Intermittency of magnetospheric dynamics through non-Gaussian distribution function of PC-index fluctuations

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[1] Dynamical behavior of the one minute resolution Polar Cap (PC) index was studied by using the 1995–2000 data sets. It was found that the probability distribution functions (PDFs) of the PC-index increments display a strong non-Gaussian shape in both positive and negative time intervals, depending on the time of an increment. This indicates that PC-index is not characterized by a global time self-similarity but rather exhibits an intermittency, previously detected in solar wind and auroral electrojet index time series. The PDFs for the PC index increments are fitted by the functional form proposed by Castaing et al. [1990] to describe intermittency phenomena in an ordinary turbulent fluid flow. The parameters that characterize the PC index increments PDF are very close to those reported before for solar wind magnetic field probability distribution functions. This indicates that the PC index adequately reflects the solar wind effects on the high-latitude magnetosphere. INDEX TERMS: 2740 Magnetospheric Physics: Magnetospheric configuration and dynamics; 2799 Magnetospheric Physics: General or miscellaneous; 2784 Magnetospheric Physics: Solar wind/ magnetosphere interactions; 2776 Magnetospheric Physics: Polar cap phenomena; 2722 Magnetospheric Physics: Forecasting. Citation: Stepanova, M. V., E. E. Antonova, and O. Troshichev, Intermittency of magnetospheric dynamics through non-Gaussian distribution function of PC-index fluctuations, Geophys. Res. Lett., 30(3), 1127, doi:10.1029/2002GL016070, 2003.

1. Introduction

[2] The Earth’s magnetosphere is a complex nonlinear dynamical system which continuously interacts with the solar wind and the ionosphere. In recent years, various methods from nonlinear dynamics, statistical physics, and complexity theory such as chaotic dynamics analysis [see Klimas et al., 1996, and references therein], models of self-organized criticality [Chang, 1992], and turbulence [Borovsky et al., 1997; Angelopoulos et al., 1999], were used to study the magnetospheric activity. However, many results, like power-law power spectra, admit several explanations, which makes it difficult an inambiguous testing of magnetospheric dynamics [Chapman and Watkins, 2001].

[3] Various multiscale complex phenomena often exhibit a behavior consisting of periods of relative quiescence which are interrupted by short bursts of activity. Such patterns in activity are often called intermittency and are observed in systems ranging from the stock market to turbulence [Vassilicos, 1995]. Burlaga [1991] studied large-scale fluctuations of the interplanetary magnetic field (IMF) and showed that the solar wind is a flow of a turbulent plasma that displays a multifractal structure and an intermittent character. Non-Gaussian nature of probability distribution function (PDF) of plasma velocity and magnetic field in the MHD solar wind turbulence has been revealed also by Marsch and Tu [1994, 1997]. They showed that these PDFs have strong deviations from the Gaussian form, especially at a small scale. The wings of the distribution appear to be stretched and higher than expected for a Gaussian, indicating that the strongest fluctuations are governed by a deterministic rather than by a stochastic dynamics. It was also found in Marsch and Tu [1994, 1997] that the radial components of both the velocity and the magnetic field look more intermittent than the two perpendicular components. Sorriso-Valvo et al. [1999] showed that in both fast and slow solar wind streams a magnetic field intensity is more intermittent than the bulk solar wind speed. Bruno et al. [1999] studied how the presence of intermittency affects the radial evolution of the anisotropy in the solar wind velocity and the magnetic field fluctuations.

[4] Apart from the solar wind, the magnetospheric dynamics itself also displays strong evidence of intermittency. Angelopoulos et al. [1999] showed that the magnetotail is in a state of bimodal convection, where the potential flow is stagnant unless driven by localized flow bursts. It was found that both the bursty bulk flow events and the ambient flows could be described as an intermittent turbulence. Consolini and De Michelis [1998] studied a time intermittency of the Auroral Electrojet (AE) index fluctuations by analyzing their PDFs at different time scales. They found that the PDFs are always non-Gaussian for the time-scales in a range of 1–120 min both for quiet and disturbed magnetosphere.

[5] Another index which carries an information about the current state of the Earth’s magnetosphere is a Polar Cap
index introduced by Troshichev and Andrezen [1985]. In this work we analyze the PC-index series for a presence of intermittency by looking at the probability distribution function of the PC-index signal increments at different time scales.

2. Data Analysis

[6] We analyze the PC-index data sets obtained at the Vostok in 1992, 1995, January 1996, and 1997–2000. More than 96% of this recorded data is suitable for the PC index analysis. 2754 gaps in time series are ignored as they present a negligible fraction of the total record time; the sections of the interrupted time series are simply concatenated together, forming the final data set of 3046487 samples. Tests on non-gap subsets show that the results obtained are robust when dealing with data set gaps in this way. This choice of a such long data set is necessary to provide a good statistics for a non-linear analysis. We have used all available data and did not make any preliminary assumption in attempt to reach as general result as possible.

[7] Figure 1 shows the PC-index probability distribution function, fitted by two log-normal distributions, $D(X) = A \exp\left[-(\log(X)-b)^2/c^2\right]$, where $X = PC$ and $X = -PC$ are positive and negative PC-indices, respectively. As seen, the PC-index is completely asymmetric with respect to zero with clear dominance of positive values (2826099 samples with 12526 gaps versus 220388 samples with 11649 gaps).

[8] To quantify the turbulent behavior of the magnetosphere, we perform a statistical study of the PDF of the PC-index fluctuations using the method proposed by Castaing et al. [1990] to approximate the PDF for velocity differences for different spatial separations $x$ in an intermittent

![Figure 1. Probability distribution function of the PC-index $D(PC)$. Black solid lines refer to the best fit of $D(PC)$ by two log-normal distribution for positive and negative branches of the PC-index (see text).](image1)

![Figure 2. Probability distribution function $Pdf[\delta PC(\tau)]$ for two different time scales ($\tau = 8$ min. and $\tau = 96$ min.) for total (○), positive (●), and negative (◆) PC-index data sets; $\sigma$ is a standard deviation of $\delta PC(\tau)$. Solid lines correspond to best fits of data with expression (1). The statistical error bars are smaller than the sign sizes.](image2)
Figure 3. Dependence of the variance of the variances $\lambda$ on the time-scale $\tau$ for total $($, positive $($, and negative $($ PC-index PDFs. Solid lines are power-low fits.

In order to study the dependence of the PDFs on the time-scale $\tau$, we analyzed the behavior of $\lambda^2(\tau)$, which is the quantitative measure of intermittency. As seen in Figure 3, $\lambda^2(\tau)$ decreases slowly with $\tau$ for all, positive and negative, values of the PC-index. The absolute value of $\lambda^2(\tau)$ is higher for negative PC-index for both the winter and the summer data sets. Results of a power law fit $\lambda^2(\tau) = \mu \tau^{-\alpha}$ are given in the Table 1. These values of $\mu$ and $\alpha$ for the PC index are compared to the ones reported in Sorriso-Valvo et al. [1999] ($\alpha_B = 0.19 \pm 0.02$, $\mu_B = 0.90 \pm 0.03$, $\alpha_V = 0.20 \pm 0.04$, $\mu_V = 0.38 \pm 0.02$ for the magnetic field and velocity fluctuations in the fast solar wind, respectively, $\alpha_B = 0.18 \pm 0.03$, $\mu_B = 0.75 \pm 0.03$, $\alpha_V = 0.44 \pm 0.05$, $\mu_V = 0.54 \pm 0.03$, for the magnetic field and velocity fluctuations in the slow solar wind, respectively) and to AE-index fluctuations [Consolini and De Michielis, 1998] (for laminar $\alpha_{AE} = 0.5 \pm 0.02$, $\mu_{AE} = 0.3 \pm 0.01$, and turbulent $\alpha_{AE} = 0.5 \pm 0.02$, $\mu_{AE} = 1.33 \pm 0.1$ phases). As seen, the obtained $\mu$ and $\alpha$ values are closer to the ones observed for the magnetic field and velocity fluctuations in the slow solar wind than the ones detected in the AE and the fast solar wind fluctuations.

Table 1. The Values of the Parameters Obtained a Power-Law Fit $\lambda(\tau) = \mu \tau^{-\alpha}$

<table>
<thead>
<tr>
<th></th>
<th>All</th>
<th>Winter</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>$\mu$</td>
<td>$\alpha$</td>
<td>$\mu$</td>
</tr>
<tr>
<td>All</td>
<td>0.13 ± 0.01</td>
<td>0.745 ± 0.006</td>
<td>0.06 ± 0.01</td>
</tr>
<tr>
<td>$PC &lt; 0$</td>
<td>0.075 ± 0.008</td>
<td>0.879 ± 0.002</td>
<td>0.00 ± 0.01</td>
</tr>
<tr>
<td>$PC &gt; 0$</td>
<td>0.11 ± 0.01</td>
<td>0.664 ± 0.008</td>
<td>0.08 ± 0.01</td>
</tr>
<tr>
<td>$0 &lt; PC &lt; 12$</td>
<td>0.11 ± 0.02</td>
<td>0.70 ± 0.01</td>
<td>0.08 ± 0.02</td>
</tr>
<tr>
<td>$PC \geq 12$</td>
<td>0.20 ± 0.08</td>
<td>0.64 ± 0.06</td>
<td>0.08 ± 0.02</td>
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3. Conclusions

Our analysis reveals the strong non-Gaussian character of probability distribution functions of the PC-index fluctuations. This is similar to the results of the turbulent fluid flow observations where the large fluctuation amplitudes dominate at small scales, being sparsely distributed as a consequence of intermittency [Castaing et al., 1990]. The intermittency detected in the PC-index fluctuations displays properties similar to the ones reported previously for the solar wind fluctuations [Sorriso-Valvo et al., 1999]. This indicates that the PC-index adequately describes the energy transfer processes from the solar wind to the polar ionosphere at different time scales. However, this similarity is
more pronounced during summer (see Table 1). Such seasonal difference is related to the difference in the ionospheric conductance in the polar cap regions due to the sunlight ionization. We assume that the more homogeneous and stable conductance during the summer creates the better connection between the solar wind dynamics and the PC index. It was also found that the level of intermittency is higher for the negative PC-index than for the positive one and is practically independent of $\tau$. Also, the scaling exponent $s$ is lower for the negative PC-index than for the total and the positive one. These trends can be due to a possible closure of the magnetosphere during long intervals of the Northward IMF with simultaneous development of the reverse magnetospheric convection and generation of the negative PC-index [Lukianova et al., 2002]. Observed trends for the PC index are different from those reported for AE-index [Consolini and De Michelis, 1998], for which $\chi^2(\tau)$ has also a power-law form but with significantly different values of the coefficient and the exponent (see Table 1). This difference can be attributed to the fact that the AE-index includes two distinct dissipative processes - an unloading process, and a directly driven process [Kamide and Kokubun, 1996; Kamide et al., 1999]. Currently existing views on the dynamics of the Earth magnetotail include a possible existence of a self-organized critical state or a driven dynamical critical state which can include “fluctuation-induced out-of-equilibrium topological transitions among metastable configurations near criticality” [Consolini and Chang, 2001, 2002] and are not inconsistent with the occurrence of intermittent turbulence. Therefore the important value of the PC-index time-series analysis is in providing the most direct information on the non-Gaussian features of the solar wind which serves as the external drive for the magnetospheric dynamics. Finally, the least perturbed nature of the information about the solar wind energy input to the magnetosphere contained in the PC index makes it extremely useful for space weather predictions.

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References


Chang, T. S., Low dimensional behavior and symmetry breaking of stochastic systems near criticality—can these effects be observed in space and in the laboratory?, *IEEE Trans. Plasma Sci.*, 20, 691–694, 1992.


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