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Characterising the *Fermi*-LAT BCUs: Optical Spectroscopy and Neural Networks

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The *Fermi*-LAT telescope has provided an unprecedented view of the GeV gamma-ray sky since its launch in 2008. The latest *Fermi*-LAT catalogue of Active Galactic Nuclei lists 1591 sources associated with AGN, of which 460 are classified as blazar candidates of uncertain type (BCU). The characterisation of the physical properties of these BCU sources is important for observational cosmology and fundamental physics, as these sources and their environments constitute a natural laboratory to study particle acceleration and matter/radiation interactions in extreme conditions. Of particular interest is the search for new and interesting/unusual sources that may be observable at very high energies by ground-based imaging atmospheric Cherenkov telescopes. Based on the observed gamma-ray properties, a number of machine learning techniques are being investigated to classify these sources. However, the classification of a blazar as a FSRQ or BL Lac depends on the optical spectral properties. Here we discuss the work that we have thus far undertaken to optically characterise a selection of sources as well as future plans to undertake classification to help calibrate an artificial neural network method.

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1. Introduction

Blazars are radio loud Active Galactic Nuclei (AGN) where the propagation direction of the relativistic jet lies close to our line of sight. This results in the thermal component of the active galaxy being overpowered by the highly Doppler boosted non-thermal emission produced in the jet. As a result, blazars are the most numerous, non-transient, γ-ray sources detected by *Fermi*-LAT. In the third *Fermi*-LAT catalogue (3FGL), of the 1785 catalogued γ-ray sources, 1088 ($\sim 61\%$) are listed as blazars, with a further 568 ($\sim 32\%$) listed as blazar candidates [1].

Blazars are sub-divided into flat spectrum radio quasars (FSRQs) or BL Lacs based on their spectral properties. FSRQs show strong emission lines, while BL Lacs show mainly featureless spectra with weak or no emission lines. Typically, a source is classified as an FSRQ if it shows emission lines with equivalent widths $|W_\lambda| > 5$ Å, while it is classified as a BL Lac if the equivalent widths are $|W_\lambda| < 5$ Å (e.g. [2, 3]). This can be understood as FSRQs having a higher accretion rate than BL Lacs (and hence more luminous accretion discs), which leads to a greater ionization of the broad and narrow line regions (see e.g. [4, 5, 6] and reference therein). Blazars can also be further subdivided into low-, intermediate- or high-synchrotron peaked blazars based on where the synchrotron component of the spectral energy distribution (SED) peaks. The limits are $\nu_{\rm peak} < 10^{14}$ Hz, 10^{14} Hz $< \nu_{\rm peak} < 10^{15}$ Hz and $\nu_{\rm peak} > 10^{15}$ Hz, respectively (e.g. [7]).

The *Fermi*-LAT 3LAC includes 1444 extra-galactic sources (in the clean sample) which are above $|b| > 10^\circ$ [7]. This includes 402 sources which are listed as blazar candidates of unknown type or BCUs (table 1). There are three different BCUs types, depending on whether the source has a published optical spectrum, which is not sensitive enough for classification (BCU I), whether there is no optical spectrum but the synchrotron peak in the SED can be found, (BCU II) or if there is no spectrum, but the source shows a blazar-like multi-wavelength SED (BCU III). These sources are an important sample to identify new TeV candidate sources that can be observed with ground-based imaging atmospheric Cherenkov telescopes (IACTs). This is particularly true for the 60 BCUs which are included in 2nd catalogue of Hard Fermi-LAT sources (2FHL) detected above 50 GeV [8].

In order to search for new sources we are currently undertaking a project to obtain optical spectra of a selection of BCUs in order to classify the sources and determine their redshifts. The redshift is particularly important for TeV observations since sources beyond $z \gtrsim 1$ are unobservable at TeV energies due to attenuation from the extragalactic background light (EBL; [9, 10, 11]). Of particular interest is the search for non-blazar sources, since only a few of these have been detected at TeV energies. Currently only 6 FSRQs and 4 radio galaxies are listed in TeVCat, compared to 57 BL Lacs.[1]

However, the large number of sources can make detailed spectroscopic follow-up of all sources difficult. For this reason, machine learning techniques are currently been developed to classify *Fermi*-LAT sources based on their γ-ray properties. Recently an artificial neural network (ANN), based on the γ-ray flaring pattern was presented by Chiaro et al. [12]. However, such methods are dependent on having classified sources that can be used to train the network. Increasing the number of classifications will significantly assist with the training of these ANNs.

[1] http://tevcat.uchicago.edu/: accessed 22 November 2016.

AGN classification	Entire 3LAC	Clean sample	Low-latitude sample
FSRQs	467	414	24
BL Lacs	632	604	30
BCUs	460	402	2
Total	**1591**	**1444**	**182**

Table 1: Summary of the source classification in the *Fermi*-LAT 3LAC [7].

This paper is structured as follows: section 2 briefly summarizes the B-FlaP method, section 3 summarizes our previous observations as well as presenting preliminary results for 3FGL J1507.6-3710, while the discussion and final conclusions are presented in section 4.

2. B-FlaP method- artificial neural networks

Chiaro et al. [12] have developed an ANN method to distinguish between FSRQ and BL Lac sources in the 3LAC catalogue based on the observed flaring pattern. The method is based on an analysis of the Empirical Cumulative Distribution Function (ECDF) of the gamma-ray light curves. These should differ in shape due to the brightness and frequency of flares observed from these sources. This classification scheme is based upon the hypothesis that BL Lacs will have fewer large flares, and smoother light curves than FSRQs.

The ANN is constructed using a two-layer feed-forward network, which consists of 10 input nodes, 6 hidden nodes and 2 output nodes. The input nodes are the flux values of the ECDFs at the 10, 20, 30, 40, 50, 60, 70, 80, 90 & 100th percentiles. The ANN assigns a likelihood (L_{BLL}) for a sources to be a BL Lac or an FSRQ ($L_{FSRQ} = 1 - L_{BLL}$). After training the ANN on $\sim 70\%$ of classified sources, a 90% accurate classification of the testing sample was obtained by assigning limits of $L_{BLL} > 0.566$ for BL Lacs and $L_{BLL} < 0.230$ for FSRQs. No classification is made for sources that are in between these limits. The ANN was applied to the *Fermi*-LAT BCUs and classified 342 BL Lacs and 154 FSRQs.

3. Optical classification

Our optical observations to classify *Fermi*-LAT BCUs started with sources listed in the previous *Fermi*-LAT 2LAC catalogue [13]. In our initial observations we focused on selecting candidate sources from the *Fermi*-LAT 2LAC that were unclassified, and had no redshift measurement (or had redshifts from low quality spectra) [14]. The selected candidates were limited to sources observable with South Africa based telescopes and spectroscopic observations have been undertaken with the Southern African Large Telescope (SALT; [15, 16, 17]), and the SAAO 1.9-m telescope, located at the South African Astronomical Observatory (SAAO) near Sutherland. So far 7 sources from the 2LAC catalogue have been classified as summarized in table 2 [14]. In addition, photometric observations to search for short and long term variability have been undertaken with the Sutherland High Speed Camera (SHOC; [18]) and the Watcher Robotic Telescope, respectively [19, 20].

2LAC name	Optical	ANN
J0044.7-3702	FSRQ	FSRQ
J0201.5-6626	FSRQ	-
J0644.2-6713	FSRQ	FSRQ
J0730.6-6607	BL Lac	BL Lac
J1218.8-4827	BL Lac	-
J1407.5-4257	BL Lac	BL Lac
J2049.8+1001	BL Lac	-

Table 2: Summary of source classification from the optical spectra [14], with a comparison to the results predicted by the ANN [12].

Our observation campaign has been extended to include unclassified sources listed in the 3LAC with priority given to sources included in the 2FHL catalogues. Below we briefly summarized the preliminary results for one source included it the 3LAC catalogue.

3.1 3FGL J1507.6-3710

3FGL J1507.6-3710 is listed as a BCU II in the 3LAC catalogue, and is characterised as an intermediate synchrotron peak blazar ($\nu_{\rm peak} = 3 \times 10^{14}$ Hz). The source is detected at a 5.5σ significance with an average flux of $F(1-100\ \mathrm{GeV}) = (4.4\pm0.9)\times10^{-10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ with a photon index of $\Gamma = 2.13\pm0.15$.

3FGL J1507.6-3710 was observed with the SpUpNIC spectrograph on the SAAO 1.9-m telescope on 2016 July 30. The spectra was reduced following the standard IRAF procedures and the preliminary, normalized spectrum is shown in figure 1. Based on the identified Ca H&K and G-band this source is at a redshift of $z = 0.240\pm0.001$. We also calculated a Ca H&K break value of $C = (f_+ - f_-)/f_+ \sim 0.13$ where the fluxes are measured between 3750–3950 Å and 4050–4250 Å in the galaxy rest frame [21, 22]. Non-active galaxies have a Ca H&K break which is $C \gtrsim 0.5$ [21], which indicates that the source has a non-thermal component. This, combined with the lack of strong emission lines, indicates that 3FGL J1507.6-3710 is a BL Lac. This confirms the classification predicted by the ANN [12].

4. Discussion and conclusions

Our on-going programme to increase the number of classified AGN sources continues to make progress. Thus far 7 new sources have been successfully classified and new observations of a selection of candidates were undertaken over three weeks in July/August 2016 with the SpUpNIC spectrograph. Here we have shown the preliminary results for one of these sources, 3FGL J1507.6-3710, which we have classified as a BL Lac at a redshift of $z = 0.240\pm0.001$. Further observation programmes are planned. In addition, these results can be used to help improve the accuracy of the machine learning technique developed by Chiaro et al. [12] since a larger number of classified sources will improve the training and increase the accuracy of the ANN.

Increasing the number of classified extra-galactic sources is important to improve our understanding of the origin of extra-galactic γ-ray emission. Given the large number of extra-galactic

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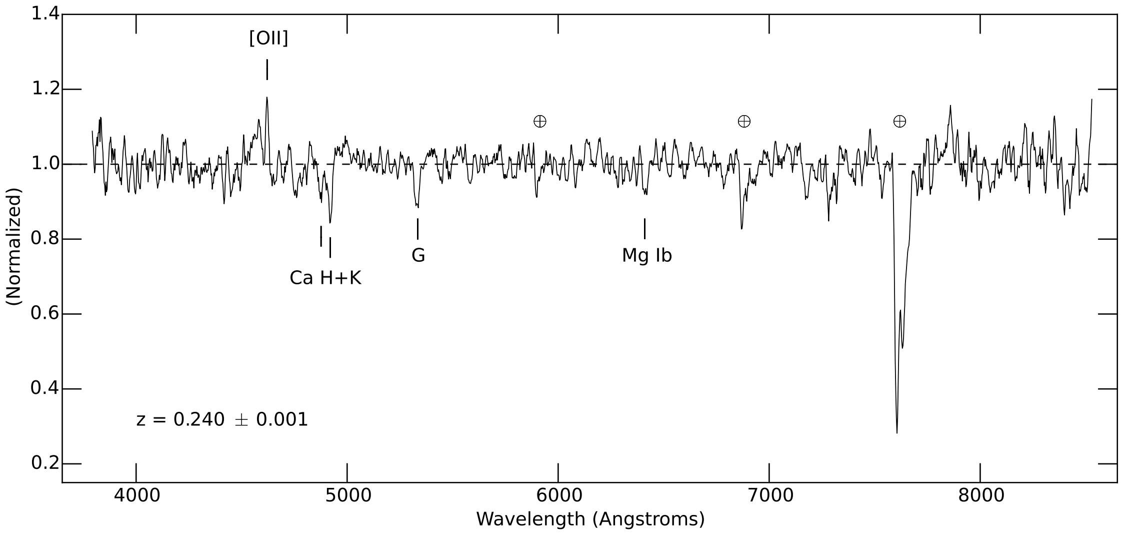

Figure 1: Combined optical spectrum for 3FGL J1507.6-3710, with the identified features marked. Telluric lines are marked with a $\oplus$.

sources, and the anticipated increase in sensitivity at TeV energies that will be possible with the Cherenkov Telescope Array (CTA; [23]), it is important to obtain classifications for the current BCUs. Optical spectroscopic programmes and machine learning techniques, such as briefly summarized here, are important tools for undertaking such classifications.

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