Acceleration of charged particles in a cosmic-phase shear flow

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It is shown that a charged particle, which has been scattered by magnetic-field inhomogeneities in a collisionless plasma, can gain energy in the presence of a plasma shear flow. The rate of energy gain, which is determined by the plasma parameters, is proportional to the square of the curl of the hydrodynamic velocity.

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1. It is known that the energy of large-scale plasma motion can be converted under certain conditions to the energy of the individual charged particles by means of some mechanism. These mechanisms include the Fermi mechanisms as well as the regular mechanism of acceleration by shock waves that propagate in a collisionless plasma.[1] These mechanisms, as well as several others, play an important role in the formation of nonthermal spectra of charged particles under different cosmic conditions.

At the present time, however, there are many experimental data which cannot be explained within the context of the known mechanisms. When satellites cross the boundary of the earth's magnetosphere, streams of high-energy electrons, which have a power spectrum in the energy region $\epsilon \gtrsim 18$ keV (see Ref. 2 and the references therein), are constantly detected.

A new mechanism of charged-particle acceleration, which is capable of explaining these experimental data, is examined in the present paper.

2. We shall investigate the idealized picture of the two-dimensional shear flow of a collisionless plasma (see Fig. 1) that is characterized by the presence of scattering centers whose role is played by magnetic-field inhomogeneities. Suppose that the hydrodynamic velocity **u** of the plasma is directed along the x axis and its magnitude varies as a function of the coordinate y. In order to establish the energy-variation law

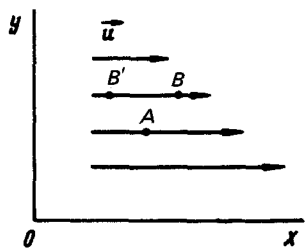

FIG. 1.

of a particle, which, after scattering elastically, moves in the medium with a velocity $v \gg u$, it is convenient to represent this motion in the form of a population of vibrations between two scattering centers with an appropriate averaging over all possible pairs. Thus, if the particle vibrates between the centers A and B and $u_A > u_B$ and $x_A < x_B$, as shown in Fig. 1, then its energy will increase since the centers A and B are brought together. However, for the center B there is a center B' that is placed symmetrically with respect to $A(y_{B'} = y_B, x_A - x_{B'} = x_B - x_A)$, so that the particle moving between the centers A and B' with the same velocity loses energy if only the quantities of the order of u/v are taken into account. In other words, within the framework of the adiabatic approximation no changes occur in the particle energy—$\langle d\epsilon/dt \rangle = 0$ (the angular brackets denote averaging).

If the terms $\sim (u/v)^2$ are taken into account, an analysis of the particle motion between the two scattering centers, which are moving with a relative velocity $dl/dt = w$, leads to the expression

$$\frac{d\epsilon}{dt} = -2\frac{w}{l}\left(1 - \frac{w}{v}\right)\epsilon ,$$

where l is the distance between the centers. It can be seen from this that the total contribution of the centers A, B, and B' to $d\epsilon/dt$ is positive and equal to $4\epsilon w^2/(lv)$. An averaging of this expression over the locations of the B center with allowance for the fact that the probability of the particle traversing a path length l without scattering is $\exp(-l/\lambda)$ gives

$$\left\langle \frac{d\epsilon}{dt} \right\rangle = a\frac{\lambda}{v}\left(\frac{du}{dy}\right)^2 \epsilon ,$$

where λ is the free path length. The numerical coefficient α in this case is equal to $1/2$; a more systematic treatment can show that its value is somewhat different.

An acceleration of charged particles, therefore, occurs in a shear flow of a collisionless plasma, and the rate of energy increase is proportional to the square of the curl of the hydrodynamic velocity of a plasma [in the analyzed case $(\mathrm{rot}\, u)^2 = (du/dy)^2$].

3. It has been established that a layer consisting of a shear flow of solar-wind plasma exists at the boundary of the earth's magnetosphere.[2] The hydrodynamic velocity of the plasma in the layer varies from zero at the inside boundary to ~ 300 km/sec at the outside boundary. The characteristic thickness of the layer is $l \sim R_E$ and its longitudinal dimension is $L \gtrsim 100\, R_E$, where R_E is the earth's radius. Particles that have path lengths $\lambda \ll l$ are accelerated efficiently by means of the mechanism discussed above. The condition $\lambda \ll l$ can be satisfied only for electrons, since $\lambda \approx \rho = 100$ km for thermal protons, where ρ is the gyroradius. Since the path lengths of solar-wind electrons have not been thoroughly investigated, we can assume that the range of accelerated electrons is $\epsilon \leqslant 1$ MeV if $\lambda \approx \rho$ (the magnetic field at the boundary of the magnetosphere is 10^{-4} G). Since the electrons usually cannot penetrate the interior boundary of the acceleration region, which is formed by the regular magnetospheric magnetic field, a density gradient of accelerated electrons, which is directed toward the earth, is formed. A corresponding diffusion flow is directed from

the earth, which accounts for the anisotropy of high-energy electrons that is recorded in the experiments.[2] The following can be said about the shape of their energy spectrum. Gnedin *et al.*[3] have analyzed the formation of the spectrum of particles, which have been accelerated by means of a mechanism for which the acceleration time constant $\tau = \epsilon/(d\epsilon/dt)$ is proportional to $\epsilon^{-\beta}$. They showed that at $\beta > 0$ a power spectrum is formed with an exponent $\gamma = -(1+\beta)$ at energies $\epsilon \gg \epsilon_0$, where ϵ_0 is the initial energy of the particles. In our case the condition $\tau \sim \epsilon^{-\beta}$ means that $\lambda \sim \epsilon^{\beta}$. We can assume that $\lambda \sim \rho$ for most of the electrons and that $\lambda \sim \epsilon^2$ at high energies. Thus we obtain a spectrum exponent γ in the limits from -3 to -1.5, consistent with the experiment: $\gamma = -2$ to -1.5 for $\epsilon = 18$–120 keV and $\gamma = -4.5$ to -3 for $\epsilon \gtrsim 100$ keV.[2] The values of $\gamma < -2$ may be attributed to the influence of energy losses.

Universality of the produced spectrum is a characteristic feature of the discussed mechanism. An important feature of this mechanism is that it involves regular, large-scale plasma motion, which sets it favorably apart from the other mechanisms, in particular, the mechanism of acceleration by turbulent pulsations.[4]

A shear plasma flow can frequently occur under space conditions. A typical example for interplanetary space is the high-velocity flow in the solar wind. Because of this, the acceleration process of charged particles in a shear flow can be important in the production of nonthermal spectra of particles, in particular, the cosmic rays.

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