Anisotropy and universality in Solar Wind turbulence. Ulysses spacecraft data.

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The Ulysses mission has been sampling the Solar Wind (SW) plasma, measuring the velocity and magnetic fields while orbiting the Sun, for the first time on a polar orbit, from 1 A.U., with the mean magnetic field almost parallel to the stream, to 6 A.U., with magnetic field almost perpendicular to the stream. This dataset allows to study properties of anisotropic MHD turbulence in SW streams and its evolution with distance, latitude and mean-field direction.

Suppression of turbulence has long been observed in the direction aligned with the large–scale mean field, by studying 2nd order longitudinal and transverse structure functions (SF). Several MHD models incorporate at various levels asymmetry of spectral indices in the field-aligned and transverse directions. For a selected bibliography in SW turbulence see [1] and [5].

1 Anisotropy of field fluctuations

Statistics of magnetic field fluctuations is reconstructed via the nth order correlation, $S^{(n)}_{\alpha_1,\ldots,\alpha_n}(\boldsymbol{r})$, which depends on separation $(\boldsymbol{r})$,

$$S^{(n)}_{\alpha_1,\ldots,\alpha_n}(\boldsymbol{r}) = \langle \delta_{\boldsymbol{r}} B_{\alpha_1} \delta_{\boldsymbol{r}} B_{\alpha_2} \cdots \delta_{\boldsymbol{r}} B_{\alpha_n} \rangle, \tag{1}$$

where $\delta_{\boldsymbol{r}} B_\alpha \equiv B_\alpha(\boldsymbol{x}+\boldsymbol{r}) - B_\alpha(\boldsymbol{x})$, and is the main quantity directly available from spacecraft data. Brackets $\langle\cdot\rangle$ in (1) indicate average over the locations $\boldsymbol{x}$. In (1) homogeneity is assumed, but not isotropy. This correlation function includes both *isotropic* and *anisotropic* contributions:

$$S^{(n)}_{\alpha_1,\ldots,\alpha_n}(\boldsymbol{r}) = S^{(n),iso}_{\alpha_1,\ldots,\alpha_n}(\boldsymbol{r}) + S^{(n),aniso}_{\alpha_1,\ldots,\alpha_n}(\boldsymbol{r}). \tag{2}$$

For $n = 2$ and $\alpha_1 = \alpha_2$, we get the 2nd order SF, connected to the energy spectrum $E_{\alpha,\alpha}(\boldsymbol{k}) = \langle |\hat{B}_\alpha(\boldsymbol{k})|^2 \rangle$ via a Fourier transform. Another widely used form of (1) is the longitudinal SF, obtained by projecting all field increments along the separation versor, $\hat{\boldsymbol{r}}$: $S^n_L(r) = \langle (\delta_{\boldsymbol{r}} \boldsymbol{B} \cdot \hat{\boldsymbol{r}})^n \rangle$.

SO(3) decomposition of correlations (1), makes it possible to analize the anisotropic structure of magnetic field fluctuation. However, such an analysis requires the whole field in a 3D volume, to be systematically worked out. Spacecraft data are instead inherently one-dimensional. However, for such data it is still possible to extract those correlation functions, such as $S^{(2)}_{xy}(r_x)$ and $S^{(2)}_{xz}(r_x)$, whose isotropic contributions are by symmetry identically zero [2]. Their measure shall therefore quantify the degree of anisotropy of magnetic field fluctuations. A recent review on SF decomposition in hydrodynamics, for experimental and numerical data analysis can be found in [5].

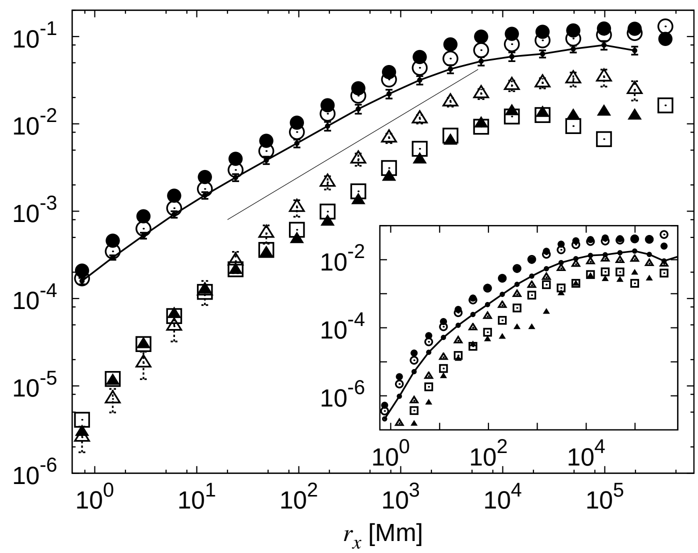

Fig. 1. Second order longitudinal, transverse and *purely anisotropic* SF. Low latitude dataset. Upper three curves: longitudinal and tranverse SF: solid line — $S^{(2)}_{xx}$; empty cirles ∘ $S^{(2)}_{yy}$; filled circles • $S^{(2)}_{zz}$. Errorbars are superimposed on — $S^{(2)}_{xx}$. Reference slope has angular coefficient of 0.7. Lower curves: purely anisotropic SF: $S^{(2)}_{xy}$, ▲ filled triangles; $S^{(2)}_{xz}$, △ empty triangles; $S^{(2)}_{yz}$, □ empty squares. Errorbars are superimposed on △ $S^{(2)}_{xz}$. Inset: fourth order SF, longitudinal, transverse and *purely anisotropic*. Solid line, — $S^{(4)}_{xxxx}$; empty circles ∘ $S^{(4)}_{yyyy}$; filled circles • $S^{(4)}_{zzzz}$. *Purely anisotropic* SF are: $S^{(4)}_{xyyy}$, ▲ filled triangles; $S^{(4)}_{xzzz}$, △ empty triangles; $S^{(4)}_{yzzz}$, □ empty squares.

Let us therefore compare the undecomposed 2nd order SF with its anisotropic content. In Fig.1 we plot the longitudinal SF of 2nd order, $S^{(2)}_{x,x}(r_x)$ and the two transverse SF in the directions perpendicular to the $\hat{\boldsymbol{x}}$ axis, $S^{(2)}_{yy}(r_x)$ and $S^{(2)}_{zz}(r_x)$. All these functions have both isotropic and anisotropic contribution:

$$S^{(2)}_{\alpha,\alpha}(r_x) = S^{(2),iso}_{\alpha,\alpha}(r_x) + S^{(2),aniso}_{\alpha,\alpha}(r_x). \tag{3}$$

The two *purely anisotropic* 2nd order SF $S^{(2)}_{xy}(r_x)$ and $S^{(2)}_{xz}(r_x)$, are plotted in the same figure. A few comments are in order. First, we notice that the *anisotropic* correlations have a smaller amplitude with respect to the full correlation functions. This suggests that the isotropic contribution in the decomposition (2) is dominant. Moreover, we see that the anisotropic curves decay slightly faster than the full correlation at small scales. In other words, isotropic fluctuations become more leading proceeding to small scales, although they do so very slowly. This is consistent with the recovery-of-isotropy assumption in some MHD models However, it is important to also control higher order statistical objects, i.e. the whole shape of the probability density distribution, at all scales. In the inset of Fig. 1 we show the same comparison between longitudinal, $S^{(4)}_{xxxx}(r_x)$, transverse, $S^{(4)}_{\alpha\alpha\alpha\alpha}(r_x)$ (with $\alpha = y, z$) and *purely anisotropic* correlations of *fourth order* (see caption in the figure). Now the situation is quite different. First, the intensity of some *purely anisotropic* components are much closer to those with mixed isotropic and anisotropic contributions, i.e. the longitudinal and transverse SF. Second, the decay rate as a function of the scale is almost the same: no recovery of isotropy is detected for fluctuations of this order any more. This is the signature that anisotropy is mainly due to intense but rare events affecting high order moments more than 2nd order moments [3]. This important conclusion is confirmed by a consistent behaviour of other statistical indicators [1].

Strong anisotropic fluctuations persist at all scales in the fast solar wind. In the equatorial region, where data of Fig. 1 belong to, the anisotropic contents of fourth order correlation function is roughly of the same order as its isotropic part, at all scales, indicating that small scale isotropy is never achieved. In the polar region, anisotropies are smaller and highly fluctuating in time, but with a spatial dependencies compatible, within statistical errors, with the one observed at low latitudes. This would indicate some universal features of anisotropic solar fluctuations independently of the latitude, at least for what concerns their scaling properties. Our results therefore point toward a crucial role played by anisotropic fluctuations in the small scales statistics.

References

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