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

Authors: Zhong Wei, Liu Wenguang, Zheng Yonggang

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Abstract

Collected observational spectral indices of 126 BL Lac objects in the high-energy and very-high-energy bands, and analyzed their spectral breaks (the difference between very-high-energy and high-energy observational spectral indices) using the mathematical model ΔΓ_obs = z + , with the aim of determining whether extragalactic background light (EBL) absorption is the primary cause of spectral breaks in high-redshift BL Lac objects. The statistical analysis yields 0, 0. The results indicate that the spectral breaks in BL Lac objects originate not only from extragalactic background light absorption but also are related to other physical processes.

Full Text

GeV-TeV Energy Spectral Analysis of BL Lac Objects

Liu Wenguang^{1,2}, **Zheng Yonggang**^{1} 1. School of Physics and Electronic Information, Yunnan Normal University, Kunming, Yunnan, China 2. The Key Laboratory of High Energy Astrophysics of Universities in Yunnan Province, Yunnan Normal University, Kunming, Yunnan, China

Abstract

We compile the observed spectral indices of 126 BL Lac objects in both the high-energy (HE, 100 MeV E < 50 GeV) and very-high-energy (VHE, E 50 GeV) bands to investigate whether extragalactic background light (EBL) absorption is the exclusive origin of spectral breaks in high-redshift sources. Using a mathematical model to analyze the spectral break (defined as the difference between VHE and HE observed spectral indices), our goal is to determine the role of EBL absorption. The results demonstrate that the observed spectral break originates not only from EBL absorption but also involves other physical

processes. Statistical analysis yields 0 and 0, indicating that both EBL attenuation and intrinsic spectral curvature contribute significantly to the energy spectral break.

Keywords: Galaxies; BL Lac objects; Radiation mechanism; Non-thermal emission; Statistics

Introduction

The continuous radiation from BL Lac objects primarily originates from jet emission regions oriented at small angles to the observer's line of sight. Their spectral energy distributions (SEDs) exhibit a characteristic double-peaked structure corresponding to two main radiation components [1-2]. The first peak is generally attributed to synchrotron radiation from ultra-relativistic electrons, while the second peak may be produced by inverse Compton scattering from relativistic electrons [3], or alternatively by synchrotron radiation from relativistic protons, pion synchrotron radiation, and other processes [4-5]. The gamma-ray SEDs show a trend of steepening [6-7], with these two main components smoothing the gamma-ray spectrum and revealing spectral breaks between different energy bands.

The universe contains a diffuse extragalactic background light (EBL), an isotropic radiation field spanning from ultraviolet to far-infrared wavelengths [8]. Very-high-energy gamma-ray photons produced in the jets of BL Lac objects interact with EBL photons during propagation through intergalactic space, creating electron-positron pairs (_VHE + _EBL → e + e) for energies above approximately 50 GeV [9-12]. This process steepens the observed spectra [13-14], particularly for sources at higher redshifts where EBL absorption becomes more pronounced [12,15-17]. The gamma-ray emission from BL Lac objects cannot be explained by secondary cascades [18-20] or axion-like particle conversions [1], making EBL absorption the primary attenuation mechanism.

Given these considerations, the observed HE and VHE spectra of BL Lac objects differ substantially. To clarify the mechanism behind spectral breaks, we investigate whether EBL absorption is the dominant cause in high-redshift sources.

Data and Sample Selection

This study analyzes BL Lac objects from the 2FHL catalog [21] and TeVCat [22]. The 2FHL catalog provides VHE observed spectral indices and intrinsic indices, while TeVCat includes both VHE and HE observed spectral indices. Since some sources appear in both catalogs, we analyze each unique source only once.

Blazars are classified into BL Lac objects and flat-spectrum radio quasars (FSRQs). The broad-line region in FSRQs affects spectral breaks through both absorption and external Compton radiation, so we exclude FSRQs from our sample [23]. From these catalogs, we select BL Lac objects and obtain 126 observed spectral indices (Γ_VHE,obs) and intrinsic indices (Γ_VHE,int), with

HE data available for 13 sources.

We further classify the sample based on synchrotron peak frequency (__peak). According to the classification scheme, we identify 13 low-synchrotron-peaked (LBL, __peak 10¹ Hz), 90 intermediate-synchrotron-peaked (IBL), and high-synchrotron-peaked (HBL, __peak 10¹ Hz) BL Lac objects.

Comparison of Observed and Intrinsic Spectra

Figure 1 shows the distributions of observed and intrinsic spectral indices. To estimate the maximum-likelihood mean and dispersion of the sample, we employ the following system of equations [25]:

² = Σ[(Γ__j - Γ)² + __j²]/N

where Γ__j represents individual spectral indices, Γ is the mean spectral index, __j are the measurement errors, and N is the total number of sources. Solving this system yields the mean spectral index and intrinsic dispersion.

For the observed spectra, we obtain a mean index Γ__0,obs = 2.96 ± 0.14 with dispersion __0,obs = 1.43. For the intrinsic spectra, the mean index is Γ__0,int = 2.55 ± 0.17 with dispersion __0,int = 1.55. The confidence intervals of the two distributions are similar, but the mean observed spectral index is significantly higher than the mean intrinsic index, indicating that the intrinsic spectrum is hard while the observed spectrum is softened by EBL absorption. The EBL correction primarily reduces the mean spectral index without substantially affecting the dispersion.

[Figure 1: see original paper]

Evolution of VHE Intrinsic Spectral Indices with Redshift

Figure 2 presents the evolution of VHE intrinsic spectral indices with redshift. Since intrinsic spectra are unaffected by EBL absorption, any redshift evolution would indicate intrinsic physical changes. The sample shows no significant evolution of intrinsic indices with redshift. The median values (black pentagons) and their uncertainties are plotted for each redshift bin, with uncertainties estimated from the distribution of sources within each bin [26].

[Figure 2: see original paper]

Analysis of Spectral Breaks

The observed HE spectrum can be fitted by a power law (Γ__HE,obs for 100 MeV E $<$ 50 GeV), while the observed VHE spectrum follows Γ__VHE,obs. In the VHE band, gamma-ray photons suffer EBL absorption, causing the observed spectral break [13].

Based on pair production physics [29-30], the optical depth __ (E,z) for EBL absorption varies with redshift. For energies below 0.1 TeV, __ 0, while for energies above 0.1 TeV, _ 0, indicating significant absorption. Current EBL models show minimal differences for energies below 10 TeV [12,31-32], suggesting that model choice does not substantially affect our results.

To examine the relationship between EBL absorption and redshift, we define the spectral break as:

Δ_obs = Γ_VHE,obs - Γ_HE,obs

Linear regression analysis yields:

Δ_obs = (1.83 ± 0.14)z + (0.08 ± 0.02)

with = 1.83 ± 0.14 0 and = 0.08 ± 0.02 0 at low redshift. This demonstrates that EBL absorption increases linearly with redshift, while its effect is minimal for low-redshift sources.

Figure 3 shows the difference between VHE observed and intrinsic spectral indices versus redshift, confirming the EBL absorption signature. The boxes, symbols, and colors follow the same scheme as Figure 2.

[Figure 3: see original paper]

Observed Spectral Break vs. Redshift

The observed spectral break is obtained by subtracting the HE observed index from the VHE observed index, while the intrinsic break derives from the difference between VHE and HE intrinsic indices. The complete sample shows a clear evolution of the observed break with redshift (Figure 4). The best-fit relation is:

Δ_obs = (2.42 ± 0.38)z + (0.62 ± 0.17)

with = 2.42 ± 0.38 0 and = 0.62 ± 0.17 0, consistent with our mathematical model. The gray shaded band includes contributions from intrinsic curvature, curvature errors, and EBL absorption, demonstrating that both EBL attenuation and other physical processes affect the observed spectral break. The break becomes more pronounced at higher redshifts.

[Figure 4: see original paper]

To verify these results at lower redshifts, we analyze a subsample with z 0.6 (Figure 5). The best-fit line is:

Δ_obs = (1.04 ± 0.07)z + (0.42 ± 0.37)

with = 1.04 ± 0.07 0 and = 0.42 ± 0.37 0. This confirms that both EBL absorption and intrinsic curvature play important roles even at low redshifts.

[Figure 5: see original paper]

Intrinsic Spectral Break Analysis

We now examine the intrinsic spectral break by comparing VHE intrinsic indices with HE observed indices (Figure 6). Since intrinsic spectra exclude EBL absorption effects, this analysis isolates the contribution of intrinsic curvature. The intrinsic break shows no evolution with redshift, as expected. Using a synchrotron self-Compton (SSC) model [34] combined with EBL models [4], we simulate the SEDs of BL Lac objects and obtain the gray shaded band, which is consistent with the mathematical model for intrinsic curvature only. This confirms that EBL absorption does not affect the intrinsic spectral break, while other physical processes (intrinsic curvature) dominate this relationship.

[Figure 6: see original paper]

Conclusions and Discussion

This study compiles observed and intrinsic spectral indices for 126 BL Lac objects to investigate the origin of spectral breaks in their gamma-ray emission. Our main findings are:

1. **EBL Absorption Effect**: The mean observed spectral index (Γ_0,obs = 2.96 ± 0.14) is significantly softer than the mean intrinsic index (Γ_0,int = 2.55 ± 0.17), demonstrating that EBL absorption systematically softens the observed spectra.

2. **Spectral Break Origin**: The observed spectral break evolves with redshift according to Δ_obs = (2.42 ± 0.38)z + (0.62 ± 0.17), where both 0 and 0. This indicates that the spectral break originates from both EBL absorption and other physical processes, particularly intrinsic spectral curvature.

3. **Intrinsic Curvature**: The intrinsic spectral break, defined as = Γ_VHE,int - Γ_HE,obs, shows no redshift evolution, confirming that it arises from intrinsic source physics rather than EBL effects.

4. **Model Consistency**: Using an SSC emission model [34] and EBL models [4], we simulate BL Lac SEDs and find results consistent with our statistical analysis. The gray shaded bands in our figures encompass both EBL absorption and intrinsic curvature effects.

The presence of hard-spectrum sources in our sample suggests that secondary emission processes may contribute to the gamma-ray emission. Possible mechanisms include cosmic-ray proton interactions with EBL photons producing secondary gamma-ray components [11,37], or high-energy photon oscillations into axion-like particles near the source with subsequent reconversion [19]. However, our statistical results firmly establish that EBL absorption is a major—but not exclusive—cause of spectral breaks in high-redshift BL Lac objects. The spectral break also depends significantly on intrinsic curvature ( ), indicating that multiple physical processes shape the observed gamma-ray spectra.

Different SED modeling approaches (e.g., log-parabolic vs. truncated power-law SSC models) yield different electron spectra and thus different intrinsic curvature values. While we employ a truncated power-law SSC model [35-36] to obtain , other methods could produce varying results. Nevertheless, our primary conclusion remains robust: observed spectral breaks in BL Lac objects result from a combination of EBL absorption and intrinsic source physics, with the relative importance of each component varying with redshift.

References: [The references section appears to be incomplete and fragmented in the original. A complete reference list would be included here in a final manuscript.]

Note: Figure translations are in progress. See original paper for figures.