ALFVÉNIC FLUCTUATIONS IN THE SOLAR WIND – ULYSSES DATA

EMIL POPESCU[2,1], NEDELIA ANTONIA POPESCU[1]

[1]*Astronomical Institute of Romanian Academy*
Str. Cutitul de Argint 5, 40557 Bucharest, Romania
[2]*Technical University of Civil Engineering,*
Bd. Lacul Tei 124, 020396 Bucharest, Romania
Email: epopescu@utcb.ro

Abstract. In this paper we analyzed the Alfvénic fluctuations in the solar wind, using data from SWOOPS and VHM instruments on board of *Ulysses* mission, for solar wind plasma parameters and magnetic field data for the year 2001. The results of this study underline the fact that, for the period when only fast stream is encountered at high heliolatitudes (between DOY 240 – DOY 348), the normalized cross-helicity σ_C has large positive values, and normalized residual energy σ_R has negative values. Also, the excess of the negative normalized cross-helicity is only the result of interplanetary processes.

Key words: interplanetary magnetic field – solar wind velocity – Alfvénic fluctuations.

1. INTRODUCTION

An important component of the turbulence measured in situ in the interplanetary medium is represented by Alfvén waves. Observations had long been limited to the ecliptic plane until recently, when the *Ulysses* spacecraft surveyed the solar wind at all latitudes.

In the ecliptic plane the solar wind structure is complicated due to the interaction of fast and slow solar wind streams. Here the Alfvénic turbulence is mainly limited to high speed streams from well delimited magnetic sectors.

Based on *Ulysses* spacecraft data, it was possible to observe that this structure, resulting from the mixture of slow and fast solar wind streams, disappears with increasing latitude, and leads to an almost constant high-speed stream (with a velocity of about 750 km s^{-1}) that originates from polar coronal hole. Inside the polar coronal holes the radial magnetic field seems to be almost constant with latitude. Here, large amplitude Alfvén waves propagating away from the Sun, covering a broad band of wavelengths, dominate the fluctuations at all points.

It is very well established that at solar maximum, because the coronal holes migrate towards the Sun's poles, in the ecliptic a predominance of slow wind is observed. For the minimum of the solar activity cycle, the solar wind presents a bimodal

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structure, consisting in a steady, fast wind at high latitudes and a slow and more variable wind at low latitudes (McComas *et al.*, 2000), or even an alternation of slow and fast streams at low latitudes.

The two solar wind regimes present different Alfvénic behaviour, with fast wind being more Alfvénic than slow wind.

2. ALFVÉN WAVES

In the solar wind, the magnetohydrodynamic (MHD) scale fluctuations are often predominantly Alfvénic. That means the velocity fluctuations vector, $\delta\mathbf{V} = \mathbf{V} - <\mathbf{V}>$, and magnetic field fluctuations vector, $\delta\mathbf{B} = \mathbf{B} - <\mathbf{B}>$, are correlated or anti-correlated for pure Alfvénic fluctuations according to the relation (Belcher and Davis, 1971; Marsch and Tu, 1993):

$$\delta\mathbf{V} = \pm\frac{\delta\mathbf{B}}{\sqrt{\mu_0\rho}}, \tag{1}$$

where ρ is the mass density (obtained by including both protons and alpha-particles), and μ_0 is the vacuum permeability (*i.e.*, permeability of free space, or magnetic constant with $\mu_0 = 4\pi 10^{-7}$ [NA^{-2}]). The mean fields $<\mathbf{B}>$ and $\mathbf{V}$ are calculated in the sequels as time averages.

The magnetic field fluctuations can be expressed in Alfvén unit (Barnes and Hollweg, 1974) as:

$$\delta\mathbf{V} = \pm\frac{\delta\mathbf{B}}{B_0}V_A, \tag{2}$$

where:

$V_A = \frac{B_0}{\sqrt{\mu_0\rho_0}}$ is the Alfvén speed;

$B_0 = |<\mathbf{B}>|$ is the magnitude of the average magnetic field;

$\rho_0 = <\rho>$ is the average solar wind density.

The radial velocity of the solar wind is larger than the Alfvén speed of the waves at distances from the Sun greater than 0.1 AU (Grappin *et al.*, 1982). At 1 AU solar wind speed is 10 times greater than Alfvén speed (typically $V_{SW} \sim 400$ km s^{-1} and $V_A \sim 40$ km s^{-1}).

The sign of the correlation in equation (2) determines if the propagation direction of an Alfvénic fluctuation is parallel or anti-parallel to the local magnetic field direction. If the sign is positive (negative) the Alfvénic waves move anti-parallel (parallel) to the field. In general, the sense of the observed correlation is related to the polarity, inward or outward, of the local magnetic field.

2.1. ALFVÉNIC FLUCTUATIONS IN THE SOLAR WIND – PARAMETERS DEFINITION

The state of the solar wind MHD turbulence can be characterized by the following parameters.

1) **Normalized cross-helicity** is a measure of correlation between magnetic and velocity fluctuations:

$$\sigma_C = \frac{2 < \delta\mathbf{v} \cdot \delta\mathbf{b} >_\tau}{< \delta\mathbf{v^2} + \delta\mathbf{b^2} >_\tau}, \tag{3}$$

with $-1 \leq \sigma_C \leq 1$.

2) **Normalized residual energy** is a measure of difference between the velocity and magnetic fluctuations energy:

$$\sigma_R = \frac{< \delta\mathbf{v} >_\tau^\mathbf{2} - < \delta\mathbf{b} >_\tau^\mathbf{2}}{< \delta\mathbf{v^2} + \delta\mathbf{b^2} >_\tau}, \tag{4}$$

with $-1 \leq \sigma_R \leq 1$.

3) **Alfvén ratio** is the ratio of velocity and magnetic fluctuations energy:

$$r_A = \frac{< \delta\mathbf{v^2} >_\tau}{< \delta\mathbf{b^2} >_\tau} = \frac{1+\sigma_R}{1-\sigma_R}. \tag{5}$$

4) **Correlation coefficient** between the vector $\delta\mathbf{v}$ and $\delta\mathbf{b}$ (Grappin *et al.*, 1982):

$$C_{VB} = \frac{< \delta\mathbf{v} \cdot \delta\mathbf{b} >_\tau}{\sqrt{< \delta\mathbf{v^2} >_\tau < \delta\mathbf{b^2} >_\tau}} = \frac{\sigma_C}{\sqrt{1-\sigma_R^2}}, \tag{6}$$

with $\sigma_R \neq \pm 1$.

In the above formula (3) - (6), $< \delta\mathbf{v} >_\tau$ is the solar wind velocity fluctuations averaged over time τ, and $< \delta\mathbf{b} >_\tau$ represents the magnetic field vector fluctuations averaged over time τ.

In studies on solar wind turbulence, the normalized cross-helicity was first used by Matthaeus and Goldstein (1982), and the normalized residual energy was first considered by Roberts *et al.*(1987).

Important remarks on the parameters σ_C and σ_R:

a) Normalized cross-helicity σ_C represents a relative measure of the energy balance between the two components of the Alfvénic turbulence;

b) Normalized residual energy σ_R represents the balance between kinetic and magnetic energy, in Alfvén units, normalized to the total energy;

c) The following relations hold: $-1 \leq \sigma_C \leq 1$, $-1 \leq \sigma_R \leq 1$, and $\sigma_C^2 + \sigma_R^2 \leq 1$;

d) Absolute values of $|\sigma_C| < 1$ correspond to a mixture of the two components and/or to the presence of non-Alfvénic variations in the solar wind parameters;

e) For ideal Alfvén waves: $\sigma_C \pm 1$ (where $+1$ indicates outward fluctuations, while -1 indicates inwards modes) and $\sigma_R = 0$ (*i.e.*, an equipartition between kinetic and magnetic energy). Thus, near maximal values of σ_C indicate the presence of highly Alfvénic fluctuations. During Alfvénic intervals the cross-helicity is high, but remains with absolute values $|\sigma_C| < 1$.

2.2. ELSÄSSER VARIABLES

Elsässer (1950) defined the **Elsässer variables**:

$$\mathbf{z}^{\pm} = \delta\mathbf{v} \pm \delta\mathbf{b}. \tag{7}$$

For simplicity, it was stated to always define $\mathbf{z}^{+}$ ($\mathbf{z}^{-}$) as an outward (inward) propagating mode (*i.e.*, an outward (inward) direction of propagation as seen from the Sun). This definition is correct as far as the interplanetary magnetic sectors are rectified (Roberts *et al.*, 1987), so that the background magnetic field is always pointing towards the Sun. This rectification can be done by rotating the magnetic field by 180^0, every time that it is directed towards the Sun.

For identifying a magnetic sector, Roberts *et al.* (1987) considered that the magnetic vector has to be positioned in the half-space encompassed by a plane perpendicular to the ecliptic and at 30^0 aside from the radial in the Earth's motion direction. This condition is equivalent with the relation $0.5 \cdot Br - 0.86 \cdot Bt > 0$, in terms of the radial (Br) and transverse (Bt) magnetic field components (Roberts *et al.*, 1987). The components of the interplanetary magnetic field in the RTN coordinates are (Br, Bt, Bn), where the three axes of the reference frame are as follows: R indicates the radial Sun-spacecraft anti-sunward direction, T is the tangential direction obtained from the cross-product between the solar rotation axis and R, and N is the normal direction which completes the frame.

For the energy (per unit mass) associated to the Elsässer variables, the formula

$$\mathbf{e}^{\pm} = < (\mathbf{z}^{\pm})^{\mathbf{2}} > \tag{8}$$

are considered.

The following definitions are often used:

$$\mathbf{e_C} = < \delta\mathbf{v} \cdot \delta\mathbf{b} > \quad (\mathbf{cross-helicity}), \tag{9}$$

$$\mathbf{e_R} = \mathbf{e^v} - \mathbf{e^b} \quad (\mathbf{residual\,energy}), \tag{10}$$

where $\mathbf{e^v}$ and $\mathbf{e^b}$ represent the kinetic and magnetic energy (per unit mass), respectively.

In terms of Elsässer variables, Tu and Marsch (1995) introduced the normalized cross-helicity and normalized residual energy with the following expressions:

$$\sigma_C = \frac{\mathbf{e}^{+} - \mathbf{e}^{-}}{\mathbf{e}^{+} + \mathbf{e}^{-}}; \quad \sigma_R = \frac{\mathbf{e^v} - \mathbf{e^b}}{\mathbf{e^v} + \mathbf{e^b}} \tag{11}$$

Is important to underline that, in terms of Elsässer variables, σ_C indicates how much an inward or outward mode is dominant with respect to the other.

Another important relation used in the study of solar wind turbulence is the **Elsässer ratio**

$$r_E = \frac{\mathbf{e}^-}{\mathbf{e}^+}. \tag{12}$$

3. THE STUDY OF SOLAR WIND TURBULENCE FOR *ULYSSES* DATA

3.1. *ULYSSES* MISSION POLAR PASSES

The periods during which the *Ulysses* spacecraft was positioned at heliographic latitude above 70^0 in the two hemispheres represent the *Ulysses* polar passes. The mission was designed such that the total duration of the polar passes to be maximized, with a minimum period of 150 days. The *Ulysses* mission studied phenomena strongly influenced by the 11 year solar activity cycle, as well as by the 22 year Hale solar magnetic cycle. Have to be noticed that from launch on 6 October 1990 to the Jupiter encounter in February of 1992, *Ulysses* travelled at solar maximum conditions in the solar cycle 22.

The *Ulysses* spacecraft operated the first fast latitudinal scan (FLS I) and polar passes in the period 1994 June (South) - 1995 September (North), during the descending phase of solar cycle 22, close to sunspot minimum (which occurred later, in 1996).

The second fast latitude scan and polar passes occurred in 2000 September (South) – 2001 December (North), during the maximum phase of solar cycle 23. It is noticeable that the maximum sunspot numbers were recorded around the southern and northern polar passes, while the equatorial pass of the second fast latitude scan was inside the Gnevyshev gap. This is the phase in the solar cycle when after a first maximum an apparent decrease of the activity appears followed by a further increase (Gnevyshev, 1977).

In 2001 the polarity reversal of the Suns polar cap magnetic fields occurred, a global reconfiguration of the heliospheric magnetic field taking place. An important feature of the solar cycle 23 is represented by the magnetic polarity change of the Sun that took place on 14 August 2001.

After the solar magnetic field reversal, a recovery of the bimodal structure of the solar wind starts soon. *Ulysses* observations at high latitudes indicate a constant high-latitude fast wind (greater than 700 km s^{-1}).

The third and the last fast latitudinal scan and polar passes happened during the period 2006 November (South) – 2008 March (North), at the minimum phase of the cycle 23, and the beginning of the cycle 24 (on 8 January 2008 the new cycle started). During this last scan, *Ulysses* obtained high heliolatitudes measurements near minimum solar activity conditions, in the conditions of the opposite magnetic field polarity compared with the first rapid scan 1994 – 1995. By means of such measurements, detailed understanding of the propagation of cosmic rays and solar energetic particles in the heliospheric magnetic field can be obtained.

Ulysses mission provided observations that clearly established different solar wind behaviour at different phases of the solar activity cycle. For a large period of the cycle around **solar minimum**, an almost unchanged characteristic is observed, which is represented by the **bimodal regime**.

This one consists of a fast and uniform flow, encountered at high heliographic latitudes (the so-called polar wind), and slower and more variable flows, originating from a belt around the equatorial plane (McComas *et al.*, 2000). The boundary between these two sorts of wind is positioned at latitudes between 15^0 to 30^0.

During **solar maximum** the conditions encountered by Ulysses were totally different from those during the Solar Minimum Mission, especially in the polar regions. The extended polar coronal holes disappeared and have been replaced by smaller and short lived coronal holes at all latitudes. The process of vanishing and then reversing polarity were encountered for the polar cap magnetic fields. In the southern hemisphere *Ulysses* observed fast and slow wind at all latitudes. The *Ulysses* Solar Maximum Mission constituted a practically new mission with specific scientific goals.

The Heliospheric Current Sheet (HCS) was highly inclined during the solar maximum, in contrast with the low inclination at solar minimum.

3.2. THE STUDY OF THE SOLAR WIND TURBULENCE – *ULYSSES* DATA FOR 2001

In the sequel the study of the turbulence of the solar wind for the year 2001 is realized using data from instruments on board of *Ulysses* spacecraft as follows: for solar wind plasma parameters – hourly data from SWOOPS; for magnetic field data - hourly data from VHM. The data are obtained from `http://ufa.esac.esa.int/ufa`.

It is known that the fast solar wind originates in large coronal holes and is relatively uniform in speed, density, temperature, while the slow solar wind originates in the hot corona and is highly variable in speed, density, temperature. For the variances in magnetic field magnitude and its radial component a little change is encountered, between fast and slow solar wind streams. A significant decrease in the variance of the transverse magnetic field components, Bt, in slow and mixed velocity streams is usually detected. But, for the transverse magnetic field components, Bt, the variances are generally larger in the fast wind. A very bursty character is present for all variances.

The normalized variances of the magnetic field components, (Br, Bt, Bn), and of the magnetic field magnitude are determined for several temporal scales with the

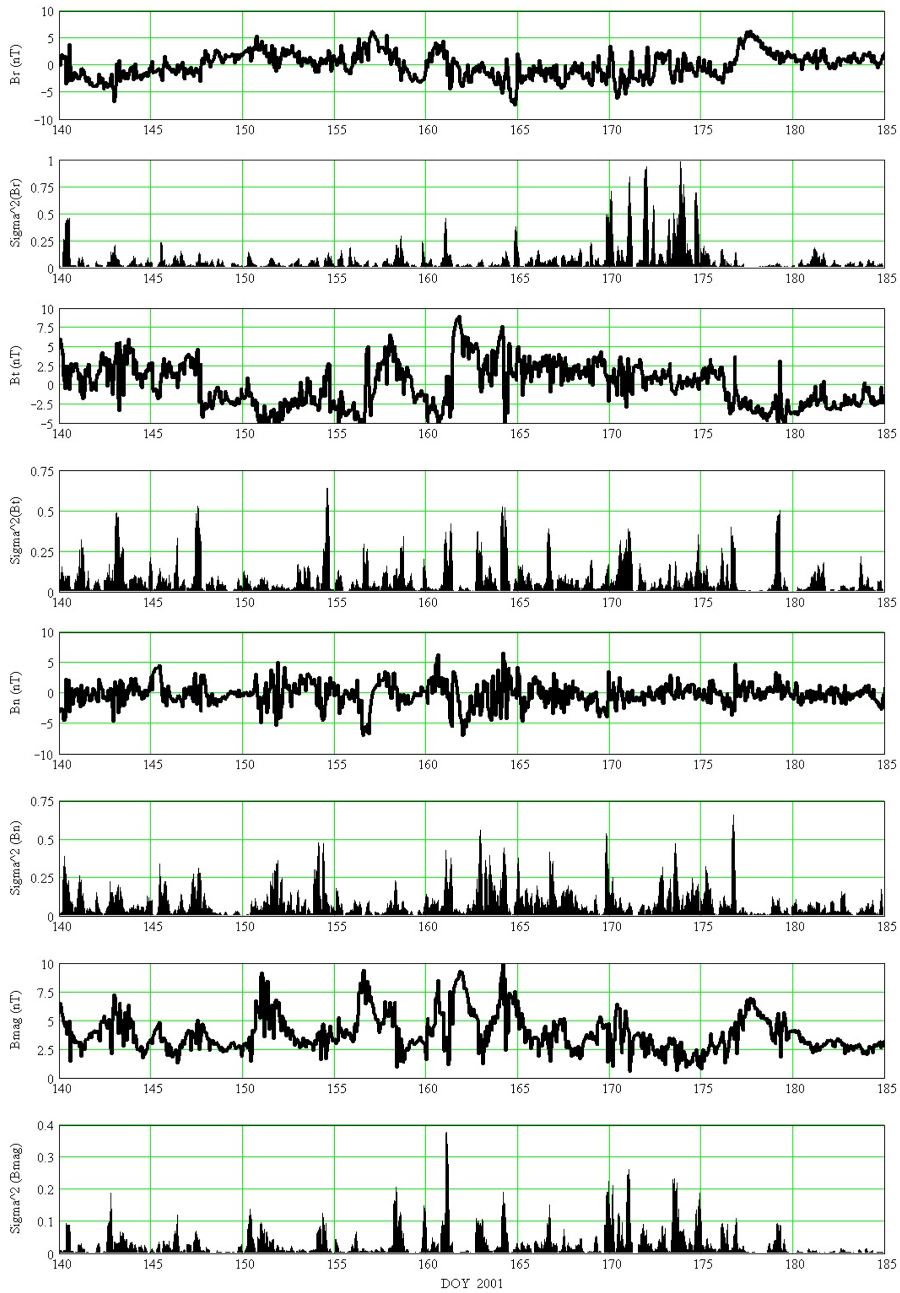

Fig. 1 – The (Br, Bt, Bn), B_{mag}, $(\sigma_r^2, \sigma_t^2, \sigma_n^2)$, and σ^2 for the interval DOY 140 – DOY 185.

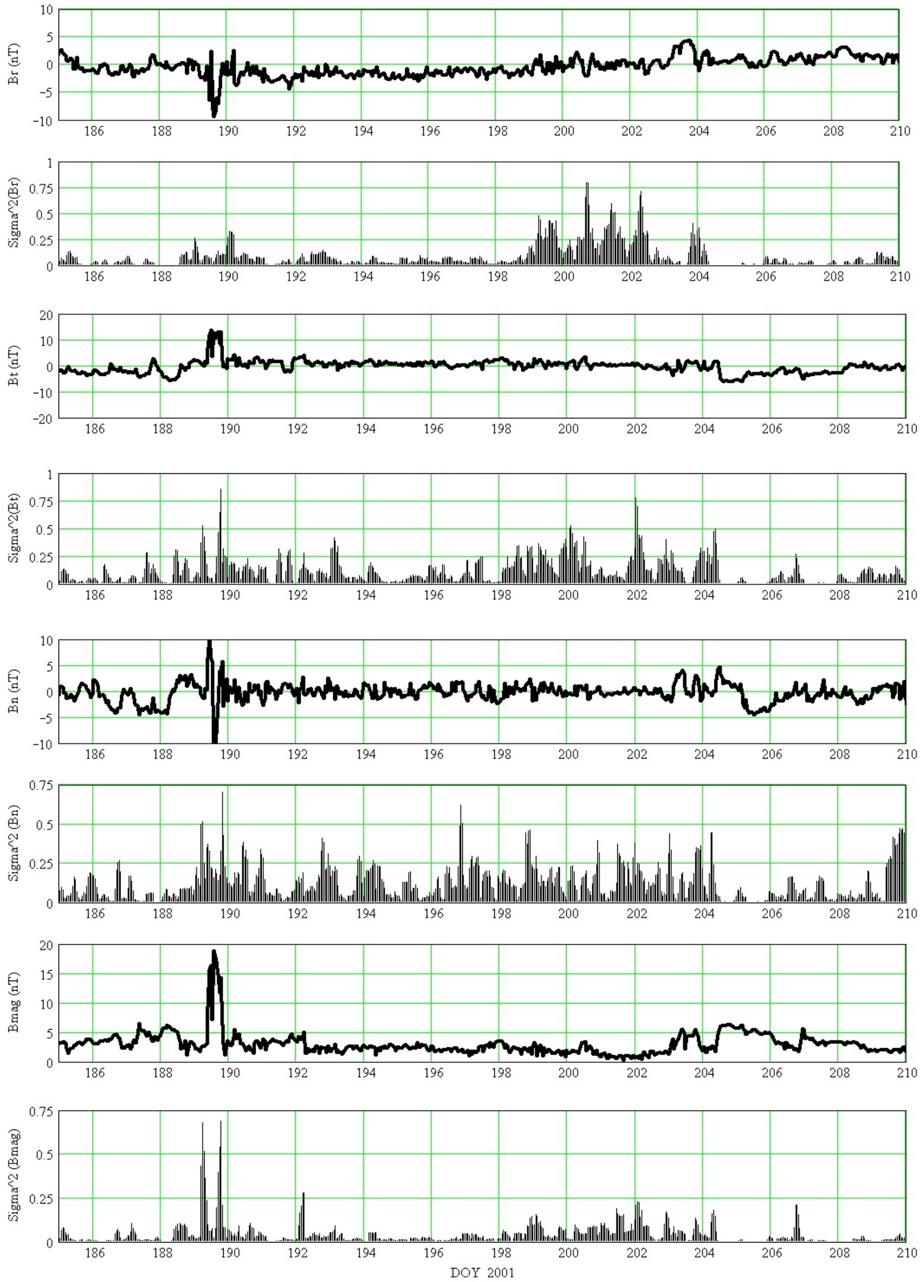

Fig. 2 – The (Br, Bt, Bn), B_{mag}, $(\sigma_r^2, \sigma_t^2, \sigma_n^2)$, and σ^2 for the interval DOY 185 – DOY 210.

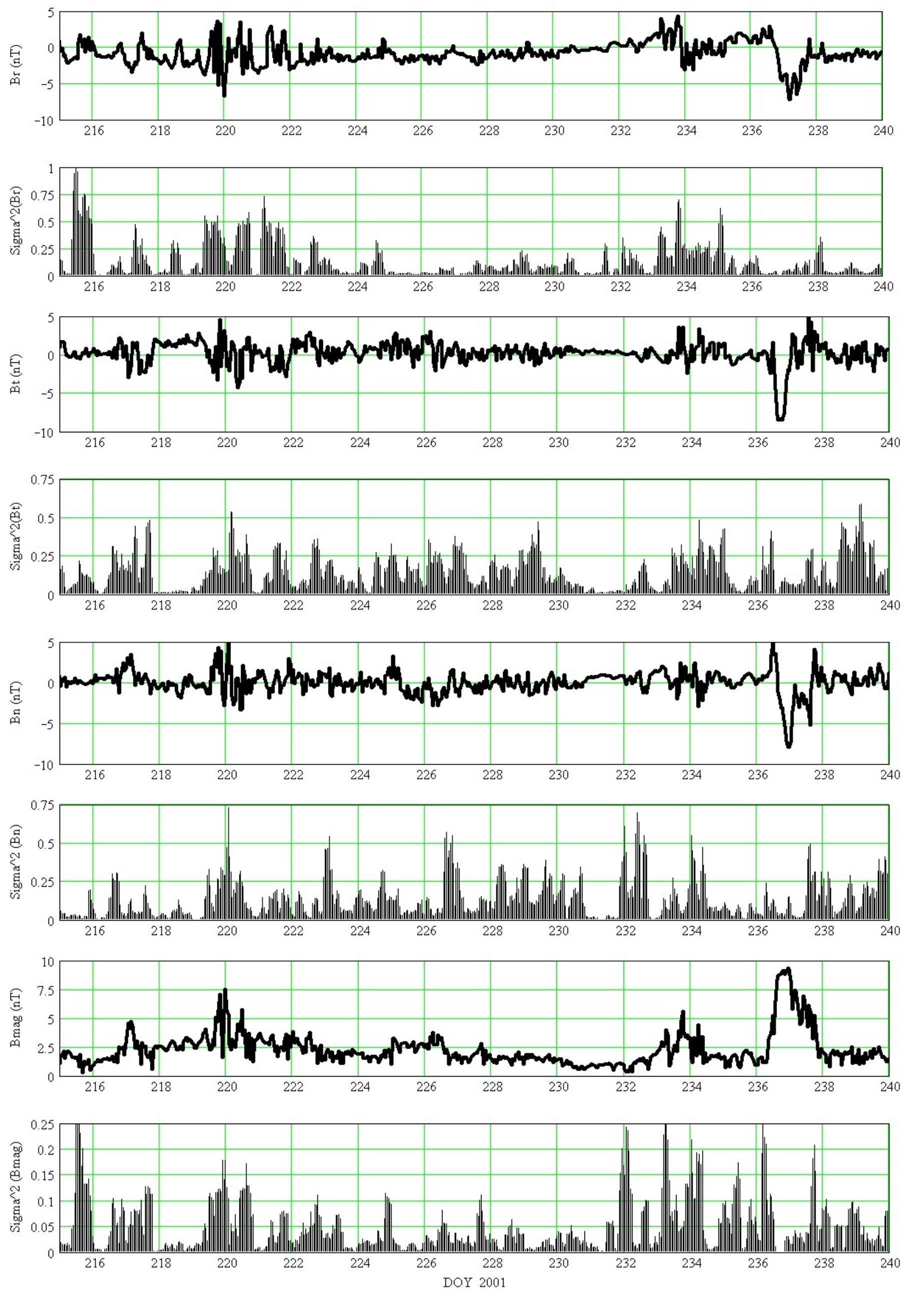

Fig. 3 – The (Br, Bt, Bn), B_{mag}, $(\sigma_r^2, \sigma_t^2, \sigma_n^2)$, and σ^2 for the interval DOY 215 – DOY 240.

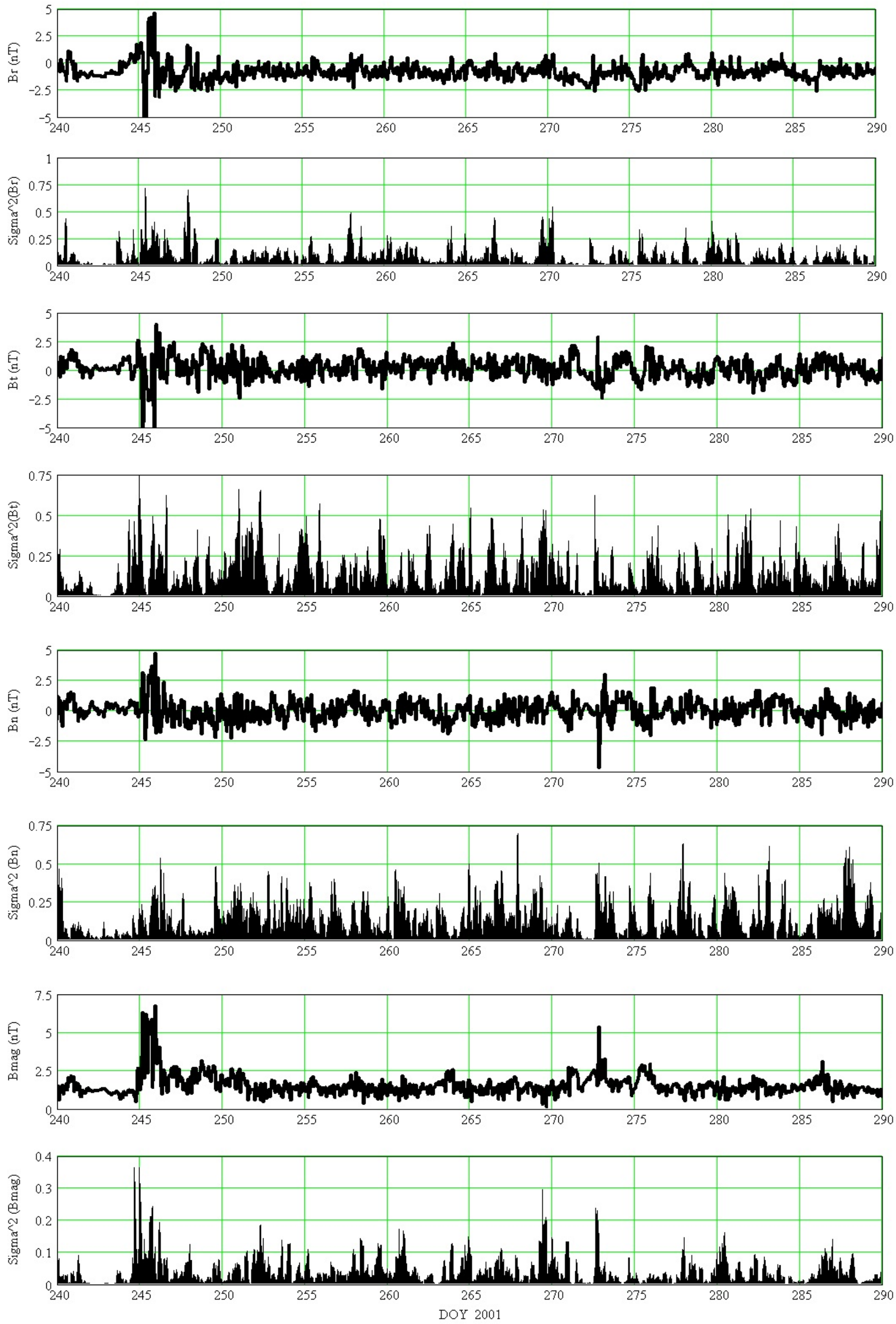

Fig. 4 – The (Br, Bt, Bn), B_{mag}, $(\sigma_r^2, \sigma_t^2, \sigma_n^2)$, and σ^2 for the interval DOY 240 – DOY 290.

following formula:

$$\sigma_i^2 = \frac{1}{n_w} \sum_{m=1}^{n_w} \frac{< B_{m,i} - < B_m >>^2}{|\mathbf{B}|^2}, \tag{13}$$

where $i = r, t, n$; n_w represents the number of points included in a temporal window of length τ; $|\mathbf{B}| = \sqrt{(\mathbf{Br})^2 + (\mathbf{Bt})^2 + (\mathbf{Bn})^2}$ is the absolute value of the magnetic field vector.

Commonly, in order to eliminate any magnetic field strength dependence, the variances are normalized to the magnetic field magnitude.

In Figs.1 – 4 from upper to lower panels we present:

- the components of the interplanetary magnetic field in RTN coordinates, denoted (Br, Bt, Bn) (panels 1, 3, 5);

- the absolute value of the magnetic field vector (panel 7, denoted B_{mag});

- the corresponding normalized variances σ_r^2, σ_t^2, σ_n^2, σ^2 (panels 2, 4, 6, 8), all as function of time.

The time is expressed in day of the year (DOY), starting with DOY 140 and ending with DOY 290. The analyzed data covered the periods when *Ulysses* traversed the equator, and passes through mid-heliolatitudes to high-heliolatitudes regions, reaching latitudes of 80.22^0 N.

In the case presented in Figs.1 – 4, the data are smoothed for a $\tau = 4$ – hours temporal window. The magnetic field components present well defined large-scale features (corresponding to some transient events), that can be recognized in the behaviour of the relevant normalized variances. Generally, the presence of the interplanetary mass ejections (ICMEs) corresponds to a sudden drop in the magnetic field variances (see panels 2, 4, 6, and 8 in Figs.1 – 4).

We followed the prescriptions of Roberts *et al.* (1987) on the rectification of the background magnetic field polarity such that $\mathbf{z}^-$ ($\mathbf{z}^+$) always corresponds to an outward (inward) direction of propagation of the Alfvnic fluctuations in the solar wind frame, as seen from the Sun. The results for different averaging times (4 and 16 hours) for the normalized cross-helicity, σ_C, and normalized residual energy, σ_R, are presented in Fig.5 and Fig.6, respectively.

It is well established that the normalized cross-helicity, σ_C, depends on the solar wind velocity regimes, having large positive values within fast stream and values close to 0 for slow streams. The normalized residual energy, σ_R, usually has negative values (Tu and Marsch, 1995).

The excess of the negative normalized cross-helicity, σ_C, can only be the result of interplanetary processes. Inside the rarefaction region (*i.e.*, region where transition from fast to slow winds takes place), σ_C tends to have negative values for longer time intervals (Bavassano *et al.*, 2006), as well as close to zero values of the σ_R. In both Figs. 5 and 6, for the period between DOY 240 – DOY 348, when only fast stream

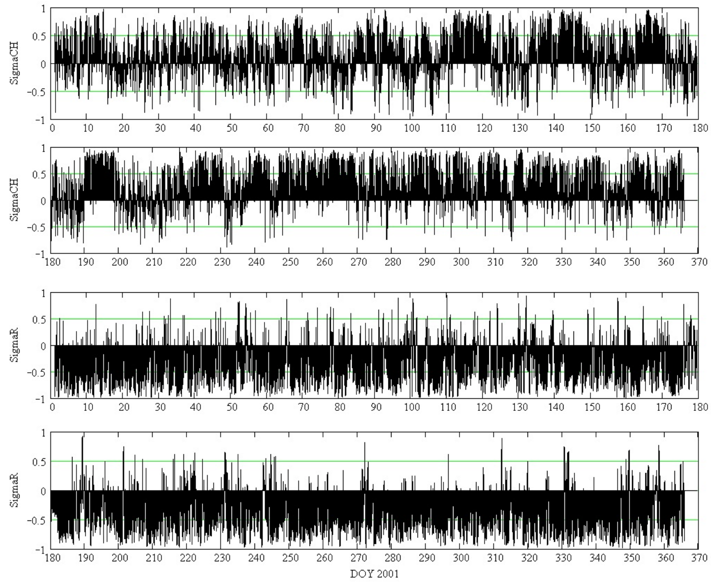

Fig. 5 – The normalized cross-helicity σ_C (panels 1 and 2), and normalized residual energy σ_R (panels 3 and 4), smoothed with a 4-hour window (*Ulysses* data for entire year 2001).

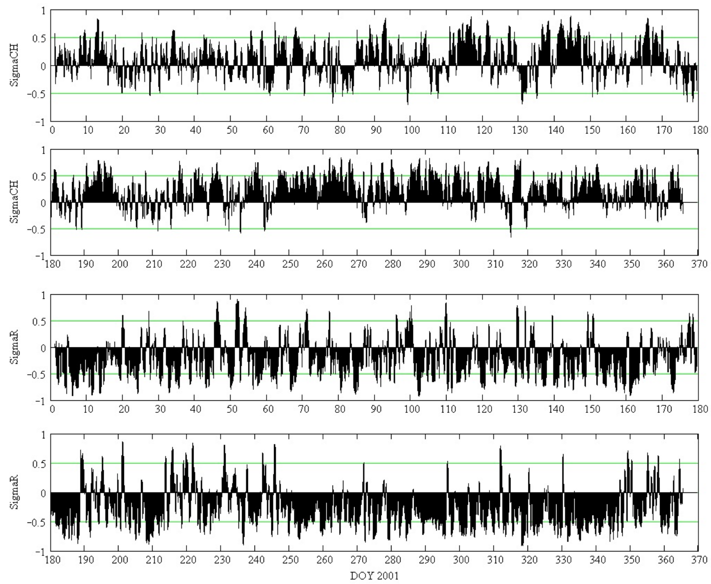

Fig. 6 – The normalized cross-helicity σ_C (panels 1 and 2), and normalized residual energy σ_R (panels 3 and 4), smoothed with a 16-hour window (*Ulysses* data for entire year 2001).

is encountered at high heliolatitudes, the normalized cross-helicity has large positive values and normalized residual energy has negative values.

The Alfvén ratio, Elsässer ratio and coefficient C_{VB} are depicted in Fig. 7, for the period DOY 140 – DOY 290. Again, for the period starting with DOY 240, when only fast stream is encountered at high heliolatitudes, it is obvious that C_{VB} is only positive with values approaching to 1, excepting for two periods when two rarefaction regions are present (the period between DOY 244 – DOY 246, and around DOY 272). $C_{VB} = 1$ is a result of the in-phase $\delta\mathbf{v}$ and $\delta\mathbf{b}$ of different amplitude. Also, for this interval of time positive but less than 1 values of σ_C are present (see also Fig. 6, panel 2).

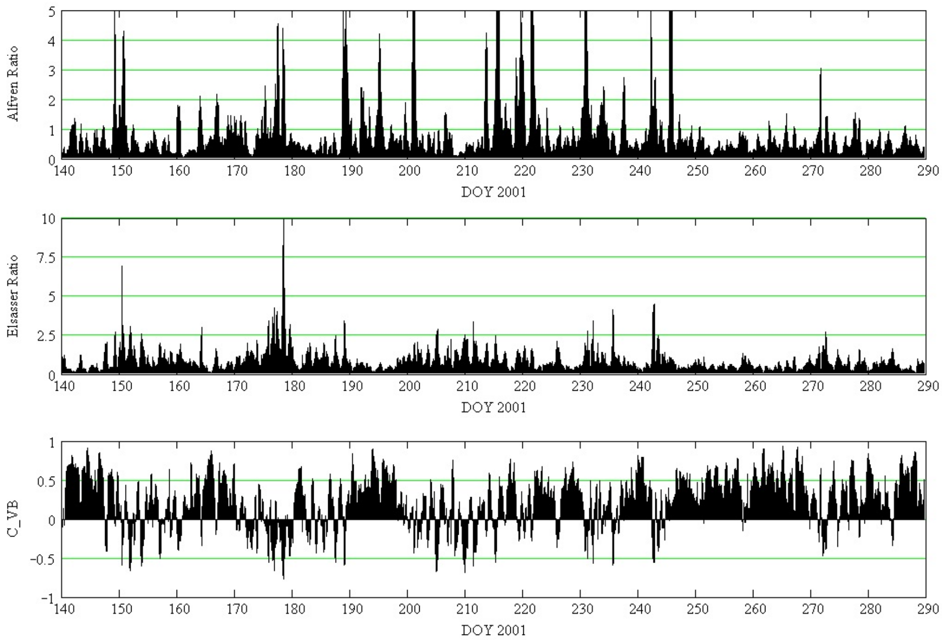

Fig. 7 – The Alfvén ratio, Elsässer ratio and coefficient C_{VB} determined for the interval DOY 140 – DOY 290 (determined for a 16-hour window).

In a forthcoming paper, the results on the behaviour of the normalized cross-helicity, σ_C, and normalized residual energy, σ_R, at different heliolatitudes will be presented, together with the analysis of the changes in the Alfvénicity of the magnetic field fluctuations, produced by the ICMEs' presence.

4. CONCLUDING REMARKS

In the present paper we analyzed the Alfvénic fluctuations in the solar wind for the year 2001, based on the data from SWOOPS instrument (for solar wind plasma data) and VHM instrument (for magnetic field data), on board of *Ulysses* mission. The results of this study underline the fact that for the period when only fast stream is encountered at high heliolatitudes (between DOY 240 – DOY 348), for the transverse magnetic field components, Bt, the variances σ_t^2 are larger than for the periods with slow wind. Also during this period, the normalized cross-helicity σ_C has large positive values and normalized residual energy σ_R has negative values. The excess of the negative normalized cross-helicity, σ_C, can only be the result of interplanetary processes.

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