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STATISTICS OF DENSITY FLUCTUATIONS DURING THE TRANSITION FROM THE OUTER SOLAR CORONA TO THE INTERPLANETARY SPACE

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ABSTRACT

This paper investigates the evolution of the plasma density fluctuations of the fast and slow solar wind from the solar corona into the interplanetary space. The study is performed by comparing the low-frequency spectra and the phase correlation of the proton density oscillations, measured in the inner heliosphere with the *Helios 2* in situ instrumentation, with those due to the large-scale density perturbations observed with UVCS/*SOHO* in the outer corona. We find that the characteristics of density fluctuations of the fast solar wind are maintained in the transition from the outer corona to the inner heliosphere, thus suggesting a coronal imprint for the heliospheric large-scale $1/f^2$ noise spectrum. In contrast, a quick dynamical evolution is observed in the slow wind, which, starting from large-scale fluctuations with strong phase correlations in the outer corona, gives rise to a Kolmogorov-like spectrum and an accumulation of density structures at small scales at 0.3 AU. This can be explained in the framework of nearly incompressible turbulence.

Key words: interplanetary medium – Sun: corona – turbulence

Online-only material: color figure

1. INTRODUCTION

The solar wind is a supersonic and super-Alfvénic magnetized plasma permeated by fluctuations over a wide range of spatial and temporal scales, whose gross features, at least at large scales, can be described in the framework of incompressible Magnetohydrodynamic (MHD) turbulence (see review by Bruno & Carbone 2005, and references therein). The solar wind plasma is indeed affected by inhomogeneities, compressible fluctuations, and anisotropy. Occasionally, mainly in the fastest streams of solar wind observed in the heliosphere, Alfvénic fluctuations are detected, namely periods where the velocity and magnetic fields are correlated to a high degree. The nature and the origin of the interplanetary inward and outward Alfvénic fluctuations are well known. Inward propagating modes cannot have a solar origin, but they are generated locally by physical processes such as velocity shears (Roberts et al. 1987) and/or parametric decay of the outward Alfvén wave energy (Tu et al. 1989). However, for the outward Alfvénic component both solar and local origins are possible in the super-Alfvénic wind. This complex system is then formed by a mixture of propagating stochastic MHD fluctuations and "static" coherent structures carried out by the solar wind, actively contributing to the turbulent development of the solar wind (Tu et al. 1984). Considerable efforts have been made, both observationally and theoretically, in order to address the issue of the origin of the "static" structures intermixing the propagating fluctuations. Nevertheless, whether the coherent components of solar wind fluctuations are the imprints of structures generated by the coronal dynamics and advected by the wind during its expansion or stationary filamentary structures locally generated by dynamical interactions between high- and low-speed streams, alternating in the ecliptic plane, or by turbulent processes, is still to be established.

Most of the above structures are due to density fluctuations that, although with a weak amplitude, play a crucial role when scaling laws of turbulence must be established or in the phenomenon of solar wind heating by turbulent fluctuations (Carbone et al. 2009). Recently, large-scale density fluctuations have been observed with the UltraViolet Coronagraph Spectrometer (UVCS) on board the *Solar and Heliospheric Observatory* (*SOHO*) in the outer corona, both in the fast (Morgan et al. 2004; Bemporad et al. 2008) and slow (Telloni et al. 2009) wind. The above analyses point to the presence of a $1/f^2$ Brownian noise, from periods of a few hours to periods of a few days. On the other hand, the occurrence of $1/f^2$ noise is well known also from the spectral analysis of interplanetary fluctuations, as widely reported in the literature (e.g., Sari & Ness 1969; Coles & Harmon 1978; Burlaga & Mish 1987; Roberts & Goldstein 1987).

The present paper aims to investigate the origin of the low-frequency spectrum of the fast and slow solar wind parameters observed in the interplanetary space, by comparing, for the first time, the spectral properties of the density fluctuations observed remotely in the outer solar corona with UVCS/*SOHO* with those of the compressive perturbations of the interplanetary plasma measured in situ in the inner heliosphere with *Helios 2*. In addition, this study investigates the presence of coherent structures in the solar wind plasma at both the coronal and heliospheric level, thus allowing us to address the issue of the origin of the coherent components of the interplanetary fluctuations. The analysis also allows the investigation of the evolution of these spatial structures, embedded in the expanding solar plasma, in their outward propagation from the outer corona to the inner heliosphere both in high-speed (Thieme et al. 1990) and low-speed streams, thus providing further evidences for the relationship existing between coronal and heliospheric fluctuations of the plasma density in the two solar wind regimes.

2. OBSERVATIONS AND DATA ANALYSIS

The observations of the fast and slow wind in the outer corona have been performed with the UVCS (Kohl et al. 1995) on board *SOHO*, during the activity minimum of solar cycle 23. The fast solar wind has been detected continuously for about 3.6 days from 13:27 UT on 2006 June 10 in the coronal hole present at the South Pole. A 10° latitude interval around the heliographic latitude of 90°S has been considered. The distance of the UVCS slit to the Sun within this latitude band is 2.3 $R_\odot$. Data referring to the slow solar wind have been acquired uninterruptedly for about 11.4 days, from 16:42 UT on 2007 December 3, when the instrument observed the equatorial, low-latitude region from 3°NE to 11°NE, at a heliocentric distance of 1.8 $R_\odot$, which can be identified as the coronal region where the slow wind is emerging and accelerated (Telloni et al. 2009). The H I Lyα line, emitted by the hydrogen atoms at 1216 Å, is detected with a temporal resolution Δt of 300 s and 120 s, for the fast and the slow solar wind, respectively. The frequency range where the spectral analysis can be performed hence lies in the range 3×10^{-6} Hz $\leqslant f \leqslant 2 \times 10^{-3}$ Hz and from 1×10^{-6} Hz $\leqslant f \leqslant 4 \times 10^{-3}$ Hz, for the fast and slow solar wind, respectively, where the upper limit is the Nyquist–Shannon frequency $f_{\rm NS} = 1/(2 \cdot \Delta t)$. The fast and slow wind data considered in this paper are at the moment the longest uninterrupted UVCS time series available, allowing thus the Fourier analysis down to frequencies of the order of 10^{-6} Hz. The observed Lyα intensity fluctuations are caused uniquely by variations of the physical properties of the emitting coronal plasma crossing the field of view, since, as discussed by Morgan et al. (2004), the UVCS instrumental contribution to the temporal variability of the line intensity can be neglected. Hence, the fluctuations of Lyα emission, observed in the fast and slow wind, can be mainly associated with neutral hydrogen density variations in the two solar wind regimes, as discussed by Bemporad et al. (2008) and Telloni et al. (2009). The density of neutral hydrogen in the ionized corona reflects that of protons. The plasma density variations in the fast and slow coronal wind are thus represented by the time evolution of the H I Lyα line intensity averaged over a 10° latitude interval around the heliographic latitude of 90°S (South Pole) and 7°NE, respectively, which are shown in the top panel of Figure 1.

The coronal plasma density fluctuations observed remotely with UVCS are compared with the interplanetary measurements obtained in situ with *Helios 2*, with the aim of investigating how the density perturbations evolve traveling from the outer corona to the inner heliosphere. This comparison is based on observations performed in both cases in a period of activity minimum, although in different epochs, namely during the minimum of solar cycle 21 and 23 for the measurements in the inner heliosphere and in the outer corona, respectively.

The *Helios 2* in situ measurements represent a unique data set, since this is the only spacecraft which ever reached such a short heliocentric distance. Being so close to the Sun, dynamical stream–stream interactions have not yet fully reprocessed the plasma which should still carry some of the original imprints of its source region. The interplanetary data we analyze consist of measurements of proton density performed at 0.3 AU, when the *Helios 2* spacecraft was located at 3°N of the heliographic equator. The data were collected from 1976 April 9 to April 12. In this time interval, *Helios 2* was observing a slow wind stream originating at lower solar latitudes. These measurements were followed by four further days of observations, from 1976 April 14 to April 17, when the spacecraft observed a high-speed stream, emerging from the equatorial extension of a polar coronal hole. As a matter of fact, during this phase of solar cycle the polar coronal holes configuration was remarkably stable and

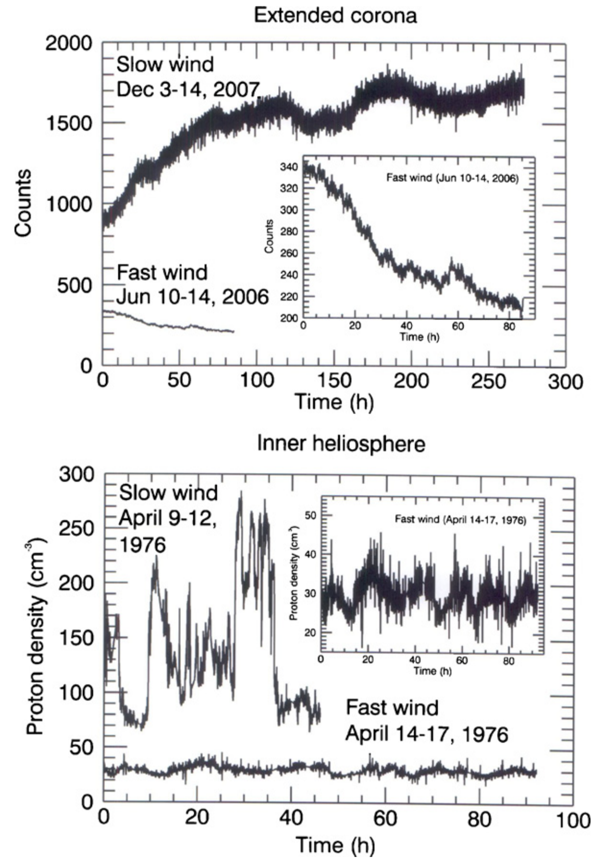

Figure 1. Top panel: evolution with time of the coronal H I Lyα line intensity observed with UVCS/*SOHO*, expressed in count units, at a heliographic latitude of 90°S (fast wind, shown also in the data box) and 7°NE (slow wind); bottom panel: evolution with time of the heliospheric proton density observed with *Helios 2* during the high- and low-speed stream observed at perihelion; data gaps are removed by linear interpolation; data referring to the fast solar wind are shown also in the box.

their meridional extensions reached very low latitudes (Villante & Bruno 1982; Bruno et al. 1982). These features allowed *Helios 2* spacecraft to sample fast coronal wind in the ecliptic during three successive solar rotations (Bruno et al. 1985). The sampling time of the observations is $\Delta t = 81$ s. Hence the spectral frequency range extends from (3–6) $\times 10^{-6}$ Hz up to the Nyquist–Shannon frequency $f_{\rm NS} = 6 \times 10^{-3}$ Hz. The time series of the proton density observed during the high and the low streams are shown in the bottom panel of Figure 1.

2.1. Frequency Analysis

The spectral analysis is performed using a Fast Fourier Transform (FFT) on data samples consisting of $N = 2^n$ elements. The frequency spectrum of fluctuations have been obtained after a linear detrending and tapering of the time series, applied to remove high frequency spurious components in the spectral analysis. The Fourier analysis of the UVCS and *Helios 2* data reveals the existence of significant power in the spectra derived from the proton density fluctuations in the frequency range $\sim 10^{-5}$ Hz $\leqslant f \leqslant 10^{-4}$ Hz at the coronal and heliospheric levels, both in the low- and high-speed solar wind. Figure 2 shows the power spectra of the coronal and heliospheric fluctuations of the plasma density in the two solar wind regimes (black and red spectra, respectively): the left panel shows the results obtained by analyzing the slow solar wind plasma, whereas the right panel shows those inferred for the fast

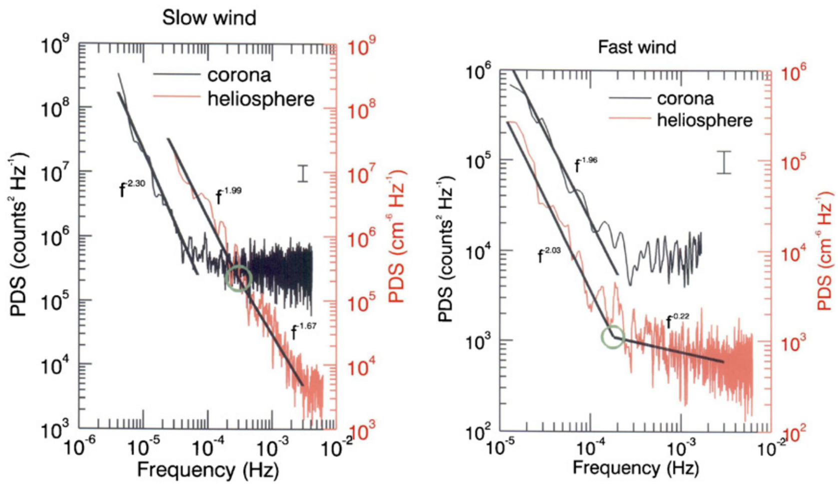

Figure 2. Power density spectra of the density fluctuations of the low- (left panel) and high- (right panel) speed streams observed in the outer corona (black spectra) and in the inner heliosphere (red spectra); thick solid lines show the $f^{-\alpha}$ slopes as inferred by the fitting functions; green circles represent the knee of the spectra; the error bar indicate a confidence level of 95%.

(A color version of this figure is available in the online journal.)

solar wind plasma. A function $f^{-\alpha}$ can be fitted to the spectra in the frequency range where they exhibit a power-law scaling, by applying the Levenberg–Marquardt least-squares minimization method with a confidence level of 95%. In the above low-frequency range, the spectral index α inferred from the slow wind data turns out to be $\alpha = 2.30 \pm 0.12$ and $\alpha = 1.99 \pm 0.08$ at the coronal and heliospheric level, respectively (left panel of Figure 2). In a similar manner, the density perturbations of the fast solar wind (right panel of Figure 2) exhibit a low-frequency spectral scaling close to $1/f^2$ dependence both in the outer corona where $\alpha = 1.96 \pm 0.12$, and in the inner heliosphere where $\alpha = 2.03 \pm 0.08$. The presence of a $1/f$ spectrum beyond $f \simeq 10^{-4}$ Hz, which could perhaps connect the flat spectrum and the $1/f^2$ spectrum, has been inferred by Bemporad et al. (2008) on the basis of longer data set, even if the $1/f$ slope extends for less than one decade. In our case, the need for a continuous time series with a regular sampling, requested in order to perform the phase coherence analysis described below, forced us to analyze a shorter data set. Perhaps due to the limited extent of our data set, we cannot attribute the same physical meaning to the connection between the low and high frequencies part of the spectrum. However, the presence of power spectra close to $1/f^2$ is very interesting, because they can describe stochastic processes close to a Brownian noise. In fact the Hurst exponent $H = (\alpha - 1)/2$ in this case is close to $H = 1/2$, a value which characterizes a stochastic process without persistence, say without memory.

Large-scale fluctuations of the proton density over timescales from a few hours to a few days are thus found in both solar wind regimes, at coronal and heliospheric heights, although the spectral power is much larger in the denser slow wind than in the tenuous fast wind. The spectral index however is different in the two cases thus indicating different physical conditions.

In the slow solar wind, the high-frequency band of the spectra of the density fluctuations results to be quite different moving from the outer corona to the inner heliosphere. The flattening observed in the corona at frequencies higher than about 10^{-4} Hz (black spectrum in the left panel of Figure 2), interpreted as Poissonian noise (Telloni et al. 2009), is not found at 0.3 AU (red spectrum in the left panel of Figure 2). Rather, in the slow solar wind, the high-frequency part of the spectrum shows a slope close to a Kolmogorov-like spectrum. Moreover, in the slow coronal wind the slope of the spectrum found at low frequencies, which results to be significantly greater than $\alpha = 2$, indicates a certain degree of persistence in the physical process which we are investigating. Hence, the coronal region where the slow wind is generated, is perhaps permeated by stochastic fluctuations which cannot be described by a simple Brownian motion, rather some long-range correlations must be present. These correlations should be the low-frequency driving for the occurrence of a turbulent energy cascade which characterizes the transition to the heliosphere, where the spectral slope becomes close to a Kolmogorov-like spectrum, as usually observed in the solar wind turbulence (Matthaeus et al. 1991; Zank & Matthaeus 1991).

The Kolmogorov spectrum for density fluctuations have been also observed in radio-wave scintillation observations in the ionized interstellar medium (Armstrong et al. 1981). Although this density spectrum is suggestive of turbulence, no theory relevant to its interpretation exists up to now. The Kolmogorov spectrum for density can be obtained, for example, by assuming that density is a passive scalar. In this case, by defining density fluctuations $\Delta\rho$ and streamwise velocity fluctuations Δu across eddies at the scale ℓ, the Yaglom's law for a passive scalar can be easily calculated to be $\langle \Delta u \Delta\rho^2 \rangle = -4/3\epsilon\ell$, where ϵ is the dissipation rate for density fluctuations (Frisch 1995). That is, if we assume a Kolmogorov phenomenology for velocity $\Delta u \sim \ell^{1/3}$, from Yaglom's law we immediately find the same phenomenology for density fluctuations, which obviously corresponds to the Kolmogorov spectrum for the spectral density. Only in the framework of nearly incompressible turbulence density fluctuations can be considered as a passive scalar and then they can give rise to a Kolmogorov spectrum (Dastgeer & Zank 2004). In our case, at least at 0.3 AU, density fluctuations can be considered as mainly due to the coronal transported structures, so that they can be treated in the framework of nearly incompressible turbulence. Of course, this is not always true. For example, at larger distance density fluctuations cannot be considered as a passive scalar because, even if they have a weak amplitude, density fluctuations have been found to deeply affect the usual turbulent scaling laws for Elsasser fields (Carbone et al. 2009).

In the fast solar wind, the power spectrum of the coronal and heliospheric density fluctuations exhibits approximately the same low-frequency $1/f^2$ dependence (black and red spectra in the right panel of Figure 2, respectively). Such a power spectrum implies a Hurst exponent $H = 1/2$ (e.g., Telloni et al. 2009) which indicates stochastic, non-correlated fluctuations characterizing the polar coronal hole region as well as the high-speed streams observed in the inner heliosphere. Hence, the comparison of the spectral indices in the two solar wind regimes shows that the coronal density variability in the fast wind differs from that observed at lower latitudes, where a spectral index α larger than 2 clearly indicates a relevant degree of persistency and time correlation in the observed density fluctuations. Power spectra with a $1/f^2$ frequency scaling are typical of time series dominated by discontinuities (e.g., Siscoe et al. 1968; Burlaga & Mish 1987; Berton 2004). The above results of a spectral index α close to 2 might imply that the fast wind from its origin in the core of polar coronal holes out to the heliosphere is dominated by discontinuities in density corresponding to compressions and rarefractions of the solar wind plasma. Structures of this kind could arise from compressive shocks and magnetoacoustic waves propagating outward from the Sun. On the other hand, they could be non-propagating inhomogeneities embedded in the solar wind, such as current sheets like tangential discontinuities separating adjacent regions characterized by different total pressure and density (Bruno & Carbone 2005). Since the same spectrum of the fast wind density fluctuations found in the inner heliosphere is observed as well in the outer corona (red and black spectra in the right panel of Figure 2, respectively), the present results provide an important clue suggesting that the discontinuities and the $1/f^2$ Brownian noise observed in the interplanetary space might have a coronal origin.

Whilst the fast solar wind emerging from the polar coronal hole is dominated by Poissonian white-noise fluctuations at frequencies higher than about 10^{-4} Hz (black spectrum in the right panel of Figure 2), in the heliospheric fast solar wind stream, the spectral index found in the high-frequency band is $\alpha = 0.22 \pm 0.03$ (red spectrum in the same panel of Figure 2), which is less steep than $\alpha = 5/3$, the index of the Kolmogorov spectrum observed in the low-speed stream (red spectrum in the left panel of the same figure). Such a frequency dependence might be interpreted in the light of the mechanism proposed by Tu et al. (1989), based on the parametric decay of the energy of the outward Alfvén waves (Primavera et al. 2003). That is, whilst the heliospheric low-speed stream is characterized by a rather good equipartition between inward and outward Alfvén waves, the fast heliospheric wind is dominated by outward propagating Alfvén waves. An outward large amplitude Alfvén wave, unstable to perturbations of density fluctuations, would decay into a backscattered Alfvén wave with lower amplitude and frequency and into a magnetoacoustic wave propagating in the same direction of the mother wave. This last compressive component characterized by density fluctuations $\delta\rho \neq 0$ would enhance the spectra at high frequencies.

2.2. *Phase Coherence Analysis*

The analysis of power spectra reveals some properties of density fluctuations, but the phases of fluctuations remain unexplored. Coherent structures embedded within a stochastic process are characterized by a certain degree of phase correlation, so that in order to infer the presence of these structures the use of the Fourier analysis is not sufficient. Thus, for this purpose we apply the tool developed by Hada et al. (2003), that is, a technique based on the fact that the time series appear to be smoother when the phases are correlated rather than when they are random (Higuchi 1988); hence also the time-delayed differences of the data sample are smaller. For a given time series $\xi(t)$ these differences can be measured by the first-order structure function $L = \langle|\Delta\xi_\tau|\rangle$, where $\Delta\xi_\tau = \xi(t+\tau) - \xi(t)$ represents the density fluctuations at the scale τ (brackets being time averages over all fluctuations at a given lag time τ). The degree of phase synchronization can be assessed by comparing the first-order structure function of the observed time series (OBS) with those of two synthetic time series derived from the observed one, preserving the amplitudes of the Fourier basis functions, but randomly shuffling their phases in one case (phase-randomized set, PRS) and setting all equal to each other in the other case (phase-correlated set, PCS). Thus the three data sets have the same power spectrum, but different phase distributions. Hence, it is possible to measure the degree of phase correlation in the observed time records by means of the phase coherence index c_ϕ, which is defined as

$$c_\phi = \frac{L_{\mathrm{PRS}} - L_{\mathrm{OBS}}}{L_{\mathrm{PRS}} - L_{\mathrm{PCS}}}, \tag{1}$$

where L_* is the first-order structure function of the three data sets (OBS, PRS, and PCS). It can be realized that the phase coherence index is a function of the timescale τ and ranges from $c_\phi \sim 0$, for a time series with random phases, to $c_\phi \sim 1$ for a completely phase-correlated data sample. The phase-coherence index c_ϕ of the density fluctuations observed in the fast and slow solar wind, at the coronal and heliospheric levels, as a function of the inverse of the time lag τ, is respectively shown in the top and bottom panels of Figure 3.

The different degrees of persistency found in the power spectra are reflected in the different values of the phase coherence of the slow wind density fluctuations assumed in the corona and heliosphere. In the corona, the coherence index is indeed larger than $c_\phi \sim 0.6$, for $\tau^{-1} \lesssim 10^{-4}$ s^{-1}, corresponding to the fact that the low-frequency range is dominated by time-correlated density fluctuations, as indicated by a spectral index α larger than 2 (cf. left panel of Figure 2). On the other hand, in the heliosphere the coherence index rapidly falls down to $c_\phi \sim 0.4$ for $\tau^{-1} \lesssim 3 \times 10^{-4}$ s^{-1}, which corresponds to the knee, or frequency break, separating the low-frequency spectral scaling from a Kolmogorov-like spectrum observed at higher frequencies in the heliospheric low-speed stream data. This is due to the fact that some uncorrelated energy input at large scales is at work in the slow wind going away from the solar corona, thus destroying the phase correlation. On the contrary, the development of the turbulent cascade accumulates coherent structures at smaller scales. This corresponds to the well-known behavior of intermittency in fully developed turbulence which is a characteristic of solar wind turbulence (cf. Bruno & Carbone 2005).

As far as the fast wind is concerned, the stochastic character of the large-scale density fluctuations, revealed by the $1/f^2$ scaling laws, at both coronal and heliospheric levels is confirmed by the low degree of phase synchronization existing in the density fluctuations, as shown in the bottom panel of Figure 3. In fact, the coherence index is low in both cases, even if a residual dynamical behavior, as described previously for the slow wind seems to be at work, namely a partial destruction of phase coherence at large scales due to energy input, and a residual dynamical behavior at small scales due to nonlinear activity.

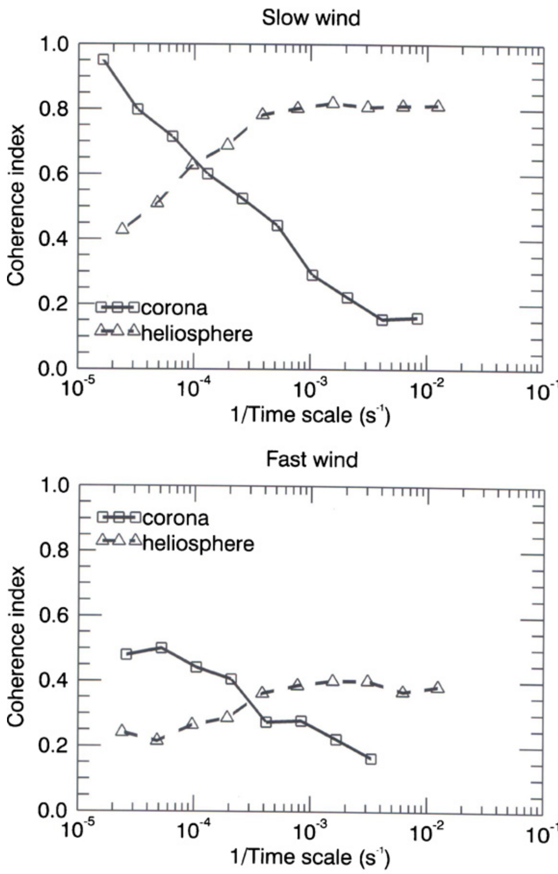

Figure 3. Phase coherence indexes c_ϕ of the density fluctuations of the low (top panel) and high (bottom panel) speed streams, observed in the outer corona (squares and solid line) and in the inner heliosphere (triangles and dashed line), as a function of the inverse of the timescale.

3. CONCLUSION

As a conclusion, we investigated density fluctuations both in the outer corona and in the interplanetary space, by comparing UVCS/*SOHO* observations of the outer corona both at high and low latitudes with *Helios 2* measurements performed at the perihelion passage at 0.3 AU on the ecliptic plane. Our main result is the evidence that density fluctuations in fast and slow solar wind evolve differently during the transition from the outer corona to the interplanetary space, and the imprints of solar wind structures reside in the outer corona. In particular, the high-speed solar stream observed in the inner heliosphere share the $1/f^2$ low-frequency spectrum with the fast solar wind observed in the polar coronal holes where the streams are first accelerated. This fact suggests that the interplanetary large-scale discontinuities, yielding such a spectral dependence, are likely to originate in the solar corona. As far as high frequencies are concerned, a weak evolution is present, namely the high frequency part of the spectrum significantly differs from a flat spectrum. At variance to high-speed streams, the slow wind shows an evident quick dynamical evolution during the transition from the corona to the inner heliosphere, thus forming a Kolmogorov-like spectrum.

Spectral slopes alone cannot give complete information on turbulence, because phase correlations are lost when the second-order moment of fluctuations is taken into account. For example the study of classical phenomena like intermittency in fully developed turbulence, due to hidden phase relationships generated during the turbulent energy cascade, requires at least a knowledge of phase correlations (Bruno & Carbone 2005). We investigated this feature by looking at a single index, say the so-called phase coherence index. Even if the scaling behavior of this parameter is the same for both fast and slow wind, their relative amplitudes allows us to distinguish between high and slow wind. In both types of wind, we found that phases of fluctuations at large scales in the outer corona are more coherent than at small scales. The enhanced role of phase coherence in slow wind, more compressive than fast wind (Bruno & Carbone 2005), is a signature for the presence of compressive discontinuities at large scales which are characterized by phase correlations. Phases of fluctuations at small scales, in the outer corona, are poorly correlated, in agreement with our conjecture for the presence of noise at these scales. However, the dynamics of fluctuations is evident when passing from the outer corona to the interplanetary space. In this passage, nonlinear interactions play a key role in the dynamics, the phase coherence at large scales are partially destroyed, and a typical turbulent evolution is observed. In fact, the presence of phase correlations at small scales, even if with a different degree for both high- and slow-speed streams, is enhanced, due to usual turbulent nonlinear energy cascade which spontaneously generates intermittent fluctuations, say singularities which are defined by their phase correlations. In the slow wind, the presence of strong density fluctuations which generates further singularities with respect to the usual turbulent cascade (Bruno & Carbone 2005) can explain the enhanced role of phase coherence in this kind of wind with respect to the fast wind.

A further interesting point of our results is that turbulence in the interplanetary space arises with both a well defined Kolmogorov-like power spectrum for density fluctuations and a phase correlation which, as already said, is due to intermittency of the density structures. This is a classical picture of turbulence. However, some few words of caution concern the spectral slope. There is no evident reasons for density fluctuations to be Kolmogorov-like, apart, as we showed here, for the case of passively advected structures. The evidence, found in this paper, that the density fluctuation spectrum evolves quickly during the transition from the outer corona to the interplanetary space, indicates that the Kolmogorov spectrum for density fluctuations is forming in a turbulent environment due to strong nonlinear interactions. Perhaps at small distances from the Sun density fluctuations might be strongly affected by transported structures, so that they can be considered as passively transported, and in this case spectral properties of fluctuations are subject to a Kolmogorov phenomenology. These findings should give a strong contribution to understand whether nearly incompressible turbulence is able to describe the quick evolutionary behavior of the density fluctuations in the slow wind, or rather the slow wind fluctuations are not to be considered as passive fluctuations. This topic requires further investigations which will be the argument of a future work.

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REFERENCES

Armstrong, J. W., et al. 1981, Nature, 291, 561
Bemporad, A., et al. 2008, ApJ, 677, L137

Berton, R. P. H. 2004, Nonlinear Process. Geophys., 11, 659
Bruno, R., & Carbone, V. 2005, Living Rev. Sol. Phys., 2, 4
Bruno, R., et al. 1982, J. Geophys. Res., 87, 10339
Bruno, R., et al. 1985, J. Geophys. Res., 90, 4373
Burlaga, L. F., & Mish, W. H. 1987, J. Geophys. Res., 92, 1261
Carbone, V., et al. 2009, Phys. Rev. Lett., 103, 061102
Coles, W. A., & Harmon, J. K. 1978, J. Geophys. Res., 83, 1413
Dastgeer, S., & Zank, G. P. 2004, ApJ, 602, L29
Frisch, U. 1995, Turbulence: The Legacy of A.N. Kolmogorov (New York: Cambridge Univ. Press)
Hada, T., et al. 2003, Space Sci. Rev., 107, 463
Higuchi, T. 1988, Phys. Rev. D, 31, 277
Kohl, J. L., et al. 1995, Sol. Phys., 162, 313
Matthaeus, W. H., et al. 1991, J. Geophys. Res., 96, 5421
Morgan, H., et al. 2004, ApJ, 605, 521
Primavera, L., et al. 2003, in AIP Conf. Proc. 679, Solar Wind Ten: Proc. Tenth International Solar Wind Conf., ed. M. Velli, F. Malara, & R. Bruno (Melville, NY: AIP), 505
Roberts, D. A., & Goldstein, M. L. 1987, J. Geophys. Res., 92, 10105
Roberts, D. A., et al. 1987, J. Geophys. Res., 92, 12023
Sari, J. W., & Ness, N. F. 1969, Sol. Phys., 8, 155
Siscoe, G. L., et al. 1968, J. Geophys. Res., 73, 61
Telloni, D., et al. 2009, ApJ, 693, 1022
Thieme, K. M., et al. 1990, Ann. Geophys., 8, 11
Tu, C.-Y., et al. 1984, J. Geophys. Res., 89, 9695
Tu, C.-Y., et al. 1989, J. Geophys. Res., 94, 11739
Villante, U., & Bruno, R. 1982, J. Geophys. Res., 87, 607
Zank, G. P., & Matthaeus, W. H. 1991, Phys. Fluids A, 3, 69