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YEREVAN PHYSICS INSTITUTE

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ON THE TRANSPARENCY OF THE METAGALAXY TO ULTRAHIGH-ENERGY GAMMA RAYS

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ՄԵԹԱԳԱԼԱԿՏԻԿԱՅԻ ԹԱՓԱՆՑԻԿՈՒԹՅՈՒՆԸ ԳԵՐԲԱՐՁՐ ԷՆԵՐԳԻԱՆԵՐԻ ՍԱՀՄԱՆԱՅԻՆ ԳԱՄՄԱ-ՔՎԱՆՏՆԵՐԻ ՀԱՄԱՐ

Ուսումնասիրված է էլեկտրոն-ֆոտոնային հեղեղների առաջացումը մնացուկային ճառագայթման դաշտում: Ստացված է գերբարձր էներգիաների սահմանային գամմա-քվանտների բացարձակ հոսք ($E \gtrsim 5.10^{19}$ էՎ) կազմավորված ֆոտոծնման π^- մեզոնների տրոհման հետևանքով, միկրոալիքների մնացուկային ճառագայթման դաշտում:

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F.A. AHARONIAN, V.V. VARDANIAN

ON THE TRANSPARENCY OF THE METAGALAXY TO ULTRAHIGH-ENERGY GAMMA RAYS

The electron-photon shower production in the field of the microwave background radiation (MBR) is considered. The absolute flux of ultrahigh-energy cascade gamma-rays ($E \geqslant 5\cdot 10^{19}$ eV), resulting from the π-meson photoproduction in the field of the MBR is obtained.

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Yerevan 1987

Препринт ЕФИ-984(34)-87

Ф.А.АГАРОНЯН, В.В.ВАРДАНЯН

К ВОПРОСУ О ПРОЗРАЧНОСТИ МЕТАГАЛАКТИКИ ДЛЯ КАСКАДНЫХ ГАММА-КВАНТОВ СВЕРХВЫСОКИХ ЭНЕРГИЙ

Рассмотрено явление формирования электронно-фотонных ливней в поле реликтового излучения. Получен абсолютный поток каскадных гамма-квантов сверхвысоких энергий ($E \geq 5 \cdot 10^{19}$ эВ), формируемый в результате фоторождения и распада π -мезонов в поле реликтового микроволнового излучения.

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Ереван 1987

1. Introduction

The discovery of the microwave background radiation (MBR) [1] gave a start to the investigation of electromagnetic cascades initiated in the MBR field. Hayakawa first paid attention to possible cascade processes in the field of the MBR [2] . Really, the mean free path λ of $\gtrsim 10^{15}$ eV electrons and gamma-rays in the field of the MBR is essentially less than the scale of the Metagalaxy ($\lambda \gtrsim 10^{22}$ cm). As a result of inverse Compton scattering and electron-positron pair production, the ultrahigh-energy electrons and gamma-rays at a distance $\sim \lambda$ produce secondary electrons (positrons) and gamma-rays which in their turn produce new "generations" of electrons and gamma-rays, etc. Thus, in the radiation field there is developed an electromagnetic cascade supported by the processes of pair production and Compton scattering in the MBR. The transparency of the Metagalaxy due to e^+e^- pair production of gamma-rays in the field of the MBR is discussed in refs.[3,4] , but the regeneration of secondary photons has not been taken into account there. In reality, one of the electrons produced in $\gamma - \gamma$ interaction, remaining a relativistic one, scatters on a MBR and again forms a high-energy gamma-ray. Thus, these two successive interactions lead to some decrease of the gamma-ray initial energy, but not to disappearance of the photon. Then the gamma-ray will again produce an electron-positron pair, etc. According to the problem on the transparency of intergalactic space, it was mentioned in ref.[5] that as a result of development of an electromagnetic cascade in the field of MBR the space transparency to $\sim 10^{19}$ eV photons becomes by more than an order of magnitude higher.

In refs.[6,7] the gamma-radiation intensities were evaluated in a wide range of energies, analyzing the energy losses at the transformation of the gamma-rays into e^+e^- pairs and vice versa. But these estimates do not consider the kinetics of electrons and high-energy gamma-rays propagation in the field of electromagnetic radiation. The spectra of cascade gamma-rays formed in the field of MBR, with regard to the high-energy particles propagation have been first calculated in refs.[8,9]. Simplifications used in these works give the gamma-ray spectra only on the qualitative level and do not allow one to judge about the quantitative characteristics of the cascade gamma-rays reaching the Earth. At the same time, the experimental data on the ultrahigh-energy cosmic-ray detection (in particular, after the operation of the "Fly's Eye" [10]) become more reliable. Under these conditions the question about the cascade gamma-ray contribution into the cosmic-ray flux of ultrahigh energies, particularly into the energy region of $\geqslant 10^{19}$ eV, demands already a quantitative answer.

The gamma-ray spectrum formed due to the development of an electromagnetic cascade in the field of the MBR is calculated in this paper. The cascade is initiated by high-energy gamma-rays and electrons formed at the π -meson photoproduction in the field of the MBR. The cascade gamma-ray spectra are obtained as a result of solution of kinetic equations for electrons and gamma-rays [11] and also for protons propagating in the field of the MBR.

2. Kinetic Equations for Distribution Functions of Electrons and Gamma-Rays

Let us consider a relativistic particle (an electron or a gamma-ray) propagating in a homogeneous photon field comprised of isotropically distributed photons of mean energies ω and density n_ω . Suppose, that in the considered region the external field is negligible. Denote the distribution functions of electrons (including positrons) and gamma-rays by $\mathcal{E}(x^\mu, p^\mu)$ and $\Gamma(x^\mu, k^\mu)$, respectively. Here $x^\mu (\mu = 0 \div 3)$ is the four-dimensional coordinate and p^μ and k^μ are the four-dimensional momenta of electrons and gamma-rays, respectively. Kinetic equations for the distribution functions $\mathcal{E}(x^\mu, p^\mu)$ and $\Gamma(x^\mu, k^\mu)$ have the following form [12] :

$$
\begin{aligned}
p^\mu \partial_\mu \mathcal{E}(x^\mu, p^\mu) &= - C_1(e\omega \to e'\gamma) + C_1'(e'\omega \to e\gamma) + 2C_2(\gamma\omega \to 2e) \\
k^\mu \partial_\mu \Gamma(x^\mu, k^\mu) &= - C_3(\gamma\omega \to 2e) + C_4(e\omega \to e'\gamma)
\end{aligned}
\tag{1}
$$

The collision term for the process + 2 → 3 + 4, where the state 1 is fixed, is represented as:

$$
C(12 \to 34) = \int_2 \int_3 \int_4 \Pi_2 \Pi_3 \Pi_4 F_1(x^\mu, p_1^\mu) F_2(x^\mu, p_2^\mu) W(12 \to 34) \delta^{(4)}(p_f - p_i) \tag{2}
$$

Here $F_1(x^\mu, p_1^\mu)$, $F_2(x^\mu, p_2^\mu)$ are the distribution functions of colliding particles, $\Pi = d^3p/2E$ is the covariant element in the momentum space, $W = \sum_{pol} |M_{fi}|^2$ is the square of the matrix element summed over the polarization states, p_i^μ and p_f^μ are the initial and the final values of the four--momentum.

The set of kinetic equations (1) reflects the fact that there are three reasons for the change in the number of electrons in the phase-space unit volume $d^3p\,dV$. The first two are connected with the inverse Compton scattering of a relativistic electron on the photons, and the third one is connected with the photoproduction of an electron-positron pair. The change in the number of photons in the phase-space unit volume $d^3k\,dV$ is connected, first, with the knoking -on the high -energy photons out of $d^3k\,dV$ due to e^+e^- photoproduction and, second, with the appearance of high-energy photons in the phase-space element due to the inverse Compton scattering of relativistic electrons on the field photons. Ignoring the angles of deflection of the electron-photon-shower particles from the axis z of their propagation, which is valid for $\omega \ll m_e c^2$ and $E \gg m_e c^2$ *, the set of equations (1) is reduced to a set of integro-differential equations, which was obtained in our previous work [11]. However, it is impossible to solve this set analytically. The approximation $4E\omega/m_e^2 \gg 1$ used in this work allows one to simplify the

---

*From here on we shall consider C = 1 for simplicity.

set of equations and obtain its solution in logarithmic approximation. In this case the set is reduced to

$$\begin{aligned} b\frac{\partial \mathcal{E}(b,t)}{\partial t} + \mathcal{E}(b,t)\cdot \ln b &= 2\int_0^{1-1/b} \Gamma(b/x,t)\frac{dx}{1-x} \\ b\frac{\partial \Gamma(b,t)}{\partial t} + 2\Gamma(b,t)\ln b &= \int_0^{1-1/b} \mathcal{E}(b/x,t)\frac{dx}{1-x} \end{aligned} \qquad (3)$$

Here $\mathcal{E}(b,t)\,db\,dt$ and $\Gamma(b,t)\,db\,dt$ are the mean number of electrons and gamma-rays in the unit intervals of the variables $b \equiv 4E\omega/m_e^2$ and $t \equiv 4\pi r_0^2 n_\omega Z$, E is the energy of the particle (the electron or the gamma-ray).

Let us use Mellin's integral transformation over b to solve the set (3). Then we shall finally obtain the following set of equations for the kinetic ones in the S-space:

$$\begin{aligned} &\frac{\partial \mathcal{E}(s+1,t)}{\partial t} + \frac{\partial \mathcal{E}(s,t)}{\partial t} - 2\frac{\partial \Gamma(s,t)}{\partial t} + 2\mathcal{Y}(s)\Gamma(s,t) = 0 \\ &\frac{\partial \Gamma(s+1,t)}{\partial t} - \frac{\partial \mathcal{E}(s,t)}{\partial t} + 2\frac{\partial \Gamma(s,t)}{\partial t} + \mathcal{Y}(s)\,\mathcal{E}(s,t) = 0 \end{aligned} \qquad (4)$$

Here $\mathcal{Y}(S) = \psi(S+2) + C_E$ where C_E is Euler's constant, $\psi(S)$ is the logarithmic derivative of the gamma function $\Gamma(S)$. Since in the present work we are interested in the equilibrium spectra of particles, i.e. spectra independent of coordinates, then the eq.(4) must be integrated over t. Assuming a gamma-ray with $b = b_0$ as an initiating one, and also adding up and subtracting the equations from the set (4) and denoting $(\mathcal{E}(S,t) \equiv \mathcal{E}(S),\ \Gamma(s,t) \equiv \Gamma(S))$ $\quad K(S) = 2\Gamma(S) + \mathcal{E}(S)$

and $R(S)=2\Gamma(S)-\mathcal{E}(S)$, we obtain

$$K(S)=b_0^{S+1}/\mathcal{J}(S)$$
$$\frac{dR(S)}{ds}-\mathcal{J}(S)R(S)/2=b_0^{S+1}/2 \tag{5}$$

Making in the second equation of the set (5) the substitution $R(S)=b_0^{S+1}\Gamma(S)$, we obtain

$$\frac{d\Gamma}{ds}+a(S)\cdot\Gamma(S)=0.5,$$
$$a(S)=\ln b_0-0.5\,\mathcal{J}(S) \tag{6}$$

The solution of the eq.(6) is

$$\Gamma(S)=\exp\left\{-\int_\infty^S a(s')ds'\right\}\left(C+0.5\int_\infty^S \exp\left\{a(s'')ds''\right\}ds'\right) \tag{7}$$

To choose the integration constant, note that at $S\to\infty$ and $b<b_0$

$$\Gamma(S)=R(S)/b_0^{S+1}=\int_0^\infty (b/b_0)^S d(b/b_0)\int_0^\infty R(b,t)dt\to 0$$

Consequently, $C=0$ and

$$\Gamma(S)=0.5\exp\left\{-\int_\infty^S a(s')ds'\right\}\int_\infty^S \exp\left\{\int_\infty^{S'} a(s'')ds''\right\}ds' \tag{8}$$

Now, returning to the functions $\mathcal{E}(S)$ and $\Gamma(S)$ we have

$$\mathcal{E}(S)=\frac{K(S)-R(S)}{2} \quad\text{and}\quad \Gamma(S)=\frac{K(S)+R(S)}{4} \tag{9}$$

To come back to the variable b, it is necessary to apply Mellin's inverse transformation to the expressions (9). First calculate the value

$$R(b)=\frac{1}{2\pi i}\int_{\delta-i\infty}^{\delta+i\infty} b^{-(S+1)}R(S)ds$$

Closing the integration contour on the right by a semicircle of infinitely large radius and expanding the integrand in the vicinity of an infinitely remote point, we obtain

$$R(b)=\frac{1}{4\pi i}\oint \frac{e^{(1/z)\ln b_o/b}}{z^3}\,dz = 0 \ , \quad b<b_o \qquad (10)$$

Now calculate the value of

$$K(b)=\frac{1}{2\pi i}\int_{\delta-i\infty}^{\delta+i\infty} b^{-(s+1)}K(s)\,ds$$

As the value $\mathcal{Y}'(s)$ never becomes zero, then all the zeroes of the function $\mathcal{Y}(s)$ are to be of the first order. Then, using (5) for $K(b)$ we obtain

$$K(b)=\sum_{k=0}^{\infty}\frac{(b/b_o)^{-(s_k+1)}}{\psi'(s_k+2)} \ ; \quad \psi(s_k+2)+C_E=0 \qquad (11)$$

The expression (11) may be represented as a series

$$K(b)=\frac{6}{\pi^2}+\sum_{k=1}^{\infty}\frac{X^{k+1-\Delta_k}}{\pi^2+[\psi(k-\Delta_k)+C_E+(k-\Delta_k)^{-1}]^2+\psi'(k-\Delta_k)-(k-\Delta_k)^{-2}} \qquad (12)$$

where

$$\Delta_k=\frac{1}{\pi}\operatorname{arcctg}\left\{[\psi(k)+C_E+1/k]/\pi\right\},$$

$$x=b/b_o$$

At $x\ll 1$ the function $K(b)\to 6/\pi^2$, but at $x\to 1$

$$K(b)\to\int_0^{\infty}\frac{\ln^{\tau-1}(1/x)}{e^{C_E\tau}\,\tilde{\Gamma}(\tau)}\,d\tau$$

Using (9), we have the following final expression for the spectra of electrons and gamma-rays:

$$\mathcal{E}(b) = 2\Gamma(b) = K(b)/2 \ , \ b < b_o \qquad (13)$$

The spectra (13) as functions of X are shown in fig.1 . The obtained solutions are valid at $b < b_o$; at $b = b_o$ the electron spectrum $\mathcal{E}(b) = 0$, while the gamma-ray spectrum diverges slightly, which, however, does not lead to divergency of the total number of gamma-rays. It should be noted that the resulting equilibrium spectra of cascade particles should be cut off at $X = 1 - 1/b_o$ due to the fact, that the electron formed at photon-photon collisions has maximum values of the variable b_e $(b_e/b_o)_{max} = 1 - 1/b_o$. Such an electron, in its turn may produce a gamma-ray with $(b_\gamma /b_o)_{max} = 1 - 1/b_o$. Hence, continuous spectra of electrons and gamma-rays are formed when $X < 1 - 1/b_o$. When solving the set (3) we did not take this restriction into account. Also note, that the spectra obtained are valid in the framework of logarithmic approximation, i.e. $\ln b \gg 1$. Thus, for the region where the solutions of (13) are valid we have

$$40/b_o \lesssim X \lesssim 1 - 1/b_o \qquad (14)$$

It is easy to show that the obtained results remain unchanged if the electron is again chosen as initiating particle. Also note, that the expression for the equilibrium spectrum is obtained under the assumption of monoenergetic spectrum of the field photons. However, if the background radiation spectrum is narrow, e.g. a Planckian one, then for the field-photon energy $\omega = 3$ kT the expression (13) describes the behaviour of the equilibrium spectra at $E > m_e^2/kT$ (~ 10^{15} eV for MBR) with sufficient accuracy.

3. Kinetic Equation for the Cosmic-Ray Spectrum

Cascade initiating ultrahigh-energy particles may be produced according to the following scheme proposed in ref.[8]. Extragalactic cosmic rays with $E \gg 5\cdot10^{19}$ eV due to π^0-meson photoproduction on relict photons produce high-energy gamma-rays from the decay $\pi^0 \to 2\gamma$, which do initiate electron-photon showers in the field of the MBR. To determine the production spectra of these gamma-rays, it is necessary to first of all calculate the equilibrium spectrum of cosmic rays in the field of the radiation. It should be noted, that since the extragalactic cosmic rays produce the same amount of π^+-mesons, then the showers may also be initiated by high-energy positrons formed at the decay $\pi^+ \to \mu^+ \to e^+$. The described scheme of the cascade development is accompanied by the well-known black-body cut off in the cosmic-ray spectrum, which was first considered in refs.[13,14]. In contrast to refs.[15,16], where the energy-loss expression was used to estimate the characteristics of the spectrum with black-body cut off, in ref.[17] the exact kinetic equation for the cosmic-ray spectrum was considered. The characteristic feature of such an approach is the account of successive interactions of the recoil proton until the reduction of its energy below the threshold one. It brings to an efficient production of π-mesons and secondary gamma-rays and positrons which then initiate electromegnetic cascades in the MBR. But in ref.[17] only the spectra of cosmic rays at different depths were discussed, while we are interested in the equilibrium spectra of cosmic rays. For their calculation let us write the kinetic equation considered by Hill and Shramm[17] as

$$\frac{\partial N}{\partial z} = \frac{n_\omega \sigma_0}{2}\left[-N\int_0^2 \delta\left(x-\frac{E_0}{E}\right) x\,dx + \int_0^2 x\,dx \int_{E_0/2}^{\infty} \delta\left(x-\frac{E_0}{E_p}\right)\delta\left(E-\frac{4E_p}{E_0}\right) N(E_p)\,dE_p\right] \quad (15)$$

where $N(E,z)\,dE$ is the number of cosmic rays in the unit energy range, $x = 1-\cos(\theta)$, $\sigma_0 = 2\cdot 10^{-28}\,cm^2$, $E_0 = 0.35 M_p^2/\omega$. Here the condition that the proton loses, on the average, one fifth of its energy to form a π -meson is also used.

In eq.(15) a monoenergetic approximation is used for photon energies, and the approximation

$$\sigma(E) = \sigma_0\,\delta(x - E_0/E) \quad (16)$$

discussed in ref. [9] is used for the π-meson photoproduction cross section. At the cosmic-ray energies $E < E_0/2$ the substitution of the MBR spectrum by a δ -function one becomes invalid, that is why the solution of this equation describes the cosmic-ray spectrum only at $E > E_0/2$. In this paper this restriction is acceptable, because here the gamma-ray spectrum at energies $\geqslant E_0/10$ is considered. For a wider energy range it is necessary to consider the real spectrum of the field photons in eq.(15).

Let the cosmic-ray injection spectrum be given as

$$q(E) = Q_p (E/E_0)^{-(\alpha+1)} \quad (17)$$

Then the integration of eq.(15) will yield the following equation for the equilibrium spectrum:

$$N(E) - \frac{4}{5}N(\frac{5}{4}E) = \frac{2Q_p}{n_\omega \delta_o}(E/E_o)^{-\alpha} \quad (18)$$

Its solution is

$$N(E) = \frac{2Q_p}{n_\omega \delta_o[1-(\frac{4}{5})^{\alpha+1}]}(E/E_o)^{-\alpha} \quad (19)$$

Cosmic rays with the equilibrium spectrum (19), when interacting with the MBR, form π^o -mesons in the process $p+\gamma \rightarrow p+\pi^o$, which decaying do form the ultrahigh-energy gamma-ray-production spectrum. That spectrum is defined as:

$$q(E_\gamma) = 4\pi\delta_o n_\omega \int_{E_\gamma}^{\infty} dE_\pi/E_\pi \int_0^2 x dx \int_{E_o/2}^{\infty} \delta(x-E_o/E)\delta(E_\pi - E/5)N(E)dE \quad (20)$$

Integrating the eq.(20), we shall obtain the final expression for the gamma-ray production spectrum

$$q(E_\gamma) = Q_\gamma(E_\gamma/E_K)^{-(\alpha+1)}, \quad E > E_K \quad (21)$$

Here

$$Q_\gamma = \frac{40\pi Q_p}{\alpha+1} \cdot \frac{2^{\alpha+1}}{1-(4/5)^{\alpha+1}} \quad ;$$

$$E_K = E_o/10$$

Let us use the gamma-ray flux observed on the "Fly's Eye" installation [18] to estimate the values of Q_p and α

$$I(E) = 109.6(E/EeV)^{-2.94} km^{-2} sr^{-1} yr^{-1} EeV^{-1}, \; E < 10\, EeV \quad (22)$$

Cosmic rays do not interact with the MBR in the considered energy range. Therefore, assuming that they fill a space region with a Hubble length scale (C/H_o), we come to the following expression for the cosmic-ray-injection spectrum:

$$q(E)=I(E)\frac{4\pi H_0}{c}=8.3\cdot 10^{-69}(E/E_0)^{-2.94}\ cm^{-3}s^{-1}eV^{-1} \quad (23)$$

where $H_0=100\ km\cdot s^{-1}Mpc^{-1}$ and $c=3\cdot 10^{10}\ cm\cdot s^{-1}$

If not assumed, that the ultrahigh-energy cosmic-ray-injection spectrum is cut off at $E > 10$ EeV, then the injection spectrum (23) may be continued into the high-energy region as well. Consequently, f.. m (23) for Q_p and α we obtain

$$Q_p=8.3\cdot 10^{-69}\ cm^{-3}s^{-1}eV^{-1}, \quad \alpha=1.94 \quad (24)$$

4. Cascade Gamma-Ray Flux within $E \geqslant 5\cdot 10^{19}$ eV

To calculate the flux of cascade gamma-rays initiated in the field of the MBR by protons having the production spectrum (21), let us use the obtained solutions of kinetic equations for the distribution functions of electrons and gamma-rays. Convoluting (13) with the production spectrum of electrons or ultrahigh-energy gamma-rays, one can obtain the equilibrium spectra of cascade gamma-rays and electrons. So, for the production spectrum (21) the cascade gamma-ray fluxes are

$$\Gamma=\mathcal{E}/2=\frac{Q_r\omega}{2\pi r_0^2 n_\omega m_e^2}\int_{E_K}^{\infty}(E_*/E_K)^{-(\alpha+1)}K(E,E_*)dE_* \quad (25)$$

Taking into consideration that $K(E,E_*)$ (see (12)) can be approximated as (within 3% of accuracy)

$$K(E,E_*)=\frac{6}{\pi^2}+\sum_{K=7}^{\infty}\frac{(E/E_*)^{K+1-\Delta_K}}{\pi^2+(\ln K+C_E)^2} \quad (26)$$

for electrons and gamma-rays we obtain

$$\Gamma = \mathcal{E}/2 = \frac{Q_\pi b_k}{8\pi r_0^2 n_\omega}\left(\frac{EX}{E_k}\right)^{-\alpha}\left[\frac{6}{\alpha\pi^2} + \sum_{k=1}^{\infty}\frac{X^{-(k+1-\Delta_k)}}{[\pi^2+(\ln k + C_E)^2][1+\alpha+k-\Delta_k]}\right] \quad (27)$$

where $X = \max\{E_k/E, 1\}$.

For energies $E > E_k$ the expression (27) is reduced to

$$\Gamma = \mathcal{E}/2 = \frac{Q_\pi b_k}{8\pi r_0^2 n_\omega}(E/E_k)^{-\alpha}\left[\frac{6}{\alpha\pi^2} + 0.2\right] \quad (28)$$

with α changing in the most interesting range $1 < \alpha \leqslant 2$. Note, that the equlibrium spectrum (28) is more flat than the production spectrum of initiating particles due to the change of the spectral index by unity. Substituting the values from (24) into (21) and (28), for the gamma-ray flux we obtain

$$\Gamma(E) = 1.7\cdot 10^{-39}(E/E_k)^{-1.94}\ cm^{-2}s^{-1}sr^{-1}eV^{-1},\ E > 4.4\cdot 10^{19}eV \quad (29)$$

As it has been earlier mentioned, the positrons from the decay $\pi^+ \to \mu^+ \to e^+$ will also contribute to the cascade gamma-ray flux. According to ref.[17] the production spectrum of these positrons is half the spectrum (21). Consequently, the gamma-ray flux due to them is also half the flux (29). The gamma-ray flux is finally given by

$$\Gamma(E) = 2.5\cdot 10^{-39}(E/E_k)^{-1.94}\ cm^{-2}s^{-1}sr^{-1}eV^{-1},\ E > 4.4\cdot 10^{19}eV \quad (30)$$

The spectrum $\Gamma(E)$ is shown in fig.2 together with the experimental data [18,19]. It is seen from the figure that at $E \gtrsim 5\cdot 10^{19}$ eV the obtained flux makes an essential fraction of the experimentally observed spectrum. Therefore, the tendency to steepening of the cosmic-ray spectrum, reported in ref.[18] and interpreted as an evidence for the existence of the black-body cut off, must be obscured in this energy range. The gamma-ray flux (30) produced due to formation of electron--photon showers is detectable for modern installations.

As it follows from the calculations presented in fig.2, the search for a diffuse flux of gamma-rays in the energy range $E > 10^{19}$ eV seems to be rather promising. The expected value of the γ/p ratio at $E > 2\cdot10^{20}$ eV may be obtained from the eqs.(19) and (28). Considering also the contribution of cascade gamma-rays initiated by positrons, we obtain

$$\Gamma(E)/N(E) \simeq 6\cdot10^{2}, \; E > 2\cdot10^{20}\,\mathrm{eV} \qquad (31)$$

At such energies the high γ/p ratio is explained by the corresponding excess of π-meson photoproduction cross section over that of e^+e^- pair production in $\gamma-\gamma$ collisions. The ratio γ/p within $5\cdot10^{19}$ eV $< E < 2\cdot10^{20}$ eV strongly depends on the energy and is not calculated in this paper. In this energy range in the kinetic equation (15) one must perform averaging over Planck's spectrum and δ-functional approximation breaks. The calculations of the γ/p ratio in a wide energy range will be published elswhere. Here we should like to note only the importance of determination of γ/p ratio, since it can be in principle measured on modern installations capable to distinguish between the proton- and gamma-ray-induced showers (for example, by analyzing the muon content in showers).

The results obtained on the absolute gamma-ray fluxes differ from those in refs.[8,9], which is apparently due to the simplifications made when considering the kinetics of propagation of electrons and gamma-rays in the radiation field. We regret that the details of calculation and the approximations being used are not considered in ref.[8], that is why it is hard to speak about the reasons for the discrepancy. As for results of ref.[9] , they are obtained in the continuous energy losses approximation for high-energy gamma rays, which is an incorrect assumption, as the processes of interaction with field photons in the considered energy range have catasrophic character. Comparison of eq.(28) obtained in the consideration of kinetic equations for electrons and gamma-rays with the analogous results from ref.[9] shows, that the cascade gamma-ray spectrum is almost by two orders of magnitude underestimated in ref.[9] . Moreover, in references cited above the kinetics of cosmic-ray propagation in photon field is not taken into account. It eventually led to by an order of magnitude underestimation of the gamma-ray absolute flux in these works.

As noted in ref.[20] , in case of large values of b ($b \geqslant 10^3$) in collisions of high-energy electrons with photons, the losses due to electron-positron pair production rather than inverse Compton scattering are dominated. However, it should be noted that since as a result of the process considered the whole energy of relativistic electrons is transferred to the electron-positron-pair component, then the role of this process in the suppression of the electromagnetic cascade is negligible. At the same time, the synchrotron losses of these electrons turn out to be more significant.

According to the estimates from refs.[8,9] , at the intergalactic magnetic field value of $\gtrsim 2\cdot10^{-11}$ gauss the electromagnetic cascade in the energy range $E \gtrsim 10^{20}$ eV is damped, and a large portion of the relativistic electron energy is transformed in the synchrotron radiation. Interaction with radio waves brings to analogous losses [21]. In ref. [22] the account of this process when considering the electromagnetic cascade initiated in the field of the MBR leads to damping of the cascade at $E \gtrsim 10^{19}$ eV. But the value of radic photon density in the intergalactic medium as well as the value of the intergalactic magnetic field is rather uncertain at present. This uncertainty may be somewhat reduced if diffuse ultrahigh-energy gamma rays ($E \gtrsim 10^{19}$ eV) are discovered.

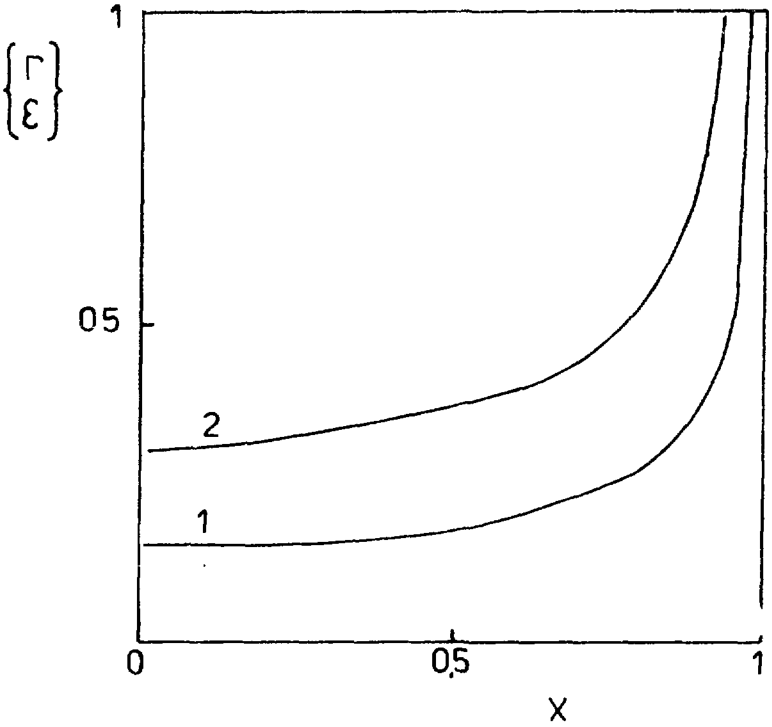

Fig.1 Equilibrium spectra of shower particles. 1 - the gamma-ray spectrum; 2 - the spectrum for electrons and positrons.

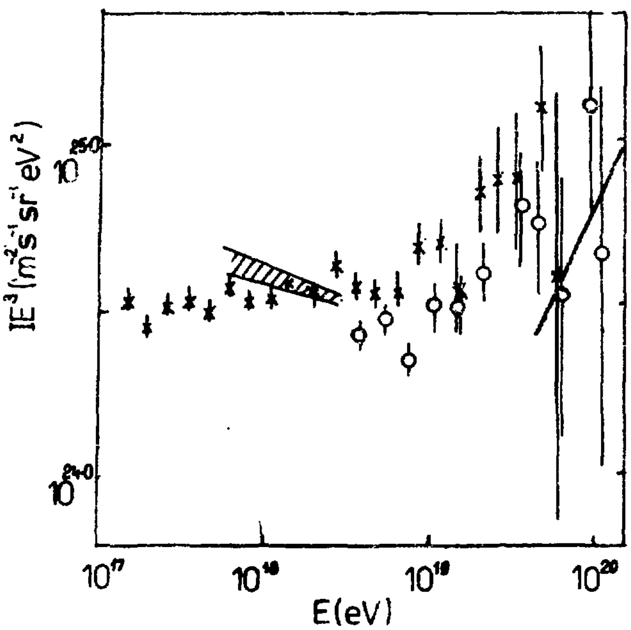

Fig.2 Ultrahigh-energy cosmic-ray fluxes.

▨ , O show the "Haverah Park" spectrum;

X show the "Fly's Eye" spectrum;

—— shows the spectrum of cascade γ -rays at $E > 5 \cdot 10^{19}$ eV.

References

1. Pensias A.A., Wilson R.W. A Measurement of Excess Antenna Temperature at 4080 Mc/s. Astrophys. J., 1966, vol.142, p.419.
2. Hayakawa S. Electron-Photon Cascade Process in Intergalactic Space. Progr. Theor. Phys. Suppl., 1966, vol.37, p.534.
3. Jelley J.V. High-Energy Gamma-Ray Absorption in Space by 3.5K Microwave Field. Phys.Rev.Lett., 1966, vol.16, p.479.
4. Could R.J., Shreder G.P. Pair Production in Photon-Photon Collisions. Phys.Rev., 1967, vol.155, p.1404.
5. Bonometto S.A. On the Transparency of Extragalactic Space to Very-High-Energy Photons. Nuovo Cim.Lett., 1971, vol.16, p.677.
6. Bonometto S.A., Lucchin F. On the Transparency of Extragalactic Space to Very-High-Energy Photons-II. Nuovo Cim. Lett., 1971, vol.25, p.1299.
7. Allcock M.C., Wdowczyk J. The Attenuation Length for High-Energy γ -Rays in the Relict Radiation. Nuovo Cim., 1972 vol.9B, p.315.
8. Wdowczyk J., Tkaczyk W., Wolfendale A.W. Primary Cosmic γ -Rays Above 10^{12} eV. J.Phys., 1972, vol.A5, p.1419.
9. Stecker F.W. Ultrahigh-Energy Photons, Electrons and Neutrinos, the Microwave Background and the Universal Cosmic-Ray Hypothesis. Astrophys. Space Sci., 1973, vol.20, p.47.
10. Baltrusaitis R.M., Cady R., Cassiday G.L. et al. The Utah Fly's Eye Detector. NIM, 1985, vol.A240, p. 410.

11. Агаронян Ф.А., Варданян В.В. Генерация релятивистских электронно-фотонных ливней в поле электромагнитного излучения. Препринт ЕФИ-827(54)-85, Ереван,1985.

12. Burns M.L., Lovelace R.V.E. Theory of Electron-Positron Showers in Double Radio-Sources. Astrophys.J., 1982, vol.262, p.87.

13. Greisen K. End to the Cosmic-Ray Spectrum? Phys.Rev.Lett., 1966, vol.16, p.748.

14. Зацепин Г.Т., Кузьмин В.А. О верхней границе спектра космических лучей. Письма в ЖЭТФ, 1966, т.4, с.114.

15. Березинский В.С., Зацепин Г.Т. О происхождении космических лучей сверхвысоких энергий. ЯФ, 1971, т.13, с.797.

16. Strong A., Wdowczyk J., Wolfendale A.W. The Gamma-Ray Background: A Consequence of Metagalactic Cosmic-Ray Origin? J.Phys., 1974, vol.A7, p.120.

17. Hill C.T., Shramm D.N. Ultrahigh-Energy Cosmic-Ray Spectrum. Phys.Rev., 1985, vol.D31, p.564.

18. Baltrusaitis R.M., Cady R., Cassiday G.L. et al. Evidence for a High-Energy Cosmic-Ray Spectrum Cutoff. Phys.Rev. Lett., 1985, vol.54, p.1875.

19. Cunningham C., Lloyd-Evans J., Pollock A.M.T. et al. The Energy Spectrum and Arrival Direction Distribution of Cosmic Rays with Energy Above 10^{19} eV. Astrophys.J., 1980, vol.236, p.L71.

20. Bonometto S.A., Luchin F., Marcolungo P. Induced Pair Production and Opacity Due to Black-Body Radiation. Astron. Astrophys., 1974, vol.31, p.41.

2I. Березинский В.С. Обратный комптон-эффект, образование пар и прохождение электронов и фотонов больших энергий через Метагалактику.ЯФ, I970, т.II, с.399.

22. Berezinsky V.S., Grigor'eva S.I., Prilutsky O.F. γ -Rays of Ultrahigh Energy. In: Proc. 13th Intern. Cosmic Ray Conf., USA, Denver, 1973, vol.1 , p.479.

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