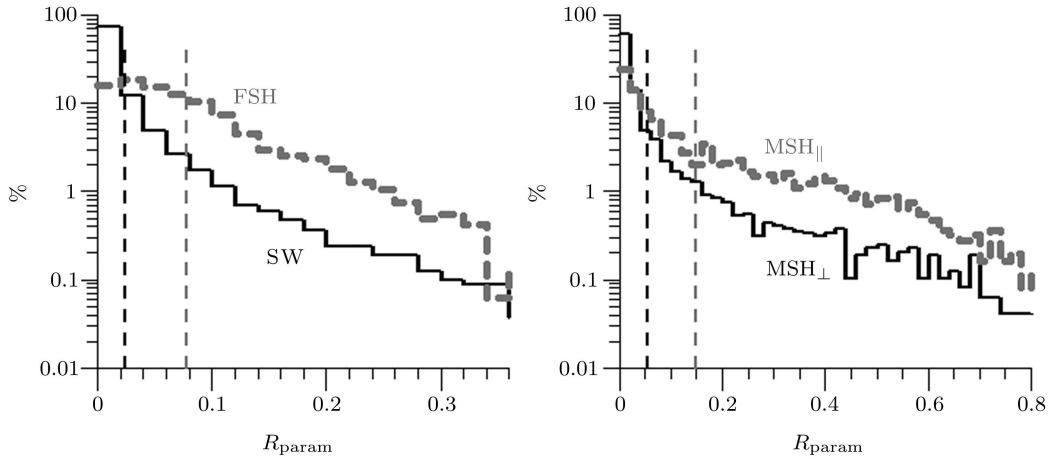


Fig.7. Histograms of R-parameter plotted using Interball-1 data in undisturbed solar wind, foreshock and magnetosheath (behind the quasi-parallel and quasi-perpendicular bow shock) in semi-logarithmic scale.

We have also calculated R-parameters for selected data sets in undisturbed solar wind, foreshock and quasi-parallel and quasi-perpendicular magnetosheath regions. The distributions of R in these regions are presented in Fig.7. In the undisturbed solar wind R is close to zero, indicating very small variations

of magnetic field direction. In the foreshock region the magnetic field fluctuates not only in magnitude (see Fig.5), but also in direction, and on the average $R \sim 0.08$. In the quasi-parallel magnetosheath region magnetic field is subjected to intensive variations of both the magnitude (see Fig.6) and direction, thus the developed turbulence dominates in this region. In the quasi-perpendicular region magnetosheath fluctuations of magnetic field direction are small ($R \sim 0.05$), while magnetic field magnitude fluctuations are rather intensive (RSD(B)$\sim$0.12), showing that compressive fluctuations dominate in this region.

5. Comparison with cluster data

We have also compared the results from Interball-1 data analysis with those from analysis of cluster magnetic field measurements during the period 01.2001–01.2003. The rule used to identify the different regions for cluster measurements is the same as that used for Interball-1 data. The selection of undisturbed solar wind and foreshock is based on the angle $\theta_{\boldsymbol{B}\mathrm{n}}$ and the correlation coefficient R(N/B) of the density and magnetic field magnitude. The intervals with R(N/B)< 0.2 and $\theta_{\boldsymbol{B}\mathrm{n}} > 45^\circ$ are considered for the undisturbed solar wind data analysis; the intervals with R(N/B)> 0.5 and $\theta_{\boldsymbol{B}\mathrm{n}} < 40^\circ$ are considered for foreshock data analysis. In the same way the identification of the quasi-parallel and quasi-perpendicular magnetosheaths is only based on whether the angle $\theta_{\boldsymbol{B}\mathrm{n}}$ was bigger than 45°. The results of cluster magnetic field data analysis are shown in Fig.8, while the histograms of R-parameter indicating the disturbance of magnetic field orientation in different regions are shown in Fig.9.

One can see that the results of cluster magnetic field data analysis are very similar to those of Interball-1 data analysis (see Figs.5 and 7). The average value of magnetic field magnitude in foreshock region is somewhat smaller than in undisturbed solar wind, and this value in the quasi-parallel magnetosheath is less than in the quasi-perpendicular one. The variations of magnetic field magnitude in undisturbed solar wind are very small and about 4 times less than in foreshock region. The distribution of magnetic field magnitude variations in the quasi-parallel magnetosheath is wider than that in the quasi-perpendicular one. Moreover, on the average the variations of magnetic field magnitude in quasi-parallel magnetosheath are about 2 times larger than those in the quasi-perpendicular one.

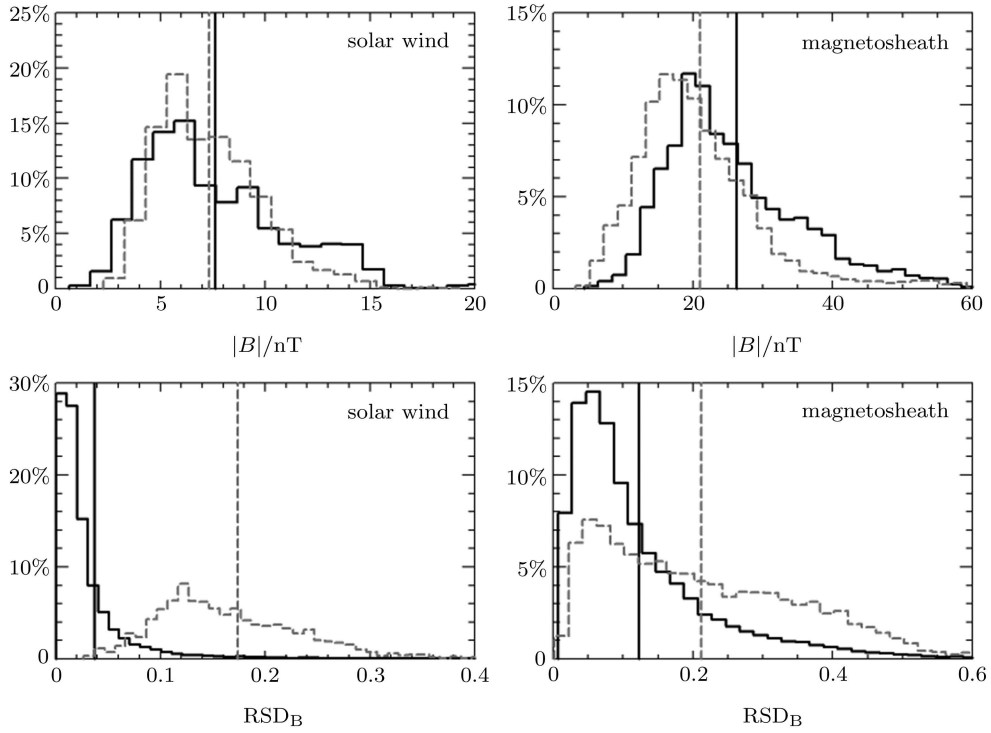


Fig.8. Histograms of magnetic field magnitudes (top panels) and their RSD(B) values on 4-min intervals (bottom panels) plotted using cluster data. On the left: solar wind (black solid curves) and foreshock (grey dashed curves) data; on the right: quasi-parallel (black solid curves) and quasi-perpendicular (grey dashed curves) magnetosheath data. Vertical lines indicate the average values of parameters.

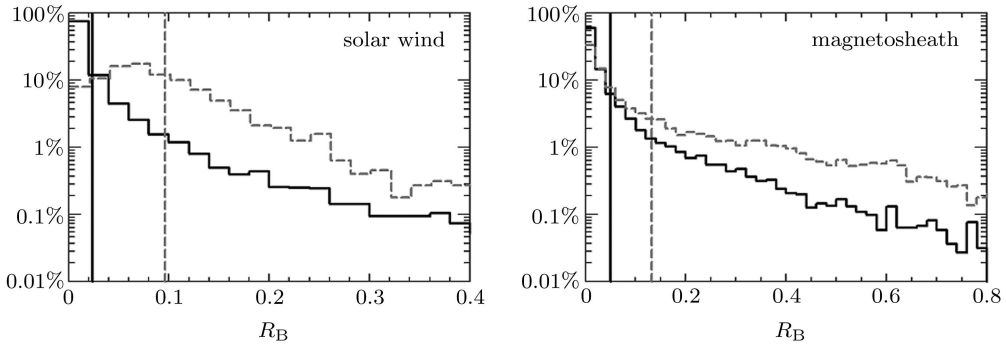


Fig.9. Histograms of R-parameter obtained from cluster magnetic field data analysis. On the left: solar wind (black solid curves) and foreshock (grey dashed curves) data; on the right: the quasi-parallel (black solid curves) and quasi-perpendicular (grey dashed curves) magnetosheath data.

The only difference between the results of cluster data analysis and those of Interball-1 data analysis is the mean of RSD(B) in foreshock. The mean value of cluster data is about 0.17 (RSD(B) = 0.17), which is higher than that of Interball-1 RSD(B) = 0.13. The reason for such a difference can be due to the difference between the orbits of spacecrafts. Interball-1 was located on the flanks and had an apogee about 200000 km, while cluster solar wind observations can generally be made in the subsolar region of the bow shock at a much smaller apogee ∼119000 km. The intensity of foreshock wave activity decreases with the distance from the bow shock.[20] Because the orbit of cluster is located closer to the bow shock, it should observe mainly strong foreshock. Near the apogee (see Fig. 2) Interball-1 can observe rather distant foreshock regions with smaller plasma and magnetic field wave activity, which will make the total statistics of variations in foreshock less disturbed.

Figure 9 shows the distributions of R-parameter in the regions considered. The distributions and average values are also very close to the results obtained from Interball-1 magnetic field data analysis. The average values of R-parameter and RSD, calculated using magnetic field magnitude and ion flux data of Interball-1 and cluster in undisturbed solar wind, foreshock and magnetosheath, are listed in Table 1. In undisturbed solar wind RSD values of ion flux and magnetic field magnitudes are very small, indicating a very low level of small-scale fluctuations of both the parameters, which are about 4% of the average background value. The magnetic field direction is also undisturbed with R-parameter about 0.02. In foreshock region the variations of both the parameters are very large and the magnetic field fluctuates not only in magnitude, but also in direction, with R ∼0.09. In the quasi-perpendicular magnetosheath the fluctuations of magnetic field direction are small (R ∼0.05–0.06), while those of magnetic field magnitude and ion flux are rather intensive (RSD(B) = RSD(F)∼0.12), which shows that the compressive fluctuations dominate in this region. In the quasi-parallel magnetosheath intensive variations of the ion flux and magnetic field are observed with amplitudes about 20% of the average background value. Magnetic field fluctuates not only in magnitude but also in direction, with R ∼0.14—a nearly developed turbulence is observed in this region.

Table 1. The mean values of R-parameter and RSD for ion flux and magnetic field variations in the undisturbed solar wind, foreshock, quasi-parallel and quasi-perpendicular magnetosheaths obtained from Interball-1 and cluster data.

SC		SW	FSH	MSHperp	MSHpar
Interball-1 (1–240s)	RSD(Flux)	0.04	0.13	0.11	0.18
	RSD (|B|)	0.04	0.13	0.12	0.21
	R-param	0.02	0.08	0.06	0.15
cluster (4–240s)	RSD (|B|)	0.04	0.17	0.12	0.21
	R-param	0.02	0.10	0.05	0.13

6. Conclusions

We have investigated the ion flux and magnetic field variations in time intervals of 1–240s in the regions of undisturbed solar wind, foreshock, quasi-parallel and quasi-perpendicular magnetosheaths using the measurements of Interball-1 and cluster spacecrafts. A large-scale statistics of observations in different regions and under the various conditions of solar wind is considered. A new method is applied to select the foreshock observations from the whole set of data in solar wind, based on the calculation of angle $\theta_{\boldsymbol{B}\mathrm{n}}$ and the feature of ion foreshock—high positive correlation of the variations in the ion flux (density) and magnetic field magnitudes.

Our study shows that in foreshock region the variations of parameters are about 3 times larger than in the undisturbed solar wind. Large-amplitude fast magnetosonic waves are observed in foreshock. It is accepted that these waves are generated by backstreaming ions, which are reflected by bow shock, through the ion–ion right-hand instability.[21,22] The features of the plasma and magnetic field turbulence in the magnetosheath are strongly controlled by the angle $\theta_{\boldsymbol{B}\mathrm{n}}$. In the magnetosheath regions topologically connected with the quasi-parallel bow shock the variations of amplitudes of ion flux and the magnetic field magnitudes are about 2 times larger and the magnetic field orientation is ∼3 times more disturbed than those in the magnetosheath regions connected with the quasi-perpendicular bow shock. The fluctuations observed in the quasi-perpendicular magnetosheath have a compressive nature. In general, it is known that the waves in the downstream of the quasi-perpendicular shocks are generated by ion temperature anisotropy. Under the high-beta conditions the mirror waves are dominant while under the low-beta conditions the proton cyclotron waves are dominant.[23−25] In the quasi-parallel magnetosheath a developed turbulence is observed.

The comparisons show that almost all the results of Interball-1 magnetic field data analysis are very similar to those of cluster data analysis not only in quality but also in quantity, in spite of the difference in observation period of about 4 years. The results of spacecraft observations considered in foreshock do not coincide well due to their difference in orbital motions—cluster spacecraft has a smaller apogee and a lower inclination.

We also obtain that, on the average, ion flux and magnetic field values in foreshock are a little smaller than those in undisturbed solar wind. This result is also obtained from cluster magnetic field data. Additional observation is required to clarify such a phenomenon.

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