INTERMITTENCY OF SOLAR WIND ION FLUX AT THE SCALE RANGE TILL TENS OF Hz

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Abstract. Solar wind is a flow of turbulent plasma. The investigation of it’s characteristics is very important part of the solution of the problem of the energy transport from the solar wind to the magnetosphere. The turbulence of the solar wind has the property of intermittency. Using data of Interball-1 spacecraft gives the possibility to study properties of solar wind turbulence in the not investigated previously frequency range under large statistics. The intermittency of solar wind ion flux fluctuations is studied using high time resolution measurements onboard Interball-1 spacecraft on scales from 0.01 to 16 Hz. The importance of the work is connected with the possibility for the first time to study the earlier unexplored (by plasma data) region of comparatively fast variations (frequency up to 16 Hz). So we significantly extend the range of intermittency observations of solar wind plasma. It is shown that the intermittency is practically absent on scales more then 1000 s and it grows to the small scales right up till $\tau = 30-60$ s. It’s behavior is rather changeable on smaller scale (less than 30 sec). Special attention is concentrated on the comparison of intermittency for intervals of solar wind observation containing SCIF (Sudden Changes of Ion Flux) to ones for intervals without SCIF. Such a comparison allows one to reveal the fundamental turbulent properties of the solar wind regions in which SCIF is frequently observed.

INTRODUCTION

Solar wind is variable by its nature and is full of fluctuations over a wide range of scales (spatial and temporal) which are strongly modified by the effects of the dynamics during the expansion into the interplanetary medium. The cascade of solar wind fluctuations of different scales shows the current solar wind turbulence (Coleman, 1986). The energy is transferred from large to small scales via a turbulent cascade. The structures of the various scales non-linearly interact between each other generating structures of other scales, till then energy is eventually dissipated into heat at molecular level (Marsch 1991). Solar wind fluctuations displays a multifractal structure and an intermittent character (Burlaga, 1991). The multifractal character of solar wind turbulent intermittent medium is described for example in papers (Milovanov et.al., 1996; Zeleniy and Milovonov, 1996) too.

Solar wind fluctuations cannot be described by a Gaussian statistics especially at a small scales (Marsch and Tu,1994, 1997;Marsch and Liu 1993). The PDF (probability distribution function) of solar wind fluctuations has fatter tails than Gaussian distributions. It means that extreme events have a higher probability than for a normal distribution. Such behavior of plasma and magnetic field variations in the MHD solar wind turbulence is a result of intermittency (the property of the medium at which the high activity regions alternate with quiescence regions). Classical power spectral analysis is not sufficient to completely describe the statistics of the fluctuations because it is based on the second moment of the PDF. Deviations from Gaussianity, i.e., intermittency may be quantified by the high-order moment of fluctuations (Burlaga,1991; Marsch and Tu, 1997). Non- Gaussian behavior of PDF of small-scale fluctuations of the solar wind velocity and interplanetary magnetic field could be presented as a convolution of Gaussians whose variances are distributed according to a lognormal distribution (Sorriso-Valvo et.,al., 1999). The authors used a method of the local intermittency measure (LIM). This method is based on the wavelet decomposition to single out the intermittent events from the time series (Bruno et.al, 2001). The Degree of the solar wind intermittency depends from the numerous factors. Thus compressive fluctuations are always more intermittent than directional fluctuations. Slow wind intermittency does not depend on the radial distance from the Sun, fast wind intermittency increases with the heliocentric distance (Bruno et.al., 2003).

In our previous papers we discussed the role of solar wind turbulent characteristics in forming of the contributory conditions to appearance of sudden change ion flux (SCIF) events (Riazantseva et.al., 2005). SCIF are characterized by rapid (sometimes less then 1 sec), large amplitude solar wind ion flux changes decreases or increases. The SCIF events are the small-scale and large-amplitude fluctuations, so they are the
part of solar wind fluctuation turbulent cascade. The SCIF events are non-uniformly distributed over the time scale. Some time periods of solar wind have many of these events, others very few; the difference may be due to different conditions of solar wind formation. One way to test this hypothesis is to determine the characteristics of solar wind turbulence in the regions with and without the SCIF events. Such analysis will be done in this paper for the intermittency characteristic of the turbulence.

Study of the turbulent behavior (including the intermittency) of very sharp fluctuations (with durations of several seconds or less as in our SCIF events) can extend the frequency range of solar wind turbulence investigations into the region of smaller time scales (down to 1 s). Intermittency for high frequency magnetic field data (up to 25 HZ) was investigated by (Alexandrova et.al., 2008). But the properties of the PDFs of plasma density fluctuations at the smaller scales were not known till now.

THE SELECTION OF THE DATA AND DESCRIPTION OF THE METHOD OF ANALYSIS.

An example on Fig.1 show the typical example of solar wind ion flux intermittent behavior - the high variability regions alternate with rather calm regions. This period contain a large numbers of SCIF (Sudden Changes of Ion Flux) (showed by arrows on Fig. 1). The study of intermittency degree was performed on the basis of analyzing of PDFs of the solar wind plasma and magnetic field scalar fluctuations on the various time scales.

\[
\delta \text{Flux}(t, \tau) = \text{Flux}(t+\tau) - \text{Flux}(t)
\]

and the same time rows for magnetic field scalar data:

\[
\delta B(t, \tau) = B(t+\tau) - B(t)
\]
are constructed for the time scales parameters $\tau$ from 0.1 s to 12 h. The PDFs of the fluctuations were calculated from these time rows for each value of $\tau$. In our previous work (Riazantseva and Zastenker, 2008) the evolution of the PDFs with time scale is observed for solar wind both with and without sharp flux changes. The PDFs for the largest time scales are near Gaussian but as the scales decrease the PDF tails become more and more flat. We use the statistical characteristics of these PDFs of parameter fluctuations such as flatness (4th order moment) (following paper (Bruno, et.al., 2003)) to investigate the intermittent behavior of the solar wind fluctuations. In particular the flatness (4th order moment):

$$F_\tau = S_\tau^4 / (S_\tau^2)^2$$  \hspace{1cm} (3)

where the structure function:

$$S_\tau^p = \langle |X(t+\tau) - X(t)|^p \rangle$$  \hspace{1cm} (4)

($\tau$- is the length-scale of the flux variation and $X$ is the investigated parameter). Since the flatness factor measures the sharpness of the peak of a distribution. This factor is a simple way to use the flatness to infer the character of the intermittency of the fluctuations. However, with this simplicity it is impossible to quantify the degree of intermittency and we can only evaluate whether a given sample is more or less intermittent than another one. If the flatness remains constant within a certain range of scales, it will indicate that those scales are not intermittent. So, in the next part we observe the result of such analysis.

**COMPARISON OF THE BEHAVIOR OF FLATNESS FOR ION FLUX AND MAGNETIC FIELD FLUCTUATIONS IN THE SLOW SOLAR WIND.**

First of all we decided to investigate the intermittency for slow solar wind without the SCIF events to have a possibility to compare the results with the results of previous works. Figure 2 shows the dependence of the flatness on the length-scale $\tau$ parameter, using 1 min resolution data.

The flatness is near 3 for large scales (it’s a typical situation for the Gaussian PDFs) and grows to the small-scale variations. So the degree of intermittency also increases at small scales. We have done the same analysis as for solar wind ion flux fluctuations, as for scalar magnetic field fluctuations. The dependences of flatness from the length scale parameters for these two cases are in close agreement within the limits of error. In paper (Bruno et.al., 2003) Bruno investigated the flatness of solar wind velocity and magnetic field fluctuations separately for slow and fast solar wind. Our results for the flatness (for ion flux and scalar magnetic field variations) are in good agreement with Bruno’s results for scalar magnetic field fluctuations in the slow solar wind. So our result confirms the previous one. The solar wind is self similar on the large scale and intermittent on the small scale. The intermittency grows to the small scale for $\tau$ from 1 min to 1 day.

![Fig.2](image_url) The behavior of flatness for ion flux and magnetic field scalar fluctuations with using 1 min Interball-1 data. The comparison with Bruno (2003) results for magnetic field scalar fluctuations.
The behavior of the flatness for ion flux and magnetic field scalar fluctuations for the solar wind with and without SCIF events revealed some differences in the intermittency behavior between the intervals with or without SCIF events. This helps to understand the nature of such events. The flatness for ion flux and scalar magnetic field fluctuations is shown in Fig. 3. The intermittency for intervals containing SCIF events is larger than for intervals not containing them. This difference disappears at large time scales (more than $10^4$ s) where the flatness approaches 3, typical for Gaussian PDF. The same behavior is observed for scalar magnetic field fluctuations. This result confirms that SCIF events are connected with the solar wind intermittency level, especially for small time scales.

**Behavior of the Flatness in the Solar Wind for the Small Scales Fluctuations.**

As discussed in part 2, in the paper (Bruno., et al., 2003) the intermittency for scales only more than $10^2$ s was investigated. The intermittency on high frequency (up to 25 Hz) was already studied in the paper (Alexandrova et al., 2008). However, this investigation focused solely on magnetic field data. We have access to high time resolution data up to 1 sec and, in some cases, up to 60 ms for plasma data. This allows us to investigate intermittency on very small scales as well. The results for different intervals of solar wind (from the numbers used in the analysis) are presented in Fig. 4. Each interval has a duration of 1-2 days and consists of high-resolution (1 sec) data. The behavior of flatness for the large scale (more than 30-60 sec) is stable and does not depend on the taken solar wind intervals. For the small scale up to 1 sec, the situation is more complicated, with the behavior of flatness parameter being absolutely different: it can increase, stay stable, or decrease. The behavior of flatness on the small scale is extremely unstable, which is of particular interest and seems to be related to the nature of turbulence. The prolongation of this dependence up to 0.1 sec is shown in Fig. 5 for 08. April of 1999. Flatness increases up to scale of 10 sec, decreases on scale up to 2 sec, and increases again up to 0.1 sec. Our result for ion flux and scalar magnetic field intermittency investigation resembles the results presented in paper (Alexandrova et al., 2008) for magnetic field $B_x$ intermittency behavior. The authors have obtained that, at the beginning, the flatness increases toward the small scales, then decreases, and then increases again at higher frequencies (10 Hz).

In spite of the variety of behavior of the flatness parameter for the small scale, the basic tendencies described in part 3 remain (see Fig. 4). The level of flatness is significantly higher for solar wind intervals with SCIF events than for solar wind intervals without them.
CONCLUSIONS.

A large degree of intermittency is observed in the solar wind ion flux and magnetic field magnitude time rows, and it grows to the small scales down to $\tau \approx 30-60$ s. Our results are in the good agreement with Bruno’s results (Bruno et. al, 2003) for scalar magnetic field fluctuations. But the statement in this paper that «probability distribution functions of a fluctuating field affected by intermittency become more and more peaked at smaller and smaller scales» is correct only right up till scale $\tau \approx 30-60$ s. We succeeded at the first time to investigate the intermittency behavior for the ion flux variation scales from $1$ to $10^2$ s. The behavior of the flatness for the scale less than $30-60$ s is not stable – it can increase, decrease or doesn’t change. The reason of this effect is not clear. The boundary between these two rates of intermittency is quantitatively near to the well-known boundary between the dissipation and inertial scales of fluctuations, what may point to their possible relation. The behavior of the flatness for ion flux and scalar magnetic field fluctuations for the
same time rows are very similar. Our result for the magnetic field and ion flux intermittency investigations for high frequency are in rather good agreement with Alexandrova’s results (Alexandrova et al., 2008) up to the scale of 0.1 sec.

The solar wind with the SCIFs (Sudden Changes of Ion Flux) is more intermittent than the solar wind without them. So the SCIFs appearance is connected with the solar wind intermittency level. These results suggest a fundamental difference in the solar wind turbulent properties if these sharp boundaries of the solar wind structures are present. The nature of such processes is not clear.

It is necessary to take into account that our results really have qualitative character, but their quantities characteristics in high frequencies region have rather bad accuracy, so the future studies are necessary.

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