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Small-scale anisotropy in the solar wind

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Abstract

We investigate small-scale anisotropy of the interplanetary magnetic field (IMF) fluctuations in the solar wind by using high resolution Cluster data in two different periods. A minimum variance analysis is performed in order to study the anisotropy at several temporal scales. The eigenvalues λ_1, λ_2, λ_3 of the minimum variance matrix and the angle θ between the mean magnetic field and the minimum variance direction are computed. Results from the statistical analysis show significant changes close to the ion cyclotron frequency.

The heliosphere is permeated by the solar wind (SW), a continuous flow of charged particles, having a solar origin. It is supersonic, superalfvénic and highly turbulent and represents a natural laboratory for studying plasma physics and turbulence properties. A wide spectrum of velocity and magnetic field fluctuations has been observed, leading to a magnetohydrodynamic description [1]. Belcher and Davis [2] showed that magnetic turbulence in the SW is anisotropic, due to the presence of a background magnetic field. Magnetic anisotropy is well characterized via the *minimum variance analysis* [3], which requires the determination of eigenvalues and eigenvectors of the cross correlation matrix. Systematic analysis of the variance matrix in the SW, at frequencies well below the ion cyclotron frequency, showed that one of the eigenvalues is always much smaller than the others [4, 5, 6]. Typical values are $\lambda_1 : \lambda_2 : \lambda_3 = 10 : 3.5 : 1.2$ [7]. This implies a nearly 2-D SW magnetic turbulence. In addition, the direction of minimum variance b_3 is roughly aligned with the mean magnetic field $\mathbf{B}_0$ and just an amplitude spread of 10° is observed [1, 7].

In the present paper statistical properties of eigenvalues and eigenvectors of the variance matrix are investigated, by using magnetic field data sampled by the Fluxgate magnetometer (FGM) on board of Cluster at a frequecy $\Delta t = 22$Hz [8]. The two datasets used refer to measurements taken in the SW on 2002 February 19-th (DS02), and on 2003 April 16-th (DS03).

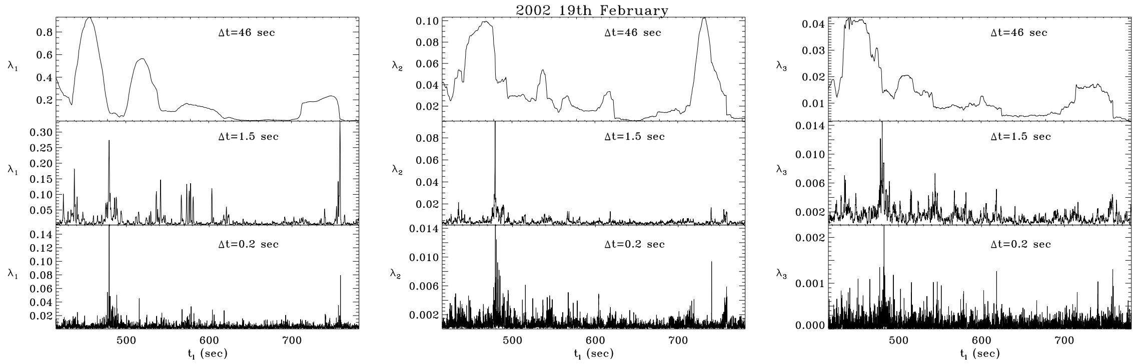

Figure 1: Amplitude of eigenvalues of maximum (on the left), medium (in the middle) and minimum (on the right) variance direction as a function of time at three scales for DS02 Cluster-1 dataset.

For each dataset of temporal length T and for each spacecraft $s = 1,2,3,4$, variance matrices of magnetic field fluctuations are computed on running windows of variable lengths $\Delta t_n = 2^n/\Delta f$ ($n = 0,1,...,N$, being the scale index), centered on time t_l ($l = 1,2,...,T-\Delta t_n$, being the window index)

$$S_{ij}^{(s)}(\Delta t_n, t_l) = \langle B_i^{(s)}(t) B_j^{(s)}(t)\rangle - \langle B_i^{(s)}(t)\rangle\langle B_j^{(s)}(t)\rangle\,, \qquad (1)$$

where i and j denote the components of magnetic field **B** along the axes of a given reference system, and brackets indicate temporal averages. The eigenvalues $\lambda_i^{(s)}(\Delta t_n, t_l)$ and the eigenvectors $b_i^{(s)}(\Delta t_n, t_l)$ are computed, as well as the angle $\theta^{(s)}(\Delta t_n, t_l)$ between the background magnetic field and the local minimum variance direction $b_3^{(s)}(\Delta t_n, t_l)$. In Fig. 1 we show the time evolution of the eigenvalues $\lambda_i^{(s)}(\Delta t_n, t_l)$ of the variance matrix for three different scales Δt_n, above and below the ion cyclotron characteristic scale (in the SW it is roughly $\Delta t_{ic} \simeq 10$sec), and for the DS02 Cluster-1 dataset. While at scales of minute eigenvalues have smooth variations, at the smaller ones they exhibit a burst-like behavior, implying a high dispersion. This is a typical signature of small scale intermittency always present in the four satellites DS02 data and in the DS03 dataset (not shown here).

In order to study the statistical properties of anisotropy in the SW, we investigate the scaling behavior of Probability Density Functions (PDF) of the eigenvalues of the variance matrix. Small differences among PDFs obtained from the four spacecraft data were observed (not shown here), then, hereafter a combined dataset, joining together the four Cluster satellites datasets, is used. From the PDFs it is possible to recognize a cross-scale effect, that is at scales of minute PDFs are peaked around a given value, while below the ion cyclotron scale, they evolve toward

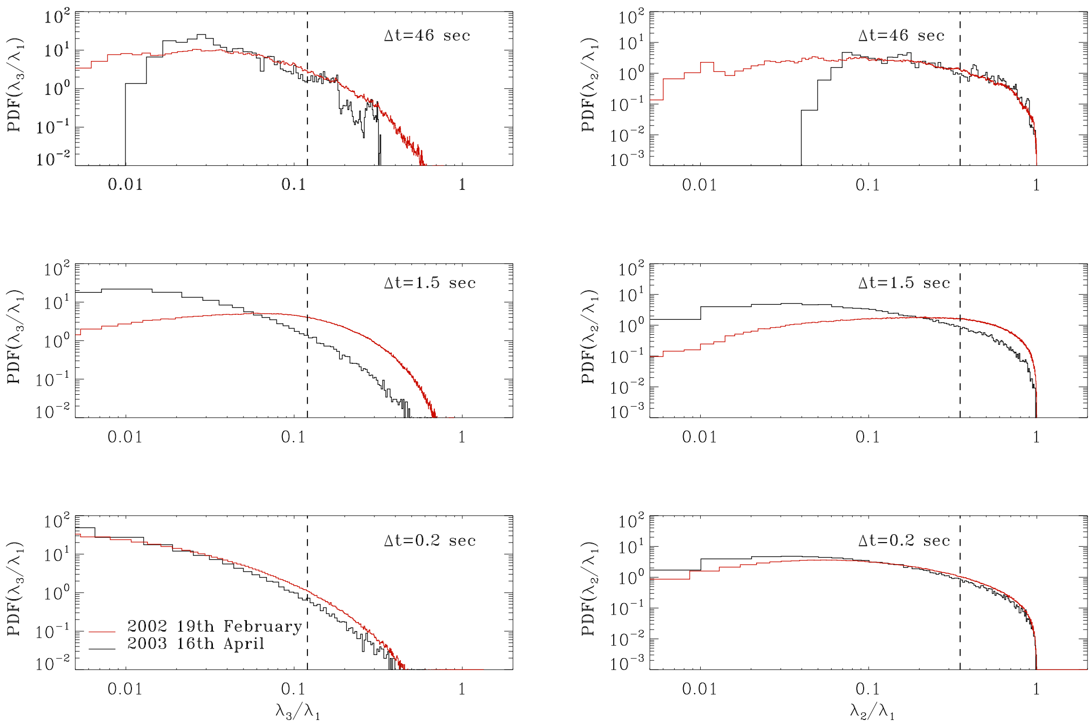

Figure 2: PDFs of the ratio between the eigenvalues of minimum and maximum variance (on the left) and of the ratio between the eigenvalues of medium and maximum variance (on the right) at three scales in the two periods. Vertical dashed lines indicate the typical values of the ratios reported in previous works.

a power-law distribution with non-negligible probability associated to low values of $\lambda_i^{(s)}$. This cross-scale is also evident from the PDFs of the ratios between the minimum and the maximum eigenvalues, and between the medium and the maximum eigenvalues (see Figure 2). Values of both $\lambda_3/\lambda_1 \leq 0.1$ and $\lambda_2/\lambda_1 \leq 0.1$ are dominant at larger scales in the two datasets, indicating the presence of a strong anisotropic turbulence [7]. The two distributions show differences probably due to some different conditions in the SW in the two periods of time. Below the ion cyclotron scale anisotropy is enhanced, expecially for the dataset of 2003 16-th April, indeed, a higher probability of occurrence associated to small values of the ratios is observed, suggesting that turbulence becomes quasi-1D. It is worth to notice that below the ion-cyclotron scale PDFs are superimposed and no differences are to be evidenced. While typical values of λ_i are reported in literature for large scale fluctuations in the solar wind (cfr. e.g. [7]), we underline that it is not possible to define a characteristic value of the eigenvalues at scales smaller than the ion-cyclotron scale, owing to the presence of a power-law distribution.

A different characterization of anisotropy can be performed by calculating values of the angle

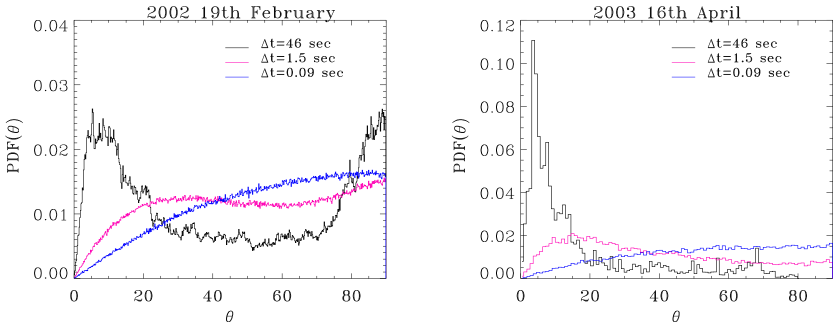

Figure 3: PDFs of the angle between the direction of minimum variance and that of the average magnetic field at three scales for DS02 (on the top) and DS03 (on the bottom).

$\theta(\Delta t_n, t_l)$ between the minimum variance and $\mathbf{B}_0$ directions, and its probability of occurrence $P(\theta)$ at scales Δt_n. In Figure 3 PDFs of θ at three scales for DS02 data and for DS03 data are shown. At scale of minute distributions are peaked around given values: for DS02 small and high angle values have a great big probability, indicating that the minimum variance direction is either aligned to $\mathbf{B}_0$ or nearly perpendicular, for DS03 the minimum variance direction is almost always parallel to $\mathbf{B}_0$. Also from this analysis it is possible to notice a difference above the ion cyclotron scale that can be related to large scale features in the periods analyzed. However, this difference disappears below the ion-cyclotron scale where, for both datasets, PDFs become broad, increasing the probability of finding angles roughly close to 90°. The probability of having a minimum variance direction nearly parallel to $\mathbf{B}_0$ becomes negligible, consequently, magnetic fluctuations are localized in a plane nearly parallel to the mean magnetic field.

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