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Positron production due to interaction of cosmological background photons

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The interaction of photons of the cosmological gamma-ray background radiation to photons of extragalactic background light with producing electron-positron pairs is considered. It is shown that the majority of positrons is produced with energy 10 GeV$-$1 TeV.

Keywords: cosmology, background radiation, positrons

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Introduction

Cosmological background radiation — is the homogeneous, isotropic radiation that fills the entire universe. The main component of the cosmological background radiation is the cosmological microwave background radiation (CMB) which is a trace of the epoch of reonization and carries information about the processes that took place at that time [1]. In addition to CMB radiation, there is background radiation in other bands. For example, the background radiation in the optical range (EBL) carries with it information about the rate of star formation [1–3]. Gamma-ray background radiation (CGB) provides us with information about the activity of galactic nuclei and the rate of supernova explosions [1,4]. The X-ray background radiation is mainly associated with the accretion process in the galactic nuclei [1,5], and the ultraviolet background radiation is associated with the radiation of young stars and nebulae [1] and accordingly carries information about these objects. One of the main processes leading to the distortion of the background radiation spectrum is the interaction of two photons with the production of an electron-positron pair [4,6]. As a result, a small number of positrons are constantly being produced in intergalactic space, including the huge voids. Most positrons are produced by the interaction of CGB photons with EBL photons, see e.g., [4–7]. Therefore we have limited ourselves to considering only this process.

1. Model

Consider the interaction of a CGB photon with an EBL photon with the production of an electron-positron pair. The cross-section of this process σ is [11]:

$$\sigma = \sigma(s) = \frac{\pi}{2} r_e^2 \cdot (1 - v^2) \cdot \Big((3 - v^4) \ln\Big(\frac{1+v}{1-v}\Big) - 2\,v\,(2 - v^2)\Big) \cdot h(s-1), \qquad (1)$$

where $r_e = \frac{e^2}{mc^2}$ — is the classical radius of the electron, m — is the rest mass of the electron, $h(x)$ — is the Heaviside function ($h(x) = 1$ at $x > 0$ and $h(x) = 0$ at $x < 0$),

$$v = \sqrt{1 - 1/s} \;\text{ and }\; s = \frac{1}{2}\,\frac{\varepsilon_l\,\varepsilon_\gamma}{m^2c^4}(1 - \cos\Psi), \qquad (2)$$

where ε_l — is the energy of the EBL photon and ε_γ — is the energy of the CGB photon, Ψ — the angle between their pulses. In the spectrum of EBL photons was taken as their observed at $z = 0$ spectrum from the work [3], where z — redshift. Two limiting cases have been considered: the case where the local density of EBL photons at redshift z simply increases by $(1+z)^3$ times its value by $z = 0$, and the case where the local density of EBL photons is proportional to the average rate of star formation $S(z)$ at a given z. To find the spectrum of CGB photons, the model proposed in the paper [4] was used. According to it, the spectrum emitted by CGB photon sources $\frac{dN_\gamma}{d\varepsilon_\gamma dt}$ is considered to be equal to [4]:

$$\frac{dN_\gamma}{d\varepsilon_\gamma dt}(\varepsilon_\gamma) = N_0 \cdot S(z) \cdot \left(\frac{\varepsilon_\gamma}{\varepsilon_0}\right)^{-\gamma} \cdot h(\varepsilon_{\max} - \varepsilon_\gamma), \qquad (3)$$

where the exponent γ and the normalization constants N_0 and ε_0 were thought to be independent of z [4], the energy $\varepsilon_{\max}$ was also thought to be independent of z. The constant N_0 was selected so that the intensity of the CGB photons at $\varepsilon_\gamma = 20$ GeV at $z = 0$ coincided with the observed intensity taken from the paper [4]. The choice of this value for spectrum normalization is related to the fact that in the work [4] the application of this model is limited to the energy range 20 GeV $< \varepsilon_\gamma <$ 1 TeV, and at low values of CGB photon energies, their flux is weaker depending on the model parameters. It was also believed that there were no CGB photon sources at $z > z_{\max}$. The dependence of the average rate of star formation $S(z)$ on the redshift was either assumed to be power $S(z) = (1+z)^\beta$ [4,9], or its

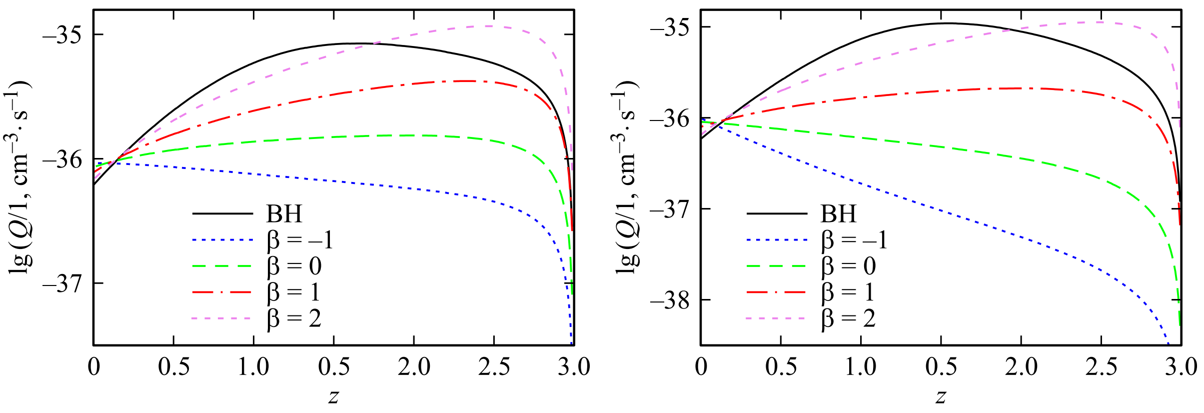

Figure 1. Positron generation rate depends Q on redshift z for various β. The BH sign indicates the case of the rate of star formation (4). The graph on the left corresponds to the case where the density of EBL photons simply increases as $(1+z)^3$, the right graph — to the case where it is proportional to the average rate of star formation $S(z)$.

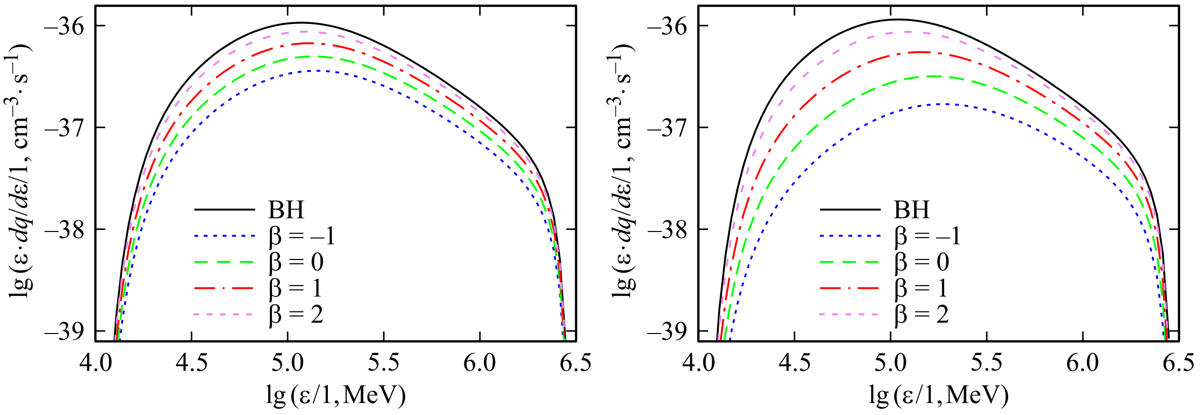

Figure 2. Positron generation intensity profile $\frac{dq}{d\varepsilon}$ of their energy ε at $z=0.5$. Designations are the same as in the Fig. 1

approximation [9] was used:

$$S(z)=\frac{C}{10^{A\,(z-z_0)}+10^{B\,(z-z_0)}},\qquad (4)$$

where $z_0=1.243$, $A=-0.997$, $B=0.248$ and the constant C is assumed to be $C=0.180M_\odot$ year^{-1} in 1 Mpc in the comoving frame of reference [9]. At the same time, during the spectrum finding of CGB photons, only their absorption on photons of the EBL spectrum with the formation of electron-positron pairs was considered. The calculation of the rate of generation of electron-positron pairs was carried out in the same way as in [7].

2. Results

Figure 1 shows the dependence of the lasing rate of Q positrons as a function of redshift z for different profiles of the average rate of star formation $S(z)$, where Q — is the number of positrons produced per 1 s in 1 cm^3 in the accompanying reference frame. The graph on the left corresponds to the case where the density of EBL photons simply increases as $(1+z)^3$, the right graph — to the case where it is proportional to the average rate of star formation $S(z)$. It can be seen that in the case of approximation (4), the maximum rate of positron generation is reached at $z\sim 1.5$ and then decreases due to a decrease in the rate of star formation. Figs. 2 and 3 show the intensity $\frac{dq}{d\varepsilon}$ of positron generation as a function of their energy ε for the redshifts $z=0.5$ and 1.5, respectively, where $\frac{dq}{d\varepsilon}$ — is the number of positrons produced in the accompanying reference frame for 1 s in 1 cm^3 with an energy ε lying in the energy interval 1 MeV. In all figures, γ was assumed to be $\gamma=-2.3$ and the energy $\varepsilon_{\max}=3$ TeV. This is due to the fact that the paper [4] shows that these parameter values provide one of the best correspondences between the spectrum of CGB photons calculated in the scope of the model under consideration and the spectrum of CGB photons observed at $z=0$. As $z_{\max}$ there was taken the value $z_{\max}=3$. It is this choice of $z_{\max}$ that causes a sharp decrease in the positron generation rate Q at z close to $z=3$ for cases $\beta=1$ and 2. It can be seen that the interaction of CGB photons with EBL photons mainly produces positrons with an energy of $\varepsilon\sim 10$ GeV–1 TeV. For positrons of such energies, the

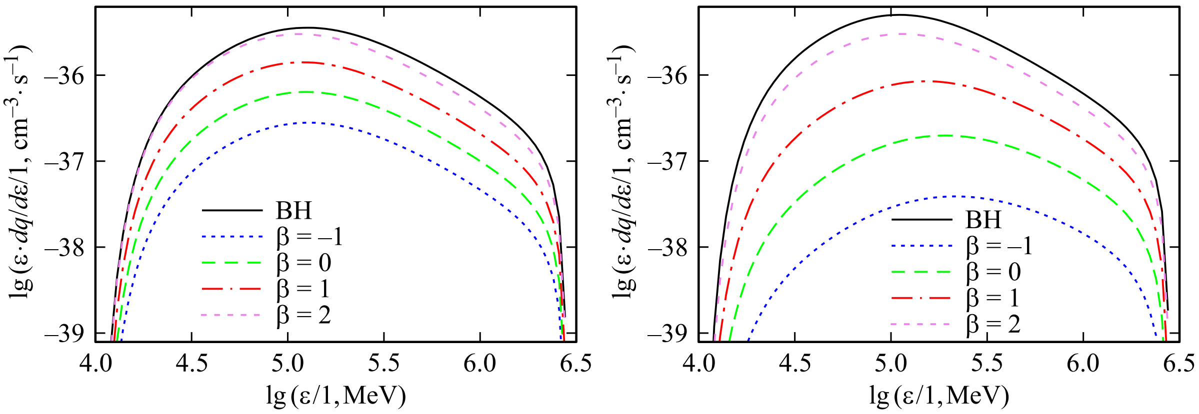

Figure 3. Same as Figure 3, but for $z = 1.5$.

annihilation time in the intergalactic medium exceeds the lifetime of the Universe [10]. Such positrons do not actually annihilate and, accordingly, gradually accumulate in the intergalactic medium [10]. And, therefore, such positrons make little or no contribution to the eventual annihilation line of positrons in intergalactic space. The observed flux of annihilation photons from them can be roughly estimated as $\sim 10^{-19}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, which is noticeably lower than the lower limit of the currently available fluxes for observation, which is $\sim 10^{-4} - 10^{-12}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ depending on the energy of the annihilation photon [10–13].

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] R. Hill, K.W. Masui, D. Scott, App. Spectr., **72** (5), 663 (2018). DOI: 10.1177/0003702818767133
[2] A. Cooray. Royal Society Open Science, **3** (3), 150555 (2016). DOI: 10.1098/rsos.150555
[3] A. Franceschini, G. Rodighiero, M. Vaccari. A & A, **487** (3), 837 (2008). DOI: 10.1051/0004-6361:200809691
[4] M. Ackermann, M. Ajello, A. Albert, W.B. Atwood, L. Baldini et al., ApJ, **799** (1), id. 86 (2015). DOI: 10.1088/0004-637X/799/1/86
[5] M. Ajello, J. Greiner, G. Sato, D.R. Willis, G. Kanbach, A.W. Strong, R. Diehl, G. Hasinger, N. Gehrels, C.B. Markwardt, J. Tueller. ApJ, **689** (2), 666 (2008). DOI: 10.1086/592595
[6] R.J. Gould, G.P. Schreder. Phys. Rev., **155** (5), 1408 (1967) DOI: 10.1103/PhysRev.155.1408
[7] R.J. Gould, G.P. Schreder, Phys. Rev., **155** (5), 1404 (1967). DOI: 10.1103/PhysRev.155.1404
[8] P.S. Behroozi, R.H. Wechsler, C. Conroy. ApJ, **770** (1), id. 57 (2013). DOI: 10.1088/0004-637X/770/1/57
[9] A.N. Popov, D.P. Barsukov, A.V. Ivanchik, S.V. Bobashev. J. Phys. Conf. Series, **2103** (1), id. 012042 (2021) DOI: 10.1088/1742-6596/2103/1/012042
[10] B.A. Nizamov, M.S. Pshirkov. Eprint arXiv:2303.03526 (2023). DOI: 10.48550/arXiv.2303.03526
[11] A. de Angelis, V. Tatischeff, I.A. Grenier, J. McEnery, M. Mallamaci et al. High Energy Astrophys., **19**, 1 (2018). DOI: 10.1016/j.jheap.2018.07.001
[12] W.B. Atwood, A.A. Abdo, M. Ackermann, W. Althouse, B. Anderson et al. ApJ, **697** (2), 1071 (2009). DOI: 10.1088/0004-637X/697/2/1071
[13] J.A. Hinton. HESS Collaboration, New Astronomy Reviews, **48** (5-6) 331 (2004). DOI: 10.1016/j.newar.2003.12.004

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