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Charged particle transport and energization by magnetic field fluctuations with Gaussian/non-Gaussian distributions

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ABSTRACT

In this paper we investigate charged particle transport and acceleration in a two-dimensional system with an uniform electric field and stationary magnetic field fluctuations. The main idea of this study is to consider dependencies of transport and acceleration rates on properties of distributions of magnetic field fluctuations. We develop a simplified model of magnetic fluctuations with a regulated distribution and apply the test particle approach. System parameters are chosen to simulate conditions typical for ion dynamics in the deep Earth magnetotail. We show that for a fixed power density of magnetic field fluctuations the particle acceleration is more effective in the system where particles interact with small-amplitude (but frequent) fluctuations. In systems with large-amplitude rare fluctuations the particle scattering is less effective and the particle acceleration is weaker.

1. Introduction

Charged particle acceleration and transport by electromagnetic turbulent fields are considered now as one of the main mechanisms responsible for generation of high-energy particles in many cosmic plasma systems: planetary magnetospheres [1–4], solar corona [5,6], supernova remnants [7]. The important problem of charged particle scattering by electromagnetic turbulence is the relation between rates of particle transport and acceleration. In many systems (planetary magnetotails, solar flares) a turbulent field develops only in compact space domains where plasma instabilities generate magnetic field fluctuations. In this case, the maximum possible energy gained by particles is limited by a time interval which particles can spend in such turbulent regions. However, electromagnetic field fluctuations result also in particle transport. Thus, there is a competition between particle spatial transport and acceleration: particles are accelerated only in the turbulent field domain, but the same field is responsible for a particle escape from this domain.

Relationship between the charged particle turbulent transport and acceleration is determined by properties of electromagnetic field fluctuations. For example, the intermittency of fluctuations can provide more effective acceleration for the same transport rate in some particular systems [8]. Thus, the investigation of charged particle interaction with electromagnetic field fluctuations with different spatial and temporal distributions is important and perspective problem of space plasma physics. In-situ spacecraft observations in the near-Earth plasma environment have revealed various properties of electromagnetic field fluctuations [9–11]. For example, distributions of magnetic field fluctuations in the magnetotail region are often significantly non-Gaussian [12]. This property should influence on charged particle transport. In this paper we investigate the corresponding effects using the test particle approach and a simple model of magnetic field fluctuations with a controlled level of deviation from the Gaussian form. We concentrate on specific plasma system (the distant Earth magnetotail) where a combination of magnetic field fluctuations [13,14] and a large-scale convection electric field [15,16] provides the effective energization of solar wind protons penetrated into the magnetosphere.

2. The magnetic field model and test particle approach

We consider the simplified system geometry: particles move in the (x, y) plane, while the magnetic field is directed along the z-axis. The magnetic field can be presented as a sum of the constant background field B_0 and fluctuating component $\delta B_z(x, y)$. There is also a constant electric field E_y provided by the solar wind interaction with the planet magnetosphere [16]. In the realistic magnetosphere configuration there is one additional component of the magnetic field $B_x(z)$ [17]. However, this component vanishes

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at the plane $z = 0$ and can be omitted for simplicity of calculations of test particle trajectories [18,8].

For magnetic field fluctuations $\delta B_z(x, y)$ we use the model proposed in [1]:

$$\delta B_z = \frac{B_1}{\sqrt{N_\theta N_k}} \sum_{n_\theta=1}^{N_\theta} \sum_{n_k=1}^{N_k} P_k \cos(\Phi)$$
$$\Phi(k, \theta, x, y) = k(x\cos\theta + y\sin\theta) + \phi_{n_k,n_\theta} \quad (1)$$

where B_1 is an amplitude of fluctuations, $N_k = 100$, $N_\theta = 100$ are number of harmonics, $P_k \sim k^{-1}$ is the spectrum taken from [3], $\phi_{n_k,n_\theta} \in [0, 2\pi]$ is randomly distributed initial phases. The angle θ is distributed uniformly as $\theta = 2\pi(n_\theta - 1)/(N_\theta - 1)$, while the wave vector is $k = \Delta k n_k$ and $\Delta k = 0.1/L_0$, L_0 is a typical spatial scale of magnetic field fluctuations (below we introduce L_0 through parameters of charged particles).

We consider a case of stationary magnetic field fluctuations when particles along their trajectories interact with spatially varying static magnetic fields. Thus, magnetic field fluctuations given by Eq. (1) do not depend on time. These fluctuations have a Gaussian distribution. To check this we calculate the differences $\Delta B_i = \delta B_z(x + (i+1)\Delta x, y + (i+1)\Delta y) - \delta B_z(x + i\Delta x, y + i\Delta y)$ with $\Delta x = \delta_0 \cos\eta$, $\Delta y = \delta_0 \sin\eta$, $\eta \in [0, 2\pi]$ is a random value, δ_0 is the step size of magnetic field calculations along a virtual line (here we set $\delta_0 = 1$), $i = 0, 1, 2, \ldots$. The distribution of ΔB_i for model (1) is shown in Fig. 1($\lambda = 1$ line).

To obtain a non-Gaussian distribution of magnetic field fluctuations we modify model (1): $\delta B_z^{(\lambda)}(x, y) = C_\lambda \,\mathrm{sign}(\delta B_z(x, y)) \times |\delta B_z(x, y)|^\lambda$ where $\delta B_z(x, y)$ is calculated with Eq. (1). The constant coefficient C_λ is used to normalize the power density of magnetic field fluctuations for different λ:

$$C_\lambda^2 = \frac{\int_{-L}^{L}\int_{-L}^{L} \delta B_z^2(x, y)dxdy}{\int_{-L}^{L}\int_{-L}^{L} |\delta B_z(x, y)|^{2\lambda}dxdy}$$

where $L = 10/\Delta k$. Distributions of magnetic field fluctuations ΔB for different λ are shown in Fig. 1. One can see that the increase of λ results in modification of the ΔB distribution: for larger λ the distribution contains more high values of ΔB. Roughly speaking, in the distribution of ΔB with large λ the small amplitude fluctuations are suppressed, while the large amplitude fluctuations are amplified. On the other side, we can modify the ΔB distribution by decreasing the λ parameter. In this case, we suppress the large amplitude fluctuations and amplify the small amplitude fluctuations. The resulting ΔB distribution is also non-Gaussian (see Fig. 1).

Distributions shown in Fig. 1 are typical for the Earth magnetosphere and solar wind [19,12,20]. Spacecraft measurements of quasi-stationary magnetic field fluctuations transform spatial-scales to time-scales because a velocity of plasma (and frozen-in magnetic field) convection is significantly larger than the spacecraft velocity. Thus, spatial scales of magnetic field inhomogeneity are measured by spacecraft as time-scales of magnetic field variations. These time-scales are inverse proportional of the plasma convection velocity. In this case, the higher velocity of plasma convection (i.e. more disturbed conditions in the magnetosphere [21,22]) corresponds to a smaller time-scale δ_0 of calculations of magnetic field differences ΔB. Indeed, the Gaussian distribution of ΔB obtained in our model with $\lambda = 1$ approximates well the magnetic field fluctuations measured during quiet geomagnetic conditions (i.e. measurements with larger δ_0), while $\lambda \neq 1$ corresponds to magnetic field fluctuations measured in more disturbed magnetosphere (i.e. measurements with smaller δ_0). The corresponding evolution of measured distributions of magnetic field fluctuations with δ_0 can be found in [12,20].

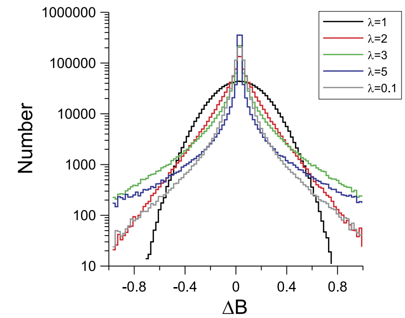

Fig. 1. Distributions of magnetic field fluctuations ΔB for different system parameters. Total number of points in each distribution is 10^6.

To investigate the charged particle interaction with fluctuating magnetic field we use the test particle approach. Equations of motions of a nonrelativistic ion with the charge q and the mass m can be written as

$$\ddot{x} = \frac{qB_0}{mc}\big(1 + b(x, y)\big)\dot{y}$$
$$\ddot{y} = \frac{qE_y}{m} - \frac{qB_0}{mc}\big(1 + b(x, y)\big)\dot{x}$$

where $b(x, y) = \delta B_z/B_0$. We introduce the dimensionless time $t \to tqB_0/mc$, the dimensionless velocities $(v_x, v_y) = (\dot{x}, \dot{y})/\sqrt{2H_0/m}$ where H_0 is an initial particle energy. The spatial coordinates are normalized as: $(x, y) \to (x, y)/L_0$ where $L_0 = \sqrt{2H_0 mc^2}/qB_0$. We also introduce the dimensionless particle energy $\varepsilon = (v_x^2 + v_y^2)/2$ and the drift velocity $V_D = cE_y/(B_0\sqrt{2H_0/m})$ characterizing the electric field intensity. For the typical conditions in the deep Earth magnetotail we can estimate $B_0 \sim 1$–3 nT [23], $\delta B_z \sim 0.1$–1 nT [13,14], ion energy $H_0 \sim 1$–2 keV [24] (and corresponding $L_0 \sim 5000$ km), electrostatic field $E_y = 0.1$–0.3 mV/m [25]. Thus, we have following values of dimensionless parameters: $b \sim 0.1$, $V_D \sim 0.1$–0.5.

Several examples of particle trajectories are shown in Fig. 2. In the case of the electric field absence ($V_D = 0$), a particle randomly walks in the plane (x, y) with the constant energy. This motion can be considered as a combination of the particle gyrorotation around the background magnetic field B_0 and the particle scattering by magnetic field fluctuations δB_z. In the system with a finite V_D the particle gains energy and a spatial scale of its gyrorotation (i.e. the particle gyroradius) increases with time. In this case, the particle motion can be considered as a combination of the regular drift along the x-axis with velocity V_D and the random walking in the plane (x, y) due to the interaction with magnetic field fluctuations. For larger value of λ the particle more often interacts with large magnetic field fluctuations, but between such interactions the particle moves in almost constant background magnetic field due to absence of small amplitude fluctuations (see distributions in Fig. 1). As a result, the drift $\sim V_D$ becomes more important in the system with $\lambda > 1$.

To statistically characterize the charged particle interaction with spatially fluctuating magnetic field we numerically integrate the ensemble of 10^6 trajectories. For this ensemble we calculate averaged particle displacements in geometrical and velocity spaces:

$$R(t) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\big(x_i(t) - x_{0i}\big)^2 + \big(y_i(t) - y_{0i}\big)^2}$$
$$V(t) = \sqrt{\frac{1}{N}\sum_{i=1}^{N} v_{xi}^2(t) + v_{yi}^2(t)}$$