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Search for high-redshift blazars with *Fermi*/LAT

Michael Kreter[*a], **Andrea Gokus**[b,c] **Matthias Kadler**[b], **Felicia Krauß**[d], **Sara Buson**[b], **Roopesh Ojha**[e], **for the *Fermi*/LAT Collaboration, Jörn Wilms**[c] **and Markus Böttcher**[a]

[a] *Centre for Space Research, North-West University, Private Bag X6001, Potchefstroom 2520, South Africa*
[b] *Lehrstuhl für Astronomie, Universität Würzburg, Emil-Fischer-Straße 31, 97074 Würzburg, Germany*
[c] *Dr. Remeis Sternwarte & ECAP, Universität Erlangen-Nürnberg, Sternwartstraße 7, 96049 Bamberg, Germany*
[d] *Penn State University, State College, Pennsylvania 16801, United States*
[e] *NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA*
michael@kreter.org

High-redshift blazars ($z \geq 2.5$) are the most powerful class of persistent γ-ray sources in the Universe. These objects possess the highest jet powers and luminosities and have black hole masses often in excess of 10^9 solar masses. In addition, high-z blazars are important cosmological probes and serve as test objects for blazar evolution models. Due to their large distance and the resulting electron/positron cascading on the extragalactic background light, their high-energy emission typically peaks below the GeV range. This makes these blazars difficult to study with *Fermi*/LAT and only the very brightest objects are detectable. Hence, only a small number of high-z blazars could be detected with *Fermi*/LAT so far. In this work, we present a strategy to increase the detection statistics at redshift $z \geq 2.5$ via a search for flaring events in high-z γ-ray blazars whose long-term averaged flux is just below the sensitivity limit of *Fermi*/LAT. Seven previously GeV undetected high-z blazars have been identified with a test statistic of TS ≥ 25 from their bright monthly outburst periods, while more detections are expected in the future.

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1. Introduction

Active galactic nuclei (AGN) are the most luminous sources in the Universe. Blazars, as a subclass of AGN are characterized by jets pointing towards Earth and show variability on timescales from minutes to months. Due to relativistic boosting of plasma in the jet, these sources appear brighter in γ-rays, compared to other types of AGN. Due to their extreme luminosities, we are able to observe blazars at large redshifts. It was previously found that the most powerful blazars were dominating the early Universe, with a peak density at redshifts of z $\sim$ 4 [1]. These blazars seem to harbor supermassive black holes (SMBHs) with masses often in excess of $10^9\,M_\odot$ [2], [3], while accreting at $\sim 10\,\%$ of the Eddington rate. This indicates that these black holes have been created very quickly and are already at the end of their formation process.
Their broadband emission is dominated by relativistic jets, especially at γ rays where the high-energy component of the spectral energy distribution (SED) peaks in the MeV to GeV regime. High-z blazars are typically dominated by their high-energy peak (see Fig. 1), which often shows luminosities of one order of magnitude brighter compared to their synchrotron peak [4]. The Large Area Telescope (LAT) onboard the *Fermi* satellite has detected thousands of blazars, confirming that they dominate the γ-ray sky [5]. However, at large redshifts ($z \geq 2.5$), blazars have been primarily detected at radio and optical surveys in the past decades,[6, 7], while only $\sim$ 12 of these sources have been detected in γ rays so far [5, 8]. Such a discrepancy can be caused by absorption on the extragalactic background light (EBL), which leads to an efficient degrading of high-energy γ rays above ~ 1 GeV [9, 10]. Therefore, the observed *Fermi*/LAT photon flux from these distant blazars is mainly dominated by their MeV emission. Besides EBL absorption, high-z blazars are more populated in radio and optical due to the larger number of observational facilities at these wavelengths.
High-z blazars are of particular interest in the field of γ-ray Astronomy, as they account for the most powerful (non-transient) astrophysical sources detected by *Fermi*/LAT. As the total sample of γ-ray detected high-z blazars is highly limited, not much is known about their simultaneous multiwavelength flaring behavior. While some authors studied quasi-simultaneous multiwavelength data from a sample of four high-z blazars [11], detailed multiwavelength modeling so far was only possible for TXS 0536+145 (z = 2.69), where it has been shown that (similar to blazars in the local Universe), the emission from high-z blazars can be described by leptonic models [12]. Recently, five new high-z blazars have been identified by *Fermi*/LAT [9], making NVSS J151002+570243 the most distant known γ-ray emitting blazar at z = 4.31. In fact, many of the high-z blazars observed by *Fermi*/LAT were only detectable due to bright flaring states [13]. In this work, we introduce a new method to search for undetected high-z γ-ray emitting blazars, which are too faint to be detected significantly (test statistic TS $\geq$ 25) on long-term periods typically considered for catalogs, but can show up as significant sources during shorter ($\sim$ monthly) periods of increased activity.

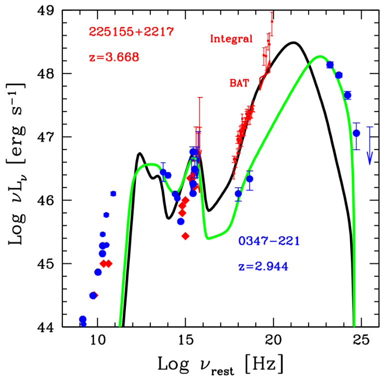

Figure 1: Example SEDs of two high-z blazars. These sources are weak at γ-ray energies, while showing strong hard X-ray emission. Figure taken from [14].

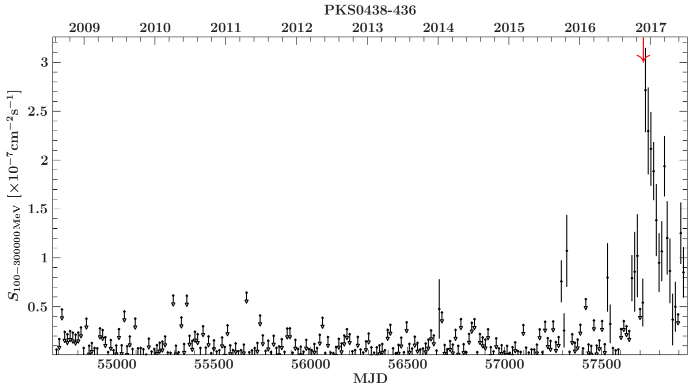

Figure 2: *Fermi*/LAT γ-ray light curve of PKS 0438−43 over $\sim$ ten years of continuous observations. The light curve is shown for the energy range of 100 MeV to 300 GeV. This source was detected in December 2016 on daily time scales during a bright flare, as indicated by the red arrow. Figure taken from [15].

2. Detection Strategy and Sample Selection

Flaring activities from previously γ-ray undetected high-z blazars have been detected several times by *Fermi*/LAT [16, 17, 18]. Such periods of enhanced activity typically only last for several days, leading to a significant detection (TS $\geq$ 25) due to a drastic background reduction, compared to long-term averaged fluxes used in catalogs. Figure 2 shows a ten-year *Fermi*/LAT, γ-ray light curve of the high-z blazar PKS 0438−43 (z = 2.83) in the energy range of 100 MeV to 300 GeV. This source was not included in the third *Fermi*/LAT Point Source catalog and is detected at GeV energies only due to its bright flare in 2016[1] [16].

In this work, we perform a systematic search for high-z blazars in the γ-ray band which are not present in any *Fermi*/LAT catalogs, by targeting a sample of 176 blazars with a redshift of $z \geq 2.5$ and a radio flux density of more than 50 mJy, taken from the Roma BZCAT Multifrequency Catalogue of Blazars[2] and the SHAO list of high-z radio-loud quasars[3]. These sources are selected because of the expected correlation between radio and γ-ray fluxes [19, 20]. The total sample consists of 169 BZCAT blazars, as well as seven SHAO sources. Monthly binned *Fermi*/LAT γ-ray light curves in the time range from 2008 August 4 to 2019 April 4 and energy range of 100 MeV to 300 GeV are calculated, while the time binning of 30 days has been chosen to identify periods which would not have been followed up by the *Fermi*/LAT Flare Advocate service [21] while keep the computing effort at a reasonable level.

2.1 Background Determination

At a test statistic level of TS $\geq$ 25 γ-ray detections are considered trustworthy, since the chance for a false positive detection is about 5×10^{-7} %. Multiple (TS $<$ 25) monthly detections from an unknown emitter, however, suggest the presence of a new γ-ray source, even if none of the

[1] PKS 0438−43 is now included in the Fourth *Fermi*/LAT Point Source catalog (4FGL)

[2] http://www.asdc.asi.it/bzcat/

[3] http://202.127.29.4/CRATIV/en/high_z.html

monthly intervals have been detected above the required (TS $>$ 25) threshold. In order to account for these sources, we measure (for the first time) the rate of false positive detections on monthly time scales over the entire γ-ray sky. We perform a similar[4] *Fermi*/LAT light curve analysis on a sample of blank sky positions. These positions are defined as coordinates without a known γ-ray source in a vicinity of 1.5°. To imitate the all-sky blazar distribution, random positions have been selected by mirroring the positions of known γ-ray sources across the galactic plane. In this way, the distribution of blank sky positions follows the observed blazar distribution in the sky. Figure 3 shows the TS distribution of monthly intervals for a total of 80 studied blank-sky positions, while the total TS distribution of all 176 studied high-z blazars is shown in Fig. 4. In order to derive a representative measurement of random fluctuations over the entire γ-ray sky, it is necessary to perform this measurement for an extremely large number of blank sky positions. To account for the (always) finite number of studied positions, we use a Poisson fit of the TS distribution in Fig. 3 to extrapolate the expected background rate towards higher TS values and to account for TS values without measured monthly intervals. By comparing the number of measured fluctuations to the observed number of monthly intervals detected from our sample of high-z blazars, we derive the Poisson probability Φ for a false positive detection of a detected monthly bin to be:

$$\Phi = \sum_i P\left(N_{is} \mid \mu_{ib}\right) dN_{is} \tag{2.1}$$

N_s corresponds to the number of "signal" monthly intervals detected from the directions of known blazars, while μ_b represents the amount of random fluctuations derived from blank-sky positions. The sum i runs over all bins in Fig. 3 which are larger or equal to the detected TS value of the considered high-z blazar. The total probability Φ_{tot} of multiple monthly intervals of a single blazar to be of purely statistical nature thus is given by:

$$\Phi_{tot} = \prod_j \Phi_j \tag{2.2}$$

The product is defined over all bins j in the blazar TS distribution in Fig. 4, which show at least one entry with a TS $\geq$ 9. A more detailed background determination can be found in [15].

3. Individual high-z blazars

3.1 TS $>$ 25 detections

Out of our sample of 176 high-z blazars, five blazars have been detected in at least one monthly interval with a test statistic of TS $\geq$ 25. Table 1 lists the relevant properties of these blazars. Three blazars from our list showed flaring activity in the past years and are associated with 4FGL sources. Two high-z blazars are not listed in the 4FGL catalog, resulting in the identification of new high-z γ-ray detected blazars. Following Table 1, the source 5BZQ J2219$-$2719 at a redshift of z = 3.63 is identified as the most distant significantly detected blazar in our work. Besides their emission at a TS level of more then 25, these blazars showed multiple monthly intervals at a TS $\geq$ 9 level. As a proof of principle of the performed background estimate, we included the known blazar

[4]The same energy and time range and binning is used.

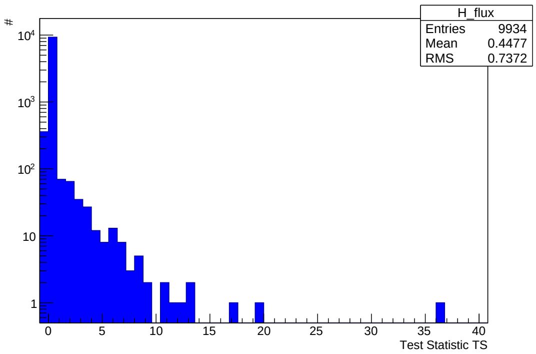

Figure 3: Test statistic distribution of a sample of 80 blank-sky positions. This histogram represents the background fluctuation for the *Fermi*/LAT variability analysis that was performed. Please note that the TS axis is scaled from zero to 40. Figure taken from [15].

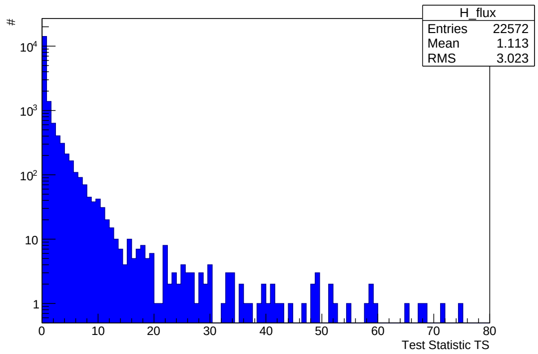

Figure 4: Test statistic distribution of 176 blazar positions selected according to Sect. 2. 22 monthly intervals are identified with a significance of TS $\geq$ 25, while at a TS $\geq$ 9 level 249 intervals are detected. Please note that the TS axis is scaled from zero to 80. Figure taken from [15].

PKS 0537−286 (z = 3.10) in our sample. This source has been detected multipe times at different significance levels on monthly time scales and even showed daily flaring activity [17]. Following Equ. 2.2 for all monthly intervals with a TS $\geq$ 9, we show that the Poisson probability of these detections to be of purely random origin can be excluded at least with $\Phi_{tot} \sim 8\,\sigma$. This provides further evidence that these blazars are observable γ-ray emitters.

Table 1: High-z blazars identified by this analysis to have been detected in at least one single monthly interval with a TS $\geq$ 25. Three of our identified blazars are known as new γ-ray sources in the recently published 4FGL catalog, while two previously unknown γ-ray blazars have been identified. The blazar PKS 0537−286 (listed in gray) has been included as a sanity check of the background estimation technique used.

Source Name	RA J2000	DEC J2000	z	Detections TS $\geq$ 9	Detections TS $\geq$ 25	γ-ray Counterpart
5BZQ J2219−2719	334.90	-27.32	3.63	3	1	-/-
5BZQ J0422−3844	65.56	-38.75	3.11	7	1	-/-
5BZQ J0733+0456	113.49	4.94	3.01	19	7	4FGL J0733.8+0455
5BZQ J1127+5650	171.92	56.84	2.89	14	3	4FGL J1127.4+5648
5BZQ J0434−4355	68.51	-43.93	2.65	9	2	4FGL J0440.3−4333
5BZQ J0539−2839	84.98	-28.67	3.10	68	36	4FGL J0539.9−2839

3.2 TS $\geq$ 9 detections

At a test statistic level of TS $\geq$ 9, a total of 249 monthly intervals have been identified from 116 high-z blazars. This indicates that the majority of blazars studied in this work are good candidates for γ-ray emitters. By studying the individual TS distribution of the 116 TS $\geq$ 9 blazars, we find that 60 blazars show multiple monthly detections. These blazars remain promising candidates for future γ-ray detections.

By considering the total amount of studied blank-sky intervals whose distribution is plotted in Fig. 3, only a fraction of $11/9934 \approx 1.1\times10^{-3} \approx 3.26\,\sigma$ monthly intervals shows a statistical fluctuation at a TS ≥ 9 level. Thus, we conclude that based on our measurements of the all-sky γ-ray background fluctuations on monthly time scales, a TS ~ 9 detection corresponds to a detection significance of about $3\,\sigma$.

4. Discussion and Outlook

In this work, we studied the MeV – GeV long-term flaring behavior of a sample of radio and optically selected blazars at redshifts of $z \geq 2.5$, undetected[5] by *Fermi*/LAT. We identified two previously γ-ray unknown blazars with a significance threshold of at least TS $\geq$ 25, while confirming significant flaring activity from three blazars, which have been included as new γ-ray sources in the most recent general *Fermi*/LAT point source catalog. We measured the expected all-sky false positive detection rate based on our variability analysis and confirmed that a $TS \sim 9$ detection corresponds to a significance level of $\sim 3\,\sigma$. Indications for multiple γ-ray flaring activity below the TS = 25 threshold have been observed in more then half of our studied blazar sample. A detailed study of potential γ-ray background sources, which could influence the observed signal has to be performed in the future in order to verify these blazar detections. However, this implies that the statistic of γ-ray detected high-z blazars can be significantly increased by searching for periods of enhanced activity. While still being closer than the most distant γ-ray detected blazar identified in [9], the blazar 5BZQ J2219−2719 at a redshift of z = 3.63 represents the farthest, significantly detected new γ-ray source identified in this work.
As the main focus of this work is to search for γ-ray flaring activity in a well defined sample of radio and optically detected high-z blazars, a dedicated analysis of the multiwavelength spectral properties will be performed at a later point. This will furthermore support the science goals of future MeV missions and provide a substantial contribution to study the early Universe [22].

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[5] As this project started before the release of the 4FGL catalog, we used the previous 3FGL *Fermi*/LAT point source catalog in which the known γ-ray sources in Tab. 1 were not listed.

[6] Any opinion, finding and conclusion or recommendation expressed in this material is that of the authors and the NRF does not accept any liability in this regard.

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