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Extragalactic background light models and GeV-TeV observation of blazars

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ABSTRACT
In this work, we use two different methods to determine the opacity of the TeV gamma-rays caused by the extragalactic background light (EBL) via e—e+ production due to photon-photon interaction. The first method, Model-Dependent Approach, uses various EBL models for estimating the opacity as a function of the redshift and energy of the TeV photons. The second method, Model-Independent Approach, relies on using the simultaneous observations of blazars in the MeV-GeV energy range from the Fermi-LAT and in the TeV band from the ground-based gammaray telescopes. We make the underline assumption that the extrapolation of the LAT spectrum of blazars to TeV energies is either a good estimate or an upper limit for the intrinsic TeV spectrum of a source. We apply this method on the simultaneous observations of a few blazars at different redshifts to demonstrate a comparative study of six prominent EBL models. Opacities of the TeV photons predicted by the model-independent approach are systematically larger than the ones estimated from the modeldependent method. Therefore, the gamma-ray observations of blazars can be used to set a strict upper limit on the opacity of the Universe to the TeV photons at a given redshift.

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1. Introduction

The extragalactic background light (EBL) is the accumulated radiation from the structure formation and its cosmological evolution. It consists of low energy photons emitted by stars and other cosmological objects at all epochs and is subsequently modified by redshifting and dilution due to the expansion of the Universe. The bulk of the EBL occurs at wavelengths from the optical-ultraviolet (UV) to the far-infrared (IR). The EBL photon field is dominated by the direct stellar emission in the optical to near-IR and by the stellar emission reprocessed by dust in the galaxies in the mid to far-IR (Hauser and Dwek 2001). Thus, the EBL is intimately connected with the star formation history of the Universe and reionisation (Robertson et al. 2010). It provides very important information about the integrated star formation rate density and the cosmology. Therefore, the absolute measurement of the EBL intensity is highly desirable. The EBL photons mostly lie in the wavelength range of 0.1–1000 μm and are assumed to be the second most energetic diffuse background in terms of the contained energy after the Cosmic Microwave Background Radiation (CMBR). Therefore, EBL has become essential for understanding the full energy balance of the Universe.

Direct measurement of the EBL is a challenging task due to the strong foreground emission in our planetary system and galaxy, some orders of magnitude larger than the actual EBL (Hauser et al. 1998; Chary and Pope 2010). Direct measurements technically require absolute calibration of the instruments and understanding for the subtraction of all measurement uncertainties. Some direct measurements in optical (Bernstein et al. 2007) and in the near-IR (Cambresy et al. 2001; Matsumoto et al. 2005) are available, but there is no general agreement about the reliability of these data from the observations (Mattila 2006). The mid-IR band is known a little from the direct observations because of higher contamination from the zodiacal light of our Milkyway galaxy. Available observations provide lower limits on the density of EBL photons by using the integrated light from discrete extragalactic sources (Madau and Pozzetti 2000; Fazio et al. 2004; Dole et al. 2006; Keenan et al. 2010). Semi-analytical modelling of the EBL density has also been performed by incorporating the simplified physical treatments of the key processes involved in the galaxy formation including gravitational collapse, merging of dark matter halos, gas cooling and dissipation, star formation, supernova feedback and metal production from the beginning of the Universe (Primack et al. 1999). Modelling of the EBL leads to definite predictions, but uncertainties in the star formation rate, initial mass function, dust extinction and evolution with redshift have led to a significant discrepancy among various EBL models (Salamon and Stecker 1998; Malkan and Stecker 1998; Stecker and de Jager 1998; Kneiske et al. 2002, 2004; Stecker et al. 2006; Franceschini et al. 2008; Gilmore et al. 2009, 2012; Finke et al. 2010, Kneiske and Dole 2010; Dominguez et al. 2011; Yoshiyuki et al. 2013; Franceschini and Rodighiero 2017). All the models

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have a limited predictive power for the EBL density, particularly as a function of time, because many details of the star and galaxy evolution remain unclear so far.

Indirect measurements of the EBL photon density are possible from the observations of the very high energy (VHE; E > 100 GeV) γ-ray emission from the distant sources. A beam of the VHE γ-ray photons travelling through the cosmological distances can be strongly attenuated by the production of electron-positron (e^--e^+) pairs in collisions with the low energy EBL photons (Gould and Schreder 1966). Despite this effect, the current generation of the ground-based instruments (HESS, MAGIC, VERITAS, TACTIC) has significantly increased the number of observed extragalactic VHE γ-ray sources. The intrinsic VHE spectra of the extragalactic sources detected by the ground-based instruments depend on the spectrum of EBL, energy of the VHE photon as well as distance of the particular source. Blazars represent a very useful class of γ-ray beamers, being numerous over a wide range of redshifts, very luminous and long-lasting sources. Despite a rigorous theoretical and observational studies in the literature, blazars are far from being standard candles, and therefore using them as tool for probing the EBL heavily depends on our understanding of their intrinsic emission and physical properties. Observation of the blazars by the large area telescope (LAT) onboard the *Fermi* satellite in the energy range from 30 MeV to more than 500 GeV provides a very strong observational evidence regarding the intrinsic MeV-GeV emission from them (Atwood et al. 2009). Combined MeV-GeV and TeV observations have provided a new tool to constrain the EBL intensity (Orr et al. 2011; Meyer et al. 2012; Abeysekara et al. 2015, 2019; Abdalla et al. 2017; Kudoda and Faltenbacher 2017; Desai et al. 2019; Acciari et al. 2019). Recently, the *Fermi*-LAT observations have been used to indirectly measure the EBL from the absorption features seen in the γ-ray spectra of blazars beyond the redshift $z > 1$ (Ackermann et al. 2012; The Fermi-LAT Collaboration 2018). Thus, TeV observation from the ground-based Cherenkov telescopes in association with the *Fermi*-LAT observations can be used as a powerful probe to study the EBL models. The details of the current status of the direct and indirect measurements of the EBL can be found in (Dwek and Krennrich 2013; Driver et al. 2016; Murthy et al. 2019; Mattila and Väisänen 2019).

In this paper, we follow a methodology similar to one proposed by Georganopoulos et al. (2010) (Georganopoulos et al. 2010) to probe the six most recent and promising EBL models using simultaneous γ-ray observations of the four selected blazars at different redshifts from the *Fermi*-LAT and ground-based instruments. The paper is organised as follows: Section 2 summarises the six EBL models used in this study. In section 3, we report on the blazar observations and present understanding of the GeV-TeV emission. Section 4 describes the framework used in the present study. Application of this methodology and results are presented in Section 5 followed by discussion and conclusion in Section 6. We have assumed a cosmology with parameters: H_0= 70 km s^{-1} Mpc^{-1}, Ω_m= 0.30, Ω_Λ= 0.70 under the framework of the flat ΛCDM geometry of the Universe.

2. EBL models

The EBL is composed of stellar light emitted and partially reprocessed by the dust in the galaxies throughout the entire history of the cosmic evolution. Although the absolute level of the EBL density remains uncertain, the collective limits on the EBL from the direct and indirect measurements confirm the expected two-peak structure in the spectral energy distribution (SED). The first hump lies in the UV-optical to near-IR wavelength range and peaks at $\lambda\sim$ 1 μm. The second hump peaks at $\lambda\sim$ 100 μm in the far-IR regime. Due to the lack of direct EBL knowledge, many models have been presented in the last two decades. Based on the current understanding of the sources producing the EBL photons and their evolution in redshift, calculation of the EBL-SED is classified in four general categories (Dominguez et al. 2011): *forward evolution* (begins with the initial cosmological conditions and follows a forward evolution with time by means of the semi-analytical models of the galaxy formation), *backward evolution* (begins with existing galaxy populations and extrapolates them backward in time), *inferred evolution* (galaxy evolution is inferred from some observed quantity such as star formation rate density of the Universe over some range in wavelength), and *observed evolution* (galaxy population is directly observed over a range of redshift that contributes significantly to the EBL). Some of the forward (Primack et al. 1999) and backward (Malkan and Stecker 1998; Stecker et al. 2006) evolution models have been disfavoured by the VHE observation of blazars. In the following, we briefly discuss six prominent EBL models which have been used in the present study.

Franceschini et al. (2008): It is a backward evolution model which provides estimates of the EBL photon density using available information on the cosmic sources producing diffuse photons in the Universe from far-UV to the sub-millimetre wavelengths over a wide range of the cosmic epochs with the best possible time and spectral resolution and their redshift evolution. This model exploits relevant data from the ground-based observatories in the optical, near-IR and sub-millimetre, as well as multi-wavelength information from the space-telescopes such as HST, ISO and Spitzer. Additional constraints are provided from direct measurements or upper limits on the EBL estimates by dedicated missions like COBE.

Gilmore et al. (2009): It is a forward evolution model based on semi-analytical models of the galaxy formation, which provides predictions of the dust extinguished UV radiation field due to the star-light and empirical estimates of the contributions due to the quasars. The model analyses predictions for the UV background that are intended to broadly span the possibilities in the star formation rate and quasar luminosity density. This model presents new calculations of the evolving UV component of the EBL out to the epoch of the cosmological reionisation at high redshift.

Finke et al. (2010): It is an inferred evolution model for the UV through IR components of the EBL from the direct stellar radiation and reprocessed stellar radiation by the dust. This model takes into account the star formation rate, initial mass function, dust extinction and main-sequence stars as black bodies. The model is also extended to include the post-main sequence stars and reprocessing of starlight by the dust. The total energy absorbed by the dust is assumed to be re-emitted as three blackbodies in the IR, one at 40 K (warm, large dust grains), one at 70 K (hot, small dust grains) and one at 450 K (polycyclic aromatic hydrocarbons). This model does not require a complex stellar structure code or semi-analytical models of the galaxy formation.

Kneiske and Dole (2010): It is also an inferred evolution model which produces a strict lower limit flux for the evolving EBL in the mid and near-IR range up to a redshift of $z = 5$. A lower limit EBL model is derived by using the lower limit data from the integration of the galaxy number counts from the optical to far-IR region. The model takes into account the time-evolution of the galaxies, and includes the effect of the absorption and re-emission of the interstellar medium. The model is used to fit the observations of Spitzer, HST, ISO and GALEX to produce the complete EBL-SED.

Dominguez et al. (2011): It is an observed evolution model in which overall spectrum of the EBL between the wavelength range of 0.1–1000 μm is derived using a noble method based on the observations only. The method is based on the observed evolution of the rest frame K-band galaxy luminosity function up to a redshift of $z\sim 4$, combined with an estimation of the galaxy SED fractions. These quantities are achieved from fitting the Spitzer Wide Area Infrared Extragalactic Survey templates to a multi-wavelength survey sample of about 6000 galaxies in the redshift range of $z = 0.2$–1 from the All-wavelength Extended Groth Strip International Survey. This model predicts EBL from UV to IR wavelength range and provides strong constraints on the EBL from UV to mid-IR; however, the far-IR component exhibits higher uncertainties.

Gilmore et al. (2012): It is a forward evolution model based on the latest semi-analytical models of the galaxy formation and evolution as well as an improved model for reprocessing of the star-light by the dust to mid and far-IR wavelengths. These semi-analytical models use a ΛCDM hierarchical structure formation scenario and successfully reproduce a large variety of the observational constraints on the galaxy number counts, luminosity and mass functions and colour bi-modality. This model treats dust emission using empirical templates and predicts the EBL considerably lower than the optical and near-IR measurements.

3. GeV-TeV γ-ray observations of blazars

Blazars are the most amazing class in active galactic nuclei (AGNs) family with a relativistic jet pointing towards the line of sight of the observer at the Earth (Urry and Padovani 1995). They are known for their broadband SED from radio to TeV-energy γ-rays and fast, large-scale variability in all bands. The present understanding of the blazars from observations points towards an SED with two spectral humps. The first hump peaks at the low energy from IR to X-ray and is assumed to be the synchrotron emission from a population of relativistic electrons in a partially ordered magnetic field. The second hump peaks at MeV-GeV energies and is thought to be the result of the inverse Compton scattering of the soft target synchrotron photons itself (Bloom and Marscher 1996), photons from a dusty torus (Blazejowski et al. 2000), photons from a broad-line region (Sikora et al. 1994), or accretion disk photons (Dermer et al. 1992) under the leptonic scenario. Alternative models associate the higher energy peak to the interaction of relativistic protons with an ambient photon field (Aharonian et al. 2002) or a hybrid population comprised of both leptons and hadrons (Böttcher 2007). For most of the blazars, it is believed that the TeV and GeV-emissions arise from the same physical mechanism and hence should be intimately related. Thus, the combined γ-ray observations of such blazars in the GeV and TeV regimes can be used to study the EBL in an indirect manner. The energy range of the *Fermi*-LAT overlaps with the low energy threshold of the current generation ground-based γ-ray telescopes like MAGIC, H.E.S.S., VERITAS and TACTIC. Thus, for the first time, there is an excellent energy overlap between the space and ground-based telescopes, allowing simultaneous observations of the continuous spectra between 100 MeV and 20 TeV produced from blazars. Blazars, that are most likely to be detected by both, the *Fermi*-LAT and the ground-based telescopes simultaneously, are therefore crucial for this study.

4. Framework

Observation of the VHE γ-rays from blazars at the cosmological distances can be used as an alternative and completely independent way with respect to direct measurements to probe the EBL. The approach is based on the study of the absorption features imprinted on the GeV-TeV spectra due to the interaction of γ-rays with the EBL photons. Measurement of the effect of suppression of the TeV γ-ray emission from the blazars at non-negligible level can provide an estimate of the EBL density in the local Universe. Two completely different phenomenological approaches for studying the EBL density predicted by various models (Section 2) are described below in detail.

4.1. Model-dependent approach

In this method, we study the effect of EBL on the propagation of VHE γ-ray photons travelling through intergalactic space from sources at known redshifts. A very important consequence of the EBL is the attenuation of the VHE γ-rays emitted by the sources at cosmological redshifts through electron-positron pair creation (Gould and Schreder 1966). The physical process involved is expressed as

$$\gamma_{VHE} + \gamma_{EBL} \rightarrow e^- + e^+ \tag{1}$$

From the theory of radiation transfer, above process gives rise to an exponential decay of the intrinsic VHE γ-ray flux emitted from the distant blazars. The observed VHE γ-ray flux on earth is related to the intrinsic flux of the source as

$$F_{obs} = F_{int} \times e^{-\tau(E,z_s)} \tag{2}$$

The optical depth $\tau(E, z_s)$ encountered by the VHE γ-rays of energy E emitted from the source at redshift z_s and travelling towards the Earth due to the EBL absorption is given by

$$\tau(E, z_s) = \int_0^{z_s} \left(\frac{dl}{dz}\right) dz \int_0^2 \frac{\mu}{2} d\mu \int_{\varepsilon_{th}}^{\infty} n_{EBL}(\varepsilon, z) \sigma_{\gamma\gamma}(E, \varepsilon, \mu) d\varepsilon \tag{3}$$

where $\mu = 1 - cos\theta$, θ being angle between the momenta of two photons in the lab frame, ε is the energy of EBL photon undergoing pair production with VHE γ-ray photon, and $n_{EBL}(\varepsilon, z)$ is the EBL photon number density. Threshold energy of the EBL photons for pair production is given by

$$\varepsilon_{th}(E, \mu, z) = \frac{2m_e^2 c^4}{E\mu(1+z)^2} \tag{4}$$

where m_e is the rest mass of electron. $\sigma_{\gamma\gamma}(E, \varepsilon, \mu)$ is the total cross-section for pair creation and is defined as (Gould and Schreder 1967)

$$\sigma_{\gamma\gamma}(E, \varepsilon, \mu) = \frac{\pi r_0^2}{2}(1-\beta^2) \left[(3-\beta^4)\ln\frac{1+\beta}{1-\beta} - 2\beta(2-\beta^2)\right] \tag{5}$$

where the Lorentz factor β represents the velocity of e^- or e^+ in the centre of mass system and it depends on E, ε and θ. r_0 is the classical electron radius. For an isotropic distribution of the low energy EBL photons, the pair production cross-section has a distinct peak close to the threshold corresponding to $\beta \approx 0.70$. This implies that the cross-section is maximised for the EBL photon interacting with a VHE γ-ray photon provided following condition is satisfied.

$$\lambda_{EBL}(\mu m) = 1.187 \times (1+z)^2 \times E(TeV) \tag{6}$$

Hence, VHE γ-rays at a rest frame energy above 1 TeV are most likely absorbed by the mid and far-IR range of the EBL photons, while those in the 100 GeV to 1 TeV regime are sensitive to the EBL photons in the near-IR and optical bands. Below 100 GeV, it is mainly UV part of EBL-SED that causes the attenuation. Below 20 GeV, there is little absorption due to the increasing scarcity of the hard UV background photons. Thus, the attenuation of the VHE γ-ray photons by the EBL can in principle be used to estimate the EBL density at wavelengths corresponding to the observations of γ-rays from blazars at cosmological redshifts. The line element for a γ-ray photon moving from source to observer in the ΛCDM cosmology is expressed as

$$\frac{dl}{dz} = \frac{c}{H_0} \frac{1}{(1+z)\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}} \tag{7}$$

Besides redshifting all energies in the proportion of $(1+z)$ for cosmological applications, the cosmic expansion dilutes the EBL density by a factor $(1+z)^3$. In addition, EBL spectral energy distribution changes because of the intrinsic evolution of the galactic population over cosmic times. The EBL photons are progressively produced by the galaxies, but their density builds up slowly through the star formation history of the Universe. Therefore, the photon comoving number density decreases with redshift and is lower in the case of expanding Universe than that in the static Universe. Also, optical and near-IR photons are produced at lower z than the far-IR photons and therefore their comoving number density decreases faster with redshift. Various methods followed to model the evolution of EBL photon density suggest that $n_{EBL}(\varepsilon, z)$ acquires an extra factor and dilutes as $(1+z)^{3-k}$ in the expanding Universe (Madau and Phinney 1996; Aharonian et al. 2007; Raue and Mazin 2008; Berezinsky et al. 2016). The value of evolution factor k lies between 1.1 and 1.8 for $z < 1$. For our present calculations, we assume $k = 1.2$ as it shows good agreement between different approaches (Raue and Mazin 2008; Meyer et al. 2012). The EBL photon spectral number density, which depends on the adopted model for the EBL, is a key ingredient in the evaluation of the optical depth. This is obtained from the SED predicted by different EBL models using the following conversion factor,

$$n(\varepsilon)[cm^{-3}eV^{-1}] = 1.70395 \times 10^{-4} \times \lambda^2[\mu m]\nu I_\nu[nWm^{-2}sr^{-1}] \quad (8)$$

Using the above methodology, optical depth of the VHE γ-ray photons for a given EBL model can be determined as a function of z_s and E. Hence, we refer this method as the *Model-Dependent Approach*.

4.2. Model-independent approach

In this method, we use near-simultaneous observations of the blazars with the *Fermi*-LAT and ground-based γ-ray telescopes. With the launch of *Fermi*-LAT, the MeV-GeV observations of the blazars are now possible in a regime where the EBL attenuation is negligible. Overlapping of the operational energy range of the *Fermi*-LAT and ground-based γ-ray telescopes makes the blazar observations an important tool to probe the opacity of the Universe to VHE γ-rays as they propagate from their sources to the Earth. The Universe appears to be largely transparent to γ-rays at all the *Fermi*-LAT energies and out to redshift $z\sim$ 2, whereas opaque to the TeV photons at $z \leq$ 0.2. We assume that, in the *Fermi*-LAT operational energy range (0.1–500 GeV), blazar spectra are good representation of the intrinsic spectra and extrapolation of the *Fermi*-LAT spectra in the VHE range (0.1–20 TeV) gives the intrinsic TeV spectra of the blazars. Therefore, if the intrinsic spectra of blazars are described by any spectral form in GeV-TeV regime without the need for a break, their observed spectra would be imprinted with a break solely attributed to the EBL absorption. From the theory of radiative transfer, optical depth for a given blazar is given by

$$\tau(E, z_s) = \ln\left(\frac{F_1}{F_2}\right) \pm \left[\left(\frac{\Delta F_1}{F_1}\right)^2 + \left(\frac{\Delta F_2}{F_2}\right)^2\right]^{\frac{1}{2}} \quad (9)$$

where ($F_1 \pm \Delta F_1$) is the *Fermi*-LAT flux extrapolated to the VHE range and ($F_2 \pm \Delta F_2$) is the corresponding TeV flux measured by the ground-based instruments. Thus, using the above expression, optical depth of the VHE photons can be estimated using the *Fermi*-LAT (MeV-GeV) and ground-based (TeV) observations of the blazars at a given z_s without using any EBL model. Hence, we refer this method as the *Model-Independent Approach*. We apply this methodology to a few selected blazars as discussed below.

5. Results

We use the methodology described in Section 4 to a few selected blazars PKS 2155–304, RGB J0710 + 591, 1ES 1218 + 304 and RBS 0413 at different redshifts to study the six EBL models. The underlying assumption in the present study is that the *Fermi*-LAT operational energy range is practically unaffected due to the EBL absorption and the spectra of blazars in the LAT energy range represent a correct measure of the intrinsic spectra in the VHE regime. Extrapolation of the MeV-GeV spectrum to the TeV energy range gives a strict upper limit on the intrinsic TeV flux of the source. The TeV fluxes measured by the ground-based telescopes carry the imprint of the EBL absorption in the blazar spectra. We briefly discuss below the *Fermi*-LAT and TeV-observations of the above four blazars and their use in the present study in the order of increasing redshifts.

5.1. PKS 2155-304

PKS 2155–304 is a high-frequency peaked BL Lac (HBL) type of blazar at redshift $z_s =$ 0.116. It was simultaneously observed by the *Fermi*-LAT and H.E.S.S. telescopes in 2008 (Aharonian et al. 2009). The time-averaged *Fermi*-LAT and VHE spectra of PKS 2155–304 are well described by a power-law with photon spectral indices of $\Gamma_1 = 1.81 \pm 0.11$ and $\Gamma_2 = 3.34 \pm 0.05$ respectively (Aharonian et al. 2009). Using these measurements, we have estimated the optical depth of VHE photons emitted from the source in the energy range 0.2–2 TeV by using the *Model-Independent Approach*. We use six different EBL models to calculate the optical depth values in the energy range 0.2–2 TeV at redshift $z =$ 0.116 using the *Model-Dependent Approach*. The optical depth values obtained from two different approaches for $z_s =$ 0.116 are shown in Figure 1 and are also reported in Table A1 (Appendix A). The blazar PKS 2155–304 was observed in the nearly quiescent state without any signature of variability in the MeV-GeV and TeV light curves. Therefore, the intrinsic VHE spectrum of the source can be modified only due to the EBL absorption. Hence, the *Model-Independent Approach* predicts the maximum opacity of the Universe to VHE γ-rays at $z_s = 0.116$. We observe that the optical depth values derived from the GeV-TeV observations in the energy range 0.2–2 TeV are larger than that from the *Model-Dependent Approach*.

5.2. RGB J0710 + 591

RGB J0710 + 591 is a well-known extreme blazar featuring in many catalogues at redshift $z_s =$ 0.125. The first VHE γ-ray emission from this source was discovered by the VERITAS array of telescopes during 2008–09 observations (Acciari et al. 2010a). The VHE observations were complemented by contemporaneous observations with the *Fermi*-LAT. The time-averaged spectra in the MeV-GeV and TeV energy bands are fitted by a simple power-law with photon spectral indices of $\Gamma_1 = 1.46 \pm 0.17$ and $\Gamma_2 = 2.69 \pm 0.26$ respectively

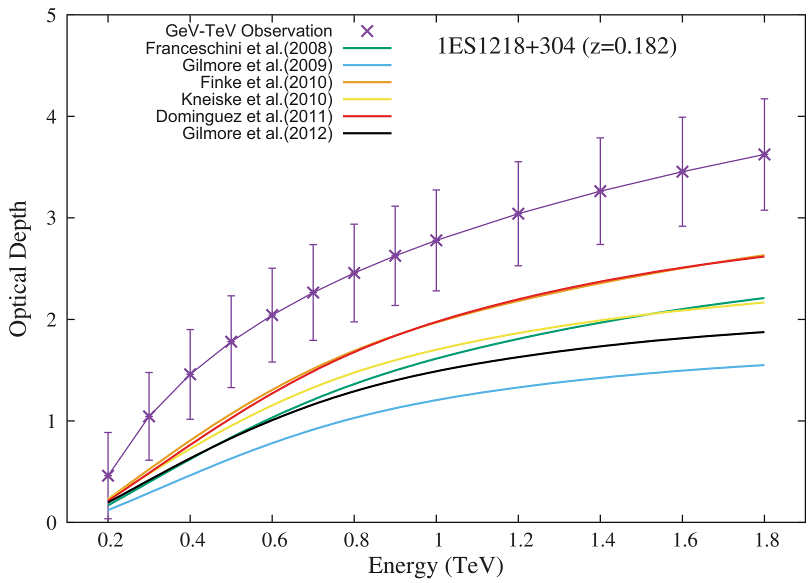

Figure 1. Comparison of the optical depth values estimated using two different methods: *Model-dependent approach* (six EBL) and *Model-independent approach* (GeV-TeV Observations) for $z_s = 0.116$.

(Acciari et al. 2010a). From these observations, we have calculated the opacity of TeV photons in the energy range 0.4–3.5 TeV by using the *Model-Independent Approach*. We also use the six EBL models to determine the opacity in the above energy range at source redshift $z_s = 0.125$ following the *Model-Dependent Approach*. The optical depth values from two different approaches are depicted in Figure 2 and are also summarised in Table A2 (Appendix A) for comparison. It is obvious from the figure that GeV-TeV γ-ray observations experience more opacity in the intergalactic space than that provided by the six different EBL models at $z_s = 0.125$. The large error bars in the values of optical depth obtained from the *Model-Independent Approach* are attributed to the uncertainties in the observed VHE spectra. Due to its relatively hard γ-ray spectra and no evidence of variability (Singh et al. 2019b), RGB J0710 + 591 is one the most suitable blazars to probe the EBL models.

5.3. 1ES 1218 + 304

The HBL object 1ES 1218 + 304 at redshift $z_s = 0.182$ belongs to a group of blazars that exhibit unusually hard VHE spectra considering their redshifts (Acciari et al. 2010b; Singh et al. 2019a). This blazar was observed by the VERITAS telescope from December 2008 to May 2009 and the time-averaged VHE spectrum was described by a power-law with a photon spectral index of $\Gamma_2 = 3.07 \pm 0.09$ (Acciari et al. 2010b). The quasi-simultaneous *Fermi*-LAT spectrum is also described by a power-law with a photon spectral index of $\Gamma_1 = 1.63 \pm 0.12$ making it one of the hardest γ-ray source. From the GeV-TeV quasi-simultaneous observations of the blazar 1ES 1218 + 304, we have estimated the optical depth of the VHE γ-ray photons coming from the source in the energy range 0.2–1.8 TeV using the *Model-Independent Approach*. Going to the higher redshift $z_s = 0.182$, we calculate the optical depth in the energy range 0.2–1.8 TeV corresponding to the six EBL models by applying the *Model Dependent Approach*. The two estimates of optical depths at $z_s = 0.182$ are shown in Figure 3 and are also reported in Table A3 (Appendix A). We clearly observe that the *Model-Independent Approach* again predicts the highest opacity as compared to the *Model-Dependent Approach*.

5.4. RBS 0413

RBS 0413 was discovered in X-ray band during the Einstein Medium Sensitivity Survey and was later identified as an HBL located at redshift $z_s = 0.190$. It is a weak source in the VHE regime. The VHE emission from this source was detected by the VERITAS telescope and was also complemented by the contemporaneous observation with the *Fermi*-LAT (Aliu et al. 2012). The observed VHE spectrum can be described by a power-law with a photon spectral index of $\Gamma_2 = 3.18 \pm 0.68$ and the MeV-GeV spectrum from the *Fermi*-LAT observations has a photon spectral index of $\Gamma_1 = 1.57 \pm 0.12$. Using these two contemporaneous observations, we have estimated the optical depth values in the energy range 0.3–0.85 TeV from the *Model-Independent Approach*. The optical depths in the same energy band have also been calculated using the six EBL models under the framework of the *Model-Dependent Approach* at $z_s = 0.190$. These values of the optical depths obtained from two different approaches are compared in Figure 4 and have also been given in Table A4 (Appendix A). The large error bars in the optical depth values obtained from the *Fermi*-LAT and VHE observations are due to

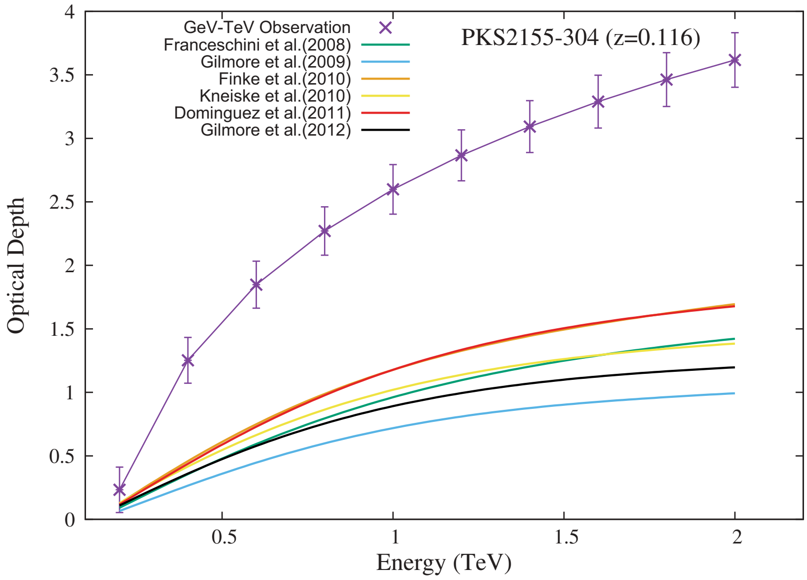

Figure 2. Same as Figure 1 for $z_s = 0.125$.

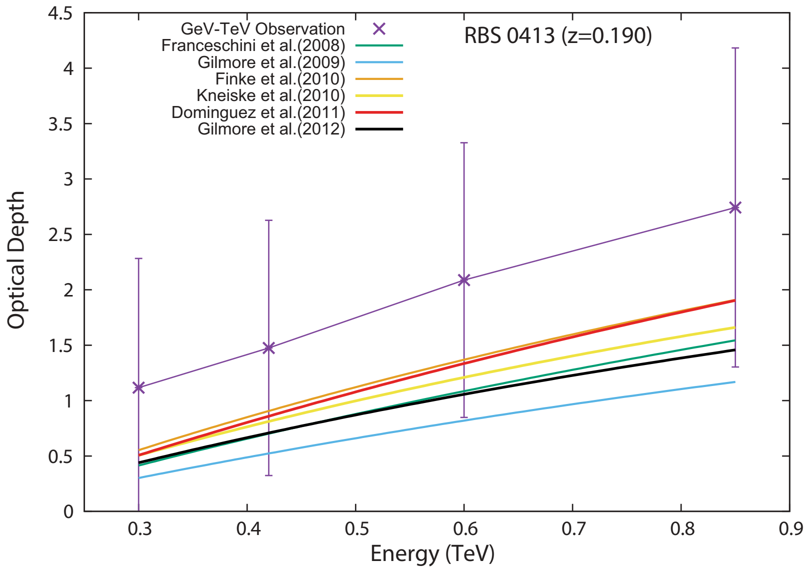

Figure 3. Same as Figure 1 for $z_s = 0.182$.

the higher uncertainties in the flux extrapolation from the LAT energy range to the TeV energies. Despite large error bars, the GeV-TeV observations predict more opacity than any EBL model used in the present study at redshift $z_s = 0.190$.

6. Discussion and conclusion

We have used two distinct and completely independent approaches to study the opacity of the Universe to the VHE γ-ray photons emitted at different redshifts. The *Model-Independent Approach* uses simultaneous observations of four selected blazars by the *Fermi*-LAT and ground-based γ-ray telescopes. The *Fermi*-LAT observations are used as a proxy for the intrinsic source emission in the GeV energy regime. The intrinsic TeV spectra of blazars are obtained by a simple extrapolation of the *Fermi*-LAT spectra to the VHE energies. The VHE spectra of blazars measured by the ground-based *TeV* instruments are expected to suffer EBL absorption of the VHE γ-ray photons. The EBL photons in different wavebands affect each part of the blazar spectrum in a different way. Over some energy band like MeV-GeV and GeV-TeV, the spectra of most of the blazars can be approximated by simple power-law shapes. That is, if the intrinsic spectrum is a power-law, the observed spectrum with the EBL absorption can also be described by a power-law with a steeper spectral index. The amount of steepening in the VHE spectra gives an indirect estimate of the EBL absorption of the *TeV* photons. From the present study, we conclude the following:

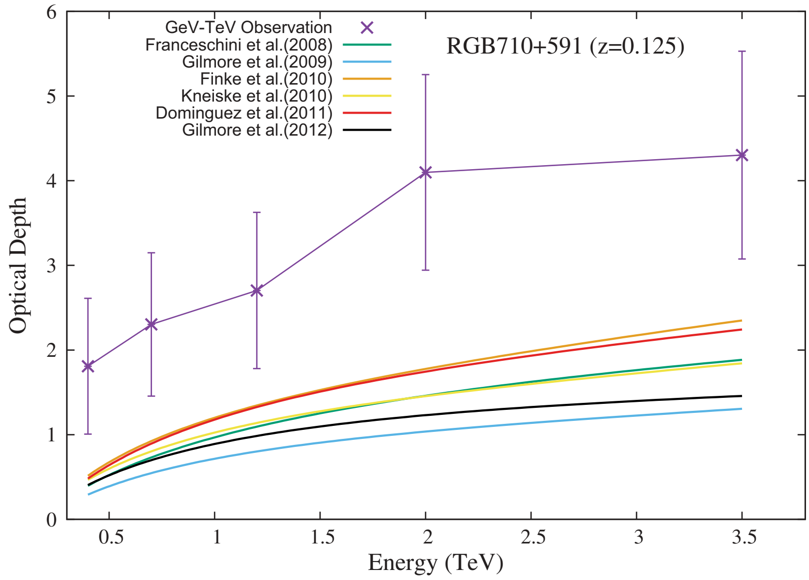

Figure 4. Same as Figure 1 for $z_s = 0.190$.

- Using the *Fermi*-LAT and TeV-observations of the selected blazar spectra, we have estimated the opacity of the Universe to the VHE γ-rays at different redshifts $z_s = 0.116, 0.125, 0.182$ & 0.190. We compare these estimates with the values calculated for six different EBL models using the *Model-Dependent Approach*.
- A comparison of the two results indicates that the *Model-Independent Approach* which completely relies on the blazar observations predicts the highest opacity of the Universe to the VHE γ-rays at all the redshifts, and it is beyond the values predicted by any EBL model used in this study. This implies that the EBL level predicted by any of the six models is not sufficient to produce the opacity of the Universe to the VHE γ-rays as expected by the GeV-TeV observations of the blazars.
- Since we assume that the extrapolation of the *Fermi*-LAT spectra to the TeV energies gives maximum level of the intrinsic TeV flux, the opacities obtained from the *Fermi*-LAT and *TeV*-observations of the blazars using the *Model-Independent Approach* can be used as upper limits for the opacity of the Universe. Therefore, any EBL model which gives opacity of the Universe through the *Model-Dependent Approach* higher than that predicted by the blazar observations can be excluded or disfavoured. However, it is important to mention here that the *Model-Independent Approach* discussed in this study is based on the assumption that the *Fermi*-LAT and VHE spectra are simultaneously measured in the quiescent state, when no temporal and spectral intrinsic variability are present in the source. The γ-ray spectra measured during the orphan flares or transient events from the blazars are not suitable for the *Model-Independent Approach*. Also, the presence of a curvature in the intrinsic combined GeV-TeV spectra of the blazars can predict higher values of the opacity using the *Model-Independent Approach*. In that case, a simple extrapolation of the *Fermi*-LAT spectra to the TeV energy range may not be a good description of the intrinsic γ-ray spectra of the blazars.
- We attribute any steepening of the blazar spectral slope other than EBL absorption intrinsic to the source. For the better prediction of the intrinsic TeV spectra, the local opacity caused by absorption taking place within the source can be incorporated while modelling the spectral energy distribution of blazars, but this is beyond the scope of this work.
- Among the six EBL models used in the present study, Gilmore et al. (2009) predict the lowest opacity, whereas models proposed by Finke et al. (2010) and Dominguez et al. (2011) give similar and highest opacity of the Universe to the VHE γ-rays at different redshifts. This indicates that Finke et al. (2010) and Dominguez et al. (2011) EBL models predict similar EBL-SED and show better consistency with the GeV-TeV observations of the blazars. Also, Franceschini et al. (2008) and Kneiske and Dole (2010) EBL models represent similar EBL intensity but show less consistency with the opacity expected from the blazar observations. The EBL models proposed by Gilmore et al. (2009, 2012) significantly differ from all other models used in the present study and both models give less opacity to the VHE γ-rays than remaining EBL models. This suggests that the *Model-Independent Approach* based on γ-ray observations either overestimates

the opacity of the Universe to the VHE γ-rays or the EBL models predict lower values of the optical depth at different redshifts. The too low values of the optical depth obtained from the *Model-Dependent Approach* can be attributed mainly to the lack of exact measurement of the EBL-SED and less understanding of the proper cosmological evolution of the EBL density in the models. The optical depth values corresponding to the Finke et al. (2010) and Dominguez et al. (2011) can be scaled up by a factor ~ 2 to get the better agreement with the *Model-Independent Approach* within statistical uncertainties at all four redshifts considered in this study. Recently, Desai et al. (2019) have used a sample of 38 blazars to measure the EBL intensity using the *Fermi*-LAT and ground-based observations (Desai et al. 2019). The optical depth at the GeV energies estimated from the *Fermi*-LAT observations (The Fermi-LAT Collaboration 2018) and TeV optical depths from the multiple spectra of 38 blazars in the energy range 0.1–21 TeV are combined with normalised opacities from the known EBL models to constrain the EBL intensity.

As the *Fermi*-LAT continuously monitors the γ-ray sky, the improved simultaneous measurements of the GeV-TeV spectra of more blazars over a range of redshift with the current generation ground-based instruments such as MAGIC, H.E.S.S., VERITAS, and TACTIC can provide a deep understanding of the existing EBL models using the approach discussed in this paper, which is similar to the one used by Georganopoulos et al. (2010). In future, the improved sensitivity of the Cherenkov Telescope Array (CTA) and its wide energy coverage will help in better understanding of the EBL (Mazin et al. 2013). With the quick accumulation of the blazars observed by the *Fermi*-LAT and ground-based γ-ray telescopes, which will be enhanced by the future CTA, the *Model-Independent Approach* can be used to measure the EBL by studying the absorption imprint in the spectra of a number of blazars with greater accuracy. Alternative scenarios to explain the VHE spectra of distant blazars and EBL absorption do exist in the literature. The intrinsic VHE spectra of blazars from the broadband SED modelling are also used as a probe for EBL models (Singh et al. 2014). Axion like particle (ALPs), which had been proposed to explain the strong-CP violation problem in the particle physics, could lead to a conversion of the VHE γ-ray photons into ALPs in the presence of intergalactic magnetic field (De Angelis et al. 2007; Singh 2019). This photon-ALP conversion drastically reduces the EBL absorption effects and enlarges the VHE γ-ray horizon. Production of secondary γ-rays along the line of sight by the interactions of cosmic-ray protons with the background photons has also been used to explain the VHE spectra of blazars at cosmological distances (Essey et al. 2011).

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No potential conflict of interest was reported by the authors.

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Appendix A.

Optical depth estimates from the *Model-Independent* (GeV-TeV observations) and *Model-Dependent* (EBL models) methods at four redshifts. The six EBL models are designated as, Fran-2008: Franceschini et al. (2008), Gil-2009: Gilmore et al. (2009), Kneis-2010: Kneiske and Dole (2010), Fink-2010: Finke et al. (2010), Domin-2011: Dominguez et al. (2011), and Gil-2012: Gilmore et al. (2012).

Table A1. $z = 0.116$ (PKS 2155–304).

		Model-Dependent					
E (TeV)	Model-Independent	Fran-2008	Gil-2009	Kneis-2010	Fink-2010	Domin-2011	Gil-2012
0.20	0.2326 ± 0.1785	0.0912	0.0658	0.1255	0.1287	0.1179	0.1089
0.40	1.2526 ± 0.1801	0.3628	0.2667	0.4708	0.4292	0.4407	0.3714
0.60	1.8476 ± 0.1851	0.6291	0.4769	0.8023	0.7137	0.7738	0.6204
0.80	2.2705 ± 0.1904	0.8397	0.6383	1.0533	0.9182	1.0369	0.8035
1.00	2.5985 ± 0.1954	1.0040	0.7569	1.2285	1.0673	1.2358	0.9371
1.20	2.8665 ± 0.2000	1.1273	0.8407	1.3629	1.1763	1.3795	1.0263
1.40	3.0931 ± 0.2043	1.2245	0.8951	1.4673	1.2478	1.4837	1.0889
1.60	3.2894 ± 0.2082	1.3012	0.9318	1.5475	1.3021	1.5634	1.1375
1.80	3.4626 ± 0.2119	1.3680	0.9652	1.6267	1.3496	1.6247	1.1682
2.00	3.6174 ± 0.2152	1.4225	0.9929	1.6948	1.3841	1.6783	1.1972

Table A2. $z = 0.125$ (RGB J0710 + 591).

		Model-Dependent					
E(TeV)	Model-Independent	Fran-2008	Gil-2009	Kneis-2010	Fink-2010	Domin-2011	Gil-2012
0.40	1.8084 ± 0.8019	0.3970	0.2917	0.5152	0.4682	0.4821	0.4059
0.70	2.3026 ± 0.8465	0.8067	0.6142	1.0413	0.8958	0.9952	0.7818
1.20	2.7035 ± 0.9230	1.2220	0.9105	1.4772	1.2739	1.4946	1.1108
2.00	4.0982 ± 1.1548	1.5388	1.0739	1.8341	1.4965	1.8158	1.2937
3.5	4.3023 ± 1.2269	1.8840	1.3055	2.3495	1.8432	2.2427	1.4579

Table A3. $z = 0.182$ (1ES 1218 + 304).

		Model-Dependent					
E (TeV)	Model-Independent	Fran-2008	Gil-2009	Kneis-2010	Fink-2010	Domin-2011	Gil-2012
0.20	0.4606 ± 0.4252	0.1683	0.1212	0.2307	0.2306	0.2149	0.1962
0.30	1.0445 ± 0.4319	0.3909	0.2845	0.5218	0.4777	0.4784	0.4148
0.40	1.4588 ± 0.4418	0.6328	0.4670	0.8206	0.7366	0.7691	0.6434
0.50	1.7801 ± 0.4521	0.8599	0.6476	1.1082	0.9833	1.0543	0.8576
0.60	2.0426 ± 0.4621	1.0645	0.8088	1.3476	1.1983	1.3115	1.0430
0.70	2.2646 ± 0.4717	1.2432	0.9455	1.5611	1.3702	1.5343	1.1982
0.80	2.4569 ± 0.4808	1.3977	1.0619	1.7396	1.5186	1.7264	1.3306
0.90	2.6265 ± 0.4893	1.5352	1.1592	1.8896	1.6400	1.8915	1.4405
1.00	2.7782 ± 0.4973	1.6534	1.2418	2.0135	1.7458	2.0311	1.5306
1.20	3.0408 ± 0.5121	1.8442	1.3628	2.2222	1.9041	2.2464	1.6614
1.40	3.2628 ± 0.5253	1.9902	1.4417	2.3768	2.0140	2.4030	1.7564
1.60	3.4550 ± 0.5373	2.1131	1.5016	2.5123	2.0951	2.5212	1.8223
1.80	3.6246 ± 0.5483	2.2101	1.5502	2.6327	2.1662	2.6187	1.8749

Table A4. $z = 0.190$ (RBS 0413).

		Model-Dependent					
E (TeV)	Model-Independent	Fran-2008	Gil-2009	Kneis-2010	Fink-2010	Domin-2011	Gil-2012
0.30	1.1164 ± 1.1669	0.4142	0.3015	0.5525	0.5058	0.5067	0.4388
0.42	1.4753 ± 1.1516	0.7175	0.5329	0.9288	0.8298	0.8743	0.7264
0.60	2.0877 ± 1.2399	1.1210	0.8518	1.4190	1.2606	1.3812	1.0972
0.85	2.7430 ± 1.4400	1.5437	1.1684	1.9089	1.6607	1.9038	1.4572