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Searching for new TeV blazars in the 3rd Fermi-LAT catalogue of hard gamma-ray sources

J.P. Marais* **and B. van Soelen**
University of the Free State
E-mail: maraisjp@ufs.ac.za, vansoelenb@ufs.ac.za

The 3rd Fermi catalogue of Hard *Fermi*-LAT Sources (3FHL), which detected 1556 sources above 10 GeV, provides an important resource for finding new candidate TeV sources for follow-up observations with the H.E.S.S. telescopes. To search for potential TeV emitting extragalactic sources, we observed a sample of five 3FHL sources classified as Blazars of unknown type (BCU) and two 3FHL sources without initial associations at other wavelengths with the SAAO 1.9-m telescope. The observations were performed during February 2017, with the SpUpNIC spectrograph on the 1.9-m telescope. Possible counterparts for the unassociated sources were determined by cross-matching objects using archival multi-wavelength data from Radio, Infrared and X-ray catalogues. Classifications were obtained for all the observed BCUs and redshifts were determined for two of them. Redshift measurements were obtained for the optical candidates of both the unassociated sources observed. Further analysis is necessary to confirm their association to the 3FHL γ-ray sources.

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*Speaker.

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1. Introduction

The most numerous extragalactic source class detected by *Fermi* are blazars. Blazars are radio-loud Active Galactic Nuclei (AGN) with relativistic jets closely orientated towards the observer's line of sight. The non-thermal emission from the closely orientated jet is Doppler boosted, greatly increasing the measured flux at all wavelengths and dominates over the thermal emission from the host galaxy and inner regions of the AGN. The Spectral Energy Distributions (SEDs) of AGN display a double humped shape consisting of a low energy component extending from radio to X-ray energies and a High Energy (HE) component that can extend from X-ray up to TeV energies. The low energy emission is considered to be synchrotron emission from a population of relativistic electrons moving along the jet. The source of the HE and Very High Energy (VHE) emission is more difficult to determine, with leptonic Inverse Compton (IC) emission and hadronic processes, such as proton synchrotron and neutral pion decay, being considered [1].

The 3rd catalogue of Hard *Fermi*-LAT Sources (3FHL) list 1556 sources detected above 10 GeV with the *Fermi*-LAT of which 76% are extragalactic in nature. This makes the extragalactic source population the most significant contributor to the HE γ-ray sky above 10 GeV seen by *Fermi* [2]. The 3FHL catalogue provides an extensive list of potential VHE emitting objects, which can be studied with Imaging Air Cherenkov Telescopes (IACT), such as the H.E.S.S. telescope. Classification and redshift measurements of 290 of these extragalactic sources, classified as blazar candidates of unknown type (BCU), still have to be made in order to constrain the γ-ray population. There are also a further 177 sources which have yet to be associated with objects at other wavelengths. Classifying the sources responsible for the γ-ray emission can potentially bring to light new source classes of γ-ray emitting objects, such as the extreme blazars [3], Dark Matter candidates [4] and even unexpected HE phenomena.

Blazars can be classified as BL Lac or Flat Spectrum Radio Quasars (FSRQ) by measuring the Equivalent Widths (EW) of their optical emission lines, with the divide set at 5 Å: BL Lacs EW $<$ 5 Å and FSRQs EW $>$ 5 Å [5]. This classification scheme takes advantage of the properties of the central regions of the AGN. BL Lacs have radiatively inefficient accretion flows which are unable to sustain a Broad Line Region (BLR), while FSRQs can sustain a BLR and illuminate the torus surrounding the AGN [6]. Measuring emission lines in optical spectra can then give an indication of the strength of the BLR emission, allowing the blazar to be classified as either a BL Lac or FSRQ.

The difference in BLR strengths between these two blazar classes also determines the processes responsible for the HE and VHE emission. In the leptonic scenario the bright FSRQ BLR and torus provide seed photons (produced external to the jet) that can be upscattered to HE and VHE γ-rays; this is known as the External Compton (EC) process. This EC emission radiatively cools the relativistic electrons before the majority of the electron population can be accelerated to very high energies. The HE and VHE emission from BL Lacs, on the other hand can also be produced from synchrotron photons upscattered to HE and VHE energies, produced through the so called Synchrotron Self Compton (SSC) emission. BL Lac jets exhibit weak radiative cooling, so their electron population can reach much higher energies than those in FSRQ jets [6, 7].

Detailed studies of γ-ray emission from blazars can provide constraints on particle acceleration and emission mechanisms in the jet environment predicted by models [8, 9, 10]. Classifying the

Fermi-LAT BCUs and unassociated sources will increase the number of blazars that can be used to constrain the mechanisms responsible for the HE emission. These constraints, applied to very distant blazars, can be used for example, to place limits on the Extragalactic Background Light (EBL), which is the integrated emission from all emitting gas, dust, stars and galaxies since the epoch of recombination and is important for the study of cosmology. The EBL provides key information about stellar and galactic evolution throughout cosmic history [11]. The EBL affects VHE γ-rays through attenuation by $\gamma\gamma$ interactions. Knowledge of the intrinsic blazar spectrum can be used to measure the amount of γ-ray attenuation by the EBL.

Classifying and measuring the redshifts of BCUs detected in the 3FHL catalogue will provide candidates for follow-up studies with H.E.S.S. and CTA. Observations with IACTs extend the broadband SEDs of blazars beyond $E > 2$ TeV and provides important constraints on blazar emission models [12]. VHE emission from blazars with a redshift $z \gtrsim 1$ are not detectable by IACTs due to $\gamma\gamma$ attenuation by the EBL. Determining the redshift of potential VHE blazars will, therefore, reduce the number of possible counterparts.

We searched for candidates for follow-up observations with IACTs by performing optical spectroscopy on a sample of five 3FHL BCUs and two unassociated 3FHL sources using the SpUpNIC spectrograph on the South African Astronomical Observatory (SAAO) 1.9-m telescope [13]. This paper is structured as follows: in Section 2, we describe the selection of optical candidates using multi-wavelength archival data; Section 3 describes the observation and analysis of the sources; while Section 4 describes the results obtained on individual sources.

2. Multi-wavelength candidate identification

The poor spatial resolution of the *Fermi*-LAT, although better than earlier γ-ray instruments like the *Energetic Gamma-ray Experiment Telescope* (EGRET), makes it difficult to determine the exact position of potential HE and VHE emitters for follow-up studies. The *Fermi*-LAT source localization is also highly dependant on the spectral index of the γ-ray detections, making the localization of sources with a softer spectral index more difficult [14]. Many methods have been used to identify likely counterparts of unassociated *Fermi* sources. These methods include, but are not limited to: multiwavelength monitoring of sources inside the *Fermi*-LAT error ellipses in order to search for correlated multi-wavelength variability (a hallmark of blazars) [15]; using broadband SED characterization to find blazar-like sources [16, 17]; searching for radio counterparts inside the *Fermi*-LAT error ellipses [18]; and using machine-learning techniques to search for blazars among multi-wavelength data [19, 20].

Many of the brighter unassociated γ-ray sources have already been associated by the methods mentioned above. Using multiwavelength monitoring to associate potential electromagnetic (radio, optical, etc.) counterparts with previously unassociated *Fermi*-LAT sources, requires variable sources continuously monitored over long periods of time. Fainter sources are more difficult to continuously monitor. Broadband SED characterisation requires fairly complete coverage over the entire energy range to successfully characterise the sources. This is difficult for the fainter sources with limited data. Machine learning can be used to study the fainter sources, but requires large datasets to successfully train the algorithms. We, therefore, identified potential candidates of two unassociated 3FHL sources observable from the SAAO Sutherland Observatory, using archival

ALLWISE and DSS[1] data [21]. The ALLWISE data allowed non-thermal dominated sources to be identified, while DSS and NOMAD[2] data were used to constrain our candidates to objects observable in the optical band, with V $\lesssim$ 18. To further constrain the number of candidates, we also used X-ray and radio data where possible. We also observed five 3FHL BCUs, confirming the optical counterparts using the same methods used to select the unassociated 3FHL optical candidates.

2.1 ALLWISE blazar strip

The infrared colours of blazars are dominated by their non-thermal synchrotron emission, clearly separating them from normal galaxies, stars and non-jetted AGN [24]. To constrain the number of optical candidates to observe, for both the unassociated sources and BCUs, we selected ALLWISE infrared sources inside, or slightly outside the *Fermi* 95% error ellipses and whose infrared colours put them inside or near the ALLWISE blazar strip. For the BCUs, this provided an initial confirmation for the optical counterpart to the γ-ray source. For the unassociated sources, without firm multiwavelength associations, this drastically reduced the number of sources that could be the source of the γ-rays.

2.2 X-ray and Radio counterparts

Further constraints were applied, using archival X-ray and radio data. Potential optical candidates were selected based on the presence of X-ray and radio sources. Unfortunately, for many of the BCUs and unassociated sources considered, X-ray and radio sources were not located close to the optical candidates, and in some instances were either absent or outside the *Fermi* error ellipses. Since all of our 3FHL targets are also weak γ-ray emitters, this could potentially indicate that their X-ray and radio emission is below the threshold of the surveys considered. This agrees with the results of Schinzel et al. [25], whose follow-up radio observations in the 4-10 GHz range, found 245 unassociated 3FGL γ-ray sources without compact radio counterparts above 2 mJy within 3σ of the γ-ray localization. Therefore, for the candidates without close X-ray or radio counterparts, all observable optical candidates were considered for follow-up observations.

3. Observations and Analysis

We performed optical spectroscopy on five Fermi 3FHL BCUs and two unassociated Fermi 3FHL sources using the SpUpNIC spectrograph on the SAAO 1.9-m Cassegrain reflector during February 2017. The observations were obtained with Grating 7 and a usable wavelength range between 3000 Å and 9000 Å. A series of bias and dome flat field exposures were taken at the start of each night. Spectrophotometric standard stars were also observed each night for flux calibration of the optical spectra. The total integration time per target varied between 3600 and 7200 seconds, in separate, consecutive 1800 second exposures, depending on source brightness and sky conditions.

Standard `IRAF/NOAO`[3] spectrophotometry reduction routines were performed on the data. `IRAF/NOAO` routines were also used for the wavelength calibration, background subtraction, spec-

[1]The Digitized Sky Survey data is accessible from http://archive.eso.org/dss/dss

[2]Naval Observatory Merged Astrometric Dataset [22] is accessible from the CDS/Vizier [23] catalog service at http://vizier.u-strasbg.fr/viz-bin/VizieR

[3]The Image Reduction and Analysis Facility can be downloaded from http://iraf.noao.edu/

3FHL Name	3FHL Type	Association	Class	Redshift
3FHL J0647.0-5138	BCU	1ES 0646-515	BL Lac	0.22687(3)
3FHL J0813.7-0353	unassociated	-	?	~ 0.3
3FHL J0935.2-1735	BCU	NVSS J093514-173658	BL Lac	-
3FHL J0937.8-1434	unassociated	-	BL Lac	-
3FHL J1042.2-4128	BCU	1RXS J104204.1-412936	BL Lac	-
3FHL J1130.5-7801	BCU	SUMSS J113032-780105	BL Lac	0.31504(2)
3FHL J1223.5-3033	BCU	NVSS J122337-303246	BL Lac	0.21935(4)

Table 1: Table of sources observed during our 2017 Feb observation campaign. The 3FHL names, source type, counterparts (if associated) are given, as well as the preliminary classification and redshift determined in this work.

tra extraction and spectra calibration using the spectrophotometric standard stars. After spectrophotometric calibration of the targets, the frames were examined and cleaned of cosmic rays and median combined to produce higher Signal-to-Noise (S/N) spectra used to determine the redshift of the source. Redshifts were determined using the `XCSAO` cross-correlation task from the `RVSAO` [26]. The observed spectra were cross-correlated against the SDSS Data Release 5 cross-correlation templates.[4]

4. Results

Table 1 lists the BCUs and unassociated sources we observed during our campaign along with, where possible, the classification and redshift measurements determined from these observations. The flux-calibrated optical spectra of our targets are presented in Figures 1. All redshift measurements were manually checked to see if the calculated redshifts matched any feature seen in the spectra. These included the 3933 and 3970 Å Ca H&K and $\sim$ 4300 Å G band features.

4.1 3FHL J0647.0-5138

The spectrum of the optical counterpart of this sources is rather flat with a Ca H&K break, at a redshift of $z = 0.22687(3)$. The absence of any emission lines is consistent with a BL Lac object. The spectrum suffers from sky contamination at wavelengths $\lambda \gtrsim 8000$ Å that could not be completely removed, but did not influence the redshift calculation.

4.2 3FHL J0813.7-0353

This source is unassociated in both the 3FHL and 3FGL catalogues. There are a total of 9 optical candidates which lie inside the ALLWISE blazar strip that were observable during our campaign. All the sources that we observed displayed BL Lac-like spectra, all with redshifts $z \sim 0.3$ (a representative spectrum is shown in Fig. 1). A single $F_{1.4\ \mathrm{GHz}} \sim 30$ mJy radio source lies inside the 3FHL error ellipse, but not near any of the observable candidates. No X-ray sources are detected inside the 3FHL error ellipse. Further observations are needed to associate the source to an optical counterpart.

[4]The SDSS cross-correlation templates can be downloaded from http://classic.sdss.org/dr5/algorithms/spectemplates/

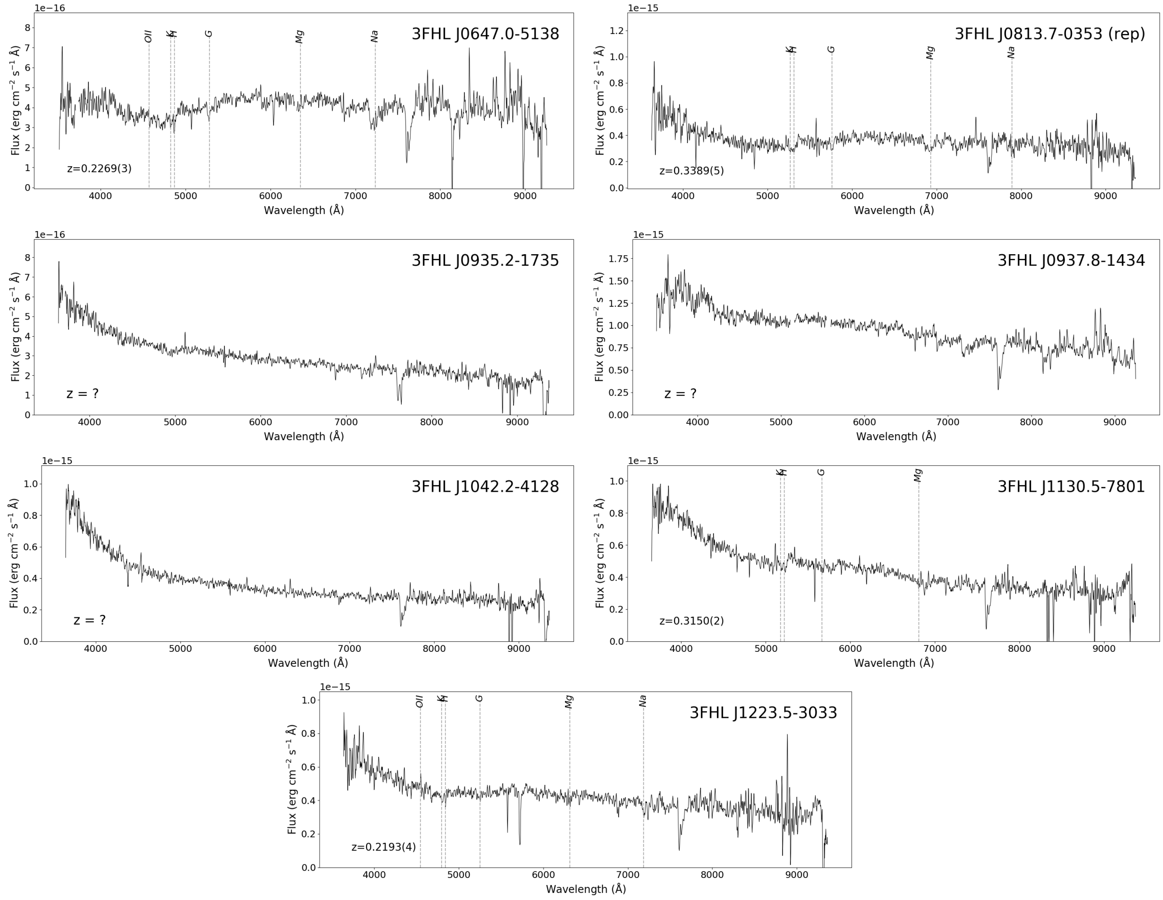

Figure 1: Calibrated spectra for our selection of 3FHL BCUs and unassociated sources that were classified as being extragalactic in nature. Their 3FHL designations and redshifts are labelled.

4.3 3FHL J0935.2-1735

The optical spectrum of the counterpart to the BCU source J0935.2-1735 shows no discernible features and no redshift could be calculated. The spectrum is blue, consistent with a non-thermal origin of the emission. We therefore tentatively classify the source as a BL Lac.

4.4 3FHL J0937.8-1434

This source is unassociated in the 3FHL catalogue, but our best optical candidate lies within the error ellipse of a $F_{1.4\ \mathrm{GHz}} \sim 5$ mJy radio source, NVSS J093754-143350. The low S/N of this spectra, prevented us from determining a redshift for this source, but the spectrum is consistent with non-thermal emission. We classified this source as BL Lac in nature due to the absence of any emission lines.

4.5 3FHL J1042.2-4128

Due to the non-thermal featureless spectrum we obtained for this source we have classified it as a BL Lac. A redshift determination was not possible due to the featureless spectrum. The optical counterpart of this source was listed in D'Abrusco et al. [27] as a potential blazar-like source, which is consistent with our observations.

4.6 3FHL J1130.5-7801

We obtained a lower S/N spectrum for this sources, but it shows the Ca H&K break and G band features consistent with a redshift of $z = 0.31504(2)$ determined from the cross-correlation. The low S/N spectrum prohibits us from determining a firm classification for this source but we tentatively classify this source as a BL Lac-type object due to the lack of emission lines.

4.7 3FHL J1223.5-3033

We calculated a tentative redshift of $z = 0.21935(4)$, via cross-correlation, for 3FHL J1223.5-3033. The low S/N of this source and weak nature of the possible [OIII] 3727 Å emission line prevents us from determining the EW of the line. Based on the presence of only the one very weak emission line, this source can be classified as BL Lac in nature.

5. Conclusion

The *Fermi* 3FHL catalogue, consisting of sources emitting above 10 GeV, is a great resource to find TeV emitting blazars for follow-up studies with IACTs. To find sources for potential follow-up studies with IACTs, we performed optical spectroscopy on five Fermi 3FHL BCUs and two unassociated Fermi 3FHL sources using the SpUpNIC spectrograph on the SAAO 1.9-m Cassegrain reflector during February 2017. Optical candidates were selected based on their ALLWISE infrared colors, which place them in well defined classes. We considered optical candidates whose ALLWISE colors put them in the so-called blazar strip, the region in infrared color space that corresponds to a non-thermal origin of the infrared emission, consistent with blazar jet dominated emission [24].

We classified six of the observed Fermi 3FHL sources as BL Lacs based on the absence of strong emission features. Redshift measurements were made for three of the 3FHL sources. All nine of the observed candidates for 3FHL J0813.7-0353, showed a non-thermal spectrum, at a redshift of $z \sim 0.3$. Further observations are necessary to determine the optical association of this source.

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