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Unidentified Active Galactic Nuclei in the Fermi-2LAC catalogue: identification of candidate sources

L. Klindt, B. van Soelen, and P.J. Meintjes

Department of Physics, University of the Free State, Bloemfontein, 9301, South Africa
e-mail: lizelkeklindt@gmail.com

Abstract. Blazars constitute the most violent astronomical objects with jet emitting radiation at all frequencies. In order to fully understand and model blazars and in particular the accretion-black hole system and superluminal jet structure, multi-wavelength observations are required. In the search for Very High Energy (VHE) sources a target sample of twenty unidentified sources with possible blazar characteristics has been constructed from sources listed in the *Fermi*-2LAC catalogue. The selected targets are all at high galactic latitude ($|b| > 10°$) with optical/radio counterparts within the *Fermi* 95% error circle. The selection criteria, which are based on source properties including radio brightness, photon spectral indices, undetermined redshifts, observability and variability, are presented along with the twenty identified sources.

Key words. galaxies: active – BL Lacertae objects: general – gamma-rays: galaxies

1. Introduction

On board the *Fermi* Gamma-ray Space Telescope spacecraft are the Large Area Telescope (LAT) and the Gamma-ray Burst Monitor (GBM), which have mapped the sky since August 2008. LAT is the main instrument on the spacecraft that covers 20% of the sky at any time and is producing a map of gamma-rays from 20 MeV to 300 GeV . The second *Fermi*-LAT AGN catalogue (2LAC) consists of a clean sample of 866 sources of which 81% are blazars and 18% are candidate blazars catalogued as Active Galactic Nuclei (AGN) of Unknown type (AGU) (Ackermann et al. 2011).

AGN are extremely active and luminous in nature due to their energy source, namely accretion onto the central supermassive black hole (SMBH). The SMBH (M_{BH} = 10^6-10^{10} $M_\odot$) that lies in the centre of the system is surrounded by an accretion disk which is extremely luminous. Matter and dust are transported within the disk towards the black hole, while angular momentum is transported outward, causing the accretion disk to heat up, resulting in the system outshining its host galaxy. Broad and narrow emission line regions are present closer and further away from the SMBH respectively. In a region near the black hole, energetic radio jets are produced which extend far out from the centre (radio-loud AGN).

The Unified Model of AGN implies that all systems consist of the basic structure of an accreting black hole system, a torus, broad and narrow line regions and, in radio loud galax-

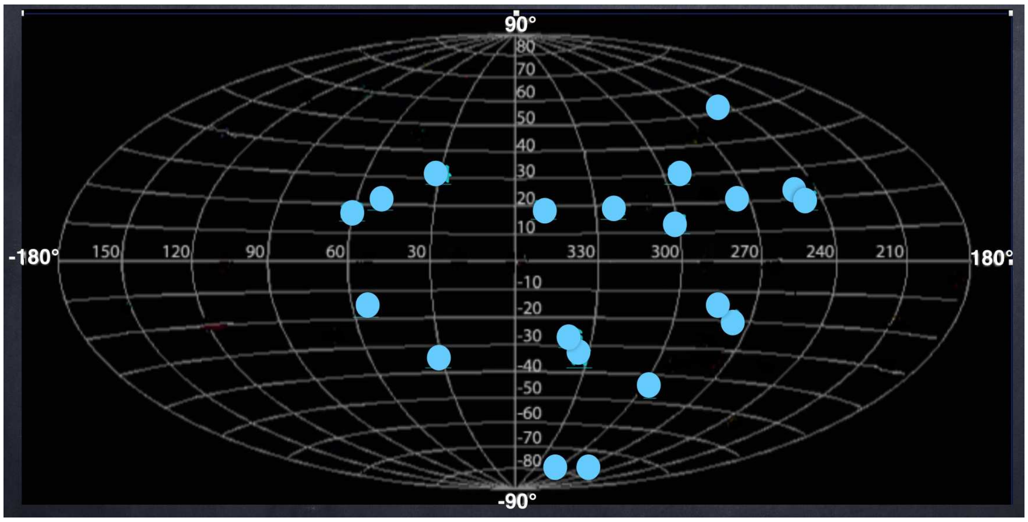

Fig. 1. The galactic positions of the *Fermi*-2LAC candidate sources. All the sources are at high galactic latitude ($|b| > 10°$) which ensures that the target sources are outside the Galactic plane.

ies, a powerful radio jet. The different observed properties of AGN are then a result of the viewing angle. Radio and Seyfert II galaxies are observed at a viewing angle of $\sim$ 90° to the jet, Seyfert I galaxies and quasars are observed at angles between 30° and 60°, and blazars are observed at angles between 0° and 30°. Since blazars are observed looking along the jet, the observed emission from the system is dominated by the highly Doppler boosted jet. See, for example, Beckmann & Shrader (2012) for a detailed discussion of AGN.

Blazars are classified into BL Lacartae objects (BL Lacs) and Flat-spectrum Radio Quasars (FSRQs) according to the strength of the observed emission lines. The spectra of BL Lac consist out of no or weak emission lines while quasars have strong narrow and broad emission lines. BL Lac objects are also subdivided into three subclasses based on their Spectral Energy Distributions (SEDs) (see e.g. fig. 30 in Abdo et al. 2010). The subclasses are Low-Energy Peaked BL Lacs (LBL) with $\nu_{\rm peak} < 10^{14}$ Hz, Intermediate-Energy peaked BL Lac (IBL) with 10^{14} Hz $< \nu_{\rm peak} < 10^{15}$ Hz and High-Energy Peaked BL Lac (HBL) with $\nu_{\rm peak} > 10^{15}$ Hz (Abdo et al. 2010). The synchrotron emission peak is located at IR/optical for LBLs and FSRQs, and UV/soft X-ray for HBLs, while the inverse Compton (IC) emission peaks at GeV-energies for LBLs/FSRQs and at TeV-energies for HBLs. Padovani & Giommi (1996) also proposed that a distinction could be made between HBLs and LBLs in terms of the ratio of the X-ray to Radio flux from a source. The authors proposed that for HBLs $f_{\rm x}/f_{\rm r} \gtrsim 10^{-11.5}$, while the ratio will be below this for LBLs. Here the X-ray flux ($f_{\rm x}$) is measured in erg cm^{-2} s^{-1} between 0.3−3.5 keV, and the radio flux ($f_{\rm r}$) is measured in Janskys at 5 GHz.

The aim of this study is to classify and characterise possible extragalactic AGN through multi-wavelength analysis within the 95% error circle of *Fermi*-LAT sources in a search to find candidate Very High Energy sources (VHE). We have focussed on selecting sources classified as AGU within the *Fermi* 2LAC (Ackermann et al. 2011). These sources will most probable include BL Lacs and Flat Spectrum Radio Quasars (FSRQs). The candidate selection criteria included various properties such as photon spectral indices, redshifts, radio brightness, γ-ray variability and observability from southern latitudes.

Table 1. Twenty blazar candidates selected among the unidentified *Fermi* 2LAC objects.

2LAC name (1)	Counterpart (2)	Vmag (3)	SpI (4)	Radio Flux (mJy) (5)
2FGL J0044.7-3702	PKS J0045-3705	19.6	2.57	330
2FGL J0113.2-3557	**PKS 0110-361**	**20.58**	**2.16**	**78**
2FGL J0201.5-6626	PMN J0201-6638	20.56	2.25	168
2FGL J0644.2-6713	PKS 0644-671	20.69	2.16	218
2FGL J0730.6-6607	**CRATES J073047-660226**	**15.13**	**1.34**	**82**
2FGL J0855.1-0712	3C 209	19.78	2.62	1157
2FGL J0919.3-2203	NVSS J091922-220757	19.95	2.00	26
2FGL J1059.0+0222	PMN J1058+0225	–	2.29	97
2FGL J1106.3-3643	**PMN J1106-3647**	**19.4**	**2.2**	**53**
2FGL J1154.1-3242	PKS 1151-324	18.88	2.03	212
2FGL J1218.8-4827	**CRATES J121901-482624**	**17.53**	**2.4**	**65**
2FGL J1407.5-4257	PKS 1404-427	17.47	1.91	149
2FGL J1617.6-2526	PMN J1617-2537	–	2.52	120
2FGL J1624.4+1123	MG1 J162441+1111	17.64	2.65	113
2FGL J1803.6+2523	NVSS J180312-252118	14.19	2.83	166
2FGL J1955.0-5639	**1RXS J195503.1-564031**	**17.25**	**1.88**	**9**
2FGL J2040.2-7109	PKS 2035-714	17.47	2.03	481
2FGL J2049.8+1001	PKS 2047+098	–	2.38	295
2FGL J2108.6-1603	**NVSS J210833-160724**	–	**2.59**	**7**
2FGL J1848.6+3241	IVS B1846+326	17.77	2.43	1015

1. *Fermi*-LAT name, from the 2FGL catalogue (Nolan et al. 2012).
2. Possible radio counterpart within the 95% error circle of the unidentified *Fermi*-LAT sources.
3. V band magnitude for the 2FGL object.
4. The spectral index Γ; $dN/dE \propto (E/E_0)^{-\Gamma}$
5. Radio flux densities (in mJy) at 4.85 GHz.

2. Candidate selection criteria

Counterparts in the optical, radio and/or X-ray wavelengths for the blazar candidate sources in the *Fermi*-2LAC were selected by considering the criteria discussed below.

2.1. High galactic latitude sources

Near the galactic plane the source density is high and therefore to exclude sources lying in the galactic plane and to eliminate source confusion, only sources at high galactic latitudes were selected ($|b| > 10°$). The galactic distribution of the candidates is shown in Fig. 1.

2.2. Photon spectral index

The gamma-ray photon spectral index, Γ, was determined by Ackermann et al. (2011) assuming a power-law spectral function $dN/dE = N_0(E/E_0)^{-\Gamma}$. Blazars catalogued in the 2FGL have photon spectral indices in the range $1.2 < \Gamma < 3$ (see e.g. fig. 17 in Ackermann et al. 2011). The selected targets for the study have spectral indices which fall into this range, which indicates that the unidentified targets could possible be blazars.

2.3. Radio brightness

Radio brightness was used to select sources with proposed radio counterparts which are bright enough to be observed with the

HartRAO 26-m telescope. However, some sources that are faint in the radio band were still included in this study, because these sources met most of the selection criteria and could still contribute to the search for VHE sources. Radio flux densities at 4.85 GHz were obtained from data catalogued in the GB6 catalogue (Gregory et al. 1996). Targets with radio flux densities > 100 mJy at 4.85 GHz were regarded as radio bright and were selected for the study.

2.4. Observability

It has been proposed to use varies telescopes in South Africa in order to undertake the multi-wavelength observations. Optical telescopes include the SAAO 1.9-m telescope that can observe sources with declinations between $-90° < \delta < +20°$, the Boyden/UFS 1.5-m telescope and the Watcher Robotic telescope with an observable declination range of $-90° < \delta < +30°$. The HartRAO 26-m radio telescope can reach northern declinations of +45°. Therefore, a maximum allowed declination limit of +35° was applied for source selection.

The sources are also faint in optical and therefore an upper optical magnitude limit of 21 mag was applied, based on the limiting magnitudes of the telescopes we propose to use.

2.5. Gamma-ray variability

Blazars exhibit strong variability over various time scales (e.g. intra-night variability and long-term variability). For example, in previous studies it have been found that the optical magnitude variability of blazars range from 0.3 mag over a few hours to 1.2 mag within a single night (Fan et al. 2004). The variability of the targets is therefore an indication of whether the candidates have potential to be a blazars or not. *Fermi*-2LAC sources with a variability index VI > 41.6 have a 99% chance to be variable over the two year observation period (Ackermann et al. 2011) and therefore the VI was used as an appropriate guideline in order to determine whether the targets will be variable. Five of our selected candidates are above the 95% confidence level for gamma-ray variability, and are therefore favorable candidates for observations. Optical photometric observations will be undertaken to confirm the variability of the targets.

2.6. Redshift

Targets with no determined redshifts were selected for this study with the exception of 2FGL J2040.2-7109 (see Table 1), which has a measured redshift but is classified as an AGU in the *Fermi*-2LAC. Optical spectroscopic observations and analysis will be performed on the targets to search for the redshifts. This can be compared to the results previously obtained for blazars (see e.g. fig. 12 in Ackermann et al. 2011).

3. Target list

Twenty candidates have been selected within the 95% error boxes of the unidentified blazar-like *Fermi*-2LAC sources that matched the selection criteria detailed in the previous section. The candidate sources are all defined as Active Galactic Nuclei of unknown type (AGU), have no measured redshifts and are all located at high galactic latitudes. Table 1 displays the properties for the targets that have been selected and Fig. 1 shows their galactic distribution. The gamma-ray photon spectral indices correlate well with the blazar range given by *Fermi*-LAT observations (Ackermann et al. 2011). The targets highlighted in bold did not meet all of the selection criteria, but were still included in this study since they were classified as AGU and fulfilled most of the selection criteria.

Six of the sources have gamma-ray photon spectral indices $\Gamma \lesssim 2$, which may point to possible VHE candidates. For example, Abdo et al. (2009) found that for the majority of AGN detected at both GeV and Tev energies, the GeV photon index was harder than 2. This is also seen within the 2LAC, where an average photon index of $\Gamma = 2.13 \pm 0.30$ was found for GeV-TeV AGN. However, the detectability

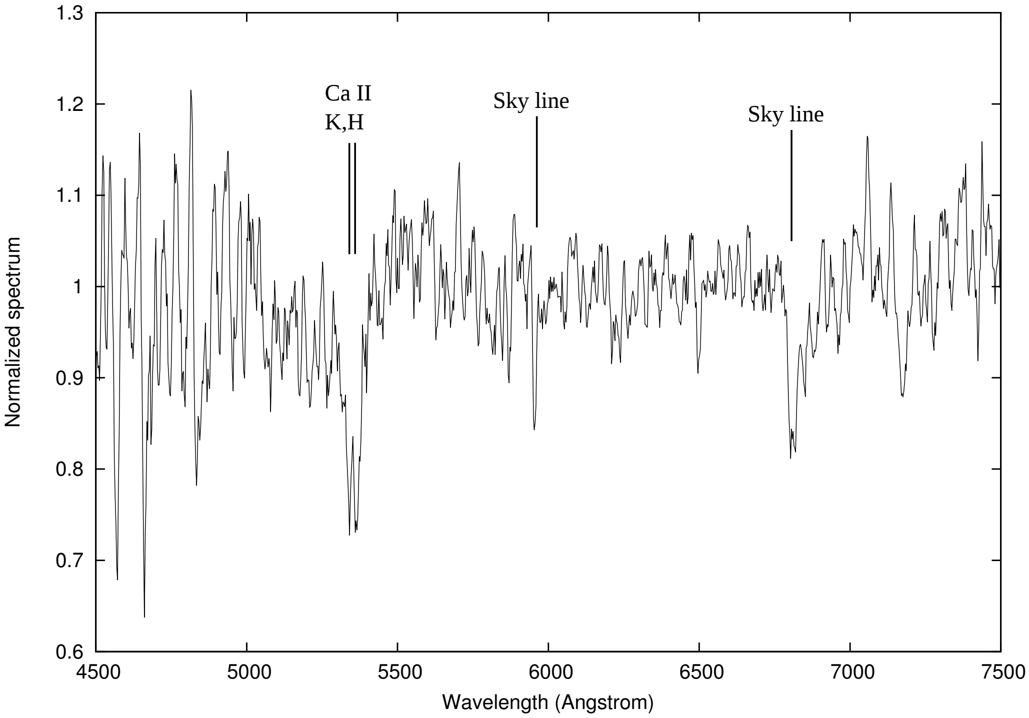

Fig. 2. Preliminary normalized spectrum of 2FGL J1218.8-4827 obtained with the SAAO 1.9-m telescope during May 2014 (resolution~ 5 Å). Potential Ca II H&K lines have been detected at 5397 Å and 5443 Å respectively. See Klindt, Meintjes & Van Soelen (2014) for a more detailed discussion.

of the candidate sources at VHE will depend on the observable flux and, therefore, further multi-wavelength observations are required to establish their redshift and SED.

4. Future works: multi-wavelengths follow-up studies

Follow-up observations at multi-frequencies are proposed for the target list using the HartRAO 26-m telescope at Hartebeesthoek (radio), the SAAO 1.9-m telescope (optical), Southern African Large Telescope (SALT) at the South African Astronomical Observatory (SAAO) near Sutherland, the Boyden/UFS 1.5-m telescope and the Watcher Robotic telescope near Bloemfontein. Spectroscopic observations of 8 of the targets have been performed with the SAAO 1.9-m telescope during June 2014 and the preliminary spectrum obtained for one of the targets, 2FGL J1218.8-4827, is shown in Fig. 2. Atmospheric lines are present at ~ 5800 Å and ~ 6800 Å, and potential Ca II H&K lines are present at 5397 Å and 5443 Å respectively. However, since the targets are faint (V-mag ~ 20) further follow-up observations are required with, for example, SALT.

Photometric observations of the candidates will be performed with the Sutherland High-speed Optical camera (SHOC) attached to the SAAO 1.9-m telescope during December 2014. The observations with SHOC will be used to search for variability of the targets, in particularly the intra-night variability which is related to shocks that propagate down the relativistic jet and interact with the surrounding medium (Marscher et al. 1991). Follow-up photometric observations will be undertaken with Watcher Robotic telescope at the UFS-Boyden Observatory and the Boyden/UFS 1.5-m telescope. The magnitude variability of blazars have been found in previous studies

(Fan et al. 2004) to vary from 0.3 mag over a few hours to 1.2 mag within a single night. Differential and absolute photometric observations will therefore be undertaken in order to search for short and long term variability and to determine the magnitudes of the target sample, which will contribute to the study of the properties of blazars and to estimate an upper mass limit of the SMBH (e.g. Meintjes & Nkundabakura 2013). The combined multi-wavelength analysis will allow us to construct a SED in order to classify and model the unidentified *Fermi* 2LAC sources.

5. Conclusions

In the search for VHE sources, AGN of unknown type in the *Fermi*-2LAC were selected to be classified and modelled with multi-wavelength analysis. The unidentified targets all exhibit blazar-like characteristics and selection criteria were established which were used to identify possible blazar-candidates. This has been used to construct a target list comprising of twenty high galactic latitude ($|b| > 10°$) counterparts within the 95% error circle. The selection criteria were based on properties such as the gamma-ray photon spectral index, radio brightness, V-band magnitude, observability from Southern latitudes, variability and redshift. Multi-wavelength follow-up studies will include optical spectroscopic and photometric observations with SAAO 1.9-m, SALT, Boyden 1.5-m telescope and Watcher Robotic telescope, potential radio observations with HartRAO 26-m. Sources which present the potential to be VHE sources can then be proposed to be observed with Imaging Atmospheric Cherenkov telescopes such as the High Energy Stereoscopic System (H.E.S.S.).

Optical spectroscopic observations with the SAAO 1.9-m have been undertaken during May/June 2014, which provided further motivation to use SALT to obtain higher signal-to-noise spectra of the targets. Photometric observations will be performed in the coming months in order to determine the variability of the targets. Multi-frequency on-line data will contribute to the construction of full SEDs for the targets which will allow classification and modelling of the unidentified 2LAC blazar-like sources.

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