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Spectrum of positrons produced due to interaction of gamma-ray extragalactic photons with soft background photons

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The interaction of the extragalactic gamma-ray background photons to soft extragalactic background photons with producing electron-positron pairs is considered. It is shown that the majority of positrons produced with energies 10 GeV−1 TeV. However, the interaction of „X-ray“ extragalactic background photons may produce the positrons with energies 10-10−100 keV.

Keywords: cosmology, background radiation, positrons.

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Introduction

Space between galaxies and galaxy clusters is filled with background electromagnetic radiation of different origin [1]. First, this is cosmic microwave background (CMB) radiation on red shift $z \sim 1000$ in the recombination epoch, second, this is extragalactic optical and infrared background light (EBL) that carries information about stars and star formation rate [1–3]. Cosmic X-ray background (CXB) radiation carries information about accretion of matter to galactic nuclei and, accordingly, about supermassive black hole formation rate in galactic centers [1,4]. There is probably also cosmic ultraviolet background (CUB) radiation that is induced by young hot stars and interstellar nebula radiation [1]. Cosmic gamma-ray background (CGB) radiation consists of active galactic nuclei radiation and probably of photons produced during supernova explosions [1,5]. Soft background radiation, including soft CGB photons, interacts with galaxy cluster medium, which induces distortions in its spectrum [6]. In addition, photons may collide and interact with each other [7]. In particular, the Breit−Wheeler process is possible in which an electron-positron pair is produced from interaction of two background photons [8]. As a result a continuous positron source that is more or less uniformly distributed throughout the universe occurs in the intergalactic and probably in the intercluster space.

1. Model

This study addresses the interaction between two photons with the energies ε and ε_γ, respectively, followed by electron-positron pair production. This is a threshold process that is possible only when $\varepsilon\varepsilon_\gamma \geq m^2c^4$, where m is the mass of electron [7]. Positron production rate in such process is calculated in this work as in [9]. Only interaction of CGB photons with EXL, CUB and CXB photons is addressed. The CGB photon spectrum was calculated as in [9] using a model proposed in [5]. Only absorption of CGB photons in the interaction with EBL photons was considered. The spectrum of produced CGB photons was a power law spectrum$dq_\gamma/d\varepsilon = N_0 \cdot \varepsilon^{-\gamma}$ at $\varepsilon < \varepsilon_{\max}$ and $dq_\gamma/d\varepsilon = 0$ at $\varepsilon \geq \varepsilon_{\max}$, where $dq_\gamma/d\varepsilon$ is the number of CGB photons with ε produced in 1 in 1 cm^3 in a single energy range in the related frame of reference [5]. The case of $\gamma = 2.3$ and $\varepsilon_{\max} = 3$ TeV was used as an example [5]. The CGB photon generation rate was assumed proportional to the mean star formation rate $S(z)$ [5] and the CGB photon generation rate normalization N_0 was calculated such that at $\varepsilon_\gamma = 20$ GeV the resulting photon flux at $z = 0$, where z is the red shift, coincides with the observed value taken from [5]. The mean star formation rate was assumed to be equal to [10]:

$$S(z) = \frac{C}{10^{A(z-z_0)} + 10^{B(z-z_0)}}, \tag{1}$$

where $z_0 = 1.243$, $A = -0.997$, $B = 0.248$ and $C = 0.180\,M_\odot\,\text{year}^{-1}\,\text{Mpc}^{-3}$ [10]. CXB, CUB and EBL photon spectra profiles as in [9] were assumed to be independent of the red shift z. The EBL photon spectrum was taken from [3], the CXB photon spectrum was taken from [4], upper limit of the CUB photon spectrum from [1] was taken as the CUB photon spectrum. Spectra used at $z = 0$ and the CGB photon spectrum taken from [5] are shown in Figure 1. Dashed line shows the CXB photon spectrum extrapolation by the power law spectrum up to the CUB and CGB photon spectra boundaries. Concentration of CXB, CUB and EBL photons in this work is assumed to be dependent on the red shift z. We limit ourselves only to two limiting cases. In the first case, the concentration of CXB, CUB and EBL background photons was assumed to be proportional $(1+z)^3$ that corresponds to maintaining the number of background photons with the expansion

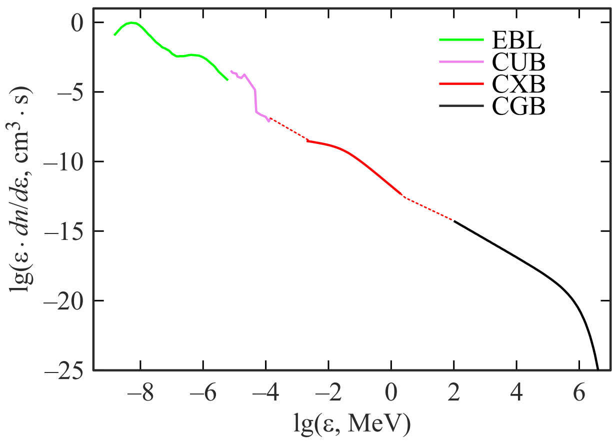

Figure 1. Used CXB, CUB and EBL photon spectra and CGB photon spectrum from [5], on the red shift $z = 0$. Dashed curves correspond to the extended CXB spectrum case.

of the universe. In the second case, the concentration was assumed to be equal to the mean star formation rate (1), which corresponds to the immediate adjustment of the number of background photons to the rate of photon generation by young stars. In both cases, the spectrum of these photons was normalized in such a way as to coincide with the observed photon concentration at $z = 0$.

2. Results

Figure 2 and 3 show a spectrum of produced positrons in the interaction of CGB photons with CXB, CUB and EBL photons. Fragments (*a*) correspond to the case when the concentration of EBL, CUB and CXB photons increases as $(1+z)^3$, and fragments (*b*) correspond to the case when the concentration is proportional to the star formation rate (1). It can be seen that at $z = 0.5$ both cases are almost the same, but at $z = 1.5$ differences are not too great. It can be seen that almost all positrons are produced with $\varepsilon \sim 10\,\text{GeV}{-}1\,\text{TeV}$. Such positrons almost don't annihilate [11] and are gradually accumulated in the intergalactic space. It is shown that, despite it was expected that the number of hypothetical CUB photons is a little less than of EBL photons (Figure 1), their contribution to the positron production rate is higher than that of EBL photons because they can interact with softer and, consequently, more CGB photons. The peak in the spectrum profile of positrons produced in the interaction between CXB and CGB photons is the calculation artefact. It is associated with the fact that, according to the model proposed in [5], we deliberately cut off the CGB photon source spectrum on the bottom at $\varepsilon_{\text{min}} = 5\,\text{GeV}$, see [9]. Position and profile of the peak depend significantly on the magnitude of ε_{min}. However, this peak almost doesn't contribute to the total positron spectrum because, at these energies, positron production prevails in the interaction of CGB photons with CUB and EBL photons. Sharp drop of spectra at $\varepsilon \approx 3\,\text{TeV}$ is associated with the chosen maximum energy of produced CGB photons $\varepsilon_{\text{max}} = 3\,\text{TeV}$. Figures 2 and 3 also show a spectrum of produced positrons in the interaction of CGB photons with each other. Dashed line shows the extended CXB photon spectrum case. This process is possible because also photons with $\varepsilon \sim 2{-}3\,\text{MeV}$ [4] are formally assigned to „X-ray" background photons, and in the case of the extended spectrum, gamma quanta with $\varepsilon \sim 1{-}10\,\text{GeV}$ also formally fell into the „X-ray" spectral region. In this case, noticeable amounts of positrons with $\varepsilon \sim 1{-}100\,\text{keV}$ can be produced and will annihilate during the typical time $\tau \sim (2{-}3)\cdot 10^9$ year [11,12]. Extension of the „X-ray" CXB photon spectrum both towards lower and higher energies almost doesn't affect the positron production rate

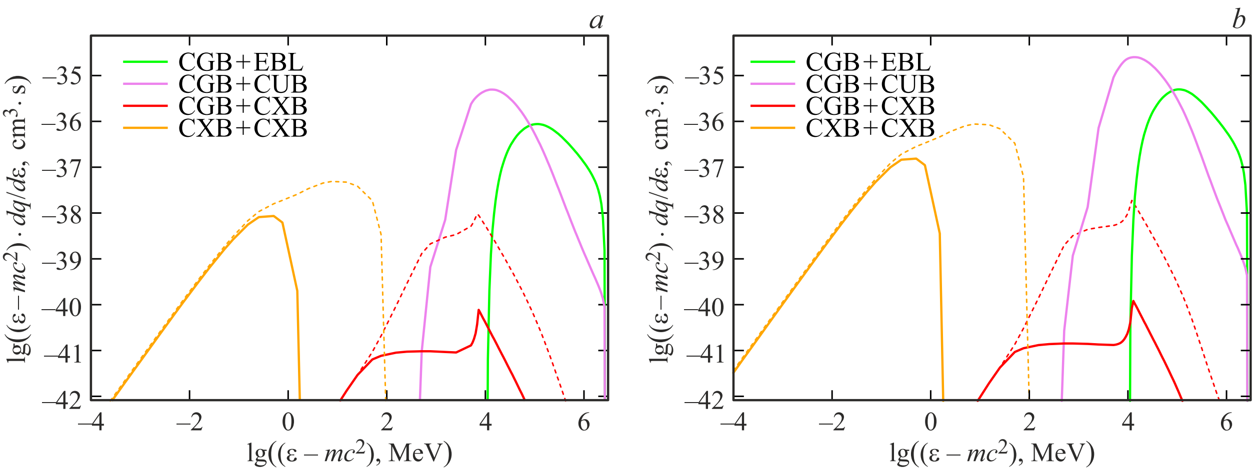

Figure 2. Produced positron spectrum on $z = 0.5$. Here, ε is the produced positron energy measured in MeV, $dq/d\varepsilon$ is the positron production rate, i.e. the number of positrons with ε that are produced in 1 s per 1 cm^3 in a single energy interval in the related frame of reference, mc^2 is the electron rest energy. *a* — the case when the concentration of EBL, CUB and CXB photons simply grows as$(1+z)^3$, and *b* — the case when it is proportional to the mean star formation rate (1). Dashed curves correspond to the extended CXB spectrum case.

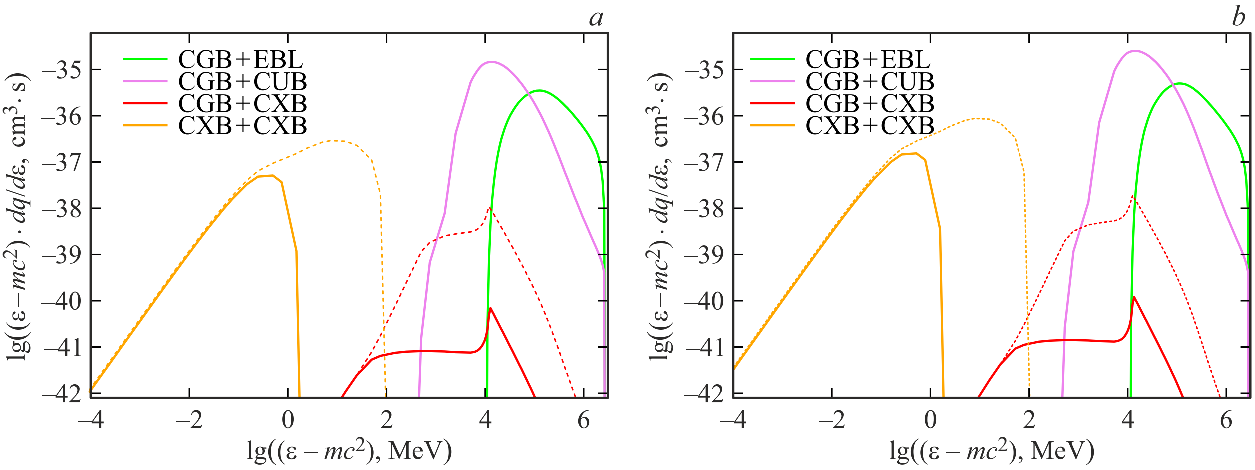

Figure 3. The same as in Figure 2, but for $z = 1.5$.

at these energies. This is associated with the fact that the main contribution to positron production is made by „X-ray“ CXB photons with energies about 1 MeV. Extension of the CXB photon spectrum up to the beginning of the CGB spectrum leads to sharp growth of positron production with 1 − 100 MeV. This work didn't address the interaction of CGB photons with more numerous CMB photons because within the employed model [5] the energy of produced CGB photons is limited to $\varepsilon_{max} = 3$ TeV and is insufficient for electron-positron pair production in the interaction with CMB photons.

Conflict of interest

The authors declare no conflict of interest.

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