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ACE/Wind multispacecraft analysis of the magnetic correlation in the solar wind

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Abstract: The propagation of galactic and solar cosmic rays in the solar wind (SW) can be strongly influenced by the SW fluctuations properties. Magnetohydrodynamic scale fluctuations in the solar wind are usually highly anisotropic, and have also been found to exhibit different properties in regions of high and low solar wind speed. Previous studies analyzed the anisotropy properties of the solar wind magnetic fluctuations at scales of the order of $(10^5 - 10^6)$ km (inertial range) using two times – single point measurements (assuming the Taylor frozen-in hypothesis), and found that the fluctuations in the fast solar wind tend to reside in wave vectors with their parallel component (to the mean magnetic field) larger than the perpendicular one, while the fluctuations in the slow wind present the opossite trend. In the present study we compare the magnetic autocorrelation function in the solar wind obtained with two times – single point observations (from a single spacecraft) with the same quantity obtained from single time – two points measurements (from simultaneous observations of two spacecraft, observing the pure spatial structures). We preliminarily compare also previous results of the anisotropy of the solar wind fluctuations, obtained from a single spacecraft, with our new multispacecraft analysis using combining observations from the ACE and Wind spacecraft.

Introduction

Theories of scattering of energetic solar particles in the heliosphere [1] and solar modulation of galactic cosmic rays [2] require knowledge of turbulence parameters to express particle diffusion coefficients.

In particular, several theories (as the quasi-linear theory [3]) need the correlation of the turbulent magnetic fields as an input that describe the cosmic-rays transport

It is known that the presence of a uniform 'direct current' (constant in space and time) magnetic field ($\mathbf{B_0}$) in a turbulent MHD system develops spectral anisotropies for isotropic initial conditions (e.g., [4, 5]): high wavenumbers components develop more readily perpendicular to $\mathbf{B_0}$ than those parallel to it.

Of the various descriptions of anisotropic wave and turbulence properties of the solar wind, the so-called 'Maltese cross' [6] illustrates level contours of the magnetic self correlation which are seen to have a cross-like pattern when plotted in a 2D plane where one of the axes is parallel to the magnetic field. There is a lobe along each axis. A suggestive but oversimplified interpretation is the presence of two components or populations: slab-like fluctuations (with wavevectors, $\mathbf{k}$, mainly parallel to the mean field: $k_{//} >> k_\perp$) and quasi-2D-like fluctuations (having $\mathbf{k}$ mainly perpendicular to $\mathbf{B_0}$: $k_\perp >> k_{//}$).

Unidirectionally propagating Alfvén waves correspond to values of the normalized cross helicity

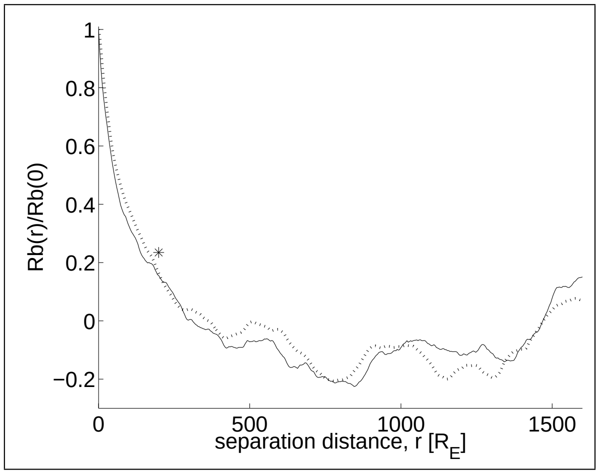

Figure 1: Comparison of Rb from ACE-SSC (solid line), Wind-SSC (dotted line), and ACE/Wind-TSC (asterisk).

(σ_c) equal to +1 or -1, depending of the sense of the propagation, while high levels of turbulence are usually accompanied by a value of σ_c close to zero (see, e.g., [7], and references therein). From an analysis of 5 years of solar wind data (one minute of time cadence) measured by the spacecraft ACE on the Sun-Earth line at 1AU, [8] shown that σ_c is roughly isotropic in the inertial range, a result plausible with similar levels of turbulence for the 'slab-like' population and for the 'quasi-2D-like' one. Using the same sample of solar wind data, [9] found that at scales of the order of $(10^5 - 10^6)$ km (i.e., the inertial range) the fluctuations in the fast solar wind present a trend to having a more abundant population with $k_{//} >> k_\perp$ than with $k_\perp >> k_{//}$, while the fluctuations in the slow wind present the opposite trend (more abundant population with $k_\perp >> k_{//}$).

All these previous studies are based on single spacecraft (SSC, using two-times/one-point) observations. Because the solar wind speed is much larger than the local Alfvén/sound speeds, the spatial correlation function can be measured in the direction of the flow direction (i.e., the solar wind fluctuations are convected in the reference frame of the spacecraft in a short time compared with the characteristic time scale of the dynamical variation of the fluctuations).

Recently a few studies on the spatial dependence of the magnetic correlation function in the solar wind from two spacecraft (TSC, using two-point/single-time) were done [10, 11, 12] using data from the Cluster fleet. However, detailed comparison between the previous studies (using the single spacecraft) and the new approach (using TSC) have not been done yet.

In the present work we present a comparison of magnetic correlation functions in the solar wind obtained from a SSC with those obtained from TSC. We also present some preliminary results from the analysis of the anisotropy of the magnetic fluctuations at the inertial range scales ($\sim 10^5 - 10^6$ km), using TSC.

Data analysis, results, and conclusions

We analyze observations of the magnetic field measured by the Advanced Composition Explorer (ACE) and Wind spacecraft, using the same samples (intervals of one day of duration, with a time cadence of one minute) than those used by [10]. Thus, we analyze here solar wind observations that correspond to a distance of ~ 1 AU from the Sun and on the ecliptic plane.

Our main goal is to compute, from two-points and single time observations, the spatial correla-

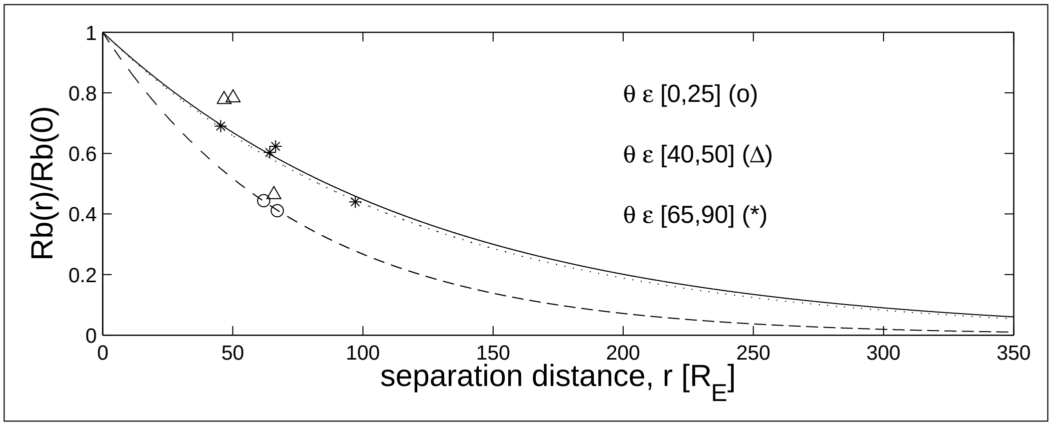

Figure 2: Observations of Rb from ACE/Wind-TSC for fast solar wind for different angular channels between the spatial lag direction and $\mathbf{B_0}$. Exponential fit is included to each angular channel (dashed line for $\theta_1\epsilon[0°, 25°]$, dotted line for $\theta_2\epsilon[40°, 50°]$, and solid line for $\theta_3\epsilon[65°, 90°]$).

tion function of the form

$$Rb(\mathbf{r}) =< \mathbf{b}(\mathbf{0}, t) \cdot \mathbf{b}(\mathbf{r}, t) > \qquad (1)$$

Note that Equation 1 is the trace of the usual two-points correlation tensor for the magnetic field, where spatial and temporal translation symmetries were assumed. $\mathbf{b}$ represents the fluctuating magnetic field, and we will study the variance-normalized correlation,

$$Rb^{norm}(\mathbf{r}) = Rb(\mathbf{r})/ < \mathbf{b} \cdot \mathbf{b} > , \qquad (2)$$

with $Rb^{norm}(\mathbf{0}) = 1$, as done in [8, 9, 10]. For simplicity of notation, we omit the "$norm$" label hereafter. The SSC correlations were computed as described in [8, 9], while the TSC correlations as described in [10].

In this preliminary work we compare values for Rb obtained from SSC and TSC for the interval (selected from all intervals analyzed in [10]) having the minimum angle (α) between the spatial lag direction for TSC (given by the relative position between ACE and Wind) and the Sun-Earth line; thus, the spatial correlation from TSC corresponds to the same direction of the intrinsec spatial lag given by SSC. This interval corresponds to the full day of Oct 4, 1999, and it corresponds to $\alpha = 3°$. The separation distance between ACE and Wind is $199R_E \sim 10^6$ km ($R_E = 6378$km, is the Earth radius).

Figure 1 shows the comparison of Rb using ACE-SSC (solid line), Wind-SSC (dotted line), and both ACE/Wind-TSC (asterisk). The mean value of the two SSC observations ($Rb_{ACE-SSC}$ and $Rb_{ACE-SSC}$) at a separation of $199R_E$ (the separation between ACE and Wind) resulted 0.16, while $Rb_{ACE/Wind-TSC} = 0.23$; that means that the TSC-SSC ratio, at spatial separations of $\sim 10^6$km, is $Rb_{TSC}/Rb_{SSC} \sim 1.3$.

In order to analyze the anisotropy of Rb from TSC, which allow us to cover spatial lag directions independently from the angle between $\mathbf{B_0}$ and the solar wind flow direction, we split the full set of analyzed intervals according with three angular channels for the angle (θ) between the direction of the spatial lag, given by the relative positions between ACE and Wind, and the mean magnetic field ($\mathbf{B_0}$): $0^0 \leq \theta_1 < 25^0$, $40^0 \leq \theta_2 < 50^0$, and $65^0 \leq \theta_3 < 90^0$.

Because from SSC in previous studies there were only a few intervals for fast solar wind and for extreme angles $\theta \sim 0°$ and $\theta \sim 90°$, in this first stage of the study we select only fast solar wind intervals ($V_{SW} > 470$ km/sec). Figure 2 shows the normalized Rb, only from TSC for fast solar wind and for different angular channels: symbol o is used to represent θ_1 (spatial lag parallel to the mean field $\mathbf{B_0}$), symbol Δ to represent θ_2 (spatial lag at intermediate angles respect to $\mathbf{B_0}$), and symbol $*$ to represent θ_3 (spatial lag perpendicular to $\mathbf{B_0}$). It is possible to observe that Rb for θ_1 is significantly lower than the values obtained for the other two directions, a result consistent with a fast solar wind having a more important population of 'slab-like' fluctuations than 'quasi-2D-like' ones.

We also compute the correlation lengths (λ^c) (computed as in [8, 9]) for Rb, considering each of the angular channels. We obtained $\lambda_1^c = 4.8 \times 10^5$km ($\theta \sim 0°$), $\lambda_2^c = 7.7 \times 10^5$km ($\theta \sim 45°$), and $\lambda_3^c = 8.0 \times 10^5$km ($\theta \sim 90°$). Thus, our result is consistent with the correlation scale obtained previously for the mixed solar wind (all angular channels and all speeds) by [10] ($\lambda^c \sim 10^6$km).

We presented here an analysis that compares Rb from SSC and TSC, and using only TSC we analyzed the anisotropy of the fast solar wind fluctuations. For the analyzed sample we found that, at separations of $\sim 10^6$ km, the magnetic correlation function computed from SSC is $\sim 30\%$ smaller than when it is computed from TSC. This is possibly a consequence of time evolution during the SSC observations. In the second case, we resist to the temptation of drawing any major conclusion concerning anisotropy because we beleive that it is necessary to make an analysis of more samples, ranging a larger angular set of bins. We plan to extend our research and present complete results elsewhere. In the meantime, we believe that ongoing studies of this type will contribute to better understanding of the solar wind fluctuations and its influence on the cosmic rays propagation in the heliosphere.

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