Optical spectroscopic observations of unclassified Active Galactic Nuclei in the Fermi-2LAC catalogue

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Abstract. Blazars constitute the most violent astronomical objects with relativistic jets emitting radiation at all frequencies. We report on optical spectroscopic observations of unclassified Active Galactic Nuclei (AGN) in the 2nd *Fermi*-LAT catalogue of AGN which exhibit blazar-like characteristics. The total target sample comprises of 19 AGN of unknown type (AGU) which are all at high galactic latitudes ($|b| > 10^{\circ}$) with optical and/or radio counterparts within the *Fermi*-LAT 95% error circle. We are commencing with a multi-wavelength campaign to classify the candidate sources by establishing Spectral Energy Distributions (SEDs) and to search for potential Very High Energy (VHE) candidates. Preliminary low-resolution spectra, obtained with the SAAO 1.9-m telescope and the Southern African Large Telescope (SALT), are mainly featureless as is expected for BL Lac objects, however Ca II K&H, MgIb and/or NaD absorption lines appear to be present, allowing for a first estimation of the redshifts which correlates favourably with that of known blazars. We report on the details of two of these sources. The shallow Ca II depression indicates that strong non-thermal emission is present in these targets and they are therefore good potential blazar sources.

1. Introduction

Active Galactic Nuclei (AGN) are galaxies that are believed to be powered by accretion onto a supermassive black hole ($M_{\rm BH} = 10^6 - 10^{10} M_{\odot}$) located at its centre. AGN can produce large relativistic jets, which emit multi-wavelength non-thermal radiation. When the relativistic jet propagates close to our line of sight the AGN is classified as a blazar, displaying rapid multi-wavelength variability, strong polarization, non-thermal emission and high apparent luminosities over the entire electromagnetic spectrum from the Doppler-boosted jet (see e.g. [1, 2, 3]). Depending on the strength of the optical emission features two distinct groups exist, namely BL Lacartae objects (BL Lacs) and Flat Spectrum Radio Quasars (FSRQs). BL Lacs are well known for their weak or absent spectral lines which is a result of the non-thermal emission in the jet that outshines the host galaxy emission. BL Lacs are optically defined as sources with emission and/or absorption lines with equivalent widths of $W_{\lambda} \leq 5$ Å, and a diluted Ca II break value less than 40% (see e.g. [4], [5], [6]). FSRQs on the other hand display both strong narrow and broad emission lines [7].

Spectral Energy Distributions (SEDs) of AGN 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 peak is due to synchrotron emission of relativistic electrons, whereas the processes producing the high-energy peak are still under debate, with models suggesting either leptonic or hadronic processes (see e.g. [8]). The leptonic model suggests that the high energy component is produced by inverse Compton (IC) scattering off either external photons from the accretion disc, dust torus or Broad Line region (External Compton - EC), or off photons produced by the synchrotron emission (Synchrotron Self Compton - SSC). In the hadronic model the emission of the high energy component is dominated by π^0 decay photons, pair cascades or synchrotron and Compton emission from secondary charged pions [9, 10, 11, 12].

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 [13], with peak frequencies of $\nu_{\text{peak}} < 10^{14}$ Hz, $10^{14} \leq \nu_{\text{peak}} < 10^{15}$ Hz, and $\nu_{\text{peak}} > 10^{15}$ Hz, respectively. Blazars exhibit diverse properties which have been studied for years, however, many questions still remain about the physical processes involved and the demographics of these sources which therefore motivates the importance of classifying and modelling these sources over multi-wavelengths.

Based on the above mentioned observational characteristics of blazars, we have identified an original target sample of 19 Active Galactic Nuclei of Unknown type (AGU) in the 2 year *Fermi*-LAT AGN Catalogue (*Fermi*-2LAC), and place particular focus on 10 targets, with the aim to classify these systems through multi-wavelength observations, and to contribute to our search for Very High Energy (VHE) sources. We have based the sample selection on criteria similar to those previously employed by [14] in a study of unidentified sources listed in the Energetic Gamma Ray Experiment Telescope (EGRET) catalogue. Onboard the *Fermi* Gamma-ray Space Telescope spacecraft is the Large Area Telescope (LAT) which has observed every region of the sky for 30 minutes every 3 hours since August 2008. The energy range covered by LAT is 20 MeV to 300 GeV [15]. In the *Fermi*-LAT 2-year Source catalogue (866 sources in the clean sample) 81% of the sources are classified as blazars and 18% as AGU which exhibit blazar characteristics [16]. We have focused on classifying a subset of these AGUs through multi-wavelength analysis which includes optical spectroscopic and photometric observations and single dish radio observations. Here we report on the optical spectroscopic results obtained for two targets namely 2FGL J1154.1-3242 and 2FGL J0730.6-6607.

2. Sample selection

The original sample we chose from the 157 AGU sources listed in the *Fermi*-2LAC included 19 targets which are observable from Southern Africa, and were selected for multi-wavelength follow-up observations (radio to gamma-rays) in order to determine their unknown properties. In the 2LAC catalogue the most likely radio and/or X-ray counterparts to the Fermi sources were established using three different statistical tests which also considered the source density in the region surrounding the LAT source [16]. We have proposed to observe the established optical/IR counterpart to the best candidate radio sources. With a few exceptions the following criteria apply to our sample (see full discussion [17]):

- Observability from Southern latitudes: to enable the utilization of the optical telescopes we used a declination limit of $-90° \leq \delta \leq +20°$. Two sources with declinations exceeding this limit were still included in our sample due to their high radio brightness and were consequently candidate sources for radio observations with the HartRAO 26-m telescope which can observe up to $\delta < 45°$.
- High Galactic latitude sources $|b| > 10°$.
- Gamma-ray photon spectral index: $1.2 < \Gamma < 3$ where $dN/dE = N_0(E/E_0)^{-\Gamma}$ (see e.g. figure 12 in [16]).

Table 1. Candidate AGUs in the *Fermi*-2LAC catalogue with blazar characteristics. The radio counterparts within the 95% error circle are listed with their corresponding V magnitude, target position, gamma-ray spectral index (Γ), radio flux density at 4.85 GHz ($S_{4.85}$) and variability index (VI). The preliminary estimated redshifts (z), obtained from the observations reported here, are also listed.

2LAC Name	Vmag	RA_{J2000}	Dec_{J2000}	Γ	$S_{4.85}$	VI	z
J0044.7-3702	19.60	00:45:12	-37:05:49	2.57	330	92.7	
J0201.5-6626	20.56	02:01:08	-66:38:13	2.25	168	39.8	
J0644.2-6713	20.69	06:44:28	-67:12:57	2.16	218	99.6	
J0730.6-6607	15.13	07:30:50	-66:02:19	1.34	82	26.8	0.106 ± 0.001
J0855.1-0712	19.78	08:55:09	-07:15:03	2.62	1157	31.2	
J1106.3-3643	17.41	11:06:24	-36:46:59	2.20	92	24.1	
J1154.1-3242	18.88	11:54:06	-32:42:43	2.03	212	20.5	0.224 ± 0.019
J1218.8-4827	17.53	12:19:02	-48:26:28	2.40	65	26.6	
J1407.5-4257	17.47	14:07:39	-43:02:34	1.91	149	22.9	
J1955.0-5639	17.25	19:55:03	-56:40:29	1.88	9	23.7	

- Radio bright sources: $S_{4.85\ GHz} \geq 100$ mJy.
- $V_{mag} \leq 21$; fainter targets are excluded from the sample due to observational limitations.
- No determined redshift (z).
- We also considered the *Fermi*-LAT variability index (VI) to determine the probability for a source to be variable, though this was not used as a strict selection criteria; sources with a variability index of $VI > 41.6$ have a 99% chance to be variable over the two year observation period. [14, 16, 18].

Based on the above mentioned criteria we are focusing on observations of 10 targets from our original sample of 19 (see table 1). These selected sources are all still identified as AGU in the very recently released 3FGL catalogue [19]. The updated positions correspond to those previously reported in the 2LAC catalogue. (In the 3LAC catalogue the number of sources has increased to 402 Blazar Candidates of Unknown type (BCU) in the Clean Sample [20]).

3. Optical observations and data analysis

The optical observations and data analysis undertaken with the SAAO 1.9-m telescope and the Southern African Large Telescope (SALT) are summarized below.

3.1. SAAO 1.9-m telescope

Optical spectra were obtained for 8 targets of the original sample (19 AGUs) during May/June 2014 with the SAAO 1.9-m telescope. We report specifically on the results obtained for one of the targets, 2FGL J1154.1-3242, on 22 and 25 May 2014. In order to search for potential lines we have undertaken broadband spectroscopic observations utilizing the SpCCD spectrograph with grating 7 in order to achieve a wavelength range of 4200 Å (spectral resolution of ~ 5 Å). The broad wavelength range allows for a wavelength coverage from approximately 3200 Å to 8000 Å. In order to achieve a signal-to-noise ratio (SNR) ~ 10, five exposures of 3600 s each were acquired and averaged. The standard spectroscopic reduction steps in IRAF were used to reduce the two-dimensional data using copper-argon comparison spectra taken after each target spectrum.

3.2. SALT
Five sources have been observed with SALT during Semester I 2015 (December 2014 – March 2015), using the Robert Stobie Spectrograph (RSS) with the pg0300 grating and with two different Camera Stations, namely 10.0° and 11.5°. We report on observations obtained for 2FGL J0730.6-6607 on 31 December 2015. The chosen configurations allowed us to access the 3200 Å – 9500 Å visible wavelength range with a resolving power of $R = 530$. We used 2 spatial dither positions (two separate spectra at different locations of the slit, shifted in the vertical axis) with an offset of 10 arcsec in order to correct for fringing effects at the longer wavelengths. In total four exposures of 120 s and 126 s each were obtained for the two configurations, respectively. The data were reduced using IRAF packages with the standard steps and by combining the one-dimensional spectra.

4. Results and Discussion
Here we only report on the results obtained for two targets, however spectroscopic data have thus far been obtained for 9 of the targets with the SAAO 1.9-m telescope and SALT, for which reductions are currently on-going. A report on the spectra of 4 of the targets is shown in [17]. A comparison between the estimated redshifts and the gamma-ray photon spectral indices of the sources, places them within the blazar range as shown in figure 19 of [16].

4.1. SAAO 1.9-m telescope observations of 2FGL J1154.1-3242
Ca II H&K and G-band absorption lines appear to be present at 4860, 4894 and 5174 Å, respectively, in the target spectrum of 2FGL J1154.1-3242 (V = 18.88 mag.) as shown in figure 1. This gives a redshift measurement of $z = 0.224 \pm 0.019$. The shallow Ca II break indicates that strong non-thermal emission is present in this target and it is therefore a potential blazar source. Similar results have been reported for a FSRQ (PKS J0820-5705) by [14].

4.2. SALT observations of 2FGL J0730.6-6607
The RSS spectrum obtained for 2FGL J0730.6-6607 is shown in figure 2. These results show absorption features, namely Ca II H&K, MgIb and NaD, which led to a redshift measurement of $z = 0.106 \pm 0.001$. We have obtained a Ca II break value of 16% and, therefore, it can be concluded that strong non-thermal emission dominates the host galaxy emission. We have obtained similar results from data undertaken with the SAAO 1.9-m telescope which is reported in [17].

5. Multi-wavelength follow-up studies
In order to successfully classify the identified sources in our sample, multi-wavelength data are required. In the optical regime we have obtained spectra for 5 targets with the SAAO 1.9-m telescope and SALT (reductions currently on-going). Six targets have been accepted for RSS observations with SALT during 2015 Semester II. Photometric observations with the Sutherland High-speed Optical Camera (SHOC) on the SAAO 1.9-m telescope were also undertaken during December 2014. These complementary observations focused on searches for rapid photometric variability which is related to shocks that propagate down the relativistic jet and interact with the surrounding medium [21].

Further multi-wavelength observations are planned, in particular radio observations with the HartRAO 26-m telescope, as well as the search of archival data in, for example, ASI Science Data Centre (ASDC)[1]. An Example of the SED of 2FGL J0730.6-6607 obtained in ASDC is shown in figure 3. The SED of this target clearly indicates two peaks at frequencies that potentially

[1] http://www.asdc.asi.it/fermi2lac/

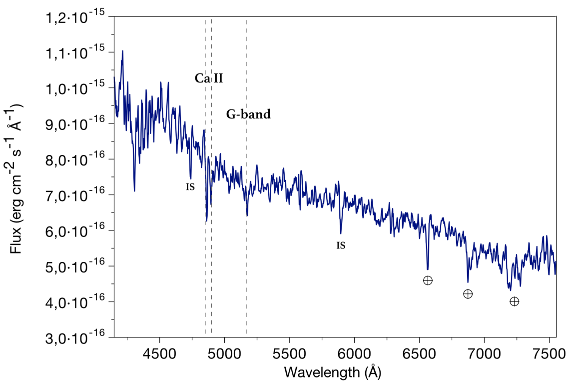

Figure 1. Optical spectrum of 2FGL J1154.1-3242 (V∼18.88 mag.) obtained with the SAAO 1.9-m telescope during May 2014. A redshift of $z = 0.224 \pm 0.019$ was obtained from the potential Ca II H&K and G-band absorption lines. Telluric lines are indicated with crossed circles.

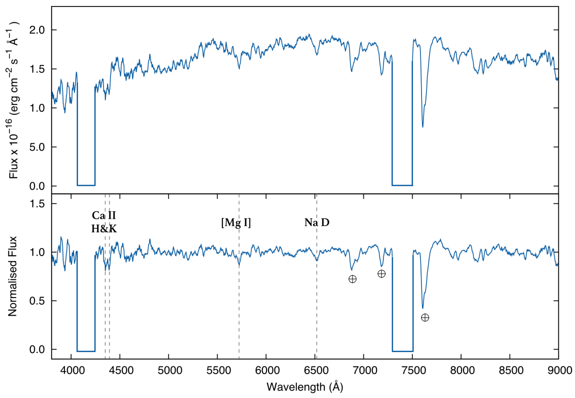

Figure 2. Flux calibrated RSS spectrum of 2FGL J0730.6-6607 (V∼15.13 mag.) obtained with SALT on 31 December 2015. A redshift of $z = 0.106 \pm 0.001$ was obtained from the Ca II H&K, MgIb and NaD lines. Top panel: flux calibrated spectrum. Bottom panel: normalized spectrum.

resemble that of HSP sources, making 2FGL J0730.6-6607 a candidate target for VHE follow-up studies.

6. Conclusion

The optical spectra obtained with the SAAO 1.9-m telescope and SALT during 2014 show promising results with the absorption features of the host galaxy present, namely Ca II H&K, MgIb and NaD lines. This allowed for estimated redshift values of $z = 0.224 \pm 0.019$ and $z = 0.106 \pm 0.001$ for 2FGL J1154.1-3242 and 2FGL J0730.6-6607, respectively. The shallow Ca II break ($< 40\%$) indicates that the targets are potentially blazars which exhibit multi-frequency non-thermal emission. In BL Lacs specifically the non-thermal emission from the jet decreases the Ca II break since the break is related to the viewing angle of the system (e.g. [5]). The double-humped shape of the SEDs with a low-energy synchrytron peak and high-energy peak resemble that of AGNs as expected, which is our first step towards classifying the identified sources in the *Fermi*-2LAC with the aim to search for VHE candidate sources. A few targets are potential HSPs and are, therefore, worth following up with TeV observations.

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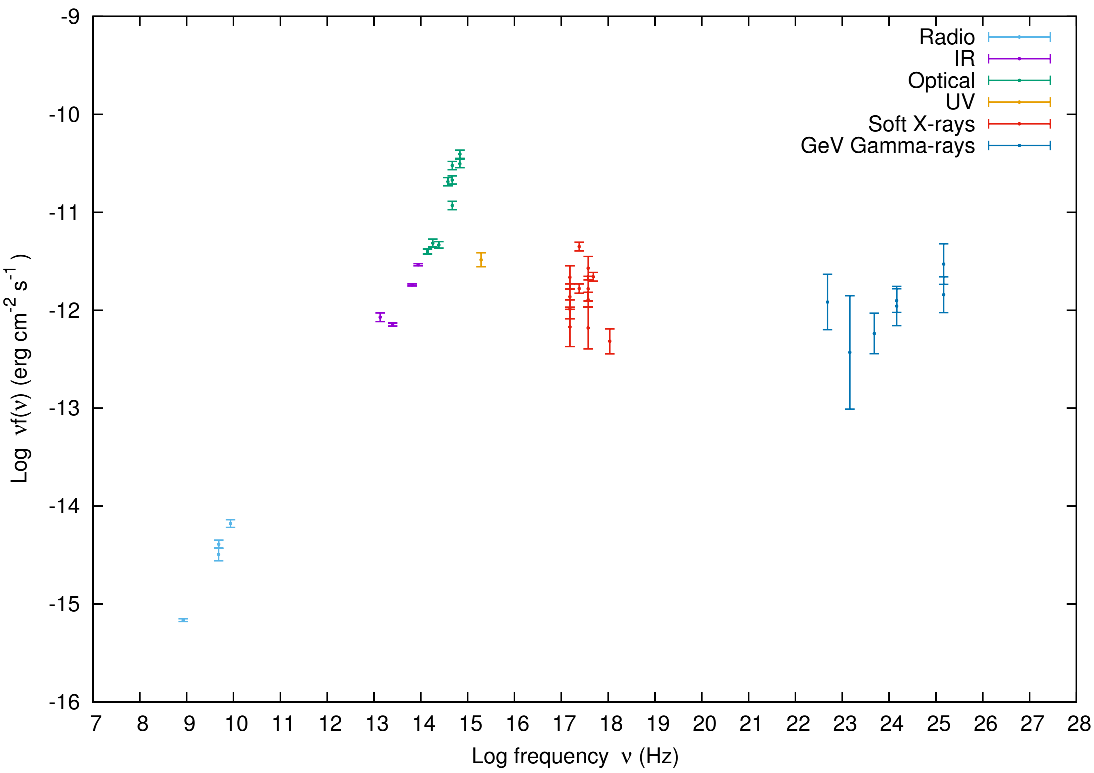

Figure 3. A Spectral Energy Distribution (SED) of 2FGL J0730.6-6607 obtained from the available multi-wavelength archived data in ASDC. The SED clearly shows the double-humped shape which is characteristic of blazars. The high-energy component shows a hard spectral index, which makes this target a VHE candidate source.

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