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# The optical depth of gamma radiation due to interaction with the thermal bremsstrahlung of hot gas in galaxy clusters.

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**Abstract.** The interaction of high energy gamma quantum to thermal bremsstrahlung photons of hot intracluster gas with producing electron-positron pair is considered. It is supposed that galaxy cluster is relaxed and electron number density and temperature profiles are spherical symmetric. The dependence of optical depth on gamma quantum energy and distance to cluster center is considered. It is shown that the optical depth due to considered interaction is about  $10^{-8} - 10^{-5}$  at gamma quantum energy 100 MeV - 1 TeV.

## 1. Introduction

The high energy gamma quanta from cosmological sources like blazar and active galactic nuclei are subjected to interaction with cosmological photon background [1]. At gamma quantum energy range  $E \sim 100 \text{ GeV} - 100 \text{ TeV}$  the interaction with optical and infrared photons of Extragalactic Background Light (EBL) is dominated [2, 3, 4]. At energy  $E \sim 100 \text{ TeV} - 10^7 \text{ TeV}$  the interaction with Cosmic Microwave Background (CMB) photons is dominated [5, 6]. At very high energy  $E > 10^7 \text{ TeV}$  the interaction with radio photons of Cosmic Radio Background (CRB) becomes important [5, 6]. In this paper we consider the interaction of gamma quantum to thermal bremsstrahlung photons of hot intracluster gas with producing electron-positron pair.

## 2. Model

The cross section of interaction of gamma quantum to thermal photon with producing electron-positron pair is [7]:

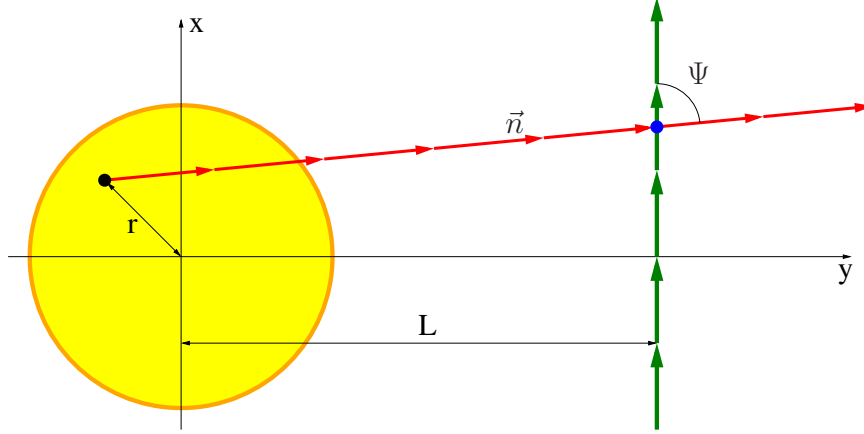
$$\sigma = \frac{\pi}{2} r_e^2 (1 - v^2) \left( (3 - v^4) \ln \left( \frac{1 + v}{1 - v} \right) - 2v(2 - v^2) \right) h(s) \quad (1)$$

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

$$v = \sqrt{1 - 1/s} \quad \text{and} \quad s = \frac{E\epsilon}{m^2 c^4} (1 - \cos \Psi), \quad (2)$$

$E$  is energy of gamma quantum,  $\epsilon$  is energy of thermal photon, radiated by intracluster gas,  $\Psi$  is angle between its impulses, see figure 1. For simplicity, we assume that gamma quantum path





**Figure 1.** A sketch to illustrate the considered geometry. The intracluster gas is shown by yellow circle, gamma quantum path is shown by green line, thermal photon path is shown by red line.

is straight line:  $\vec{x}(s) = L\vec{e}_y + \vec{e}_x s$  at distance  $L$  to cluster center, see figure 1. Optical depth  $\tau$  is calculated by formula

$$\tau = \int_{-\infty}^{+\infty} ds \int_{-\infty}^{+\infty} d^3p (\sigma(\Psi) \cdot (1 - \cos \Psi) \cdot f(\vec{x}(s), \vec{p})) \quad (3)$$

where  $f(\vec{x}, \vec{p})$  is distribution function of thermal photons at point  $\vec{x}$ ,  $\vec{p}$  is photon impulse,  $\epsilon = pc$ .

We consider only relaxed clusters with spherically symmetric gas distribution, i.e. electron number density  $n$  and temperature  $T$  depend only on distance  $r$  to cluster center. Also we assume that intracluster gas is optically thin and hence [8]

$$f(\vec{x}, \vec{p}) = \frac{2\pi}{h} \frac{c^2}{\epsilon^3} \int_0^{+\infty} \epsilon_\nu(\vec{x} - \lambda\vec{n}, \vec{p}) d\lambda \quad (4)$$

where  $\vec{n} = \vec{p}/p$ ,  $\epsilon_\nu(\vec{x}, \vec{p})$  is volume emissivity. We take into account only thermal bremsstrahlung from intracluster gas and, for simplicity, neglect helium and metals contribution. Hence  $\epsilon_\nu$  may be written as [8]

$$\epsilon_\nu(\vec{x}, \vec{p}) = \frac{8}{3} \sqrt{\frac{2\pi}{3}} mc^2 r_e^3 \sqrt{\frac{mc^2}{T(r)}} n^2(r) g(\epsilon, T(r)) \exp\left(-\frac{\epsilon}{T(r)}\right) \quad (5)$$

where  $g(\epsilon, T)$  is Gaunt factor. For simplicity, we assume that it is equal to [9]

$$g(\epsilon, T) = \frac{\sqrt{3}}{\pi} K_0\left(\frac{\epsilon}{2T}\right) \exp\left(\frac{\epsilon}{2T}\right) \quad (6)$$

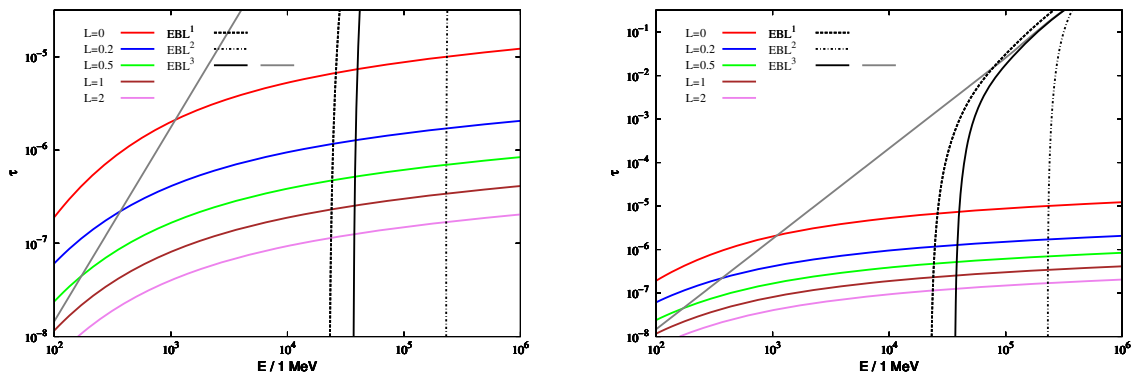
where  $K_0(x)$  is Macdonald function.

### 3. Results

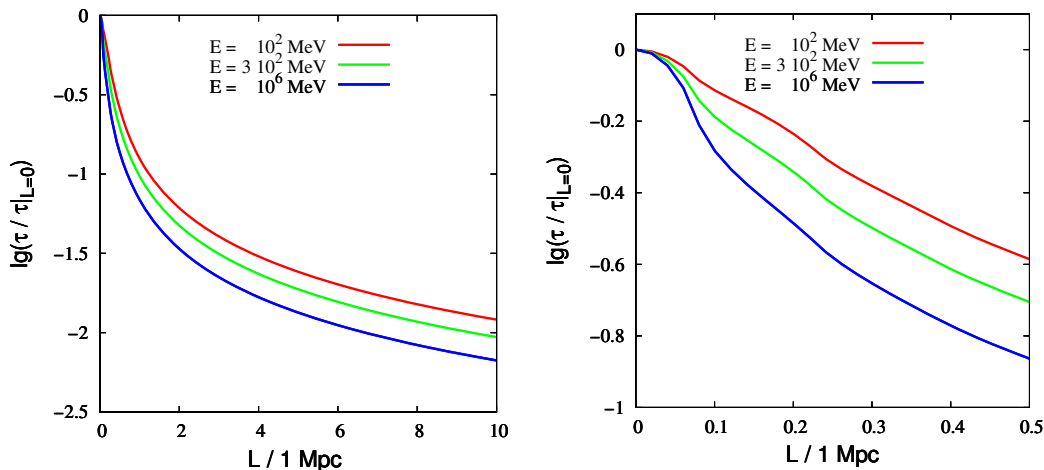
At first let us to consider galaxy cluster Abell 2204 [10]. The electron number density and temperature profile used in calculation are shown in table 1 [10]. We assume that angular distance to cluster is  $D = 541.6$  Mpc ( $z = 0.1523$ ), so  $r_{200} = 11.2'$  radius of cluster corresponds

**Table 1.** Electron number density  $n(r)$  and temperature  $T(r)$  profile of Abell 2204, used in calculation. Spatial distance  $(r/1 \text{ Mpc}) = (1.76 \text{ Mpc}/11.2') (r/1')$ . Data are taken from [10].

Bin		1	2	3	4	5	6	7	8
Radius (arcmin)		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
$n(r)$ ( $10^{-3} \text{cm}^{-3}$ )		24.4	5.30	1.79	0.86	0.47	0.27	0.11	0.06
$T(r)$ (keV)		2.7	7.2	10.4	12.9	9.0	5.8	4.0	5.7

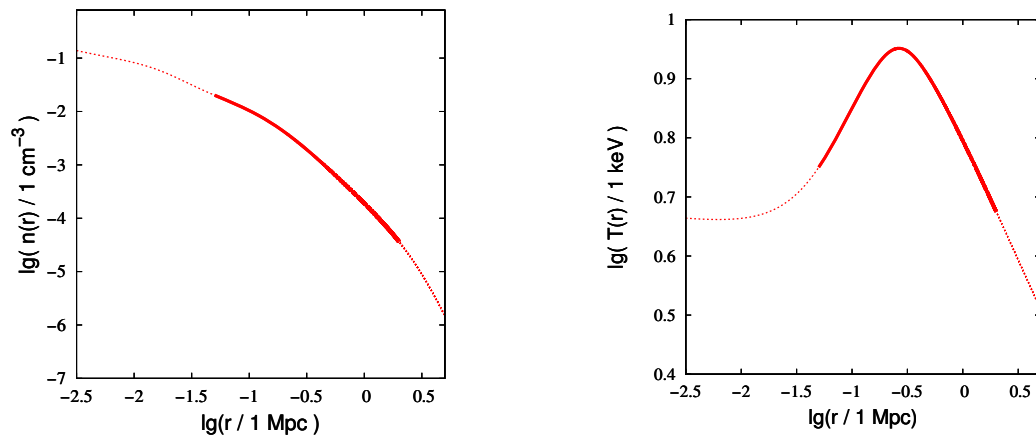


**Figure 2.** The dependence of optical depth  $\tau$  on gamma quantum energy  $E$  in case of Abell 2204 is shown. The optical depth  $\tau$  due to interaction with EBL photons is shown by black lines. For simplicity, we assume that EBL spectrum does not depend on  $z$ . Dashed line (EBL<sup>1</sup>) corresponds to EBL spectrum taken from [12], dot-dashed line (EBL<sup>2</sup>) corresponds to EBL spectrum taken from [13], black solid line (EBL<sup>3</sup>) corresponds to EBL spectrum taken from [2], gray solid line corresponds to its extrapolation by power law to large energies. The left and right graphs differ in the scale only.

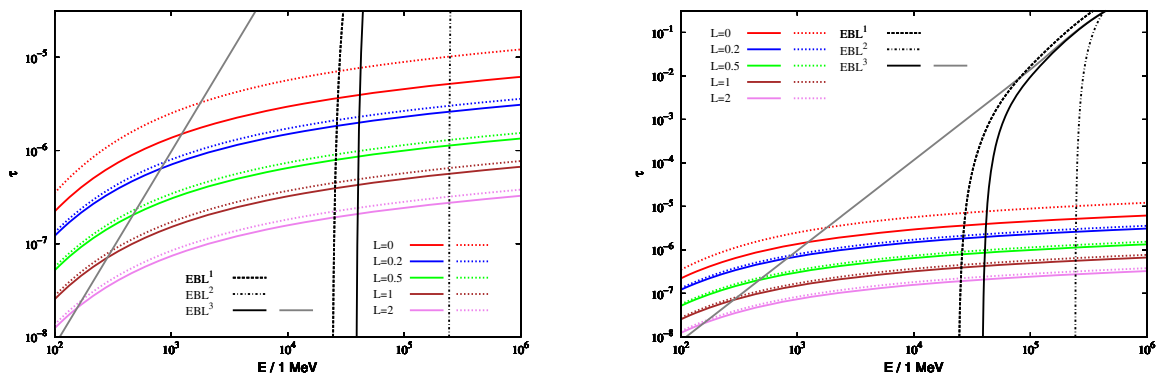


**Figure 3.** The dependence of normalized optical depth  $\tau / \tau|_{L=0}$  on distance  $L$  to cluster center in case of Abell 2204 is shown. The left and right graphs differ in the scale only.

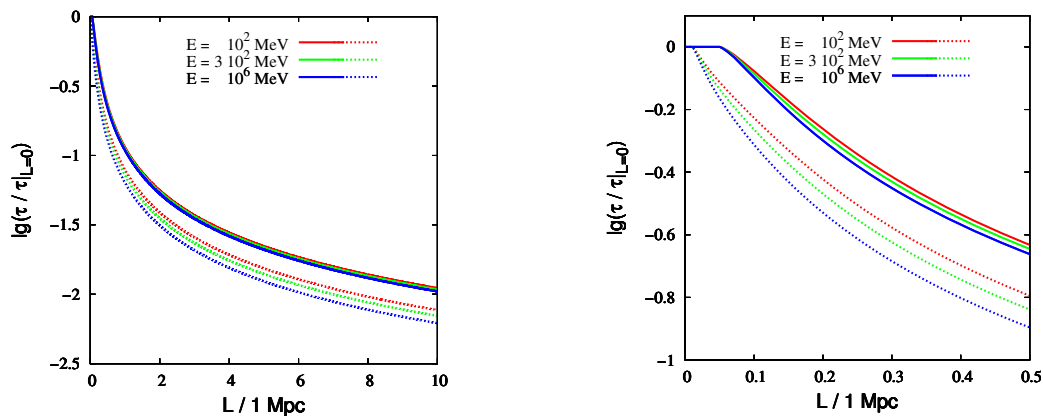
to 1.76 Mpc [10]. The dependence of optical depth  $\tau$  on gamma quantum energy  $E$  is shown in figure 2. The dependence of normalized optical depth  $\tau / \tau|_{L=0}$  on distance  $L$  to cluster center



**Figure 4.** The electron number density  $n(r)$  and temperature  $T(r)$  profiles of galaxy cluster Abell 478 taken from [11] are shown in left and right panels correspondingly. Observed profiles are shown by solid lines, its extrapolations are shown by dashed line.



**Figure 5.** The same as in figure 2, but the dependence of optical depth  $\tau$  on gamma quantum energy  $E$  in case of Abell 478 is shown. The optical depth calculated by observed profiles  $n(r)$  and  $T(r)$  is shown by solid line, the depth calculated by extrapolated profiles is shown by dashed line.



**Figure 6.** The same as in figure 5, but dependence of normalized optical depth  $\tau / \tau|_{L=0}$  on distance  $L$  to cluster center is shown

is shown in figure 3, where  $\tau|_{L=0}$  is optical depth in case of gamma quantum passed through cluster center.

Now we consider galaxy cluster Abell 478 with redshift  $z = 0.0881$  [11]. The electron number density and temperature profiles taken from [11] are shown in figure 4. The dependence of optical depth  $\tau$  on gamma quantum energy  $E$  is shown in figure 5. The dependence of normalized optical depth  $\tau/\tau|_{L=0}$  on distance to cluster center is shown in figure 6. It is easy to see that normalized optical depth profile depends on gamma quantum energy  $E$  only slightly. Plateau at  $L = 0$  in figure 6 is because of we exclude contribution of gas in cluster center.

In this paper we consider only gamma quantum energy range  $E \sim 10^2$  MeV – 1 TeV. In this range the input of interaction with CMB and CRB photons to optical depth is negligible small [6]. We receive that optical depth due to gamma quantum interaction with thermal bremsstrahlung photons of hot intracluster gas is negligible compared to input of interaction with EBL-photons at gamma quantum energy  $E > 10^2$  GeV but it may give at least a comparable input to optical depth at energy range  $E \sim 10^2$  MeV – 10 GeV.

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