ULTRAHIGH ENERGY GAMMA RAYS - CARRIERS OF COSMOLOGICAL INFORMATION

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ABSTRACT

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

One of the most significant problems of cosmology is the nature of the evolution of the Universe. Observational data being the basis of contemporary cosmological models are not numerous: Hubble law of redshift for galaxies, element abundances, observation of cosmic microwave background radiation (MBR). The significance of MBR discovery predicted in the Big-Bang model should particularly be stressed. Meanwhile, radioastronomical measurements give an information on MBR only near the Earth, i.e. at present epoch. Experimental confirmation of evolution of MBR, i.e. its probing in remote epochs, might obviously present a direct verification of the hypothesis of hot expanding Universe. The carriers of similar cosmological information should be particles which, firstly, effectively interact with MBR, and secondly, make it possible to identify unambiguously the epoch of interaction. These requirements are satisfied with gamma rays of ultrahigh energies ($E_\gamma \geqslant 10^{13}$ eV) emitted by discrete sources at cosmological distances.

The cross section of e^+- e^- pair production at photon-photon collisions of gamma rays with isotropically distributed monoenergetic photons depends only on parameter $b = \hbar\omega E_\gamma / m^2c^4$, E_γ and $\hbar\omega$ being the energies of gamma rays and field photons, respectively. Starting from the threshold value of b=1 the cross section increases rapidly to the maximum at b=3, and then decreases slowly as $b^{-1} \ln b$ /1/. In the case of Planckian distribution of MBR (temperature T_0 = 2.7 K) the free path λ of gamma rays is minimal at $E_\gamma \sim 10^{15}$ eV being equal to ~8 kpc. A weak increase of $\lambda \propto E_\gamma \ln^{-1} E_\gamma$ at $E_\gamma \gg 10^{15}$ eV is explained by the decrease of the cross section at $b \gg 1$, whereas at $E_\gamma \ll 10^{15}$ eV the free path $\lambda(E_\gamma)$ increases sharply due to the threshold nature of the reaction owing to which gamma rays interact only with the Wien "tail" photons of MBR. In the latter case a simple dependence of λ on E_γ takes place /1,2/:

$$\lambda(E_\gamma) \simeq 1.8 \cdot 10^{-2} \left[\left(1 + \frac{3}{4\nu}\right) \sqrt{\nu} \right]^{-1} e^{\nu} \ \mathrm{Mpc}, \tag{1}$$

where $\nu = m^2c^4 / \kappa T_0 E_\gamma$. At E_γ changing in the range $(0.7 \div 1.4) \cdot 10^{14}$ eV, λ changes in a wide range $10^{1} \div 10^{4}$ Mpc. In Eq.(1), however, the evolution of MBR is not taken into account, whereas it becomes essential for $R \geqslant 100$ Mpc. The evolution of the MBR in the Big-Bang model being considered, the optical depth τ with respect to pair production is expressed in the form /2/:

$$\tau(E_\gamma) = \frac{r_0^2 (kT_0)^3}{2\sqrt{\pi}\hbar^3 c^2 H_0} \frac{(1+z_0)^2 [1+(1+z_0)^2 g^2]}{2g\sqrt{1+\Omega z_0}} \nu^{-1/2} e^{-\nu/(1+z_0)^2} , \qquad (2)$$

where

$$g = 1 + \frac{\Omega}{4}(1+z_0)^3 \left[\int_0^{z_0} \frac{dx}{(1+x)^2\sqrt{1+\Omega x}} \right]^2 .$$

T_0 =2.7 K is the present value of MBR temperature, E_γ is the energy of detected gamma rays, H_0 is the Hubble constant, z_0 is the cosmological redshift of the gamma-ray source, and $\Omega = \rho/\rho_{cr} = 8\pi G\rho/3H_0^2$. The accuracy of Eq.(2) is acceptable if $\nu[1-(1+z_0)^{-2}] > 3$. Since observable spectrum of gamma rays $N(E_\gamma)$ is related to initial gamma-ray spectrum of the source $N_0(E_\gamma)$ by equation $N = N_0 \cdot \exp(-\tau)$, in the energy range of E_γ , when $\tau(E_\gamma) \geqslant 1$, a sharp cutoff of the spectrum $N(E_\gamma)$ should be expected. Eqs.(1) and (2) correspond to Planckian distribution of MBR. Meanwhile, the reliable data which are in good agreement with this distribution correspond only to Rayleigh-Jeans part of the spectrum. Moreover, for submillimeter wavelengths there are intensely discussed in literature possible deviations of MBR from Planckian distribution, particularly due to comptonization of MBR /3/. The analysis performed by Field and Perrenod /4/ indicates that current observational data do not contradict the comptonization parameter $y \leqslant 0.05$. The deviations of MBR from Planckian distribution ($y=0$) may lead to noticeable shift of expected cutoff energy E_c , determined by equation $\tau(E_c) = 1$.

Thus, cutoff energy E_c of the spectrum N/N_0 is defined by the distance R from the source, by the spectrum of MBR in submillimeter range, and by the character of MBR evolution in time. Therefore there is a unique opportunity to solve a number of urgent cosmological problems /2/.

i) Probing of submillimeter range of MBR spectrum.

The distance R to the gamma-ray source with $z_0 \ll 1$ being known, the optical depth τ depends mainly on MBR spectrum at submillimeter wavelengths. In Fig.1 the spectra N/N_0 expected from a source at the distance R=5 Mpc (corresponding to distance of the nearest radiogalaxy Cen A) are plotted. Comptonization parameter y changes from 0 to 0.05, the cutoff energy E_c shifts down from $1.4 \cdot 10^{14}$eV to $8 \cdot 10^{13}$eV. It can be seen from the figure that to obtain the comptonization parameter with accuracy of $\Delta y = 0.01$ the energy resolution of a detector should be $\leqslant 10\%$.

ii) QSO distance ranging.

Though most of astronomers are in agreement that the redshifts of QSOs have a cosmological origin, there is not yet a final refutation of the arguments brought in favour of the local placement of these surprising objects (see, e.g. /5/). Above we have discussed the possibility to probe the submillimeter range of the MBR spectrum observing the sources at well-known distances R. Supposing now that the spectrum of MBR is established with sufficient accuracy, it would be possible to carry out model-independent estimations of the distances to the extragalactic sources: $R = \lambda(E_c)$. To prove unambiguously the cosmological origin of QSOs, it would be enough to observe even one QSO spectrum with cutoff in the range $E_c \leq 10^{14}$eV. Precise measurements of R is however a more complicated problem. For example, to determine the value of R with accuracy of ~50% the energy resolution of detectors should be $\leq 5\%$. Moreover, when carrying out precise spectrometric measurements, it should be taken into account that the secondary gamma rays produced at development of relativistic electromagnetic cascade in MBR field may result in deviations of observed spectrum from the law $N/N_o = \exp(-\tau)$. This is illustrated in Fig.2 where the spectrum of gamma rays which is formed at R=100 Mpc from a source is shown. Numerical calculations have been performed by Monte-Carlo simulation in accordance with /6/. As one can see from the figure, the cutoff region is somewhat "smeared" around the value of E_c expected from the condition $\lambda(E_c)$=100 Mpc. It should be noted, however, that the deflections of secondary electrons in magnetic field being taken into account, a detector with angular resolution $\Delta\theta \leq 5$ will not be sensitive to the photons of the electromagnetic cascade, if $H \geq 3 \cdot 10^{-9}$ G.

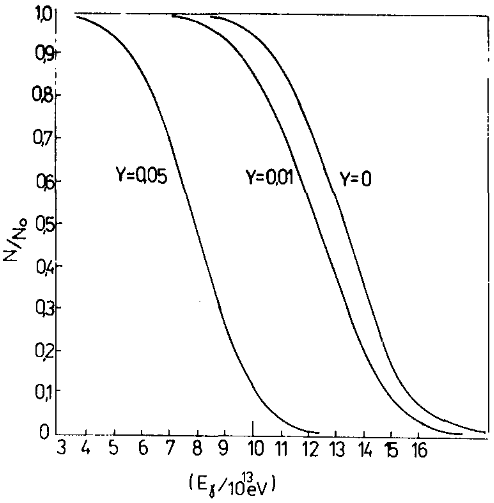


Fig. 1

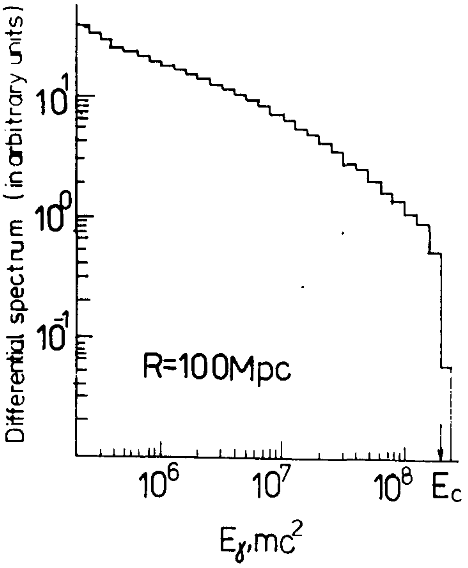
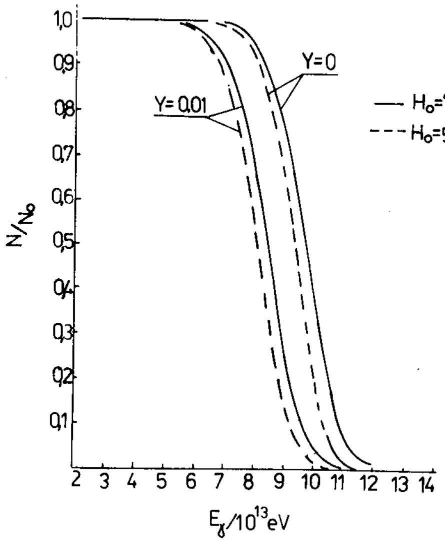


Fig. 2

Provided the cosmological origin of redshifts of QSOs, it will be possible to measure Hubble constant for distances $R \geq 100$ Mpc. In Fig.3 the spectra expected from a gamma-ray source with z_o=0.025, corresponding to R =100 Mpc (H_o=75 km/s Mpc) or to R=150 Mpc (H_o=50 km/s Mpc), are given. For the choice of H_o from these two values, the energy resolution of a detector should be not worse than 5%. For realization of above mentioned problems most suitable objects seem to be nearest QSOs 3C 273 (z_o=0.158) and 0241+622 (z_o=0.043), for which the effects of MBR evolution are not so significant.

Fig. 3



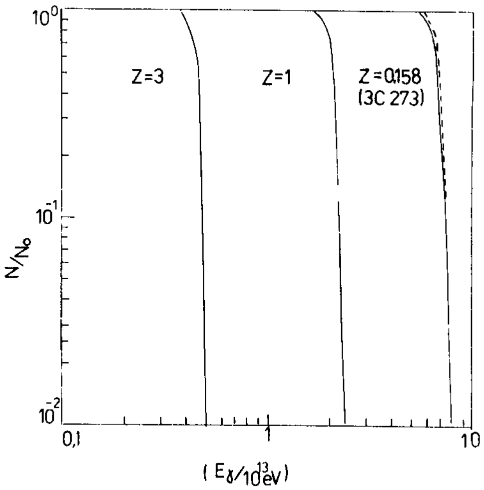


Fig. 4

iii) Probing of MBR in remote epochs.

The observations of UHEGR from distant QSOs with $z_0 \geqslant 1$ will give unique information on MBR in remote epochs. Since according to the model of hot expanding Universe both temperature of MBR and energy of gamma rays were $(1+z_0)$ times as great as the detected ones, expected cutoffs will be $(1+z_0)^2$ times shifted towards smaller energies. In the case of Planckian distribution this follows directly from Eq.(2). In Fig.4 it is seen that for different z_0 the cutoffs should be expected in the wide energy range $10^{12} \div 10^{14}$ eV (solid curves). In the absence of MBR evolution in time the spectra will be cut off near $E_4 \sim 7 \cdot 10^{13}$eV (dotted curve). Since possible deviations of MBR spectrum from Planckian distribution and uncertainties of H_0 cannot result in substantial changes of E_c from the law $E_c \propto (1+z_0)^{-2}$, the observations of QSOs with $z_0 \geqslant 1$ may give unambiguous information on presence or absence of MBR evolution in time. Obviously, for these observations it is not necessary to have high energy resolution of detectors.

In conclusion, it should be noted that correlated $\gamma - \nu$ observations will enable one to establish unambiguously the nature of cutoffs expected in UHEGR spectra of QSOs and AGN: whether these cutoffs are related to the absorption in MBR or they simply reflect the peculiarities in the spectra of parent accelerated protons. Theoretically expected fluxes of high-energy gamma rays and neutrino from QSOs and AGN allow us to hope that the considered possibilities can be realized (at least partially) in the near future.

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