# Dynamics of the Solar Wind

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A brief review of typical features of the variations in the solar wind parameters (plasma and magnetic field) over a very wide range of time-scales – from several years up to several seconds is presented. Some topics related to poorly known up to now - spatial correlation length, very fast (and sharp) variations in plasma density and magnetic field module and spectral features of solar wind dynamics are discussed.

## Introduction

Solar wind (SW) is highly variable medium in which a lot of fluctuations of plasma and interplanetary magnetic field (IMF) are observed in all measured ranges of frequencies (see, for example, paper [1]). The investigation of solar wind variations is very important as for fundamental solar and heliospheric physics as for pragmatic point of view – because these variations are the main agents control the magnetospheric magnetic field disturbances. The task of this brief review is to give to reader the general impression about solar wind dynamics at the Earth's orbit.

We summarize some main features of long-scale plasma and magnetic field fluctuations (in sections 1 and 2) and suggest to the reader's attention some quantitative characteristics of the middle- and small-scale variations obtained by our direct spacecraft measurements (especially for plasma) with very high time resolution (in sections 3 - 5).

## 1. Solar wind variability during solar cycle

On the basis of systematic solar wind observations during 1965-2002 it is possible to conclude that the monthly- or yearly-averaged solar wind parameters changes are rather small during the last four solar cycles (see, for example, [2]). As it is shown in mentioned paper the yearly-averaged value of IMF module is changed during the solar cycle not more than by 30%, value of bulk velocity – not more than by 50%, and value of solar wind dynamic pressure – not more than by 2 times. These values are in contrast with changes of many other solar parameters (flux of energetic particles, UV intensity, X-ray and radio bursts, number of flares and so on) which are more changeable during the solar cycle.

So, we can conclude that solar wind long-scale fluctuations is mainly the manifestation of solar processes more faster than the cycle period but more slowly than solar flares or similar changes of solar activity.

## 2. Long-scale variations in solar wind parameters

Significant solar wind variations may be found if we look at the data on the scale of day or several days. Typical example of systematic (during one year) observations of the main SW parameters – bulk velocity, density, and ion temperature is presented by their hourly-averaged values from [3]. These measurements were made by WIND spacecraft with 1.5 *min* time resolution.

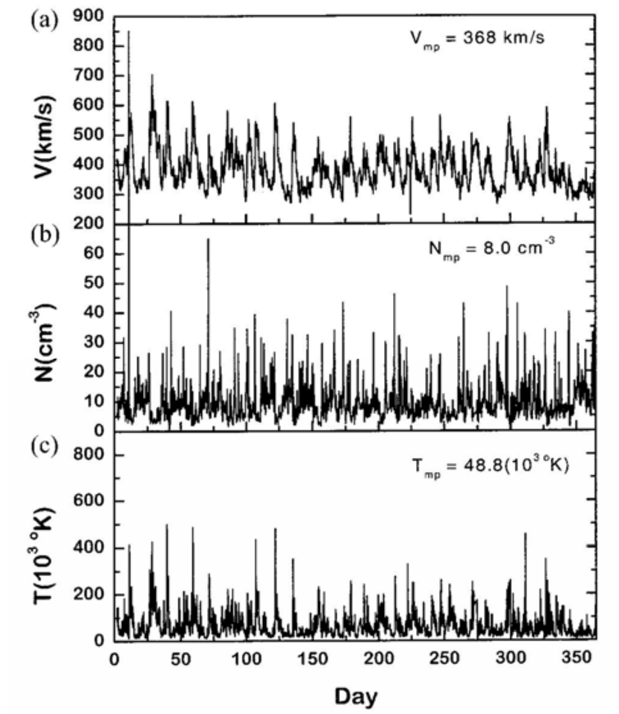


*Fig.1. Variations of hourly-averaged values of solar wind velocity (a), density (b) and ion temperature (c) during 1997 by WIND data. Mean values are written on the panels.*

It is clearly seen that variability of mentioned SW parameters is strongly expressed on such time scale. In average (except of some unusual events) the ranges of variations of hourly-averaged values are: for bulk velocity – 300-500 *km/s*, for plasma density – 5-20 $cm^{-3}$, for ion temperature – (30-200)·$10^3$ *K*.

In Fig.1 we can note in the beginning of year the very large peak of density – up to 150 $cm^{-3}$.

This unique observation took place during the well-known extreme event (one of the largest among the observed ones) – coming to Earth the magnetic cloud on January 10-11, 1997, as the result of the strong coronal mass ejection (CME) from the Sun (see, for example, [4]).

As conclusion of this section we need emphasize that usually solar wind parameters fluctuate on the scale of hours or days with amplitudes about 2 times for velocity and about 3-5 times for density and ion temperature. But in some Sun/heliospheric events the value of solar wind density can increase (or decrease) up to 10-30 times comparing with its average level.

## 3. Spatial correlations of middle-scale solar wind variations

The interesting and pragmatically important topic is the estimation of the correlation length of the SW parameters. This problem was investigated in details in our works by comparison of the simultaneous observations onboard several spacecrafts.

In Fig.2 we present the example of such comparison from the paper [5]. The panels "a" and "b" show the solar wind ion flux observations during 14 hours by three spacecraft – *IMP 8*, *WIND* and *Interball-1*. All data are shifted to the *Interball-1* position by solar wind propagation time. It is seen the very good coincidence (correlation coefficient is equal to 0.92-0.96) of the measurements by three spacecraft in spite that distances between them are up to 150 $R_E$ ($R_E$ is the Earth radii) along $X_{SE}$ axes and up to 30 $R_E$ in the plane perpendicular to $X_{SE}$ axes (we used the GSE coordinate system).

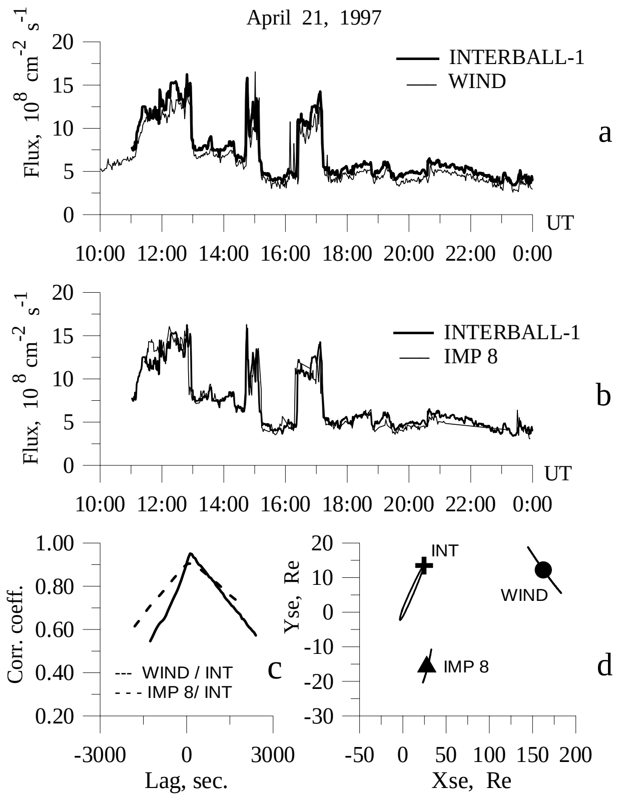


*Fig.2. Example of solar wind ion flux correlations by three spacecraft measurements.*

In the Fig.3 also we can see the large statistics of such comparisons for about 500 of 6-hours intervals of the SW ion flux measurements. It is seen that for 51% of intervals the correlations are very high - more than 0.8. For the 37% of intervals the correlations are rather fair - from 0.5 till 0.8. And only for 12% of intervals the correlations are poor – less than 0.5.

The analysis of large amount of such data [5] allows us to conclude that for solar wind middle-scale variations the persistent time of parameters is really more than 1 *hour* (usual time for solar wind propagation from L1 point to the Earth). We also conclude that the mean correlation length of solar wind parameters in the $Y_{SE}Z_{SE}$ plane is significantly larger than about 100 $R_E$. It means that this correlation length is larger than cross-section of the magnetosphere. This estimate is very important for space weather prediction based on observations near L1 point.

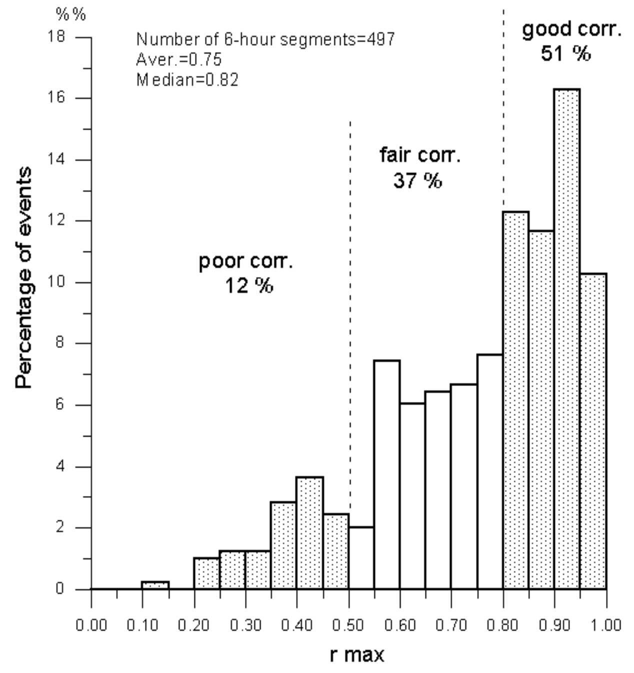


*Fig.3. Statistics of middle-scale structures correlations.*

## 4. Middle- and small-scale solar wind variations

Systematic investigations show that the relative standard deviation (RSD) of solar wind parameters is very convenient characteristic for the estimation of the levels of variations. Here the RSD is the ratio of usual standard deviation of parameter during some interval to the mean value of parameter in this interval. For middle-scale variations we used the 1 *hour* intervals with 1 *min* resolution measurements and for small-scale variations – 1 *min* intervals with 1 *sec* resolution measurements.

Based on our high time resolution measurements onboard *Interball-1* satellite we obtained some data for SW and IMF variations in the middle-scale and especially in small-scale ranges. In the Fig.4 (from paper [6]) there are the histograms of RSD distributions for ion flux and IMF module calculated with the large statistics of such variations. It is seen that these distributions have the long "tails" in the high variations' side.

So, using the presented data (see the Fig.4) we can conclude that as for ion flux, as for IMF module the average values of RSD for typical solar wind are equal about 3% for the fast (1 *sec*) changes and about 10% for more slow (1 *min*) changes. These values include evidently the result of operation of all kind of waves and plasma instabilities that take place in the solar wind when it comes to the Earth orbit. These estimations are important in practice for study of solar wind interaction with the magnetosphere.

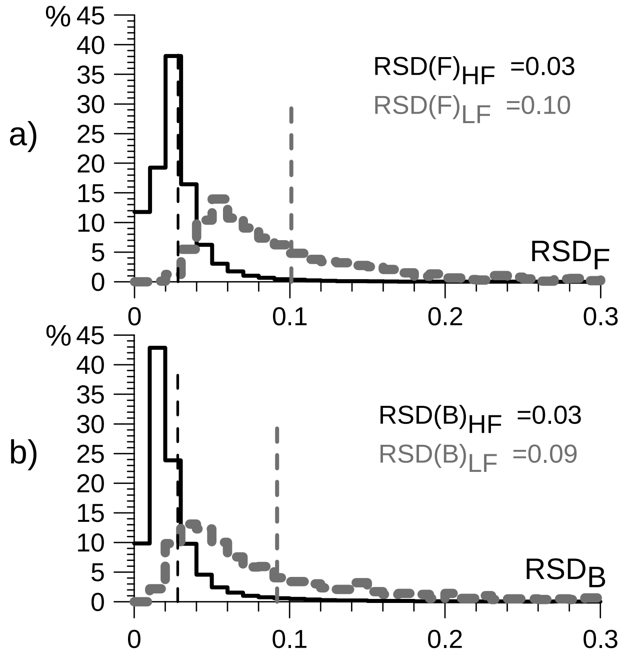


*Fig.4. Relative standard deviations (RSD) for ion flux (F) (panel a) and IMF magnitude (B) (panel b) for low (LF - gray) and high (HF - black) frequencies variations. Mean values are shown by dashed lines and are written on the panels*

It is necessary to mention that using SW measurements with high time resolution we observed rather often the sharp (with duration from several seconds to several minutes) and large (with amplitude from 20% to several times) changes of solar wind ion flux (density). These density changes are really the sharp boundaries of the solar wind middle-scale and small-scale structures (see, for example, [7]). In the Fig.5 we show two typical examples of such observations. On panel "a" it is seen the large (by 3 times increase relative to background) and sharp solar wind ion flux pulse with increasing front duration about 1 *min* and decreasing one duration about 5 *min*. This pulse was measured "simultaneously" by two widely separated (about 200 $R_E$) spacecraft *WIND* and *Interball-1* and their observations are very similar.

On panel "b" we show the large and very sharp ion flux pulse with duration only 6 *sec* and fronts as short as 0.5 *sec*. It is seen that magnetic field also changes with the same durations but in anticorrelation to the plasma density. Our estimation allows us to conclude that such a short plasma density increase or decrease belongs to the boundaries as thin as only a few proton gyroradii.

The large and sharp changes of solar wind density (and dynamic pressure) are very important for solar wind interaction with magnetosphere. As it was shown in paper [8] each such solar wind dynamic pressure variation have a response as a similar sharp disturbance of magnetospheric magnetic field and may generate some geomagnetic field pulsations.

Significantly large statistics of such events' observations allow us to conclude that such sharp solar wind structures boundaries are created somewhere in the solar wind and then conserve their shape and duration (or even are steepened) during the way from L1 point to the Earth (see paper [9]).

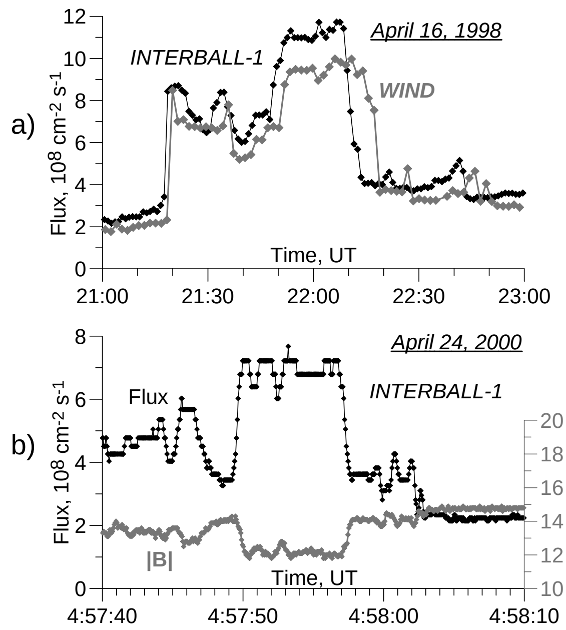


*Fig.5. Examples of short (a) and very short (b) solar wind ion flux and magnetic field pulses.*
*a) Interball-1 and WIND ion flux measurements with 1 min. resolution (WIND data are shifted by 3500 s on propagation time to Interball-1 position).*
*b) Interball-1 ion flux (F) and magnetic field (|B|) measurements with 60 ms resolution.*

## 5. Spectral features of solar wind variations

It is important for space plasma physics to investigate the power spectra of variations in solar wind ion flux in the wide range of frequency. An example of such spectra obtained by our measurements with very high-time resolution is presented in Fig.6 (from paper [10]).

It is shown that these spectra are well described by power law, but the slope of spectrum depends on the range of frequency. In the low frequency range ($10^{-4}$ – $3{\cdot}10^{-2}$ *Hz*) the slope of spectrum is well approximated by value $s = -1.1$. For the middle frequencies ($10^{-2}$ – $3{\cdot}10^{-1}$ *Hz*) the slope of spectrum is near $s = -1.7$. This value is very similar to the classic Kolmogorov's one (5/3) for the developed turbulence. For the highest frequencies from investigated ones ($7{\cdot}10^{-2}$ – 5 *Hz*) the spectrum is significantly steeper up to value $s = -2.2$. The difference in the slopes of spectra is connected with the difference of mechanisms creating the observed variations of SW parameters (some plasma waves and instabilities and so on) but these processes are not well investigated up to now.

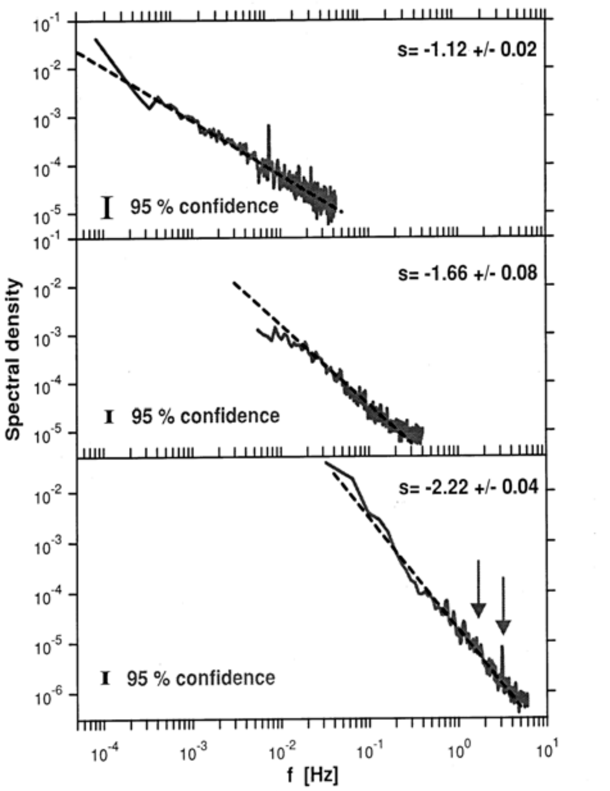


*Fig. 6. Power spectra of solar wind ion flux variations for three ranges of frequencies [10]. The slopes of the spectra (s) are written on the panels. Arrows mark the protons and alpha-particles' gyro-frequencies.*

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