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GAMMA RAYS AND CYCLOTRON RADIATION X-RAYS OF GALACTIC AND METAGALACTIC ORIGIN

V. L. GINZBURG and S. I. SYROVAT-SKIĬ

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

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The intensity of gamma rays from the decay of neutral pions produced in nuclear collisions of cosmic rays in interstellar and intergalactic space is calculated. The intensity of cyclotron x-radiation of electrons (and positrons), which are the products of $\pi^{\pm}$ meson decay, is determined under the same conditions. The corresponding values of the intensities of gamma and x rays are several orders of magnitude below the intensities of the cosmic gamma and x rays registered in some investigations.

RECENT papers[1-4] report experimental data, albeit tentative, which favor the assumption that a noticeable flux of gamma and x rays of cosmic origin exists. The most probable source of γ rays with energy $E > 50$ MeV are neutral pions produced in nuclear collisions between cosmic rays in the interstellar or intergalactic medium. Kraushaar and Clark[1] did not register in their experiments all the gamma rays with energy $E > 50$ MeV, the expected intensity of which, $I_\gamma(E > 50 \text{ MeV})$, is proportional to the integral $\int nI_{cr}dl$ along the line of sight (n is the gas concentration and I_{cr} is the intensity of cosmic rays of all energies encountered in practice). Estimates of the value of $I_\gamma(E > 50 \text{ MeV})$ for the galaxy and the metagalaxy are contained in several papers [1,5,6] and will not be repeated here. In the experiments of Firkowski[2] and Suga[3] the measurements were made of the intensity $I_\gamma(E > 10^{15} \text{ eV})$, which, according to the data of [2,3] are of the same order as or lower than $10^{-3} I_{cr}(E > 10^{15} \text{ eV})$. Giacconi et al[4] observed x rays with wavelengths $\lambda \sim 3$ Å and with intensity, averaged over all directions, $I_r \sim 10^{-8}$ erg/cm^2 sec-sr (in the experiment $I_r \sim 2$ photons/cm^2 sec-sr).

If hard cosmic γ rays are actually observed, then it is natural to attempt to relate their occurrence with the decay of neutral pions of suitable energy. But then the observed x rays could, in principle, be due to cyclotron radiation[4,7]. (The production of the neutral pions is connected with the appearance in the mean of two $\pi^{\pm}$ mesons, which lead in the final analysis to the appearance of electrons and positrons. The latter indeed give rise to cyclotron radiation as they move in the cosmic magnetic fields.)

The possible significance of even the first steps in the field of γ- and x-ray astronomy can hardly be overestimated. Of particular importance in this respect are experiments of the type carried out by Kraushaar and Clark[1], which make it possible to obtain valuable information on the metagalactic space[1,5,6]. Experiments on hard γ and x rays can, of course, also prove exceedingly useful from the point of view of gaining new information on outer space. In this connection we analyze here the question of the intensity of the γ and x rays produced as a result of nuclear interactions between cosmic rays in the galaxy and the metagalaxy.

1. GAMMA RAY INTENSITY

We assume for the intensity of the cosmic rays at the earth, in the interval $10 \le E \le 10^6 - 10^7$ BeV, a value[8]

$$I(E)\,dE = 1.5\,E^{-2.6}\,dE = KE^{-\gamma}\,dE \text{ particles/cm}^3\text{ sec-sr}, \qquad (1)$$

where the particle energy E is measured in BeV ([8] gives the integral spectrum

$$I(>E) = \int_E^\infty I(E)dE = 0.93E^{1-\gamma}, \quad \gamma = 2.6 \pm 0.03).$$

At the high energies of interest to us ($E > 10^3$ BeV), there are no reliable data on the chemical composition of the cosmic rays. However, if we extrapolate the composition known for lower energies, then the protons constitute about one-half of the particles of energy larger than a given value[5]. On the other hand, for nuclei of given energy each nucleon has a lower energy and therefore plays a lesser role from the point of view of the calculation (which will be presented below) of the number of pions of given energy. We disregard in what follows, however, the fact that can lead to a decrease in intensity by at most a factor of two (under the assumption that at a given total energy the number of nuclei does not exceed the number of protons and $\gamma > 2$). In other words, we assume all the particles in (1) to be protons. There are no grounds for introducing the corresponding refinement (account of the chemical composition), if we bear in mind not only the lack of sufficiently complete information on the composition, but also the inavoidable inaccuracy of all the other data (we refer to the values of the cosmic ray intensity $I \equiv I_{cr}$ and also to the gas concentration n along the entire line of sight).

The interaction between the cosmic rays and the nuclei (protons) of the interstellar medium has a cross section $\sigma \approx 4 \times 10^{-26}\ \mathrm{cm}^2$. This causes the production of $\nu(E) = \nu_0 E^{\delta}$ pions (one-third each neutral, positive, and negative), and their total energy is $\nu \bar{E}_\pi = kE$, $k = k_0 E^{\alpha}$. We assume in what follows the values

$$\nu_0 = 3.3, \qquad \delta = 1/4, \qquad k_0 = 1/3, \qquad \alpha = 0. \tag{2}$$

Consequently the average energy of the produced meson is (all energies are in BeV)

$$\bar{E}_\pi = kE/\nu(E) \approx 0.1\, E^{3/4}. \tag{3}$$

In a unit volume there occur $\sigma n(\mathbf{r}) I(E)\, dE$ interactions due to cosmic rays of intensity $I(E)$. This results in the production of the following number of pions (we refer to pions produced by cosmic rays moving within a unit solid angle; the total number of pions is obtained by multiplying (4) by 4π, since the cosmic rays are isotropic):

$$q_\pi(E_\pi) = \sigma n(\mathbf{r})\, \nu_0 E^{\delta} I(E)\, dE = \sigma n(\mathbf{r})\, K_\pi E^{-\gamma_\pi} dE_\pi,$$
$$E = (E_\pi \nu_0/k_0)^{1/(1+\alpha-\delta)}, \quad I(E) = KE^{-\gamma},$$
$$\gamma_\pi = \frac{\gamma + \alpha - 2\delta}{1 + \alpha - \delta}, \quad K_\pi = K\frac{\nu_0}{1+\alpha-\delta}\left(\frac{k_0}{\nu_0}\right)^{\gamma_\pi - 1}. \tag{4}$$

If we now assume the values in (2), and also put $K = 1.5$ and $\gamma = 2.6$ [see (1)], then $K_\pi = 0.105$, $\gamma_\pi = 2.8$, $K_{\pi^\pm} = 2/3\, K_\pi$, $K_{\pi^0} = 1/3\, K_\pi$, and consequently

$$q_{\pi^\pm}(E_\pi) = \sigma n \cdot 0.07\, E_\pi^{-2.8} \quad \pi^\pm\text{-mesons/cm}^3\ \text{sec-sr-BeV}$$
$$q_{\pi^0}(E_\pi) = \sigma n \cdot 0.035\, E_\pi^{-2.8} \quad \pi^0\text{-mesons/cm}^3\ \text{sec-sr-BeV} \tag{5}$$

We note that according to Greisen[10] the spectrum for the generation of $\pi^\pm$ mesons in the atmosphere (on the absorption free path, i.e., for $n\sigma \sim 2$) has the form $q_{\pi^\pm}(E_\pi) = 0.156\, E_\pi^{-2.64}\, dE$. This value almost coincides with (5) for $\sigma n = 1$ and $E_\pi = 1$ BeV, but differs by approximately a factor of six for $E_\pi = 10^6$ BeV. When a neutral pion decays into two γ quanta, the energy of each quantum in the neutral-pion rest system is obviously $E_\gamma^* = m_{\pi^0}c^2/2$. In a system in which the total neutral-pion energy is E_π, the energy of the quantum is $E_\gamma = zE_\gamma^* + \sqrt{z^2-1}\,E_\gamma^* \cos\theta^*$, where $z = E_\pi m_\pi c^2$ and θ^* is the angle between the momentum of the quantum and the velocity of the laboratory frame, measured in the π^0-meson rest frame (the decay is isotropic in this frame). The γ-ray distribution function has in the laboratory system the form

$$f(E_\gamma, z)\, dE_\gamma = dE_\gamma / E_\gamma^* \sqrt{z^2 - 1}, \quad z \geqslant (E_\gamma^2 + E_\gamma^{*2})/2E_\gamma E_\gamma^*.$$

Hence

$$q_\gamma(E_\gamma)\, dE_\gamma = dE_\gamma \int_{E_{\pi,\,min}}^{\infty} \sigma n\, K_{\pi^0} E_\pi^{-\gamma_\pi} f(E_\gamma, z)\, dE_\pi$$
$$= \sigma n K_{\pi^0} \frac{2}{\gamma_\pi} E_\gamma^{-\gamma_\pi} dE_\gamma$$

(under the assumption that $E_\gamma \gg E_\gamma^* = m_\pi c^2/2$). In our case $\gamma_\pi = 2$, and by virtue of (5) we have for the number of produced γ rays

$$q_\gamma(E_\gamma) = \sigma n \cdot 0.025\, E_\gamma^{-2.8}\ (\text{cm}^3\ \text{sec-sr-BeV})^{-1},$$
$$q_\gamma(>E_\gamma) = \int_{E_\gamma}^{\infty} q_\gamma(E_\gamma)\, dE_\gamma$$
$$= \sigma n \cdot 0.014\, E_\gamma^{-1.8}\ (\text{cm}^3\ \text{sec-sr})^{-1}. \tag{6}$$

The intensity of the γ rays in a certain direction is

$$I_\gamma(>E_\gamma) = \int q_\gamma(>E_\gamma)\, dL$$
$$= 5.6 \cdot 10^{-28} E_\gamma^{-1.8} N(L)\ (\text{cm}^2\ \text{sec-sr})^{-1}, \tag{7}$$

where $N(L) = \int n\, dL$ is the total number of nucleons in the medium along the line of sight.

According to (1) and (7), the ratio of the intensities of the γ rays and of all the cosmic rays with energy larger than E will be

$$\xi = I_\gamma(>E)/I(>E) \approx 6 \cdot 10^{-28} N(L)\, E^{-0.2}. \tag{8}$$

Since the spectrum (1) used in the calculations pertains to energies $E > 10$ BeV, formula (8) is suitable for $E = E_\gamma \gtrsim 10$ BeV, while formula (7) is suitable for $E_\gamma \gtrsim 1 - 3$ BeV. In addition, if the spectrum (1) becomes steeper for $E \gtrsim 10^7$ BeV (and this is probable), then our calculations exaggerate the value of $I_\gamma(>E_\gamma)$ for $E_\gamma > 10^5$ BeV. The accuracy of the value -0.2 for the exponent in

(8) is, of course, low. It is important, however, that the exponent is small (even for $E = 10^5$ BeV $= 10^{14}$ eV the factor $E^{-0.2}$ is equal merely to $1/10$).

For metagalactic space the most probable (but far from firmly established) value is $n \approx 10^{-5}$ and $N(L) \approx 5 \times 10^{22}$ (the photometric radius of the universe is $R_{ph} \approx 5 \times 10^{27}$, cf. [1,5,6]). Therefore, assuming that the spectrum of the cosmic rays is the same everywhere and has the form (1), we obtain for $E = 10^5$ BeV [1)]

$$\xi_{Mg} \approx 3 \cdot 10^{-5} E^{0.2} = 3 \cdot 10^{-6}. \quad (9)$$

There are all grounds for assuming[5,6] that the intensity of the cosmic rays in metagalactic space, in the region of relatively low energies ($E \sim 10^9 - 10^{11}$ eV) is considerably lower than in the galaxy. On the other hand, nothing can be said with respect to the higher energies. It is most natural to assume that for $E \sim 10^5$ BeV the situation is still little changed in comparison with that prevailing at lower energies, and then the estimate (9) for the ratio of the metagalactic γ rays to the galactic cosmic rays is still strongly exaggerated. We can conceive, however, of another situation, wherein the spectrum of the metagalactic cosmic rays differs substantially from the galactic one.

This can be best illustrated with an example. Let us assume that the spectrum of the intergalactic cosmic rays has the form $I_{Mg}(E) \approx 10^{-3}E^{-2}$, i.e., at $E = 1$ BeV the intensity is 10^3 times larger than galactic, but $\gamma = 2$ in place of 2.6. Then, the other assumptions remaining the same as before, we have for the metagalaxy

$$I_\gamma(>E_\gamma) \approx 5 \cdot 10^{-30} E_\gamma^{-1} N(L),$$

$$\xi \approx 5 \cdot 10^{-30} N(L) E^{0.6} \sim 3 \cdot 10^{-7} E^{0.6}$$

(here, of course, we took in (8) the galactic value for the intensity I). For $E = 10^5$ BeV we have $\xi_{Mg} \approx 3 \times 10^{-4}$, i.e., two orders of magnitude higher than the estimate (9). Thus, the value $\xi \sim 10^{-3}$ for $E \sim 10^6$ BeV (this is precisely the value for which there are some experimental indications[2,3]) would be compatible with the notion of the metagalactic origin of the γ rays, under the condition that the total energy of the cosmic rays in the metagalaxy is low (see [5,6]), if their spectrum is appreciably harder than galactic [2)]. Actually, however, it is quite difficult to make such an assumption.

In fact, in this example we have $I_{Mg}/I_G \sim 10^{-3}E^{0.6}$. But then $I_{Mg}/I_G \gtrsim 1$ for $E \gtrsim 10^5$ BeV, and this should strongly influence the spectrum of the hard cosmic rays in the galaxy. In other words, under the conditions of sufficiently free exchange of cosmic rays between the galaxy and the metagalaxy (and this is most probable[5]) the principal role would be played in this case on earth, at energies $E > 10^{15}$ BeV, by the cosmic rays of metagalactic origin. Yet at $E > 10^{15}$ BeV the exponent γ in the spectrum of the cosmic rays is not smaller but rather larger than 2.6. Thus, the assumption that $\gamma \approx 2$ in the metagalaxy is possible only if far reaching additional hypotheses are used (one could assume, for example, that the spectrum with $\gamma \approx 2$ is observed only beyond the limits of the local galaxy group or the local supergalaxy, etc.). Such assumptions could be defended only under the pressure of sufficiently convincing facts. By the same token, a check on the preliminary data concerning the existence of hard γ rays[2,3] is particularly essential.

The metagalactic γ and x rays could be distinguished from the galactic ones primarily by the angular distribution. Thus, metagalactic radiation should in first approximation be isotropic. In Appendix I we calculate the values of $N(L)$ for the galaxy, inasmuch as the corresponding expression may prove useful in many cases. Here we present elementary estimates of $N(L)$ for the three main directions and for the halo in the direction of the pole. In the latter case $n \sim 10^{-2}$ and the dimension is $L \sim 3 \times 10^{22}$ cm (the radius of the halo is $R \sim 4 \times 10^{22}$). In the galactic disc $n \sim 1$ and we have in the directions of the center, anticenter, and the pole $L_c \sim 6 \times 10^{22}$, $L_{ac} \sim 1.2 \times 10^{22}$, and $L_p \sim 4 \times 10^{20}$, respectively. Thus

[1)]A similar calculation of the γ-ray flux is given by Maze and Zawadski.[11] We nevertheless present the corresponding formulas because they will be useful later in the calculation of the electron spectrum. When it comes to the numerical estimates, the most important discrepancy with the calculations of [11] is connected with the choice of N(L). Indeed, the value assumed in [11] for metagalactic space is $n \gtrsim 10^{-3}$, which leads to an estimate $N(L) \gtrsim 5 \times 10^{24}$. However, the entire aggregate of available data would hardly allow us to use for the metagalaxy a value appreciably larger than $n \sim 10^{-5}$ (see [5]).

[2)]Estimates show[5] that the summary γ radiation from all galaxies is in all probability much smaller than the γ radiation from the metagalactic medium for $I_{Mg} \sim I_G$, i.e., under the condition that the metagalaxy is filled with cosmic rays with galactic intensity. In addition, there is no indication of the existence of a noticeable flux of hard γ rays even from the most powerful discrete sources.[12] We note further that according to [13] we have $\xi < (1-4) \times 10^{-4}$ for γ quanta with $E \approx 10^{16}$ eV.

$$N_{h,p} \sim 3\cdot 10^{20},\quad N_c \sim 6\cdot 10^{22},\quad N_{ac} \sim 1.2\cdot 10^{22},\quad N_{d,p} \sim 4\cdot 10^{20},$$
$$\xi_c \sim 4\cdot 10^{-6},\quad \xi_{ac} = 7\cdot 10^{-7},\quad \xi_p \sim 4\cdot 10^{-8},\quad (10)$$

where we put in the estimate of ξ in (8) $E = 10^5$ BeV and where the value of ξ_p is obtained with account of the contributions from both the disc and the halo (we put $N_p = N_{d,p} + N_{h,p}$). For the galaxy as a whole (averaging over all angles) we have $\xi_h \sim 10^{-7}$.

Taking into account their unavoidably approximate nature, connected with the inaccurate knowledge of the concentration n, all these estimates agree with those given in Appendix I. It is clear from (10) that even in the direction of the center we cannot expect a value $\xi \sim 10^{-3}$. The latter value is larger than the average estimate for the galaxy by four orders of magnitude, and we see no real possibility of eliminating this gap by varying one parameter or another. Thus, observation of the flux of hard γ rays with an isotropic distribution and with $\xi > 10^{-4} - 10^{-5}$ would be quite difficult to explain.

In addition to what has already been said, we note that the appearance of hard γ rays can likewise not be related, in all probability, with the production of π^0 mesons in collisions between very hard cosmic rays and thermal photons[14]. It is obvious that in this case $I_\gamma \sim \sigma N_{ph}(L) I$, where σ is the corresponding cross section for π^0-meson production, N_{ph} is the number of photons along the line of sight, and I is the intensity of the cosmic rays (since the energy of the thermal photons is $\epsilon \sim 1$ eV, the π^0 mesons are produced only by nucleons with energy $E \gtrsim 10^{17}$ eV). In accordance with[14] we shall assume that $\sigma \sim 5 \times 10^{-28}$ cm^2 (allowing for the production of several π^0 mesons). Further, the concentration of the electrons is $n_{ph} \sim 1$ in the halo and $n_{ph} \sim 10^{-3}$ in the metagalaxy (see [5,6]; in [14] it is assumed that $n_{ph} \sim 0.3$ in the metagalaxy, for which there are no grounds). From this we get $N_{ph} \sim 3 \times 10^{22}$ for the halo (in the pole direction) and $N_{ph} \sim 5 \times 10^{24}$ for the metagalaxy, and accordingly $\xi_G = I_\gamma/I \sim 10^{-5}$ and $\xi_{Mg} \sim 2 \times 10^{-3}$. Here, however, the intensity of the cosmic rays pertains to particles with energy $E > 10^{17}$ eV, which produce γ rays with energy on the order of $10^{15} - 10^{16}$ eV. On the other hand, if we define the ratio $\xi = I_\gamma(>E)/I(>E)$ as above, then the values of ξ decrease by several orders of magnitude (in this region of the spectrum $I(>E) \sim E^{-2}$ and consequently the transition from 10^{17} to 10^{16} eV corresponds to a change in E by a factor of 10^2).

We note, incidentally, that when $n_{ph} \sim 10^{-3}$ ($w_{ph} = \epsilon n_{ph} \sim 10^{-3}$ eV/cm^3) the absorption of hard γ rays in the metagalactic space (brought about by production of electron-positron pairs on thermal photons)[15] can usually be neglected (the maximum value of the absorption coefficient corresponding to γ rays with $E \sim 10^{12}$ eV amounts to $\mu_{max} \approx 7 \times 10^{-26} w_{ph}$, where w_{ph} is in eV/cm^3 and μ is in cm^{-1}; if $w_{ph} = 10^{-3}$ then $\mu L \sim 0.35$ even on a path $L = 5 \times 10^{27}$ cm).

2. INTENSITY OF CYCLOTRON X RAYS FROM THE SECONDARY ELECTRONS

Let us estimate now the number of electrons produced as a result of the decay of charged pions, and let us determine the intensity of the cyclotron radiation of these electrons in interstellar magnetic fields.

An analysis of the kinematics of the decays $\pi^\pm \to \mu^\pm + \nu$ and $\mu^\pm \to e^\pm + \nu + \bar{\nu}$ leads to the following expression for the intensity of the sources of such electrons (see Appendix II):

$$q_e(E)\,dE = \sigma n(\mathbf{r})\,\varkappa(\gamma)\,K_{\pi^\pm}E^{-\gamma}dE. \qquad (11)$$

Here $K_{\pi^\pm}$ is the coefficient in the differential energy spectrum of production of charged pions, γ is the exponent of this spectrum, and the coefficient $\kappa(\gamma)$ is determined by the relation

$$\varkappa(\gamma) = \left(\frac{m_\mu}{m_\pi}\right)^{\gamma-1}\frac{2(\gamma+5)}{\gamma(\gamma+2)(\gamma+3)},\quad \varkappa(2.8) \approx 0.13, \qquad (12)$$

where m_μ and m_π are the muon and pion masses.

For the charged pion production spectrum obtained above [see (5)] we obtain at $\sigma = 4 \times 10^{-26}$ cm^2

$$q_e(E) = n(\mathbf{r})\,3.6\cdot 10^{-28}E^{-2.8}\ \text{electrons/cm}^3\ \text{sec-sr-BeV} \qquad (13)$$

The energy of the electrons that have a maximum cyclotron radiation intensity at a frequency ν is determined by the expression

$$E \approx 4.7\cdot 10^2\,(\nu/H_\perp)^{1/2}\ \text{eV}. \qquad (14)$$

Here $H_\perp$ is the magnetic field component perpendicular to the direction of motion of the particle (measured in Oersteds). The frequency ν is measured in cps. For $\nu = 10^{18}$ ($\lambda = 3$ Å) and for an average $H_\perp \sim 5 \times 10^{-6}$ Oe the electrons, according to (14), should have an energy $E \approx 2 \times 10^{14}$ eV. The electrons of interest to us, with energy $E > 10^{14}$ eV, experience in practice, on moving in the interstellar or intergalactic medium, only cyclotron radiation losses. These losses are equal to (for $E \gg mc^2$)

$$-\left(\frac{dE}{dt}\right)_M = \beta E^2 = \frac{2c}{3}\left(\frac{e^2}{mc^2}\right)^2 H_\perp^2 \left(\frac{E}{mc^2}\right)^2$$
$$= 0.98\cdot 10^{-3} H_\perp^2 \left(\frac{E}{mc^2}\right)^2 \text{eV/sec} \quad (15)$$

If the electron energy is E_0 at the instant $t = 0$, then $E(t) = E_0(1 + 3.8 \times 10^{-15} H_\perp^2 E_0 t)^{-1}$, where E is in eV and t is in seconds. For $E_0 \sim 10^{14}$ eV the energy of the electron in a field $H_\perp \sim 3 \times 10^{-6}$ decreases by one-half in a time $t_{1/2} \sim 2.5 \times 10^{11}$ sec $\sim 10^4$ yr. During this time, moving along the force line with a velocity $v_{||} \sim 10^{10}$, the electron traverses a path $L \sim 3 \times 10^{21}$ cm. In the case of the galaxy the magnetic field is in all probability tangled and curved, and the characteristic dimension of the region with quasi-homogeneous field is $l \lesssim 100$ parsec $\approx 3 \times 10^{20}$ cm. In similar conditions the displacement of the electron (from the place where it is produced) in a time $t_{1/2}$ is of the order of $L \sim \sqrt{l v t_{1/2}} \lesssim 10^{21}$ cm. Such a distance is still small compared with the radius of the halo, $R \sim (3 - 5) \times 10^{22}$ cm. We can therefore assume in first approximation that in a time $t \sim t_{1/2}$ the electrons with energy $E \gtrsim 10^{14}$ eV remain in the region in which they are produced. In other words, unlike the problem of the cyclotron galactic radio emission of relatively soft electrons ($E \sim 10^9$ eV) [5,16], the diffusion of hard electrons, which is considered here, can be neglected.

As regards the statement made above that the losses of non-cyclotron nature can be neglected, it is clear from the following expression for the bremsstrahlung and Compton losses [5]

$$-E^{-1}(dE/dt)_{br} = 8\cdot 10^{-16} n \text{ sec}^{-1} \quad (16)$$

$$-\left(\frac{dE}{dt}\right)_C \sim c\pi\left(\frac{e^2}{mc^2}\right)^2 n_{ph} \frac{(mc^2)^2}{\varepsilon} \ln\frac{2\varepsilon E}{(mc^2)^2}$$
$$\sim 10^{-14}\left(\frac{mc^2}{\varepsilon}\right)^2 w_{ph} \ln\frac{2\varepsilon E}{(mc^2)^2} \text{ eV/sec} \quad (17)$$

where n is the concentration of the gas (in practice, hydrogen) and w_{ph} is the energy density of the thermal photons having an energy ϵ, expressed in eV. Formula (17) for the Compton losses pertains to the case when the electron energy is $E \gg (mc^2)^2/\epsilon \sim 3 \times 10^{11}$ eV (with $\epsilon \sim 1$ eV, corresponding to cosmic conditions). We note that the losses connected with the production of electron-positron pairs by fast electrons on thermal photons is another one-and-one-half orders of magnitude smaller than (17). When $E \sim 10^{14}$, $H_\perp \sim 3 \times 10^{-6}$, $n \sim 1$, and $w_{ph} \sim 1$ the losses, according to (15) – (17), are $-(dE/dt)_{cyc} \sim 4 \times 10^2$ eV/sec, $-(dE/dt)_{br} \sim 0.1$ eV/sec, and $-(dE/dt)_C \sim 10^{-2}$ eV/sec, which confirms the statements made above.

Under the assumption that the change in the electron energy is determined only by the cyclotron radiation losses and that the spatial diffusion is immaterial, the energy spectrum of the electrons can be obtained from the relations

$$-\frac{\partial}{\partial E}\{\beta E^2 N(E)\} = 4\pi q_e(E), \qquad N(E) = \frac{4\pi}{\beta E^2}\int_E^\infty q_e(E')\,dE'. \quad (18)$$

Here $\beta = 3.9 \times 10^{-15} H_\perp^2$ (eV-sec)$^{-1}$ is the coefficient in expression (15) for the cyclotron radiation losses. Using the source spectrum (13) and putting $H_\perp \approx 5 \times 10^{-6}$ Oe we get

$$N(E) = n(\mathbf{r})\cdot 2.5\cdot 10^{-11} E^{-3.8} \text{cm}^{-3}\cdot\text{BeV}^{-1}$$
$$= n(\mathbf{r})\cdot 3.7\cdot 10^{-19} E^{-3.8} \text{ cm}^{-3} \text{ erg}^{-1} \quad (19)$$

To determine the spectral intensity of the cyclotron radiation of these electrons we use the well known relation (see [6])

$$I(\nu) = 1.35\cdot 10^{-22} a(\gamma_e) K_L H^{(\gamma_e+1)/2}(6.26\cdot 10^{18}/\nu)^{(\gamma_e-1)/2}$$
$$\text{erg/cm}^2\text{ sec-sr-cps} \quad (20)$$

where γ_e is the exponent of the differential electron spectrum [in our case $\gamma_e = 3.8$; see (19)], $a(3.8) = 0.073$, and K_L is the coefficient in the spectrum of the electrons along the line of sight. For the spectrum (19) this coefficient is equal to

$$K_L = 3.7\cdot 10^{-19}\int n(\mathbf{r})\,dL = 3.7\cdot 10^{-19} N(L),$$

where the integration is along the line of sight in some direction of interest to us.

Substituting the corresponding values in formula (20) and putting $H \approx (3/2\overline{H_\perp^2})^{1/2} \approx 6 \times 10^{-6}$, we get

$$I(\nu) = N(L)\cdot 2.2\cdot 10^{-28}\nu^{-1.4} \text{ erg/cm}^2\text{ sec-sr-cps}$$

$$I(>\nu) = \int_\nu^\infty I(\nu)\,d\nu$$
$$= N(L)\cdot 5.5\cdot 10^{-28}\nu^{-0.4} \text{ erg/cm}^2\text{ sec-sr} \quad (21)$$

which is equivalent to the intensity of the x-ray quanta ($E_r = h\nu$ is measured in keV)

$$J(>E_r) = \int_{E_r/h}^\infty \frac{I(\nu)\,d\nu}{h\nu}$$
$$\approx 1.1\cdot 10^{-26} N(L) E_r^{-1.4} \text{ quantum/cm}^2\text{ sec-sr} \quad (22)$$

Formula (20) is suitable for a power-law electron spectrum without limitation on the frequency region, while formulas (21) and (22) are based on the use of the specific spectra (13) and (19), which pertain only to electrons with energies $E > 1 - 5$ BeV.

Thus, the expected intensity of the x-ray cyclotron radiation with wavelengths $\lambda \le 8$ Å ($\nu \ge 4 \times 10^{17}$ sec^{-1}, $E_r \ge 1.7$ keV) amounts to

$$I(\nu > 4\cdot 10^{17}) \approx N(L)\cdot 5.0\cdot 10^{-35}\ \text{erg/cm}^2\ \text{sec-sr}$$

$$J(E_r > 1.7\ \text{keV}) \approx N(L)\cdot 5.2\cdot 10^{-27}\ \text{quantum/cm}^2\ \text{sec-sr} \quad (23)$$

Using the values of (10) for the quantity N(L) of gas along the line of sight in different galactic directions, we can readily obtain the following estimates for the expected intensity of x-ray emission with wavelength $\lambda < 8$ Å (in units of quantum/cm^2 sec-sr)

$$J_c \approx 3\cdot 10^{-4},\quad J_{ac} \approx 6\cdot 10^{-5},\quad J_p \approx 4\cdot 10^{-6},\quad J_G \approx 10^{-5}. \quad (24)$$

For the direction to the galactic pole we take into account here the fact that the disc and the galactic halo give approximately the same contribution, if the gas masses contained in them are the same.

For the metagalaxy, under the condition that the intensity of the cosmic rays and the magnetic field intensity are the same everywhere and are equal to the galactic values, the expected intensity of the x-ray quanta is

$$I_{Mg} \approx 2.6\cdot 10^{-4}\ \text{quantum/cm}^2\ \text{sec-sr}. \quad (25)$$

However, the assumption that such conditions exist in the metagalaxy, particularly with respect to the field, is quite unlikely[5,6].

We note that the absorption of x rays with $\lambda < 8$ Å in the interstellar medium is relatively small[17]. Thus, for $\lambda \approx 3$ Å the optical thickness is $\tau \approx 7 \times 10^{-24} N(L)$, i.e., we have $\tau \approx 0.4$ even for $N(L) = 5 \times 10^{22}$. For $\lambda = 8$ Å the absorption is approximately five times larger, and is thus already noticeable for the metagalaxy or in the direction of the galactic center. However, even in the direction of the anticenter, let alone the pole, $N(L) \sim 1.2 \times 10^{22}$ and $\tau(\lambda = 8\ \text{Å}) \approx 3.3 \times 10^{-23} N(L) \sim 0.4$. Giacconi et al[4] measured the flux of x rays in the wavelength interval 2 – 8 Å and used 3 Å as the average wavelength. On going over from $\lambda = 8$ Å to $\lambda = 3$ Å the values of (24) and (25) decrease by a factor of 4. Inasmuch as the x-ray flux observed in [4] was $J \sim 2$ quantum/cm^2 sec-sr, it is perfectly clear that this flux can in all probability not be attributed to the cyclotron radiation mechanism[7] (provided, of course, the interstellar space does not contain a sufficient number of primary high-energy electrons; such electrons could come, for example, from supernova shells[5]).

APPENDIX I

CALCULATIONS OF THE FUNCTION N(L) FOR THE GALAXY MODEL

We shall assume that the distribution of the gas in the galaxy has the symmetry of an ellipsoid of revolution, with

$$n(r)\,dV = \frac{N_t}{\pi^{3/2}a^2c}\exp\left\{-\frac{(x-x_\odot)^2+y^2}{a^2}-\frac{z^2}{c^2}\right\}dx\,dy\,dz$$
$$= \frac{N_t}{\pi^{3/2}a^2c}\exp\{-(r^2\cos^2 b - 2rq\cos b\cos l + q^2 + \varepsilon r^2\sin^2 b)\}\,dV. \quad (A.1.1)$$

Here N_t is the total number of nucleons in the system, l and b are the galactic longitude and lattitude, $\epsilon = a^2/c^2$, and $q = x_\odot/a$, the distance from the sun to the galactic center; r and q are measured in units of a (a is the dimension of the major semiaxis).

The number of particles along the line of sight is

$$N(l,b) = \int_0^\infty n(r)\,dL = \frac{M}{2\pi ac}(\cos^2 b + \varepsilon\sin^2 b)^{-1/2}$$
$$\times \exp\left\{-q^2\frac{\cos^2 b\sin^2 l + \varepsilon\sin^2 b}{\cos^2 b + \varepsilon\sin^2 b}\right\}\frac{2}{\sqrt{\pi}}\int_{\xi_0}^\infty e^{-\xi^2}d\xi;$$
$$\xi_0 = -q(\cos^2 b + \varepsilon\sin^2 b)^{-1/2}\cos b\cos l. \quad (A.1.2)$$

For the galactic pole ($b = \pm\pi/2$) we have

$$N_p = \frac{N_t}{2\pi a^2}\exp\{-q^2\}. \quad (A.1.3)$$

In the galactic plane ($b = 0$) we have

$$N(l) = \frac{N_t}{2\pi ac}\exp\{-q^2\sin^2 l\}\left(1 + \frac{2}{\sqrt{\pi}}\int_0^{q\cos l} e^{-\xi^2}d\xi\right). \quad (A.1.4)$$

For the center ($l = 0$, $b = 0$) and the anticenter ($l = \pi$, $b = 0$) we have

$$N_c = \frac{N_t}{2\pi ac}\left\{1 + \frac{2}{\sqrt{\pi}}\int_0^q e^{-\xi^2}d\xi\right\},$$
$$N_{ac} = \frac{N_t}{2\pi ac}\left\{1 - \frac{2}{\sqrt{\pi}}\int_0^q e^{-\xi^2}d\xi\right\}. \quad (A.1.5)$$

For the disc we put $N_t = M/1.67 \times 10^{-24} \approx 1.7 \times 10^{66}$ (the mass of gas in the disc is $M = 2.8 \times 10^{42}$), $a = 12$ kiloparsec $\approx 3.7 \times 10^{22}$ cm, $c = 130$ parsec $= 4 \times 10^{20}$ cm, and $q = 0.67$ (the distance from the sun to the galactic center is $x_\odot \approx 8$ kiloparsec). In the case of the halo we put $N_t = 1.7 \times 10^{66}$ and $a = c = 3.7 \times 10^{22}$.

We then arrive at

$$N_{h,p} = 1.3 \cdot 10^{20}, \quad N_c = 3 \cdot 10^{22}, \quad N_{ac} = 6.4 \cdot 10^{21}, \quad N_{p,d} = 1.3 \cdot 10^{22}. \tag{A.1.6}$$

These values are approximately half the values of (10). The reason for this difference lies simply in the fact that we put in (10) n ~ 1, whereas the value assumed above for the mass M corresponds more likely to a concentration n ~ 0.5. We also calculate the value averaged over all angles

$$\overline{N} = \frac{1}{4\pi}\int N(l, b)\, d\Omega = \frac{1}{4\pi}\int_0^{2\pi} dl \int_{-\pi/2}^{+\pi/2} N(l, b) \cos b\, db, \tag{A.1.7}$$

in the case of spherical symmetry (for a = c)

$$\overline{N} = \frac{N_t}{2\pi a^2} e^{-q^2} \left\{1 + \frac{q^2}{3} + \frac{q^4}{10} + \ldots\right\}, \tag{A.1.8}$$

which gives with the values chosen for the halo

$$\overline{N}_h = 1.5 \cdot 10^{20}. \tag{A.1.9}$$

When a ≫ c we have for q < 1

$$\overline{N} = \frac{N_t}{2\pi a^2} e^{-q^2} \left\{\ln 2\frac{a}{c} + \frac{q^2}{2}\left(1 - \frac{c^2}{a^2}\ln 2\frac{a}{c}\right) + \ldots\right\}. \tag{A.1.10}$$

Hence

$$N_d \approx 6.8 \cdot 10^{20}. \tag{A.1.11}$$

APPENDIX II

KINEMATICS OF THE $\pi \to \mu \to e$ DECAY

The probability of the appearance of an electron with energy $y = E^*/mc^2$ in the $\mu^\pm \to e^\pm + \nu + \overline{\nu}$ decay of a muon at rest is determined by the expression

$$w(y)\, dy = 12y\sqrt{y^2 - 1}\, y_m^{-4} \left\{(y_m - y) + \frac{2}{9}\rho\,(4y - 3y_m)\right\}, \tag{A.2.1}$$

where $y_m \approx m_\mu/2m \approx 105$ is the maximum energy of the decay electron, and the experimental values of the Michel parameter ρ are close to $\rho = 3/4$.

In the decay of a meson with energy $z = E_\mu/m_\mu c^2$ the energy $x = E/mc^2$ of an electron emitted in the muon rest mass at an angle θ^* with energy y, is equal to

$$x = yz + \sqrt{y^2 - 1}\sqrt{z^2 - 1} \cos\theta^*. \tag{A.2.2}$$

A distribution isotropic in the angles θ^* corresponds to an energy distribution

$$f(x, y, z)\, dx = dx/2\sqrt{z^2 - 1}\sqrt{y^2 - 1} \tag{A.2.3}$$

in the interval

$$|x - yz| \leqslant \sqrt{y^2 - 1}\sqrt{z^2 - 1}. \tag{A.2.4}$$

Therefore the energy spectrum of the muons $I_\mu(z)$ corresponds to a decay-electron energy spectrum

$$I_e(x)\, dx = dx \iint \frac{W(y)\, I_\mu(z)\, dy\, dz}{2\sqrt{z^2 - 1}\sqrt{y^2 - 1}}, \tag{A.2.5}$$

where the integration is over the region of the variables y and z satisfying the condition (A.2.4) and the condition $y \leq y_m$.

In the $\pi^\pm \to \mu^\pm + \nu$ decay the muon kinetic energy is low ($E^*_{k,\mu} \approx 4$ MeV) and the difference between its velocity and that of the decaying high-energy pion can be neglected, putting $E_\pi/m_\pi c^2 \approx E_\mu/m_\mu c^2 = z$ and $I_{\pi^\pm}(z)\, dz = I_\mu(z)\, dz$. In the case of a power-law pion spectrum $I_{\pi^\pm}(E) = K_{\pi^\pm}E^{-\gamma}$ (i.e., $I_{\pi^\pm}(z) = (m_\pi c^2)^{1-\gamma}K_{\pi^\pm}z^{-\gamma}$), the integration in (A.2.5) under the condition $x \gg y_m$ leads to the following expression for the decay electron spectrum (accurate to terms of order $1/y_m^2$):

$$I_e(E)\, dE = K_e E^{-\gamma}\, dE, \tag{A.2.6}$$

$$K_e = \left(\frac{m_\mu}{m_\pi}\right)^{\gamma-1} \frac{12\,(1 + {}^2/_9\,\rho\,(\gamma - 1))}{\gamma(\gamma + 2)(\gamma + 3)} K_{\pi^\pm}. \tag{A.2.7}$$

When $\rho = 3/4$ we get expression (12) of the text.

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