Using the Extragalactic Gamma-Ray Background to Constrain the Hubble Constant and Matter Density of the Universe

Houdun Zeng1,2 and Dahai Yan3,4

1 Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, People’s Republic of China
2 Key Laboratory for the Structure and Evolution of Celestial Objects, Yunnan Observatories, Chinese Academy of Sciences, Kunming 650216, People’s Republic of China; zhd@pmo.ac.cn
3 Center for Astronomical Mega-Science, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing 100012, People’s Republic of China
4 Department of Astronomy, Key Laboratory of Astroparticle Physics of Yunnan Province, Yunnan University, Kunming 650091, People’s Republic of China

Abstract

The attenuation produced by extragalactic background light (EBL) in γ-ray spectra of blazars has been used to constrain the Hubble constant \((H_0)\) and matter density \((\Omega_m)\) of the universe. We propose to estimate \(H_0\) and \(\Omega_m\) using the well-measured \(>10\) GeV extragalactic γ-ray background (EBG). This suggestion is based on the fact that the \(>10\) GeV EGB is totally explained by the emissions from blazars, and an EBL-absorption cutoff occurs at \(\sim 50\) GeV in the EGB spectrum. We fit the \(>10\) GeV EGB data with modeled EGB spectrum. This results in \(H_0 = 64.9^{+4.5}_{-4.0}\) km s\(^{-1}\) Mpc\(^{-1}\) and \(\Omega_m = 0.31^{+0.14}_{-0.13}\). Note that the uncertainties may be underestimated due to the limit of our realization for EBL model. Independent determination of \(\Omega_m\) by other methods would improve the constraint on \(H_0\).

Key words: galaxies: jets – gamma rays: diffuse background – gamma rays: galaxies

1. Introduction

A precise and accurate measurement of the Hubble constant \((H_0)\) would provide a deep understanding of fundamental physics questions. Multiple paths to independent estimates of \(H_0\) are needed in to access and control its systematic uncertainties (Suyu et al. 2012).

Gamma-ray astronomy provides a new approach to estimate \(H_0\) (Salamon et al. 1994; Mannheim 1996). The optical depth of the γ-ray photons emitted by extragalactic objects, \(\tau_{\gamma\gamma}\), scales as \(n_{\text{EBL}}\sigma_T l\), where \(n_{\text{EBL}}\) is the photon density of the extragalactic background light (EBL), \(\sigma_T\) is the Thomson cross section, and \(l\) is the distance from the γ-ray source to Earth. \(l\) is inversely proportional to \(H_0\) and \(n_{\text{EBL}}\) also depends on \(H_0\). Therefore, through determining the optical depth \(\tau_{\gamma\gamma}\), one can estimate \(H_0\).

Such an approach has been pursued by latter studies. With simulated TeV spectra of blazars, Blanch & Martinez (2005) studied the possibility of using γ-ray absorption to constrain cosmological parameters. Using the EBL density based on galaxy counts, Barrau et al. (2008) derived \(H_0 > 74\) km s\(^{-1}\) Mpc\(^{-1}\) at the 68% confidence level, from the TeV spectrum of Mrk 501. With the cosmic γ-ray horizon extracted from multwavlength observations of TeV blazars (Domínguez et al. 2013), Domínguez & Prada (2013) derived \(H_0 = 71.8^{+14.6}_{-7.2}\) (stat)\(^{+12.3}_{-3.4}\) (syst) km s\(^{-1}\) Mpc\(^{-1}\) and \(\Omega_m = 0.38^{+0.16}_{-0.16}\). With modeling of the TeV spectrum of Mrk 501, Biteau & Williams (2015) derived \(H_0 = 88 \pm 13\) (stat) \(\pm 13\) (syst) km s\(^{-1}\) Mpc\(^{-1}\) by analyzing 106 TeV spectra of 38 blazars. The Fermi Large Area Telescope (LAT) observations of blazars provide good determinations of \(\tau_{\gamma\gamma}\) (Abdollahi et al. 2018). Using \(\tau_{\gamma\gamma}\) measured from Fermi LAT GeV spectra (Abdollahi et al. 2018) and TeV spectra (Desai et al. 2019), Domínguez et al. (2019) derived \(H_0 = 68.0^{+4.2}_{-4.1}\) km s\(^{-1}\) Mpc\(^{-1}\) and \(\Omega_m = 0.17^{+0.07}_{-0.08}\) with the combination of the EBL models of Finke et al. (2010) and Domínguez et al. (2011). The constraint on \(H_0\) from γ-ray attenuation has been significantly improved in the past 10 years.

The above constraints on \(H_0\) are all derived from point sources. Here, we propose to constrain \(H_0\) and \(\Omega_m\) using the extragalactic γ-ray background (EBG). The EGB spectrum has been well measured from 0.1 GeV to \(\sim 800\) GeV by the Fermi LAT. This spectrum can be described by a power law with a photon index of 2.32 that is exponentially cut off at \(\sim 50\) GeV (Ackermann et al. 2015). The cutoff is caused by the EBL absorption (Ajello et al. 2015). Similar to the idea proposed by Salamon et al. (1994), the γ-ray absorption in the EGB spectrum could also be used to constrain the cosmological parameters.

EGB is dominated by the emission of γ-ray blazars (Ajello et al. 2015; Ackermann et al. 2016). With the source count distribution of hard-spectrum blazars, Ackermann et al. (2016) estimated that blazars can explain almost the totality (86–14%) of the \(>50\) GeV EGB. In particular, the calculation performed with improved luminosity function (LF) and modeling of the spectral energy distributions of blazars showed that blazars account for the totality of the \(>10\) GeV EGB (Ajello et al. 2015). Besides, modeling of the EGB spectrum also depends on \(H_0\). Therefore, we can use the above information to constrain \(H_0\) and \(\Omega_m\).

2. Method

2.1. Calculation of the EGB Spectrum

We follow Ajello et al. (2015) to compute the EGB spectrum contributed by blazars,

\[
F_{\text{EGB}}(E_{\gamma}) = \int_{\Gamma_{\text{min}}=1.0}^{\Gamma_{\text{max}}=10^2} d\Gamma \int_{z_{\text{min}}=6}^{z_{\text{max}}=10^{-3}} dz \left[ \frac{L_{\gamma}\Phi(L_{\gamma}, z, \Gamma)}{d\Omega} \frac{dN_{\gamma}}{dE} \right] \frac{dV}{dz d\Omega},
\]

(1)
where the LF, $\Phi(L_\gamma, z, \Gamma)$ (at redshift $z$, for sources of $\gamma$-ray luminosity $L_\gamma$), is described as a broken power law multiplied by the photon index distribution $\frac{dN}{dT}$ (Equation (1) in Ajello et al. 2015). The $\gamma$-ray spectrum of each blazar, $\frac{dN}{dT}$, is modeled as a broken power law (Equation (11) in Ajello et al. 2015). $\frac{dV}{dzd\Omega}$ is the comoving volume element per unit redshift and unit solid angle, which is written as

$$\frac{dV}{dzd\Omega} = \frac{cd^2}{H_0(1 + z)^2} E(z),$$

where $E(z) = [\Omega_\Lambda + \Omega_m(1 + z)^3]^{1/2}$, $\Omega_\Lambda = 1 - \Omega_m$ in a flat $\Lambda$CDM cosmology, and $dL$ is the luminosity distance.

### 2.2. Absorption of $\gamma$-Rays

The optical depth of the $\gamma$-ray photons emitted at redshift $z$ as a function of observed $\gamma$-ray photon energy, $E_\gamma$, is calculated by (e.g., Razzaque et al. 2009)

$$\tau_{\gamma\gamma}(E_\gamma, z) = c^2 \pi r_s^2 \frac{m_e^2 c^8}{E_\gamma} \int_0^z \frac{dz_1}{(1 + z_1)^2} \left| \frac{dt}{dz} \right|$$

$$\times \left[ \int_\gamma^{\infty} \int_0^\infty d\epsilon_1 \epsilon_{\text{EBL}}(\epsilon_1, z_1) \varphi(s_0) \right],$$

where $\left| \frac{dt}{dz_1} \right| = \frac{1}{H_0(1 + z_1)^2 E(z_1)}$, $s_0 = E_\gamma \epsilon_1(1 + z_1)/m_e^2 c^4$, and $\varphi(s_0)$ is adopted from Gould & Shréder (1967). We use the model of Razzaque et al. (2009) to calculate the comoving EBL density,

$$\epsilon u(\epsilon, z) = (1 + z)^4 \epsilon^2 N_e \int_0^\infty dz'' \left| \frac{dt}{dz''} \right| \psi(z''),$$

$$\times \int_{M_{\text{max}}}^{M_{\text{min}}} dM \left( \frac{dN}{dM} \right)$$

$$\times \int_{z_d(M, z)}^{\infty} d\epsilon' \left| \frac{dt'}{d\epsilon'} \right| f_{\text{esc}}(\epsilon') \frac{dN(\epsilon', M)}{d\epsilon' dt}(1 + z'),$$

where $\psi(z)$ is the star formation rate (SFR) in unit of $M_\odot \, \text{yr}^{-1} \, \text{Mpc}^{-3} \, \frac{dN}{dM}$ is the initial mass function (IMF), $f_{\text{esc}}(\epsilon)$ is the escape fraction of photons from the host galaxy, and $\frac{dN(\epsilon', M)}{d\epsilon' dt}$ is the total number of photons emitted from a star. The normalization is determined by $N^{-1} = \int_{M_{\text{min}}}^{M_{\text{max}}} dM (dN/dM) M$.

### 2.3. Verification of Our Calculations

We calculate the contribution to the EGB from blazars with the pure luminosity evolution (PLE) LF in Ajello et al. (2015) and the EBL models in Razzaque et al. (2009) (solid lines). The dashed line is the one without EBL absorption. Data points are from Ackermann et al. (2015).

### 3. Results

Calculations of LF and SFR depend on the measurements of $H_0$ and $\Omega_m$. Ajello et al. (2015) constructed the LF with $H_0 = 67 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$ and $\Omega_m = 0.3$. In our purpose, the LF should be modified with different cosmological parameters. Therefore, the LF in Equation (1) is

$$\Phi(L_\gamma, z, \Gamma) dL_\gamma dz d\Gamma = \Phi_{\text{Ajello15}}(L_\gamma, z', \Gamma') \frac{dV}{dz' d\Omega} dl_\gamma dz' d\Gamma'.$$
The SFR in Equation (4) is modified as (e.g., Domínguez et al. 2019),

\[ \psi(z) = \frac{\psi_{\text{HBOQ}}(z') H_0 E(z)}{H_0' E'(z)}. \]  

(6)

The primed quantities are computed with \( H_0' = 67 \text{ km s}^{-1} \text{ Mpc}^{-1} \) for the LF, and \( H_0' = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \) for the SFR, and \( \Omega_m' = 0.3 \).

### 3.1. Dependence on \( H_0 \)

Calculations of both the intrinsic EGB spectrum and \( \tau_{\gamma\gamma}(E, z) \) depend on \( H_0 \) and \( \Omega_m \). In Figure 2, we can see that the intrinsic spectrum strongly relies on \( H_0 \), especially at the energies below 100 GeV (left panel; \( H_0 \) is fixed to 67 km s\(^{-1}\) Mpc\(^{-1}\) in the calculation of the optical depth); and the dependence of \( \tau_{\gamma\gamma}(E, z) \) on \( H_0 \) occurs at the energies above 100 GeV (right panel; \( H_0 \) is fixed to 67 km s\(^{-1}\) Mpc\(^{-1}\) in the calculation of the intrinsic EGB spectrum).

### 3.2. Fitting Results

We use the modeled EGB spectrum to fit the >10 GeV observed data. \( H_0 \) and \( \Omega_m \) are set to free, and the other parameters are fixed to those in Ajello et al. (2015) and in Razzake et al. (2009). The Markov Chain Monte Carlo (MCMC) technique is used to perform our fitting. More details of our MCMC method can be found in Yan et al. (2013).

Figure 3 shows the best-fitting results with EBL Model B. We obtain \( H_0 = 72^{+10}_{-9} \text{ km s}^{-1} \text{ Mpc}^{-1} \) and \( \Omega_m = 0.23^{+0.04}_{-0.13} \). In the fitting, \( H_0 \) is anticorrelated with \( \Omega_m \) (see the 2D confidence contours of the parameters in the right panel), which is consistent with the result obtained by using the EBL model of Finke et al. (2010) in Domínguez et al. (2019). We note that the calculated EGB spectrum below 5 GeV is more sensitive to \( H_0 \) and \( \Omega_m \) (see the solid and dashed lines in the left panel of Figure 3). This effect is brought by the LF.

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\( \Delta H_0 = 2 \text{ km s}^{-1} \text{ Mpc}^{-1} \)

\( \Delta H_0 = 20 \text{ km s}^{-1} \text{ Mpc}^{-1} \)

Figure 2. Dependence on \( H_0 \). The results are produced by fixing \( \Omega_m = 0.3 \). Left: \( H_0 \) is varied from 65 km s\(^{-1}\) Mpc\(^{-1}\) to 69 km s\(^{-1}\) Mpc\(^{-1}\) in the calculation of the intrinsic EGB spectrum. Right: \( H_0 \) is varied from 47 km s\(^{-1}\) Mpc\(^{-1}\) to 87 km s\(^{-1}\) Mpc\(^{-1}\) in the calculation of \( \tau_{\gamma\gamma}(E, z) \).

Figure 3. Fitting results with the EBL Model B. Left: best fitting to the EGB spectrum above 10 GeV (solid line), and the result calculated with \( H_0 = 67 \text{ km s}^{-1} \text{ Mpc}^{-1} \) and \( \Omega_m = 0.3 \) (dashed line). Right: 1D marginalized probability distribution and 2D confidence contours of the parameters, and the dashed line represents the mean of the parameter.

5 Here we report the posterior probability means for the parameters.
Figure 4 shows the best-fitting results with EBL Model C. We obtain $H_0 = 63.1^{+6.2}_{-4.7}$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_m = 0.44^{+0.13}_{-0.09}$. The uncertainties on $H_0$ are at the 9% level. Again, there is a strong degeneracy between $H_0$ and $\Omega_m$ in this model. The EGB spectrum calculated with $H_0 = 67$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_m = 0.3$ is almost same with the best-fitting EGB spectrum.

Supposing that the two EBL models are equally possible, we derived the combined results in Figure 5 of $H_0 = 64.9^{+4.5}_{-4.3}$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_m = 0.31^{+0.13}_{-0.14}$.

### 4. Discussion and Conclusions

We simultaneously constrain $H_0$ and $\Omega_m$ via fitting the >10 GeV EGB spectrum. Two EBL models are adopted to investigate their impacts on the constraints. The EBL Model B in Razzaque et al. (2009) leads to $H_0 = 72^{+10}_{-9}$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_m = 0.23^{+0.14}_{-0.13}$, and the EBL Model C in Razzaque et al. (2009) leads to $H_0 = 63.1^{+6.2}_{-4.7}$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_m = 0.44^{+0.13}_{-0.09}$. The constraints obtained by using the two EBL models are consistent. The combined results are $H_0 = 64.9^{+4.5}_{-4.3}$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_m = 0.31^{+0.13}_{-0.14}$. Our constraints are mainly given by the blazars below the redshift of 1.5 (see Figure 1).

Using the latest $\gamma$-ray attenuation data obtained from $\gamma$-ray spectra of blazars, Domínguez et al. (2019) obtained $H_0 = 71.0^{+7.4}_{-5.8}$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_m = 0.21 \pm 0.06$ with the EBL model of Finke et al. (2010), and $H_0 = 65.0 \pm 2.9$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_m = 0.14 \pm 0.06$ with the EBL model of Domínguez et al. (2011). Their combined results are $H_0 = 68.0^{+1.4}_{-1.4}$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_m = 0.17^{+0.07}_{-0.08}$. Our results are in agreement with theirs.
The uncertainties on $H_0$ are comparable with those obtained by Domínguez et al. (2019). There is a clear degeneracy between $H_0$ and $\Omega_m$ in our calculation. Measurement of $\Omega_m$ using other independent methods would improve the constraint on $H_0$.

We choose the two easily calculated EBL models to examine the uncertainties introduced by the EBL models. Actually, these two models belong to the same methodology, i.e., the physically motivated model. These two models use the same assumption for SFR, and only differ in IMFs. Different assumptions for SFR may introduce extra uncertainties on $H_0$. In addition, we cannot examine the uncertainties introduced by different methodologies of building EBL models (e.g., Domínguez et al. 2019). The uncertainties in our results mainly come from EBL models. Therefore, we may underestimate the uncertainties in our results.

Currently, the values of $H_0$ measured from type Ia supernovae and from cosmic microwave background radiation (CMB) are discrepant at 3σ (Riess et al. 2018). Alternative methods of measuring the Hubble constant, like the method presented here, is helpful to understand this discrepancy.

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ORCID iDs

Houdun Zeng @ https://orcid.org/0000-0001-8500-0541
Dahai Yan @ https://orcid.org/0000-0003-4895-1406

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