Absorption of Photons from Distant Gamma-Ray Sources

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Being the largest gravitationally bound structures in the Universe, galaxy clusters are huge reservoirs of photons generated by the bremsstrahlung of a hot cluster gas. We consider the absorption of high-energy photons from distant cosmological gamma-ray sources by the bremsstrahlung of galaxy clusters. The magnitude of this effect is the third in order of smallness after the effects of absorption by the cosmic microwave background and absorption by the extragalactic background light. Our calculations of the effect of absorption by the bremsstrahlung of galaxy clusters have shown that this effect manifests itself in the energy range 1–100 GeV and can be $\tau \sim 10^{-5}$.

Keywords: cosmology, gamma-ray emission, bremsstrahlung, galaxy clusters.

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INTRODUCTION

The emission from active galactic nuclei (quasars, blazars, etc.) and gamma-ray bursts is of special interest in astrophysics, because the spectra of these sources contain information about the physical conditions and the composition of matter in the Universe at various stages of its evolution. For example, the spectra of distant blazars in the gamma-ray range \((E > 100 \text{ GeV})\) are currently studied with highly sensitive Cherenkov telescopes, such as H.E.S.S and VERITAS (Abramowski et al. 2013; Lenain 2014; Pfrommer 2013). In this case, it is very important to take into account the factors leading to spectral distortions as high-energy photons propagate through intergalactic space. The absorption of gamma-ray photons with the production of electron positron pairs when gamma-ray photons collide with background photons plays the most important role here (Ruffini et al. 2016). For gamma-ray photons with energies \(E \sim 100 \text{ GeV} - 100 \text{ TeV}\) this is mainly the interaction with extragalactic background light (EBL) photons (Franceschini et al. 2008; Sinha et al. 2014; Dwek and Krennrich 2013). In the energy range \(E \sim 100 \text{ TeV} - 10^7 \text{ TeV}\) the interaction with cosmic microwave background (CMB) photons dominates (De Angelis et al. 2013; Gould and G.P. Schreder 1967b). At energies \(E > 10^7 \text{ TeV}\) the interaction with cosmic radio background (CRB) photons becomes important (De Angelis et al. 2013; Gould and Schreder 1967b; Reesman and Walker 2013).

Galaxy clusters are the largest gravitationally bound objects in the Universe. An appreciable fraction of the cluster baryonic matter is a tenuous \((n \sim 10^{-3} - 10^{-2} \text{ cm}^{-3})\) hot \((T \sim 1 - 10 \text{ keV})\) intracluster gas (see, e.g., Vikhlinin et al. 2006; Patej and Loeb 2015). The scattering of photons by particles of this gas leads to distortions in the spectra of distant sources (Sunyaev and Zeldovich 1972). In addition, due to the bremsstrahlung of electrons in this gas, clusters also turn into huge \((R \sim 1 - 10 \text{ Mpc})\) reservoirs of photons (Lea et al. 1973). Therefore, apart from the extragalactic background components listed above, distortions in the spectra of distant cosmological gamma-ray sources can also be caused by the interaction of gamma-ray photons with bremsstrahlung photons of the hot gas in galaxy clusters.

In this paper the effect of photon absorption with the production of an electronpositon pair on bremsstrahlung is calculated and compared with the effect of absorption by the cosmic microwave background.
INTERACTION OF GAMMA-RAY EMISSION WITH THE EXTRAGALACTIC BACKGROUND

Consider the interaction between two photons with the production of an electron-positron pair:

\[ \gamma_E + \gamma_\epsilon \rightarrow e^+ + e^-, \]

where \( \gamma_E \) is the incident gamma-ray photon with energy \( E \) and \( \gamma_\epsilon \) is the background photon with energy \( \epsilon \). Its cross section is given by the following expression (Gould and Schreder 1967a):

\[ \sigma = \pi r_e^2 \frac{1 - \beta^2}{2} \left[ (3 - \beta^4) \ln \left( \frac{1 + \beta}{1 - \beta} \right) - 2 \beta (2 - \beta^2) \right] H(s - 1), \]

where \( r_e = e^2/(mc^2) \) is the classical electron radius, \( m \) is the electron rest mass, \( \beta = v/c \) is the center-of-mass velocity of the electron and positron divided by the speed of light, and \( H(x) \) is the Heaviside step function, \( H(x) = 1 \) at \( x > 0 \) and \( H(x) = 0 \) at \( x \leq 0 \). The relations between the center-of-mass velocity \( \beta \) of the produced particles, the photon energies \( E \) and \( \epsilon \), and the angle \( \theta \) between the photon propagation directions are defined by the following equations (Gould and Schreder 1967a):

\[ s = \frac{eE}{2m^2c^4} (1 - \cos \theta), \quad \beta = \sqrt{1 - \frac{1}{s}}. \]
Consider a high-energy photon (with energy \( E \)) propagating in a medium with low-energy photons. The gamma-ray photon absorption probability per unit length at point \( \vec{x} \) is (Gould and Schreder 1967a)

\[
\frac{d\tau}{dx}(\vec{x}) = \int_{-\infty}^{+\infty} \sigma(E, \epsilon, \Psi)(1 - \cos(\Psi))f(\vec{x}, \vec{p}), d^3p
\]  

where \( f(\vec{x}, \vec{p}) \) is the distribution function of the low-energy photons, \( \vec{p} \) is their momentum, and \( \epsilon = pc \). Let us integrate this expression along the line of sight from \( z = 0 \) (the cosmological redshift corresponding to the present epoch and the time of signal observation) to \( z = z_s \) (the cosmological redshift of the gamma-ray source). The optical depth will then be

\[
\tau = \int_{0}^{z_s} \int_{-\infty}^{+\infty} \sigma(E, \epsilon, \Psi)(1 - \cos(\Psi))f(\vec{x}, \vec{p})\frac{dx}{dz}d^3p dz,
\]  

where all quantities are taken on the photon trajectory and the factor \( dx/dz \) describes the dependence of the distance on redshift. In the standard \( \Lambda CDM \)-cosmological model it has

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**Fig. 2:** The bremsstrahlung spectra used are indicated by the black solid curves. \( dN/d\epsilon \) is the number of photons per unit volume per unit energy interval. Curve 1 corresponds to \( n_e = 10^{-2} \text{ cm}^{-3}, T_e = 8 \text{ keV}, R = 7 \text{ Mpc} \); curve 2 corresponds to \( n_e = 10^{-3} \text{ cm}^{-3}, T_e = 5 \text{ keV}, R = 5 \text{ Mpc} \); and curve 3 corresponds to \( n_e = 10^{-4} \text{ cm}^{-3}, T_e = 3 \text{ keV}, R = 3 \text{ Mpc} \). The spectra used (for \( z = 0 \)) are also shown: the gray solid, back dashdotted, and gray dotted lines indicate the CMB, EBL, and CRB spectra, respectively.
Fig. 3: Optical depth $\tau$ for a gamma-ray photon with energy $E$ corresponding to the spectra shown in Fig. 2 $z_s = 0.01$ and $z_c \ll 1$.

the following form (at $z \ll z_{eq} = 3365$, Ade et al. (2016), where the radiation contribution $\Omega_r$ may be neglected):

$$\frac{dx}{dz} = \frac{c}{H_0 (1 + z) \sqrt{\Omega_\Lambda + \Omega_M (1 + z)^3}},$$

(6)

where $\Omega_\Lambda = 0.692$ and $\Omega_M = 0.308$ are the relative fractions of dark energy and dark matter, respectively (in units of the critical density), $H_0 = 67.8$ km/s Mpc is the Hubble constant at the present epoch (Ade et al. 2016).

**INTERACTION OF GAMMA-RAY EMISSION WITH THE BREMSSTRAHLUNG OF GALAXY CLUSTERS**

Let us estimate the hot-gas bremsstrahlung power in a galaxy cluster. When a fast charged particle collides with an ion, it undergoes deceleration and emits bremsstrahlung photons. For a plasma that has a Maxwellian velocity distribution of electrons with temperature $T_e$ the emissivity of matter $\varepsilon_\nu$ can be written as (Lang 1980)

$$\varepsilon_\nu = \frac{8}{3} \left( \frac{2\pi}{3} \right)^{1/2} \frac{Z^2 e^6}{m^2 c^3} \left( \frac{m}{kT_e} \right)^{1/2} n_i n_e g(\epsilon, T_e) \exp \left( -\frac{\epsilon}{kT_e} \right),$$

(7)
where $\nu$ is the bremsstrahlung photon frequency, $\epsilon = h\nu$, $Z$ is the ion charge (for simplicity we will assume that $Z = 1$), $n_e$ and $n_i$ are the electron and ion densities, respectively, $n_i = n_e$, $T_e$ is the electron temperature, $g(\epsilon, T_e)$ is the Gaunt factor (see, e.g., Zheleznyakov 1997):

$$g(\epsilon, T_e) = \frac{\sqrt{3}}{\pi} K_0(\epsilon/2kT_e) \exp \left( \frac{\epsilon}{2kT_e} \right),$$

(8)

where $K_0(z)$ is a Macdonald function.

For simplicity we will consider only small old relaxed clusters with a spherically symmetric gas distribution. We will assume that $z$ is virtually constant on the cluster scales. When considering the passage of a gamma-ray photon near the cluster, we can then use a flat metric. Therefore, we will assume that near the cluster the gamma-ray photon propagates along a straight line $\vec{x}(s) = L\vec{e}_y + s\vec{e}_z$ (Fig. 1). Consequently, supposing that the density of gas bremsstrahlung photons in the cluster rapidly decreases we can write

$$\tau \left( \frac{E}{1 + z_c} \right) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \sigma(E, \epsilon, \Psi)(1 - \cos \Psi) f(\vec{x}(s), \vec{p}) d^3p ds,$$

(9)

where $z_c$ is the cluster redshift.

We will also assume that the cluster is optically thin for bremsstrahlung. This is a good approximation at $\epsilon \gg \epsilon_T$, where the frequency $\nu_T = \epsilon_T/h$ can be estimated as (Lang...
Fig. 5: Optical depth $\tau$ versus gamma-ray photon energy $E$ for the cluster Abell 2204.

1980)

$$\nu T \approx 5 \text{ MHz} \left( \frac{T_e}{1 \text{ keV}} \right)^{-0.675} \left( \frac{n_e}{1 \text{ cm}^{-3}} \right) \left( \frac{\ell}{1 \text{ Mpc}} \right)^{1/2}, \quad (10)$$

where $\ell$ is the extent of the plasma-filled region. Accordingly,

$$f(\vec{x}, \vec{p}) = \frac{2\pi}{\hbar \epsilon^3} \int_0^{+\infty} \varepsilon(\vec{x} - \lambda \vec{n}, \vec{p}) d\lambda, \quad (11)$$

where $\vec{n} = \vec{p}/p$. We will take into account the fact that the electron density $n_e$ and the gas temperature $T_e$ depend only on the distance $r$ to the cluster center and that the gas radiates isotropically. Then,

$$\varepsilon(\vec{x}, \vec{p}) = \int_0^{+\infty} \varepsilon(\epsilon, \Psi)(|\vec{x}| - r) d\epsilon. \quad (12)$$

Substituting Eqs. (11) and (12) into (9) gives

$$\tau \left( \frac{E}{1 + z_c} \right) = \int_0^{+\infty} \int_0^{+\infty} \int_0^{\pi} \sigma(E, \epsilon, \Psi)(1 - \cos \Psi) \frac{2\pi \varepsilon(\epsilon, \epsilon)}{\hbar c} I(r, L) d\Psi d\epsilon dr, \quad (13)$$

where the function $I(r, L)$ is

$$I(r, L) = 4\pi r \arcsin \left( \frac{r}{L} \right) \text{ at } r < L,$$

$$I(r, L) = 2\pi^2 r \text{ at } r \geq L. \quad (14)$$
Fig. 6: Normalized optical depth $\tau / \tau_{|L=0}$ versus impact parameter $L$ for the cluster Abell 2204. The graphs differ only by the scale.
Fig. 7: Electron density $n_e(r)$ and gas temperature $T_e(r)$ versus distance $r$ to the cluster center for the cluster Abell 478: the black solid curves indicate the observed density and temperature profiles; the gray solid curves indicate their extrapolations. The data were taken from Vikhlinin et al. (2006).
Fig. 8: Same as Fig. 5 for the cluster Abell 478: the black solid curve indicates the optical depth for the observed density and temperature profiles; the gray solid curve indicates the optical depth for their extrapolations.

OPTICAL DEPTH

Consider first the simplest cluster model: a gas sphere of radius $R$ with a constant density $n_e$ and temperature $T_e$, i.e., $n_e$ and $T_e$ are constant at $r < R$ and zero at $r > R$. Let us find the optical depths $\tau$ for three cases of galaxy cluster model parameters:

1) $n_e = 10^{-2}$ cm$^{-3}$, $T_e = 8$ keV, $R = 7$ Mpc,

2) $n_e = 10^{-3}$ cm$^{-3}$, $T_e = 5$ keV, $R = 5$ Mpc,

3) $n_e = 10^{-4}$ cm$^{-3}$, $T_e = 3$ keV, $R = 3$ Mpc.

In Fig. 2 the black solid curves indicate our estimates of the bremsstrahlung spectrum $dN/d\epsilon$ at the cluster center $r = 0$ for the cases listed above, where $dN/d\epsilon$ is the number of photons with energy $\epsilon$ per unit volume per unit energy interval. Figure 2 also shows the cosmic microwave background (CMB) spectrum at $z = 0$ (thick gray curve), the extragalactic background light (EBL) spectrum at $z = 0$ taken from Franceschini et al. (2008) (black dashdotted curve), the cosmic radio background (CRB) spectrum from Fixsen et al. (2011) (gray dashed curve), and the cosmic X-ray background (CXB)
spectrum from Ajello et al. (2008) (black dashed curve). Figure 3 presents the optical depth $\tau(E)$ for absorption for these spectra provided that the gamma-ray source is at $z_s = 0.01$, while the cluster is located, accordingly, at lower $z$. When calculating $\tau$ for bremsstrahlung, we used Eq. (13) and set $L = 0$. In addition, since $z_c \lesssim 10^{-2} \ll 1$, we neglected the photon redshift. Note that in this case $\tau$ does not depend on the specific $z = z_c$ between the source and the observer at which the cluster itself is located. The optical depth for the CMB, EBL, CRB, and CXB spectra was calculated from Eq. (5) with $z_s = 0.01$. The photon distribution function $f(\vec{x}, \vec{p})$ was assumed to be isotropic. We also took into account the fact that the CMB temperature in the standard cosmological model depends on $z$ as $T = T_0 (1 + z)$, where $T_0 = 2.725$ K is the CMB temperature at $z = 0$ (Fixsen 2009). The EBL, CRB and CXB spectra were assumed to be independent of $z$. Figure 4 shows the same quantities, but the source is at $z_s = 0.1$. Likewise, we neglected the redshift of the photons after their passage through the cluster, $z_c \ll 1$, and assumed the EBL, RB, and CXB spectra to be independent of $z$. Since we supposed that $T_e = \text{const}$, the normalized optical depth $\tau/\tau|_{L=0}$ does not depend on the energy and depends only on the density profile. In the case of $n_e = \text{const}$ under consideration we have

$$\tau/\tau|_{L=0} = 1 - \frac{1}{2} \frac{L^2}{R^2} \text{ at } L < R, \tag{15}$$

$$\tau/\tau|_{L=0} = \frac{1}{\pi} \left[ \sqrt{\frac{L^2}{R^2}} - 1 - \arcsin \left( \frac{R}{L} \right) \left( \frac{L^2}{R^2} - 2 \right) \right] \text{ at } L > R, \tag{15}$$

at $R \ll L$ this expression takes the form

$$\tau/\tau|_{L=0} \approx \frac{4}{3} \frac{R}{L}. \tag{16}$$

| $r$  | $1'$ | 0–0.5 | 0.5–1.5 | 1.5–2.5 | 2.5–3.6 | 3.6–4.9 | 4.9–6.7 | 6.7–9.2 | 9.2–12.8 |
|-----|-----|-------|--------|--------|--------|--------|--------|--------|--------|
| $n_e(r)$ | $10^{-3}$ cm$^{-3}$ | 24.4 | 5.30 | 1.79 | 0.86 | 0.47 | 0.27 | 0.11 | 0.06 |
| $T_e(r)$ | keV | 2.7 | 7.2 | 10.4 | 12.9 | 9.0 | 5.8 | 4.0 | 5.7 |

Table 1. Profiles of the electron density $n_e(r)$ and gas temperature $T_e(r)$ in the cluster Abell 2204. The data were taken from Basu et al. (2010)

Consider the gas in the cluster Abell 2204 ($z_c = 0.1523$) (Basu et al. 2010). The dependences of the electron density $n_e(r)$ and gas temperature $T_e(r)$ on the distance to the cluster center $r$ are given in Table 1 (Basu et al. 2010). In our calculations we proceeded
Fig. 9: Same as Fig. 6 for the cluster Abell 478: the black solid curves indicate the optical depth for the observed density and temperature profiles; the gray solid curves indicate the optical depth for their extrapolations.
from the fact that the cluster radius $r_{200} = 11.2'$ corresponds to 1.76 Mpc (Basu et al. 2010). In Fig. 5 the black solid curves indicate the dependence of the optical depth $\tau(E)$ on photon energy $E$ calculated from Eq. (13) for $L = 0$ and $L = 1$ Mpc. The optical depth corresponding to the interaction with EBL (black dashdotted curve) and CXB (black dashed curve) photons assuming that the source is immediately behind the cluster $z_s = z_c$ is also shown. The interaction with EBL and CXB photons was calculated as for the case shown in Fig. 3. In Fig. 6 the ratio $\tau / \tau|_{L=0}$ is plotted against the impact parameter $L$ to the cluster center.

Consider now the cluster Abell 478 ($z_c = 0.0881$) (Vikhlinin et al. 2006). The electron density $n_e(r)$ and gas temperature $T_e(r)$ are plotted against the distance $r$ to the cluster center in Fig. 7. The observed profile is indicated by the black solid line; its extrapolation is indicated by the gray solid line. Figure 8 presents the dependence of the optical depth $\tau(E)$ on photon energy $E$ calculated from Eq. (13). The black solid curves correspond to the optical depth for the observed density and temperature profiles, while the gray solid curves correspond to the optical depth for their extrapolations. The curves for $L = 1$ Mpc virtually merge together. Figure 8 also shows the optical depth in the interaction with background photons for $z_s = z_c$; its calculations were carried out as for the case shown in Fig. 3. In Fig. 9 the ratio $\tau / \tau|_{L=0}$ is plotted against the impact parameter $L$ to the cluster center. The black curves correspond to the optical depth for the observed density and temperature profiles, while the gray ones correspond to the optical depth for their extrapolations. The plateau at $L = 0$ in Fig. 9 stems from the fact that we disregarded the contribution of the cluster center to the bremsstrahlung.

RESULTS

The spectra of distant sources must undergo changes due to the influence of the absorption of photons with the production of electron-positron pairs. As a result of the scattering by the cosmic microwave background, the Universe is opaque for radiation with an energy above 100 TeV. The second most intense type of background photons in the Universe is presumably the extragalactic background light. The cross section for the interaction of EBL photons with gamma-ray photons reaches its maximum at energies of the latter 100 GeV – 1 TeV (De Angelis et al. 2013). At ultrahigh energies $E \sim 10^6$ TeV the Universe is opaque due to the interaction with the cosmic radio background (CRB).
We ascertained that the interaction with gas bremsstrahlung photons in galaxy clusters makes a minor contribution to the optical depth compared to the absorption on CMB, EBL, and CRB photons almost for all gamma-ray photon energies. However, we found that for energies $E \sim 1 \text{ GeV} - 100 \text{ GeV}$ this effect can dominate and is $\tau \lesssim 10^{-5}$. 
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