The gamma quanta absorption due to interaction to the thermal bremsstrahlung of hot gas in spheroidal galaxy cluster

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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 gas temperature and electron number density have spheroidal distribution in galaxy cluster. The dependence of optical depth on eccentricity and orientation of spheroid is considered.

1. Introduction
The high energy gamma quanta from cosmological sources like blazar and active galactic nuclei are subjected to interaction to cosmological photon background [1]. At gamma quantum energy range $E \sim 100 \text{ TeV} - 10^7 \text{ TeV}$ the interaction to Cosmic Microwave Background (CMB) photons is dominated [2, 3]. At energy $E \sim 100 \text{ GeV} - 100 \text{ TeV}$ the interaction to optical and infrared photons of Extragalactic Background Light (EBL) is dominated [4, 5, 6]. At smaller energies $E \sim 100 \text{ MeV} - 10 \text{ GeV}$ the interaction to Cosmic Xray Background (CXB) photons [7] may become important. The interaction of gamma quantum to thermal bremsstrahlung photons of hot intracluster gas with producing electron-positron pair in case of spherical galaxy cluster was considered in [8]. In this paper we consider the case of spheroidal galaxy cluster.

2. Model
The cross section of interaction of gamma quantum to thermal photon with producing electron-positron pair is [9]:

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

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

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

$E$ 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
can write $\tau = \frac{\int_{-\infty}^{+\infty} ds \int_{-\infty}^{+\infty} d\lambda \cdot (1 - \cos \Psi) \cdot f(\vec{x}(s), \vec{p})}{\int_{-\infty}^{+\infty} d\lambda}$

where $f(\vec{x}, \vec{p})$ is distribution function of thermal photons at point $\vec{x}$, $\vec{p}$ is photon impulse, $\epsilon = pc$, $p = |\vec{p}|$. We consider only enough small cluster with optically thin intracluster gas, hence we can write

$$f(\vec{x}, \vec{p}) = \frac{2\pi \epsilon^2}{h^3} \int_{0}^{+\infty} \varepsilon_\nu(\vec{x} - \lambda \vec{n}, \vec{p}) d\lambda$$

where $\vec{n} = \vec{p}/p$, $\varepsilon_\nu(\vec{x}, \vec{p})$ is volume emissivity, $\lambda$ is photon path length from its birth point $\vec{x} - \lambda \vec{n}$ to point $\vec{x}$. We take into account only thermal bremsstrahlung from intracluster gas and, for simplicity, neglect helium and metals contribution. Hence $\varepsilon_\nu$ may be written as [10]

$$\varepsilon_\nu(\vec{x}, \vec{p}) = \frac{8}{3} \sqrt{\frac{2\pi}{3}} mc^2 \frac{v^2}{r_e} \sqrt{\frac{mc^2}{T(\zeta)}} \frac{\epsilon(\epsilon, T(\zeta))}{T(\zeta)}$$

where $g(\epsilon, T)$ is Gaunt factor. For simplicity, we assume that it is equal to [11]

$$g(\epsilon, T) = \frac{\sqrt{3}}{\pi} K_0 \left( \frac{\epsilon}{2T} \right) \exp \left( \frac{\epsilon}{2T} \right)$$
where $K_0(x)$ is Macdonald function. We assume that gas temperature $T$ and gas number density $n$ depends on coordinates only through variable $ζ$, i.e. $n = n(ζ(\vec{x}))$ and $T = T(ζ(\vec{x}))$ [12], where

$$ζ^2 = x^2 + y^2 + z^2 + K (z \cos χ + x \sin χ)^2$$

(7)

where $K = -e^2$ in case of prolate spheroid and $K = e^2/(1 - e^2)$ in case of oblate spheroid, $e$ is spheroid eccentricity, angle $χ$ determines spheroid inclination to plane of sky.

**Figure 3.** The dependence of optical depth $τ$ on gamma quantum energy $E$ in case of Abell 1689 [12] is shown by red line. The optical depth due to interaction with EBL spectra, taken from [4], is shown by blue line. The optical depth due to interaction with CXB spectra, taken from [7], is shown by yellow line. The left and right graphs differ in the scale only.

**Figure 4.** The dependence of optical depth $τ$ on distance to cluster center $L$ at various value of angle $φ$ in case of Abell 1689 [12] is shown. Left graph corresponds to gamma quanta energy $E = 10^3$ MeV, right graph corresponds to $E = 10^4$ MeV.

3. Results
At first, let us to consider the simple model of oblate galaxy cluster with constant temperature $T = 3$ keV and constant electron number density $n = 10^{-4}$ cm$^{-3}$ and semi-major axis $R = 3$ Mpc. The dependence of optical depth $τ$ on distance to cluster center $L$ is shown in figure 2. It is easy to see that optical depth $τ$ only slightly depends on eccentricity $e$ and angle $φ$.

The optical depth of galaxy cluster Abell 1689 ($z = 0.183$) [12] is shown in figures 3 and 4. We assume that the cluster is oblate spheroid with eccentricity $e ≈ 0.7$ and inclination angle

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χ ≈ 45° [12]. The electron number density and temperature profiles taken from [12] are shown in figure 5. The dependence of optical depth τ on gamma quantum energy E at L = 0 is shown in figure 3. The figure 3 also shows the optical depth τ due to interaction with EBL spectra (blue line) and CXB spectra (yellow line). Its are calculated by using formula (3) with background photon distribution function \( f(\vec{x}, \vec{p}) = \frac{1}{4\pi^2} \frac{dn}{d\epsilon} (\epsilon) \), where background photon energy spectra \( \frac{dn}{d\epsilon} (\epsilon) \) is taken from [4] in case of EBL spectra and is taken from [7] in case of CXB spectra. Also, for simplicity, we assume that background photon spectra \( \frac{dn}{d\epsilon} \) does not depend on redshift z. The dependence of optical depth τ on distance L to cluster center is shown in figure 4.

4. Conclusion

The dependence of optical depth due to gamma quanta interaction with thermal bremsstrahlung photons of hot intracluster gas on eccentricity and orientation of spheroidal galaxy cluster is considered. It is shown that optical depth in case of spheroidal cluster differs from case of spherical cluster \( e = 0 \) only slightly.

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