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Particle acceleration by stochastic fluctuations and dawn-dusk electric field in the Earth's magnetotail

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Abstract

This work is devoted to investigate the interaction between protons and stochastic time-dependent electromagnetic fields generated by oscillating clouds of finite size, randomly positioned in the x–y-plane. The geometry of the system is two-dimensional and, beside the time-dependent electromagnetic fluctuations, a steady-state, dawn-dusk electric field, E_y, has been added along the y-direction. The simultaneous presence of the stochastic time-dependent fluctuations and of the constant electric field component in the same system gives rise to two types of acceleration mechanisms operating on test particles: a second order Fermi-like process and a direct acceleration. By performing a parametric study, we extensively study the contribution of the two processes to proton acceleration. The energy values reached by test particles in this simple model are in good agreement with those observed in the Earth's magnetotail region. Possible applications to the problem of particle acceleration in the terrestrial magnetosphere are widely discussed, and guidelines for future works are drawn.

Keywords: Magnetotail; Acceleration; Beams; Stochastic acceleration processes

1. Introduction

A reach variety of accelerated particles is observed throughout the Earth's magnetospheric environment (Nakamura et al., 1991; Ashour-Abdalla et al., 1993), e.g. in the geomagnetic tail, ranging from tens of keV to 100–200 keV (Decoster and Frank, 1979; Keiling et al., 2004). These particles are observed as beamlets at the lobeward edge of the plasma sheet boundary layer (PSBL), the separatrix layer between the magnetotail lobe and the plasma sheet (Zelenyi et al., 2006; Grigorenko et al., 2007). It is believed that the PSBL ion beams represent the result of non-adiabatic ion acceleration in the current sheet of the Earth's magnetotail. This phenomenon has been addressed in many theoretical papers which considered ion beam acceleration by the dawn-dusk electric field, which is due to the large scale coupling between the solar wind and the Earth's magnetosphere at the magnetopause (Buchner and Zelenyi, 1990; Zelenyi et al., 2006; Grigorenko et al., 2007). But realistic values of this large scale electric field ($E_y \simeq 0.1$–0.3 mV/m) lead to maximum potential drops of the order of 30 keV, while particles exceeding 100 keV are also observed (Keiling et al., 2004). Grigorenko et al. (2009) have recently shown that, beside E_y, another acceleration mechanism is required in order to explain the observations. Since the more energetic beams are regularly observed during both quiet and disturbed periods, the acceleration mechanism has to be of a quasi-steady nature, and not simply related to large scale magnetic reconnection. The energy distribution of such ion beams along the y-direction indicates ion energization by a strong (presumably inductive) electric field. One such mechanism can be the evolution of electromagnetic perturbations in the

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magnetotail (Ambrosiano et al., 1988; Dmitruk et al., 2004; Drake et al., 2006; Zelenyi et al., 2008), that are very frequently observed in the middle and in the distant tail (Hoshino et al., 1994; Bauer et al., 1995; Borovsky et al., 1997; Voros et al., 2007).

Here we propose that an additional energization mechanism, with respect to E_y and alternative to the impulsive acceleration by reconnection (Ambrosiano et al., 1988; Litvinenko and Somov, 1993; Pritchett and Coroniti, 2004; Lui et al., 2005), is a Fermi-like acceleration (LaRosa et al., 1996; Petrosian and Liu, 2004) due to the presence of moving magnetic structures, which mimic the magnetic fluctuations observed by spacecraft in the distant magnetotail. The description of magnetic fluctuations may be done in terms of vortexes and of localized moving clouds of plasma and magnetic field (Chmyrev et al., 1988; Verkhoglyadova et al., 1999; Borovsky and Funsten, 2003; Voros et al., 2007), as suggested by the inhomogeneity of the current sheet structure, as well as a range of spacecraft observations.

Protons are assumed to move in the neutral sheet, and the two dimensional (2D) numerical model described in Perri et al. (2007) is used to capture the essential features of particle acceleration in the neutral sheet, while the motion perpendicular to the sheet is neglected. The simultaneous presence of the stochastic time-dependent fluctuations and of the constant electric field component in the same system gives rise to two types of acceleration mechanisms operating on protons: a second order Fermi-like process and a direct acceleration. We adopt a simplified 2D model in order to directly compare the contribution to the acceleration process of these two mechanisms, being both effective inside the current sheet. By varying the features of electromagnetic fluctuations, we show that the combined effect of E_y and of the moving clouds can explain a range of energetic ion observations, including the typical energies and the typical acceleration times.

2. Numerical model

A test particle numerical code is used in which protons interact with electromagnetic fields generated by N random positioned clouds in the x–y current sheet plane (Perri et al., 2007, 2009). The electric and magnetic fields are given by $\mathbf{B} = \nabla \times \mathbf{A}$ and $\mathbf{E} = -\nabla\phi - \partial\mathbf{A}/\partial t$, in the gauge where $-\nabla\phi = E_y\mathbf{e}_y$, with $E_y = \text{const}$. This electric field is due to the interaction of the solar wind with the Earth's magnetosphere: it originates as the motional electric field in the solar wind. In the magnetotail, this is usually called dawn-dusk electric field, because of its prevailing direction during magnetic reconnection at the low latitude magnetopause, and has a semi-steady character.

The vector potential has components $\mathbf{A} = (A_x(\mathbf{r},t), A_y(\mathbf{r},t), 0)$ in the x–y-plane, that are given by $A_x = A_y = A_0\sum_n \psi(\xi_n)$, where the sum is over the N clouds, $\psi(\xi_n) = e^{-\xi_n}$ and $\xi_n = |\mathbf{r} - \mathbf{r}_n(t)|/l_{cl}$, with $|\mathbf{r} - \mathbf{r}_n(t)|$ the difference between particle and cloud positions and l_{cl} the typical size of the clouds. The electromagnetic field equations are (Perri et al., 2007):

$$\boldsymbol{E}(\boldsymbol{r},t) = (\delta E_x, E_y + \delta E_y, 0) \tag{1}$$

where $\delta E_x = \delta E_y = \delta E$ and

$$\delta E = -\frac{A_0}{l_{cl}} \sum_n \frac{\partial\psi}{\partial\xi_n} \frac{[(x - x_n(t))\dot{x}_n(t) + (y - y_n(t))\dot{y}_n(t)]}{|\boldsymbol{r} - \boldsymbol{r}_n(t)|} \tag{2}$$

and

$$B_z(\boldsymbol{r},t) = \delta B_z = -\frac{A_0}{l_{cl}} \sum_n \frac{\partial\psi}{\partial\xi_n} \frac{[(x - x_n(t)) - (y - y_n(t))]}{|\boldsymbol{r} - \boldsymbol{r}_n(t)|} \tag{3}$$

In this model no magnetic field components along the x–y-plane are present since $A_z = 0$ and A_x and A_y do not depend on z. We have only a random time-dependent magnetic field along z-direction. The non-constant (fluctuating) terms in Eqs. (2) and (3) are generated by the clouds oscillating in the x–y-plane according to $x_n(t) = x_{n0} + a\cos(\omega t + \alpha_n)$ and $y_n(t) = y_{n0} + a\sin(\omega t + \beta_n)$, where x_{n0} and y_{n0} are the initial random coordinates of the n-th cloud, a is the oscillation amplitude, ω is the oscillation frequency, and α_n and β_n are the initial random phases along x and y, respectively. For simplicity, the amplitude a of the oscillation has the same value as l_{cl} (we checked that variations of the parameter a do not influence the particle dynamics). Also, $N = 100$ clouds are put in the simulation box.

Typically, 5000 test particles (i.e., protons) are put into a squared $L \times L$ simulation box at random positions and with velocities extracted from a Gaussian distribution, $f_v(t_0)$, having a standard deviation $v_{\text{th}} = 120$ km/s, corresponding to an initial energy of the order of 100 eV. This is a characteristic value for protons coming from the magnetospheric mantle and reaching the magnetotail. Each particle trajectory is integrated until it leaves the simulation box; afterwards, in order to keep the total number of particles in the x–y-plane constant, a leaving particle is replaced by another randomly positioned in the $L \times L$ box and having a speed extracted from the initial distribution $f_v(t_0)$. During the simulation time, particle motion is described by the usual equations of motion

$$\begin{aligned} \frac{d\mathbf{x}}{dt} &= \mathbf{v} \\ \frac{d\mathbf{v}}{dt} &= \mathbf{E} + \mathbf{v} \times \mathbf{B} \end{aligned} \tag{4}$$

which have been normalized assuming a normalization magnetic field $B_0 = 2$ nT (Hoshino et al., 1994; Perri et al., 2009) and a box size value of $L = 10^5$ km (this being a rough estimate of the cross tail width (Perri et al., 2009)). The corresponding proton gyroperiod is about 30 s. From these, a normalization proton gyrofrequency $\omega_0 = 0.2$ s^{-1}, a normalization speed $v_0 = \omega_0 L = 2 \times 10^4$ km/s, and a normalization electric field $E_0 = B_0\omega_0 L = 40$ mV/m have been easily obtained.