A&A 573, A47 (2015)
DOI: 10.1051/0004-6361/201425048

Astronomy & Astrophysics

Probing cluster environments of blazars through $\gamma\gamma$ absorption
(Research Note)

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Received 24 September 2014 / Accepted 12 October 2014

ABSTRACT

Most blazars are known to be hosted in giant elliptic galaxies, but their cluster environments have not been thoroughly investigated. Cluster environments may contain radiation fields of low-energy photons created by nearby galaxies and/or stars in the intracluster medium that produce diffuse intracluster light. These radiation fields may absorb very high energy γ rays (VHE; $E \gtrsim 100$ GeV) and trigger pair cascades with further production of subsequent generations of γ rays with lower energies via inverse Compton scattering on surrounding radiation fields leaving a characteristic imprint in the observed spectral shape. The change of the spectral shape of the blazar reflects the properties of its ambient medium. We show, however, that neither intracluster light nor the radiation field of an individual nearby galaxy can cause substantial $\gamma\gamma$ absorption. Substantial $\gamma\gamma$ absorption is possible only in the case of multiple, $\gtrsim$5, luminous nearby galaxies. This situation is not found in the local Universe, but may be possible at larger redshifts ($z \gtrsim 2$). Since VHE γ rays from such distances are expected to be strongly absorbed by the extragalactic background light, we consider possible signatures of γ-ray induced pair cascades by calculating the expected GeV flux which appears to be below the *Fermi*-LAT sensitivity even for ~10 nearby galaxies.

Key words. radiation mechanisms: non-thermal – BL Lacertae objects: general – BL Lacertae objects: individual: 1ES1440+122 – galaxies: clusters: general

1. Introduction

Blazars are the brightest objects among active galactic nuclei (AGN) because of a relativistic jet pointed close to the line of sight. They are characterized by highly variable, non-thermal dominated emission across the entire electromagnetic spectrum, from radio through γ-ray frequencies. They dominate the extragalactic γ-ray sky both at GeV energies, observed by the *Fermi* Large Area Telescope (LAT), and in very-high-energy (VHE; $E > 100$ GeV) γ rays, observable by ground-based Cherenkov telescope facilities.

VHE γ rays from sources at cosmological distances are subject to absorption by $\gamma\gamma$ pair production on various target photon fields (Gould & Schréder 1967), with photons of energy $E = 1\,E_{\rm TeV}$ TeV primarily interacting with target photons of wavelength $\lambda_{\rm target} = 2.4\,E_{\rm TeV}\,\mu$m. Hence, photons in the energy range ~0.1–1 TeV interact predominantly with optical – near-infrared light. The extragalactic background light (EBL) is usually considered to be the dominant target photon field for $\gamma\gamma$ absorption of cosmological VHE γ-ray sources (e.g. Stecker et al. 1992; Primack et al. 1999; Franceschini et al. 2008; Finke et al. 2010), and this effect is commonly expected to limit the VHE γ-ray horizon, out to which VHE γ-ray sources are expected to be observable with ground-based Cherenkov telescope facilities, to $z \lesssim 0.5$. However, the EBL is not expected to be perfectly homogeneous and, in particular, galaxies near the line of sight to the blazar, or the cluster environment of the blazar, may provide additional target photon fields which may potentially increase the expected $\gamma\gamma$ opacity. In this paper, we study the $\gamma\gamma$ opacity provided by intervening, individual galaxies, as well as the collective photon fields provided by the cluster environment of the blazar's host galaxy.

Most blazars are known to be hosted in giant elliptical galaxies, but their cluster environments are poorly characterized. They might contain low-energy (optical, infrared) radiation fields created e.g. by a nearby galaxy or stars which escaped their galaxies (diffuse intracluster light, ICL; e.g. Burke et al. 2012), which may absorb VHE γ rays leaving a characteristic imprint in the observed spectrum. Moreover, such radiation fields can trigger pair cascades as the electron-positron pairs produced in $\gamma\gamma$ absorption may generate further generations of γ rays via inverse Compton (IC) scattering on the surrounding radiation fields. In the case of effective pair cascade development, a considerable fraction of the energy in VHE photons is re-emitted at lower energies, significantly changing the spectral shape of the blazar emission. The change of the spectral shape reflects the properties of the ambient medium, in particular the properties of the radiation field and the magnetic field (see e.g. Roustazadeh & Böttcher 2010, 2011, for a discussion of $\gamma\gamma$ absorption and cascading within the immediate AGN environment).

In Sect. 2, we discuss the effect of the ICL, while Sect. 3 contains the discussion of the effect of individual galaxies, applying our considerations to the specific example of the VHE γ-ray blazar 1ES 1440+122 in Sect. 4. We briefly discuss the effect of $\gamma\gamma$ induced pair cascades in cluster environments in Sect. 5, and summarize our findings in Sect. 6. The following cosmological parameters are used throughout the paper: Hubble constant, $H_0 = 67.3\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, mean mass density, $\Omega_\mathrm{m} = 0.315$, and dark energy density, $\Omega_\lambda = 0.686$ (Planck Collaboration XVI 2014).

2. Intracluster light

In this section we consider the possible γ-ray absorption due to the ICL. To calculate the optical depth due to $\gamma\gamma$ absorption we define the region of the ICL as a sphere with radius R_ICL with an isotropic distribution of photons and a constant photon density. For a photon spectrum peaking at an effective energy $\epsilon_\mathrm{eff} = E_\mathrm{eff}/(m_\mathrm{e}c^2)$ the differential photon density can be approximated by

$$n(\epsilon, \boldsymbol{r}) = \frac{L_\mathrm{ICL}}{\pi R_\mathrm{ICL}^2 c \epsilon_\mathrm{eff}^2 m_\mathrm{e} c^2} H(R_\mathrm{ICL} - r)\delta(\epsilon - \epsilon_\mathrm{eff}), \tag{1}$$

where L_ICL is the total luminosity of the ICL in the region considered, r is the distance from the centre of the ICL region, m_e is the electron mass, c is the speed of light, and $H(x)$ is the Heaviside function ($H(x) = 1$ if $x > 0$ and $H(x) = 0$ otherwise). For a rough estimate of the optical depth we use a delta-function approximation of the $\gamma\gamma$ cross section of two photons with normalized energies ϵ_1 and ϵ_2 (where $\epsilon = h\nu/(m_\mathrm{e}c^2)$),

$$\sigma_{\gamma\gamma}(\epsilon_1, \epsilon_2) = \frac{1}{3}\sigma_\mathrm{T}\epsilon_1\delta\left(\epsilon_1 - \frac{2}{\epsilon_2}\right), \tag{2}$$

where σ_T is the Thompson cross section. The $\gamma\gamma$ optical depth for a γ-ray photon with normalized energy ϵ_γ in a photon field with a differential photon density $n(\epsilon, \Omega, x)$ is given by (Gould & Schréder 1967)

$$\tau_{\gamma\gamma} = \int \mathrm{d}x \int \mathrm{d}\Omega(1 - \mu) \int \mathrm{d}\epsilon\, n(\epsilon, \Omega, x)\, \sigma(\epsilon, \epsilon_\gamma, \mu), \tag{3}$$

where $\mathrm{d}x$ is the differential path travelled by γ-ray photon, $\mathrm{d}\Omega$ is the solid angle element, $\mu = \cos\theta$, and θ is the interaction angle between the γ-ray photon and a target photon. Taking into account Eqs. (1) and (2) and assuming that the γ-ray source is located in the centre of the ICL region, the $\gamma\gamma$ optical depth can be calculated analytically as

$$\tau_{\gamma\gamma} = \frac{4L_\mathrm{ICL}\sigma_\mathrm{T}}{3R_\mathrm{ICL}c\epsilon_\mathrm{eff}^2 m_\mathrm{e}c^2}\frac{2}{\epsilon_\gamma}\delta\left(\epsilon_\gamma - \frac{2}{\epsilon_\mathrm{eff}}\right). \tag{4}$$

For the characteristic γ-ray energy

$$E_\gamma = \frac{2}{\epsilon}m_\mathrm{e}c^2 = 522 E_\mathrm{eV}^{-1}\,\mathrm{GeV}, \tag{5}$$

where E_eV is the energy of the target photon in eV, the $\gamma\gamma$ optical depth can then be estimated as

$$\tau_{\gamma\gamma}(E_\mathrm{eV}) = 2.4\times10^{-12}E_\mathrm{eV}^{-1}\left(\frac{L_\mathrm{ICL}}{L_\odot}\right)\left(\frac{R_\mathrm{ICL}}{10\,\mathrm{kpc}}\right)^{-1} \tag{6}$$

$$= 2.4\times10^{\frac{M_\odot - M_\mathrm{ICL}}{2.5} - 12}E_\mathrm{eV}^{-1}\left(\frac{R_\mathrm{ICL}}{10\,\mathrm{kpc}}\right)^{-1}. \tag{7}$$

In a search for ICL in a sample of ten clusters at redshifts $0.4 < z < 0.8$, Guennou et al. (2012) detected diffuse light in all ten clusters with typical sizes of a few tens of kpc and a total ICL magnitude in the range from –18 to –21. Those authors also show that there are no strong variations in the amount of ICL between $z = 0$ and $z = 0.8$ with just a modest increase (Guennou et al. 2012). HST ACS[1] images in the *F814W* filter were used in this study. The HST *F814W* filter covers a wavelength range from 6948 Å to 10 043 Å with an effective wavelength of $\lambda_\mathrm{eff} = 8186.4$ Å which corresponds to an energy of $E_\mathrm{eff} = 1.5$ eV. Using the lowest measured value of the absolute magnitude of the ICL and a size of the ICL region of 10 kpc, we can estimate an upper limit on the ICL optical depth as

$$\tau_{\gamma\gamma} < 4.8\times10^{-2}E_\mathrm{eV}^{-1}. \tag{8}$$

However, for a more precise estimate of the ICL luminosity, the absolute ICL magnitude should be corrected by the bolometric correction which is dependent on the effective temperature of the source (Girardi et al. 2008). Unfortunately, the analysis performed in Guennou et al. (2012) was unable to determine colours of the detected ICL sources, but e.g. Adami et al. (2005) determine the colours of the diffuse light sources in the Coma cluster to correspond to quite old stellar populations. For an effective temperature in the range of ~4000–6000 K the bolometric correction for the *F814W* filter is estimated to be roughly 0.5 (Girardi et al. 2008), which would decrease the upper limit for the optical depth even further. Therefore, we can firmly conclude that even in the most favourable configuration, the $\gamma\gamma$ absorption due to the ICL is negligible.

3. Nearby galaxies

The $\gamma\gamma$ absorption of the blazar emission due to an intervening galaxy close to the line of sight between the observer and a blazar is discussed in detail in Barnacka et al. (2014). They show that only in the case of a very compact and, at the same time, luminous galaxy and a small value of the impact parameter (distance of closest approach of the γ-ray trajectory to the nucleus of the galaxy) of $\lesssim 10\ R_\mathrm{eff}$, where R_eff is the effective radius of the galaxy, is substantial $\gamma\gamma$ absorption possible. However, they also note that galaxies of such high luminosities are typically giant ellipticals or large spirals with larger effective radii than 1 kpc and, thus, the expected $\gamma\gamma$ absorption from the radiation field of an intervening galaxy is always neglible (Barnacka et al. 2014).

However, in cluster environments it is possible that a blazar is surrounded by several companion galaxies. In this case, the combined radiation field of all nearby galaxies should be considered, and it might still provide a substantial $\gamma\gamma$-absorption opacity. The optical depth of the combined radiation field can be estimated as

$$\tau_{\gamma\gamma} = \int \mathrm{d}x \int \mathrm{d}\Omega\,(1 - \mu) \int \mathrm{d}\epsilon\, n_\mathrm{tot}(\epsilon, \Omega, x)\, \sigma(\epsilon, \epsilon_\gamma, \mu) \tag{9}$$

where $n_\mathrm{tot}(\epsilon, \Omega, x)$ is the total differential photon density of the combined radiation field of all the nearby galaxies. The total differential photon density is the superposition of the photon densities of the radiation fields created by individual galaxies, i.e.

$$n_\mathrm{tot}(\epsilon, \Omega, x) = \sum_{i=1}^{N} n_i(\epsilon, \Omega, x), \tag{10}$$

where N is the number of nearby galaxies. Therefore the optical depth of the combined radiation field can also be represented

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[1] The Advanced Camera for Surveys (ACS) aboard the *Hubble* Space Telescope (HST).

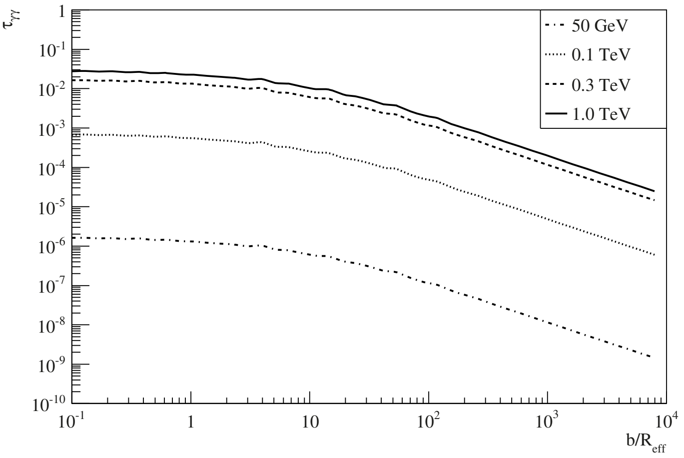

Fig. 1. γ-γ optical depth of a radiation field of a companion galaxy as a function of the impact parameter b presented for different γ-ray energies, assuming the galaxy is located at the same distance. The parameters of the galaxy are assumed to be $R_{\rm eff} = 1$ kpc, $L = L_{\rm MW}$, and $T = 5000$ K.

as the sum of the optical depths due to the individual radiation fields from individual galaxies, i.e.

$$\tau_{\gamma\gamma} = \sum_{i=1}^{N} \tau^{i}_{\gamma\gamma}. \qquad (11)$$

In order to calculate the optical depth due to the radiation field of an individual galaxy and to study its dependence on the location of the galaxy with respect to the blazar, its luminosity and effective temperature, we followed the assumptions presented in the Appendix of Barnacka et al. (2014): the galaxy is approximated by a flat disk with a De Vaucouleurs surface brightness profile, and the spectrum of the galaxy is approximated by black-body radiation. The inclination of the disk is characterazed by the inclination angle i between the disk normal vector and the line of sight. Barnacka et al. (2014) showed that the optical depth is only weakly dependent on the value of the inclination angle, so in the calculations performed in this paper we assume $i = 0°$. The integration is perfomed numerically, properly accounting for the angular dependence.

Figure 1 shows the resulting $\gamma\gamma$ optical depth for γ rays passing through the radiation field of a companion galaxy as a function of the impact parameter b for different γ-ray energies. The galaxy is assumed to have the same luminosity as the Milky Way, $L_{\rm MW} = 9.2 \times 10^{43}$ erg/s, with an effective radius of $R_{\rm eff} = 1$ kpc and effective temperature of $T = 5000$ K. The figure shows that for such an individual companion galaxy the $\gamma\gamma$ absorption is negligible. To cause significant absorption a luminosity of $L \gtrsim 10\, L_{\rm MW}$ is needed for the galaxy with the same parameters because the optical depth is linearly dependent on luminosity. The dependence of the $\gamma\gamma$ optical depth on the effective temperature of the galaxy is shown in Fig. 2. According to the resonance condition in Eq. (5), with $E_{\rm eff} \approx 2.8\, kT$, photons of $E_\gamma = 1.1\, T_{5000}^{-1}$ TeV are most efficiently absorbed by photons emitted by a black-body emitter at $T = 5000\, T_{5000}$ K. Hence, photons with energies below ~1 TeV are approaching this condition with increasing black-body temperature, so the optical depth increases.

Equation (11) suggests that $\gamma\gamma$ absorption might become substantial when the blazar is surrounded by $\gtrsim$5 companion galaxies. The optical depth also depends on the location of the companion galaxy with respect to the observer. Obviously, the absorption will be more effective when the companion galaxy is located in front (as seen from the observer on Earth) rather than behind the blazar. To calculate the dependence of the optical depth on the location of the galaxy with the respect to the observer we define the x-axis with an origin in the blazar and aligned with the jet, assuming that the jet is pointing towards the observer. The resulting dependence of the optical depth on x is illustrated in Fig. 3

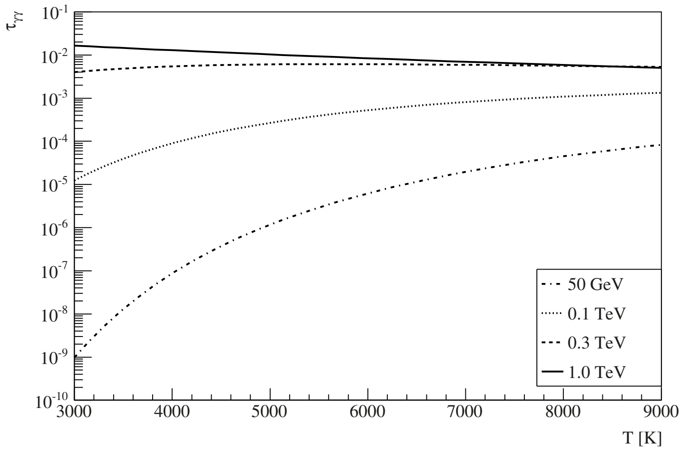

Fig. 2. Same as Fig. 1, but as a function of temperature T for the impact parameter of 10 $R_{\rm eff}$.

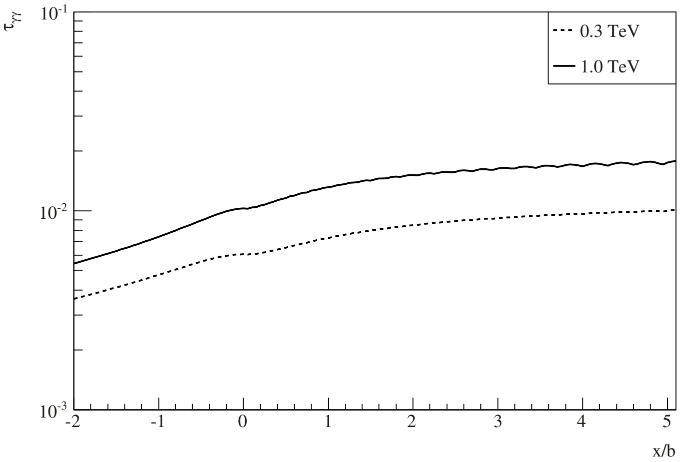

Fig. 3. Same as Fig. 1, but as a function of the location of the companion galaxy with respect to the source of the γ-ray emission for the impact parameter of 10 $R_{\rm eff}$.

4. 1ES1440+122

For a search of possible candidates of blazars with nearby companions, we used the HST survey of BL Lacertae objects (Scarpa et al. 2000a,b; Urry et al. 2000; Falomo et al. 2000) in which 110 objects were observed. For a subset of 30 nearby ($z \lesssim 0.2$) BL Lac objects with the highest signal-to-noise ratios a morphological sudy was performed, including the investigation of the near environment and a search for companions (Falomo et al. 2000). For 11 out of the 30 objects close companions were found. For three of them (0706+592, 1440+122, and 2356−309) very close ($\delta < 1.2''$) compact companions were detected located at projected distances of 1–5 kpc from the nucleus, assuming the same redshift as the BL Lac object. For four objects (0829+046, 1229+645, 1440+122, and 1853+671) companion galaxies were detected located at projected distances of

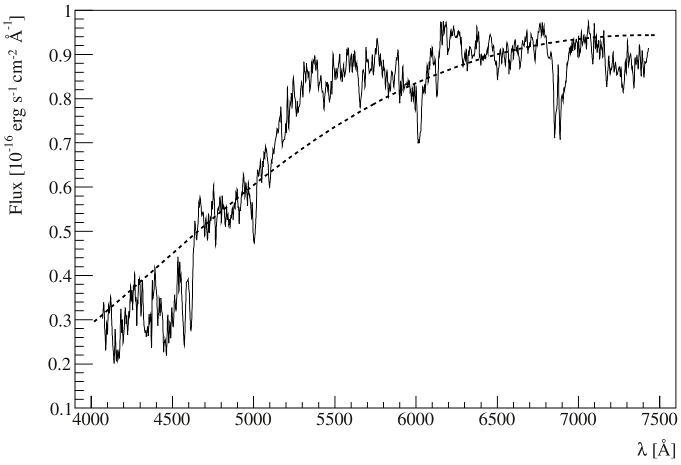

Fig. 4. Spectrum of a companion galaxy of 1ES1440+122 (solid line, Sbarufatti et al. 2006) approximated by a Planckian distribution (dashed line).

10–20 kpc from the BL Lac object. Among these objects, there are only three which are detected at both GeV (Ackermann et al. 2011) and TeV energies: 0706+592 (Acciari et al. 2010), 1440+122 (Benbow for the VERITAS Collaboration 2011), and 2356−309 (Aharonian et al. 2006). Only one of these has a companion galaxy: 1440+122. Two others have relatively faint compact companions with absolute magnitudes of −15 and −17.3. Therefore, we have chosen 1ES 1440+122 for a case study, as a primary candidate for possible $\gamma\gamma$ absorption because of the nearby companions.

The source 1ES1440+122 is a BL Lac type object detected in all energy bands across the electro-magnetic spectrum, from radio to VHE γ rays. It is located at a redshift $z = 0.162$ (Schachter et al. 1993) and appears to be located in a rich environment, being surrounded by ~20 galaxies (Heidt et al. 1999). According to the HST survey (Falomo et al. 2000), 1ES1440+122 features two close companions: a galaxy at an angular distance of 2.5″ and a very close compact companion at the distance of 0.3″. Giovannini et al. (2004) showed that the close compact companion of 1ES1440+122 is a foreground star and therefore it is not of interest for this paper. An optical spectroscopy study (Sbarufatti et al. 2006) revealed a spectrum of the close companion galaxy classifying it as an elliptical galaxy at a redshift of $z = 0.161$, showing that these objects are located in the same cluster. The projected distance between 1ES1440+122 and the companion galaxy is ≃13 kpc. The R-band apparent magnitude of the companion galaxy is $m_R = 17.2$ (Sbarufatti et al. 2006) which corresponds to an absolute magnitude in the R-band of $M_R = -23.4$. This corresponds, neglecting the bolometric correction, to a luminosity of $\simeq 8 \times 10^{44}$ erg/s, which is about 10 times higher than the luminosity of the Milky Way. The effective temperature of the galaxy is estimated to be $T \simeq 3900$ K using a fit of a Planckian distribution to the spectrum of the galaxy obtained in Sbarufatti et al. (2006, see Fig. 4).

In Fig. 5, the optical depth of the $\gamma\gamma$ absorption caused by the radiation field of the companion galaxy of 1ES1440+122 is shown as a function of γ-ray energy for different values of the effective radius of the galaxy. Substantial absorption is possible only in the case of a relatively small effective radius of the galaxy, $R_{\rm eff} \lesssim 1$ kpc. However, the typical size of such luminous galaxies is much bigger, of the order of $R_{\rm eff} \gtrsim 10$ kpc. Therefore, significant absorption by the radiation field of this individual galaxy is very unlikely.

5. Cascade emission

As mentioned above, if a VHE γ-ray blazar is surrounded by $\gtrsim$5 luminous galaxies $\gamma\gamma$ absorption might become substantial. Although we failed to find examples of such dense environments with multiple companion galaxies, such environments might exist at higher redshifts of $z \gtrsim 2$ where cluster environments are believed to have been denser than at the present epoch. However, the VHE γ-ray emission from blazars at $z \gtrsim 2$ is heavily absorbed by the EBL and cannot be detected. Therefore, it is impossible to examine blazar environments directly by studying TeV emission. Nevertheless, absorbed γ rays might be re-emitted at GeV energies through Compton-supported, γ-ray-induced pair cascades and contribute to the observed GeV emission. Below we provide simple estimates of the flux level of the expected GeV emission from γ-ray-induced pair cascades in the combined photon field of several companion galaxies.

Based on the example of 1ES1440+122 which neighbours a luminous elliptical galaxy, the maximum optical depth in the radiation field of a single nearby galaxy is $\tau_{\rm max} \simeq 0.02$. For N nearby galaxies with similar properties the maximum optical depth is then $\tau_{\rm max}^{\rm tot} \simeq N\tau_{\rm max}$. Assuming that all energy in the absorbed γ-ray emission is re-emitted at GeV energies, we can find the most optimistic estimate for the flux from the cascade emission in the limit that the magnetic field is weak enough not to deflect the electrons/positrons in the cascade from the primary direction of the γ rays. In that case, the secondary γ rays are re-emitted in the same direction and with the same beaming characteristic as the original VHE γ-ray beam, and the expected cascade emission in the GeV energy band is

$$F_{\rm casc}^{\rm GeV} \simeq \left(1 - {\rm e}^{-\tau_{\rm max}^{\rm tot}}\right) F_{\rm int}^{\rm TeV} \simeq \tau_{\rm max}^{\rm tot} F_{\rm int}^{\rm TeV}, \tag{12}$$

where the intrinsic TeV flux from the blazar jet can be approximated by

$$F_{\rm int}^{\rm TeV} \simeq \frac{1}{2}\frac{L}{4\pi d_L^2}, \tag{13}$$

where d_L is the luminosity distance to the blazar and the factor of 1/2 accounts for the presence of two jets; $L = 10^{44}\, L_{44}$ erg s^{-1} is the inferred isotropic VHE γ-ray luminosity which usually does not exceed $\sim 10^{44}$ erg s^{-1} for known VHE γ-ray blazars. In the case of the substantial magnetic field ($B \gtrsim 10^{-14}$ G), electrons/positrons in the cascade may be deflected out of the primary VHE γ-ray beam, and the GeV γ rays will be re-distributed over a larger solid angle, resulting in a lower flux.

For two different assumed values of the redshift $z = 0.1$ and $z = 2.0$, the upper limits for the observed cascade GeV emission are

$$z = 0.1: \quad F_{\rm casc}^{\rm GeV} \simeq 2.1 \times 10^{-14} L_{44} N\, {\rm erg\, cm^{-2}\, s^{-1}}, \tag{14}$$

$$z = 2.0: \quad F_{\rm casc}^{\rm GeV} \simeq 1.8 \times 10^{-17} L_{44} N\, {\rm erg\, cm^{-2}\, s^{-1}}. \tag{15}$$

Comparing this to the *Fermi*-LAT sensitivity of $F_{\rm min}^{\rm LAT} \sim 10^{-12}$ erg cm^{-2} s^{-1}, it is obvious that even for ~10 nearby, luminous companion galaxies and a large intrinsic VHE luminosity of the high-redshift blazar, the expected cascade flux is not expected to make a measurable contribution to the GeV γ-ray flux from galaxy clusters hosting radio-loud AGN.

6. Summary

We have evaluated the optical depth for VHE γ rays produced in blazars due to $\gamma\gamma$ absorption in the cluster environments of the

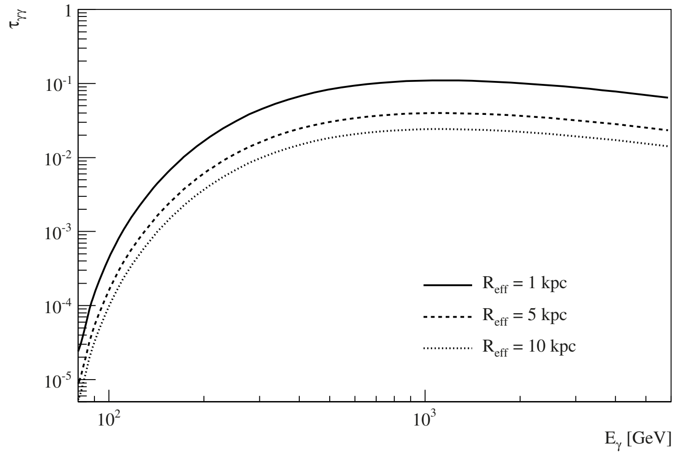

Fig. 5. $\gamma\gamma$ opacity of the γ ray emitted from 1ES1440+122 in the radiation field of the companion galaxy as a function of the γ-ray energy for various values of the effective radius of the companion galaxy.

blazar's host galaxy. Considering target photon fields from the intracluster light and companion galaxies within the cluster, we conclude that neither of these fields is likely to constitute a substantial opacity to $\gamma\gamma$ absorption, unless a large number ($\gtrsim$5) of very luminous, compact galaxies are located close to the line of sight of the blazar beam. This situation is not found in the local Universe, but may be possible at larger redshifts ($z \gtrsim 2$). Since VHE γ rays from such distances are expected to be heavily attenuated by $\gamma\gamma$ absorption by the EBL, we considered the possible signatures of VHE γ-ray induced, Compton-supported pair cascades following the $\gamma\gamma$ absorption of blazar emission in dense cluster environments, but concluded that the expected GeV flux level is unlikely to be detectable by *Fermi*-LAT.

Acknowledgements. The authors thank C. Burke for stimulating discussions on the intracluster light. M.B. acknowledges support from the South African Department of Science and Technology through the National Research Foundation under NRF SARChI Chair grant No. 64789.

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