TURBULENCE IN THE SOLAR WIND AS SEEN BY CLUSTER CIS EXPERIMENT: PRELIMINARY RESULTS ON INTERMITTENCY AND SCALING LAWS.

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ABSTRACT

One of the most interesting features of solar wind turbulence is the intermittent character of its velocity fluctuations. A direct consequence of this would imply that small eddies are less and less space filling if turbulence is looked at in the framework of a classical Richardson's cascade. This phenomenon would cause solar wind turbulence to be intermittently distributed in space. In other words, the global scale invariance required in the K41 theory would release towards a local scale invariance where different fractal sets characterized by different scaling exponents can be found. The first solar wind plasma measurements made by the CIS experiment onboard Cluster spacecraft reveal the existence of some differences of the intermittent character of the fluctuations as observed by two different spacecraft. Although thiese findings are based on a preliminary analysis and expect to be confirmed by a similar analysis performed on magnetic field data, our study fully confirms previous findings reported in literature that ascribe to the presence of the border between adjacent flux tubes an important role in the intermittency of solar wind fluctuations.

1. INTRODUCTION

Turbulent flows are characterized by a statistical relation between velocity differences $\delta v_s = |\vec{V}(\vec{x} + \vec{s}) - \vec{V}(\vec{s})|$ and the energy transfer rate ϵ_s at the scale separation $s = |\vec{s}|$ (Kolmogorov, 1962) $\delta v_s \sim (\epsilon_s s)^{1/3}$ In addition, it has been shown that, once we take into account the Alfvén decorrelation effect of the large scale magnetic field (Kraichnan, 1965), a similar scaling can be obtained for Magnetohydrodynamic (MHD) turbulence (Carbone, 1993), $\delta v_s \sim (V_A \epsilon_s)^{1/4} s^{1/4}$ where V_A is the Alfvén velocity of the largest scale. The self–similarity of the fluctuations reflects in their scaling as a simple power law and it is usually studied via the so–called *p–th* structure functions ${S_s}^p =< {\delta v_s}^p >$. Consequently a scaling for ${S_s}^p$ is readily obtained, once we introduce the scaling exponent ξ_p, through the relation ${S_s}^p \sim s^{\xi_p}$, where $\xi_p = p/m$ with $m = 3$ or $m = 4$ in case we are dealing with a fluid or a magnetofluid, respectively. In case fluctuations are affected by intermittency, i.e. when the energy transfer rate ϵ is not constant (Landau's objection) but intermittently fluctuates, a new scaling has to be evaluated ${S_s}^p \sim l^{p/m} < \epsilon^{p/m} >$. Expressing $\epsilon^{p/m}$ via a scaling relation with s, we can write $< \epsilon^{p/m} > \sim s^{\tau_{p/m}}$ and, consequently, $\xi_p = p/m + \tau_{p/m}$. If observations show a departure from the simple $\xi_p = p/3$ (or $\xi_p = p/4$ for the MHD case) this is an indication that intermittency is present.

Within the past decade, several studies have addressed the problem of intermittency as observed in the solar wind fluctuations. The first observations of intermittency are due to Burlaga (1991) who studied the behavior of the exponent ξ_p of the structure functions of wind speed recorded in the outer heliosphere. Similar studies were performed for the inner heliosphere by Marsch and Liu (1993) who highlighted differences between fast and slow wind. Later on, Ruzmaikin et al., (1995), fitting magnetic field intermittency as observed by Ulysses with their model of random–phased Alfvénic turbulence, found a close agreement with the expected Kraichnan scaling for a magnetofluid (3/2). Carbone et al., (1995) found that, similarly to ordinary (unmagnetized) fluids, solar wind fluctuations exhibit properties of Extended Self Similarity (Benzi et al., 1993). Moreover, relying on this feature, they were able to find some evidence that differences exist between scaling exponents

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in ordinary flows and hydromagnetic flows. Tu et al. (1996) modified the Tu's (1988) model of developing turbulence including intermittency effects and obtaining a new expression for the scaling exponent ξ_p. Horbury and Balogh (1997) studying the scaling of interplanetary fluctuations observed by Ulysses, concluded that magnetic field fluctuations are more Kolmogorov–like rather than Kraichnan–like. Lately, Sorriso et al., (1999) have shown that the non-Gaussian behavior of the Probability Distribution Functions of solar wind velocity and magnetic field fluctuations at small scales can be represented by a convolution of Gaussians whose variances are distributed according to a log-normal distribution (Castaing et al. 1990). Moreover, they suggested that the most intermittent magnetic and velocity structures are mainly due to compressive phenomena as successively shown by Veltri and Mangeney (1999) and Bruno et al. (2001) who, basing their analysis on a wavelet signal decomposition (Farge, 1990), were able to locate and study in detail intermittent events in the solar wind flow.

Cluster gives us a new opportunity to improve our knowledge about intermittency of interplanetary turbulence since it allows to study for the first time a multi–point measurement performed in the solar wind.

2. DATA ANALYSIS

The following analysis has been performed on plasma data recorded by the hot ion analyser of the CIS experiment onboard Cluster (see Reme et al., (1997) for a description of the experiment) during day 22.02.2001 when the spacecraft were immersed in the solar wind as shown in Figure 1. Data used in the analysis refer to available solar wind speed as measured onboard s/c 1 and 3 once per spin (4 sec). During the time interval of interest which our analysis refer to, the two s/c were separated by roughly 600 km and were performing solar wind observations. The traces of the wind speed relative to the two s/c are shown in Figure 2. These observations, which look pretty much alike to a naked eye, show that at the time of the observation, the two s/c were sampling slow solar wind flowing at an average speed of 350 km/sec. As a matter of fact these two traces are different as proven by the structure functions shown in Figure 3. In the left panel of this Figure we show results relative to the whole time interval. The first 6 moments of the velocity differences are shown from bottom to top and differences between the two s/c become visible starting from the fourth moment on, especially at scales smaller than 12 sec. However the structure functions do not show a clear power law and different scaling seem to be present in each of them depending on the range of scales we consider. This phenomenon is clearly reduced if we consider the second half of the day [12:25–24:00] during which the velocity profile is much more structured than during the previous 12 hours. Results relative to this time interval are shown on the right panel. Power laws are clearly recognizable together with a scale break around 10^3 sec where moments become flat indicating that the probability distribution functions of velocity differences at various scales tend to be gaussian and scale independent.

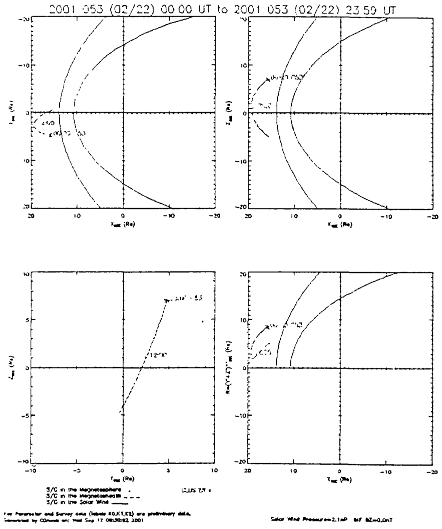

Figure 1. Position of Cluster s/c during day 22.02.2001 in GSE coordinate system, projected onto different planes. Position of the earth's bow–shock and magnetopause are also shown. The distance separating different s/c cannot be resolved in the plot. Source: http://csds-fr.cnes.fr:8080/cdms

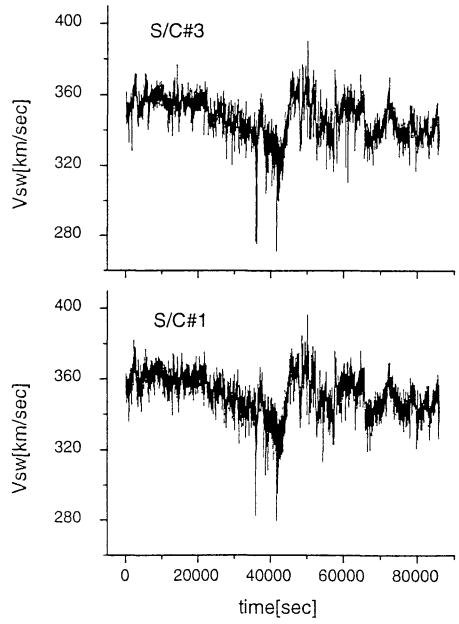

Figure 2. Wind speed measured on s/c 3 (upper panel) and s/c 1 (lower panel) expressed in km/sec

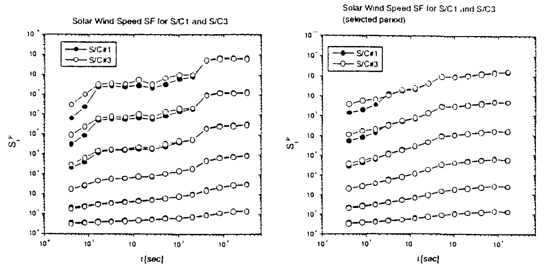

Figure 3. Structure functions relative to the whole time interval spanning throughout day 22 are shown on the left panel and refer to the first 6 moments starting from the bottom. Structure functions, in the same format but, referring to the selected time interval $(12^h : 25^m to 24^h : 00^m)$ *are shown on the right panel.*

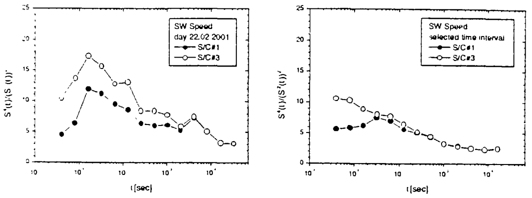

Figure 4. Flatness of wind speed fluctuations computed for different time scales and obtained from the structure fuctions shown in Figure 3.

One of the implications of intermittency is the fact that, moving from larger to smaller scales, probability distribution functions of the differences evolve from gaussian to peaked distributions, i.e, the tails of the distributions become more and more stretched. An intuitive implication is that extreme deviations from the average are more probable than they would be if they were distributed according to a gaussian distribution. A quantitative estimate of the flatness (or peakdeness) of a distribution relative to a normal distribution with the same mean and standard deviation, can be obtained from the 4^{th} moment of the distribution, the flatness, which is equal to 3 for a Gaussian distribution. The usual expression for this parameter is the following $F_s = \frac{<v_s(t)^4>}{<v_s(t)^2>^2}$ but, it can be also directly estimated from the structure functions $F_s = \frac{S_s{}^4}{(S_s{}^2)^2}$ Following the definition given by Frisch (1995), a random function is said to be intermittent if the flatness of its fluctuations grows without bound when we include smaller and smaller scales. In Figure 4 we show the behavior of this parameter, directly computed from the SFs, for both s/c and for the whole time interval on the left panel and, for the selected time interval on the right panel. Concentrating our attention on the left panel, we notice that the flatness increases for both spacecraft when we look at smaller and smaller scales. Following the criterion given by Frisch we can conclude that both traces show intermittency and that s/c 3 is more intermittent than s/c 1. Moreover, the major hump shown by both traces at scales around a few tens of seconds might indicate that upstream waves particularly active at the end of the first half of the day might play a relevant role. As a matter of fact, focusing on the second half of the day (right panel), much of the differences have been reduced although, at the smallest scales s/c 3 is still more intermittent than its companion. Upstream waves are certainly not the only possible cause of intermittency and the Local Intermittency Measure, a numeric method suggested by Farge (1990), allows to identify other possible sources. This method is based on the wavelet transform's capability to unfold a signal into both space l and scale η using the multiresolution analysis where the scales covered are all powers of 2 of the original time resolution (Mallat, 1989). As shown by Meneveau (1991), the following expression $F_\eta \equiv < C^4_{\eta,l} >_l / < C^2_{\eta,l} >^2_l$ where $C_{\eta,l}$ is a wavelet co-

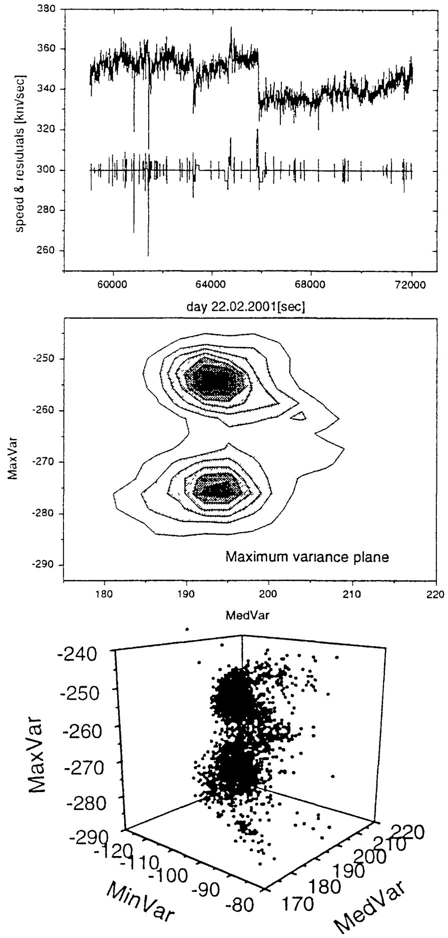

Figure 5. Top panel: selected time interval from the wind speed trace recorded by s/c 3. The contribution due to intermittency, extracted from the original trace via LIM, is also shown in the same panel after a constant value of 300 km/sec has been added to it for graphic reasons. Medium panel: contour levels inferred from the maximum variance plane and relative to the position of the tip of the velocity vector. The gray level increases with increasing the presence of the vector's tip in a given region of the plane. Bottom panel: the position of the vector's tip plotted in the minimum variance reference system.

efficient at scale η and location l, defines the flatness F of the wavelet coefficients for each scale η and is an estimate of the flatness of the fluctuations at the same scale η contained in our data sample. At this point, adopting a recursive method (Bianchini et al., 1999) similar to the one introduced by Onorato et al. (2000) to study experimental turbulent jet flows, we are able to locate in the time domain those scales that cause intermittency. In other words, we are able to extract the intermittent component from our turbulent data sample. In the top panel of Figure 5 we show a time interval lasting slightly more than 3 hours taken from the trace of s/c 3 already shown in Figure 2. The spiky trace shown on the same panel is the intermittent signal extracted from the above trace and added to a constant of 300km/sec for graphic reasons. One of the largest intermittent events identifies the clear velocity discontinuity roughly located in the middle of the interval. This discontinuity separates two regions characterized not only by a different speed level but also by a different orientation of about 1.9° of the average velocity vector as shown by the projection of these fluctuations on the maximum variance plane (middle panel) and in the 3-D plot (bottom panel) where we show the position of the tip of the velocity vector in the minimum variance reference system. These results are similar to those already found in Helios magnetic field data (Bruno et al., 2001) showing that some of the intermittent events are due to the border between adjacent flux tubes representing the coherent structure of the wind convected away from the Sun during its expansion.

3. SUMMARY AND CONCLUSIONS

We study and compare the intermittent character of solar wind velocity fluctuations as recorded by Cluster S/C1 and S/C3 while separated by only about 600 km during day 22.02.2001

SFs for both S/C show that a scaling break appears to be at scales around 15 min ($\sim 10^3$ sec). Intermittency is much reduced at larger scales and fluctuations are more Gaussian. Contrary to what expected, intermittency does not increase all the way to the smallest scales but it is stronger roughly between 10 and 10^3 seconds suggesting that upstream waves might play a considerable role. Even analyzing the second half of the day, much less dominated by upstream waves, S/C3 is still slightly more intermittent than its companion. The present study is rather preliminary and needs to be corroborated by much better statistics before final conclusions can be drawn, however, in case these findings should be confirmed by magnetic field data our results would represent the first evidence that the local intermittent character of interplanetary fluctuations can slightly change even on scales of a few hundred kilometers. Moreover, our results also show that upstream turbulence is not the only cause of intermittency. As a matter of fact, Local Intermittency Measure allows to identify other intermittent events which seem to be represented by the border of adjacent flux tubes as recently reported in literature (Bruno et al., 2001)

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REFERENCES

Benzi, R., G. Paladin, G. Parisi, et al., 1984, J. Phys., A17, 3521

Bianchini, L., E. Pietropaolo, R. Bruno, 1999, Proc. 9th European Meeting on Solar Physics, "Magnetic Fields and Solar Processes", Florence, Italy, 12–18 September, ESA SP–448, 1141

Bruno, R., B. Bavassano, E. Pietropaolo, et al., 1999, Solar Wind IX Conference, held in Nuntucket (MA), 5–9 October, 1998, edited by S.R. Habbal, R. Esser, J.V. Hollweg, and P. Isenberg, AIP, 471, 539

Bruno, R., V. Carbone, P. Veltri, et al., 2001, Planetary Space Sci., 49, 1201

Burlaga, L., 1991, J. Geophys. Res. 96, 5847

Carbone, V., 1993, Phys. Rev. Lett. 71, 1546

Carbone,V., Veltri, P., Bruno, R., 1995, Phys. Rev. Lett. 75, 3110

Castaing, B., Gagne, Y., and Hopfinger, 1990, Physica D 46, 177

Farge, M., Holschneider, M., Colonna, J. F., 1990, Topological Fluid Mechanics, ed. H.K. Moffat, Cambridge: Cambridge University Press, 765

Frisch, U., 1995, Turbulence: the legacy of A. N. Kolmogorov, Cambridge University Press

Horbury, T. A., Balogh, 1997, Nonlinear Processes in Geophysics, 4, 185

Kolmogorov, A. N., 1962, J. Fluid mech. 177, 133

Kraichnan, R. H., 1965, Phys. Fluids 8, 1385

Mallat, S., 1989, IEEE, Trans. on Pattern Anal. Machine Intell. 2, 7

Marsch, E., and Liu, S., 1993, Ann. Geophysicae 11, 227

Meneveau, C., and Sreenivasan, K. R., 1987, Phys. Rev. Lett. 59, 1424

Meneveau, C., 1991, J. Fluid Mech. 232, 469

Neugebauer, M., 1981, Fundamentals of Cosmic Physics, 7, 131

Onorato, M., Camussi, R., Iuso, G, 2000, Phys. Rev. E 61, 1447

Reme, H., J.M. Bosqued, J.A. Sauvaud, et al.,1997, Space Science Rev., 79, 303.

Ruzmaikin, A., Feynman, J., Goldstein, B., et al., 1995, J. Geophys. Res. 100, 3395

Sorriso–Valvo, L. , Carbone, V., Veltri, P., et al., 1999,Geophys. Res. Lett. 26, 1801

Tu, C. -Y., 1988, J. Geophys. Res. 93, 7

Tu, C.-Y, Marsch, E., Rosenbauer, H., 1996, Ann. Geophys. 14, 270

Veltri, P., and Mangeney, A., 1999, in Solar Wind IX, edited by S. Habbal, AIP Conf. Publ., 543