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Statistical analysis of the magnetic fluctuations in boundary layers of Earth's magnetosphere

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Abstract

Investigation of statistical features of the magnetic fluctuations in boundary layers of Earth's magnetosphere and plasma of the solar wind, on different time scales, is carried out using magnetic field measurements from Cluster-II with a sampling frequency of 22.5 Hz in 2007–2010. We have studied the changes of shape and parameters of probability density function for magnetic fluctuations in the solar wind, foreshock region, postshock region and magnetosheath.

In particular, the evolution of maximum of probability density function and the structure functions of different orders as characteristics of turbulent processes for different time scales are investigated. Structure functions of high orders are used to determine the character of turbulent processes and the resulting diffusion in these regions. We have found that the highest intermittency is observed in the postshock region. Furthermore, magnetic turbulence in the middle magnetosheath corresponds to log-Poisson turbulent cascade model, and that in the SW plasma conforms to the Iroshnikov–Kraichnan's model.

Keywords: Turbulent model; Intermittency; Statistical properties of boundary layers; Earth's magnetosphere

1. Introduction

Despite the more than 60 years of research and plenty of significant results, the satisfactory theory of magnetohydrodynamic turbulence can't be yet established. Even the simplest cases are still not fully understood:

- How does the turbulence amplify, sustain and shape magnetic fields? What is the structure and spectrum of this field at large and small scales? The problem of turbulence is thus directly related to the fundamental problem of magnetogenesis.
- How the energy transfers between cascades and how it is dissipated? (e.g. in accretion discs of Solar corona, the heating of plasma may be due to the turbulence processes)
- How turbulence of the plasma flow and magnetic field increases and constrains the heat transfer?

This is not a complete list of questions facing the analysis of space and laboratory plasma.

Usually, the framework of the study does not provide answers to all posed problem, but significantly can help in understanding the pattern of turbulent properties and processes of self-organization of complex systems, including plasma and magnetic field.

Satellite studies of space plasma yields the experimental data on the properties of turbulence in the range of spatial and temporal scales that are inaccessible in laboratory experiments on Earth. The interaction of the magneto-

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sphere and magnetosheath, core processes globally interconnects and synchronizes with lowest-frequency resonances of noontime magnetosheath (Budaev et al., 2008). On the average scales, in a turbulent boundary layers (TBL) such self-organization processes occurs due to inverse cascades, that can be caused by reflected waves from the boundary, locally focused concave obstacle as an example, cusps narrowness. Thus, we are not dealing with a sequence of additive reactions to disturbances in the solar wind and magnetosheath, but with a complex large-scale nonlinear system. This is a "catastrophic" restructuring of currents and magnetic topology (rapid and slow jets, the transition from laminar stagnant region to irregular structures of boundary layer). There is a relation on the history (at times, the characteristic relaxation Alfven flows), the appearance of abnormally large correlations over large temporal and spatial scales and the formation of coherent structures in the form of jets that provide an abnormal transfer of plasma (Budaev et al., 2008).

Under the interaction of the solar wind with the Earth's magnetosphere, the intermittency can form. Furthermore, active regions coexisting with passive quasi-laminar flows. In this process, plasma parameters observed as random variables with a non-Gaussian distribution function, and when turbulent pulsations have much larger amplitudes, the probability of extreme events can be significantly greater than assumed by the Gaussian law (i.e. normal distribution). Intermittency is observed in hydrodynamic turbulent flows of neutral media and in the magnetized plasma with large and moderate Reynolds numbers (<1000). A feature of the intermittency in plasma boundary layers is the presence of magnetic and electric fields, leading to an additional process anisotropy.

Since random pulse velocity and fields characterize turbulence, the statistical physics and probability theory are the best to describe.

Generally, you cannot build a closed system of equations describing the dynamics of turbulent plasma; the results are mostly limited to semi-assessments. An exception is the case of weak turbulence when the quasi-linear approximation is able to describe anomalous transport processes.

Therefore, it is necessary to determine from the experiment the statistical properties of the fluctuations of environmental parameters related to the scale invariance, and obtain estimates for type and turbulent diffusion processes. This will qualitatively and quantitatively describe the features and processes of turbulent transport and help us to understand key properties of the transport processes in the transition layer. High-time resolution magnetic field measurements from Cluster-II satellites are suitable for this investigation.

While we present an analysis of magnetic field and comparison of it with different turbulence models, there exist other investigation of transition layers, some latter articles cover both computer modeling of collisionless plasma (e.g. Karimabadi et al. (2014), where they run multiple plasma models to study interaction of magnetic reconnection, shocks and turbulence development) and statistical study of space missions data. The three articles (Huang et al., 2013; Sahraoui et al., 2010; Roberts et al., 2015) provide a study of magnetic field correlation and two of them on K-mean filtering and need further analysis to compare with other methods.

2. Observational data

Twenty-five events of the magnetic field measurements obtained by Cluster-II mission in 2007–2009 with a frequency resolution of 22.5 Hz were analyzed to reveal the features of turbulent processes in the transition regions of the Earth's magnetosphere. In these events the satellites moved from the solar wind (SW hereafter) to the foreshock (FSH hereafter), passed through the bow shock and the postshock (PSH hereafter) into the deep of the magnetosheath (MSH hereafter), then crossed the magnetopause (MP hereafter) to enter into the magnetosphere.

During the transition from SW to MP the rate of fluctuations of the field changes dramatically, so the relative standard deviation is: 0.05–0.25 for SW region; 0.2–0.4 for FSH region and 0.5 for PSH region. Moreover, deep in the MSH region the rate of fluctuations drops to 0.1–0.3.

3. Results of analysis

3.1. Features of the probability density functions of fluctuations

In order to investigate features of the probability density functions of magnetic field fluctuations we analyzed the statistical properties of the absolute value of magnetic field variations $dB = B(t+\tau) - B(t)$ in the different regions of geospace and at different time scales.

The dependence of the maximum of the probability density distribution of the fluctuations P_0 on the shift in time τ can be approximated by the power-law dependence $P_0(\tau) \sim \tau^{-s}$. For the case of Gaussian distribution parameter $s = 0.5$; in the general case (the Lèvi distribution) $s > 0.5$. For the turbulence with intermittency the presence of considerable fluctuations on distribution's wings appear due to the abundance of energy of large-scale disturbances, which are generated by external source or boundaries of flows. The investigation of changes of the maximum of the probability density function of magnetic field fluctuations on various time scales was applied, for example, to the study of magnetic turbulence in the magnetospheric tail during the period of current disruption (Consolini et al., 2005). The kurtosis analysis from Chen et al. (2014) also shows that the distribution is highly non-Gaussian and did not change over regions (except for the solar wind, see Fig. 2) which comes with a good agreements to our results.

The dependence of maximal value of probability density function of magnetic fluctuations $P_0(\tau)$ on time shift τ