Post-print of Fermi-LAT blazar detections located at the gamma-ray horizon of extragalactic background light absorption

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Abstract

Extragalactic Background Light (EBL) is the diffuse electromagnetic radiation from far-infrared to ultraviolet wavelengths permeating the entire universe, carrying crucial information about cosmic evolution. Since gamma-ray photons can undergo two-photon annihilation with the EBL during their propagation through the universe, exploring the cosmic gamma-ray optical depth is vital for understanding the EBL. Detecting horizon photons from distant gamma-ray sources, where EBL absorption is significant ($\tau_{\gamma\gamma} \gtrsim 1$, where $\tau_{\gamma\gamma}$ is the absorption optical depth between high-energy gamma-ray photons and low-energy background photons), is a direct and effective method. Based on the latest Fermi-LAT gamma-ray source sample, a systematic gamma-ray data analysis was performed on 448 sources after meticulous screening and careful redshift identification. By comparing these with mainstream EBL models, the results reveal 46 horizon photons originating from 36 blazars, with the most distant source reaching a redshift of 2.944. Further gamma-ray time-domain analysis indicates that the most intense flares of some blazars are coincident with the detection times of the horizon photons. This batch of horizon photons from flat-spectrum radio quasars provides constraints on the location of the jet emission region. Meanwhile, blazars emitting horizon photons can serve as important targets for observation by next-generation space-based and ground-based gamma-ray telescopes.

Full Text

Preamble

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Detection of Fermi-LAT Blazars Located Beyond the Gamma-ray Horizon of Extragalactic Background Light Absorption*

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摘要

Extragalactic Background Light (EBL) consists of diffuse electromagnetic radiation spanning from far-infrared to ultraviolet wavelengths that permeates the entire universe.

This radiation carries vital information regarding the evolution of the cosmos. Because gamma-ray photons can undergo two-photon annihilation with the EBL as they propagate through space, exploring the gamma-ray optical depth of the universe is essential for understanding the EBL. A direct and effective method for this exploration involves detecting "horizon photons" —photons from distant gamma-ray sources where the absorption by the EBL is significant ($\tau_{\gamma\gamma} \gtrsim 1$, where $\tau_{\gamma\gamma}$ represents the optical depth of absorption between high-energy gamma-ray photons and low-energy background photons). Utilizing the latest sample of gamma-ray sources from Fermi-LAT, we conducted a systematic gamma-ray data analysis of 448 sources following meticulous screening and rigorous redshift identification. By comparing our findings with mainstream EBL models, the results reveal 46 horizon photons originating from 36 blazars, with the most distant source reaching a redshift of 2.944. Furthermore, gamma-ray time-domain analysis indicates that the most intense flares of certain blazars are temporally coincident with the detection of these horizon photons.

The collection of horizon photons originating from Flat Spectrum Radio Quasars (FSRQs) imposes constraints on the location of the emission regions within the jets. At the same time, the blazars that emit these horizon photons serve as critical targets for observations by the next generation of space-based and ground-based gamma-ray telescopes.

关键词

Galaxies: active, Galaxies: jets, Cosmology: cosmic background radiation; CLC number: P158;

Document code: A

The contributions to this background include the activity of supermassive black holes as well as the annihilation of dark matter particles. The infrared component originates from the re-radiation of dust after it absorbs and obscures the aforementioned optical-ultraviolet radiation. As a fundamental component of the universe, the extragalactic background light (EBL) represents the accumulation of radiation from the infrared to the ultraviolet bands since the Big Bang. It contains critical information regarding cosmic evolution and is of significant research importance [**?**].

In practice, the precise measurement of the extragalactic background light is extremely difficult. This is because the Earth is not only immersed in the EBL but is also situated within other diffuse foreground radiations with much higher flux densities. The primary sources of interference include zodiacal light, as well as starlight from the Milky Way’ s faint stars and scattered light from high-galactic-latitude dust. Given that the radiation intensity of zodiacal light decays with increasing wavelength starting from 10 μm, the 100 μm region serves as an effective detection window for the EBL [**?**]. In the near-infrared band, specifically 1–5 μm, the

引言

Introduction

Extragalactic Background Light (EBL) is a diffuse electromagnetic radiation that permeates the entire universe, spanning wavelengths from the far-infrared to the ultraviolet (e.g., $0.1-1000$ m) [**?**]. As a component of the cosmic background radiation, the EBL represents the most significant energy output in the universe second only to the Cosmic Microwave Background (CMB). The spectral energy distribution (SED) of the EBL exhibits a characteristic double-peak structure, reaching local maxima at approximately 1 m (the Cosmic Optical Background, COB) and 100 m (the Cosmic Infrared Background, CIB), with a minimum occurring around 10 m. The optical-ultraviolet portion of the EBL is primarily attributed to starlight emitted by galaxies throughout cosmic history.

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Introduction

Extragalactic Background Light (EBL) holds significant research importance. This is because the starlight from Population III stars in the early universe (at redshifts of approximately 8-10) shifts into this waveband due to cosmological redshift [**?**]. Recently, the New Horizons probe, located 40 AU from the Sun, provided detections of the near-infrared EBL [**?**]. In addition to direct detection, the intensity of the EBL can be constrained by constructing galaxy luminosity functions based on observations from current infrared and optical astronomical facilities and calculating their cumulative radiation. Due to the large uncertainties at the faint end of the luminosity function, galaxy counting methods typically only provide a lower limit for the EBL [**?**].

Since the inception of gamma-ray astronomy, astronomers have recognized that distant gamma-ray sources can be used to indirectly constrain the intensity of the EBL [?]. As gamma-ray photons travel through the universe, they undergo a two-photon annihilation process ($\gamma + \gamma \rightarrow e^{+} + e^{-}$) through interaction with the EBL [?]. In other words, the gamma-ray opacity of the universe is closely related to the strength of the EBL. For very-high-energy (VHE) gamma-ray photons, the corresponding absorbed EBL band is in the near-infrared at approximately $\epsilon \sim 0.8(E/\mathrm{TeV})^{-1}$ eV, where ϵ is the energy of the EBL photon and E is the energy of the gamma-ray photon. In the gamma-ray sky, gamma-ray bursts (GRBs) and blazars are the primary extragalactic gamma-ray sources [?]. Blazars are a special class of active galactic nuclei (AGN) with powerful relativistic jets pointed toward Earth; the radiation from these jets is significantly amplified due to beaming effects. Typical observational characteristics of blazars include electromagnetic radiation across all bands from radio to VHE gamma rays, as well as rapid, large-amplitude variability [?]. Based on different optical spectral features, blazars are divided into Flat Spectrum Radio Quasars (FSRQs) and BL Lacertae objects (BL Lacs). The former possess efficient accretion disks that produce prominent optical emission lines, while the latter have lower black hole accretion efficiency, resulting in optical spectra characterized by a smooth power-law distribution. The broadband spectral energy distribution (SED) of blazars exhibits a double-peak structure. The low-frequency peak is generally thought to originate from synchrotron radiation of relativistic electrons, while the high-frequency peak extends into the gamma-ray energy range, though its radiative origin remains a subject of significant debate. Based on the position of the low-frequency peak, blazars are further classified into Low-Synchrotron-Peaked blazars (LSP, $< 10^{14}$ Hz), Intermediate-Synchrotron-Peaked blazars (ISP, 10^{14}–10^{15} Hz), and High-Synchrotron-Peaked blazars (HSP, $> 10^{15}$ Hz).

Early observations of VHE gamma rays from blazars by ground-based Cherenkov gamma-ray telescopes have played an important role in studies constraining the EBL.

The H.E.S.S. (High Energy Stereoscopic System) telescope observed hard gamma-ray spectra from nearby BL Lac objects (e.g., H 2356-309 and 1ES 1101-232), placing stringent constraints on the flux levels of the EBL [?]. Interestingly, the MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov) telescope also detected VHE gamma-ray radiation from the FSRQ 3C 279 at a redshift of 0.536 [?].

This implies that the universe is more transparent to gamma-ray photons than previously imagined. More than a decade of successful operation of the Fermi Gamma-ray Space Telescope has greatly advanced the field of gamma-ray astronomy. It carries two core scientific instruments: the Large Area Telescope (LAT [?]) and the GLAST Burst Monitor (GBM). The Fermi-LAT offers advantages such as a wide detection energy range (0.1 GeV to over 500 GeV), a large effective area, and a wide field of view. To date, it has discovered thousands of extragalactic gamma-ray sources [?], with the most distant reaching a redshift of 4.3 [?]. These sources systematically characterize the gamma-ray opacity of the universe at different redshifts [?] and play a crucial role in constraining the star formation history [?].

However, the aforementioned methods typically require assuming an intrinsic radiation spectrum (before absorption) to compare with the observed spectrum, using the resulting difference to measure the strength of EBL absorption. One type of intrinsic spectrum assumption is based on relativistic cosmic ray acceleration theory, which posits that the particle spectrum cannot be too hard ($\Gamma > 1.5$, where $f(\nu) \propto \nu^{-\Gamma}$, Γ is the gamma-ray power-law index, $f(\nu)$ is the flux, and ν is the frequency) [?]. Another relatively model-independent method involves using a GeV–TeV spectrum extrapolated from the MeV–GeV energy range as the intrinsic spectrum [?]. In reality, our current understanding of particle acceleration processes remains very limited, and the observed gamma-ray spectra of blazars exhibit diverse and complex characteristics.

For example, the SEDs of blazars, particularly FSRQs, often exhibit systematic curvature [?]. These limitations introduce unavoidable systematic uncertainties into the selection of intrinsic spectra. The ability of the Fermi-LAT telescope to resolve individual gamma-ray photon events provides a research pathway for constraining EBL models that is independent of intrinsic spectrum assumptions: namely, searching for "horizon" gamma-ray photons with an optical depth $\tau_{\gamma\gamma} \gtrsim 1$. A typical example is the 2013 detection by Fermi-LAT of two VHE photons from PKS 0426−380 (redshift $z = 1.1$) with energies of 122 and 134 GeV, respectively [?]. Although related search efforts have been ongoing, most existing work is limited to

individual analyses of a small number of sources [?]. This paper aims to use 16 years of Fermi-LAT data to systematically search for EBL horizon gamma-ray photons from blazars. Currently, the Fermi AGN sample (The Fourth Catalog of Active Galactic Nuclei Detected by the Fermi Large Area Telescope: Data Release 3, 4LAC-DR3 [?]) has listed the energy of the highest-energy photon for each source using the first 12 years of data. We have included an additional 4 years of the latest data. More importantly, we have exhaustively collected redshift detection information for these blazars and performed careful screening, which is critical for determining whether an arriving photon is a horizon photon. Searching for more horizon photons can deepen our understanding of the EBL. Furthermore, we have systematically conducted time-domain analysis of the target sources to explore the origin of horizon photons and place constraints on the energy dissipation mechanisms of blazars. This paper adopts the standard Λ-Cold Dark Matter (ΛCDM) cosmological model ($\Omega_M = 0.32$, $\Omega_\Lambda = 0.68$, and a Hubble constant $H_0 = 67$ km s^{-1} Mpc^{-1}, where Ω_M is the matter density parameter and Ω_Λ is the dark energy density parameter) [?].

Sample Construction and Fermi-LAT Data Analysis

Candidate Selection

Because the effective area of Fermi-LAT decreases rapidly above 500 GeV, we only select known sources with redshifts greater than 0.5.

Fermi-LAT Data Processing

We collected PASS 8 data from the first 16 years of Fermi-LAT operation (August 4, 2008, to August 4, 2024) in the direction of the candidates. We utilized the latest version of the software (Fermitools 2.2.0) to perform a comprehensive data analysis to search for horizon photons. The energy range for the analysis is 1 GeV to 1 TeV. We used the ULTRACLEANVETO data class (photon event class `evclass = 1024`, event type `evtype = 3`). First, data filtering was performed: on one hand, we considered contamination from Earth' s atmospheric gamma-ray radiation (setting the maximum zenith angle to $z_{\rm max} = 105^\circ$); on the other hand, we excluded poor-quality data (data quality `DATAQUAL > 0`, telescope configuration `LATCONFIG = 1`). We then used the Unbinned likelihood analysis method in the `gtlike` tool to fit the data and extract the gamma-ray observational information for the target sources. In the likelihood analysis, a Region of Interest (ROI) with a radius of 5° centered on each target source' s position was considered.

The parameters for all gamma-ray sources within this region [?], as well as the normalization parameters for the Galactic diffuse background (`gll_{iem}v07.fits`) and the isotropic extragalactic diffuse gamma-ray background (`iso_P8R3_{ULTRACLEANVETO}V3_v1.txt`), were left free during the fit. Parameters for background gamma-ray sources outside the ROI were kept fixed at their default values.

For blazars confirmed to have horizon photons, we further conducted time-domain gamma-ray data analysis. To ensure sufficient statistics, we used the SOURCE data class (`evclass = 128`, `evtype = 3`), with the corresponding extragalactic gamma-ray template `iso_P8R3_{SOURCE}V3_v1.txt`. Meanwhile, the energy range for this data was 0.1 GeV to 1 TeV. Because the spatial resolution of Fermi-LAT for sub-GeV photons is poorer than for GeV photons, we set $z_{\rm max} = 90^\circ$ and the ROI radius to 10° in the likelihood analysis.

In the time-domain analysis, background sources with weak detection significance were removed from the model file to maintain fit convergence. When the detection significance of the target source was low, a flux upper limit at the 95% confidence level was provided.

Based on the latest Fermi-LAT gamma-ray source catalog (Fermi Large Area Telescope Fourth Source Catalog Data Release 4, 4FGL-DR4 [?]), we carried out a search for EBL horizon gamma-ray photons. First, we excluded gamma-ray sources at low Galactic latitudes ($|b| < 10^\circ$), as the diffuse gamma-ray background in this region is much higher and more dominant than at high Galactic latitudes. Additionally, the Galactic plane is affected by internal Galactic sources, resulting in a higher density of gamma-ray sources that complicates data processing. Second, even at high Galactic latitudes, there are numerous gamma-ray pulsars, and many gamma-ray sources have unclear low-energy counterparts (e.g., no counterpart or multiple counterparts). Therefore, we only considered gamma-ray sources whose low-energy counterparts are clearly identified as AGN. Given the difficulty of detecting horizon photons, sources with low detection significance (Test Statistic $TS < 200$) were not considered in this study. Here, $TS = -2\Delta \ln(\zeta_0/\zeta)$ (where ζ_0 is the maximum likelihood value for the null hypothesis of no source, and ζ is the maximum likelihood value for the alternative hypothesis of a source), defined as the log-likelihood ratio between different models (with or without the target source) in the gamma-ray data analysis [?]. At the same time, we only considered sources with no analysis warnings (`data flag = 0`). Finally,

Determining the redshift information of blazars is crucial for searching for horizon gamma-ray photons. Although the redshifts of FSRQs with prominent emission lines are

easy to detect, their gamma-ray spectra are generally softer than those of BL Lac objects, making it more difficult for them to produce VHE gamma-ray photons [?]. In fact, detecting the redshifts of BL Lac objects is a well-known challenge, especially for HSP sources [?]. For sources at lower redshifts (e.g., $z < 0.5$), searching for the radiation signatures of the host galaxy in optical-to-near-infrared spectra and images is an effective method for constraining the redshift.

A more direct method requires large-aperture optical telescopes (5–8 m class) to perform high-signal-to-noise, high-dispersion spectroscopic observations. This allows for direct redshift measurement using potential weak intrinsic emission lines, while the detection of possible foreground absorption lines can provide a reliable lower limit for the redshift.

Admittedly, broadband photometric observations can provide redshift constraints for large numbers of objects, but for individual sources, the accuracy of photometric redshifts is usually insufficient.

Concurrent with Fermi-LAT gamma-ray sky surveys, follow-up optical spectroscopic observations have been ongoing [?], primarily targeting gamma-ray sources without redshift or spectral classification information, also known as blazar candidates of uncertain type (BCUs). As the Cherenkov Telescope Array (CTA) is set to begin operation, optical spectroscopic observations of HSP BL Lac objects are continuing [?]. Using archival data, we have carefully screened the redshifts of our candidates. This study considers sources with spectroscopic redshifts and excludes those with only photometric redshifts. Most of these redshift measurements come from the identification of dual absorption/emission lines. A few sources with only a single absorption/emission line are included in the sample but are given a special identifier. BL Lac objects for which only a purely smooth power-law spectrum was detected were also excluded.

结果

Detection of Horizon Photons

We conducted a systematic analysis of Fermi-LAT data for 448 sources using the ULTRACLEANVETO event class. Among the various Pass 8 data subselections, this class possesses the lowest cosmic-ray background contamination, thereby effectively mitigating the risk of detected gamma rays being misidentified background events.

The data analysis yielded source model files capable of describing the observed data. Based on these files and utilizing the `gtsrcprob` tool, we calculated the association probability of each photon event with its respective target object. During the selection process for horizon photons, we only retained photons with an association probability exceeding 90%. An additional selection criterion was the detected energy of the photon, which was required to be higher than the energy corresponding to an extragalactic background light (EBL) absorption optical depth of $\tau_{\gamma\gamma} = 1$ at the target source' s redshift. In this study, we considered several mainstream EBL models, specifically those by Finke et al. [?], Domínguez et al. [?], and Gilmore et al. [?]. Since the model by Domínguez et al. [?] is relatively the most optically thin, photons satisfying the condition of an EBL absorption optical depth greater than 1 in this model clearly meet the definition of horizon photons. To remain conservative, we also include photons in this paper that satisfy the conditions of the moderately optically thin model by Finke et al. [?].

Prior to finalizing the sample, we performed an independent secondary redshift verification for each source. During this inspection, we discovered that the SDSS redshift measurements for several sources were derived from automated batch processing scripts and were unreliable; consequently, these sources were excluded from the results of this study.

This paper presents 46 photons, whose origins, energies, arrival times, and association probabilities with their corresponding blazars are listed. Among them, 20 photons satisfy the most stringent criteria, meaning they fulfill the condition $\tau_{\gamma\gamma} \gtrsim 1$ even under the most optically thin EBL model [?]. The energy range of these photons spans from approximately 40 GeV to 364 GeV. The 40 GeV photon originated from a Flat Spectrum Radio Quasar (FSRQ) at a redshift as high as 2.944. In fact, high-redshift blazars are extremely faint; among the thousands of known extragalactic gamma-ray blazars, there are currently no more than 20 sources with a redshift greater than 3. Interestingly, we also identified two horizon photons from a blazar at a redshift of 2.86, with energies of 76 GeV and 43 GeV, respectively. The horizon photon detection data analyzed in this study covers the period from the early stages of the Fermi-LAT mission (Mission Elapsed Time, MET: 239991691, or 2008-08-09) to the recent past (MET: 722539649, or 2023-11-24). A total of six horizon photons were discovered after the publication of the 4LAC-DR3 [?] catalog. Because the angular resolution of Fermi-LAT reaches its optimum at energies above 10 GeV, the (identification) probabilities for the detected photons are generally high. Of the 46 photons, only two have an association probability lower than 95%.

Based on the redshift information in 4LAC-DR3 [?] and the selection criteria described above, we screened 400 gamma-ray blazars as candidates. Furthermore, an additional 48 sources were added to the analysis using redshift information provided by the NASA/IPAC Extragalactic Database (NED). For the small number of sources where the 4LAC-DR3 redshift information was inconsistent with the NED data, we performed a careful identification to determine their true redshift values. Next, we performed···

NED: https://ned.ipac.caltech.edu/

Detection of Fermi-LAT Blazars Located at the Gamma-ray Horizon of Extragalactic Background Light Absorption

Abstract

The Extragalactic Background Light (EBL) is the diffuse radiation field produced by all stars and galaxies throughout the history of the universe. High-energy gamma-ray photons emitted by distant sources are absorbed through pair production ($\gamma\gamma \rightarrow e^+e^-$) as they interact with EBL photons during propagation. This absorption effect is energy-dependent and distance-dependent, defining a "Gamma-ray Horizon" where the optical depth $\tau = 1$. In this study, we utilize the latest Fermi-LAT catalogs and EBL models to identify and analyze blazars located near this horizon. By examining the spectral softening of these sources, we provide constraints on EBL density and discuss the implications for galaxy evolution and cosmology.

1. Introduction

Extragalactic Background Light (EBL) represents the integrated emission from all extragalactic sources across the electromagnetic spectrum, primarily spanning from ultraviolet to far-infrared wavelengths. It serves as a fundamental repository of the universe' s star formation history and galaxy evolution. However, direct measurement of the EBL is challenging due to intense foreground contamination from zodiacal light and Galactic emission.

An alternative method to probe the EBL is through the observation of high-energy gamma-rays from extragalactic sources, such as blazars. When gamma-ray photons with energy E_γ travel through intergalactic space, they can interact with EBL photons of energy ϵ to produce electron-positron pairs. This process occurs when the center-of-mass energy exceeds the threshold:

$$\epsilon \geq \frac{2m_e^2c^4}{E_\gamma(1-\cos\theta)}$$

where m_e is the electron mass and θ is the interaction angle. This interaction leads to an exponential attenuation of the observed gamma-ray flux:

$$F_{obs}(E) = F_{int}(E) \cdot e^{-\tau(E,z)}$$

where F_{int} is the intrinsic spectrum and $\tau(E, z)$ is the optical depth, which depends on the gamma-ray energy and the redshift z of the source.

The "Gamma-ray Horizon" is defined as the contour in the energy-redshift plane where the optical depth $ (

Gamma-ray Source

Arrival Time (MET)

Photon Energy/GeV

gtsrcprob Probability

EBL Model

Finke et al.[8]

Finke et al.[8]

Finke et al.[8]

Domínguez et al.[9]

Finke et al.[8]

Domínguez et al.[9]

Domínguez et al.[9]

4FGL J0043.8+3425

Finke et al.[8]

4FGL J0050.7-0929

Domínguez et al.[9]

4FGL J0108.6+0134

Finke et al.[8]

4FGL J0120.4-2701

Finke et al.[8]

4FGL J0237.8+2848

Finke et al.[8]

4FGL J0238.6+1637

Domínguez et al.[9]

4FGL J0334.2-4008

Finke et al.[8]

4FGL J0349.8-2103

Finke et al.[8]

Domínguez et al.[9]

Domínguez et al.[9]

Finke et al.[8]

Finke et al.[8]

Finke et al.[8]

4FGL J0538.8-4405

Domínguez et al.[9]

4FGL J0630.9-2406

Finke et al.[8]

4FGL J0808.2-0751

Domínguez et al.[9]

4FGL J0811.4+0146

Domínguez et al.[9]

4FGL J0909.7-0230

Domínguez et al.[9]

4FGL J0957.6+5523

Domínguez et al.[9]

4FGL J1107.6+0222

Finke et al.[8]

4FGL J1159.5+2914

Finke et al.[8]

4FGL J1253.8+6242

Domínguez et al.[9]

4FGL J1303.0+2434

Domínguez et al.[9]

4FGL J0008.0+4711

4FGL J0022.5+0608

4FGL J0033.5-1921

4FGL J0428.6-3756 4FGL J0433.6+2905 4FGL J0457.0-2324

Gamma-ray Source

Arrival Time (MET)

Photon Energy/GeV

gtsrcprob Probability

EBL Model

4FGL J1310.5+3221

Finke et al.[8]

Finke et al.[8]

Finke et al.[8]

Finke et al.[8]

Finke et al.[8]

Finke et al.[8]

Finke et al.[8]

Domínguez et al.[9]

Domínguez et al.[9]

4FGL J1427.9-4206

Finke et al.[8]

4FGL J1722.7+1014

Domínguez et al.[9]

4FGL J1748.6+7005

Domínguez et al.[9]

4FGL J1918.2-4111

Domínguez et al.[9]

4FGL J2147.3-7536

Domínguez et al.[9]

4FGL J2232.6+1143

Finke et al.[8]

4FGL J2253.9+1609

Domínguez et al.[9]

4FGL J1316.1-3338

4FGL J1345.5+4453 4FGL J1419.5+3821

-ray photon Energy/GeV

4FGL J1427.0+2348

4FGL J0008.0+4711 and 4FGL J1427.0+2348 are the only two sources capable of contributing three cosmic horizon photons, while the remaining six sources each contribute two. Given the significant impact of Extragalactic Background Light (EBL) absorption, this low detection rate of horizon photons is fundamentally consistent with our theoretical expectations. Furthermore, the arrival times of different horizon photons originating from the same source exhibit substantial variance; the time intervals between detections range from as short as several months to as long as a decade. This temporal distribution suggests that the production of horizon photons may be closely linked to gamma-ray flares occurring during different activity periods of the blazars.

Model C of Finke et al.[8] Dominguez et al.[9] Fiducial model of Gilmore et al.[35] BL Lac

Redshift

Characteristics of Radiative Horizon Photon Blazars

Utilizing information on gamma-ray sources and their low-energy counterparts provided by the 4LAC-DR3 [**?**], we conducted an investigation into the characteristics of radiative horizon photon blazars. Blazars are traditionally classified into Flat Spectrum Radio Quasars (FSRQs) and BL Lacertae objects (BL Lacs) based on whether significant emission lines are observed. From a physical perspective, it is generally believed that this classification stems from differences in the accretion efficiency of the central black holes in these two types of objects.

However, some studies suggest that selection effects may be the primary cause; specifically, the dominant jet radiation may dilute the broad emission line radiation, thereby leading to···

1 Detected horizon photon and their comparison with EBL models

These 46 photons originate from 36 blazars; in most cases, each source contributes only a single photon. However, 8 blazars are capable of contributing multiple horizon photons individually, as shown in . Notably,

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Abstract

The Extragalactic Background Light (EBL) is the diffuse radiation field that fills the universe, primarily originating from the integrated light of all stars and galaxies throughout cosmic history. High-energy gamma-ray photons emitted by distant extragalactic sources, such as blazars, undergo pair production ($\gamma\gamma \rightarrow e^+e^-$) through interactions with EBL photons, leading to energy-dependent attenuation of the observed spectra. The "gamma-ray horizon" is defined as the distance (or redshift z) at which the optical depth $\tau(E, z)$ for a gamma-ray of energy E reaches unity. In this study, we utilize the latest Fermi Large Area Telescope (Fermi-LAT) catalogs and long-term observational data to identify and analyze blazars located near or beyond this horizon. By examining the spectral softening and cutoff features in these sources, we provide constraints on current EBL models and explore the implications for the evolution of the cosmic radiation field. Our results demonstrate that the detection of high-redshift blazars in the GeV range remains a critical tool for probing the transparency of the universe and the history of star formation.

1. Introduction

Blazars, a subclass of active galactic nuclei (AGN) with relativistic jets pointed nearly directly toward Earth, are the most numerous sources in the high-energy gamma-ray sky. Their emission spans the entire electromagnetic spectrum, from radio to very-high-energy (VHE) gamma rays. For distant blazars, the interaction between gamma-ray photons and the Extragalactic Background Light (EBL) becomes a significant factor in spectral analysis. The EBL consists of photons produced by star formation (ultraviolet to optical) and the subsequent re-radiation by dust (infrared).

As gamma-ray photons travel through intergalactic space, they may interact with EBL photons to produce electron-positron pairs. This process, known as EBL absorption, effectively "dims" the high-energy signal from distant sources. The probability of this interaction is quantified by the optical depth $\tau(E, z)$, which depends on both the photon energy E and the source redshift z. The gamma-ray horizon is the contour in the $E - z$ plane where $\tau = 1$, representing the boundary beyond which the

FSRQs also exhibit phenomena where their emission lines cannot be detected [**?**]. Efficient accretion triggers bright radiation from the accretion system, with a corresponding spectral range covering infrared to ultraviolet wavelengths. This implies that gamma-ray photons from blazars must not only escape absorption by the extragalactic background light (EBL) but also overcome absorption by the intrinsic radiation within the active galactic nucleus (AGN). Consequently, it should, in principle, be more difficult to detect horizon photons from FSRQs. However, in our final sample of blazars with detected cosmic horizon photons, the number of BL Lacs and FSRQs is identical, with 18 sources each. This distribution is consistent with the ratio of these two classes in the parent 4LAC-DR3 sample [**?**].

Beyond BL Lacs and FSRQs, radio-loud narrow-line Seyfert 1 (RLNLS1) galaxies also possess powerful relativistic jets directed toward Earth and exhibit significant gamma-ray emission; however, our sample does not include any sources of this type. This absence is likely due to the current rarity of such sources. In fact, very-high-energy (VHE) radiation from RLNLS1s has not yet been detected, and most of these sources have redshifts less than 1 due to the difficulties associated with infrared spectral line identification. Additionally, it is worth noting that the source 4C+55.17 in our sample is considered a potential young radio source due to its relatively compact large-scale radio structure and stable gamma-ray emission, although a blazar origin model has not been entirely ruled out [?].

In addition to optical classification, blazars can be categorized based on the peak frequency of their synchrotron emission. There appears to be a positive correlation between the peak frequencies of the two components in a blazar' s spectral energy distribution (SED). Consequently, a higher synchrotron peak frequency generally corresponds to a higher inverse Compton (high-energy) peak frequency. This leads to the observational result that the high-energy peak frequencies of High-synchrotron-peaked (HSP) blazars are typically higher than those of Low-synchrotron-peaked (LSP) blazars, and their gamma-ray spectra are correspondingly harder [?]. While the majority of Flat Spectrum Radio Quasars (FSRQs) are classified as LSP, BL Lacertae objects exhibit a much broader distribution of synchrotron peak frequencies, spanning multiple categories including LSP, Intermediate-synchrotron-peaked (ISP), and HSP types.

The position of the synchrotron peak frequency is generally considered to be anti-correlated with the source' s radiant power, a phenomenon known as the "blazar sequence" [?]. The primary characteristic of this sequence is that the luminosity of High-synchrotron-peaked (HSP) BL Lacs is significantly lower than that of Low-synchrotron-peaked (LSP) Flat Spectrum Radio Quasars (FSRQs). However, whether the "blazar sequence" reflects an underlying physical reality or is merely a result of selection effects remains a subject of considerable debate [?].

Analyzing these blazars with horizon photon radiation from the perspective of spectral energy distribution (SED) classification, we find that the majority of sources in our sample are LSPs. Out of the 36 sources, only 3 are HSPs and 4 are Intermediate-synchrotron-peaked (ISPs). This distribution is not unexpected; as previously mentioned, half of the sources in the sample are FSRQs. However, even if we consider only the BL Lacs within the sample, there are 11 LSPs, accounting for more than half of the sub-sample. While the current number of sources remains quite limited and statistical fluctuations may significantly affect our inferences regarding the true distribution, another possible explanation is the cosmological evolution of BL Lacs.

This phenomenon may be attributed to evolution effects, as High-synchrotron-peaked (HSP) BL Lac objects exhibit significant negative evolution, characterized by a rapid decline in number density at redshifts greater than 0.5 [?]. Notably, the sample used in this study exclusively contains sources with redshifts exceeding 0.5. Despite this, we identified one HSP BL Lac, 4FGL J0630.9-2406, which possesses a high lower-limit redshift of 1.238; this discovery is of particular significance for understanding the distribution of these objects.

The relationship between the γ-ray power-law spectral index Γ and the energy flux for the blazars in our sample is shown in [Figure 2: see original paper], where the energy flux is integrated over the range of 0.1–100 GeV. Blazars exhibiting horizon photons are clearly concentrated at the high-flux end of the entire 4LAC-DR3 [**?**] blazar population, with most sources having a brightness exceeding 10^{-11} erg$\cdot$cm$^{-2}\cdot$s^{-1}. This is consistent with physical expectations, as horizon photons can only be detected when there is sufficient photon statistics. Indeed, we successfully detected horizon photons in several of the brightest Flat Spectrum Radio Quasars (FSRQs), such as CTA 102 and 3C 454.3.

The γ-ray spectral indices of the blazars in our sample are distributed roughly between 1.8 and 2.5. Notably, while a significant portion of FSRQs in the 4LAC-DR3 [**?**] catalog possess spectral indices greater than 2.5, we did not detect horizon photons in these specific sources. One possible explanation is that these soft-spectrum FSRQs may experience strong intrinsic γ-ray absorption, where the soft photons originate from the Broad Line Region (BLR) or coronal radiation in the inner regions of the accretion disk. Furthermore, our sample does not include any BL Lac objects with extremely hard γ-ray spectra ($\Gamma \simeq 1.5$).

These sources typically belong to the HSP BL Lac category. As previously discussed, such sources are predominantly local (with redshifts less than 0.5); consequently, they were not included within the redshift selection criteria of this study.

Energy Flux/(erg • cm−2 • s−1)

4LAC-DR3 BL Lac 4LAC-DR3 FSRQ BL Lac

10−10

10−11

10−12

Powerlaw index

Comparison of 4LAC-DR3 [26] blazars. [Figure 2: see original paper] Distributions between the energy flux and the γ-ray spectral index of the blazars that emit horizon photons, with the entire 4LAC-DR3 [26] blazar population plotted as the background.

Time-domain correlation between γ-ray flux variations and the arrival of horizon photons in blazars.

As shown in , among the 36 sources, only two did not exhibit significant optical variability. One of these, NVSS J110735+022225, is relatively faint, and limited statistical data may have affected the detection of its variability. Given that the vast majority of the sources exhibit significant long-term γ-ray variability, we conducted a detailed γ-ray time-domain analysis of these 34 sources to investigate the potential correlation between γ-ray flux levels and the detection of horizon photons in blazars.

Variability is one of the characteristic observational features of blazars, and their γ-ray flux typically exhibits significant fluctuations over time.

The Fermi γ-ray source catalog provides the annual average light curves for each source [?]. Using the variability index (VI [?]) method, it is possible to determine whether the variability of each source is statistically significant (at a 99% confidence level, or $VI > 28$). We have listed the logarithmic variability index values for each source.

4FGL name

Low-energy counterpart Energy Flux PL index lg (VI) Spectral type SED type

4FGL J0008.0+4711

MG4 J000800+4712

1.87 $\times 10-11$

BL Lac

1.659[41]

4FGL J0022.5+0608

PKS 0019+058

2.23 $\times 10-11$

BL Lac

2.86[42]

4FGL J0033.5-1921

KUV 00311-1938

2.89 $\times 10-11$

BL Lac

0.505[43]

4FGL J0043.8+3425

GB6 J0043+3426

2.47 $\times 10-11$

0.966[31]

4FGL J0050.7-0929

PKS 0048-09

3.65 $\times 10^{-11}$

BL Lac

0.635[44]

4FGL J0108.6+0134

4C +01.02

1.14 $\times 10^{-10}$

2.1[45]

4FGL J0120.4-2701

PKS 0118-272

3.39 $\times 10^{-11}$

BL Lac

0.558[46]

4FGL J0237.8+2848

4C +28.07

1.23 $\times 10^{-10}$

1.206[31]

4FGL J0238.6+1637

PKS 0235+164

9.17 $\times 10^{-11}$

BL Lac

0.94[47]

4FGL J0334.2-4008

PKS 0332-403

3.08 $\times 10^{-11}$

BL Lac

1.357[32]

4FGL J0349.8-2103

PKS 0347-211

1.30 $\times 10^{-11}$

2.944[48]

4FGL J0428.6-3756

PKS 0426-380

1.92 ×10−10

BL Lac

1.11[49]

4FGL J0433.6+2905

MG2 J043337+2905

2.60 ×10−11

BL Lac

0.91[50]

4FGL J0457.0-2324

PKS 0454-234

1.81 ×10−10

1.003[51]

4FGL J0538.8-4405

PKS 0537-441

1.57 ×10−10

BL Lac

0.894[52]

4FGL J0630.9-2406

TXS 0628-240

4.81 ×10−11

BL Lac

1.238[53]

4FGL J0808.2-0751

PKS 0805-07

5.93 ×10−11

1.837[54]

4FGL J0811.4+0146

OJ 014

3.39 ×10−11

BL Lac

1.148[55]

4FGL J0909.7-0230

PKS 0907-023

2.12 ×10−11

0.957[56]

4FGL J0957.6+5523

4C +55.17

9.05 ×10−11

0.9[45]

4FGL J1107.6+0222 NVSS J110735+022225

5.71 ×10−12

BL Lac

1.074[34]

4FGL J1159.5+2914

1.05 ×10−10

0.725[45]

4FGL J1253.8+6242 NVSS J125359+624257

4.58 ×10−12

BL Lac

0.867[32]

4FGL J1303.0+2434

1.61 ×10−11

BL Lac

0.993*[57]

Ton 599

MG2 J130304+2434

Detection of Fermi-LAT Blazars Located at the Gamma-ray Horizon of Extragalactic Background Light Absorption

Abstract

The Extragalactic Background Light (EBL) is the diffuse radiation field that fills the universe, primarily originating from the integrated light of all galaxies throughout cosmic history. High-energy gamma rays emitted by distant sources, such as blazars, undergo pair production ($\gamma\gamma \to e^+e^-$) through interactions with EBL photons, leading to energy-dependent attenuation of the observed spectra. The "gamma-ray horizon" is defined as the redshift-dependent energy at which the optical depth τ reaches unity. In this study, we utilize data from the Fermi Large Area Telescope (Fermi-LAT) to investigate a sample of blazars located near this horizon. By analyzing the spectral properties and redshift distribution of these sources, we aim to provide constraints on current EBL models and explore the transparency of the universe to high-energy radiation. Our results demonstrate that the detected population of Fermi-LAT blazars is consistent with standard EBL evolution models, though individual outliers may suggest the need for further refinement of local EBL density estimates or the consideration of exotic physics such as axion-like particles.

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1. Introduction

Blazars are a subclass of active galactic nuclei (AGN) characterized by relativistic jets pointed nearly directly toward the observer. They are the most numerous sources in the high-energy gamma-ray sky and serve as ideal probes for studying the Extragalactic Background Light (EBL). The EBL consists of photons produced by stars and galaxies since the epoch of recombination, as well as radiation from the accretion processes of black holes. Because direct measurements of the EBL are challenging due to intense foreground contamination from zodiacal light and Galactic emission, indirect methods using gamma-ray observations have become a primary tool for EBL research.

When high-energy gamma rays propagate through intergalactic space, they interact with low-energy EBL photons. This interaction results in the production of electron-positron pairs, effectively removing gamma rays from the primary beam. The probability of this interaction is quantified by the optical depth $\tau(E, z)$, which depends on both the energy of the gamma ray E and the redshift of the source z. The gamma-ray horizon is defined as the contour in the $E - z$ plane where $\tau(E, z) = 1$. Sources observed beyond

4FGL name

Low-energy counterpart Energy Flux PL index lg (VI) Spectral type SED type

4FGL J1310.5+3221

OP 313

3.58 ×10

0.996[45]

4FGL J1316.1-3338

PKS 1313-333

2.32 ×10−11

1.21[58]

4FGL J1345.5+4453

B3 1343+451

9.32 ×10−11

2.542[31]

4FGL J1419.5+3821

B3 1417+385

5.83 ×10−12

1.832[45]

4FGL J1427.0+2348

PKS 1424+240

1.15 ×10−10

BL Lac

0.604[59]

4FGL J1427.9-4206

PKS 1424-41

3.48 ×10−10

1.522[54]

4FGL J1722.7+1014

TXS 1720+102

1.24 ×10−11

0.732[60]

4FGL J1748.6+7005

S4 1749+70

4.52 ×10−11

BL Lac

0.77[61]

4FGL J1918.2-4111

PMN J1918-4111

2.46 ×10−11

BL Lac

1.591[32]

4FGL J2147.3-7536

PKS 2142-75

4.58 ×10−11

1.139[62]

4FGL J2232.6+1143

CTA 102

4.19 ×10−10

1.037 [45]

4FGL J2253.9+1609

3C 454.3

8.44 ×10−10

0.859[45]

Note: when the redshift value is marked with an asterisk, it indicates that the redshift measurement is based on a single emission line/absorption line. Energy Flux is in unit of erg · cm−2 · s−1, with the integration range from 0.1 to 500 GeV. lg (VI)>1.4 indicates significant variability, where VI stands for variability index.

We found that in some sources, the arrival of horizon photons is temporally correlated with the most intense gamma-ray flares observed over the past decade. For example, in early 2017, the well-known blazar CTA 102 exhibited a violent multi-wavelength outburst [?], during which the gamma-ray flux varied by approximately three orders of magnitude. A photon with an energy of 98 GeV was detected during this high-flux state. Another example is the blazar OP 313; although this source had remained in a relatively quiescent state for more than ten years, it recently exhibited significant gamma-ray activity for the first time, with a flux variability exceeding two orders of magnitude. A 103 GeV photon was detected precisely when the gamma-ray flux reached its peak, as shown in [Figure 3: see original paper]. The increase in statistical significance brought about by such flux enhancements naturally amplifies the probability of detecting horizon photons.

More importantly, blazar gamma-ray emission typically exhibits a "bluer-when-brighter" observational behavior. This phenomenon may stem from the injection of a large number of fresh, high-energy particles, which makes horizon photons easier to detect. However, it is noteworthy that for many sources, the detection of horizon photons is not directly correlated with gamma-ray flux levels. Notable examples include the famous blazar 3C 454.3 and the high-redshift blazar PKS 0347-211, as shown in [Figure 4: see original paper]. These photons were not detected during the strongest flaring periods of these blazars; instead, they were captured during the quiescent phases between flares.

Given the limited sample size and the complex underlying causes of optical variability, this paper does not explore the generation mechanisms of horizon photons in depth. Future research may further investigate these mechanisms by expanding the sample size and conducting comprehensive multi-wavelength observations.

讨论

Constraints on the Location of Gamma-ray Emission Regions in FSRQs

The location of the gamma-ray emission region in blazars remains one of the core unresolved issues in the field of Active Galactic Nucleus (AGN) jets. This uncertainty severely constrains our understanding of jet evolution, relativistic particle acceleration, and radiation processes. Given the rapid gamma-ray variability observed in blazars [?], the emission region is expected to be highly compact. Under the assumption of a conical jet geometry, such a compact region should be located relatively close to the central supermassive black hole. Theoretical calculations suggest that when the emission region is situated between the Broad Line Region (BLR) and the dust torus (approximately $0.01-1$ pc from the black hole), the models can effectively explain the multi-wavelength broadband spectral energy distribution of blazars [?]. However, radio observations present a different perspective. By monitoring radio dynamics to determine the ejection time of jet knots and using radio imaging to observe the source, researchers have challenged these proximity models.

By determining the size of the optically thick region of the radio core (i.e., where the synchrotron self-absorption optical depth equals 1) and combining this with measurements of the time delay between gamma-ray and radio light curves, the location of the emission region can be inferred. Results obtained through this method tend to suggest that the emission region is located several parsecs away from the black hole. In extreme cases, such as when gamma-ray variability lags behind the radio light curve, this distance can reach several tens of parsecs [?]. For Flat Spectrum Radio Quasars (FSRQs), there is a lack of dense and intense external photon fields at such great distances from the black hole, making it theoretically difficult to produce high-luminosity gamma-ray emission (measured in units of 10^{-8} ph $\cdot$ cm^{-2} $\cdot$ s^{-1} between 0.1 and 500 GeV, as seen in sources like CTA 102, $z = 1.04$).

Arrival of a

97.9 GeV photon

-ray flux

MJD/day Arrival of a

102.81 GeV

photon

TS Value

in unit of 10—8 ph • cm—2 • s—1 between 0.1 and 500 GeV

60 OP 313, z=0.996

-ray flux

The photon fields within blazars are diverse, originating from both the synchrotron radiation of the jet itself and external structures such as the accretion disk corona, the broad-line region (BLR), and the dust torus. Generally, the frequency and density of the photon fields from the external accretion system decrease as the distance from the black hole increases. Searching for the imprints of corresponding absorption processes in the gamma-ray spectra of blazars can provide direct observational support for these models. Notably, the spectral breaks observed in the GeV energy range of blazars are highly consistent with the absorption features expected from BLR photons [?].

At the same time, some studies suggest that the GeV spectral cutoff in the blazar 3C 454.3 may originate from the absorption of soft X-ray photons in the coronal region [?]. The detection of horizon photons from blazars can effectively constrain the location of their emission regions. Considering that gamma-ray photons have already undergone significant absorption by the extragalactic background light (EBL), if their intrinsic absorption were also substantial, the absorption-corrected intrinsic luminosity would be overestimated, thereby deviating from theoretical expectations.

We have identified more than ten horizon photons originating from Flat Spectrum Radio Quasars (FSRQs). This suggests that, at least during certain periods for a subset of FSRQs, the emission region must be located outside the broad-line region, where intrinsic absorption effects are relatively weak. Furthermore, we found that the arrival times of horizon photons from some blazars are associated with intense gamma-ray flares. Research has indicated that shifts in the location of the emission region—for example, moving from inside to outside the BLR—can explain the multi-wavelength flaring phenomena observed in blazars [?]. An outer emission region corresponds to weaker soft-photon absorption, which facilitates the detection of horizon photons; this is entirely consistent with our research findings.

TS Value

Observations with Next-Generation Space-Based and Ground-Based Gamma-Ray Telescopes

Gamma rays represent the highest energy band of electromagnetic radiation and are inherently linked to fundamental non-thermal physical processes, such as the acceleration, propagation, and radiation of ultra-high-energy cosmic rays. While the Fermi-LAT telescope has been successfully conducting observations for nearly 17 years, the development of next-generation space-based gamma-ray telescopes is currently in full swing. One strategic approach focuses on the low-to-medium energy gamma-ray band, specifically $0.1 - 100$ MeV. A representative example of this direction is NASA' s AMEGO-X project (All-sky Medium-Energy Gamma-ray Observatory eXplorer [?]). Observations in the low-to-medium energy range can provide a wealth of astrophysical information; however, detecting and analyzing radiation in this band remains a significant challenge due to the diversity of radiation mechanisms and the complexity of its origins. To address these challenges, a research team led by the Purple Mountain Observatory of the Chinese Academy of Sciences has proposed the Very Large Area gamma-ray Space Telescope (VLAST [?]) project. Given that VLAST operates within the GeV–TeV energy range···

MJD/day

Taking the blazars CTA 102 (upper) and OP 313 (lower) as examples, [FIGURE:N] illustrates their multi-wavelength characteristics. In the light curves, the circular points represent flux data points, while the triangles denote flux upper limits. The accompanying histograms display the corresponding Test Statistic (TS) values. Notably, the detections of horizon photons temporally coincide with the strongest γ-ray flares for several blazars, as clearly demonstrated in the cases of CTA 102 and OP 313.

In the -ray light curves, circles and triangles correspond to flux measurement and upper limits, along with TS values displayed as bars.

Gamma-ray photons undergo dual absorption during their propagation: first, the ubiquitous absorption by Extragalactic Background Light (EBL), and second, the intrinsic absorption within the source itself. The low-energy photons responsible for this intrinsic absorption originate from···

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···the development of the gamma-ray astronomy field [?]. The Cherenkov Telescope Array (CTA) [?] is the next-generation Cherenkov gamma-ray telescope currently under construction. Triggered by observations from Fermi-LAT, the Large-Sized Telescope (LST)—part of the initial CTA construction—detected very-high-energy (VHE) gamma-ray radiation from the quasar OP 313 (at a redshift of $z = 0.996$), making it one of the most distant VHE gamma-ray sources known to date [?]. The detection significance in the 100–250 GeV energy range reached 8.7σ, and Fermi-LAT detected a photon with an energy of 103 GeV during a high-flux state, as shown in [Figure 3: see original paper]. Leveraging the massive effective collection area of next-generation ground-based gamma-ray telescopes, combined with the survey capabilities of space-based gamma-ray telescopes and multi-wavelength follow-up observations, we will be able to precisely characterize the multi-band variability of blazars during outbursts. This will allow for the effective capture of "horizon photons," deepening our understanding of the location of jet energy dissipation zones and related physical processes, while providing new observational constraints on EBL models.

Arrival of a 143.4 GeV photon

TS value

-ray flux

in unit of 10−8 ph · cm−2 · s−1 between 0.1 and 500 GeV 3C 454.3, z=0.859

MJD/day Arrival of a

39.6 GeV

photon

TS Value

in unit of 10−8 ph · cm−2 · s−1 between 0.1 and 500 GeV PKS 0347-211, z=2.944

MJD/day

总结

Systematic Search for Gamma-Ray Horizon Photons from Blazars

In this study, we conducted a systematic search for gamma-ray photons originating from the cosmic gamma-ray horizon, characterized by significant absorption by the Extragalactic Background Light (EBL). We initially selected 448 gamma-ray sources from the 4FGL-DR4 catalog for comprehensive Fermi-LAT data analysis, applying rigorous screening criteria based on Galactic latitude, detection significance, and data reliability. Furthermore, we meticulously verified the redshifts for each of these sources.

By comparing our observations with leading EBL models, such as those proposed by Finke et al. [?], we identified 46 gamma-ray photon events with an EBL absorption optical depth (τ) greater than 1. Even when considering the most optically thin EBL model [?], 20 such photon events remain. These 46 photons originate from 36 distinct blazars, consisting of an equal distribution of BL Lac objects and Flat Spectrum Radio Quasars (FSRQs). Notably, no horizon photons were detected from radio galaxies or radio-loud narrow-line Seyfert 1 galaxies. Our analysis suggests that the detection of horizon photons does not exhibit a significant correlation with the accretion efficiency of the supermassive black hole at the center of the Active Galactic Nucleus (AGN).

Although FSRQs are often expected to exhibit intrinsic gamma-ray absorption, the detection of a significant population of horizon photons from these sources suggests that, at least during certain periods, their gamma-ray emission regions must be located outside the Broad Line Region (BLR). This positioning allows the high-energy radiation to escape significant internal absorption. We further performed a temporal analysis of the blazars in our sample and found that while the arrival of horizon photons coincides with the peak flare state in some sources, it is also common for there to be no observable correlation between flux levels and the detection of horizon photons.

The sample provided by this research, particularly those sources with multiple horizon photons or high redshifts, identifies critical observational targets for next-generation space-based and ground-based gamma-ray telescopes. These findings offer a valuable foundation for future studies of EBL evolution and the intrinsic physics of high-energy emission in blazars.

-ray flux

The Very Large Area Gamma-ray Space Telescope (VLAST) possesses excellent acceptance, with its comprehensive detection capability expected to improve by an order of magnitude compared to Fermi-LAT. To verify key technologies and conduct scientific observations of solar gamma rays, the VLAST pathfinder mission is scheduled for launch in 2026. Given that Fermi-LAT has already detected horizon photons from blazars at redshifts around 3—such as PKS 0019+058 ($z = 2.86$) and PKS 0347−211 ($z = 2.944$) in the current sample—it is anticipated that VLAST, with its superior detection performance, will further expand the sample size of high-redshift blazars and push the boundaries of the redshift limit. In the future, it is expected that GeV gamma-ray horizon photons will be detected at redshifts of 4 or even higher, providing critical observational evidence for studying the history of star formation and evolution in the early universe.

Detections of horizon photons show no direct observational connections with the major γ-ray flares for other blazars in our sample, taking blazars 3C 454.3 (upper) and PKS 0347-211 (lower) as examples.

As a ground-based gamma-ray and cosmic ray detector, the Large High Altitude Air Shower Observatory (LHAASO) has significantly advanced the study of ultra-high-energy gamma rays.

Subsequent observations are expected to effectively constrain Extragalactic Background Light (EBL) models and explore the history of star formation and evolution in the high-redshift universe.

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Abstract

The Extragalactic Background Light (EBL) is the diffuse radiation field that fills the universe, primarily originating from the integrated light of all stars and galaxies throughout cosmic history. High-energy gamma-ray photons emitted by distant extragalactic sources, such as blazars, undergo pair production ($\gamma\gamma \to e^+e^-$) through interactions with EBL photons, leading to a significant

attenuation of the observed gamma-ray flux. This absorption effect is energy-dependent and redshift-dependent, defining a "gamma-ray horizon" where the optical depth τ reaches unity. In this study, we utilize the latest Fermi Large Area Telescope (Fermi-LAT) catalogs and long-term observation data to identify and analyze a sample of blazars located near or beyond this gamma-ray horizon. By analyzing the spectral energy distributions (SEDs) and the high-energy cutoffs of these sources, we provide constraints on current EBL models and investigate the implications for cosmic star formation history and galaxy evolution. Our results demonstrate that the Fermi-LAT is capable of detecting high-energy emissions from sources at significant redshifts, offering a powerful probe into the transparency of the universe to gamma-rays.

1. Introduction

The study of the Extragalactic Background Light (EBL) is fundamental to our understanding of the evolution of the universe. As the second most energetic diffuse background after the Cosmic Microwave Background (CMB), the EBL encodes the history of star formation, galactic evolution, and the contribution of active galactic nuclei (AGN) across cosmic time. However, direct measurement of the EBL is extremely challenging due to the overwhelming foreground contamination from zodiacal light and galactic emissions.

An alternative and effective method to probe the EBL is through the observation of high-energy gamma-rays from distant extragalactic sources. When gamma-ray photons travel through intergalactic space, they interact with low-energy EBL photons (ranging from ultraviolet to far-infrared) via the pair-production process:

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

This interaction results in an energy-dependent attenuation of the intrinsic gamma-ray spectrum. The degree of attenuation is described by the optical depth $\tau(E, z)$, which depends on the photon energy E and the source

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Detections of Fermi-LAT Blazars at the -ray Horizon by the EBL Absorption

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Abstract

Extragalactic Background Light (EBL) is the cosmic diffuse electromagnetic radiation that ranges from the far-infrared to the ultraviolet bands, and contains important information on the evolution of the universe. Since during their traveling through the cosmos, the -ray photons are suffered by the absorption by the EBL, investigations of the -ray opacity of the universe are helpful to understand the EBL. Detections of rays with significant EBL absorptions (i.e., 1) from distant -ray sources, is an effective and direct approach to constrain the EBL models. In this study, after careful selections and thorough redshift scrutinization on the sources listed in the latest FermiLAT -ray catalog, we perform systematic Fermi-LAT data analyses on 448 -ray sources. By comparison with the widely adopted EBL model, 46 horizon -ray photons from 36 blazars are detected, of which the most distant one is at redshift of 2.944. Among the blazars, the numbers of flat spectral radio quasars (FSRQs) and the BL Lacertae objects are equal. Further temporal -ray analyses reveal that occasionally arrival of the horizon photons coincide with the unprecedentedly intense -ray flares.

Detections of handful of horizon -ray photons from the FSRQs put a tight constraint on the location of the energy dissipation region of the jet. Meanwhile, the blazars that emit horizon photons are crucial targets for the observations of the next generation of the space and ground -ray telescopes.

Key words galaxies: active, galaxies: jets, cosmology: cosmic background radiation