Multi-wavelength classification of unidentified AGN in the *Fermi*-2LAC catalogue

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Abstract. Certain selection criteria have been applied to sources listed in the *Fermi*-2LAC catalogue in order to construct a target sample of twenty unidentified sources at high galactic latitudes with possible blazar characteristics. Blazars constitute the most violent and active astronomical objects which emit radiation at all wavelengths. Therefore multi-wavelength analysis provides the opportunity to construct a Spectral Energy Distribution (SED), which will allow the identification and modelling of the candidate sources. Preliminary spectroscopic results yield spectra of four observed targets which resemble that of BL Lac or flat spectrum radio quasars (FSRQs) with optical counterparts. Estimated redshifts are obtained within the range $0.11 < z < 0.37$. Potential Ca II H&K, MgIb and/or NaD spectral lines have been detected in the spectra of four targets, which motivates further observations in order to identify spectral lines that are possibly present.

1. Introduction

The *Fermi* Gamma-ray Space Telescope spacecraft with the Large Area Telescope (LAT) and the Gamma-ray Burst Monitor (GBM) have been in operation since August 2008. The LAT is the main instrument on the spacecraft and covers 20% of the sky at any time in the energy range 20 MeV to 300 GeV [1]. The *Fermi*-LAT 2-year Source catalogue (2FGL) consists of a clean sample of 866 sources of which 81% are blazars and 18% are candidate blazars of unknown type [2]. The aim is to classify possible extragalactic Active Galactic Nuclei (AGN) through multi-wavelength analysis within the 95% error circle of the *Fermi*-LAT, and to undertake spectral modelling of these systems.

AGN are extremely energetic objects powered by accretion onto a supermassive blackhole [3]. When the relativistic jet propagates close to our line of sight the AGN is classified as a blazar, and displays rapid variability, high polarization and non-thermal emission from the jet at multi-wavelengths. Blazars are classified into BL Lacartae (BL Lac) and Flat-spectrum Radio Quasars (FSRQs) according to the strength of their emission lines (see e.g., [4]). The spectra of BL Lac consist of no or weak emission lines while quasars have strong narrow and broad emission lines. Spectral energy distributions (SEDs) of blazars are characterised by two-peaks, namely a low-energy peak extending from radio to UV/X-rays, and a high-energy peak that extends from X-rays to GeV/TeV gamma-rays. The low-energy component is due to synchrotron emission, whereas the processes producing the high-energy component are still under debate, with models suggesting either leptonic or hadronic processes (see e.g., [5]). Depending on the peak frequency of the low energy component, BL Lac objects can be classified as either low-, intermediate-, or high-synchrotron peaked (LSP, ISP, or HSP) sources [6], with peak frequencies of $\nu_{peak} < 10^{14}$ Hz, $10^{14} \leq \nu_{peak} < 10^{15}$ Hz, or $\nu_{peak} > 10^{15}$ Hz, respectively.

Multi-wavelength observations will be undertaken in order to construct a SED which will allow modelling and classification of twenty unclassified 2 Year *Fermi*-LAT AGN Catalogue (2LAC) sources. These observations will be undertaken with the SAAO 1.9-m telescope (SpCCD and SHOC), the Southern Africa Large Telescope (SALT), the Boyden/UFS 1.5-m telescope, the Watcher Robotic Telescope and possibly the HartRAO 26-m radio telescope, which will be complemented with archival data obtainable at the NASA/IPAC Extragalactic Database (NED). The selection is based on criteria that consider properties such as high galactic latitude, photon spectral indices, redshifts, radio brightness and gamma-ray variability [7]. Spectroscopic observations will be utilized to determine the redshifts and spectral lines present of the targets and photometric observations will be used to determine the variability of the sources, particularly the intra-night variability. For BL Lac and FSRQs the intra-night variability may be an indicator of the non-thermal emission in shocked regions of the jets (see e.g., [7]). The optical observations will contribute to multi-wavelength observations with the aim to model the target sample.

2. Source Selection

Counterparts in other wavelengths of the blazar candidate sources in the *Fermi* 2LAC were selected by considering a certain selection criteria as discussed in Section 2.1.

2.1. *Selection Criteria*

2.1.1. *High galactic latitude sources*. Near the galactic plane the source density is high and therefore to eliminate source confusion and to exclude galactic background diffuse emission, only sources at high galactic latitudes were selected e.g. $|b| > 10°$.

2.1.2. *Gamma-ray Photon Spectral index*. Assuming a power law $dN/dE = N_0(E/E_0)^{-\Gamma}$ for blazars, the 2FGL blazar-type sources show spectral indices in the range of $1.2 < \Gamma < 3$ (see e.g., figure 17 in [2]).

2.1.3. *Error circle*. The counterpart has to be within the 95% (2 sigma) error circle that is associated with the *Fermi*-LAT object. This strategy was applied on the *Fermi*-LAT data which is available within the ASI Science Data Center (ASDC).

2.1.4. *Radio brightness*. Radio brightness was used to select sources within the error circles which are bright enough in the radio band for single dish observations e.g. the HartRAO 26-m telescope. However some sources that are faint in the radio band were still selected to contribute to this study. The Vizier database was used to obtain the radio flux densities at 4.85 GHz. The data were mainly catalogued in the GB6 [8]. Sources with radio flux densities above 100 mJy were considered to be radio bright and would be appropriate candidates for radio observations.

2.1.5. *Observability*. The declination of the sources had to be chosen such that multi-wavelength observations were possible from South Africa. The SAAO 1.9-m telescope can observe sources between $-90° < \mathrm{dec} < 20°$, while HartRAO can reach northern declinations up to 45°. The sources are also faint and therefore an upper optical magnitude limit of 21 mag was applied, based on the limiting magnitudes of the telescopes we propose to use.

2.1.6. *Gamma-ray variability*. Blazars exhibit strong variability over various times scales over all frequencies. Sources in the Fermi-2LAC are classified as being variable in gamma-rays in 24 time bins (one per month) if they have a variability index VI>41.6 (at a 99% confidence level) [1]. The detection of such variability is limited by the time bins and the brightness of the sources. The candidate sources we have selected have a range of variability indices, but 5 are above a 95% confidence level for gamma-ray variability. Further multi-wavelength observations are required to establish variability for the other sources

2.1.7. *Redshift*. For this study sources were selected which have no determined redshifts (with the exception of one source, see table 1). This, therefore, provides further motivation to observe the targets and compare the measured redshifts with that of previously obtained results for blazars (see e.g. figure 12 in [2]).

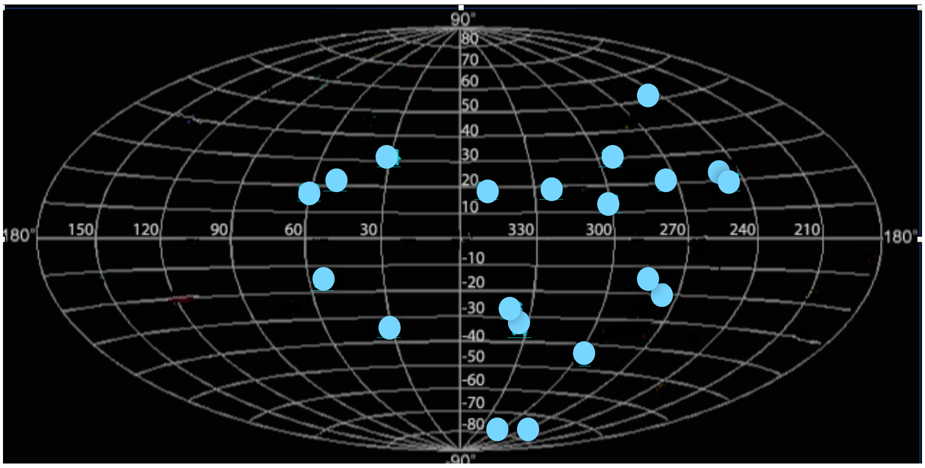

Figure 1. The galactic positions of the candidate sources that are tabulated in Table 1. All the sources are at high galactic latitude (/*b*/ > 10°) which ensures that the selected sources are outside the Galactic plane.

2.2. *Target list*

Twenty radio and optical counterparts have been selected within the 95% error boxes of the unidentified blazar-like *Fermi* 2LAC sources. The candidate sources are defined as Active Galactic Nuclei of unknown type (AGU) and are all located at high galactic latitudes (/*b*/ > 10°). The properties by which the targets have been selected are displayed in table 1, while the galactic distribution is shown in figure 1. The gamma-ray photon spectral indices correlate well with the blazar range given in *Fermi*-LAT observations [2].

3. Multi-wavelength follow-up studies

Radio, optical spectroscopic and photometric follow-up observations are proposed for the target list using the HartRAO 26-m telescope at Hartebeesthoek, the SAAO 1.9-m telescope and/or Southern African Large Telescope (SALT) at the South African Astronomical Observatory (SAAO) near Sutherland. Spectroscopic observations of a subset of targets targets have been performed with the SAAO 1.9-m telescope during June 2014, however since the targets are faint (V ~ 20 mag.) further spectra are required which will be proposed for SALT. Intended photometric observations of the sources will possibly be proposed for the Sutherland High-speed Optical camera (SHOC) attached to the SAAO 1.9-m telescope. The optical photometric measurements will be used to determine the variability of the targets which can be classified into three groups namely intra-day/night, short-term and long-term variability. Fast photometric observations with SHOC are proposed, with the aim to detect possible intra-night variability which is related to shocks that propagate down the relativistic jet and interacts with the surrounding medium. The observations proposed to detect the intra-night variability will be combined with a long-term monitoring campaign using the Watcher Robotic telescope at the UFS-Boyden Observatory. In previous studies it has been found that the magnitude variability of blazars ranges from 0.3 mag over a few hours to 1.2 mag within a single night [9]. Similar studies of selected unidentified counterparts of the EGRET sources have been undertaken, where one of the targets PKS 0820-5705 yielded an intra-night variability of 1.2 magnitude in the B-filter [7].

The *Fermi* data ranges from 20 MeV - 300 GeV and, therefore, to determine whether the targets peak in the TeV energies (such as high synchrotron peak BL Lac, HSP) multi-wavelength analysis is required to construct a Spectral Energy Distribution (SED). Blazars have characteristic SEDs which contain two peaks caused by processes within the systems namely synchrotron radiation (lower-frequency peak) and inverse Compton scattering (higher-frequency peak). The presence of the two peaks suggest blazar sources and the frequency at which the peak is located will allow one to determine whether it is a FSRQ or BL Lac.

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

No.	2LAC name (1)	Counterpart (2)	RA (hh mm ss) (3)	Declination (° ' ") (4)	Vmag (5)	SpI (6)	ePos (deg) (7)	SED (8)	Radio Flux (mJy) (9)	*z* (10)
1	2FGL J0044.7-3702	PKS J0045-3705	00 45 12	-37 05 48	19,6	2,57	0,153	-	330	-
2	2FGL J0113.2-3557	PKS 0110-361	01 12 39	-35 51 28	20,58	2,16	0,19	-	78	-
3	2FGL J0201.5-6626	PMN J0201-6638	02 00 53	-66 36 43	20,56	2,25	0,18	LSP	168	-
4	2FGL J0644.2-6713	PKS 0644-671	06 44 28	-67 12 57	20,69	2,16	0,05	-	218	-
5	2FGL J0730.6-6607	CRATES J073047-660226	07 30 50	-66 02 19	15,13	1,34	0,092	HSP	82	-
6	2FGL J0855.1-0712	3C 209	08 55 10	-07 15 07	19,78	2,62	0,213	-	1157	-
7	2FGL J0919.3-2203	NVSS J091922-220757	09 19 26	-22 00 45	19,95	2,00	0,163	LSP	26	-
8	2FGL J1059.0+0222	PMN J1058+0225	10 59 06	+02 25 04	-	2,29	0,151	-	97	-
9	2FGL J1106.3-3643	PMN J1106-3647	11 06 35	-36 46 59	19,4	2,2	0,14	-	53	-
10	2FGL J1154.1-3242	PKS 1151-324	11 54 32	-32 37 51	18,88	2,03	0,10	-	212	-
11	2FGL J1218.8-4827	CRATES J121901-482624	12 19 02	-48 26 27	17,53	2,4	0,144	-	65	-
12	2FGL J1407.5-4257	PKS 1404-427	14 07 40	-43 02 32	17,47	1,91	0,088	LSP	149	-
13	2FGL J1617.6-2526	PMN J1617-2537	16 17 21	25 37 23	-	2,52	0,168	-	120	-
14	2FGL J1624.4+1123	MG1 J162441+1111	12 24 55	11 12 28	17,64	2,65	0,306	-	113	-
15	2FGL J1803.6+2523	NVSS J180312-252118	18 03 12	+25 21 19	14,19	2,83	0,29	-	166	-
16	2FGL J1955.0-5639	1RXS J195503.1-564031	19 55 03	-56 40 30	17,25	1,88	0,076	HSP	9	-
17	2FGL J2040.2-7109	PKS 2035-714	20 40 08	-71 14 52	17,47	2,03	0,123	HSP	481	0,162
18	2FGL J2049.8+1001	PKS 2047+098	20 49 46	+10 03 14	-	2,38	0,139	-	295	-
19	2FGL J2108.6-1603	NVSS J210833-160724	21 08 33	-16 07 24	-	2,59	0,214	-	7	-
20	2FGL J1848.6+3241	IVS B1846+326	18 48 34	32 44 00	17,77	2,43	0,116	-	1015	-

(1) *Fermi*-LAT name (from 2FGL catalogue; Ackermann et al. 2011).
(2) Possible radio counterpart within the 95% error circle of the unidentified *Fermi*-LAT sources.
(3) Right ascension for counterpart.
(4) Declination for counterpart.
(5) V band magnitude for the 2FGL object.
(6) The spectral index alpha; $dN/dE = N_0(E/E_0)^{-\Gamma}$.
(7) The spectral index alpha; *Fermi*-LAT 95% error radius.
(8) Spectral energy distribution; Low-synchrotron peak (LSP) associated with LBLs; High-synchrotron peak (HSP) associated with HBLs.
(9) Radio flux densities (in mJy) at 4.85 GHz [8].
(10) Redshift of the unidentified source.

4. Spectroscopic Results

Spectroscopic observations of four targets undertaken with the SAAO 1.9-m telescope during May/ June 2014 are reported here. The preliminary spectra of the targets are mainly featureless showing potential absorption lines of the host galaxy as shown in figure 2. Ca II H&K lines ($\lambda_{rest,H}$ = 3935 Å; $\lambda_{rest,K}$ = 3970 Å) are present in the spectra of 2FGL J1218.8-4827, 2FGL J1407.5-4257 and 2FGL J2049.8+1001, and MgIb (λ_{rest} = 5174 Å) and NaD (λ_{rest} = 5894 Å) absorption lines are detected in the spectrum of 2FGL J0730.6-6607. Using the preliminary results a rough estimate of the redshifts have been determined (see table 2) with

$$z = (\lambda_{obs}/\lambda_{rest}) - 1, \quad (1)$$

where λ_{obs} is the observed wavelength and λ_{rest} is the rest wavelength of the corresponding absorption line. No other lines have been determined in the spectra since the sources are faint (V ~ 20 mag.) therefore one needs to consider further observations of the targets in order to confirm the presence of other possible spectral lines. When considering the estimated redshifts and the photon spectral indices of the sources, a comparison can be made with the redshifts determined in [2]. These preliminary redshifts resemble that of BL LAC or FSRQ objects which comprise a significant fraction of the *Fermi*-LAT gamma-ray sources [10; 11].

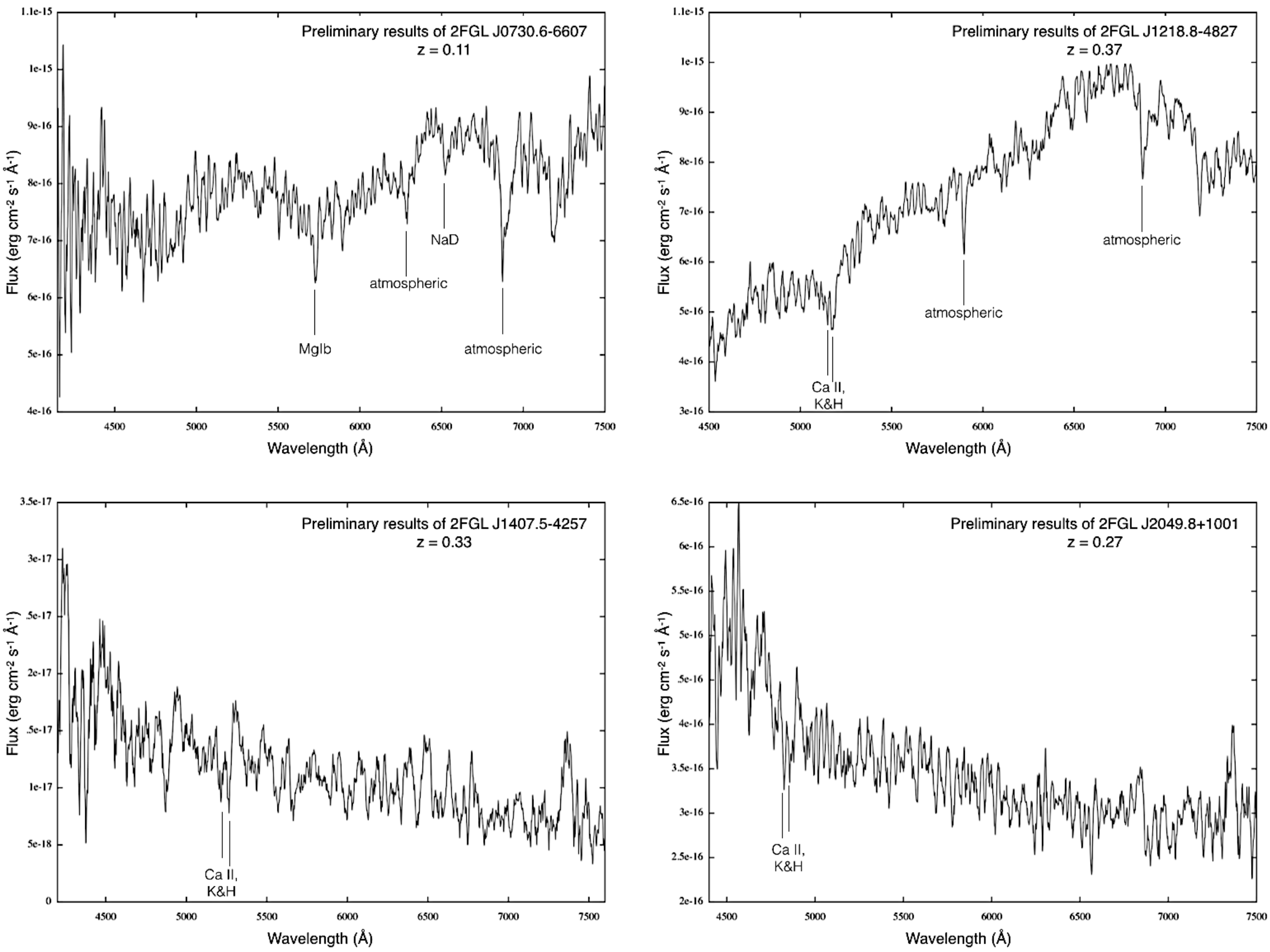

Figure 2. Spectra of four observed optical counterparts of the *Fermi*-2LAC targets with the SAAO 1.9-m telescope during May/June 2014. Potential Ca II H&K, MgIb and NaD lines are present. Estimated redshifts have been determined from the absorption lines giving a redshift range of 0.11 < z < 0.37.

Table 2. Measured absorption lines in the spectra of four unclassified *Fermi*-2LAC sources. Estimations of the redshifts are obtained from Ca II H&K, MgIb and NaD absorption lines that featured in the spectra.

2LAC name	Ca II, H (Å)	Ca II, K (Å)	MgIb (Å)	NaD (Å)	Redshift, z
2FGL J0730.6-6607	-	-	5727	6521	0.11
2FGL J1218.8-4827	5397	5443	-	-	0.37
2FGL J1407.5-4257	5210	5264	-	-	0.33
2FGL J2049.8+1001	4825	4863	-	-	0.23

5. Conclusion

The selection criteria which were used to identify possible blazar-candidates in the 2LAC have been applied to construct a target list comprising of twenty 2LAC sources. Only sources which are at high galactic latitude were included to ensure that the galactic diffuse emission was excluded and to limit confusion since the galactic plane is densely packed with sources. Spectroscopic observations for four of the unidentified *Fermi*-2LAC target sources undertaken compare favourably to that of blazars with non-thermal emission. We have identified Ca II H&K, MgIb and/or NaD absorption lines in the spectra of these sources which allowed for an estimation of the redshifts. The preliminary redshifts range $0.11 < z < 0.37$ allows one to conclude that the candidates lie in a similar redshift range as reported for the classified blazars [2]. Further multi-wavelength observations are underway to establish variability and the SEDs for these sources.

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