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Neutrino from extragalactic cosmic ray interactions in far infrared background

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Diffuse background of high energy neutrinos arising from interactions of cosmic ray protons with far infrared radiation background in extragalactic space is calculated. It is assumed that cosmic ray spectrum at superhigh energies has extragalactic origin and is proton dominated.The cosmological evolution of extragalactic sources of cosmic ray protons as well as infrared-luminous galaxies is taken into account in the calculation.

1. Introduction

The extragalactic background of high energy neutrinos studied in this paper arises from collisions of high energy cosmic ray (CR) protons emitted by local sources (e.g., by active galactic nuclei) in extragalactic space, with extragalactic background of infrared photons. All previous studies (except the most recent ones [1, 2]) took into account the interactions of CR protons with relic photons ($T \cong 2.7K$) only. Evidently, other components of the extragalactic radiation background also must be taken into account in calculation of the extragalactic background of high energy neutrinos. The interval of photon wavelengths which is potentially most important from this point of view is $(1 - 1000)\mu m$, i.e., the infrared region. At last fifteen years infrared astronomy developed very intensively (see, e.g., reviews [3, 4]), and now the rather well-grounded calculation of ENB from interactions of cosmic rays with extragalactic infrared photons became possible [1, 2].

For the concrete calculation of infrared background we chose the paper of Dwek *et al* [5], where the synthetic spectral energy distributions in the large diapason of values of the total luminosities were derived, and the simple double power-law form of the local luminosity function (i.e., the present-day number density) of infrared galaxies suggested by Soifer *et al* [6]. As for the CR spectrum: we do not know well enough the extragalactic cosmic ray spectrum and, therefore, we are forced to use the crucial hypothesis about extragalactic origin of high energy CR's. Everywhere in our calculations we use the extragalactic model (the crossover energy $\sim 3 \times 10^{17} eV$) and normalize our theoretical CR spectrum on experimental CR data.

Neutrino flux from interactions of high energy cosmic rays with infrared background was recently calculated by Stanev [1]. Our work differs from that of [1] in several respects. The main difference is that in [1] there is no non-trivial cosmological evolution of infrared background: this evolution is assumed to be the same as of microwave background radiation. Besides, in [1] there is no separating of contributions to ENB from infrared and optical diapasons of the background while we calculate ENB from far-infrared part of the radiation background only.

2. Extragalactic CR proton spectrum at different epochs

To obtain approximate expressions for the spectra and intensities of CR protons in extragalactic space we use the cosmological transport (kinetic) equation without integral term, i.e., we work in the continuous energy loss approximation introduced, for these problems, by Berezinsky and Grigor'eva [7]. This equation is written as

$$\frac{\partial n(E,z)}{\partial z} + \frac{\partial}{\partial E}\left[\beta(E,z)n(E,z)\right] - \frac{3n(E,z)}{1+z} = g(E,z). \quad (1)$$

Here, $n(E,z)$ is the number density of CR protons with a given redshift z, the function $\beta(E,z)$ is the change of proton energy in unit interval of z,

$$\beta(E,z) = \frac{E}{1+z} - E \cdot t_p^{-1}(E,z)\frac{dt}{dz}. \quad (2)$$

The first term in r.h.s. of eq. (2) takes into account adiabatic energy losses (those due to the cosmological expansion). The function $t_p^{-1}(E,z)$ is the cooling rate of protons via $p\gamma \to \pi X$ and $p\gamma \to pe^+e^-$ reactions at the cosmological epoch with redshift z. In our approximation, the cooling rate consists from two parts,

$$t_p^{-1}(E,z) = t_{p,r}^{-1}(E,z) + t_{p,infr}^{-1}(E,z), \quad (3)$$

(cooling due to interactions with relic and infrared components of the extragalactic radiation background).

The function $g(E,z)$ in r.h.s. of the kinetic equation describes the combined source of extragalactic cosmic rays. This source function can be written in the form

$$g(E,z) = \rho(z)\eta(z)f(E)\frac{dt}{dz}. \quad (4)$$

Here, $\rho(z)$ is the number density of local CR sources (e.g., AGNs) in the proper (physical) volume, $\rho(z) = \rho_0(1+z)^3$, $\eta(z)$ is the activity of each local source (the integrated number of produced particles per second), $\eta(z) = (1+z)^m\eta_0\theta(z_{max}-z)$. Writing this, we assume that the cosmological evolution of cosmic ray sources can be parametrized by power law with the sharp cut-off at some epoch with redshift z_{max} (m and z_{max} are considered as parameters of a model of the combined source). At last, the function $f(E)$ in eq.(4) describes a form of the differential energy spectrum of the local source.

3. Far infrared extragalactic background

For a calculation of the extragalactic radiation background it is convenient to use the cosmological transport equation which is analogous to that used in the previous section. The function which must be found is the number density of infrared photons at different cosmological epochs, $n^{IR}(E_\gamma,z)$. The expression for the source function of the kinetic equation is

$$g^{IR}(E_\gamma,z) = \int \frac{dL}{L}\rho(z,L)S^{IR}(E_\gamma,L)\frac{1}{E_\gamma}\cdot\frac{dt}{dz}. \quad (5)$$

Here, the function S^{IR} is the spectral luminosity ("spectral energy distribution") of a luminous local source (which is in this case an infrared-luminous galaxy with a given total infrared luminosity L). The function $\rho(z,L)$ in eq.(5) is the number density of infrared-luminous galaxies with a given luminosity L in the proper (physical) volume, which is connected with the local luminosity function $\rho(0,L)$ by the relation

$$\rho(z,L) = \rho\left(0, \frac{L}{(1+z)^{\gamma_l}}\right)(1+z)^{3+\gamma_d}, \quad (6)$$

where γ_d and γ_l are parameters determining the cosmological evolution of the luminosity of the local source, and evolution of the comoving density of these sources, respectively.

The resulting expression for the number density of infrared photons in extragalactic space is (neglecting energy losses of these photons during their travelling) is

$$n^{IR}(E_\gamma,z) = \int\limits_z^{z_{max}} dx\left(\frac{1+z}{1+x}\right)^3 \int \frac{dL}{L}\rho(x,L)S^{IR}\left(E_\gamma\frac{1+x}{1+z},L\right)\cdot\frac{1}{E_\gamma}\left|\frac{dt}{dx}\right|. \quad (7)$$

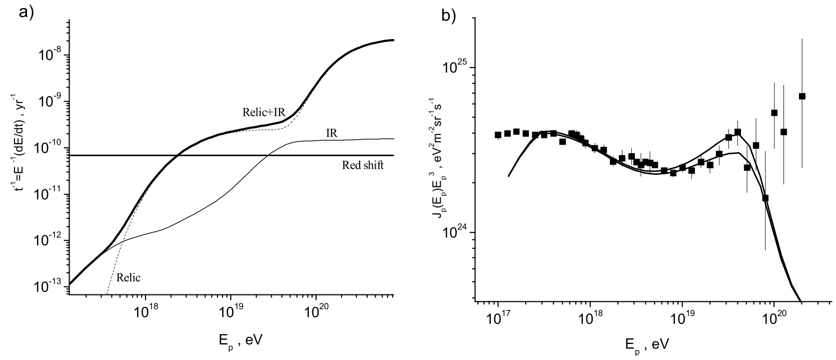

Figure 1. a) Proton cooling rates in relic and infrared photon background. **b)** Extragalactic CR proton spectrum calculated with (lower curve) and without (upper curve) taking into account energy losses in infrared background.

The cooling rate of CR protons in infrared radiation background is expressed through n^{IR} by the formula

$$t^{-1}_{p,infr}(E,z) = \frac{c}{2\gamma_p^2} \int\limits_{\epsilon_{th}}^{\infty} d\epsilon_r \sigma(\epsilon_r) f(\epsilon_r) \epsilon_r \int\limits_{\frac{\epsilon_{th}}{2\gamma_p}}^{\infty} d\epsilon \frac{n^{IR}(\epsilon, z)}{\epsilon^2} \tag{8}$$

($\gamma_p = E/m_p$). Here, ϵ_r is the photon energy in the CR proton rest system, $\sigma(\epsilon_r)$ is the photoabsorbtion cross section, $f(\epsilon_r)$ is the relative proton energy loss in $p\gamma$-collision (in the observer system).

We used the following model for the cosmological evolution of infrared sources:

$$\begin{aligned} \rho(z,L) &= \rho\left(0, \frac{L}{(1+z)^{\gamma_l}}\right) \cdot (1+z)^{3+\gamma_d}, & z \leq z_{flat}, \\ \rho(z,L) &= \rho\left(0, \frac{L}{(1+z_{flat})^{\gamma_l}}\right) \cdot (1+z_{flat})^{\gamma_d}(1+z)^3, & z_{flat} < z \leq z_{cut}, \end{aligned} \tag{9}$$

and $\rho(z,L) = 0$ for $z > z_{cut}$. The parameters are as follows: $\gamma_d = 3, \gamma_l = 2, z_{flat} = 1, z_{cut} = 4$.

On Fig. 1a we show the proton cooling rate on infrared photon gas (together with corresponding function for the relic photon case). One can see that at proton energy $\sim (3 \div 4) \times 10^{19}$ eV, the contribution of infrared photons in total cooling rate is noticeable. The results of two calculations of extragalactic CR proton spectrum (with and without taking into account energy losses on infrared photons) are shown on Fig. 1b. The theoretical CR spectrum at $z = 0$ was normalized on experimental data; from such normalization we obtained the value of the product $\rho_0\eta_0$ entering eq.(4) for the source function of the CR proton kinetic equation, $\rho_0\eta_0 \approx 1.4 \times 10^{-42} cm^{-3} s^{-1}$. For the calculation of the CR spectrum we used the following set of parameters determining the spectrum slope and cosmological evolution of CR sources: $\gamma = 2.5, m = 3.5, z_{max} = 5$. We assumed that extragalactic spectrum of CRs dominates beginning from $E_0 = 3 \times 10^{17}$eV.

The choice of cosmological evolution parameters $\gamma_d, \gamma_l, z_{flat}, z_{cut}$ used in the calculation of infrared background and CR spectrum is justified by our prediction of the spectral intensity $E_\gamma I(E_\gamma)$ of infrared background measured experimentally (Fig. 2a).

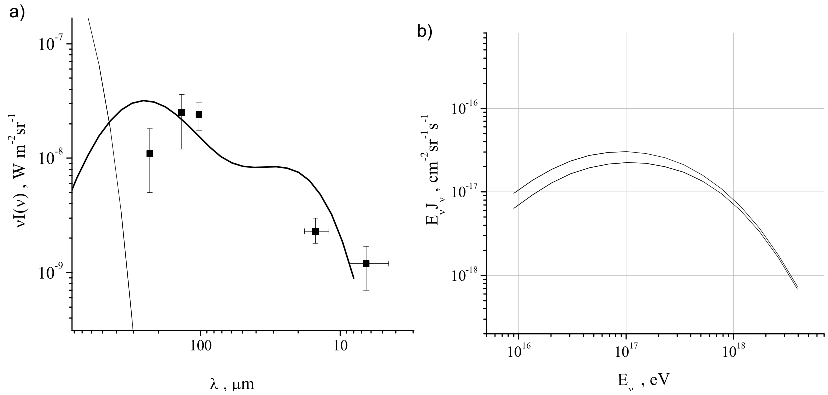

Figure 2. a) Far infrared radiation background calculated using the model of [5] and eq.(9). **b)** Extragalactic muon neutrino background: $\gamma_d = 3, \gamma_l = 2, z_{flat} = 1$; $z_{cut} = 4$ (upper curve), $z_{cut} = 3$ (lower curve).

4. Extragalactic spectra of high energy neutrinos

For simplicity we use in this work one-pion approximation, i.e., we assume that in $p\gamma$-reaction only two particles (neutron and pion) are produced. In this case, as is well known the pions have approximately isotropic distribution in the center of mass system and, as a consequence, the step-like energy spectra in the observer system. The main photoproduction reaction, $p_{CR} + \gamma_{infrared} \to \pi^+ + n$, and subsequent decays of π^+ and μ^+ lead to production of ν_μ,$\tilde{\nu}_\mu$, ν_e. In the present work we will be interested only in $(\nu_\mu + \tilde{\nu}_\mu)$-flux. Therefore, we add together the neutrino from pion and muon decays. Neutron produced in the photoproduction process will decay giving proton, long before the next interaction with photons of the background. Results of the neutrino spectra calculation are shown on Fig. 2b.

5. Conclusions

In spite of the fact that the density of infrared photons in extragalactic space is much smaller (~ 1.5 photons/cm^3) than that of relic microwave photons, the neutrino background appears to be not so small, due to the lower threshold for photoproduction and, especially, due to much stronger time evolution of infrared background in comparison with that of relic photons. The predicted neutrino fluxes are comparable, more or less, with the neutrino fluxes from other extragalactic sources at energy region near 10^{17} eV (γ-ray bursts, topological defects, etc) and deserve further theoretical and, in future, experimental studies.

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