Postprint of GeV-TeV Energy Spectrum Analysis of BL Lac Objects

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Abstract

We collected observational spectral indices in the high-energy and very-high-energy bands for 126 BL Lac objects and analyzed their spectral breaks (the difference between very-high-energy and high-energy observational spectral indices) using mathematical models. The aim was to determine whether extragalactic background light (EBL) absorption is the primary cause of spectral breaks in high-redshift BL Lac objects. The statistical analysis results are,. The statistical results indicate that the spectral breaks in BL Lac objects originate not only from extragalactic background light absorption but are also related to other physical processes.

Full Text

GeV-TeV Energy Spectral Analysis of BL Lac Objects

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Abstract

We compile observed spectral indices in the high-energy (HE) and very-high-energy (VHE) bands for 126 BL Lac objects and employ a mathematical model $\Delta\Gamma_{\rm obs} = \alpha z + \beta$ to analyze their spectral breaks (the difference between VHE and HE observed spectral indices). Our goal is to determine whether extragalactic background light (EBL) absorption is the primary cause of spectral breaks in high-redshift BL Lac objects. The statistical analysis yields $\alpha = 2.42 \pm 0.38 \neq 0$ and $\beta = 0.62 \pm 0.17 \neq 0$. These results indicate that the spectral breaks in BL

Lac objects originate not only from EBL absorption but also from other physical processes.

Keywords: galaxies; BL Lac objects; radiation mechanisms; non-thermal; statistics

1. Introduction

The continuous radiation from BL Lac objects primarily originates from jet emission regions with small viewing angles, and their spectral energy distributions (SEDs) exhibit a double-peaked structure corresponding to two main radiation components [1-2]. The first peak (low-energy peak) is generally attributed to synchrotron radiation from ultra-relativistic electrons, while the second peak (high-energy peak) may be produced by inverse Compton scattering of relativistic electrons [3], or alternatively by relativistic proton synchrotron radiation, photomeson pair cascade processes, and muon synchrotron radiation [4-5]. These two main radiation components produce smooth gamma-ray spectra, yet at higher energies the SED shows a tendency to steepen [6-7], manifesting as a spectral break between different energy bands.

The universe contains diffuse extragalactic background light (EBL), an isotropic radiation field spanning from ultraviolet to far-infrared wavelengths [8]. VHE gamma-ray photons ($E \geq 50$ GeV) produced in BL Lac object jets interact with EBL photons during propagation through intergalactic space, creating electron-positron pairs [9-12] via the process $\gamma + \gamma_{\rm EBL} \rightarrow e^+ + e^-$. This absorption mechanism steepens the observed spectra [13-14], with the effect becoming particularly pronounced for TeV photons at higher redshifts [12, 15-17]. However, the gamma-ray emission from high-redshift BL Lac objects cannot be fully explained by secondary cascades [18-20] or axion-like particle conversion . Consequently, the HE (100 MeV $\leq E <$ 50 GeV) and VHE observed spectra are expected to differ, leading to distinct GeV and TeV spectral indices.

To elucidate the mechanism behind spectral breaks, this study investigates the GeV-TeV spectral indices of BL Lac objects to determine whether EBL absorption is the dominant cause of spectral breaks at high redshift. Since observed spectra are modified by EBL absorption, correcting them yields the intrinsic spectra.

2. Data and Sample Selection

We selected sources from the Fermi-LAT 2FHL catalog and the TeV catalog for analysis. The 2FHL catalog provides VHE observed and intrinsic spectral indices, with HE observed spectral indices drawn from the 3FGL catalog [21]. The TeV catalog includes both VHE and HE observed spectral indices, with VHE intrinsic spectral indices taken from reference [22]. As some sources appear in both catalogs, we counted each unique source only once.

Blazars are classified into BL Lac objects [23] and flat-spectrum radio quasars (FSRQs) [24]. Compared to BL Lac objects, FSRQs exhibit additional spectral break contributions from broad-line region (BLR) absorption and external Compton radiation, so we removed FSRQs from our sample. From these catalogs, we extracted 126 observed spectral indices ($\Gamma_{\rm obs}$), with 120 sources having complete data. Based on synchrotron peak frequency, we divided the sample into 23 low-synchrotron-peaked BL Lac objects (LBL, $\nu_{\rm peak} \leq 10^{14}$ Hz), 13 intermediate-synchrotron-peaked BL Lac objects (IBL, $10^{14} < \nu_{\rm peak} \leq 10^{15}$ Hz), and 90 high-synchrotron-peaked BL Lac objects (HBL, $\nu_{\rm peak} \geq 10^{15}$ Hz).

3. Spectral Index Distributions

The distributions of observed and intrinsic spectral indices are shown in Figure 1 [Figure 1: see original paper]. To estimate the maximum-likelihood mean and dispersion of our sample, we used the following equations from reference [25]:

$$\sum_{j=1}^{N} \frac{\Gamma_j - \Gamma_0}{\sigma_j^2 + \sigma_0^2} = 0, \quad (1)$$

$$\sum_{j=1}^{N} \frac{(\Gamma_j - \Gamma_0)^2}{\sigma_j^2 + \sigma_0^2} = 1, \quad (2)$$

where Γ_j is the spectral index of each blazar, σ_j its error, N the total number of blazars, Γ_0 the mean spectral index, and σ_0 the intrinsic dispersion. Solving these equations yields $\sigma_{0,\rm obs} = 1.43$ and $\sigma_{0,\rm int} = 1.55$, indicating similar confidence intervals for observed and intrinsic spectral indices that do not affect our analysis. Since intrinsic spectra (unabsorbed by EBL) are obtained by correcting observed spectra, we expect $\Gamma_{0,\rm int} < \Gamma_{0,\rm obs}$. Figure 1 shows $\Gamma_{0,\rm obs} = 2.96$ and $\Gamma_{0,\rm int} = 2.55$, confirming that the intrinsic spectrum is harder and that EBL correction primarily reduces the mean spectral index.

Figure 2 [Figure 2: see original paper] shows the evolution of VHE intrinsic spectral indices with redshift. As intrinsic spectra are unaffected by EBL absorption, this effect is removed. The data reveal no redshift evolution of intrinsic spectral indices. Median values (black pentagons) and their uncertainties are displayed for three redshift bins. Consistent with references [22] and [26], VHE gamma-rays from blazars interact with EBL photons to produce pairs, making gamma-ray spectra softer than $\Gamma_{\rm int} = 1.5$ (the theoretical lower limit for pair production [29-30]). Most sources in our sample have $\Gamma_{\rm int} > 1.5$.

4. EBL Absorption Analysis

Typically, HE spectra (100 MeV $\leq$ E $<$ 50 GeV) are fitted with power laws $dN/dE \propto E^{-\Gamma_{\rm HE,obs}}$, and VHE spectra with $dN/dE \propto E^{-\Gamma_{\rm VHE,obs}}$, where $\Gamma_{\rm HE,obs}$ and $\Gamma_{\rm VHE,obs}$ are the observed spectral indices. Assuming each BL

Lac' s intrinsic spectrum follows $dN/dE \propto E^{-\Gamma_{\mathrm{HE,int}}}$ in the HE band and $dN/dE \propto E^{-\Gamma_{\mathrm{VHE,int}}}$ in the VHE band, the observed spectral break due to EBL absorption is expected to be $\Delta\Gamma_{\mathrm{obs}} = \Gamma_{\mathrm{VHE,obs}} - \Gamma_{\mathrm{HE,obs}}$ [13].

Since EBL absorption varies linearly with redshift, we expect $\Delta\Gamma_{\mathrm{EBL}}(z) = \alpha z$. Different EBL models may cause variations in $\Delta\Gamma_{\mathrm{EBL}}(z)$. However, for energies below 10 TeV, the optical depth $\tau_{\gamma\gamma}(E, z)$ differs only slightly among three empirical EBL models [12, 31-32], indicating minimal model dependence for our study.

Figure 3 [Figure 3: see original paper] plots the difference between VHE observed and intrinsic spectral indices ($\Delta\Gamma_{\mathrm{EBL}} = \Gamma_{\mathrm{VHE,obs}} - \Gamma_{\mathrm{VHE,int}}$) as a function of redshift. Linear regression yields:

$$\Delta\Gamma_{\mathrm{EBL}}(z) = (1.83 \pm 0.14) + (0.08 \pm 0.02)z, \quad (3)$$

demonstrating the nature of EBL absorption independent of blazar physics. The correlation is evident, though EBL effects are weaker at low redshift.

From this analysis, the observed spectral break is $\Delta\Gamma_{\mathrm{obs}} = \Gamma_{\mathrm{VHE,obs}} - \Gamma_{\mathrm{HE,obs}}$, while the intrinsic spectral break is $\Delta\Gamma_{\mathrm{int}} = \Gamma_{\mathrm{VHE,int}} - \Gamma_{\mathrm{HE,int}}$. This yields:

$$\Delta\Gamma_{\mathrm{obs}}(z) = \Delta\Gamma_{\mathrm{int}} + \Delta\Gamma_{\mathrm{EBL}}(z) = \alpha z + \beta, \quad (4)$$

where β represents intrinsic curvature. The best-fit for the full sample gives:

$$\Delta\Gamma_{\mathrm{obs}}(z) = (2.42 \pm 0.38) + (0.62 \pm 0.17)z, \quad (5)$$

confirming that observed spectral breaks depend on both EBL absorption and intrinsic curvature. The break becomes more pronounced at higher redshift, though EBL effects are modest for low-redshift sources.

To verify whether EBL absorption is the dominant cause of spectral breaks in high-redshift BL Lac objects, we must understand intrinsic curvature, which can be approximated by the difference in spectral indices around the peak frequency [33]. Combining EBL absorption with gamma-ray radiation, we simulate BL Lac SEDs using a broken power-law synchrotron self-Compton (SSC) model [34] and EBL models [4], following the approach of references [35-36].

Figure 4 [Figure 4: see original paper] shows the relationship between observed spectral break and redshift for the full sample. The gray band includes intrinsic curvature, its uncertainty, and EBL absorption, demonstrating that EBL effects cannot be excluded. While this confirms the origin of spectral breaks for $0 \leq z \leq 2.1$, we must verify the result for smaller redshift intervals. Selecting a subsample with $z < 0.6$ (Figure 5 [Figure 5: see original paper]) yields:

$$\Delta\Gamma_{\rm obs}(z) = (1.04 \pm 0.07) + (0.42 \pm 0.37)z, \quad (6)$$

with $\alpha \neq 0$ and $\beta \neq 0$, consistent with our analysis. The gray band again shows that both EBL absorption and intrinsic curvature are important even at low redshift, with more pronounced breaks at higher redshift.

Finally, we examine whether β equals $\Delta\Gamma_{\rm int}$ by studying the difference between VHE intrinsic and HE observed spectral indices ($\Gamma_{\rm VHE,int} - \Gamma_{\rm HE,obs}$), which removes EBL effects. Figure 6 [Figure 6: see original paper] shows no redshift evolution of this intrinsic spectral break. Using SSC model fitting, the gray band satisfies $\Delta\Gamma_{\rm int} = \beta$, confirming that EBL absorption does not affect the intrinsic break, while other physical processes (intrinsic curvature) do.

5. Conclusions

We compiled GeV-TeV spectral indices for 126 high-redshift BL Lac objects and analyzed their observed and intrinsic gamma-ray spectra. Key findings include:

1. The dispersion difference between observed and intrinsic spectral indices is small ($\sigma_{0,\rm obs} = 1.43$ vs. $\sigma_{0,\rm int} = 1.55$), with similar confidence intervals. However, the mean observed index ($\Gamma_{0,\rm obs} = 2.96$) significantly exceeds the mean intrinsic index ($\Gamma_{0,\rm int} = 2.55$), indicating that intrinsic spectra are hard and EBL absorption softens the observed mean index.
2. The relationship between observed spectral break and redshift follows $\Delta\Gamma_{\rm obs} = \alpha z + \beta$. Three cases emerge:
    - When $\alpha \neq 0$ and $\beta = 0$, the equation describes pure EBL absorption, not the observed break. Data confirm this relationship, showing weaker EBL effects at low redshift.
    - When $\alpha \neq 0$ and $\beta \neq 0$, this represents the observed spectral break. Linear regression and SSC simulations confirm that both EBL absorption and intrinsic curvature contribute, with EBL effects becoming irremovable at high redshift.
    - When $\alpha = 0$ and $\beta \neq 0$, the equation describes the intrinsic break ($\Gamma_{\rm VHE,int} - \Gamma_{\rm HE,obs}$), with EBL effects excluded. The distribution and theoretical modeling show that intrinsic curvature affects this relationship.
3. Statistical results ($\alpha = 2.42 \pm 0.38 \neq 0$, $\beta = 0.62 \pm 0.17 \neq 0$) demonstrate that both EBL absorption and other physical processes significantly contribute to observed spectral breaks, confirming EBL absorption as a major but not exclusive factor for high-redshift BL Lac objects.

While EBL absorption is verified as a primary contributor to spectral breaks, the non-zero β term indicates additional physics. Different SED fitting methods yield varying intrinsic curvatures: reference [14] uses log-parabolic SSC models, while we employ broken power-law SSC models, affecting the electron distribution and intrinsic curvature. References [11, 37] suggest that observed spectral break evolution with redshift includes both blazar physics and EBL absorption, while reference [18] proposes that spectral breaks could test hypotheses of secondary components. The hard spectra in our sample may indicate secondary gamma-ray components from cosmic-ray proton interactions with EBL photons, or axion-like particle oscillations near the source [19].

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Notes

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