Supplementary acceleration of charged particles in a moving magnetized plasma

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(Submitted 26 March 1985)
Zh. Eksp. Teor. Fiz. **89**, 1624–1631 (November 1985)

An equation describing the propagation of fast charged particles in a moving magnetized plasma is derived in the diffusion approximation from the collisonal Boltzmann equation by taking into account accelerating processes. The possibility of a supplementary acceleration of charged particles in such a medium is demonstrated in the presence of two types of scatterers: magnetic field fluctuations (magnetic inhomogeneities) in the background plasma and an ensemble of magnetic "clouds" (shock waves and other magnetohydrodynamic discontinuities, plasma flows and ejections). Estimates of the efficiency of supplementary acceleration in various astrophysical objects are given. The mechanism considered can also be realized in laboratory conditions.

I. INTRODUCTION

Numerous experimental data from terrestrial experiments as well as from space measurements have shown that in interplanetary space there exists a steadily blowing solar wind (a moving plasma with a frozen magnetic field), various plasma ejections from the sun, shock waves, tangential discontinuities, high velocity flows of magnetized plasma related to the coronal holes, etc. The existence of these phenomena allows us to assume the following model for the dynamical processes leading to the modulation and acceleration of fast charged particles (cosmic rays) in interplanetary space (as well as in other astrophysical objects with similar characteristics). There exist two media, by origin unrelated to each other, which are moving with different velocities. The first medium is the background plasma with a frozen magnetic field (the solar wind) and the second is an ensemble of magnetic clouds (the medium of "heavy" particles), moving with velocity different from the velocity of the first medium.

When high-energy charged particles propagate in such a medium, additional interaction effects take place. New possibilities for acceleration of cosmic rays (CR) in such an environment will be considered here.

The acceleration of charged particles to high energies is usually associated with chaotic motion of the magnetized plasma and with shock waves created in various astrophysical processes (the Fermi mechanism). Let $\mathbf{u}(\mathbf{r},t)$ be the hydrodynamic velocity of the plasma with frozen magnetic field $\mathbf{B}(\mathbf{r},t)$. Then the acceleration of charged particles is determined by the random component of $\mathbf{u}$. In addition, the particles will gain energy by passing shock fronts[1,2] and tangential discontinuities,[3] where $\mathbf{u}$ is discontinuous, and also macroscopic flows of magnetized plasma.[4] A review of the literature on the theory of the acceleration processes in the universe can be found in Refs. 5–8. Interesting additional possibilities for accelerating fast charged particles in cosmic environments arise if one considers the present model of the medium in which such particles propagate. Let a magnetized plasma with magnetic field $\mathbf{B}(\mathbf{r},t)$ move with hydrodynamic velocity $\mathbf{u}$ and suppose there exists an ensemble of magnetic "clouds", the "heavy particle" medium characterized by the hydrodynamic velocity $\mathbf{V}(\mathbf{r},t)$. The $\mathbf{B}$, $\mathbf{u}$, and $\mathbf{V}$ vectors, in general, can have both regular and random components. We will associate the small-scale fluctuations of the $\mathbf{B}$ fields with the velocity $\mathbf{u}$ and the motion of the magnetic clouds (the "heavy particles"), which scatter the cosmic rays at an arbitrary angle, with the velocity $\mathbf{V}$. Such media can be found in interplanetary space, in a transition sheath on the boundary with interstellar space, in the galactic space (the galactic wind and an ensemble of shock waves due to outbursts from novae and supernovae, stellar winds), in radio-galaxies with powerful ejections, and in other active extragalactic objects.

A theory of the propagation of fast charged particles in such a medium based on the Boltzmann kinetic equation is presented below. Some limiting cases are considered and estimates of characteristic parameters are obtained. We should emphasize here that the shock waves and other hydrodynamic discontinuities will also be considered below as clouds, but, nevertheless, they are only viewed as scatterers and not as particle accelerators.

2. DERIVATION OF THE EQUATION

In accordance with the above arguments, consider the following model of the medium. Let $\mathbf{u}(\mathbf{r},t)$ be the hydrodynamic velocity of the medium with a frozen magnetic field $\mathbf{B}(\mathbf{r},t)$ and suppose that there exists an ensemble of magnetic clouds, moving with identical velocities $\mathbf{V}(\mathbf{r},t)$. Let us express the distribution function of the magnetic clouds (heavy particles) in the form

$$\varphi(\mathbf{r}, \mathbf{V}, t)=n(\mathbf{r}, t)\delta\{\mathbf{V}-\mathbf{V}(\mathbf{r}, t)\},$$

where n is the density of the clouds and δ is the Dirac delta function. Then the Boltzmann equation can be written as

$$\frac{\partial f}{\partial t}+\mathbf{v}\frac{\partial f}{\partial \mathbf{r}}+\frac{e}{c}[\mathbf{v}-\mathbf{u}, \mathbf{B}]\frac{\partial f}{\partial \mathbf{p}}=\mathrm{St}\, f, \tag{1}$$

where $f(\mathbf{r},\mathbf{p},t)$ is the distribution function of the particles in the cosmic rays, $\mathbf{v}$ and $\mathbf{p}$ are the velocity and momentum of the particles respectively, e is the charge, c is the velocity of light and the collision term is given by

$$\mathrm{St}\, f=n\int |\mathbf{v}-\mathbf{V}|\sigma(|\mathbf{v}-\mathbf{V}|, \alpha)\{f(p')-f(p)\}d\Omega_1, \tag{2}$$

where σ is the scattering cross section of the particles on a cloud, α is the scattering angle and $d\Omega_1$ is the element of the

 0038-5646/85/110940-05$04.00

solid angle of the scattering. Expression (2) has been obtained by integrating over $d\mathbf{V}$, where it has been assumed that $\mathbf{V}=\mathbf{V}(\mathbf{r},t)$.

Let $\mathbf{B}=\mathbf{B}_0+\mathbf{B}_1$ and $f=F+f_1$, where $\mathbf{B}_0=\langle\mathbf{B}\rangle$ is the regular part of the field, $\mathbf{B}_1$ is the random component, and $\langle\mathbf{B}_1\rangle=0$. Here $F=\langle f\rangle$ and f_1 is the random component of the distribution function, respectively. The angle brackets denote averaging over the random field $\mathbf{B}_1$. Then, Eqs. (1) and (2) yield an equation for F:

$$\frac{\partial F}{\partial t}+\mathbf{v}\frac{\partial F}{\partial \mathbf{r}}+\frac{\varepsilon}{c^2}[\mathbf{v}-\mathbf{u},\boldsymbol{\omega}]\frac{\partial F}{\partial \mathbf{p}}=\mathrm{St}_1 F+\mathrm{St}\,F, \qquad (3)$$

where ε is the total energy of the particle, $\boldsymbol{\omega}=ec\mathbf{B}_0/\varepsilon$, St$F$ is defined by expression (2) with the substitution $f\to F$ and

$$\mathrm{St}_1 F=\frac{\partial}{\partial p_i}D_{ik}\frac{\partial F}{\partial p_k}, \qquad (4)$$

where, as usually, summation over repeating indexes $i,k=1,2,3$ is implied. The tensor D_{ik} here is defined as

$$D_{ik}=\frac{p^2}{2\Lambda_{B_1}}|\mathbf{v}-\mathbf{u}|\left\{\delta_{ik}-\frac{(\mathbf{v}-\mathbf{u})_i(\mathbf{v}-\mathbf{u})_k}{(\mathbf{v}-\mathbf{u})^2}\right\}, \qquad (5)$$

where $\Lambda_{B_1}=6c^2p^2/\sqrt{\pi}el_c\langle B_1^2\rangle$ has the meaning of a scattrering length and l_c is the correlation length of the random field (see, for example, Ref. 7).

On expanding F in spherical haromonics in the momentum space and retaining the first two terms in the expansion, we have

$$F(\mathbf{r},\mathbf{p},t)=N(\mathbf{r},\mathbf{p},t)+\frac{\mathbf{p}}{p}\mathbf{J}(\mathbf{r},\mathbf{p},t). \qquad (6)$$

The following manipulations are performed with Eq. (2). We transform StF to the local reference frame, associated with the magnetic cloud. In this coordinate system F is expanded according to (6) and the resulting equation is transferred back to the rest frame (this procedure takes the recoil energy of the scattering into account). Next, Eq. (6) is substituted into Eqs. (3) and (4). The resulting equation is first integrated over the element $d\Omega/4$ of solid angle in momentum space and then multiplied by $3p_i/4\pi p$ and integrated over $d\Omega_1$. As a result of these transformations, we finally have

$$\frac{\partial N}{\partial t}+\frac{v}{3}\frac{\partial J_k}{\partial x_k}=\frac{1}{p^2}\frac{\partial}{\partial p}\left\{\frac{p^2\varepsilon}{3c^2}[\mathbf{u}\boldsymbol{\omega}]\mathbf{J}\right.$$
$$\left.+\frac{p^3}{3}\left(\frac{\mathbf{v}}{\Lambda_A}+\frac{\mathbf{u}}{\Lambda_{B_1}}\right)\mathbf{J}+\frac{p^4}{3}\left(\frac{v^2}{\Lambda_A}+\frac{u^2}{\Lambda_{B_1}}\right)\frac{\partial N}{\partial p}\right\}, \qquad (7)$$

$$\frac{\partial J_i}{\partial t}+v\frac{\partial N}{\partial x_i}-[\mathbf{J}\boldsymbol{\omega}]_i-\frac{\varepsilon}{c^2}[\mathbf{u}\boldsymbol{\omega}]_i\frac{\partial N}{\partial p}$$
$$=-v\left(\frac{1}{\Lambda_A}+\frac{1}{\Lambda_{B_1}}\right)J_i-p\left(\frac{v_i}{\Lambda_A}+\frac{u_i}{\Lambda_{B_1}}\right)\frac{\partial N}{\partial p}. \qquad (8)$$

Here $\Lambda_A=1/n(\mathbf{r},t)\sigma_{\mathrm{tr}}(v)$ is the mean free path with respect to scattering by the clouds,

$$\sigma_t=\int\sigma(1-\cos\theta)\,d\Omega_1$$

is the total cross section and θ is the angle between $\mathbf{p}$ and $\mathbf{p}'$. We have neglected the terms containing u^3, V^3, $u^2\mathbf{J}$, and $V^2\mathbf{J}$, as well as higher order terms with respect to $\mathbf{u}$ and $\mathbf{V}$.

Suppose now that $\mathbf{u}=\mathbf{u}_0+\mathbf{u}_1$ and $\mathbf{V}=\mathbf{V}_0+\mathbf{V}_1$, where $\mathbf{u}_0=\langle\mathbf{u}\rangle$ and $\mathbf{V}_0=\langle\mathbf{V}\rangle$, and $\langle\mathbf{u}_1\rangle=\langle\mathbf{V}_1\rangle=0$ (here the angle brackets denote averages over the random velocities $\mathbf{u}_1$ and $\mathbf{V}_1$). By substituting these expressions into Eqs. (7) and (8) and averaging over $\mathbf{u}_1$ and $\mathbf{V}_1$, we obtain

$$\frac{\partial N}{\partial t}=\frac{\partial}{\partial x_k}\left(\varkappa_{kl}\frac{\partial N}{\partial x_l}-\frac{p}{3}\frac{q_k}{\nu^2+\omega^2}\frac{\partial N}{\partial p}\right)$$
$$+\frac{1}{p^2}\frac{\partial}{\partial p}\left\{\frac{p^3}{3}\frac{\mathbf{q}_A\nabla N}{\nu^2+\omega^2}+\frac{p^4}{3v^2}(\nu_A\langle V^2\rangle+\nu_{B_1}\langle u^2\rangle+d)\frac{\partial N}{\partial p}\right\}, \qquad (9)$$

where the collision frequency of the particles in the cosmic rays is written $\nu=\nu_A+\nu_{B_1}$ ($\nu_A=v/\Lambda_A$ and $\nu_{B_1}=v/\Lambda_{B_1}$ being the collision frequencies with the clouds and with the fluctuations of the random magnetic field, respectively). The quantities $\varkappa_{kl}$, $\mathbf{q}$, $\mathbf{q}_A$, and d are defined by

$$\varkappa_{kl}=\frac{v^2\nu}{3(\nu^2+\omega^2)}\left(\delta_{kl}-\frac{1}{\nu^2}\omega_k\omega_l-e_{kil}\frac{\omega_i}{\nu}\right), \qquad (10)$$

where e_{kil} is the antisymmetric tensor,

$$\mathbf{q}=\nu[\mathbf{u}_0-\mathbf{W}_0,\ \boldsymbol{\omega}]-\nu^2\mathbf{W}_0-\omega^2\mathbf{u}_0+\boldsymbol{\omega}\{(\mathbf{u}_0\boldsymbol{\omega})-(\mathbf{W}_0\boldsymbol{\omega})\}, \qquad (11)$$

$$\mathbf{q}_A=\mathbf{q}-2\nu[\mathbf{u}_0-\mathbf{W}_0,\ \boldsymbol{\omega}], \qquad (12)$$

$$d=\frac{1}{\nu^2+\omega^2}\{\nu\omega^2u_0^2-\nu(\mathbf{u}_0\boldsymbol{\omega})^2-2\nu\omega^2(\mathbf{u}_0\mathbf{W}_0)+2\nu(\mathbf{u}_0\boldsymbol{\omega})(\mathbf{W}_0\boldsymbol{\omega})$$
$$-\nu^3\mathbf{W}_0^2-\nu(\boldsymbol{\omega}\mathbf{W}_0)^2\}, \qquad (13)$$

$$\mathbf{W}_0=\frac{\nu_A}{\nu}\mathbf{V}_0+\frac{\nu_{B_1}}{\nu}\mathbf{u}_0. \qquad (14)$$

The first term in Eq. (9) contains two components. The first describes the anisotropic diffusion, characterized by the diffusion tensor (10) and the second gives the particle energy change due to the motion of the medium. The second term in Eq. (9) describes the acceleration of the particles. Its first component is the result of the positive density gradient in the galactic cosmic rays (CR) and of the radial motion of the medium (in the case of the solar CR, characterized by a negative gradient, this component has the opposite sign, i.e., describes deceleration of the particles). The second componet describes the acceleration of the particles due to scattering on the clouds and fluctuations of the random magnetic field. This leads to an effective regular velocity of the medium $\mathbf{W}_0$ described by expression (14), which is defined not only by the regular components of the velocity of the magnetic clouds $\mathbf{V}_0$ and the frozen magnetic field $\mathbf{u}_0$, but also by collision frequencies characterizing the scattering of the CR particles on the clouds and fluctuations of the random magnetic field, namely, to some extent, depending on the energy of the particles in the CR.

In order to clarify the physical meaning of these results we will consider some limiting cases.

3. THE CASE $\vec{\mathbf{B}}_0\equiv 0$

In this case Eq. (9) has the following form

$$\frac{\partial N}{\partial t}=\frac{\partial}{\partial x_k}\left(\varkappa\frac{\partial N}{\partial x_k}+\frac{p}{3}W_{0k}\frac{\partial N}{\partial p}\right)$$
$$+\frac{1}{p^2}\frac{\partial}{\partial p}\left(-\frac{p^3}{3}\mathbf{W}_0\nabla N+p^2D\frac{\partial N}{\partial p}\right). \qquad (15)$$

Here, D is the diffusion coefficient in momentum space, defined as $D = D_A + D_{B_1} + D_0$, where

$$D_A = p^2\langle\Delta V^2\rangle/3v\Lambda_A, \quad D_{B_1} = p^2\langle\Delta u^2\rangle/3v\Lambda_{B_1},$$
$$\langle\Delta V^2\rangle = \langle V^2\rangle - V_0^2, \quad \langle\Delta u^2\rangle = \langle u^2\rangle - u_0^2,$$

and D_0 is given by

$$D_0 = \frac{p^2}{3v}\frac{(\mathbf{V}_0-\mathbf{u}_0)^2}{\Lambda_A+\Lambda_{B_1}}. \tag{16}$$

For $\mathbf{V} = \mathbf{u}$, Eqs. (9) and (15) reduce to equations derived previously (see Ref. 7). In this case the acceleration of the cosmic rays in interplanetary space (as well as in other astrophysical objects) is described by the terms containing D_{B_1} and $\nabla\mathbf{u}$.

If, in contrast, $\mathbf{V} \neq \mathbf{u}$ holds there exists, in effect, two types of scatterers, which originate independently, then, as can be seen from Eqs. (15) and (16), a systematic acceleration will be observed even when $D_A = D_{B_1} = 0$.

Equation (15) leads to an additional interesting conclusion. If one neglects the term containing D, then the energy change of the CR for $\mathbf{V} = \mathbf{u}$ is determined by the quantity $\nabla\mathbf{u}$ and for $\nabla\mathbf{u} = 0$ the energy remains unchanged [the first term on the right hand side of Eq. (15)]. If, however, $\mathbf{V} \neq \mathbf{u}$, then, even in the case $\nabla\mathbf{V} = \nabla\mathbf{u} = 0$, the energy of the CR will change, since $\mathbf{W}_0$ depends on $\mathbf{r}$ via Λ_A and Λ_{B_1} since $\nabla\mathbf{W}_0 \neq 0$ for a given dependence of Λ_A and Λ_{B_1} on $\mathbf{r}$. One should again emphasize here that Eq. (15) differs from that usually treated by the fact that it contains $\mathbf{W}_0$ instead of $\mathbf{u}$ and D instead of D_{B_1}. Also D contains not only D_{B_1} as a component (the Fermi acceleration on the frozen inhomogeneities of the magnetic field) but also D_A (the Fermi acceleration on the clouds) and D_0, representing a new type of acceleration, which is due to the differences in the regular velocities of the medium and the clouds, rather than between the random velocities. It will be shown below that this effect is especially important in considering the processes of propagation and acceleration of cosmic rays in interplanetary space, stellar winds, clouds of novae and supernovae, double stars, extragalactic radio-sources, etc.

4. SPATIALLY UNIFORM CASE

Suppose that $D_A = D_{B_1} = 0$ and that the medium is uniform. Then Eq. (15) becomes

$$\frac{\partial N}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_0 \frac{\partial N}{\partial p}\right). \tag{17}$$

According to Eq. (16), let $D_0 = 4p^2/\tau$, where τ is a constant, given by

$$\tau = 3v(\Lambda_A+\Lambda_{B_1})/4(\mathbf{V}_0-\mathbf{u}_0)^2. \tag{18}$$

By multiplying Eq. (17) by p^3dp and integrating, we obtain

$$\frac{\partial\langle p\rangle}{\partial t} = \int p\frac{\partial}{\partial p}\left(\frac{4p^4}{\tau}\frac{\partial N}{\partial p}\right)dp,$$

where $\langle p\rangle = \int pNp^2dp$. This yields $d\langle p\rangle/dt = \langle p\rangle/\tau$, or $\langle p\rangle = p_0\exp(t/\tau)$; thus τ defined in Eq. (18) has the meaning of a characteristic time for particle acceleration due to the difference between the regular velocities of the background plasma and the clouds. It follows from Eq. (18) that this acceleration mechanism is more efficient when $\mathbf{u}_0 = 0$ (in this case the magnetized medium must be characterized by $\Lambda_{B_1} < \infty$, since otherwise $\tau \to \infty$ and the acceleration vanishes). Still higher acceleration efficiency is expected, as seen from Eq. (18), when the velocities of the clouds and the medium are opposite to each other (as, for example, in double stars, colliding galaxies, etc.). Let us analyze the possibility for this acceleration mechanism to occur in some astrophysical objects.

5. ASTROPHYSICAL APPLICATIONS

a. The possibility of efficient acceleration in the interplanetary space

The medium in interplanetary space with a frozen magnetic field (the solar wind) expands radially with velocity $\mathbf{u}_0 = u_0\mathbf{r}/r$, where $u_0 \sim 4\times10^7$ cm/s. Here the role of magnetic clouds which scatter the cosmic rays is played by various plasma formations, generated in the outbursts on the sun (with characteristic velocity of 8×10^7–2×10^8 cm/s), high velocity flows of magnetized plasma, associated with the coronal holes (velocities of 6×10^7–10^8 cm/s), ejections of plasma blobs with frozen magnetic fields, etc. The scattering cross section on these objects depends on the energy of the CR, while their density and the characteristic distance between them depends on the level of the solar activity and the distance from the sun. In periods of increased solar activity, when the chromospheric outbursts are quite frequent (1-2 outbursts per day, on the average), the characteristic distance between the shock waves (for an average velocity $V_0 = 10^8$ cm/s) is $\sim 7\times10^{12}$ cm. First, we consider particles with relatively high energies $E_k \sim 100$ MeV/nucleon. For these particles $\Lambda_{B_1} \sim 3\times10^{12}$ cm. (For solar cosmic rays of such energy, $\Lambda_{B_1} \sim 10^{12}$ cm,[1] but this value corresponds to the region near the orbit of the earth. The average value of Λ_{B_1} over the whole heliosphere will be larger, as follows from the 11-year modulation of the galactic cosmic rays[10]).

If we set $\Lambda_A \sim 7\times10^{12}$ cm, $u_0 = 4\times10^7$ cm/s and $v = 10^{10}$ cm/s Eq. (18) yields $\tau = 2\times10^7$ s for the characteristic acceleration time. On the other hand, the characteristic time spent by such particles in the interplanetary space is $T \sim r_0^2/2v\Lambda_{B_1}$, where $r_0 \sim 100$ AU is the characteristic dimension of the heliosphere, so that $T \sim 3\times10^7$ s and, therefore, the acceleration is quite significant. For lower-energy particles, Λ_{B_1} decreases slightly, but neverless, Λ_A remains unchanged, so that τ remains practically constant. The value of T, however, increases slightly and therefore the acceleration efficiency is slightly higher. The time spent by very low-energy particles in the heliosphere is basically determined by the outward convection of the solar wind, i.e., 1–2 years (the time the solar wind takes to reach the boundary of the heliosphere, which can be found from the delay in the long-term variations of the galactic cosmic rays relative to the activities on the sun[10]). Therefore, the acceleration efficiency for these particles can be higher than that for particles with energies of ~ 100 MeV.

Particles with still higher energies (several GeV) are characterized by $\Lambda_{B_1} \sim 10^{13}$ cm and $v \sim 3\times10^{10}$ cm/s and the expected τ is $\sim 10^8$ s, while $T \sim 3\times 10^6$ s. Thus the acceleration by the present mechanism is inefficient.

Let us address now the question of the acceleration in the transition region between the solar wind and the interstellar space. In explaining the time delay in the revival of the intensity of the galactic cosmic rays when the solar activity decreases, it was suggested in Ref. 11 that a transition region of thickness $L \geqslant 100$ AU exists at a distance of ~ 100 AU from the sun, in which the velocity of the solar wind is nearly zero (in this region it is subsonic). Magnetic fields and fluctuations are steadily forced into this region and, therefore, Λ_{B_1} may be quite small. Since the convective removal of the cosmic particles does not take place here, this layer will not modulate the flow of the galactic CR directly. Nevertheless, a characteristic transit time $T \sim L^2/2v\Lambda_{B_1}$ is necessary in order to pass the layer. This time is found from the observations of the long-term variations of the galactic CR (see Ch. 8 in Ref. 10), namely $T \sim 10^8$ s for the particles of energy $E_k \sim 1$ GeV and $T \sim 3\times 10^7$ s for $E_k \sim 5$ GeV. Then $\Lambda_{B_1} \sim 3\times 10^{11}$ cm and 10^{12} cm for particles of ~ 1 and ~ 5 GeV respectively. On the other hand, shock waves and various plasma ejections reach the transition layer with a relatively low velocity loss, and thus one may expect for the subsonic solar wind $u_0 \sim 0$ and $\vec{V}_0 \sim 5\times 10$ cm/s (according to direct measurements on Pioneer-10, the velocity of the shock waves at a distance $\gtrsim 30$ AU is practically the same as at the earth's orbit). Since shock waves and plasma formations are injected into the transition region over a long period of time, the characteristic length between them may be even smaller than in the region of the supersonic solar wind, i.e., in any case one can assume $\Lambda_A \sim 7\times 10^{12}$ cm. Then $\tau \sim 6\times 10^7$ s for $E \sim 1$ GeV and $\tau \sim 7\times 10^7$ s for $E \sim 5$ GeV. A comparison between the calculated values of τ with the values of T given above shows that particles with energies $E \lesssim 1$ GeV can be accelerated quite efficiently in the transition layer, while particles with energies $E \gtrsim 5$ GeV cannot be accelerated very efficiently. Efficient acceleration in this layer can also be experienced by the interstellar space particles, which explains the appearance of the so-called "anomalous" component of the cosmic rays in the vicinity of the earth at certain periods of solar activity.

b. The acceleration efficiency in interstellar space

As a result of a large number of shock waves in the interstellar space due to outbursts of novae and supernovae, as well as because of other active processes, many moving scattering centers are created, so that Λ_A does not have to be too large. If the effective mean free path for scattering on shock waves and other moving plasma formations in the disc is $\Lambda_A^d \sim 4pc$ and $V_0 \sim 10$ cm/s, then, as can be easily shown, a very efficient acceleration via the above-considered mechanism is expected. Indeed, it follows from the data on the relative abundance of Be^{10}, that the lifetime of the CR in the disc and halo as $T = T_d + T_h = 3\times 10^7$ years. On the other hand, the data on chemical and isotopic compositions show that the total amount of matter, which the CR intersect in the Galaxy (in the low-energy range) is ~ 7 g/cm^2. Since the densities in the disc and the halo are $\sim 10^{-24}$ g/cm^3 and 10^{-26} g/cm^3, respectively, we obtain the relation $T_h \times 3\times 10^{10} \times 10^{-26} + T_d \times 3\times 10^{10} \times 10^{-24} = 7$ g/cm^2. Then, on using $T_d + T_h = 3\times 10^7$ years $\simeq 10^{15}$ s, we get $T_d \sim 2.2\times 10^{14}$ s $\simeq 7\times 10^6$ years and $T_h \sim 7.8\times 10^{14}$ s $\simeq 2.3\times 10^7$ years. The dimension of the halo is $r_h \sim 15$ kpc $\sim 5\times 10^{22}$ cm, so that $\Lambda_{B_1}^h = r_h^2/2vT_h \sim 5\times 10^{19}$ cm ~ 15 pc. Similarly, in the disc (characteristic thickness $L_d \sim 1$ kpc $\sim 3\times 10^{21}$ cm) we obtain $\Lambda_{B_1}^d \sim L_d^2/2vT_d \sim 6\times 10^{17}$ cm ~ 0.2 pc. Then, as follows from Eq. (18), the characteristic acceleration time is $\tau_d \sim 3\times 10^{13}$ s $\sim 10^6$ years, while $T_d \sim 7\times 10^6$ years, namely, for the parameters used, three orders of magnitude increase in the energy is possible. Let us consider now the possibility of acceleration in the halo. Shock waves can, of course, propagate in the halo. Furthermore, a galactic wind may have a velocity of $u_0 \sim 10^7$ cm/s. If the velocity of the shock waves in the halo is $V_0 \sim 2\times 10^7$ cm/s and the distance between them $\Lambda_A^h \sim 15$ pc (lower values of Λ_A^h are inconsistent with the data on T_h), then $\tau_h \sim 2\times 10^{17}$ s $\sim 7\times 10^9$ years in the halo, which is considerably larger than T_h (about 2.3×10^7 years). Therefore, the acceleration in the halo is extemely inefficient. Even if $V_0 \sim 10^8$ cm/s (which, obviously, is very improbable), the value of τ_h is almost 3 times larger than T_h, i.e., the acceleration is negligible.

c. The acceleration efficiency in the galactic collisions

Suppose that the values of Λ_A^h, Λ_A^d, Λ_B^h, Λ_B^d, T_h, T_d for the colliding galaxies are the same as for our galaxy. Let the velocity of each galaxy be $\sim 10^8$ cm/s, i.e., $|\mathbf{V}_0 - \mathbf{u}_0| \sim 2\times 10^8$ cm/s. Then for the halo we obtain

$$\tau_h = \frac{3.3\cdot 10^{10}\cdot 2.15\cdot 10^{18}}{4(2\cdot 10^8)^2}\ \mathrm{s} = 10^{14}\ \mathrm{s} \sim 3\cdot 10^6\ \text{years}.$$

Comparing this value with T_h (approximately 2.3×10^7 years), we obtain the possibility of accelerating particles by a factor of 10^3–10^4 during their confinement time in the halo. Estimates for collisions of discs yield $\tau_d = 3\times 10^{12}$ s $\sim 4\times 10^4$ years, which is almost two orders of magnitude lower than T_d, and it therefore seems that one could have expected acceleration of particles to extremely high energies. This, apparently, does not occur, according to the modern viewpoint, since collisions of discs are impossible because of the gradual deceleration of the halos and their reflection from each other (stellar systems, nevertheless, continue their motion, passing through each other). Thus, quite efficient acceleration of particles (energy gain of 10^3–10^4) in galactic collisions can be expected in interactions between the two halos.

[1] L. I. Dorman and G. I. Friedman, in "Voprosy Magnitnoĭ Gidrodinamiki i Dinamiki Plazmy" (Problems of Magneto-Hydrodynamics and Plasma Dynamics), Riga, Izd. Zinatne, 1959, p. 77.
[2] G. F. Krymskiĭ, Doklady Akad. Nauk SSSR, **234**, 1306 (1977) [Sov. Phys. Doklady, **22**, 327 (1977)].
[3] I. I. Alekseev, A. P. Kropotkin, and A. P. Shabanskii, Izv. AN SSSR, Ser. Fiz. **34**, 2318 (1970) [Bull. of the Academy of Sciences of the USSR, Physical Series, 34, 2067 (1970)].
[4] E. G. Berezhko, Pis'ma Zh. Eksp. Teor. Fiz. **33**, 416 (1981) JETP Lett. **33**, 399 (1981)].

[5]L. I. Dorman "Uskoritel' nye Protsessy v Kosmose" (Acceleration Processes in Space) Moscow, Izd. VINITI, 1971.
[6]L. I. Dorman "Eksperimental' nye i Teoreticheskie Osnovy Astrofiziki Kosmicheskikh Luchei" (Experimental and Theoretical Foundations of Astrophysics of Cosmic Rays) Moscow, Nauka, 1975.
[7]I. N. Toptygin "Kosmicheskie Luchi v Mezhplanetnykh Magnitnykh Polyakh" (Cosmic Rays in Interplanetary Magnetic Fields) Moscow, Nauka, 1983.
[8]V. S.Berezinskii, S. V. Bulanov, V. L. Ginzburg, V. A. Dogel, and V. S. Ptuskin "Astrofizika Kosmicheskikh Luchei" (Astrophysics of Cosmic Rays) Moscow, Nauka, 1984.
[9]L. I. Dorman and L. I. Miroshnichenko "Solnechnye Kosmicheskie Luchi" (Solar Cosmic Rays) Moscow, Nauka, 1968.
[10]L. I. Dorman, "Variatsii Galakticheskikh Kosmicheskikh Luchei" (Variations in Galactic Cosmic Rays) Moscow, Izd. MGU, 1975.
[11]I. V. Dorman and L. I. Dorman, Izv. AN SSSR, Ser. Fiz. **31**, 1273 (1967) [Bull. of the Academy of Sciences of the USSR, Physical Series, **31**, 1239 (1967)].

Translated by L. Friedland