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ЦЕНТРАЛЬНЫЙ НАУЧНО-ИССЛЕДОВАТЕЛЬСКИЙ ИНСТИТУТ
ИНФОРМАЦИИ И ТЕХНИКО-ЭКОНОМИЧЕСКИХ ИССЛЕДОВАНИЙ
ПО АТОМНОЙ НАУКЕ И ТЕХНИКЕ

F.A.AHARONIAN, A.M.ATOYAN

ULTRA-HIGH ENERGY GAMMA-RAYS - CARRIERS OF COSMOLOGICAL INFORMATION

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ГАММА-КВАНТЫ СВЕРХВЫСОКИХ ЭНЕРГИЙ - НОСИТЕЛИ КОСМОЛОГИЧЕСКОЙ ИНФОРМАЦИИ

Обсуждается возможность проверки ряда космологических гипотез путем поиска завалов в спектрах гамма-излучения сверхвысоких энергий от внегалактических источников.

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ULTRA-HIGH ENERGY GAMMA-RAYS - CARRIERS OF COSMOLOGICAL INFORMATION

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A possibility to verify a number of cosmological hypotheses by searching the cutoffs in spectra of ultra-high energy gamma-rays (UHEGR) from extragalactic sources is discussed.

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1. Introduction

One of the most significant problems of cosmology is the nature of the evolution of the Universe. Contemporary cosmological models are based on poor observational data: the Hubble law of redshifts, element abundances, observation of microwave background radiation (MBR). The significance of the MBR discovery for the model of hot expanding Universe (Big Bang) should be particularly noted. In the frame of this model the MBR was predicted, and the abundances of the simplest nuclei in the Universe could be explained (e.g., see [1]). The recent development of the Big Bang model is presumably connected with the discovery of MBR. As a consequence, other cosmological models are practically not considered at present (see, however, [2]). Meanwhile, radioobservations give information on MBR only near the Earth, i.e. in the contemporary epoch. At the same time a characteristic feature of all modifications of the Big Bang model is the considerable evolution of MBR. Hence, the experimental proof of the MBR evolution, i.e. probing of MBR in remote epochs, might present a direct certification of the Big B[illegible] hypothesis.

Similar information can be obtained only by investigations of particles having interacted with MBR in remote epochs. Obviously the carriers of the information are those particles which, firstly, effectively interact with MBR, and, secondly, allow to identify unambiguously the epoch of the interaction. The latter condition is reduced to the matching of these particles to certain sources with large redshifts ($z \geqslant 1$), and hence, to their straightforward propagation in the intergalactic space. Only the "labeled" gamma-rays of ultra-high energies, i.e. the photons with energies $E_\gamma \geqslant 10^{13}$ eV, emitted by sources at cosmological distances satisfy all these requirements. The main interaction channel of these high-energy gamma-rays in the intergalactic space is the photoproduction of e^+e^- pairs in the MBR field [3-6]. It should be noted that owing to small density of the intergalactic gas ($\langle \ell \rho \rangle \lesssim \frac{c}{H_0} \rho_{cr} \simeq \frac{3H_0c}{8\pi G} \sim 0{,}1 \frac{g}{cm^2}$) this reaction is practically the only one possible at the energies $E_\gamma < 10^{21}$ eV, therefore, the information arrives at the observer without any significant distortion.

2. Interaction of gamma-rays with MBR

Two colliding photons with energies E_γ and ε may produce an e^+e^- pair, provided

$$E_\gamma \geqslant 2m_e^2 c^4 / \varepsilon (1 - \cos \theta) \qquad (1)$$

where θ is the collision angle, m_e is the electron rest mass. In the case of propagation of gamma-rays in the isotropic field of photons with the mean energies $\hbar\omega$, the photoproduction cross section, averaged over the angle θ , depends only on the parameter $b = E_\gamma \hbar\omega / m_e^2 c^4$:

$$< \sigma > = \frac{1}{2} \int_{-1}^{1-2/b} (1 - \cos\theta)\, \sigma_0 \, d\cos\theta, \qquad (2)$$

where σ_0 is the total cross section of e^+e^- pair production. Starting from the threshold value of $b = 1$, it increases rapidly ($\propto (b-1)^{3/2}$) to the maximum at $b = 3$, and then slowly decreases as $b^{-1} \ln b$ [4]. The mean free path λ of gamma-rays in the black-body radiation field with the temperature T_0 was calculated in [4]:

$$\lambda^{-1} = \frac{\alpha^2}{\pi \Lambda} \left(\frac{\kappa T_0}{m_e c^2} \right)^3 f(\nu) . \qquad (3)$$

Here $\alpha = 1/137$, $\Lambda = \hbar / m_e c \simeq 3.86 \cdot 10^{-11}$ cm. The function $f(\nu)$, where $\nu \equiv (m_e c^2)^2 / \kappa T_0 E_\gamma$ is tabulated in [4]. It has a maximum $f_{max} \sim 1$ at $\nu \sim 1$. In the limit of $\nu \ll 1$ the function $f(\nu)$ can be expressed in the form

$$f(\nu) \simeq \frac{\pi^2}{3} \nu \ln(0{,}467/\nu) + \nu^2 \left[\frac{1}{3} \ln^3 \nu^{-1} + (2\ln 2 - 1) \ln^2 \nu^{-1} \right] . \qquad (4)$$

In the opposite limit of $\nu \gg 1$ the analytical expression for $f(\nu)$ given in [4], is not correct, and since we are further on interested in this very range of ν , we bring here the corrected formula for $f(\nu)$.

Expanding the cross section σ_0 in eq.(2) in temrs of the parameter $(b-1)^{1/2}$ and integrating over the angle θ , we easily find the averaged cross section near the threshold of the reaction ($b - 1 \ll 1$).

$$< \sigma > = \frac{4\pi r_0^2}{3 b^2} \left[(b-1)^{3/2} + \frac{3}{10} (b-1)^{5/2} \right] . \qquad (5)$$

Then for the function $f(\nu)$ we have ($\nu \gg 1$):

$$f(\nu) = \left(1 + \frac{3}{4\nu}\right)\sqrt{\pi\nu}\, e^{-\nu}. \qquad (6)$$

It follows from eq.(3) that the mean free path λ of gamma-rays in the MBR field with $T_0 = 2.7$ K is minimal at $E_\gamma \simeq 10^{15}$ eV ($\nu \sim 1$) and is ~ 8 kpc. For the gamma-rays both of smaller and greater energies the free path increases due to different reasons. At $E_\gamma \gg 10^{15}$ eV the free path slowly increases as $E_\gamma \ln^{-1} E_\gamma$ due to decreasing behaviour of the cross section at $b \gg 1$, whereas at $E_\gamma \ll 10^{15}$ eV λ decreases abruptly (exponentially) since owing to the threshold of the reaction gamma-rays may interact only with photons in the Wien "tail" of MBR distribution. In the latter case a simple dependence of λ on E_γ holds:

$$\lambda \simeq 1{,}8 \cdot 10^{-2}\left[\left(1 + \frac{3}{4\nu}\right)\sqrt{\nu}\,\right]^{-1} e^{\nu} \qquad (7)$$

It follows from eq.(7) that λ changes in a broad range $\lambda \sim 10^{3} \div 10^{4}$ Mpc, corresponding to distances to QSOs, when E_γ changes in the range $(1.4 + 0.7) \cdot 10^{14}$ eV. It should be however noted that eq.(7) is obtained under condition of isothermal Planckian distribution of MBR. Meanwhile, for cosmological distances the evolutionary effects e.g. the temperature change of MBR in the Big Bang model, may become very important, and they should be taken into account.

Let N photons with the energies $E_\gamma(z) = E_\gamma(1+z)$ move in the direction to the observer. The rate of beating these photons out of the beam is given by equation

$$\frac{dN}{dt} = -Nc\int_{\omega_0(z)}^{\infty} \langle\sigma\rangle \frac{dn(\omega,z)}{d\omega}\, d\omega, \qquad (8)$$

where $dn/d\omega$ being the distribution of MBR photons in the z epoch.

In the case of Planckian distribution of MBR we may use

$$dn(\omega, z) = \frac{\omega^2 d\omega}{\pi^2 c^3 \left\{ \exp\left[\frac{\hbar\omega}{kT(z)} \right] - 1 \right\}} \qquad (9)$$

where

$$T(z) = T_0(1+z) , \qquad (10)$$

T_0 = 2.7 K is the temperature of MBR at present. E_γ is the energy of detected gamma-rays, and

$$\hbar\omega_c(z) = m_e^2 c^4 / E_\gamma(1+z) \qquad [illegible]$$

Equation [illegible] describes [illegible] rate in the expanding system of [illegible] for the laboratory observer's frame the effect of relativistic retardation of time should be taken into account

$$[illegible] \qquad [illegible]$$

where

$$\varphi = [illegible]$$

$$H_0 t(z) = \int_0^z \frac{dx}{(1+x)^2 \sqrt{1+\Omega x}} \qquad [illegible]$$

H_0 is the Hubble's constant, $\Omega = \rho/\rho_{cr}$, $\rho_{cr} = 6 \cdot 10^{-30}$ g/cm^3 is the critical density (at H_0 = 55 km/s·Mpc) (see e.g. [1]). Expressing then dt by dz , and integrating eq.(8) over $d\omega$ and dz (0 to z_0), we finally obtain

$$N(E_\gamma) = N_0(E_\gamma) \exp\left[-\tau(E_\gamma, z_0)\right] , \qquad (14)$$

where

$$\tau(E_\gamma, z_0) = A\sqrt{\nu} \int_0^{z_0} \varphi(z) \frac{e^{-\nu/(1+z)^2}}{\sqrt{1+\Omega z}} dz \simeq$$

$$\simeq \frac{A}{2}\,\frac{(1+z_0)^3}{(1+\Omega z_0)^{1/2}}\,\varphi(z_0)\,\nu^{-1/2}\,e^{-\nu/(1+z_0)^2}\left[1+O\left(\frac{1}{\nu}\right)\right]. \tag{15}$$

$$A=\frac{r_0^2(\kappa T_0)^3}{\sqrt{\pi}\,\hbar^3 c^2 H_0}\ ; \qquad \nu=\frac{m_e^2c^4}{\kappa T_0 E_\gamma}\ . \tag{16}$$

As it will be seen below, in the energy range of interest the magnitude of the parameter $\nu \gg 1$, therefore, the accuracy of the approximate formula (15) is quite sufficient if $\nu\left[1-(1+z_0)^{-2}\right]>3$. At $z_0 \to 0$ from the condition $\tau(E_\gamma, z_0)=1$ one may obtain a formula for the mean free path λ coinciding with eqs. (3) and (6), taking into account that $R=cz_0/H_0$ for $z_0 \ll 1$.

We have so far assumed that the Planckian distribution of MBR is valid. In fact, however, the observational date which are in a good agreement with this distribution law, relate mainly to the Rayleigh-Jeans part of the spectrum i.e. to $\lambda_{MBR} < 1$ mm. For shorter wavelengths there are no reliable data as yet. Meanwhile, the possible deviations of the MBR distribution from the Planckian law in submillimeter range of wavelengths is widely discussed in literature (see e.g. [8]). Particularly, it may be due to the comptonization of MBR, if a late energy release has occured (at $z \leq 10^4$). In this case the MBR spectrum is described by the expression [1,8]

$$n(x,y)=\frac{e^{-9y/4}}{\sqrt{4\pi y}}\int_0^\infty \frac{1}{e^{x\xi}-1}\,\xi^{\left(\frac{1}{2}-\ln\xi/4y\right)}\,d\xi \tag{17}$$

where $x \equiv \hbar\omega/\kappa T_0$, and the comptonization parameter y is equal to

$$y=\int \frac{\kappa T_e(t)}{m_e c^2}\,\sigma_T c N_e(t)\,dt\ . \tag{18}$$

The analysis performed by Fild and Perrenod [9] indicates that the available observational data do not contradict the magnitude of $y \leqslant 0.055$. Even at so small comptonization parameter the deviations of the MBR spectrum from the Planckian one in the Wien "tail" become very significant and result in a noticeable shift of the expected cut-off point in high-energy gamma-ray spectra.

3. Possible cosmological tests

[illegible] emit gamma rays with the [illegible] spectrum up to the [illegible] absorption [illegible] then [illegible]

[illegible]

[illegible] thickness of inter[illegible] [illegible]

As has been noted above, the mean free path (corresponding to $\tau_\lambda(E_\gamma) = 1$) is minimal for gamma-rays with energies $\sim 10^{15}$ eV and is ~ 8 kpc. It means that the intergalactic space is opaque for photons with energies $E_\gamma \geqslant 10^{15}$ eV. For this very reason the detection of primary gamma-rays with $E_\gamma \geqslant 10^{15}$ eV has become the first observational certification of the existence of Galactic sources of ultra-high energy gamma-rays [10].

In the case of photons of smaller energies the mean free path λ sharply increases due to the threshold of the reaction enabling only the photons in the Wien "tail" of MBR distribution to interact with the gamma-rays of those energies.

As it follows from eq.(8), when E_γ changes in the energy range $(0.7 \div 1.4) \cdot 10^{14}$ eV, λ changes in a wide range $10^4 - 10^1$ Mpc. Thus, in a relatively narrow range of energies a sharp cut-off in the high-energy gamma-ray spectra of extragalactic sources should be expected. The precise cut-off point of the spectra depends on the distance R to the source on the spectrum of MBR in submillimeter range of wavelengths as well as on the evolution of MBR in time. This fact yields a unique possibility to solve a number of cosmological problems.

It should be noted that at present a number of ground-based installations for investigations of primary gamma-rays in the energy ranges $10^{11} \div 10^{13}$ eV (detecting the Čerenkov radiation of small air showers) and $E_\gamma \geqslant 5 \cdot 10^{14}$ eV (searching for EAS with anomalously small content of muons) successfully operate. And it is remarkable that both these techniques have a principle possibility to widen the range of measurements to $10^{13} - 10^{14}$ eV. This allows to hope that the fundamental possibilities considered may be realized (at least partially) in a not so far future.

3.1 Investigation of extragalactic sources with small z_0

a) Objects with well known distances

The distance R to the source with small z_0 being known, the optical thickness $\tau_R(E_\gamma)$ and, therefore, the expected cut-off energy E_c are determined only by the MBR spectrum at submillimeter wavelengths. Thereby, the direct probing of this not yet investigated range of MBR becomes possible. As has been noted above, at these wavelengths some deviations of the spectrum from the Planckian distribution are expected first of all due to the possible comptonization of MBR, in which case the spectrum of MBR is described by eq.(17).

In fig.1 the gamma-ray spectra N/N_0 expected from a source at $R = 5$ Mpc (corresponding to the radiogalaxy Cen A) are shown. The cut-off energy E_c further on defined by equation $N(E_c)/N_0(E_c)=e^{-1}$ is essentially shifted towards the smaller energies from $E_c \simeq 1.4 \cdot 10^{14}$ eV to $E_c \simeq 8 \cdot 10^{13}$ eV, when the comptonization parameter y changes from $y = 0$ to $y = 0.05$, respectively. As is seen, in order to separate $\Delta y = 0.01$ detectors should have an energy resolution of $\sim 10\%$.

It should be noted here that there also may occur deviations from the Planckian distribution due to other reasons. For example, a hump may occur in the wavelengths [illegible] due to the superposition of [illegible] recombination radiation [illegible] 2) [illegible] measurements of [illegible] them [illegible] using probes [illegible] not only because of difficulties (owing to a [illegible]) and local background radiation, but what is much more essential, they may be impossible at all owing to a presumed background radiation of the interstellar dust [13] and gas [14]. Obviously, the influence of these factors is excluded in the method of investigation suggested here.

[illegible] the shape of the MBR spectrum at submillimeter wavelengths, the high-energy gamma-ray sources at well known distances should be investigated. Along with the above-mentioned radiogalaxy Cen A as convenient sources for this purpose may serve the active galaxies NGC 4151 ($R = 20$ Mpc), MGC 8-11-11 ($R = 160$ Mpc) and 3C 120 ($R = 200$ Mpc) from which according to contemporary ideas, ultra-high energy gamma-rays are expected. For widening the probing range of MBR towards shorter wavelengths, the observations of more remote objects, i.e. QSOs are needed. However, it is necessary to make sure before that QSOs are really located at cosmological distances.

b) QSO's distance ranging

The QSOs, which have been discovered more than 20 years ago, are still covered with mystery. Though most astronomers agree that the redshifts observed in the optical spectra of QSOs have a cosmological origin, there is, however, no final refutation of the arguments in favor of local placement of these objects (e.g., see [15]). The main obstacle for elucidation of this problem is the absence of a model-independent method for determination of the distances to QSOs.

We have discussed above the opportunity to reconstruct the submillimeter spectrum of MBR investigating the spectra of ultra-high energy gamma-ray sources with known distances to them. Provided the spectrum is established with sufficient accuracy, it will be possible to determine model-independently the distances to extragalactic sources, using the relation $R = \lambda(E_c)$, where E_c is the cut-off energy in the observed gamma-ray spectrum N/N_0, and λ is the mean free path of gamma-rays. For the Planckian distribution of MBR λ is given by eq.(7).

Unfortunately, due to very abrupt dependence of λ on E, this problem seems to be very difficult from the experimental viewpoint. The error in R, caused by uncertainty of E_c, can be approximated in the energy range [illegible] as

$$dR/R \sim \nu \, dE_c/E_c \sim 10 \, dE_c/E_c \qquad (20)$$

that is, to obtain the value of R with the accuracy $\leqslant 50\%$, the energy E_c should be determined with an accuracy not worse than 5%.

Moreover, there is another reason for possible uncertainties in E_c. Indeed, the condition $R \gg \lambda(E_\gamma)$ itself does not mean that the intergalactic medium is entirely opaque for the gamma-rays of these energies. Not only the absorption of the high-energy gamma-rays, but also their production due to the Compton scattering of secondary electrons and positrons take place in the MBR field. Obviously, the observable spectrum of high-energy gamma-rays will be defined by relativistic electromagnetic cascade in the MBR field. In fig.2 the high-energy gamma-rays spectrum which is formed at the distance $R = 100$ Mpc from the source of monochromatic radiation with $E_\gamma = 10^{15}$ eV is shown. The numerical calculations of the electromagnetic cascade was performed by the Monte-Carlo simulation technique according to [16]. Owing to large values of optical thicknesses with respect to photoproduction and Compton scattering processes, the observed spectra weakly depend on the initial spectra of gamma-rays emitted in the range of superhigh energies $E_\gamma \gg E_c$, i.e., gamma-rays come to the observer with a "standard" spectrum. As is seen from fig.2, the spectrum cut-off is slightly deviated from the value E_c which is expected from the condition $\tau(E_c) = 1$. This will worsen the accuracy of distance ranging. It should be noted, however, that the spectrum shown in fig.2 was calculated without taking into account the magnetic field. In the magnetic field with a characteristic scale of magnetic inhomogeneities of the order Λ greater than the Larmouer radius r_L, the secondary electrons will be deflected at the length Λ to an angle $\Delta\theta \sim r_L/\Lambda$ [17]. For characteristic magnitudes of $H \sim 3 \cdot 10^{-9}$ Gs and $\Lambda \sim 10^{21}$ cm in the intergalactic space [17] we have $\Delta\theta \sim 0.1$. At the same time, since the mean free path of electrons with $E_{\gamma} \sim 10^{14}$ eV ($\Lambda_{c.r.} \sim 10^{22}$ cm) is greater than Λ, in effect the secondary electrons will be deflected out of the beam prior to secondary gamma-ray emission in the inverse Compton scattering process. Therefore, a detector with angular resolution $\Delta\theta < 5^{\circ}$ will be not sensitive to secondary photons of electromagnetic cascade.

While the test of cosmological origin of QSO's redshifts seems to be a relatively easy experimental problem, the accurate measurment of distances to QCOs requires precise spectral measurements. If the cosmological origin of the redshifts is established for certain, it will be possible to determine the value of Hubble's constant for distances $R > 100$ Mpc, i.e. $H_0 = cz_0/R$. In fig.3 the spectra from a source with $z_0 \simeq 2.5 \cdot 10^{-2}$ that corresponds to $R = 100$ Mpc or $R = 150$ Mpc at $H_0 = 75$ km/s · Mpc or $H_0 = 50$ km/s · Mpc, respectively, are shown. As is seen from this figure, in order to choose one of these values for H_0, a detector with the energy resolution not worse than 5% is needed. At the same time one should once more stress the significance of the accurate knowledge of the MBR spectrum at submillimeter wavelengths.

For the realization of the above task, the nearest QSOs ($z_0 \ll 1$) such as 3C 273 and 0241+622, for which the evolution effects are not very essential, seem to be most convenient. The observation of QSOs with $z_0 \gtrsim 1$ allows investigation of the character of the MBR evolution in time.

3.2. Extragalactic sources with $z_0 \gtrsim 1$

Provided the cosmological origin of QSO's redshifts is finally confirmed, it will be possible to use the observations of these most remote objetcs of the Universe ($z_0 \lesssim 3$) for probing the MBR in ancient epochs. According to contemporary viewpoints, the MBR should strongly evolve in time. The temperature and photon density of MBR increase proportional to $(1 + z)$ and $(1 + z)^3$, respectively. Besides, the gamma-rays have been more energetic in the epoch z, i.e. $E_\gamma(z) = E_\gamma \cdot (1+z)$ E_γ being the energy of detected gamma-rays. All these factors bring to an essential increase of optical depth and, therefore, to a significant shift of the expected cut-off energy E_c. The cut-off energy E_c is determined by equation $\tau(E_c, z_0) = 1$ where z_0 is the redshift of the source, and $\tau(E_\gamma, z_0)$ is the photoproduction optical depth, which is described by eq.(15) in the case of the Planckian distribution of MBR. One may easily ensure that the main dependence of E_c on z_0 is described by the relation $E_c \propto (1 + z_0)^{-2}$. Hence, z_0 being even as small as $z_0 = 0.1$, the evolution of MBR will lead to a 20% shift of the cut-off energy E_c

In fig.4 the spectra of high-energy gamma-rays expected from sources with different z_0 are given. It is seen that if the evolution of MBR takes place, the cut-off of the gamma-ray spectra should be expected in a wide range of energies $E_\gamma \sim 10^{12} \div 10^{14}$ eV depending on the magnitude of z_0 (solid curves). In the opposite case (no evolution of MBR) all the cut-offs will be about $\sim 7 \cdot 10^{13}$ eV (dotted curve).

Thus, the reliable observation of even one QSO with $z_0 \gtrsim 1$ will give unambiguous information on the presence or absence of the MBR evolution. It should be noted that the spectra given in fig.4 are calculated for the Planckian distribution of MBR and for $H_0 = 75$ km/s · Mpc. Possible derivations of MBR from the Planck's distribution law as well as uncertainty in H cannot result in a substantial change of the cut-off energy Indeed, E_c depends on H_0 only logarithmically, and at the maximum available $y = 0.055$ [9] the value of E_c shifts only twice (see fig.1). Moreover, compairing a number (at least two) of spectra with various E_c would enable to exclude these uncertainties and to come to unambiguous conclusions. Obviously, a high energy resolution of detectors is not necessary for this problem.

We have so far assumed that QSOs and AGNs emit gamma-rays of ultra-high energies. Forcible arguments in favour of possible acceleration of particles and production of secondary neutrinos and gamma-rays (due to π -meson decay) of ultra-high energies in QSOs and AGNs were given in [18,19]. Though the ultra-high energy gamma-rays may be absorbed in the field of X-ray photons directly in the source [20], it is, however, essential first of all for gamma-rays of moderate energies ($E_\gamma < 10^{12}$ eV) being connected with the decreasing behaviour of the photoproduction cross section ($\propto E^{-1} \ln E$) at $E_\gamma \gg \frac{m_e^2 c^4}{\hbar\omega}$. As a result, the gamma-rays with $E_\gamma > 10^{12}$ eV easily overcome the X-ray "barrier" of sources [21]. Besides, there are observational evidences of the possible anisotropy of the radiation of QSOs and AGNs [22], which also favours the gamma-ray escape from the source. It is worth noting that gamma-rays with $E_\gamma > 10^{12}$ eV have already been observed from the nearest active galaxy Cen A ($R = 5$ Mpc) [23].

Theoretically expected luminosities in neutrino and gamma-rays of ultra-high energies from QSOs and AGNs allow to hope that they can be detected in the designed experiments for registration of neutrinos (DUMAND project) and gamma-rays [24]. Correlated $\gamma - \nu$ observations seem to be very important since they will allow to establish unambiguously whether the cut-offs of the spectra are connected with absorption of gamma-rays in MBR field or they simply reflect the peculiarities in the spectra of accelerated protons and nuclei.

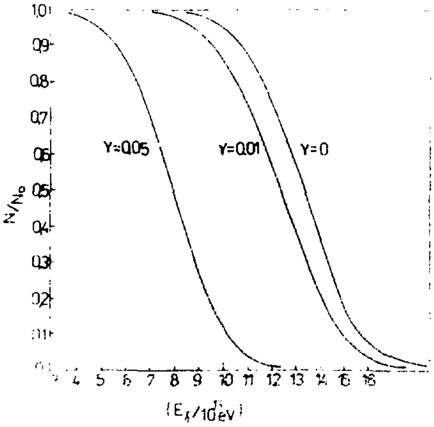

1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
N/N₀
Y=0.05
Y=0.01
Y=0
4
5
6
7
8
9
10
11
12
13
14
15
16
(E_γ/10 eV)

Fig.1

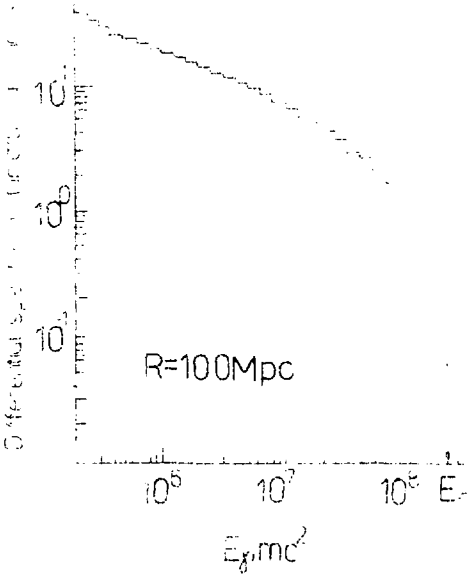
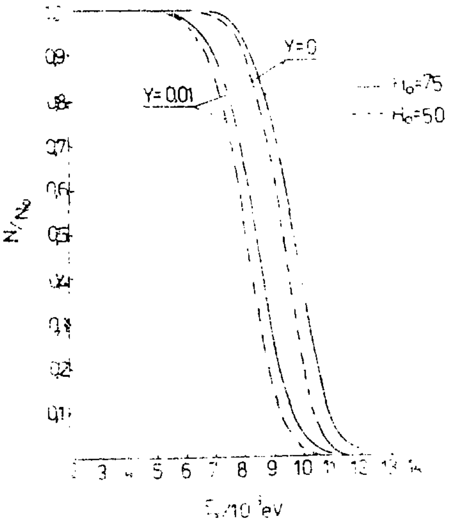
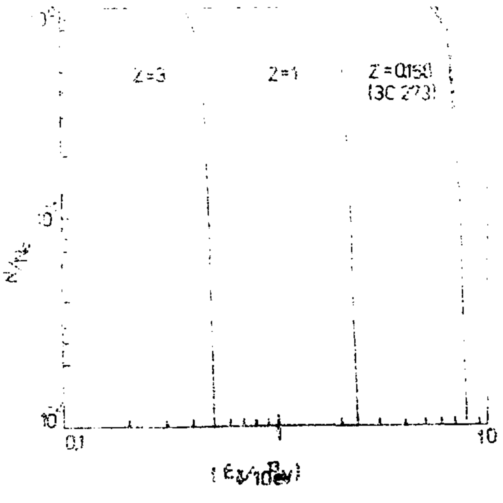

10
10
10
R=100Mpc
10⁵
10⁷
10⁹
E
E_γ/mc²

Fig.2



N/N0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Y=0
Y=0.01
H0=75
H0=50
3
4
5
6
7
8
9
10
11
12
13
14
E/10 eV

Fig.3



N/N0
Z=3
Z=1
Z=0.158
(3C 273)
0.1
1
10
(Eγ/10 eV)

Fig.4

Figure Captions

Fig. 1 Gamma-ray spectra N/N_0 expected from a source at the distance $R = 5$ Mpc for different values of comptonization paremeter y.

Fig. 2 Monte-Carlo calculations of the gamma-ray spectrum $N(E_\gamma)$ formed by electromagnetic cascade in the intergalactic space (the distance from the source $R = 100$ Mpc).

Fig. 3 Gamma-ray spectra N/N_0 expected from the source with cosmological redshift $z_0 = 0.$[illegible]

Fig. 4 Gamma-ray spectra N/N_0 expected from sources [illegible] different values of cosmological redshifts [illegible]. [illegible] dotted curve corresponds to a spectrum [illegible] with $z_0 = 1$, if MBR evolution is absent

References

1. Зельдович Я.Б., Новиков И.Д. Строение и эволюция Вселенной. М.: Наука, 1975.

2 Alfven H. Cosmic Plasma, D.Reidel publ.comp, 1981.

3 Jelley J.V. High-energy gamma-ray absorption in Space by a 3.5 K microwave field. - Phys.Rev.Lett., 1966, vol.16, p.479.

4 Gould R.J., Schreder G.P. Opacity of the Universe to high-energy photons. - Phys.Rev., 1967, vol.155, p.1404.

5 Brown R.W., Mikaelian K.O., Gould R.J. Absorption of high-energy cosmic photons through double pair production in photon-photon collisions. - Astrophys.Lett., 1973, vol.14, p.203.

6 Иоширян Н.А., Матинян С.Г. К вопросу о превращении фотонных пар в адроны при высоких энергиях. Письма в ЖЭТФ, 1968, т.7, с.232.

7 Gould R.J. Galactic absorption of high-energy gamma-rays from Cyg X-3. - Astrophys.J., 1973, vol.274, p.L23.

8 Zeldovich Ya.B., Sunyaev R.A. The spectrum of primordial radiation, its distortions and significance. - Astrophys. Space Sci., 1969, vol.4, p.302.

9 Field G.B., Perrenod S.C. Constraints on a dense hot intergalactic medium. - Astrophys.J., 1977, vol.215, p.717.

10 Агаронян Ф.А., Мамиджанян Э.А., Никольский С.И., Тукиш Е.И. Первичное гамма-излучение с энергией 10^{14}-10^{16} эВ и возможные источники космических лучей в Галактике. Астрофизика, 1985, т.21.

11 Зельдович Я.Б., Курт В.Г., Сюняев Р.А. Рекомбинация водорода в горячей модели Вселенной. ЖЭТФ, 1968, т.55, с.278.

12. Peebles P.J.E. Recombination of primeval plasma. - Astrophys.J., 1968, vol.153, p.1.

13 Partridge R.B., Peebles P.J.E. Are young galaxies visible ? The integrated backgrouns. - Astrophys.J., 1967, vol.147, p.377.

14 Petrosian V., Bahcall J.N., Salpeter E.E. Fine structure transitions and the background microwave radiation. - Astrophys.J., 1969, vol.155, p.157.

15 Burbidge G. Evidence for non-cosmological redshifts - QSO's near bright galaxies and other phenomena, in: Objects of high redshift, Eds. G.O.Abell, P.J.E.Peebles, 1980, p.9

16 Aharonian F.A., Kirillov-Ugryumov V.G., Vardanian V.V. Development of high-energy electromagnetic cascades [illegible] ed by relativistic electrons and gamma-rays in hot [illegible] gases. - Preprint EPU-676(60)-83, 1983.

17 Гинзбург В.Л., Сыроватский С.И. Происхождение космических лучей. М.: Изд-во АН СССР, 1963.

18 Berezinsky V.S., Ginzburg V.L. On high-energy neutrino radiation of quasars and active galactic nuclei. - [illegible], 1981, vol.194, p.[illegible]

19 Kafatos M., Shapiro M.M., Silberberg R. Extragalactic variable sources and cosmic-ray acceleration near massive black holes. - Comments on Astrophys., 1981, vol.9, p.179.

20 Bassani L., Dean A.J. Absorption of gamma-rays in active galaxies as a test of the jet hypothesis. - Nature, 1981, vol.294, p.332.

21 Агаронян Ф.А., Варданян В.В., Кириллов-Угрюмов В.Г. Релятивистские электронно-фотонные ливни в ядрах активных галактик и квазаров. Астрофизика, 1984 ,т.20, с.2[illegible]3.

22 Bassani L., Dean A.J., Sembay S. Super-Eddington luminosity characteristics of active galactic nuclei. - Astron.

Astrophys., 1983, vol.125, p.52.

23 Stenger V.J. Dumand and high-energy neutrino astronomy. - Preprint HDC-1-84, Univ.Hawaii, 1984.

24 Grindlay J.E., Helmken H.F., Brown R.H., Davis J., Allen R.L., Evidence for the detection of gamma-rays from Centaurus A at $E_\gamma \geqslant 3 \cdot 10^{11}$ eV. - Astrophys.J., 1975, vol.197, p.L9.

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