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Non-extensive statistical analysis of magnetic field during the March 2012 ICME event using a multi-spacecraft approach

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HIGHLIGHTS

- We present results concerning Tsallis statistics and solar wind dynamics at CME events.
- Strong non-extensive statistical character was observed in the period of CME event.
- During the shock period showed the strengthening of the non-extensive character.
- The space plasmas clearly reveal phase transition during shock events.

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ABSTRACT

In this study we present some new and significant results concerning the dynamics of interplanetary coronal mass ejections (ICMEs) observed in the near Earth at L1 solar wind environment, as well as its effect in Earth's magnetosphere. The results are referred to Tsallis non-extensive statistics and in particular to the estimation of Tsallis q-triplet, $(q_{stat}, q_{sen}, q_{rel})$of magnetic field time series of the ICME observed at the Earth resulting from the solar eruptive activity on March 7, 2012 at the Sun. For this, we used a multi-spacecraft approach based on data experiments from ACE, CLUSTER 4, THEMIS-E and THEMIS-C spacecraft. For the data analysis different time periods were considered, sorted as "quiet", "shock" and "aftershock", while different space domains such as the Interplanetary space (near Earth at L1 and upstream of the Earth's bowshock), the Earth's magnetosheath and magnetotail, were also taken into account. Our results reveal significant differences in statistical and dynamical features, indicating important variations of the magnetic field dynamics both in time and space domains during the shock event, in terms of rate of entropy production, relaxation dynamics and non-equilibrium meta-stable stationary states.

So far, Tsallis non-extensive statistical theory and Tsallis extension of the Boltzmann–Gibbs entropy principle to the q-entropy principle (Tsallis, 1988, 2009) reveal strong universality character concerning non-equilibrium dynamics (Pavlos et al. 2012a,b, 2014a,b; Karakatsanis et al. 2013). Tsallis q-entropy principle can explain the emergence of a series of new and significant physical characteristics in distributed systems as well as in space plasmas. Such characteristics are: non-Gaussian statistics and anomalous diffusion processes, strange and fractional dynamics, multifractal, percolating and intermittent turbulence structures, multiscale and long spatio-temporal correlations, fractional acceleration and Non-Equilibrium Stationary States (NESS) or non-equilibrium self-organization process and non-equilibrium phase transition and topological phase transition processes

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according to Zelenyi and Milovanov (2004). In this direction, our results reveal clearly strong self-organization and development of macroscopic ordering of plasma system related to strengthen of non-extensivity, multifractality and intermittency everywhere in the space plasmas region during the CME event.

1. Introduction

The last decades many scientists have worked for the understanding of the solar wind plasma dynamics through complexity theory. Burlaga [1–4] showed that speed fluctuations bear a multifractal structure in recurrent streams measured between 1 and 6 AU. The large scale magnetic field fluctuations as observed in the outer heliosphere (∼25 AU) were found to have a multifractal formation [2]. Also, small-scale velocity fluctuations were observed near ∼8.5 AU including multifractal structure, suggesting that solar wind turbulence consists of a mixture of sheets and space-filling eddies of various sizes. The concept of intermittent turbulence process in the solar wind plasma was further studied by many scientists ([5–8] and references therein). Theoretical models for explaining the self-similar, multiscale, multifractal and intermittent MHD turbulent character of the solar wind system, were also developed by many scientists [9–16]. The concept of self-organization and low-dimensional chaotic process for solar wind and space plasmas was supported also in a series of novel studies of Burlaga [17,1–4,18], Pavlos et al. [19–25] Burlaga and Forman [26]; Burlaga et al. [27], and Macek [13,14].

Traditionally the quantities of key interest in turbulence theory are two-point correlation functions and structure functions of the vector or solar fields. These quantities depend on the field differences between two points in space and time, allowing resolving a broad range of spatio-temporal scales of the turbulent fluctuations. According to Marsch and Tu [11], the fluctuating fields in the solar wind are often large in the moving frame and from a practical point of view their time histories resemble strongly the time evolution of mathematical random variables. The observed small-scale fluctuations of solar wind MHD quantities appear to be composed of waves and convecting pressure-balanced structures which occur as short-lived and nonlinearly coupled excitations on a broad range of scales. Temperature fluctuations were detected and found to play a prominent role in the local pressure balance, often distinctly anti-correlated with the magnetic field amplitude fluctuations and well correlated with the solar wind speed. This signature may stem from coronal heating and pressure-equilibration processes to adjacent plasma flow tubes near the Sun. The turbulent properties and compressibility are scale dependent and vary in close connection with the interplanetary magnetic field and the stream structure.

The Sun initially generates a broad-band spectrum of fluctuations which strongly develop and are further modified in the radially expanding wind by shear, compression and rarefaction associated with stream interactions and by damping and dissipation of the fluctuation amplitudes owing to large-scale inhomogeneity and microscopic plasma processes [11]. Burlaga [1–4] showed that speed fluctuations bear a multifractal structure in recurrent streams measured between 1 and 6 AU. The large scale magnetic field fluctuations as observed in the outer heliosphere (∼25 AU) were found to have a multifractal formation [2]. Also, small-scale velocity fluctuations were observed near ∼8.5 AU including a multifractal structure, suggesting that solar wind turbulence consists of a mixture of sheets and space-filling eddies of various sizes. Milovanov and Zelenyi [28–30] and Zelenyi and Milovanov [31] introduced fractional models of the self-affine and fractal temporal and spatial distribution of solar wind random magnitudes. In addition, Zelenyi and Milovanov [32], through the introduction of fracton excitations, managed to discriminate between the internal fractional processes of the solar wind as a driving mechanism of the self-organized solar wind dynamics and the fractional temporal and spatial characteristics caused by the photospheric fractional dynamics. More generally, according to Zelenyi and Milovanov [31], the complex character of the solar wind system can include the existence of non-equilibrium (quasi)-stationary states (NESS) having the topology of a percolating fractal set. The stabilization of a system near the NESS is perceived as a transition into a turbulent state determined by self-organization processes. The large-scale order of the NESS turbulent state can be identified with the generalized symmetries of a fractal disk diffeomorphic to a fractal set at the percolation threshold [33]. The structural stability of the NESS as a symmetric turbulent phase is maintained due to multi-scale correlations with divergence of the correlation length for the fractal distribution. The long-range correlation effects manifest themselves as a strange non-Gaussian behavior of kinetic processes near the NESS plasma state.

Coronal mass ejections (CMEs) are a transient type of solar wind which originate from closed magnetic field regions in the solar corona and are ejected from the solar atmosphere, transporting large quantities of plasma ($\sim 10^{15}$–10^{16} g) and magnetic flux ($\sim 10^{15}$ Wb) into interplanetary space [34,35]. They were identified by images observed in the 1970a when events were detected in images from coronagraphs like Skylab [36]. The interplanetary extensions of CMEs are commonly referred to as interplanetary coronal mass ejections (ICMEs). ICMEs also drive Interplanetary (IP) shocks in events where their bulk speed relative to the ambient solar wind is greater that the fast magnetosonic speed of the upstream solar wind [37]. This speed differential is typically large enough for a shock to form that is detached from the ICME and precedes it. The solar wind plasma between the shock and oncoming front of the ICME is compressed as well as diverted around the ICME. This region is termed as the 'sheath' region and is characterized by high turbulent magnetic field [38]. Thus, when an ICME moves past the spacecraft in the solar wind the following sequence of structures would be detected: