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Small scale anisotropy of magnetic turbulence in the solar wind

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Abstract. The anisotropy of magnetophydrodynamic turbulence is investigated by using data from the solar wind by the Helios 2 satellite. We investigate the behaviour of the complete high-order moment tensors of magnetic field increments and we compare the usual longitudinal structure functions which have mixed contributions, namely isotropic plus anisotropic, with the fully anisotropic contribution. We discuss the radial dependence of anisotropy and intermittency, and the different types of wind.

Key words. Solar wind – Magnetic turbulence – Intermittency – Anisotropy

1. Introduction

Small-scales isotropy is at the heart of the Kolmogorov theory of fully developed turbulence (Kolmogorov 1941). However, evidences for the presence of anisotropies for both scalar fields (Sreenivasan 1991) and velocity fields (Shen and Warhaft 2000) have been found in latest experiments. It seems thus important to define some new statistical tool to account for this. Suppose that for a given statistical measurable quantity, scaling features can be splitted into an isotropic and an anisotropic part. The measure of the ratio between the anisotropic and the isotropic part as the scale goes down can give an estimation of anisotropic effects. Since is possible to define quantities for which the isotropic part is exactly zero, we can measure scaling laws related entirely to the anisotropic part(Kurien 2000). A formal analysis to reveal the isotropic and anisotropic contributions to structure functions, can be performed by considering their SO(3) decomposition (Arad et al. 1999). This is based in a foliation of various j-sectors of the linear space generated by the structure functions.

Turbulence in charged fluids, described by Magnetohydrodynamic (MHD), is intrinsically anisotropic (Biskamp 1997; Carbone and Veltri 1990; Carbone et al. 1995). A background magnetic field $\mathbf{B}_0$ introduces a privileged direction. It has been shown that even if isotropy is restored at large scales, intermediate scales and mainly small scales are strongly anisotropic and the return to isotropy at small scales does not hold (Carbone and Veltri 1990; Carbone et al. 1995). Anisotropy of MHD fluctuations in the solar wind, due to the background magnetic field has been investigated through the minimum variance analysis (Bruno et al. 1995). Here we investigate the scaling properties of anisotropy of the interplanetary magnetic field, by using the data analysis technique described extensively

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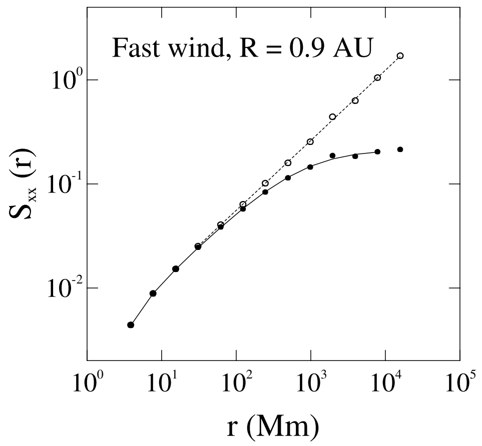

Fig. 1. The second-order longitudinal structure function of interplanetary magnetic field within fast wind at 0.9AU (black symbols), plotted versus the scale r in log–log axes, together with the compensated function (white symbols). Full line represents the fit with the function (1), while the dotted line is a power-law with exponent 0.67 ± 0.02.

in Ref. (Shen and Warhaft 2000). The data we use in this work are 6 seconds measurements of the Interplanetary Magnetic Field (IMF), as recorded by Helios 2 instruments. Because of their different physical properties, fast and slow wind streams are separed (Sorriso-Valvo et al. 1999) and interface shoks and velocity shears are avoided. Moreover, the radial evolution is considered (Bruno et al. 2004), so that two different samples for each wind type have been selected, at two well separated distances from the Sun, namely at 0.9 AU and 0.3 AU (1 AU $\simeq$ 1.5 × 108 km), each stream including about three days of records (∼ 5 × 104 data points). The spacecraft being blown by solar wind within the eclyptic plane along the (almost) radial direction, say x, measurements of the magnetic field components $b_i(x)$ are provided (with $i = x, y, z$), so that the independent elements of the n-th order tensor are then computed from the time series as $S_{\alpha_1,\alpha_2,\cdots,\alpha_n}(r) =$

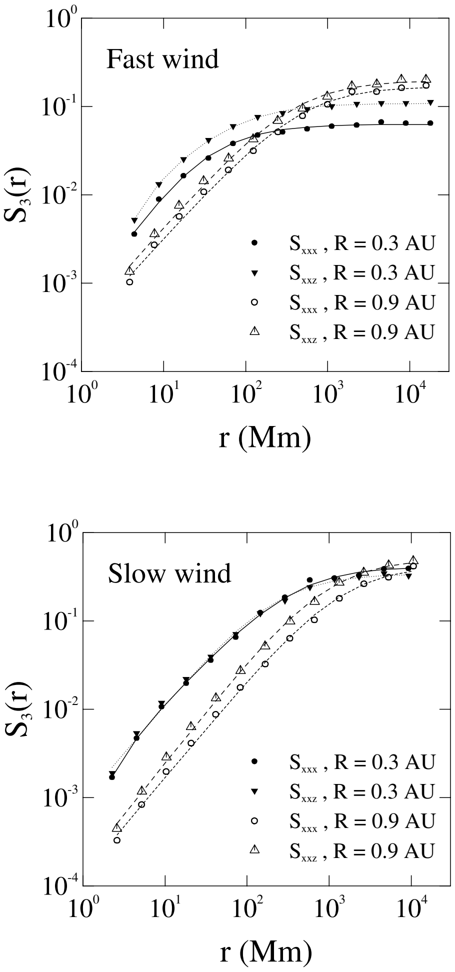

Fig. 2. The third order mixed structure function of interplanetary magnetic field within fast and slow wind, both at 0.9AU and 0.3AU (see legenda), plotted versus the scale in log–log axes, together with the fit with the function 1 (lines).

$$\langle [b_{\alpha_1}(x+r) - b_{\alpha_1}(x)]$$
$$[b_{\alpha_2}(x+r) - b_{\alpha_2}(x)] \cdots [b_{\alpha_n}(x+r) - b_{\alpha_n}(x)] \rangle$$

In order to measure the contribution from the anisotropic part of the field differences, the whole tensor should be studied. For each scale, and thus as far as scaling laws are concerned, some of the components of the tensor can be proven to have contribution from the anisotropic part of the field only (Kurien 2000). Is it thus possible to compare the scaling behavior of such components with the one of the longitudinal structure function (e.g., for the second order, $i = j = x$), which includes both isotropic and anisotropic contributions. To do this, all the structure functions, which display multiple power-law ranges, can be fitted by the following Batchelor relation (Kurien 2000)

$$S_{\alpha_1,\alpha_2,\cdots,\alpha_n}(r) = \frac{A_{\alpha_1,\alpha_2,\cdots,\alpha_n}\eta^n\,(r/\eta)^n}{[1 + B_{\alpha_1,\alpha_2,\cdots,\alpha_n}\,(r/\eta)\,2]^{C_{\alpha_1,\alpha_2,\cdots,\alpha_n}}} \times \times [1 + D_{\alpha_1,\alpha_2,\cdots,\alpha_n}\,(r/L_0)]^{2C_{\alpha_1,\alpha_2,\cdots,\alpha_n}-n} \quad (1)$$

The free parameters in equation (1) includes the dissipation scale η and the integral scale L_0, which need to be estimated from the data. The multiple power-law behavior of the structure functions is described by equation (1) through the exponent $C_{\alpha_1,\alpha_2,\cdots,\alpha_n}$. Figure 1 display one example of the second order structure function, together with the fit with equation (1), as well as a compensated function and a power-law fit. Figure 2 shows the behaviour of some third order mixed structure functions,and in particular the components of the tensor which have no $j = 0$ isotropic contribution copmpared with the usual longitudinal structure functions, for both fast and slow wind, at two heliocentric distances. It is evident that equation (1) can reproduce the data with very good agreement. The observation of the structure functions reveals a number of evidences. First of all, the stricking difference between fast and slow wind is clear, in particular within the streams closer to the sun. The presence of evolution with the distance is also clear, and is stronger for fast wind. In fact, the scaling of the structure functions of fast wind seems to evolve toward the slow wind scaling as the distance from the sun is increased. In particular, the power-law scaling become more and more clear far from the sun, and is already evident near the sun for slow wind. This seems to indicate that turbulence is completely developed only in slow wind, and the inertial range is extended moving away from the sun. Let us now turn the attention to the differences between the tensor components. It is evident that for slow wind close to the sun the differences between the longitudinal and the anisotropic components are small, so that anisotropy seems to be important. These differences increase at 0.9AU, but are still small. In fast wind, on the contrary, The scaling is quite different at 0.3AU and get more similar at 0.9AU.

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