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ENERGETIC PARTICLE ACCELERATION IN A MAGNETOSPHERIC STRONG TURBULENT PLASMA

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Strong plasma turbulence [*Galeev and Sagdeev*, 1973] is possible in a plasma with a field-aligned current. Such current takes place in high latitude regions of the Earth magnetosphere especially under disturbed conditions. Field-aligned current enhancement can lead to generation of plasma electrostatic instabilities and development of nonlinear electrostatic structures (solitons), which effectively accelerate charged particles. There are evidences of effective acceleration of suprathermal charged particles by a strong plasma turbulence in the Earth magnetosphere [*Shiokawa and Yumoto*, 1993; *Nagasuma et al.*, 1995; *Lyatsky et al.*, 1998].

In this paper we consider suprathermal particle acceleration by a strong plasma turbulence along slightly inhomogeneos magnetic field. We use a simplified model of nonlinear structures as a set of condensers with oscillations on the plasma frequency and casual jumps of oscillation phase. The chosen model of turbulence yields comparatively simple characteristics of particle dynamics and permits to write equations for particle distribution function evolution, calculate diffusion coefficients in the longitudinal velocity space [*Bespalov and Misonova*, 1998], find the solution of these equations in some particular cases and estimate energy absorbed by particle flux.

The model of plasma turbulence and particle motion

Let us consider charged particle flux propagating in slightly inhomogeneous magnetic field

$$B_z = B_0\left(1-\frac{z}{a}\right), \quad 0 \le z << a \tag{1}$$

and in the electric field of one-dimensional set of condensers

$$E_z = \sum_{n=0}^{\infty} E_n \cos\left(\omega_p t + \varphi_n(t)\right)\cdot\left[\Theta\left(z-z_n\right)-\Theta\left(z-z_n-d_n\right)\right]. \tag{2}$$

Here E_n is the amplitude of the field of the n-th condenser, z_n and $z_n + d_n$ are the coordinates of its plates, ω_p is the plasma frequency, $\Theta(x)$ is the unit function, $\varphi_n(t)$ is a function of the casual part of the n-th condenser oscillation phase

$$\varphi_n(t) = \sum \varphi_{nk}\left[\Theta\left(t-\tau_{n,k+1}\right)-\Theta\left(t-\tau_{n,k}\right)\right], \tag{3}$$

where φ_{nk} has equal probability in interval from 0 to 2π. We restrict ourselves only by the case of comparatively fast particles, with characteristic longitudinal velocity $v = v_z$ changing not significantly in the course of particle movement through a condenser and a space between two condensers. That condition takes the form

$$\Delta v \sim \frac{\langle E_n\rangle q_m}{\omega_p} + \frac{v_\perp^2\langle l_n\rangle}{va} << v, \tag{4}$$

where q_m is the charge per unit mass, l_n is the distance between two condensers, $v_\perp$ is the particle transverse velocity. In formula (4) and further the corner brackets mean averaging over the set of condensers. The interaction of such particles with condensers field is similar to the Brownian motion and can be described by the Fokker-Plank equation [*Ishimaru*, 1975], which in the drift approximation has the form

$$\frac{\partial f}{\partial t} + v\frac{\partial f}{\partial z} + \frac{\mu B_0}{2a}\frac{\partial f}{\partial v} = \frac{\partial}{\partial v}\left(D_v\frac{\partial f}{\partial v}\right), \tag{5}$$

where $$D_v = \frac{\langle\Delta v\Delta v\rangle}{2\tau} \tag{6}$$

is the diffusion coefficient, τ is the time of averaging, $\mu = \frac{v_\perp^2}{B}$ is the transverse adiabatic invariant. In the next Section we shell formalize the expression for the diffusion coefficients.

The diffusion coefficients in the longitudinal velocity space

Diffusion coefficient (6) depends on correlation between neighboring condenser oscillations and hierarchy of the characteristic times: the time of particle movement through a condenser, time of particle movement through a space between two condensers and phase correlation time τ_φ (that between two successive jumps of casual phase).

Let the phase correlation time be much smaller than that of particle movement through one condenser. In this case the oscillation phase of a condenser changes many times during particle movement through it. For the diffusion coefficient we get the expression

$$D_v = \frac{q_m^2 \langle E_n^2 d_n \rangle \tau_\varphi}{4\langle l_n \rangle}. \tag{7}$$

Let the phase correlation time is much more than the time of particle movement through one condenser and much smaller than that of particle movement through a space between two condensers. In that case the phase of each condenser in the moment when a particle moves through it can be considered as constant. For the diffusion coefficient we obtain an expression

$$D_v = \frac{D}{|v|}, \quad D = \frac{q_m^2 \langle E_n^2 d_n^2 \rangle}{4\langle l_n \rangle}. \tag{8}$$

It should be mentioned, that for hierarchy of characteristic times considered above correlation between neighboring condenser phases is not important.

The same result (8) we obtain in the case, when the phase correlation time exceeds that of particle movement through a space between two condensers, but neighboring condensers oscillate independently. A typical velocity dependence of the diffusion coefficient for the case of independent oscillations of neighboring condensers is presented in Fig. 1.

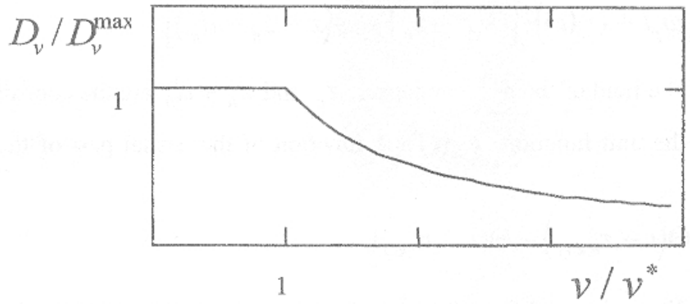

Fig. 1. The diffusion coefficient for independent oscillations of neighboring condensers $(v^* = \frac{\langle d_n \rangle}{\tau_\varphi})$.

Now let us consider the case of statistically dependent oscillations of neighboring condensers. We assume that a series of N condensers oscillate in phase, phases of different series being independent. Restricting ourselves by the case of spatially periodic system of condensers $(E_n = E,\ d_n = d,\ l_n = l)$ we obtain the following expression for the diffusion coefficient

$$D_v = \frac{q_m^2 (Ed)^2}{4l\, v}\left[\frac{1}{2} + \frac{1}{N^*}\sum_{n=1}^{N^*}\sum_{m=1}^{n-1}\cos(\psi_n - \psi_m)\right],$$
$$\psi_n = \frac{q_m^2 (Ed)^2 a}{\mu B_0}\sqrt{1 + \frac{l\delta\mu B_0}{av^2}n}\ ,\quad N^* = \max\left\{N, \left[\frac{\tau_\varphi v}{l}\right] + 1\right\}. \tag{9}$$

This result reveals the condition, under which the effect of regular magnetic force on turbulent diffusion becomes significant. It takes place if decrease of the time of particle movement through a space between two condensers caused by the regular magnetic force and period of plasma oscillations becomes comparable.

For the case when $\frac{l\mu B_0 N}{v^2 a} << 1,\ 1 << N^*$ we can simplify expression (9)

$$D_v = \frac{(q_m Ed)^2 N^*}{4l\,|v|} \times$$
$$\times \left\{ \Theta\left(|v| - N^* V^*\right) + \sum_{k\neq 0}\left[\Theta\left(v - \frac{V^*}{k} - \frac{V^*}{k^2 N^*}\right) - \Theta\left(v - \frac{V^*}{k} + \frac{V^*}{k^2 N^*}\right)\right]\right\}, \quad (10)$$

where $V^* = \dfrac{l\omega_p}{\pi}$. Diffusion coefficient (10) is significant for velocities exceeding $N^* V^*$ and abruptly drops for lower values. Narrow velocity ranges close to $v = \dfrac{V^*}{k}$ usually are not so important for the acceleration process.

Some properties of accelerated particle fluxes

We can write a general solution of stationary kinetic equation (5) with the diffusion coefficients obtained above. The solution for the important velocity range $v > \dfrac{d_n}{\tau_\varphi} > 0$ has the following form

$$f(\zeta, v) = \int_0^\infty f_0(v_0)\left\{ \frac{1}{\sqrt{\pi\zeta}} e^{-\gamma^2\zeta + \gamma\left(v^2 - v_0^2\right)} \left[e^{-\frac{\left(v^2 - v_0^2\right)^2}{4\zeta}} + e^{-\frac{\left(v^2 + v_0^2\right)^2}{4\zeta}} \right] - \right.$$
$$\left. - 2\gamma\, e^{2\gamma v^2}\left(1 - erf\left(\frac{v^2 + v_0^2 + 2\gamma\zeta}{2\sqrt{\zeta}}\right)\right)\right\} dv_0, \quad \zeta = 4Dz, \quad \gamma = \frac{\mu B_0}{2Da}, \quad (11)$$

where $erf(x)$ is the integral of errors, $f_0(v)$ is the particle distribution function on the boundary $z = 0$. In Fig.2 are shown the velocity dependencies of function (11) for three successive coordinates $z_1 < z_2 < z_3$ in the case of boundary distribution function has the form $f_0(v) = A\,\delta(v - v_0)$.

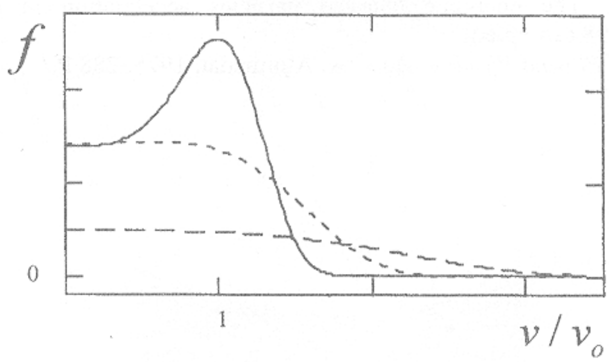

Fig. 2. The distribution function for three successive coordinates z_1 (solid line), z_2 (dotted line), z_3 (dashed line).

The average kinetic energy of a flux particle $\overline{W}$ depends on the coordinate z in the following way

$$\overline{W} \approx 1{,}65 m\sqrt{zD}, \quad \frac{\overline{W}_0}{Dm^2} << z << \left(\frac{Da}{B_0\mu}\right)^2, \quad (12)$$

$$\overline{W} \approx \frac{\mu B_0 z}{2a}, \quad \left(\frac{Da}{B_0\mu}\right) << z,$$

where $\overline{W}_0$ is the characteristic particle energy on the boundary $z = 0$. Estimations (12) indicate that for smáll distances an effective acceleration of particle fluxes by a set of condensers dominates over that caused by a regular force. The results are plausible for a turbulent layer with a thickness $z \ll a$.

Conclusions

The problem of particle acceleration by strong magnetospheric plasma turbulence has been considered. It is shown, that a strong plasma turbulence plays the role of a giant accelerator of charged particles:

- The diffusion coefficients in the longitudinal velocity space have been calculated for the simplest model of a set of condensers with oscillations at the plasma frequency and for linear inhomogeneity of regular magnetic field.
- The conditions of a possible effect of regular magnetic force on the turbulent diffusion have been clarified.
- The acceleration effect is greater for stronger time and spatial correlation of condenser oscillation phases.
- The solution of the stationary equation with a known boundary distribution has been found.
- The average kinetic energy of accelerated flux particle has been estimated.

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