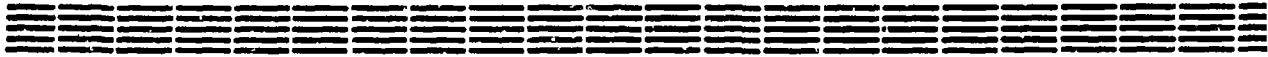


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ЕРЕВАНСКИЙ ФИЗИЧЕСКИЙ ИНСТИТУТ
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INTERACTION OF ULTRAHIGH ENERGY COSMIC
RAYS WITH MICROWAVE BACKGROUND RADIATION

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ԳՆԲԲԱՐՁՐ ՏԻԵՋԵՐԱԿԱՆ ՃԱՌԱԳԱՅՑՆԵՐԻ ՓՈՒԱԶԴԵՆՈՒԹՅՈՒՆԸ:
ՄՆԱՅՈՐԴԱՑԻՆ ՃԱՌԱԳԱՅՑՄԱՆ ՀԵՏ

Քննված է ,,սապատի,, և ,,սևամարմին կտրման,, կազմավորման չորձընթացը տիեզերական մոտազայթման սպեկտրում, որոնք առաջանում են Մ -մեզոնների ֆոտոծնման ռեակցիայի հետևանքով՝ պրոտոնների մնացորդային մոտազայթման/Մճ/ ֆոտոնների հետ ըսլաման ժամանակ: Առաջվել է Տճ և Մճ տարածումը նկարագրող կինետիկական հավասարում՝ հաշվի առնելով բնույթը: Տճ պրոտոնների՝ անփոփոխ կինետիկական հավասարման լուծմամբ ստացված, հավասարակշիռ սպեկտրը համաձայնվում է /առաջին մոտավորություն/ անփոփոխ կինետիկական հավասարման լուծմանը, որը դուրս է բերվել էներգիայի անընդհատ կորուստի մոտավորություն: Սակայն, տեղային աղբյուրների սպեկտրերը, հատկապես, $\epsilon > 10^9$ տարի տարածման ժամանակի համար, նկատելիորեն տարբերվում են անընդհատ կորուստի մոտավորության հավասարման լուծումից՝ ստացվածներից: Ինչպես հավասարակշիռ, այնպես էլ տեղային աղբյուրների սպեկտրերը զգալիորեն տարբերվում են հնարավոր Մճ սպեկտրի շեղման հաշվարկման դեպքում՝ պլանկյանից, վինի տիրույթում: Այսպես, վերջերս հայտնաբերված Մճ սպեկտրում մոտազայթման ,,ավելցուկի,, համար մերձմիլիմետրային տիրույթում ,,սևամարմին կտրման,, էներգիան և նրան նախորդող ,,սապատը,, շեղվում են դեպի փոքր էներգիաների կողմը: Մասնավորապես, $\epsilon > 10^9$ տարի Տճ տարածման ժամանակի համար ,,սևամարմին կտրման,, էներգիան չի գերազանցում $E \approx 4 \cdot 10^{19}$ էվ:

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Երևան 1989

* ԼԳՀ ՄՓԳՀԻ



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INTERACTION OF ULTRAHIGH ENERGY COSMIC RAYS
WITH MICROWAVE BACKGROUND RADIATION

The formation of the bump and black-body cutoff in the cosmic-ray (CR) spectrum arising from the π -meson photoproduction reaction in collisions of ~~the~~ CR protons with the microwave background radiation (MBR) photons is studied. A kinetic equation which describes CR proton propagation in MBR with account of a catastrophic nature of the π -meson photoproduction process is derived. The equilibrium CR proton spectrum obtained from the solution of the stationary kinetic equation is in general agreement with spectrum obtained under assumption of continuous energy loss approximation. However spectra from local sources, especially for the times of propagation $t > 10^9$ years differ noticeably from those obtained in the continuous loss approximation. ~~Both the equilibrium and the local source spectra are modified when taking into account the possible deviation of the MBR spectrum from the Planckian one in the Wien region. Thus, for the recently measured MBR spectrum which reveals an essential "excess" in the submillimeter region the black-body cutoff and the preceding bump shift noticeably towards lower energies. In particular, for the CR propagation time $t > 10^9$ years the energy of black-body cutoff does not exceed $E \sim 4 \cdot 10^{19}$ eV.~~

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ВЗАИМОДЕЙСТВИЕ КОСМИЧЕСКИХ ЛУЧЕЙ СВЕРХВЫСОКИХ
ЭНЕРГИЙ С РЕЛИКТОВЫМ МИКРОВОЛНОВЫМ ИЗЛУЧЕНИЕМ

Рассмотрен процесс формирования "горба" и "чернотельного обрезания" в спектре космических лучей (КЛ), возникающих в результате реакции фоторождения π - мезонов при столкновениях протонов с фотонами реликтового излучения (РИ). Получено кинетическое уравнение, описывающее распространение КЛ в РИ, с учетом катастрофического характера процесса фоторождения. Равновесный спектр протонов КЛ, полученный в результате решения стационарного кинетического уравнения, согласуется (в первом приближении) с решением стационарного кинетического уравнения, выведенного в приближении непрерывных потерь энергии. Однако, спектры от локальных источников, особенно для времен распространения $t > 10^9$ лет, заметно отличаются от спектров, получаемых при решении уравнения в приближении непрерывных потерь. ~~Как равновесный, так и спектр от локальных источников существенно видоизменяются при учете возможного отклонения спектра РИ от планковского в вишневской области. Так, для обнаруженного недавно при аппроксимации избытка излучения в спектре РИ в субмиллиметровом диапазоне энергии "чернотельного обрезания" и предшествующий ей "горб" сдвигаются в область меньших энергий. В частности, для времени распространения КЛ $t > 10^9$ лет энергия "чернотельного обрезания" не превосходит $E \approx 4 \cdot 10^{19}$ эВ.~~

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1. Introduction

The ultrahigh-energy cosmic-ray (CR) interaction in the intergalactic space with the microwave background radiation (MBR) gives rise to a CR spectrum black-body cutoff predicted more than 20 years ago by Greisen [1] and by Zatsepin and Kuzmin [2]. Unfortunately, the available set of experimental data does not allow us to draw an unambiguous conclusion concerning the presence or absence of such spectral peculiarity (see, e.g. [3]). At the same time, in the energy range $E > 10^{19}$ eV the Fly's Eye has detected some excess (bump) in the spectrum [4], which agrees with the evidence obtained by Haverah Park [5], Volcano Ranch [6] and Akeno [7] groups to a tendency of spectrum flattening in this energy region. With a lesser confidence this peculiarity is also revealed in the data of Yakutsk [8] and Sydney [9] EAS arrays.

Hill and Schramm [10], examining the ultrahigh-energy proton transfer in the MBR field, arrived at a rather important conclusion that due to the pion photoproduction process there

is formed besides the black-body cutoff also a bump (preceding the cutoff). The latter spectral peculiarity is apparently due to a sharp (exponential) energy dependence of proton free path (owing to the threshold nature of $\gamma p \rightarrow \pi N$ process, protons with energy $E < 10^{20}$ eV interact only with the Wien "tail" of the MBR spectrum). Protons with energy $E \sim (0.5 \div 1) \cdot 10^{20}$ eV (depending on the time of propagation in intergalactic medium) effectively interact with the MBR, lose their energy and accumulate in the energy region $E \sim (1 \div 5) \cdot 10^{19}$ eV where the probability of interaction with the MBR sharply falls off. Hill and Schramm [10] believe that the bump is connected with recoil protons and may be revealed only when the exact transport equation is used. However, the mentioned effect is such strong that displays qualitatively in different approximations. Therefore, the remark of authors of Ref.[11] that the bump in the CR spectrum occurs in the continuous energy loss approximation too, is true, and the absence of proper concern to this spectral feature in the early works is accounted for by the fact that as a rule the integral spectra, where the bump displays in the form of a flat "step" [12], were considered *).

At the same time the calculations of Hill and Schramm [10] (based on numerical solution of the transport equation with the collisional integral for photomeson processes) are in disagreement with calculations of Berezhinsky and Grigor'eva (carried out within continuous energy loss approximation) [11].

*) It should be noted, however, that the differential spectrum was considered in the early paper of Konstantinov et al. [13].

The discrepancy cannot be due only to the account of the effect of possible cosmological evolution of MBR by Berezhinsky and Grigor'eva [11] (as it is suggested in Ref. [11]), since the essential discrepancy is also maintained at small propagation times (see also Ref. [14]), when the evolutionary effects are negligible. Taking into account the exceptional importance of this question from the viewpoint of solution of the problem of ultrahigh-energy CR origin, it seems to us urgent to carry out a detailed analysis in order to reveal the correct approach to UHE proton propagation in the MBR field. In our analysis of the CR transport kinetics we shall restrict ourselves to the approximation in which the cosmological evolution effects connected with both MBR and CR sources are neglected. Such an approximation is convenient to separate the influence of the mentioned effects on the resultant proton spectrum and is used to investigate peculiarities of the kinetics of CR transfer in the MBR field in a "pure form". Furthermore, evidently, up to the values of propagation time $t \leq 10^9$ years ($z \leq 0.1$) the evolutionary effects cannot play an essential part in CR spectrum formation. For the same times one may also neglect the proton energy losses for e^+e^- pair production. The proton characteristic "lifetime" with respect to the cited process even at energies $E \sim (1 \div 10) \cdot 10^{19}$ eV, where it achieves a maximum, turns out to be too large - $\tau_{\pm} = E/(dE/dt) \sim 5 \cdot 10^9$ years [15]. Therefore, this process affects weakly the dynamics of CR spectrum formation during the time of their propagation in the MBR field $t \leq 10^9$ years.

A much more essential part in the CR spectrum formation,

at least for $t \leq 10^9$ years, can be played by possible deviation of the MBR spectrum from the Planckian one in the Wien "tail" region where the interaction of protons of $E \leq 10^{20}$ eV with the MBR photons just occurs. Hitherto the CR spectra formed in the intergalactic medium were calculated on the assumption that the MBR is described exactly by the Planckian distribution. Actually, the observed data that are in good agreement with the Planckian distribution attribute to wavelength region $\lambda > 1$ mm. The possible deviation of the MBR spectrum is not excluded, moreover, it is predicted within the Big Bang model (see, e.g. [16,17]). In particular, it can be caused by inverse Compton scattering (comptonization) of MBR photons by hot electrons [18]. Because of methodical difficulties the MBR spectral measurements in this range have become feasible only recently. The rocket measurement carried out by the Japan-American group have shown a noticeable excess of radiation in the MBR spectrum at $\lambda < 1$ mm as compared to the Planckian distribution [19]. This radiation excess in the Wien region turns out to be sufficient to considerably shift down along the energy scale the expected spectral peculiarities - the bump and black-body cutoff produced due to interaction of CR with MBR.

2. Equilibrium CR Spectrum in the Universe

Considering the diffuse proton spectrum within the universal CR hypothesis we shall neglect the effects connected with cosmological evolution of both MBR and CR sources. The equilib-

assumption of continuous energy loss approximation is defined from the equation:

$$\frac{\partial}{\partial E} \left(- \frac{dE}{dx} F \right) = q(E). \quad (1)$$

Here $q(E) = Q(E/E_0)^\gamma$ is the CR production spectrum given, as a rule, in a power-law form; dE/dx is the rate of CR energy losses due to their interaction with MBR.

Solution of Eq.(1) has a form:

$$F(E) = \frac{q(E)}{- \frac{1}{E} \frac{dE}{dx} (\gamma-1)} \quad (2)$$

The rate of energy losses of protons interacting with black-body radiation at a temperature T are determined as follows [11] :

$$- \frac{1}{E} \frac{dE}{dx} = \frac{kT}{2\pi^2 (c\hbar)^3 \Gamma^2} \int_{\epsilon_c}^{\infty} d\omega_r \mathcal{G}(\omega_r) \zeta(\omega_r) \omega_r \left[-\ln(1 - e^{-\omega_r/2\Gamma kT}) \right] \quad (3)$$

where ω_r is photon energy in the proton rest frame, $\mathcal{G}(\omega_r)$ is total cross section of proton interaction, $\zeta(\omega_r)$ is a portion of energy lost by a proton per one collision, ϵ_c is the threshold energy of reaction in the proton rest frame.

For the proton energy loss rate due to photomeson process Berezhinsky and Grigor'eva [11] suggest a convenient analytical expression:

$$- \frac{1}{E} \frac{dE}{dx} = \frac{2(kT)^3 \mathcal{G}' \epsilon_c^2}{\pi^2 (c\hbar)^3 m_p c^2} \exp \left[- \frac{\epsilon_c}{2\Gamma kT} \right] \quad (4)$$

where $\Gamma \equiv E/m_p c^2$ is the proton Lorentz factor,

$\varepsilon_0 = m_T c^2 (1 + m_T/2m_p) \simeq 145 \text{ MeV}$, $\sigma' = 6.8 \cdot 10^{-36} \text{ cm}^2/\text{eV}$. This expression is obtained for Planckian MBR distribution in the approximation when the cross section and the energy portion lost by the proton in one interaction act are determined by their values at threshold energy $\omega_r \sim \varepsilon_0$:

$$\zeta(\omega_r) = \zeta'(\omega_r - \varepsilon_0) \quad \text{and} \quad \chi(\omega_r) = \frac{\omega_r}{m_p c^2} \frac{1 + (m_p c)^2 / 2\omega_r m_p}{1 + \omega_r / m_p c^2}. \quad (5)$$

This approximation, according to Ref. [11], is valid in the energy range $E \lesssim 3 \cdot 10^{20} \text{ eV}$ to the accuracy of 20%.

The CR with energy less than some critical energy E_{cr} practically do not interact with MBR in case when the considered CR region is large enough (for the optical thickness of medium with respect to photomeson process at energies of interest ($E \gg E_{cr}$) to be $\tau_{p\gamma} \ll 1$) but not infinite. At energies $E > E_{cr}$ the CR spectrum formed in this region sharply steepens and behaves in accordance with Eq. (2). The value of E_{cr} depends mainly on the size of CR confinement region (in fact on the propagation time of CR). Insofar as the value of critical energy is not amenable to exact definition, the spectrum cutoff energy is convenient to specify by a parameter $E_{1/2}$ at which the differential flux of protons is reduced twice as compared to the spectrum extended with the same power-law index from the low-energy to high-energy range:

$$\frac{1}{2} q(E) \frac{c}{H_0} = \frac{q(E)}{-\frac{1}{E} \frac{dE}{dX} (\gamma - 1)}. \quad (6)$$

In Eq.(6) the quantity c/H_0 corresponds to the Hubble size of the Universe.

Solving Eq.(6) with respect to E for $H_0 = 100 \text{ km/s/Mpc}$ and $\gamma = 3$ we obtain $E_{1/2} \sim 5 \cdot 10^{19} \text{ eV}$. It should be noted that in order to calculate exactly the "black-body cutoff" energy we must know the CR lifetime t . For this time we used in Eq.(6) the value of the Hubble time $1/H_0 \sim 10^{10}$ years which actually should be considered as the upper limit for t . However, since $E_{1/2} \sim \ell n t$, the value $E_{1/2} \sim 5 \cdot 10^{19} \text{ eV}$ characterizes sufficiently correctly the place of the "black-body cutoff".

The above-cited continuous energy loss approximation was used by many authors in the analysis of equilibrium proton spectrum in the intergalactic space. To prove this approximation, consider the solution of a more general kinetic equation for equilibrium spectrum which takes into account fluctuations of energy losses of protons in interaction with MBR.

The kinetic equation which describes the equilibrium proton spectrum with account of fluctuations in $p\gamma$ -interactions has a form:

$$Q(E) = F(E)/\lambda - \hat{A}F(E). \quad (7)$$

The first term in this equation describes the proton generation(source) function. The second term describes the escape of protons from the energy interval $(E, E+dE)$, and the third term describes the proton arrival to the mentioned energy range owing to the photopion processes.

Let the protons generate with a power-law differential spectrum:

$$Q(E) = Q(E/E_0)^{-\gamma} \quad (8)$$

Assuming that the production of the resultant from reaction $\gamma p \rightarrow \pi N$ particles (nucleon and pion) in the c.m.s. occurs isotropically (this assumption is quite correct near the reaction threshold), we have

$$\lambda^{-1} = \frac{kT}{2\pi^2 (ch)^3 \rho^2} \int_{\epsilon_0}^{\infty} d\omega_r \rho(\omega_r) \omega_r \left[\ln(1 - e^{-\omega_r/2\pi kT}) \right], \quad (9)$$

$$\hat{A}F = \frac{kT}{2\pi^2 (ch)^3 \rho^2} \int_{\epsilon_0}^{\infty} d\omega_r \rho(\omega_r) \varphi(\omega_r) \omega_r \int_{z_-(\omega_r)}^{z_+(\omega_r)} dz F\left(\frac{E}{z}\right) z \left[\ln(1 - e^{-\frac{\omega_r z}{2\pi kT}}) \right], \quad (10)$$

where

$$\varphi^{-1} = \left[\left(\frac{\omega_r}{m_p c^2} - \frac{m_\pi^2}{2m_p^2} \right)^2 - \frac{m_\pi^2}{m_p^2} \right]^{1/2} / (1 + 2\omega_r/m_p c^2) \quad (10a)$$

$$z_{\pm} = \left[\left(1 + \frac{\omega_r}{m_p c^2} - \frac{m_\pi^2}{2m_p^2} \right) \pm \varphi \right] / (1 + 2\omega_r/m_p c^2)$$

In the energy range $E < 3 \cdot 10^{20}$ eV the main contribution to the integral of variable ω_r is made by the region near the reaction threshold. Therefore, the integral term in Eq.(7) approximately can be presented as

$$\hat{A}F = \frac{kT}{2\pi^2 (ch)^3 \rho^2} \int_{\epsilon_0}^{\infty} d\omega_r \rho(\omega_r) \omega_r \varphi(\omega_r) \int_{z_-(\omega_r)}^{z_+(\omega_r)} dz F\left(\frac{E}{z}\right) z \left[\ln(1 - e^{-\frac{\omega_r z}{2\pi kT}}) \right] \quad (11)$$

This approximation allows us to present the kinetic equation solution in an analytical form using the Mellin integral transformation [20] :

$$F(E) = \frac{\varphi(E)}{A(\gamma)\lambda^1(E)}, \quad (12)$$

where

$$A(\gamma) = 1 - \varphi(\epsilon_0) \int_{z_-(\epsilon_0)}^{z_+(\epsilon_0)} dz z^{\gamma-1} = 1 - [1 - \xi(\epsilon_0)]^{\gamma-1} \quad (13)$$

Obviously, function $\lambda(E)$ has a meaning of proton free path relative to the pion photoproduction process.

Noticing that $\lambda^{-1} \cong \frac{1}{E\xi(\epsilon_0)} \frac{dE}{dx}$ (cf. Eqs.(3) and (12)) and $A(\gamma) \cong \xi(\epsilon_0)(\gamma-1)$ (since $\xi(\epsilon_0) \cong 0.15 \ll 1$), we are convinced that the solution of kinetic equation in the continuous loss approximation (2) coincides with the solution of transport kinetic equation (11). It should be emphasized that the given result is obtained assuming that in the energy region of interest, $E \lesssim 10^{20}$ eV, the main contribution is made by collisions near the photoproduction threshold in the nucleon rest frame. This question needs a more detailed analysis. Here we shall just restrict ourselves to the remark that according to Ref. [11] a similar approximation provides in the energy range $E \lesssim 3 \cdot 10^{20}$ eV the accuracy of energy losses $\lesssim 20\%$ (formula (4) is obtained precisely in this approximation).

Consider now the interaction of protons with MBR with respect to a possible deviation of MBR spectrum from the Planckian distribution predicted in the framework of some mo-

dels (see, e.g. [16,17]). In particular, Zeldovich and Sunyaev [18] predicted an essential distortion of MBR spectrum in the submillimeter range due to comptonization of radiation on hot electrons, if a late energy release (at $z \lesssim 10^4$) has occurred. The comptonized MBR spectrum is described by the expression [18] :

$$n(x, y) = \frac{1}{\sqrt{4\pi y}} \int_0^{\infty} n(\xi, 0) \exp\left[-\frac{(\ln X/\xi + 3y)^2}{4y}\right] \frac{d\xi}{\xi} \quad (14)$$

where $X = \omega/kT$, $n(x, 0)$ is the Planckian radiation spectrum, and

$$y = \int \frac{kT_e(t)}{m_e c^2} \sigma_T c n_e(t) dt \quad (15)$$

is the so-called comptonization parameter y , i.e. the product of the dimensionless electron temperature $kT_e/m_e c^2$ and mean number of scatterings per photon.

For a long time the question about the extent of distortion of MBR spectrum remained open due to the lack of experimental data in the submillimeter range. It follows from the analysis carried out by Field and Perrenod [21] that the observations do not contradict the values of comptonization parameter $y \leq 0.05$. Even for such small values of the comptonization parameter the deviation from the Planckian distribution ($y = 0$) in the Wien region becomes significant, and therefore one should expect a noticeable influence of this effect on the proton spectrum shape, in particular on the value of the cutoff energy $E_{1/2}$. The corresponding calculations presented in Appendix 1 support this assumption.

Recently, very important measurements concerning the MBR spectrum have been carried out in the submillimeter range which point out a significant radiation excess (as compared to the Planckian spectrum) at $\lambda = 0.709$ mm and $\lambda = 0.481$ mm [19]. These data together with ones obtained earlier in the wavelength range $\lambda > 1$ mm may be approximated by the comptonized black-body radiation spectrum with the parameter $y \simeq 0.02$ and temperature $T \simeq 2.7$ K [19,22]. Calculations show that for $y = 0.02$ the cutoff energy $E_{1/2}$ for the equilibrium proton spectrum turns out to be considerably less ($E_{1/2} \sim 4 \cdot 10^{19}$ eV) than was assumed before for "pure" Planckian spectrum of MBR ($E_{1/2} \sim 5 \cdot 10^{19}$ eV). Account of evolutionary effects can only reduce this value of cutoff energy. Therefore, with account of this effect it is impossible to explain experimental data in the framework of the universal one-component CR model which assumes uniform distribution of non-evolving CR sources in the Universe.

The UHE CR spectrum at $E \leq 4 \cdot 10^{19}$ eV is studied by several groups, and the data of all large installations, being in agreement with each other within the error limits, do not point out the tendency of spectrum steepening at such energies (the data of the Fly's Eye and Yakutsk installations, though testified to a possible steepening of the spectrum but only at energies above $5 \cdot 10^{19}$ eV [3]). Actually, in the energy range $1 \div 5 \cdot 10^{19}$ eV an opposite tendency, namely a noticeable flattening of the spectrum is observed. Therefore, within universal one-component model of CR protons it is impossible to explain the measured UHE CR flux above $E \sim 4 \cdot 10^{19}$ eV.

3. CR Spectrum from Local Sources

If the CR sources are located not far from our Galaxy, then the black-body cutoff is shifted towards the region of higher energies (or may be absent at all) owing to the smallness of CR propagation time. A real candidate for such a group of CR sources is the Local Supercluster (LS), most likely the active galaxies in it (see, e.g. [23]).

Insofar as the main supplier of CR in this case is a small number of objects that are at distances about $10 \div 20$ Mpc, then the study of CR spectra from local sources becomes necessary.

The differential CR proton spectra from local sources were calculated by Hill and Schramm [10] based on the solution of the kinetic equation which took into account the catastrophic character of photomeson interactions, and also by Berezhinsky and Grigor'eva [11] in the continuous energy loss approximation. Below, it will be shown that the latter approximation to describe the local source spectrum is not correct, especially for the propagation times $t > \hat{\tau}(E)$, where $\hat{\tau} = \lambda(E)/c$; $\lambda(E)$ is the proton free path in the MBR field with respect to π -meson photoproduction (see Eq.(9)).

The kinetic equation for protons traversing the MBR field, under assumption that all particles propagate in the same way irrespective of energy (i.e. the diffusion coefficient is energy-independent), has a form:

$$\frac{\partial F(E, t)}{\partial t} = -\frac{c}{\lambda} F(E, t) + c \hat{A} F(E, t), \quad (16)$$

where λ and \hat{A} are determined by Eqs.(9) and (10).

For simplicity we shall ignore the evolutionary effects of both MBR and CR sources and assume the power-law shape (8) for the injection spectrum.

Eq.(16) considerably simplifies for the energy region $E > 3 \cdot 10^{20}$ eV, where the interaction total cross section is nearly constant ($\sigma_0 \sim 10^{-28}$ cm²), and the fraction of proton energy lost per one interaction varies in the interval [0, 1] with the average value $\xi \sim 0.5$. Then we have

$$\frac{\partial F(E, t)}{\partial t} = -\frac{1}{\tau_0} F(E, t) + \frac{1}{\tau_0} \int_0^1 \frac{dz}{z} F(E/z, t), \quad (17)$$

where

$$\frac{1}{\tau_0} = \sigma_0 c n_w$$

and n_w is the field photon density with the average energy ~ 3 kT.

For Eq.(17) we can obtain an analytical solution using the Mellin integral transformation over energy variable (see, e.g. [20]). Thus, for the proton source function $\delta(E-E_2)$ one obtains

$$F(E, t) = \frac{1}{2\pi i} \int_{-i\infty}^{i\infty} ds (E_2/E)^s e^{-A_0(s)t} \quad (18)$$

where

$$A_0(s) = \frac{1}{\tau_0} \left[1 - \int_0^1 z^s dz \right] = \frac{s}{\tau_0(s+1)} \quad (19)$$

For the proton power-law source function (8) we obtain a solution:

$$F(E, t) = q(E) e^{-A_0(\delta) \cdot t} \quad (20)$$

where $A_0(\delta) = c n_w \sigma_0 (1 - 1/\delta) = \frac{\delta - 1}{\delta \cdot \tau_0}$.

Consider now this problem in the continuous energy loss approximation. In case of the proton power-law source function the equation solution in this approximation can be presented as (see, e.g. [11]):

$$F(E, t) = q(E) \alpha^{-\delta+1} \beta(E_g) / \beta(E), \quad (21)$$

where $\alpha = E_g/E$, $\beta(E) = \frac{1}{E} \frac{dE}{dt}$, E_g is the proton energy at a time $t = 0$ (when escaping from the source) if at a time $t = \tau$ it equals E .

Assuming that the photoproduction cross section at $E > 3 \cdot 10^{20}$ eV approximately is $\sigma_0 \approx 10^{-28}$ cm² and the energy fraction lost by a proton per collision $f \sim 0.5$, we have

$$\beta(E) = f / \tau_0 \quad (22)$$

Then

$$E_g = E \exp [f \cdot t / \tau_0] \quad (23)$$

and respectively

$$F(E, t) = q(E) \exp\left\{- (\gamma-1) \frac{t}{\tau_c}\right\}. \quad (24)$$

Comparing Eqs. (20) and (24) we are convinced that the continuous energy loss approximation describes correctly the proton spectrum under the condition:

$$A_0(\gamma) = \frac{(\gamma-1) \dot{f}}{\tau_c} \quad \text{or} \quad \gamma = \dot{f}^{-1} \approx 2. \quad (25)$$

Thus, in the energy region $E > 3 \cdot 10^{20}$ eV the solution in the continuous energy loss approximation agrees with the solution of the kinetic equation which takes into account the catastrophic nature of interaction, only at the value of the differential spectrum index $\gamma = 2$. At other values of the production spectrum index the difference between the solutions of (20) and (24) becomes essential, especially for the times $t \gg 1/\zeta_0 c n_{\omega} \sim 2 \cdot 10^7$ years.

At the same time for the equilibrium differential proton spectrum formally obtained (on the assumption that the Metagalaxy is populated uniformly by CR sources) in integration of Eqs. (20) and (24) over t from zero to infinity the difference between the two approximations ($F^{(cat)} \sim \frac{\tau_c q(E)}{\gamma-1}$ and $F^{(con)} \sim \frac{\tau_c q(E)}{(\gamma-1) \dot{f}}$) is considerably less: $F^{(cat)}/F^{(con)} \sim \gamma \dot{f}$. This is accounted for by the fact that the main contribution to the equilibrium spectrum which represents a superposition of spectra of uniformly distributed local sources comes from sources located at relatively close distances corresponding to the propagation time

$$t \leq 1/c\sigma_0 n_{cr} .$$

This simple example points out that though the continuous energy loss approximation describes the equilibrium CR spectrum relatively correctly, this approximation when considering spectra from local sources may lead to essential errors. Presumably this is the main reason of the discrepancy between the results obtained in Refs [10] and [11] .

The energy range $E > 3 \cdot 10^{20}$ eV where it is possible to obtain simple analytical expressions are most likely of general interest. In the energy range less than $3 \cdot 10^{20}$ eV the solution of Eq.(12) can be obtained by iterations (see Appendix 2).

Fig. 1 shows differential CR spectra (normalized to initial production spectrum $\eta = F(E)/Q(E)$) from a single source for the various CR propagation times both in the continuous energy loss approximation and with account of the catastrophic nature of the photomeson processes. One can see from Fig.1 that whereas for times $t = 2 \cdot 10^7$ years the difference between the two solutions is insignificant (at least in the energy range $E < 2 \cdot 10^{20}$ eV), for large times this difference turns out to be essential. Here it should be noted that both solutions reveal the presence of the bump preceding the black-body cutoff. However the bump in the solution of the exact kinetic equation is smoother and wider than in the continuous energy loss approximation, which is naturally due to the account of the $p-\gamma$. interaction fluctuation in the exact kinetic equation.

Fig. 2 presents the proton spectra from the local source at distances 36 Mpc ($t \approx 1.1 \cdot 10^8$ years) and 288 Mpc

($t \simeq 9.2 \cdot 10^8$ years), obtained, as in Fig.1, in two approximations. Ibidem we present spectra obtained by Hill and Schramm [10] by numerical integration of the exact kinetic equation which takes into account the catastrophic nature of the $p\gamma$ -interaction (the values $R = 36$ Mpc and 288 Mpc are chosen namely for the comparison with the numerical calculations of [10]). We carried out calculations for the production spectrum index $\chi = 3$. The comparison of curves in Fig.2 points out that besides the discrepancy in spectra obtained in the continuous energy loss approximation and by solving exact transport kinetic equation (see also Fig.1), there also takes place a noticeable discrepancy between our results and results of Hill and Schramm [10] obtained practically under the same assumptions about the nature of the photomeson process. It is difficult to clarify the cause of this discrepancy, since calculations in Ref.[10] were carried out numerically. Nevertheless, we'd like to emphasize one feature in spectra obtained in [10] which is difficult to understand from the viewpoint of simple physical considerations. As can be seen from Fig.2, the energy of black-body cutoff of Hill and Schramm spectrum [10] obtained for the proton propagation path of 36 Mpc is approximately $6 \cdot 10^{19}$ eV. Meanwhile the proton free path in the MBR field for this energy is about 200 Mpc [11,24]. It is evident that even without account of particle arrival from the region of higher energies (which is just the cause of bump formation) the deviation of the spectrum from the initial production spectrum at this energy cannot exceed 20%

$$(\eta = F(E, t)/q(E) \sim \exp(-\lambda/R) \simeq 0,8$$

As in the case of the equilibrium proton spectrum, the deviation of the MBR distribution from the Planckian one in the Wien region affects significantly the proton spectrum from the local source. This can be seen from Fig. 3 where proton spectra from the local source for various values of the comptonization parameter η are shown. At the given CR propagation time the bump and hence the cutoff energy $E_{1/2}$ (determined from the condition $\eta = 0.5$) shift towards the lower energy region. For example, if for the Planckian spectrum of MBR ($\eta = 0$) and $t = 10^9$ years the bump maximum corresponds to $E_b \simeq 4.5 \cdot 10^{19}$ eV, and the cutoff energy is $E_{1/2} \simeq 6.2 \cdot 10^{19}$ eV, then for the comptonized MBR spectrum with $\eta = 0.02$ the corresponding energies are considerably less: $E_b \simeq 3 \cdot 10^{19}$ eV and $E_{1/2} \simeq 4.2 \cdot 10^{19}$ eV.

As was mentioned above, the recent rocket measurements of MBR spectrum in the submillimeter range [19] have revealed a significant deviation of the MBR spectrum from Planckian distribution. In case of approximation of these data by the comptonized radiation spectrum a good agreement is achieved for the value of comptonization parameter $\eta = 0.02$ [19, 22].

Fig. 4 shows proton spectra from the local source for 2 values of CR propagation time ($3 \cdot 10^8$ years and 10^9 years), formed in the MBR field in the case of the "pure" Planckian and comptonized Planckian (with $\eta = 0.02$) MBR spectra. We arrive at an interesting conclusion when comparing these spectra to experimental data on UHE CR fluxes. Notwithstanding the existing uncertainty and ambiguity of these data, we can claim that the CR spectrum cutoff, if any, occurs no sooner than at

$E \sim 5 \cdot 10^{19}$ eV (see, e.g. [3]). As can be seen from Fig.4, in case of "pure" Planckian MBR distribution at the value of CR propagation time $t = 10^9$ years the expected black-body cutoff $E_{1/2}$ turns out to be higher than $5 \cdot 10^{19}$ eV and does not contradict at least the Fly's Eye data [4]. Meanwhile the account of the deviation of the MBR spectrum from the Planckian one results in a noticeable shift of proton spectrum towards a lower energy region; in particular, for $\gamma = 0.02$ and cosmic ray propagation time $t \sim 10^9$ years the energy of black-body cutoff does not exceed $\sim 4 \cdot 10^{19}$ eV. This contradicts the data of all the installations including the Fly's Eye and Yakutsk array. Curves in Fig.4 are obtained for the value of the index of the proton power-law production spectrum $\gamma = 2.5$. However this statement is valid for other values of γ as well.

Fig.5 presents proton spectra from the local source for the CR propagation time $t = 3 \cdot 10^8$ years and for three values of the proton production spectrum index: $\gamma = 2.3; 2.5; 3$. The figure shows that whereas the cutoff energy depends weakly on the value of γ , the less is γ the more pronounced is the bump. This can be explained by the fact that the amount of high-energy particles interacting with MBR and producing a bump is considerably greater in the flat spectrum than in the steep spectrum of production. Note also that the deviation of MBR spectrum from the Planckian one practically does not distort the proton spectrum but shifts it towards the lower energy region.

Finally, we'd like to note that due to the poor information on the MBR spectrum in the submillimeter region we have to make

some assumption about spectral shape of MBR at $\lambda < 1$ mm. For certainty here we suggest the comptonization spectrum of black-body radiation (Eq.(14)), though other interpretations of the observed deviation of the MBR spectrum from Planckian one cannot be unambiguously ruled out.

4. Summary

The basic conclusions of the present study can be summarized as follows:

1. The equilibrium spectrum of universal CR protons is analyzed with account of possible deviation of the MBR spectrum from the Planckian one in the submillimeter range. The recently revealed excess in the MBR spectrum in this wavelength range results in a noticeable shift of the energy of black-body cutoff in the proton differential spectrum. Instead of the black-body cutoff at $E_{M2} \sim (4.5 \div 5) 10^{19}$ eV (depending on the value of the index of production spectrum and Hubble constant) one should expect a cutoff at the energy $E_{M2} \sim (3.5 \div 4) \cdot 10^{19}$ eV. Insofar as none of the EAS installations has revealed a break of spectrum at such energies, we can claim that the experimental data on ultrahigh-energy CR spectrum cannot be explained (at least by CR protons) within a one-component universal CR hypothesis.

2. CR spectra from local sources are studied and it is shown that the continuous energy loss approximation fails for this problem. In particular, the energy of black-body cutoff turns out to be somewhat less than the corresponding value

obtained in continuous energy loss approximation. Besides, for the CR propagation times $t \geq 10^9$ years the bump preceding the cutoff of spectrum becomes less pronounced.

As in case of equilibrium universal proton spectrum, the account of the measured excess in the submillimeter range of MBR spectrum leads to a noticeable shift of both the cutoff and the bump towards the lower energy region. With account of this effect for the CR propagation times $t \geq 10^9$ years the energy of black-body cutoff does not exceed $E_{1/2} \sim 4 \cdot 10^{19}$ eV, which contradicts the data of all the EAS installations including the Fly's Eye. Moreover, owing to the excess of the MBR spectrum in the submillimeter range the energy of black-body cutoff turns out to be less than 10^{20} eV even for the CR propagation time $t \sim 10^8$ years. Hence, if the data of Haverah Park and Volcano Ranch actually reflect the absence of CR spectrum break up to the energy $E \sim 10^{20}$ eV, then with respect to new data on MBR spectrum we can claim that the CR propagation time cannot essentially exceed $t \sim 10^8$ years. In case of rectilinear propagation of CR this time corresponds to the distance to the source ~ 30 Mpc, which is comparable to the characteristic size of the Local Supercluster. Therefore, in the presence of even a weak diffusion of CR in the intergalactic medium (which seems to be natural and follows from the observed level of anisotropy of CR) the characteristic scale of the capture region of UHE ($\geq 10^{19}$ eV) turns out to be too small, not exceeding a few Mpc, which seems to be rather problematic from any point of view.

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APPENDIX 1

Energy Loss Rate of Protons in the Field of Photons of Comptonized Black-Body Radiation

The energy loss of protons in case of photon spectrum (14) characterizing the black-body radiation comptonized by hot electrons can be presented in the form:

$$-\frac{1}{E} \frac{dE}{dt} = \frac{ckT}{2\pi^2 (ct)^3 \Gamma^2} \int_{\epsilon_0}^{\infty} d\omega_r \delta(\omega_r) f(\omega_r, \omega_r) \int_{\omega_r/2\Gamma kT}^{\infty} dx n(x, y) \quad (A1-1)$$

where

$$\int_{\omega_r/2\Gamma kT}^{\infty} dx n(x, y) = \frac{1}{\sqrt{4\pi y}} \int_{\omega_r/2\Gamma kT}^{\infty} dx \int_0^{\infty} n(z, 0) \exp\left[-\frac{(\ln \frac{x}{z} + 3y)^2}{4y}\right] \frac{dz}{z} = I_0 \quad (A1-2)$$

Having done a replacement of variables $x/z = -1/t$ we have:

$$I_0 = \frac{1}{\sqrt{4\pi y}} \int_0^{\infty} \frac{dt}{t^2} \exp\left[-\frac{(\ln 1/t + 3y)^2}{4y}\right] \left\{ -\ln \left[1 - \exp\left(-\frac{\omega_r t}{2\Gamma kT}\right) \right] \right\} \quad (A1-3)$$

In the energy region $E < 3 \cdot 10^{20}$ eV the expression (A1-3) somewhat simplifies, and Eq.(A1-1) can be written out in the form:

$$-\frac{1}{E} \frac{dE}{dt} = \frac{ckT}{2\pi^2 (ct)^3 \Gamma^2} \frac{1}{\sqrt{4\pi y}} \int_0^{\infty} \frac{dt}{t^2} \exp\left[-\frac{(\ln 1/t + 3y)^2}{4y}\right] \times \quad (A1-4)$$

$$\times \int_{\epsilon_0}^{\infty} d\omega_r \delta(\omega_r) f(\omega_r) \omega_r \exp\left[-\frac{\omega_r t}{2\Gamma kT}\right]$$

Following Ref. [11], the cross section of the reaction

$P\gamma \rightarrow N\pi$ near the threshold $\epsilon_0 = 145$ MeV can be presented in the form $G(\omega_r) \approx G'(\omega_r - \epsilon_0)$. Then for the proton energy loss in the region $E < 3 \cdot 10^{20}$ eV we have

$$-\frac{1}{E} \frac{dE}{dt} \approx \frac{2cG'\epsilon_0 \psi(\epsilon_0)}{\pi^2 (ct/kT)^3} \frac{1}{\sqrt{4\pi y}} \int_0^\infty \frac{dt}{t^4} e^{-\beta t} \exp\left[-\frac{(\ln t/t + 3y)^2}{4y}\right]. \quad (A1-5)$$

Calculate the integral

$$I_1 = \frac{1}{\sqrt{4\pi y}} \int_0^\infty \frac{dt}{t^4} e^{-\beta t} \exp\left[-\frac{(\ln t/t + 3y)^2}{4y}\right]; \quad \beta \equiv \frac{\epsilon_0}{2\Gamma kT} \quad (A1-6)$$

using the saddle-point method.

Denote

$$\chi(t) = -4 \ln t - \beta t - (\ln t/t + 3y)^2/4y. \quad (A1-7)$$

At the saddle point we have

$$\chi'(t) = -\frac{4}{t} - \beta + \frac{1}{2yt} (-\ln t + 3y) = 0, \quad (A1-8)$$

and hence

$$t_0 = \exp[-2\beta t_0 y - 5y]. \quad (A1-9)$$

For low values of y ($2\beta t_0 y \ll 1$)

$$t_0 \approx \frac{1 - 5y}{1 + 2\beta y} \quad (A1-10)$$

So, for I_1 we have

$$I_1 = \frac{1}{\sqrt{2y|\chi''(t_0)|}} e^{\chi(t_0)} \quad (A1-11)$$

Finally, for the proton energy loss rate in the field of comptonized black-body radiation in the energy region $5 \cdot 10^{19} \leq E \leq 3 \cdot 10^{20}$ eV we have a simple expression

$$\frac{1}{E} \frac{dE}{dt} \approx \frac{1}{E} \frac{dE}{dt} \Big|_{y=0} \times \exp[\beta(1-t_0(y))], \quad (\text{A1-12})$$

where $\frac{1}{E} \frac{dE}{dt} \Big|_{y=0}$ is energy loss rate of protons in the black-body radiation field with pure Planckian distribution ($y = 0$).

APPENDIX 2

The Proton Spectrum from the Local Source with Account of Fluctuations in the Photomeson Production Process

The kinetic equation (16) in the integral form can be written as

$$F(E, t) = q(E) e^{-t/\tau} + \int_0^t dt' q(E) e^{-(t-t')/\tau} \hat{A} F(E, t'). \quad (\text{A2-1})$$

The solution of this equation we present in the form of an iterative series:

$$F_n(E, t) = q(E) e^{-t/\tau} - q(E) \int_0^t dt' e^{-(t-t')/\tau} \hat{A} F_{n-1}(E, t'), \quad (\text{A2-2})$$

where $F_0(E, t) = q(E) e^{-t/\tau}$ is the initial approximation for the spectrum. For numerical calculations it is convenient to pass to a new function $f(E, t)$ using the replacement

$$F(E, t) = \varphi(E) \{ (E, t) \}. \quad (\text{A2-3})$$

Then for $\{ (E, t) \}$ we obtain a solution in the form

$$\{ (E, t) \} = e^{-t/\tau} + \int_0^t dt' e^{-(t-t')/\tau} \hat{A}_1 \{ (E, t') \}, \quad (\text{A2-4})$$

where the integral term is

$$\hat{A}_1 \{ = \frac{c \kappa T}{2\pi^2 (ck)^3 \Gamma^2} \int_{\varepsilon_0}^{\infty} d\omega_r \mathcal{G}(\omega_r) \varphi(\omega_r) \omega_r \times \int_{z_-(\omega_r)}^{z_+(\omega_r)} dz z^{\delta+1} \{ (E/z, t) \} \left[-\ln \left(1 - \exp \left(-\frac{\omega_r z}{2\Gamma \kappa T} \right) \right) \right]. \quad (\text{A2-5})$$

In the energy region $E \leq 3 \cdot 10^{20}$ eV the integral term approximately may be presented as follows:

$$\hat{A}_1 \{ = \frac{c \kappa T}{2\pi^2 (ck)^3 \Gamma^2} \int_{\varepsilon_0}^{\infty} d\omega_r \mathcal{G}(\omega_r) \omega_r \varphi(\varepsilon_0) \int_{z_-(\omega_r)}^{z_+(\omega_r)} dz z^{\delta+1} \times \{ (E/z, t) \} \exp \left[-\frac{\omega_r z}{2\Gamma \kappa T} \right] \approx \tau(E/z_0) \{ (E/z_0, t) \} z_0^{\delta-1}, \quad (\text{A2-6})$$

where z_{\pm} , φ are determined by expressions (10a), while

$$z_0 = 1 - \{ (\varepsilon_0) \} \quad (\text{A2-7})$$

Then the solution for function $\{ (E, t) \}$ can be presented in the form

$$\{ (E, t) \} = \sum_{n=0}^{\infty} z_0^{n(\delta-1)} \sum_{j=0}^n \frac{e^{-t/\tau_j} \tau/\tau_j}{\prod_{l=0}^j [1 - \tau_l/\tau_j]} \quad (\text{A2-8})$$

where

$$\tau_j = \tilde{\tau}(E/z_0^j) \quad (\text{A2-9})$$

Account of the MBR deviation from the Planckian spectrum (in case of its approximation by the spectrum of comptonized black-body radiation (14)) for the proton spectrum from the local source can be carried out just like for the equilibrium proton spectrum (see Appendix 1).

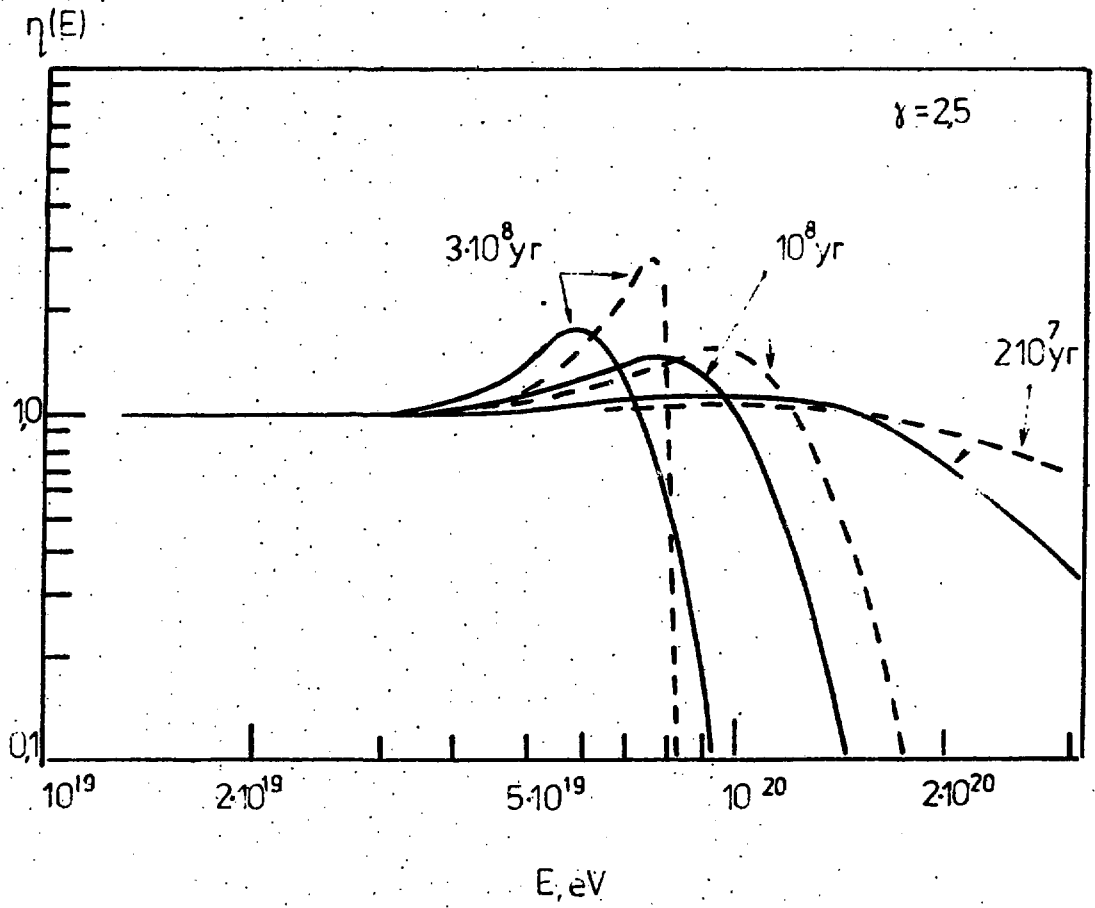


Fig. 1

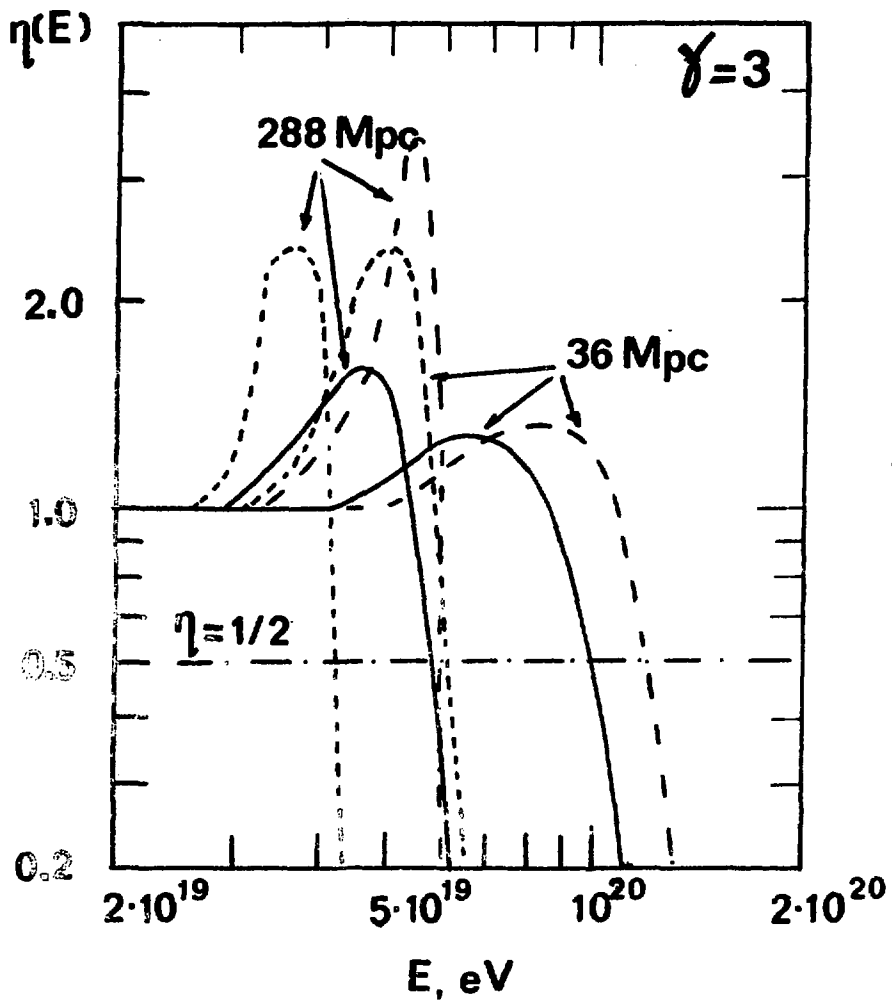


Fig.2

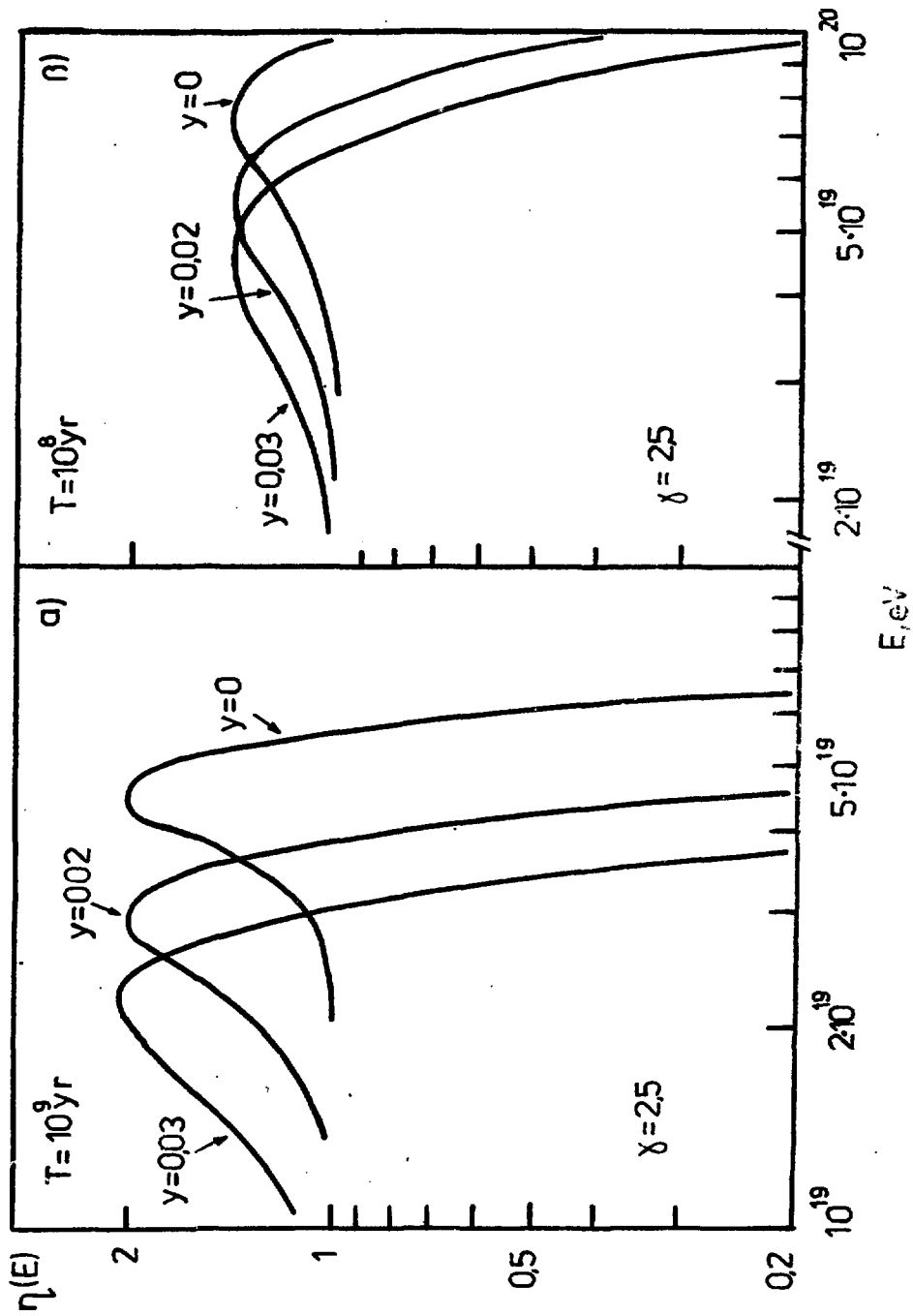


FIG. 3

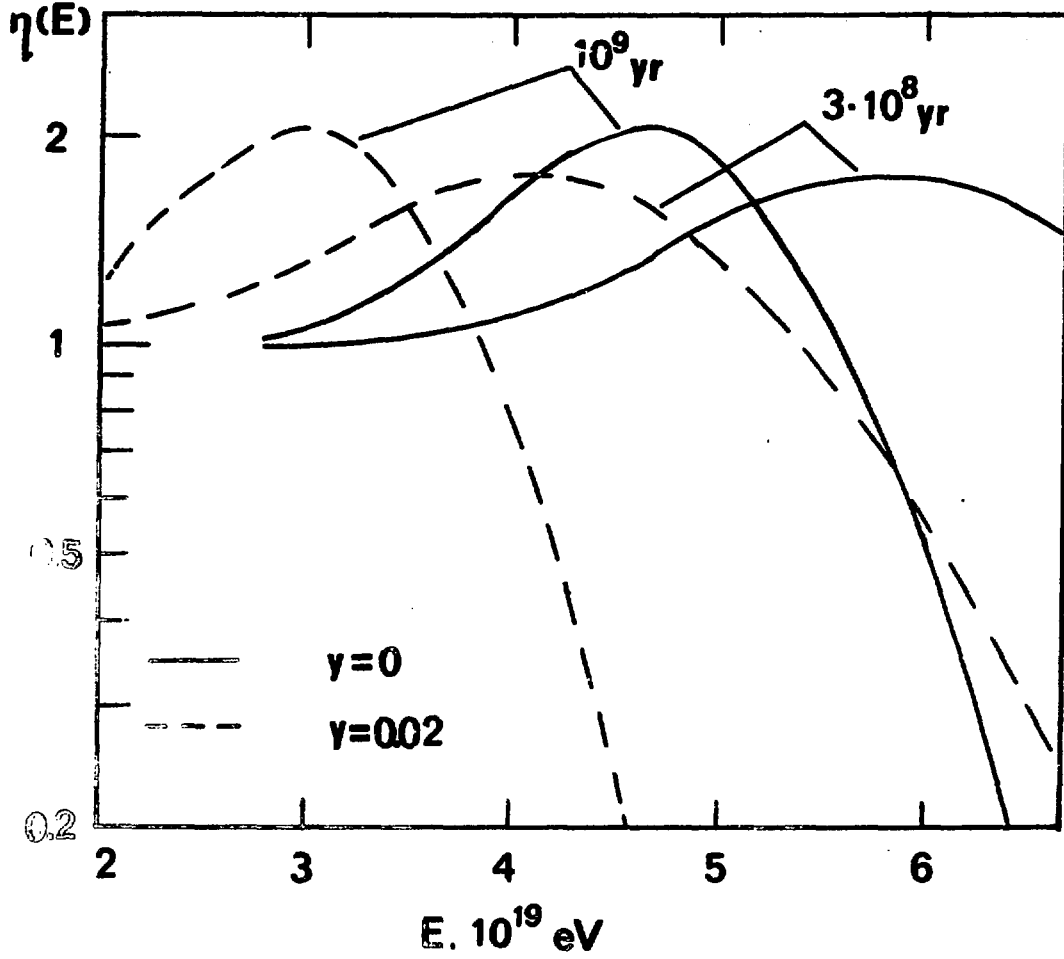


Fig.4

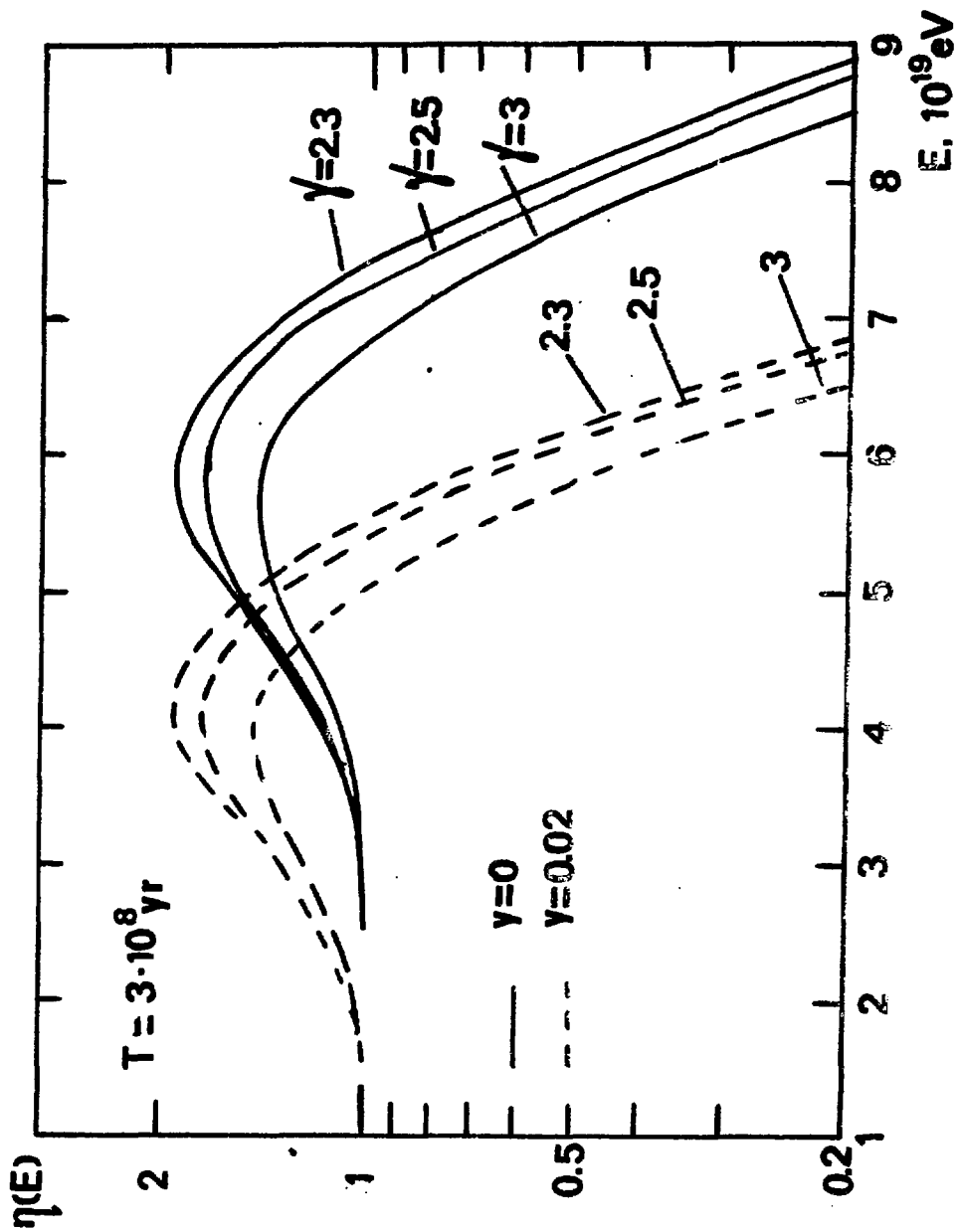


FIG. 5

Figure Captions

Fig.1. Differential spectra of protons from the local source for the different CR propagation times t marked near the curves. The index of the power-law production spectrum of protons $\gamma = 2.5$; the MBR spectrum is "pure" Planckian. Solid curves refer to the kinetic equation solution that takes into account the catastrophic nature of the photomeson production; dashed curves refer to the spectra obtained in the continuous energy loss approximation. Here and in the following Figures the proton spectrum is normalized to the production spectrum: $\eta(E) \equiv F(E)/q(E)$.

Fig.2. Differential proton spectra for the values of CR propagation paths in the intergalactic medium, marked near the curves. Solid curves - a solution of the kinetic equation that takes into account the catastrophic nature of the photomeson production; dashed curves - spectra obtained in the continuous energy loss approximation; dots - spectra from Ref. [10]. The proton production spectrum index $\gamma = 3$.

Fig.3. Differential proton spectra for the various values of the comptonization parameter η of MBR spectrum marked near the curves. a) $T = 10^9$ years; b) $T = 10^8$ years. The proton production spectrum index $\gamma = 2.5$.

Fig.4. Differential proton spectra for the values of CR propagation time $t = 3 \cdot 10^8$ years and 10^9 years. Solid curves - Planckian distribution of MBR spectrum; dashed - the comptonized black-body spectrum of MBR with $y = 0.02$. The proton production spectrum index $\gamma = 2.5$.

Fig.5. Differential proton spectra for the propagation time $t = 3 \cdot 10^8$ years and for three values of the proton production spectrum index, marked near the curves. Solid curves - the Planckian spectrum of MBR; dashed - the comptonized black-body spectrum of MBR with $y = 0.02$.

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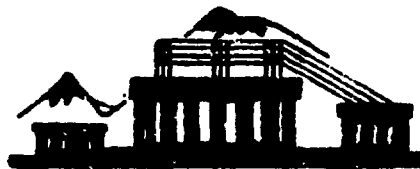
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