New mechanism for acceleration of cosmic particles in the presence of reflectively noninvariant turbulence

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It is shown that charged particles are accelerated in a gyrotropic turbulent cosmic plasma in the presence of an average magnetic field.

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1. Different acceleration mechanisms play a large role in the formation of nonthermal spectra of high-energy particles (cosmic rays).[1–3] The search for such mechanisms does not continue today by accident.[1] In this paper we examine a new mechanism for accelerating particles in the presence of a reflectively noninvariant (gyrotropic) turbulence (RNIT). In the past, interest in gyrotropic turbulence resulted primarily from the capability of RNIT to generate magnetic fields (α effect).[4] Thus the dynamo of magnetic fields and acceleration of charged particles could result from a single effect. It turns out that the efficiency of this mechanism of acceleration is $(\lambda/R)^2$ times greater than the efficiency of the well-known Fermi acceleration mechanism[5] (R is the Larmor radius, λ is the free path before scattering by magnetic inhomogeneities).

2. We shall examine a magnetic field **H**, frozen in the plasma moving with mean mass velocity $\mathbf{u}_n$. In the presence of turbulence, the fields **H** and $\mathbf{u}_n$ against a background of relatively large scale (with scale L) components contains small scale (with characteristic scale l, $l \ll L$) fluctuations. Averaging separates the scales:

$$\mathbf{H} = \mathbf{B} + \mathbf{h}, \quad \mathbf{B} = \langle \mathbf{H} \rangle, \quad \mathbf{u}_n = \mathbf{V} + \mathbf{u}, \quad \mathbf{V} = \langle \mathbf{u}_n \rangle .$$

The kinetic equation for the distribution function of high-energy ($R_{st} \gg 1$, R_{st} is the characteristic Larmor radius in a field **h** particles propagating in the turbulent cosmic plasma has the form[6]

$$\frac{\partial f}{\partial t} + \mathbf{v}\frac{\partial f}{\partial \mathbf{r}} + \langle \mathbf{F} \rangle \frac{\partial f}{\partial \mathbf{p}} = St, \tag{1}$$

$$\mathbf{F} = \frac{e}{c}[\mathbf{v} - \mathbf{u}_{n}, \mathbf{H}].$$

It is easy to see that

$$\langle \mathbf{F} \rangle = \frac{e}{c}[\mathbf{v} - \mathbf{V}, \mathbf{B}] - \frac{e}{c}\langle [\mathbf{u}\mathbf{h}] \rangle \cdot \tag{2}$$

Usually the electric field $-(1/c)\langle[\mathbf{uh}]\rangle$ is assumed to be zero. The derivation of the kinetic equation with allowance for this field is given in Ref. 7. In the absence of an average magnetic field, there is no correlation between **u** and **h**. However, in the theory of a turbulent dynamo, it is shown that for RNIT with $B \neq 0$, the following relation is satisfied[4]:

$$\langle [\,\mathbf{u}\mathbf{h}\,] \rangle = -\nu_T \,\mathrm{rot}\,\mathbf{B} + \alpha\mathbf{B}, \quad \alpha = -\frac{\tau}{3}\langle \mathbf{u}\,\mathrm{rot}\,\mathbf{u} \rangle, \tag{3}$$

where ν_T is the turbulent magnetic viscosity, and τ is the characteristic time of turbulent pulsations.

3. Let us examine acceleration of particles caused by the electric field $-(1/c)\langle[\mathbf{uh}]\rangle$ (3). We note that the vector $\langle[\mathbf{uh}]\rangle$, in contrast to the electric field $-(1/c)[\mathbf{VB}]$, has a component oriented along the vector **B**, and the average magnetic field does not hinder acceleration. The electric field $-(1/c)\{\mathbf{u}_n\mathbf{H}\}$, of course, is perpendicular to the magnetic field **H**. But **H** is the superposition of fields **B** and **h** acting on particles in a completely different manner. The characteristic spatial scale of magnetic fluctuations is small ($l \ll R_{st}$) and the interaction of particles with the field **h** has the nature of weak random scattering. In addition, the motion of the particles is close to Larmor rotation around the force lines of the field **B**, even if $B/\sqrt{\langle h^2\rangle} \sim 1$.[8]

In order to examine the effect of acceleration in pure form, we shall assume that the average value of the hydrodynamic velocity of the medium is equal to zero and the average characteristics of the system do not depend on the coordinates. We note that in this case there is no generation of the average field, $\partial\mathbf{B}/\partial t = 0$.[4] Equation (1), after incorporating (2) and (3) becomes

$$\frac{\partial f}{\partial t} + \frac{e}{c}([\mathbf{v}\,\mathbf{B}] - \alpha\mathbf{B})\frac{\partial f}{\partial \mathbf{p}} = \frac{v}{2\lambda}\hat{L}^2 f, \tag{4}$$

$$\hat{L} = [\,\mathbf{P}\frac{\partial}{\partial \mathbf{p}}\,], \quad \lambda = \frac{3c^2p^2}{2e^2 l \langle h^2 \rangle \int_0^\infty \psi(x)\,dx},$$

ψ is the correlation function of the magnetic inhomogeneities.

We shall assume that the function f is weakly anisotropic in momentum space. The isotropization is caused by scattering by magnetic inhomogeneities. Retaining the first two terms in the expansion of the distribution function in a series of spherical harmonics and using the usual method of moments, we obtained an equation for the phase density of particles $N(p)$:

$$\frac{\partial N}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p} p^2 D_p \frac{\partial N}{\partial p}, \qquad D_p = p^2 \frac{\alpha^2 \lambda}{3vR^2}, \qquad R = \frac{cp}{eH} . \tag{5}$$

4. The right side of (5) describes acceleration. In the presence of an electric field $\mathbf{E} = -(\alpha/c)\mathbf{B}$ the particle flux $\mathbf{j}$ is parallel to the given field

$$\mathbf{j} = \mathbf{B}\frac{\alpha\lambda e}{3c}\frac{\partial N}{\partial p} .$$

The current along the electric field leads to the appearance of an energy source:

$$Q = e\int_0^\infty \mathbf{j}\mathbf{E}p^2\,dp = \frac{4\alpha^2\lambda_0}{3R_0^2}\int_0^\infty p^3 N(p)\,dp , \tag{6}$$

where λ_0 and R_0 are the characteristic free path and Larmor radius, respectively. Equation (6) can also be obtained directly from (5).

We easily find the acceleration time $T_p = p^2/D_p$ with the help of (5):

$$T_p = 3vR^2/\gamma\lambda < u^2 > . \tag{7}$$

Here $\gamma = \alpha^2/\langle u^2\rangle$ is a measure of the gyrotropy of turbulence, and $0 \leqslant \gamma \leqslant 1$. In the case of the second-order Fermi acceleration mechanism, the acceleration time $T_{pF} = 3v\lambda/\langle u^2\rangle$.[5] The ratio of the times $T_{pF}/T_p = \gamma(\lambda/R)^2$ is large, which indicates the high efficiency of the mechanism examined here compared to the mechanism in Ref. 5 in the presence of RNIT and $B \neq 0$. For the solar wind, as can be assumed, $\gamma \sim 0.8$.[9] Thus, for 1-GeV particles and characteristic fields, we obtain $T_{pF}/T_p \sim 100$, and $T_p \sim 100$ days, which coincides in order of magnitude with the diffusion time of particles in the interplanetary space, i.e., the acceleration mechanism being examined is efficient. We note that for relativistic particles T_p does not depend on energy. In addition, the characteristic functions of the operator $(1/p^2)(\partial/\partial p)p^2D_p(\partial/\partial p)$ are power-law functions of momentum, i.e., the accelerated particles have a power-law spectrum.

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