GIANT MOLECULAR CLOUDS AS REGIONS OF PARTICLE ACCELERATION

Dogiel V.A., Gurevich A.V., Istomin Ya.N., Zybin K.A.
P.N.Lebedev Physical Institute of the USSR Academy of Sciences, Moscow, USSR.

One of the most interesting results of investigations carried out on the satellites SAS-II and COS-B is the discovery of unidentified discrete gamma-sources. Possibly a considerable part of them may well be giant molecular clouds /I/. Gamma-emission from clouds is caused by the processes with participation of cosmic rays /2/. The estimation of the cosmic-ray density in clouds has shown that for the energy $E \sim$ I GeV their density can $10-10^3$ times exceed the one in intercloud space /3,4/. We have made an attempt to determine the mechanism which could lead to the increase in the cosmic-ray density in clouds.

The main results of these studies are as follows: I. In clouds there may occur particle acceleration. 2. The density of protons ejected by clouds in interstellar (intercloud) space is equal to I-I0% of the observed one. 3. Such a mechanism of acceleration, if it is realistic, necessitates a change in the existing concept of the formation of the chemical composition of cosmic rays in the Galaxy. 4. In its characteristics the intensity of non-thermal (synchrotron) emission from clouds is similar to the emission from H II-regions. This allows us to suppose that a part of radioemission, which was considered earlier to be thermal is acutally a non-thermal emission from molecular clouds.

In our estimations we have used the following parameters of the molecular clouds: dimension $R = 10$ pc. hydrogen mass $M = 10^5 M_\odot$, neutral gas density $N_n = 10^3$ cm^{-3}, degree of ionization $N_i / N_n = 10^{-6}$.

The crucial moment in our model is that the neutral gas of molecular clouds is turbulized. According to observations, the turbulence spectrum has the form /5/: $u(L)^{km/sec} \simeq$ $\simeq$ I.I L^{α} (pc) for $0.I < L < I00$ pc. Here u is velocity, L is scale, the parameter $\alpha \simeq 0.38$. Below we discuss how the energy of the neutral gas can be transformed into the energy of accelerated particles.

The spectrum of magnetic field fluctuations. According to the condition $\nu_{ei} > \nu_{en}, m_i/m_e \, \nu_{in}$ the equations for the velocity of the ionized plasma component and for the magnetic field $\bar{B}$ have the form

$$d\bar{V}/dt = -\nabla P/\rho - [\bar{B} \cdot curl \bar{B}]/4\pi\rho - \nu_{in}(\bar{V} - \bar{u}) + \eta_i \nabla^2 \bar{V}$$

$$\partial \bar{B}/\partial t = curl[\bar{V}\bar{B}] \,, \quad \partial\rho/\partial t = -div(\rho\bar{V}) \,, \quad div\bar{B} = 0 \qquad (I)$$

Here i, e, n stand for the ion, electron, and neutral plasma components; ν is collision frequency of corresponding particles, η_i is ion viscosity which is the largest for the assumed parameters.

The frequency interval for motions of the ionized component is as follows $\nu_{ni} < \omega = 2\pi V(L)/L \ll \nu_{in}$. According to the first inequality, we can neglect the influence of the ionized component on the neutral one. According to the second inequality ($\omega/\nu_{in} \ll$ I),we obtain v(L) $\simeq$ u(L) from the first equation of the system (I). Note that the interval of L values is determined by the relation $L_o > L > L_{min}$, $L_{min} = L_o Re^{-1/(1+\alpha)}$, $Re = u_o L_o/\eta_i$ ($u_o = 10^6$ cm/sec, $L_o = 10^{19}$ cm, $L_{min} = 10^{13}$ cm). The eigenvalues ω of the system (I) are imaginary, $\omega = i V_A^2/(\nu_{in} L)^2$, and hence the magnetic field on the scale L > L_{min} is excited only under the action of an inducing force (friction between charged and neutral components) on the scale L_{min}. Then the spectrum of magnetic field fluctuations has the form/7/: $B^2(L) = B_m^2 \cdot (L/L_{min})^{-5}$ for $L > L_{min}$. The estimations give $B_m \simeq 10^{-5} - 10^{-6}$ oe.

Equations of motion for particles in random electromagnetic fields. In a magnetic field B $\sim 10^{-5}$ oe protons with energies $E_p \simeq$ 3-30 GeV and electrons with energies $E_e \simeq 10^2 - 10^3$ GeV turn out to be magnetized, i.e. $\gamma < \omega_H \tau_c$ (here ω_H is cyclotron frequency, γ is gamma-factor of particles, τ_c is correlation time $\tau_c = L_{min}/c$). For magnetized particles one can derive (see /8/) the equation for the distribution function f :

$$\frac{\partial f}{\partial t} = \nabla(A_x \nabla f) + \frac{\partial}{\partial \gamma}\left(\gamma A_\gamma \frac{\partial}{\partial \gamma}(\gamma f) + p f\right) \qquad (2)$$

Here A_x and A_γ are diffusion coefficients in the coordinate and energy spaces, p is the function describing energy losses of particles.

$$A_x \simeq \frac{\pi c\, L_{min}}{6}, \quad A_\gamma \simeq \frac{\pi u_o^2}{3 c\, L_{min}} \qquad (3)$$

The equation of motion for nonmagnetized particles has the form

$$\frac{\partial f}{\partial t} = \gamma^2 \mathcal{D}_x \nabla^2 f + \frac{\partial}{\partial \gamma}\left(\gamma^2 \mathcal{D}_\gamma \frac{\partial}{\partial \gamma}\left(\frac{f}{\gamma^2}\right)\right) \qquad (4)$$

$$\mathcal{D}_x = \frac{m^2 c^4}{6 \nu_o}, \quad \nu_o = e^2 \int_0^\infty \langle B^2 \rangle_{\tau, v\tau}\, d\tau, \quad \mathcal{D}_\gamma = \frac{2}{3}\frac{e^2}{m^2 c^4} \int_0^\infty \langle V^2 \rangle_{\tau, v\tau} \langle B^2 \rangle_{\tau, v\tau}\, d\tau \qquad (5)$$

Cosmic-ray density in a cloud. Let us assume the distribution function f of particles inside a cloud or radius R to be described by equations (2) and (4) and let outside the cloud the equation have the form

$$\frac{\partial f}{\partial t} = \nabla(\mathcal{D}_o \nabla f) \qquad (6)$$

where $\mathcal{D}_o$ is the spatial diffusion coefficient in interstellar space, $\mathcal{D}_o = 10^{28}$ cm^2 /sec/2/. We obtain from the expressions (3) that inside a cloud the spatial diffusion coefficient is much smaller, $A_x \simeq 10^{23}$ cm^2/sec. and the value $A_\gamma \simeq 10^{-11}$ sec^{-1}. At infinity (r $\to \infty$) we set up the cosmic-ray spectrum in intercloud space, f_∞ , and assume it to be similar to the one observed near the Earth ($f_\infty = K E^{-\lambda}, \lambda \simeq 3$). Then inside the cloud ($r < R$) there holds the following solution for magnetized particles ($\omega_H \tau_c > \gamma \gg 1$)

$$f = \frac{2 N_\infty}{\varkappa} \lambda \frac{R}{r} \sin\left(\pi \frac{r}{R}\right) \cdot \gamma^{-(1+\pi \frac{\lambda}{\varkappa})} \qquad (7)$$

Here $N_\infty = \int^\infty f_\infty d\gamma$, the quantity $\varkappa = \lambda\sqrt{\Delta_\gamma R^2/\Delta_x}$. Thus, a statistic acceleration in random electric fields ($\mathcal{E}(L) = -\frac{1}{c}\cdot[\vec{v}B]$) of a cloud leads to generation of hard spectra.The spectrum of non-magnetized particles ($\gamma \gg \omega_H \tau_c$) has the form

$$f = C\gamma^{3/2} K_{1/4}[(\pi^2 \mathcal{D}_x/(R^2 \mathcal{D}_\gamma)\gamma^2/2] \qquad (8)$$

Here C is the constant determined from the conditions of joining of the solutions (7) and (8), $K_\nu(x)$ is a McDonald function. The solution (8) falls exponentially in the energy range $\gamma \gg \omega_H \tau_c$.

If we take as f_∞ the proton spectrum observed near the Earth, we obtain that the proton density inside a cloud can exceed more than by an order of magnitude the proton density in intercloud space for proton energies $E \simeq$ I GeV.

Not let us pass over to astrophysical applications of this model.

I. Gamma-emission from molecular clouds and determination of the cosmic-ray gradient from the background emission in the Galaxy. The total gamma-emission flux ($E_\gamma > 100$ MeV) from a molecular cloud makes up about 10^{35} erg/sec. Assuming that in the Galaxy there exist several thousands of such clouds ,we come to the conclusion that the considerable part of gamma-emission from the galactic disk consists of emission from molecular clouds. It is thus clear that inside the solar circle, where a large amount of molecular hydrogen is concentrated, we cannot determine the gradient of cosmic-rays which is due to cosmic ray leakage from the Galaxy. The cosmic ray gradient calculated there from the diffusion gamma-emission of the galactic disk will simply reflect the mean density of cosmic rays accelerated in the clouds. This cosmic-ray density must, in turn, be proportional to the nonuniform distribution of molecular hydrogen in the galactic disk.

In connection with what has been said it is important to measure the spectral index of gamma-sources and of the diffusion gamma-emission of the galactic disk where the main part of gas is concluded in the clouds. If acceleration does take place in the clouds, the gamma-radiation intensity for $E \gg$ 100 MeV has the following dependence: $I_\gamma \propto E_\gamma^{-1}$. If not, then $I_\gamma \propto E_\gamma^{-2.75}$.

2. Molecular clouds as antiproton sources in the Galaxy. As the estimates show, the antiproton density inside clouds can be of the order of 10^{-12} (cm^{3}GeV)$^{-1}$ for energies $E_{\bar{p}} \simeq$ I GeV. Calculating the antiproton flux from the clouds we obtain that the antiproton density in intercloud medium must be $n_{\bar{p}}(E_{\bar{p}} \simeq 1\,\text{GeV}) \simeq 10^{-14}$ (cm^{3}GeV)$^{-1}$. This value corresponds to the antiproton density observed near the Earth. According to our calculations, the antiproton density must fall like $n_{\bar{p}} \propto E_{\bar{p}}^{-1.4}$ in the relativistic energy range. In the nonrelativistic region (30 MeV < $E_{\bar{p}}$ < I GeV) the antiproton density weakly depends on the particle energy ($n_{\bar{p}} \propto E^{-0.5}$). Thus, the origin of galactic antiprotons (see ref./9/) can be explained in the framework of our model.

3. Molecular clouds and secondary nuclei in the composition of galactic cosmic rays. There exists a problem of the origin of light secondary nuclei in the Galaxy. The calculations of the grammage passed by cosmic rays before the formation of secondary nuclei give the following results: for antiprotons ($E_{\bar{p}} > 1$ GeV) $x \simeq 21$ gr/cm^2 /10/, for deuterium $x \simeq 15$ gr/cm^2 /11/, for He^3 $x \simeq 15$ gr/cm^2 /12/. For heavier nuclei, beginning with the group Li, Be, B, the calculations of X give approximately the same value: $X \simeq 5$ gr/cm /2/. All these calculations are made in the assumption diffusion or leaky-box models.

As our estimates show, light nuclei (P, D, He^3) can be effectively accelerated in the clouds since their acceleration time ($\sim 1/\Delta_\delta$) is much less than the characteristic lifetime of particles (through the nuclear collisions). For heavier nuclei with an atomic number $A \gtrsim 10$ the situation is quite opposite, and therefore their acceleration in clouds is not effective. From this we can assume that the P, D, and He^3 nuclei are formed in molecular clouds, and heavier secondary nuclei in interstellar (intercloud) medium in the process of propagation diffusion of primary cosmic rays.

4. Molecular clouds and positrons in the composition of cosmic rays. As the estimates show, for the energies $E \simeq 1$ GeV their density of positrons $n_{e^+} \simeq 10^{-12}$ (cm^3 GeV)$^{-1}$ and the dependence of the density on the particle energy E_e is as follows: $n_e(E > 1\,GeV) \propto E_e^{-1}$. The estimates show that the density of positrons ejected by the clouds in intercloud space is equal to the one observed near the Earth for $E \simeq 1$ GeV. In the diffusion model the positrons ejected from the clouds into intercloud space must have the spectrum $I_{e^+} \propto E_{e^+}^{-1.7}$ for $E_{e^+} > 1$ GeV. If there is no acceleration in the clouds, the positron spectrum must have the form $I_{e^+} \propto E_{e^+}^{-3.4}$ /2/.

The observations /12/ just show an anomalously high positron intensity for energies $E_{e^+} \sim 10$ GeV near the Earth that is in accordance with our model.

5. Radioemission of molecular clouds. According to the above characteristics of the electron spectrum in the clouds, the intensity J_ν of radioemission from the clouds does not depend (or depends weakly) on the frequency ν: $J_\nu \simeq$ const. The flux of radioemission from a cloud can be of the order of $\Phi_\nu \simeq 10^{21} - 10^{22}$ erg/sec for all frequencies up to $\nu < 10^{12}-10^{16}$Hz where the spectrum of radioemission from the cloud suddely falls.

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