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Anomalous scaling in solar wind fluctuations

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Abstract. We discuss the radial evolution of the scaling properties of interplanetary magnetic field and velocity fluctuations observed in the solar wind. We found that the radial increase of intermittency can be explained by the competing action between stochastic and coherent fluctuations. While stochastic fluctuations are due to propagating Alfvén waves, coherent structures are likely to be represented by the border between adjacent convected flux tubes imbedded in the wind.

Key words. Solar Wind – MHD turbulence – Non–linear dynamics

1. Introduction

Solar wind is a magnetofluid pervaded by fluctuations over a wide range of scales which are strongly effected by the dynamics during the expansion into the interplanetary medium. Large fluctuations of solar origin containing energy interact non–linearly with other fluctuations of local origin giving rise to an energy exchange between different scales, eventually producing an energy cascade towards smaller scales. This phenomenology seems to be in agreement with Kolmogorov's model (Kolmogorov, 1941) since a typical spectral slope close to -5/3 can be generally found in the solar wind fluctuations. However, solar wind turbulence is strongly anisotropic and poorly single scale–invariant (see review by Tu and Marsch, 1995), two of the fundamental hypotheses at the base of Kolmogorov's theory. Moreover, since the probability distribution function (PDF) of these fluctuations is not Gaussian, a classical spectral analysis is not sufficient to fully describe them and it is necessary to look at higher order moments of the PDFs. These other moments can be obtained directly from the differences of the fluctuating field over all the possible spatial scales. Once this new approach was employed within the solar wind context (Burlaga, 1991; Marsch and Liu, 1993; Tu and Marsch, 1993; Carbone et al., 1995), it revealed the highly intermittent character of interplanetary fluctuations, i.e. the global scale invariance required in the Kolmogorov theory was reduced to a local scale invariance (in k–space) where different fractal sets were characterized by different scaling exponents (see Frisch, 1995,

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Table 1. From left to right: time interval in dd:hh, heliocentric distance in AU, average wind velocity in km/sec

time interval	radial distance	$< \mathbf{V} >$
105:12–107:12	0.29	729
99:12–101:12	0.34	405
75:12–77:12	0.65	630
72:00–74:00	0.69	412
49:12–51:12	0.88	643
46:00–48:00	0.90	433

and references therein). In practice, PDFs at large scales are quite similar to Gaussian distributions but, at smaller scales the tails of the distributions become higher and higher than expected for a Gaussian. As a consequence, the value of the flatness factor of these distributions would increase with decreasing the scale of interest. Sorriso–Valvo et al., (1999) studied quantitatively the effect of intermittency on the PDFs of the increments over different scales and, adopting Castaing's model (Castaing et al., 1990), showed that the non-Gaussian behavior of the PDFs of solar wind fluctuations at small scales can be represented by a convolution of Gaussians whose variances are distributed according to a log-normal distribution. Thus, intermittency can be simply estimated looking at the behavior of the flatness factor of the PDFs for different scales. Following Frisch, (1995), a time series can be considered intermittent if this parameter increases as the scale of interest becomes smaller. In the following we report about the radial behavior of the flatness factor at different scales as a function of the solar wind velocity regime within the inner heliosphere.

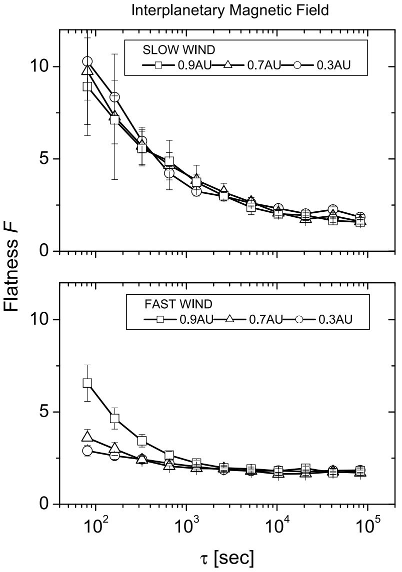

Fig. 1. Flatness factor $\mathcal{F}$ for magnetic field fluctuations as a function of time scale expressed in seconds. The upper panel refers to slow wind, the lower panel refers to fast wind. The three different symbols refer to three different heliocentric distances as illustrated at the top of each panel.

2. Data Analysis and Results

We used 81 sec averages of magnetic field and plasma data recorded by Helios 2 s/c during 1976. The analyzed time intervals with the corresponding heliocentric distances and solar wind speed are listed in Table 1. Helios data is extremely valuable since it is the only existing interplanetary data set recorded between 0.3 and 1 AU. Moreover, Helios observed the same corotating fast stream at different heliocentric distances during consecutive solar rotations allowing us to estimate the radial gradients of physical parameters. We computed, scale by scale, the following flatness estimator

$$F(\tau) = \frac{< S^4(\tau) >}{< S^2(\tau) >^2}$$

where τ is the time scale of interest and $S^p(\tau) =< |f(t+\tau) - f(t)|^p >$ is the Structure Function of order p of the generic function $f(t)$. The flatness factor $\mathcal{F}$ was studied for vector fluctuations,

$$\delta \boldsymbol{f}(t,\tau) = \sqrt{\sum_{i=x,y,z} (f_i(t+\tau) - f_i(t))^2}$$

Fluctuations with no intermittency would keep the value of $\mathcal{F}$ constant throughout the range of scales, otherwise, $\mathcal{F}$ would increase at smaller scales. Moreover, values of $\mathcal{F} \sim 3$ at a given scale would suggest that fluctuations are gaussianly distributed. The behavior of $\mathcal{F}$, for magnetic field fluctuations and for both slow and fast wind, is shown in Figure 1 as a function of time scale. The three different curves in each panel refer to three heliocentric distances and confirm that both fast and slow wind are intermittent since $\mathcal{F}$ increases at smaller scales. The radial excursion influences only the fast wind which shows an increasing intermittency as the distance from the sun increases. In addition, since $\mathcal{F}$ increases at small scales more slowly for fast than for slow wind, these last one can be considered more intermittent. In particular, $\mathcal{F}$ within slow wind starts to increase at much larger scales than in fast wind, suggesting that intermittency is already present at hourly scales.

Results relative to fast and slow wind velocity fluctuations are shown in Figure 2 in the same format as of the previous Figure. Although the general trend shown in both panels confirms that intermittency increases with distance also for wind velocity, we notice that within slow wind these fluctuations are generally slightly less intermittent than the corresponding magnetic field fluctuations. Moreover, the behavior of these curves doesn't depend on heliocentric distance. On the contrary, the behavior of $\mathcal{F}$ within fast wind (lower panel) suggests that the intermittency of these fluctuations is quite similar to that of magnetic field fluctuations (Figure 1, lower panel). This last result, as it will be discussed in the next section, derives from the strong contribution given by Alfvénic fluctuations.

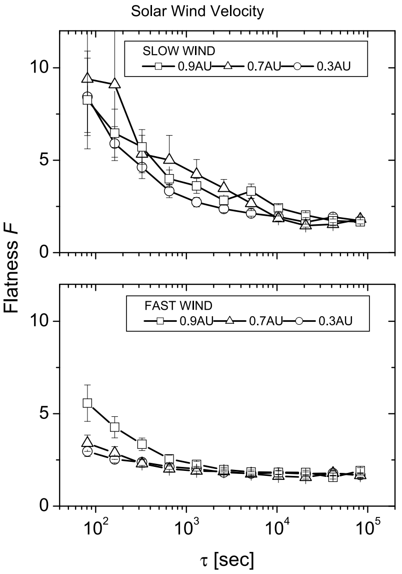

Fig. 2. Flatness factor $\mathcal{F}$ for wind velocity differences as a function of time scale expressed in seconds. The upper panel refers to slow wind, the lower panel refers to fast wind. The format is the same used for Figure 1.

3. Conclusions

We studied the radial evolution of intermittency associated with magnetic field and wind velocity fluctuations between 0.3 and 1 AU on the ecliptic plane for time scales ranging between 81 sec and 24 hours. Since one of the main effects of intermittency is that of increasing the value of the flatness factor of the PDFs of the fluctuations we concentrated our attention on the behavior of this parameter at different scales. We found that magnetic field fluctuations are generally slightly more intermittent than the corresponding velocity fluctuations (probably due to the fact that magnetic field has to obey to $\nabla \cdot B = 0$) as it was already noticed by Bruno et al., (1999) and that slow wind is generally more intermittent than fast wind. We also found that while intermittency for slow wind doesn't change with distance, it clearly increases for fast wind. To explain these observa-

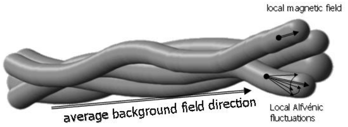

Fig. 3. Schematic representation of interplanetary flux tubes pervaded by Alfvénic fluctuations. Each tube is characterized by a local magnetic field along which Alfvénic fluctuations propagate. The border of each tube can be thought of as a tangential discontinuity

tions, we can imagine interplanetary fluctuations made of two distinct components: one due to coherent, non propagating structures convected by the wind and, another one made of propagating, stochastic fluctuations, i.e. Alfvénic modes. As a matter of fact, Veltri and Mangeney, (1999) and Bruno et al., (2001) already showed that some of the events causing intermittency are either compressive phenoma like shocks or planar sheets like tangential discontinuities separating adjacent flux–tubes. We sketch this idea in Figure 3,

where coherent structures, represented by flux–tubes, are permeated by Alfvénic stochastic fluctuations. Each flux tube is characterized by a local magnetic field along which Alfvénic fluctuations mainly propagate and the border between two adjacent flux–tubes is a tangential discontinuity. While sampling coherent structures increases intermittency, sampling stochastic fluctuations tend to decrease it. At 0.3 AU power associated to directional fluctuations largely exceeds that associated to compressive fluctuations and thus the corresponding intermittency is very low. However, as the wind expands, the Alfvénic contribution is depleted because of turbulent evolution Tu and Marsch, (1995) and, consequently, the underlying coherent structures convected by the wind becomes more relevant. On the other hand, slow wind doesn't show radial behavior because Alfvénic fluctuations have a less dominant role than within fast wind and their turbulent evolution is much slower.

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