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DIFFUSE EXTRAGALACTIC GAMMA-RADIATION ABOVE BLACK-BODY CUTOFF

ЦНИИатоминформ
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ԴԻՖՈՒԶԱՅԻՆ ԱՐՏԱԳԱԼԱԿՏԻԿԱԿԱՆ ԳԱՄՄԱ-ՃԱՌԱԳԱՅԹՈՒՄԸ ՏԻԵԶԵՐԱԿԱՆ ՃԱՌԱԳԱՅԹՄԱՆ ՍՊԵԿՏՐԻ ,,ՍԵՎԱՄԱՐՄԻՆ ԿՏՐՄԱՆ,, ԷՆԵՐԳԻԱՅԻ ՏԻՐՈՒՅԹՈՒՄ

Քննարկվում է գամմա-քվանտների հնարավոր ներդրումը տիեզերական ճառագայթների/Տճ/ սպեկտրի ,,սևամարմին կտրման,, էներգիայի տիրույթում: Այդ գամմա-քվանտները առաջանում են մնացորդային ճառագայթման /Մճ/ դաշտում ռելյատիվիստական էլեկտրամագնիսական կասկադի կազմավորման հետևանքով: Գերբարձր էներգիաների մասնիկների հեղեղը առաջանում է պրոտոնները Մճ ֆոտոնների հետ փոխազդեցությունից ծնված՝ մեզոնների տրոհման ժամանակ: Ցույց է տրված, որ միջգալակտիկական տարածքում մագնիսական դաշտի և ռադիոֆոնի էներգիայի խտության որոշակի նշանակությունների դեպքում կասկադային գամմա-քվանտների հոսքը մասամբ կարող է թաքցնել պրոտոնների սպեկտրում ,,սևամարմին կտրումը:

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DIFFUSE EXTRAGALACTIC GAMMA-RADIATION ABOVE BLACK-BODY CUTOFF

A possible contribution of gamma-rays predicted within the universal cosmic ray (CR) hypothesis to the energy range of CR spectrum above black-body cutoff is calculated. These gamma-rays arise from the relativistic electromagnetic cascade generated in the field of microwave background radiation (MBR). The ultrahigh energy photons and electrons that initiate the cascade are produced at the decay of π-mesons created in interactions of photons with the MBR. Simple analytic expression for cascade gamma-ray spectrum is obtained from the solution of cascade kinetic equations for electrons and photons as well as for protons propagating in the MBR field. The obtained results essentially differ from the relevant ones of previous investigations. The reasons for this discrepancy are discussed. It is shown that at certain values of magnetic field and radio-wave density in the intergalactic space the flux of cascade gamma-rays may at least partly mask the black-body cutoff in the proton spectrum.

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ДИФФУЗНОЕ ВНЕГАЛАКТИЧЕСКОЕ ГАММА-ИЗЛУЧЕНИЕ В ОБЛАСТИ ЭНЕРГИИ "ЧЕРНОТЕЛЬНОГО ОБРЕЗАНИЯ" СПЕКТРА КОСМИЧЕСКИХ ЛУЧЕЙ

В работе обсуждается возможный вклад гамма-квантов в область энергии "чернотельного обрезания" спектра космических лучей (КЛ) Эти гамма-кванты возникают в результате формирования релятивистского электромагнитного каскада в поле микроволнового реликтового излучения (РИ). Инициирующие этот каскад частицы сверхвысоких энергий образуются при распаде π - мезонов,рождаемых во взаимодействиях протонов с фотонами РИ. Спектр каскадных гамма-квантов получен в результате решения кинетических уравнений для электронов и гамма-квантов, а также протонов, распространяющихся в поле РИ. Полученный результат отличается от результатов более ранних работ. Обсуждаются причины этого расхождения. Показано, что поток каскадных гамма-квантов при определенных значениях плотности энергии магнитного поля и радиофона в межгалактическом пространстве может по крайней мере частично маскировать "чернотельное обрезание" в спектре протонов.

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1. Introduction

According to the existing ideas the ultrahigh-energy (UHE) cosmic rays (CR) are of extragalactic origin at least in the energy range $E > 10^{19}$ eV. At such energies the CR interact effectively with the microwave background radiation (MBR) owing to the π-meson photoproduction process. As a result, in the intergalactic medium an equilibrium CR spectrum with Greisen-Zatsepin cutoff at $E \sim 5 \cdot 10^{19}$ eV is formed [1,2]. The noticeable deviation of the MBR spectrum revealed recently in the Wien region [3] being taken into account, the black-body cutoff is to shift towards the region of lower energies ($E \sim 4 \cdot 10^{19}$ eV) [4] . The secondary π-mesons while decayed produce electrons and gamma-rays which initiate electromagnetic cascade in the MBR field. The feasibility of the cascade process in the intergalactic space was emphasized originally by Hayakawa [5] . Later this question was often referred to, in particular to explain EAS data in the energy range

$E > 10^{19}$ eV [6-8] . In these works attempts were made as to describe quantitatively the electromagnetic cascade in the photon gases; however a certain progress in this field was achieved only recently [9-13] .

In the present study we investigate a possible contribution to the CR energy spectrum at $E > 10^{19}$ eV coming from the cascade gamma-rays unavoidably produced within the model that implies homogeneous population of the Metagalaxy by the CR sources (hereafter universal CR hypothesis). These gamma-rays being a result of the electromagnetic cascade in the MBR field, initiated by the decay products of the pion photoproduction process, are genetically coupled to the black-body cutoff of CR spectrum and can even mask it under certain conditions. The cascade gamma-ray spectrum is obtained from the solution of kinetic equations for electrons and gamma-rays taking into account the equilibrium proton spectrum, formed in the MBR field.

2. Source Function of Gamma-Rays Due to Interactions of CR with MBR

The UHE particles (electrons and photons) initiating the electromagnetic cascade arise by the following scheme. The extragalactic CR with $E > 10^{19}$ eV, due to the π°-meson photoproduction on the MBR photons produce high-energy photons from the $\pi^{\circ} \rightarrow 2\gamma$ decay. These gamma-rays just initiate electron-photon showers in the MBR field. It should be noted that the CR interacting with MBR produce nearly the same number of π^{+}-mesons and therefore the showers will be initiated also by high-energy positrons - the products of the $\pi \rightarrow \mu \nu_{\mu}$ and $\mu \rightarrow e \nu_{e} \nu_{\mu}$ decays. In order to calculate the photon and positron production spectra, it is necessary to use the equilibrium proton spectrum in the Metagalaxy filled with MBR photons at a temperature T = 2.7 K. As shown in our previous paper [4], the equilibrium CR spectrum in the MBR field has a form:

$$F_{p}(E) = \frac{q_{p}(E)}{A(\gamma)\,\lambda^{-1}(E)} , \tag{1}$$

where

$$\lambda^{-1}(E) = \frac{kT}{2\pi^{2}(c\hbar)^{3}\Gamma^{2}} \int\limits_{\varepsilon_{0}}^{\infty} d\omega_{r}\, \sigma_{t}\, \omega_{r} \left[-\ln\left(1-\exp\left(-\frac{\omega_{r}}{2\Gamma kT}\right]\right.\right.;$$

$$A(\gamma) = 1 - \left[1-\xi(\varepsilon_{0})\right]^{\gamma-1} , \quad \Gamma \equiv E/m_{p}c^{2} .$$

Here $\sigma_{t}(\omega_{r})$ is the total pion photoproduction cross section caused mainly by two reactions: $p\gamma \rightarrow p\pi^{\circ}$ and $p\gamma \rightarrow n\pi^{+}$; $\varepsilon_{0} = m_{\pi}c^{2}\left(1+\frac{m_{\pi}}{2m_{p}}\right) \simeq 0.145$ GeV is the threshold of the pion photoproduction reaction, m_{π} , m_{p} are pion and nucleon masses, $\xi(\varepsilon_{0})$ is the share of energy lost by the nucleon at the reaction threshold energy. The CR production spectrum (source function) is given by the simple power-law distribution:

$$q_{p}(E) = Q_{p}(E/E_{0})^{-\gamma} ; \quad E_{0} = \frac{\varepsilon_{0} m_{p} c^{2}}{2kT} \simeq 2,9 \cdot 10^{20} \text{ eV} . \tag{2}$$

Spectrum (1) contains only protons, since neutrons even of ultrahigh energies (for the time scale of interest) decay before they interact with MBR. However, since the protons produced in the neutron decays take practically the whole energy ($E_p \simeq E_n$), these protons also should be taken into account. Formally they are taken into account in Eq.(1), since the reaction $p\gamma \to n\pi^+$ is considered not as a process of proton disappearance but as a process of nucleon energy degradation [4].

The source function of gamma-rays from decay of photoproduced π^0-mesons may be presented as

$$q(E_\gamma) = \frac{\kappa T}{\pi^2 (c\hbar)^3 \Gamma^2} \int_{E_\gamma}^{\infty} \frac{dE_\pi}{E_\pi} \int_{E_{1/2}}^{\infty} dE\, F_p(E)\, \delta(E_\pi - E\xi) \int_{\varepsilon_0}^{\infty} d\omega_r\, \sigma_{\pi^0}\, \omega_r \left[-\ln\left(1 - e^{-\omega_r/2\Gamma\kappa T}\right)\right] \quad (3)$$

where σ_{π^0} is total cross section of π^0-meson production.

The parameter $E_{1/2}$ in expression (3) is a characteristic energy of black-body cutoff. In the model of Metagalaxy homogeneously populated by CR sources the equilibrium proton spectrum in the energy range $E > E_{1/2}$ is determined by Eq.(1), and the value for the black-body cutoff is $E_{1/2} \sim 5 \cdot 10^{19}$ eV*). Note that at $E \ll E_{1/2}$ (practically for $E \lesssim 10^{19}$ eV) the equilibrium proton spectrum repeats the shape of the production spectrum, since protons at such energies practically do not interact with MBR, and the absolute proton flux at these energies is determined by the size of CR capture region (more exact, by CR "lifetime" in this region).

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*) For simplicity hereafter we neglect the deviation of MBR spectrum from the Planckian one.

The energy share lost by the nucleon per single collision owing to pion photoproduction is

$$\xi(\omega_r) = \frac{\omega_r}{m_p c^2} \, \frac{1 + (m_\pi c)^2 / 2\omega_r m_p}{1 + 2\omega_r / m_p c^2}$$

For ω_r variation range from the threshold value ~ 0.145 GeV to 1 GeV this fraction varies rather weakly from 0.15 to 0.35. In the energy region of interest, $E_\gamma > 10^{19}$ eV, the main contribution corresponding to the maximal probability of interaction of protons with the MBR photons comes from the region $\omega_r \sim 0.3 - 0.5$ GeV, therefore below we shall use the value $\xi(\omega_r \simeq 0.4 \text{ GeV}) \simeq 0.23$.

It should be noted that the gamma-ray source function (3) depends weakly on the character of interaction. Indeed, substituting the equilibrium proton spectrum (1) into Eq.(3) we arrive at the expression for $q(E_\gamma)$ independent of the interaction cross section:

$$q(E_\gamma) = \frac{1}{A(\gamma)} \int_{E_\gamma}^{\infty} \frac{dE_\pi}{E_\pi} \int_{E_{1/2}}^{\infty} dE\, q_p(E)\, \delta(E_\pi - E\cdot\xi). \quad (4)$$

This is explained by the fact that if the equilibrium spectrum is inversely proportional to the integral

$$\int_{\varepsilon_0}^{\infty} d\omega_r\, \sigma_t(\omega_r)\, \omega_r \left[-\ln\left(1 - \exp\left(-\frac{\omega_r}{2\Gamma\kappa T}\right)\right)\right]$$

which characterizes the interaction rate of protons with the field photons, then the gamma-ray production rate is proportional to the same integral (taking into account that in the gamma-ray energy region of interest $\sigma_{\pi^0} = \frac{1}{2}\sigma_t \simeq \frac{1}{2}(\sigma_{\pi^0} + \sigma_{\pi^+})$)

For the same reason the gamma-ray production spectrum is independent of the field photon number density. Evidently, this statement is valid only in case of effective interaction of protons with MBR (which is just the case with $E > 5 \cdot 10^{19}$ eV); otherwise, we may neglect the distortion of proton energy spectrum, and therefore the gamma-ray source function will be proportional to the cross section of interaction as well as to the number density of target photons.

Integrating expression (4), we obtain the gamma-ray source function:

$$q(E_\gamma) = Q_\gamma \begin{cases} (E_\gamma/E_*)^{-\gamma}, & E_\gamma \geq \xi E_{1/2} \\ (E_{1/2}/E_0)^{-\gamma} & E_\gamma < \xi \cdot E_{1/2} \end{cases} \qquad (5)$$

where $Q_\gamma = \dfrac{Q_p}{\xi A(\gamma) \cdot \gamma}$; $E_* = \xi \cdot E_0$

Thus, due to the secondary π^0 decay the gamma-ray production spectrum (5) is formed which has the same index as the proton production spectrum (2).

It should be stressed once more that the gamma-ray source function (5) is calculated here using the proton equilibrium spectrum (1), and not the production spectrum of protons with the simple power-law shape $\propto E^{-\gamma}$ up to highest energies (as it was done in Refs [6,7]). In the latter case the incorrect shape of gamma-ray source function arises. For example, Stecker [14] (see also Ref.[7] where formula (9), however, contains error in the spectral index) using δ-functional approximation for the pion photoproduction cross section has obtained a gamma-ray spectrum steeper than Eq.(5) ($q(E_\gamma) \propto E_\gamma^{-(\gamma+1)}$).

Note also that the equilibrium proton spectrum (1) corresponds to a purely Planckian distribution of MBR photons. With account of the recently revealed deviation of the MBR spectrum from the Planckian one in the submillimeter range [3] the equilibrium proton spectrum undergoes a modification, in particular the black-body cutoff occurs considerably earlier [4] . However this effect influences insignificantly the source function of gamma-rays at $E > 3 \cdot 10^{19}$ eV, since these gamma-rays are generated by protons with the energy $E > 2 \cdot 10^{20}$ eV which interact predominantly with the MBR spectrum region corresponding to the distribution maximum.

3. The Spectrum of Cascade Gamma-Rays

The kinetic equations that describe the development of electromagnetic cascade in the MBR field have a rather complicated form. However in the energy region $E \gg \dfrac{(m_e c^2)^2}{4\langle\omega\rangle}$, where m_e is the electron mass, and $\langle\omega\rangle \cong 3$ kT they can be reduced to the following system [15] :

$$\begin{aligned} b\,\frac{\partial \mathcal{E}(E,t)}{\partial t} + \mathcal{E}(E,t)\ln b &= 2\int_0^{1-1/b} \Gamma(E/x,t)\,\frac{dx}{1-x} \\ b\,\frac{\partial \Gamma(E,t)}{\partial t} + 2\Gamma(E,t)\ln b &= \int_0^{1-1/b} \mathcal{E}(E/x,t)\,\frac{dx}{1-x}\ ; \end{aligned} \qquad (6)$$

$$b = 4E\langle\omega\rangle/(m_e c^2)^2\ ;\quad t = 4\pi r_0^2 n_\omega Z\ ,$$

where $\mathcal{E}(E,t) = F_e(E,t) \cdot E$ and $\Gamma(E,t) = F_\gamma(E,t) \cdot E$; $F_e(E,t)$ and $F_\gamma(E,t)$ are respectively the fluxes of cascade electrons and gamma-rays at depth t ; r_0 is the classical electron radius, n_ω is the average density of field photons, z is the distance travelled by shower particles.

The solution of Eq.(6) for the equilibrium spectrum of the cascade shower initiated by one particle (electron or photon) with energy E_i has a form [15] :

$$\Gamma = \frac{\varepsilon}{2} = \frac{b_i}{4}\sum_{n=0}^{\infty}\frac{(b/b_i)^{-(S_n+1)}}{\psi'(S_n+2)} \; ; \qquad b_i = \frac{4E_i\langle\omega\rangle}{(m_ec^2)^2} \tag{7}$$

The values of S_n are determined from the solution of equation

$$\psi(S_n+2)+C_E=0,$$

where $\psi(S)$ is a logarithmic derivative of Gamma-function $d\ln\Gamma(s)/ds$, and $C_E = 0.5772$ is the Euler constant.

Thus, convolving the cascade particle spectrum (7) with the source function (5) we come to the flux of cascade gamma-rays (F_γ) and electrons (F_e):

$$F_\gamma = F_e/2 = \frac{4\pi}{E}\int\Gamma(E,E_i)\,q(E_i)\,dE_i \tag{8}$$

Taking into account that the function $\Gamma(E,E_i)$ with an accuracy no worse than 3% is approximated by the expression [15],

$$\Gamma = \frac{\omega E_i}{4\pi r_0^2 n_\omega (m_ec^2)^2}\left[\frac{6}{\pi^2}+\sum_{n=1}^{\infty}\frac{(E/E_i)^{n+1-\Delta_n}}{\pi^2+(\ln n+C_E)^2}\right] \tag{9}$$

for the cascade electrons and gamma-rays we obtain

$$F_\gamma = \frac{1}{2}F_e = (E/E_*)^{-\gamma+1}\frac{Q_\gamma b_*}{4r_0^2 n_\omega}\left[\frac{6}{(\gamma-2)\pi^2}+0,25\right], \; E>0,17E_* \tag{10}$$

(for index γ varying in the most interesting interval $2<\gamma\leq 3$) and

$$F_\gamma = F_e/2 = \frac{(0,17)^{-\gamma+1}Q_\gamma b_*}{4r_0^2 n_\omega}\left\{\frac{6}{\gamma-2}\,\frac{0,17E_*}{E}+\frac{3}{\pi^2}\left[\left(\frac{0,17E_*}{E}\right)^2-1\right]+\right.$$
$$\left.+\sum_{n=1}^{\infty}\frac{(0,17E_*/E)^{-(n-\Delta_n)}}{[\pi^2+(\ln n+C_E)^2](\gamma-1+n-\Delta_n)}+\sum_{n=1}^{\infty}\frac{1-(0,17E_*/E)^{-(n-n_\Delta-1)}}{[\pi^2+(\ln n+C_E)^2](n-\Delta_n-1)}\right\} \tag{11}$$

for $E < 0.17\,E_*$.

Here $$\Delta_n = \frac{1}{\pi}\,\mathrm{arcctg}\left\{[\psi(n)+C_E+1/n]/\pi\right\}$$

The values of Q_p and γ can be determined from the experimental data on CR spectrum. For example, according to the Fly's Eye data [16] the CR spectrum in the energy range $E < 10^{19}$ eV has the form:

$$I(E) = 2.9\cdot 10^{19}\,E^{-2.94}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{ster}^{-1}\,\mathrm{eV}^{-1} \tag{12}$$

In the energy range $E < 10^{18}$ eV the CR interact weakly with the MBR; therefore, assuming that the CR sources populate the region with a size of Hubble scale c/H_0 (universal CR hypothesis), for the CR proton production spectrum we have:

$$q_p(E) = I(E)\,\frac{4\pi\cdot H_0}{c} = 2.75\cdot 10^{-68}\,(E/E_0)^{-2.94}\mathrm{cm}^{-3}\mathrm{s}^{-1}\mathrm{eV}^{-1} \tag{13}$$

(here we use the value H_o = 100 km/s Mpc).

Extrapolating the spectrum (13) to the region of higher energies by a simple power law and comparing (13) with the CR production spectrum (2), for Q_p and γ we obtain:

$$Q_p = 2.75\cdot 10^{-68}\ \mathrm{cm^{-3}s^{-1}eV^{-1}};\qquad \gamma = 2.94 \tag{14}$$

As already mentioned, a contribution to the CR flux will be also made by the cascade gamma-rays initiated by positrons (from decay of photoproduced π^+-mesons). The injection spectrum of these positrons is similar to the gamma-ray injection spectrum (5) but is about a factor of two less than the latter (e.g. Ref.[17]). This conclusion results from the kinematic consideration of π^+-meson decays and is valid under the assumption that the production cross sections for π^0 and π^+ -mesons are comparable. Actually, near the threshold (~ 150 MeV) the production rate of π^+ -mesons is much higher than that of π^0 -mesons because of direct E1 transition where the pion is being emitted as S -wave. By the way, this π^+ meson production channel plays a dominant role in the proton spectrum formation in the black-body cutoff region. Nevertheless, since in the gamma-ray energy region of interest, $E > 3\cdot 10^{19}$ eV, the interaction of protons with MBR occurs in the interval $\omega_r \sim 300 - 500$ MeV (where the cross sections of π^+ and π^0 meson production are comparable) the assumption $q(E_\gamma) = 2q(E_e)$ is quite acceptable.

Thus, the gamma-ray flux exceeds Eq.(10) by a factor of 1.5, since the cascade gamma-ray spectrum is independent of

the fact as to whether the positron or photon initiates the electromagnetic cascade. Substituting the values of Q_p and γ from Eq.(14) into Eqs (10) and (11) we obtain an absolute flux of cascade gamma-rays $I(E_\gamma)=F_\gamma/4\pi$. It is shown in Fig.1 together with the equilibrium proton spectrum $I(E_p)=F_p/4\pi$ ($F_p(E)$ is determined by Eq.(1)), calculated for the size of Metagalaxy $R \simeq c/H_o$. One can see from Fig.1 that in the energy region $E \gtrsim 10^{20}$ eV the flux of gamma-rays exceeds the flux of the parent particles - protons. This at first sight paradoxical result is due to a contribution into the flux (10) made by the gamma-rays coming from more distant regions than protons. Indeed, at such high energies the free path of gamma-rays with respect to the e^+e^- pair production, $\lambda_\gamma^{(\pm)}$ becomes greater than the proton free path caused by pion photoproduction, $\lambda_p^{(\pi)}$. Moreover, owing to the cascade behavior of propagation of gamma-rays the latters are effectively accumulated from distances considerably exceeding the photon free path, $\lambda_\gamma^{(\pm)}$. The gamma-ray absorption length corresponding to the cascade process λ_{cas} is given in the Appendix and for the case γ = 3 it is $\lambda_{cas} = b/8\pi r_0^2 n_\omega$, i.e. $\ln b$ times as large as the $\lambda_\gamma^{(\pm)}$. As to the ultra-high-energy proton absorption length, it is only 3/2 times exceeds the free path relative to pion photoproduction: $\lambda_p = \left(\frac{\gamma}{\gamma-1}\right)\lambda_p^{(\pi)}$, where $\gamma = 3$ [4]. Hence the absorption length for gamma-rays considerably exceeds the corresponding length for protons and therefore, in case of uniform distribution of CR sources in the Metagalaxy the ultrahigh-energy gamma-rays accumulate from considerably more extended regions than the protons do. Emphasize that the absorption length of cascade gamma-rays grows linearly with energy. Just this fact is responsible for the increase by the unity of the spectral index of cascade gamma-ray flux as compared to the spectral index of proton production spectrum, which in turn leads to the excess of the gamma-ray flux over the proton flux at energies $E \geq 10^{20}$ eV, and hence to partial masking of black-body cutoff.

It should be noted that the flux of cascade electrons (electrons and positrons) is twice the flux of cascade gamma-rays at the same energy (see Eq.(7)). However these electrons do not reach the Earth owing to their drastic synchrotron losses in the galactic disk [7] .

The equilibrium spectrum of cascade gamma-rays (10) differs essentially from the spectra calculated in Refs [6,7]. For example, the comparison of Eq.(10) with the relevant Eq.(24) of Ref.[7] (which define the relation between source function of gamma-rays with equilibrium spectrum of cascade gamma-rays) reveals that in Ref.[7] the cascading effect is underestimated by a factor about four. Presumably this is due to the continuous energy loss approximation used by Stecker [7] to analyze the kinetics of high-energy gamma-ray and electron propagation in photon gas. On the other hand, the source function of gamma-rays, calculated in Ref. [7] , is overestimated (see Sect. 2), and it partially compensates the underestimation in the cascading effect. The same problem was considered numerically by Wdowczyk et al. [6,18] . Unfortunately, the details of calculations as well as approximations being used are not presented

in Refs [6,18] , so it is difficult to us to discuss their results. Here we may emphasize only that in Refs [6,18] the source function for gamma-rays has been calculated using the production spectrum of protons (as in Ref. [7]) instead of the equilibrium one which should lead to incorrect shape and overestimation of source function.

So far we have neglected the influence of intergalactic magnetic field and radio-wave background on the efficiency of cascade development. If the strength of extragalactic magnetic field $B \geq 10^{-9}$ Gauss, the electromagnetic cascade will be sharply suppressed, since the main portion of relativistic electrons is spent on continuous synchrotron radiation without production of high energy photons [6,7] . The synchrotron losses substantially suppress the cascade development at $E > E_{cr}$, where E_{cr} is a critical energy of cascade particles for the given value of magnetic field. Thus, the extragalactic magnetic field $B \geq 2\ 10^{-11}$ Gauss leads to cascade suppression at $E > 10^{20}$ eV [6] and hence to the absence of noticeable flux of cascade gamma-rays in the CR black-body cutoff region. The contemporary estimate of intergalactic magnetic field, based on Faraday rotation measures, is very low, $B < 3 \cdot 10^{-11}$ Gauss [19]. If this estimation is true, then the synchrotron energy losses cannot essentially suppress the cascade development in the Metagalaxy up to $E \sim 10^{20}$ eV.

The situation concerning the effect of radio-wave background on the cascade development in the MBR field is less clear.

As is known, the density of galaxies and their luminosities at the present epoch are insufficient to provide the observed isotropic component of radio radiation [20] . Therefore, most of astronomers imply that this radiation is connected with evolving objects - powerful radiogalaxies and QSO's [20] (see, however, Ref.[21]). In this case the detected isotropic component of radio radiation is related with the whole Metagalaxy (i.e. has universal origin), and its effect should be taken into account when considering the equilibrium gamma-ray spectrum. The radio background affects the cascade development by two reasons. Firstly, at $E > 3 \cdot 10^{19}$ eV gamma-rays interact with radio-waves more effectively than with MBR, which leads to the decrease of their free path due to e^+e^- pair production [6] . Secondly, the radio background decreases the electron free path (due to Compton scatterings), the latter effect being more important than the former one [22]. The influence of radio background on the equilibrium gamma-ray spectrum was quantitatively studied in Ref.[8] , where the radio background has been considered as the source for continuous energy losses of electrons. However, this assumption leads to the underestimation of cascade at energies $E \gtrsim 10^{19}$ eV (especially at $E > 10^{20}$ eV). Indeed, for the electrons and gamma-rays of these energies the problem can be reduced to the electron continuous energy loss approximation only if the target photon average energy $\omega \ll (m_e c^2)^2/E \sim 3 \cdot 10^{-9}$ eV or $\nu \ll 1$ MHz. Though we have no reliable information on the radiation in this band, but there are some evidences on the sharp cutoff of spectrum below $\nu \sim 2$ MHz [20] (this may be connected with

absorption of radio waves within the sources). In the frequency range $\nu > 10$ MHz, where the observational data are more confident *), the parameter $b \equiv \frac{4E\omega}{(m_e c^2)^2} \gg 1$ and hence the energy of upscattered secondary particles (electron or photon) is of the same order as the primary particle energy. So the electromagnetic cascade will be developed effectively also in the field of radio waves, therefore the radio background influence on the equilibrium gamma-ray spectrum is not so drastic as it follows from the electron continuous energy loss approximation. The quantitative consideration of this problem seems necessary; however it is complicated due to poor information on the genuine universal long-wave radio background. From this point of view it is worth noting that the observations in the future experiments of diffuse gamma-rays at $E > 10^{19}$ eV will give us a valuable information on the universal long-wave radio background as well as on the magnetic field in the intergalactic space.

4. Discussion

The main conclusion of the present study may be formulated as follows: if the contemporary estimate of the upper limit of intergalactic magnetic field $B < 3 \cdot 10^{-11}$ Gauss [20] is true, and if the genuine universal radio-wave background is below the observed flux of isotropic component of radio radiation,

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*) Note, however, that even in this band the procedure of extraction of extragalactic isotropic radio component is not free of uncertainties [20].

then the noticeable flux of UHE gamma-rays, which may at least partially mask the black-body cutoff in CR spectrum should be expected. Now we would like to discuss briefly whether there are any experimental evidence to or against this conclusion.

Fig. 1 shows the Fly's Eye experimental data on UHE CR spectrum as well as the proton and gamma-ray equilibrium spectra calculated within a universal one-component model of CR in the energy range $10^{18} - 10^{20}$ eV (see Eqs (13), (14)), assuming uniform population of Metagalaxy by CR sources. As is firmly established by several experimental groups, some flattening or even bump is observed in the CR spectrum at $E \sim (1 \div 5)\cdot 10^{19}$ eV (e.g. Ref.[23]). This peculiarity is absent in the calculated proton spectrum (nor in the total "$p + \gamma$ " spectrum) in Fig. 1. This is due to the fact that the proton spectrum is found by solving the stationary equation for infinite medium (formally implied for the Hubble scale $R \simeq c/H_0$). In the case of proton spectrum from local source (sources) located at distances $\lambda_p \ll d \ll c/H_0$ (or for CR propagation time 10^8 years $\ll T \ll 10^{10}$ years) the bump unavoidably occurs as a result of accumulation of recoil protons in a range $E \sim (1 \div 5)\cdot 10^{19}$ eV [17,24,4] . In the same proton spectra another peculiarity (a dip) appears as a result of continuous energy losses of protons due to e^+e^- production in MBR field [17,24] .

However both the bump and dip may be explained also within the universal CR hypothesis, assuming that this component ("U(p)"-component) is responsible for spectrum energy range $E > 10^{19}$ eV only, and the low energy domain ($E < 10^{19}$ eV)

is due to another (most probably, galactic) component ("G"-component) with break at $E \sim 10^{19}$ eV. Obviously, in this case the power-law index of production spectrum of universal protons should be less than 3. Then the dip occurs at the crossing point of spectra of two components and a bump arises due to the flatness and black-body cutoff of "U(p)"-component. It can be seen from Fig. 2, where the spectrum of "U(p)"-component with $\gamma = 2.4$ is presented (the spectrum is normalized so that to fit the experimental fluxes of Fly's Eye and Haverah Park at $E \sim 10^{19}$ eV)*).

In Fig. 2 we also present the equilibrium spectrum of universal gamma-rays (hereafter "U(γ)"-component), genetically coupled with "U(p)"-component. In this figure the experimental points of Fly's Eye and Haverah Park are presented as well. As it follows from Fig. 2, the experimental fluxes of both installations at $E \sim 10^{19}$ eV may be interpreted as superposition of "G" and "U(p)" components, and in the energy range $E \sim (1 \div 5)\ 10^{19}$ eV as total flux of "U(p)"- and "U(γ)"-components.

In the energy region $E > 5\cdot 10^{19}$ eV the contribution of universal gamma-ray component becomes dominant. At the same time in this very energy region a discrepancy between fluxes of different installations, particularly of Fly's Eye and Haverah Park, takes place. Then a question arises, if this discrepancy

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*) The spectrum of "U(p)"-component is obtained for pure Planckian distribution of MBR. The account of deviation of MBR spectrum from the Planckian one leads to the shift of black-body cutoff towards lower energies[4]. However, for simplicity we neglect this effect.

is caused by different efficiencies of UHE gamma-ray detection by different installations.

To compare the detected UHE particle spectrum with the calculated spectra, it is necessary to take into account the method for primary particle energy estimation, which is different for various installations. Thus, for Fly's Eye installation a parameter which is used for energy estimation is a total number of electrons along the whole shower, i.e. the cascade curve integrated over depth. In accordance with Ref.[25] this number at $E > 10^{19}$ eV essentially depends on the sort of a primary particle (photon or proton) initiating the atmospheric cascade. Up to the depth of 850 g/cm^2 corresponding to the Fly's Eye location, the 10^{20} eV photon creates nearly as many electrons as the proton of $E \sim 10^{19}$ eV does, and when increasing the primary photon energy the total number of particles in a shower up to depth 1000 g/cm^2 decreases. This unusual conclusion is due to the Landau-Pomeranchuk-Migdal (LPM) effect that determines the cascade curve of the purely electromagnetic shower at such energies. Hence all the primary photons of the energy from 10^{20} eV to 10^{21} eV will be detected by Fly's Eye as protons of the energy lower by a factor of $\eta \sim 10 - 100$. Thus, in order to compare with Fly's Eye data, the gamma-ray spectrum calculated in energy range $10^{20} - 10^{21}$ eV should be shifted in energy by a factor of η towards the lower energies and only then summed with the calculated proton spectrum. This however means that the Fly's Eye cannot reveal these gamma-rays, since in the energy range $\lesssim 10^{19}$ eV their contribution to the CR flux is negligible. So, the Fly's Eye turns out insensitive

to the photons, and probably this is the reason of the lack of events detected by this installation above black-body cutoff.

At depths $x \gtrsim 1200$ g/cm^2 the size of shower from the primary photon (with account of LPM effect) becomes comparable with the size of shower from primary proton of the same energy. Therefore, if the ground parameter (such as $\rho(600)$ at Haverah Park) is used for estimation of primary energy, then this estimate may be considered as a correct one even for shower initiated by primary photon. In other words, the installation Haverah Park could be able to detect primary photons above black-body cutoff (it is worth noting that all the eight Haverah Park extra-high energy events ($E \gtrsim 10^{20}$ eV) have been detected at large zenith angles, $\theta \geq 30^\circ$ [23], which corresponds to depth $\gtrsim 1200$ g/cm^2).

If the above-given arguments are valid, then it becomes understandable the detection by Haverah Park events with energy above black-body cutoff and the lack of such events in Fly's Eye experiment. This qualitative interpretation, of course, needs a detailed study of extra-high energy cascades caused by both protons and photons with the characteristics of the given installation being taken into account. Moreover, the influence of geomagnetic field should be also taken into account, since primary photons with energy $E_0 \geq 5 \cdot 10^{19}$ eV begin interact with the magnetic field of $B_\perp \geq (0.2 \div 0.3)$ Gauss. Due to this process, by McBreen and Lambert [26] a conclusion was made that primary photons at such high energies could not be detected. However the real situation is different. The primary photons interacting with the geomagnetic fiel initiate the electromagnetic cascade in this field leading to the transfer of the predominant fraction of primary energy ($\geqslant 99\%$) to secondary gamma-rays possessing energies $E_\gamma \sim (10^{-4} \div 10^{-1})\, E_0$ prior to entering the Earth atmosphere. These gamma-rays further initiate cascades in the atmosphere, and as the LPM effect for energies $E < 10^{19}$ eV is negligible, the superposition of these cascades becomes comparable with the cascade initiated by primary proton with the same energy. This problem is to be discussed in more detail elsewhere.

In conclusion we would like to note that it seems valuable to re-analyze the accumulated data on extra-high energy EAS keeping in mind that at least some of them may be caused by primary photons. Concerning the future experiments one should, of course, carry out spectral measurements for primary protons and photons separately, i.e. effectively identify the proton and gamma-ray induced showers.

APPENDIX

As shown in Ref. [15] , the set of equations (6) in (s , λ) variables (the transition to variable s is realized via Mellin transformation over ℓ , and the transition to variable λ is implemented via Laplace transformation over t) has a form:

$$\begin{aligned} &\lambda \mathcal{E}(s+1,\lambda) + \partial \mathcal{E}(s,\lambda)/\partial s - 2\partial \Gamma(s,\lambda)/\partial s + 2J(s)\Gamma(s,\lambda) = 0 \\ &\lambda \Gamma(s+1,\lambda) - \partial \mathcal{E}(s,\lambda)/\partial s + 2\partial\Gamma(s,\lambda)\partial s + J(s)\mathcal{E}(s,\lambda) = \Gamma(s+1,0) \end{aligned} \qquad (A.1)$$

The solution of Eq.(A.1) for function $\Gamma(s,\lambda)$ in case when the cascade is initiated by the gamma-ray with has a form:

$$\Gamma(s,\lambda) = \frac{1}{4}\sum_{k=0}^{\infty} \frac{(-\frac{3}{4}\lambda\ell_i)^k\, \ell_i^{s+2}}{J(s)\,J(s+1)\cdot J(s+k)} \;;\quad J(s) = \psi(s+2) + C_E \qquad (A.2)$$

Defining the analytical continuation of the sum (A.2) as

$$\sum \frac{(-\frac{3}{4}\lambda\ell_i)^k}{J(s)\cdots J(s+k)} = \frac{1}{2\pi i}\int_{-i\infty}^{+i\infty} dp\, \bar{\Gamma}(p+1)\,\bar{\Gamma}(-p)\left(\frac{3\ell_i\lambda}{4}\right)^p F(s,p+1) \qquad (A.3)$$

where for $F(s,p)$ the following difference equation is fulfilled:

$$F(s,p)/J(s,p) = F(s,p+1)\,;\quad F(s,0) = 1 \qquad (A.4)$$

for the cascade gamma-ray spectrum we obtain:

$$\Gamma(\mathcal{E},t,\mathcal{E}_i)=\frac{1}{4(2\pi i)^2}\iint\limits_{-i\infty}^{+i\infty} ds\,dp\left(\frac{\mathcal{E}_i}{\mathcal{E}}\right)^{s+1}\Gamma(p+1)\left(\frac{3}{4}\frac{\mathcal{E}_i}{t}\right)^{p+1}F(s,p+1). \qquad (A.5)$$

Let now the source function is given in a power-law form $q(\mathcal{E}_i)=Q\mathcal{E}_i^{-\gamma}$. Then the spectrum at a depth t is determined by its convolution with the spectrum (A.5):

$$F_\gamma(\mathcal{E},t)=\frac{1}{E}\int dE_i\, q(\mathcal{E}_i)\Gamma(\mathcal{E},t,\mathcal{E}_i) \qquad (A.6)$$

Integration of expression (A.6) leads to the following result:

$$F_\gamma(\mathcal{E},t)=\frac{Q}{4(2\pi i)^2\mathcal{E}}\iint\limits_{-i\infty}^{+i\infty} ds\,dp\,\mathcal{E}^{-(s+1)}\Gamma(p+1)\left(\frac{3}{4t}\right)^{p+1}F(s,p+1)\times$$

$$\times\int\limits_{\mathcal{E}}^{\infty} d\mathcal{E}_i\,\mathcal{E}_i^{-\gamma+s+p+2}=\frac{Q}{4}\mathcal{E}^{-\gamma}\sum_{n=0}^{\infty}\frac{(-1)^n}{n!}\left(\frac{4}{3}\frac{t}{\mathcal{E}}\right)^n F(\gamma+n-2;n) \qquad (A.7)$$

For function F we have:

$$F(\gamma-2+n,-n+1)=F(\gamma-2+n,-n)/J(\gamma-2);\quad F(\gamma-2,0)=1. \qquad (A.8)$$

Therefore

$$F(\gamma-2+n,-n)=J(\gamma-2)F(\gamma-2+n,-n+1)=\left[J(\gamma-2)\right]^n \qquad (A.9)$$

Thus, for the cascade gamma-ray spectrum we finally obtain:

$$F_\gamma(\mathcal{E},t)=\frac{Q}{4}\mathcal{E}^{-\gamma}e^{-\frac{4t}{3\mathcal{E}}J(\gamma-2)} \qquad (A.10)$$

Hence, the photon absorption length , i.e. the distance

at which the flux of photons falls off by a factor of e is

$$t=\frac{3\mathcal{E}}{4J(\gamma-2)} \qquad (A.11)$$

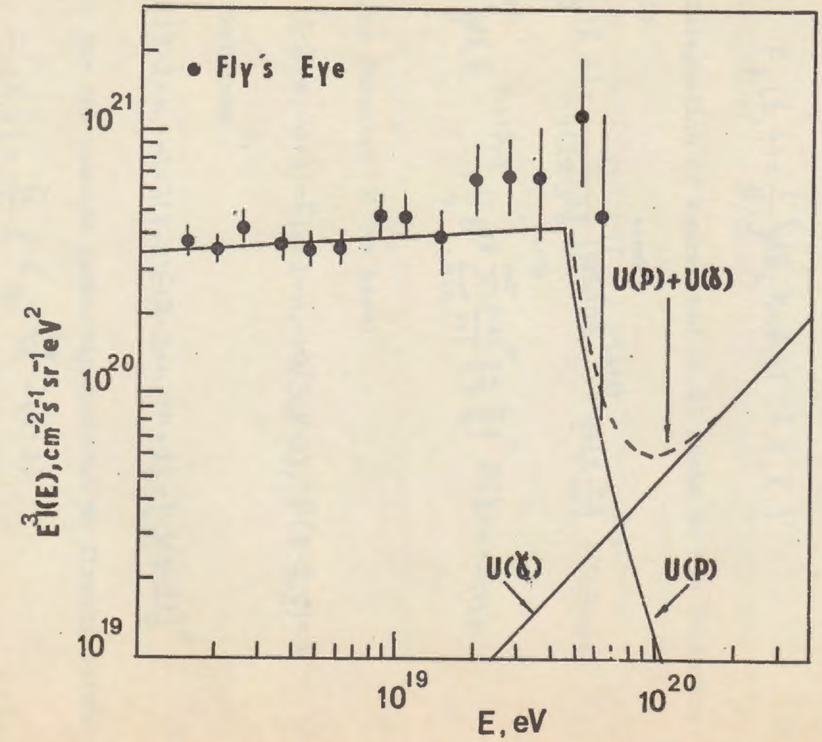
• Fly's Eye
$E^3I(E), cm^{-2}s^{-1}sr^{-1}eV^2$
10^{21}
10^{20}
10^{19}
10^{19}
10^{20}
E, eV
U(P)+U(γ)
U(γ)
U(P)

Fig.1

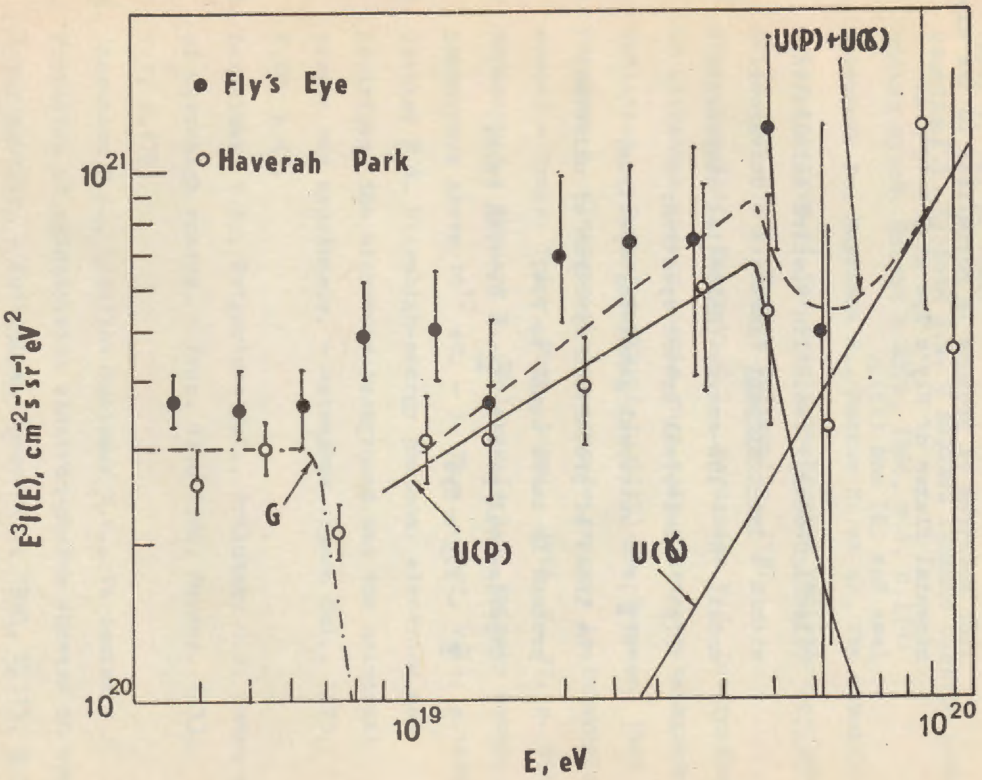
• Fly's Eye
○ Haverah Park
$E^3I(E), cm^{-2}s^{-1}sr^{-1}eV^2$
10^{21}
10^{20}
10^{19}
10^{20}
E, eV
U(P)+U(γ)
G
U(P)
U(γ)

Fig.2

Figure Captions

Fig.1. Equilibrium proton and gamma-ray spectra calculated within a universal <u>one-component</u> model. The production spectrum of protons is normalized to the experimental fluxes of Fly's Eye at $E < 10^{19}$ eV (see Eqs (2) and (13)).

Fig.2. Ultrahigh-energy radiation spectra calculated within a <u>two-component</u> (galactic + universal) model. "G" - low-energy (galactic) component; "U(p)" - universal proton spectrum; "U(γ)" - universal gamma-ray spectrum. The index of production spectrum of universal protons is taken equal to 2.4. Experimental points: ○ - Haverah Park, ● - Fly's Eye.

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ДИФФУЗНОЕ ВНЕГАЛАКТИЧЕСКОЕ ГАММА-ИЗЛУЧЕНИЕ В ОБЛАСТИ ЭНЕРГИИ "ЧЕРНОТЕЛЬНОГО ОБРЕЗАНИЯ" СПЕКТРА КОСМИЧЕСКИХ ЛУЧЕЙ
(на английском языке, перевод Асланян З.Н.)

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