OPTICAL ARCHIVAL SPECTRA OF BLAZAR CANDIDATES OF UNCERTAIN TYPE IN THE 3RD FERMI LARGE AREA TELESCOPE CATALOG

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Abstract

Despite the fact that blazars constitute the rarest class among active galactic nuclei (AGNs) they are the largest known population of associated $\gamma$-ray sources. Many of the $\gamma$-ray objects listed in the Fermi-Large Area Telescope Third Source catalog (3FGL) are classified as blazar candidates of uncertain type (BCUs), either because they show multifrequency behaviour similar to blazars but lacking optical spectra in the literature, or because the quality of such spectra is too low to confirm their nature. Here we select, out of 585 BCUs in the 3FGL, 42 BCUs which we identify as probable blazars by their WISE infrared colors and which also have optical spectra that are available in the Sloan Digital Sky Survey (SDSS) and/or Six-Degree Field Galaxy Survey Database (6dFGS). We confirm the blazar nature of all of the sources. We furthermore conclude that 28 of them are BL Lacs, 8 are radio-loud quasars with flat radio spectrum and 6 are BL Lac whose emission is dominated by their host galaxy.

Subject headings: galaxies: active - galaxies: BL Lacertae objects - radiation mechanisms: non-thermal

1. Introduction

According to the unification scenario of radio-loud active galactic nuclei (AGNs), blazars are an extreme class of extragalactic sources, whose emission is due to a relativistic jet pointed closely aligned towards the observer's line of sight (see e.g., Blandford & Rees 1978, Urry & Padovani 1995). There are two main subclasses of blazars, flat spectrum radio quasars (FSRQ) and BL Lac objects. We label them according to the nomenclature of the Roma-BZCAT catalog (Massaro et al. 2009): if their optical spectrum is featureless or shows only optical emission/absorption lines with equivalent widths EW $< 5\AA$ (Stickel et al. 1991) the blazar is classified as BL Lac (i.e., BZB), while if it shows a typical quasar-like optical spectrum it is labeled as blazar of quasar type (i.e., BZQ). We also indicate BL Lacs exhibiting optical spectra of a typical elliptical galaxy (with a low Ca H&K break contrast) as BL Lacs of galaxy type (BZGs, see e.g. Massaro et al. 2012a, 2015 for details).

Although they have a low sky density ($\sim 0.1$ sources/degree$^2$), blazars constitute the most numerous population of extragalactic $\gamma$-ray sources. According to the Third catalog of active galactic nuclei detected by the Fermi-Large Area Telescope (3LAC, Ackermann et al. 2015), 29% of the sources detected are FSRQs and 41% BL Lacs. Also 28% of the sources detected above 100 MeV present multifrequency behaviour similar to blazars (e.g. flat radio spectra and/or X-ray counterpart, see e.g. Ackermann et al. 2015 and references therein), but often no optical spectra are available to precisely determine its class, or their signal-to-noise ratio could be too low to allow us a precise determination of their nature (Ackermann et al. 2012). When such situation occur $\gamma$-ray objects are classified as blazar candidates of uncertain type (BCUs). These sources belong to the $\gamma$-ray class labelled as active galaxies of uncertain type (AGUs) in the first and second releases of the Fermi-LAT Point Source Catalog (1FGL, Abdo et al. 2010 and 2FGL, Nolan et al. 2012). According to the 3LAC, the BCU sources are divided into three sub-types:

- **BCU I:** The counterpart has a published optical spectrum but it is not sensitive enough for a classification as a FSRQ or a BL Lac.
- **BCU II:** The counterpart is lacking an optical spectrum but a reliable evaluation of the SED synchrotron-peak position is possible.
- **BCU III:** The counterpart is lacking both an optical spectrum and an estimated synchrotron-peak position but shows blazar-like broadband emission and a flat radio spectrum.

Using the infrared (IR) colors as proxy of the blazar-like behavior, Massaro et al. (2012b) showed that BCUs feature the same IR emission as known $\gamma$-ray blazars (Massaro et al. 2011, D’Abrusco et al. 2012). Motivated by this result, a search of IR selected blazar candidates was also extended to include the unidentified/unassociated $\gamma$-ray sources (see e.g., Massaro et al. 2012a, D’Abrusco et al. 2013, Massaro et al. 2013) with different procedures developed and follow up observations (see e.g., Álvarez Crespo et al. 2016a, Álvarez Crespo et al. 2016b).
Here we combine the study of the IR colors of the BCUs with the search of the optical spectra available in the latest releases of Sloan Digital Sky Survey (SDSS DR12, Alam et al. 2015) and Six-Degree Field Galaxy Survey Database (6dFGS DR3, Jones et al. 2009), aiming to confirm their BL Lac or FSRQ nature and estimate their redshifts.

This updated search in the literature is complementary to our investigation of multifrequency observations (see e.g., Cowperthwaite et al. 2013, Massaro et al. 2013a; Paggi et al. 2013; Massaro et al. 2013b) and to the optical spectroscopic campaign carried out to confirm the blazar-like nature of BCUs and γ-ray blazar candidates selected to be potential counterparts of the UGSs (see e.g., Paggi et al. 2014; Massaro et al. 2015; Landoni et al. 2015; Ricci et al. 2015).

This paper is organized as follows: Section 2 describes the sample considered for the analysis and the underlying selection criteria; Section 3 is devoted to the archival optical analysis. Section 4 details the emission/absorption features of the sources. Finally, the summary and conclusions are given in Section 5.

We use cgs units unless otherwise stated. Spectral indices, $\alpha$, are defined by flux density $S_\nu \propto \nu^{-\alpha}$ and flat spectra when sources with $\alpha < 0.5$. WISE magnitude at [3.4], [4.6], [12], [22] μm (i.e., the nominal bands) are in the Vega system. WISE magnitudes are not corrected for the Galactic extinction since, as shown in our previous analyses, such corrections only affects significantly (i.e., but less than $\sim$3%) the magnitude at 3.4μ for sources lying at low Galactic latitudes (see e.g., D’Abrusco et al. 2014). This will also allow us a direct comparison with color-color diagrams published in previous works (Massaro et al. 2012a; Massaro et al. 2012b).

2. SAMPLE SELECTION

Our initial sample consists of 585 BCUs selected from the 3FGL. We first searched for the counterpart in the WISE all-sky survey in the AllWISE Source Catalog (Cutri et al. 2012) with a search radius of 3.3” (see D’Abrusco et al. 2014), to test whether their IR colors are consistent with those of known Fermi blazars (Massaro et al. 2011). In Figures 1 and 2 we overlay the IR counterpart of the BCUs in the [3.4] - [4.6] vs [4.6] - [12] color-color plane, locating those compatible with known γ-ray emitting BZBs and BZQs. The BZQs are located in the redder part of the locus occupied by the gamma-ray emitting blazars, while the BL Lacs lie on the bluer part, according to Massaro et al. (2012a). Afterwards we crossmatched the sky positions of their radio counterparts with SDSS DR12 and 6dFGS DR3 within 2 arcsec radius chosen, searching for the sources in the footprint of both surveys. We found 124 unique matches in the SDSS and 73 in the 6dFGS for the BCUs selected within 2 arcsec, however out of these crossmatches only 15 in SDSS and 22 on 6dFGS had a spectrum available.

SDSS DR12 represents the culmination of the third phase of the survey. It includes all data taken through 14 July 2014, and encompasses more than 1/3 of the entire celestial sphere, more than four million spectra (see Alam et al. 2015 for more details). On the other hand 6dFGS is a combined redshift and peculiar velocity survey which covers most of the southern sky, excluding galactic latitudes $|b| < 10$ degrees (see Jones et al. 2004, Jones et al. 2009).

We collected spectra and classified each source, determining the redshift in the cases where emission/absorption features were clear. We classify the source as noted above: as a BZB if the $EW_{rest} < 5\text{Å}$ when detected, as a BZG if the emission is dominated by the host elliptical galaxy rather than by non-thermal continuum arising from the jet (Massaro et al. 2012a); and when the $EW_{rest} > 5\text{Å}$ and flat radio spectrum, it appears as a BZQ.

In Table 1 we report the 1FGL, 2FGL and 3FGL names together with their classifications and the assigned counterpart for each release of the Fermi catalogs. In Table 2 we report the name of the BCUs in both 3FGL and WISE all-sky survey in the AllWISE Source catalog together with the survey name, the quality of the spectra for 6dFGS or the signal to noise ratio for SDSS, the classification and the redshift. In Table 3 we report the BCUs already included in the BZCAT, with the 3FGL name, the WISE all-sky survey name, the telescope, the quality of the spectra for the cases in which it was found in the 6dFGS, the classification, the redshift and some notes about each source.

3. ARCHIVAL OPTICAL ANALYSIS

We visually inspected all the optical spectra to avoid misclassifications due to artefacts from the automated spectral analysis and line identifications. The SDSS and 6dFGS classification performed by their automatic procedures sometimes give a value for the redshift for BZBs even though there is no clear evidence of emission/absorption lines. We ignore them, using our own values.

We emphasize that in the 6dFGS, redshift measurements are obtained semi-automatically, and spectra are assigned a quality value $Q$ based on visual inspection on a scale of 1 to 6 through assessment of every redshift. $Q = 1$ is assigned to unusable measurements, $Q = 2$ to possible but unlikely redshifts, $Q = 3$ for reliable redshifts and $Q = 4$ for high-quality redshifts (Jones et al. 2009). The quality of the spectra in the 6dFGS does not stand for the quality in terms of signal to noise as it is required in the 3LAC for the classification of a source as a BCU I, but only a visual assessment of the redshift. Since by definition most BL Lacs lack of emission/absorption features, their redshifts cannot be measured, so it is expected that the quality given by 6dFGS is $Q = 1$. To confirm this statement, we searched for sources classified as BL Lacs in the BZCAT in the footprint of 6dFGS, and checked the quality of the spectra. From the 82 BL Lacs with a spectrum in the 6dFGS, 51 have $Q = 1$, 16 $Q = 2$, 10 $Q = 3$ and 5 $Q = 4$. Consequently, even if $Q = 1$ or $Q = 2$, if we do not see any feature we classify the source as BZB.

Nine sources of our initial sample were already reported in the Roma-BZCAT, five of them outside the footprint of both sources considered. We include them in our analysis because they became available after the 3LAC publication, so we can update the latest release of the Fermi AGN catalog. For those outside the footprint we found their spectra in the literature and we were able to update the 3LAC classification. We report these Roma-BZCAT sources on Table (3) and the literature for which we found information is in the column (7), together with the Roma-BZCAT name.

We found that 28 sources are BZBs, and confirm/estimate the redshift only for 3 of them. Eight sources are classified as BZQs because they have a flat spectrum ($\alpha < 0.5$) in the radio band at 1-8 GHz and/or even at lower frequencies (Massaro et al. 2013b; Massaro et al. 2013d). The remaining six sources are classified as BZGs.

4. SOURCE DETAILS

10 http://wise2.ipac.caltech.edu/docs/release/allwise/
Here we report the details of the emission/absorption features found in each source. If the object is a featureless BZB, we do not mention it.

3FGL J0009.6-3211 was classified as a BZG at \( z=0.02 \) because of the absorption features G band (\( \lambda = 4416.9 \AA, \text{EW} = 18.1 \AA \)), Mg (\( \lambda = 5312.7 \AA, \text{EW} = 4.9 \AA \)) and Na (\( \lambda = 6052.9 \AA, \text{EW} = 3.3 \AA \)); and the emission line H\( \alpha \) (\( \lambda = 6763.8 \AA, \text{EW} = 1.8 \AA \)).

3FGL J0028.8+1951 was found to be a BZQ at \( z=1.55 \) because of the features C IV (\( \lambda = 1548.7 \AA, \text{EW} = 4.8 \AA \)); [C III] (\( \lambda = 1862.6 \AA, \text{EW} = 17.0 \AA \)); Mg (\( \lambda = 7137.9 \AA, \text{EW} = 29.3 \AA \)); [O III] (\( \lambda = 9494.6 \AA, \text{EW} = 8.6 \AA \)).

We found for the source 3FGL J0339.2-1738 the absorption features Ca H&K (\( \lambda = 3630.9 \AA, \text{EW} > 50.6 \AA \)), Mg (\( \lambda = 3630.9 \AA, \text{EW} > 50.6 \AA \)), Na (\( \lambda = 3630.9 \AA, \text{EW} > 50.6 \AA \)). It is a BZG at \( z=0.06 \).

For the source 3FGL J0904.3+4240 we find the following features: C IV (\( \lambda = 3630.9 \AA, \text{EW} > 50.6 \AA \)); [C III] (\( \lambda = 4462.1 \AA, \text{EW} = 39.9 \AA \)); Mg (\( \lambda = 6562.6 \AA, \text{EW} = 61.4 \AA \)) and O II (\( \lambda = 8727.6 \AA, \text{EW} = 13.9 \AA \)). Then we classify the source as a BZQ at \( z=1.34 \).

In 3FGL J1003.6+2608 assuming the line identified is O II (\( \lambda = 7194.9 \AA, \text{EW} = 4.9 \AA \)) the redshift estimate is \( z=0.93 \) for the BZB.

In 3FGL J1315.4+1130 there is an absorption feature, CA H&K (\( \lambda = 6801.7 - 6868.3 \AA, \text{EW}_{\text{obs}} = 2.0 - 4.4 \AA \)) that enables us to measure a redshift of \( z=0.73 \). and to classify it as a BZB.

We classify the source 3FGL J1322.1+0838 as a BZQ at \( z=0.32 \) because of the identification of the lines Mg (\( \lambda = 3683.4 \AA, \text{EW} > 48.7 \AA \)); Ca H&K (\( \lambda = 5218.6 - 5268.4 \AA, \text{EW} = 1.6 - 1.1 \AA \)); [O III] (\( \lambda = 6638.5 \AA, \text{EW} = 1.8 \AA \)); H\( \alpha \) (\( \lambda = 8726.1 \AA, \text{EW} = 4.7 \AA \)).

For 3FGL J1342.7+0945 we were able to identify the absorption features Ca H&K (\( \lambda = 5048.5 - 5091.6 \AA, \text{EW} = 1.8 - 2.0 \AA \)) and Mg (\( \lambda = 6636.9 \AA, \text{EW} = 1.9 \AA \)); and the emission lines O II (\( \lambda = 4782.3 \AA, \text{EW} = 2.4 \AA \)) and H\( \alpha \) (\( \lambda = 8436.4 \AA, \text{EW} = 5.9 \AA \)). It is a BZG at \( z=0.28 \).

In 3FGL J1412.0+5249, due to the absorption features Ca H&K (\( \lambda = 4236.1 - 4271.9 \AA, \text{EW} = 8.7 - 6.0 \AA \)); G band (\( \lambda = 4633.3 \AA, \text{EW} = 6.5 \AA \)); Mg (\( \lambda = 5571.1 \AA, \text{EW} = 6.0 \AA \)) and Na (\( \lambda = 6325.9 \AA, \text{EW} = 3.9 \AA \)), we classify it as a BZG at \( z=0.08 \).

The source 3FGL J2346.7+0705 is a BZB, but due to the absorption feature Ca H&K (\( \lambda = 4612.2 - 4649.0 \AA, \text{EW} = 0.3 - 0.9 \AA \)) it is possible to estimate a redshift of \( z=0.17 \).

In Figures 3, 4, and 5 we show the optical spectra for each one of the classifications of our analysis, as an example of a BL Lac, a BZQ and a BZG.

5. SUMMARY AND CONCLUSIONS

We performed a combined analysis of the mid-IR properties of the 43 BCUs in the 3LAC with the optical spectra. In Figures 1 and 2, we plot the positions of the BZBs and BZQs respectively, in the WISE IR color-color space in comparison with the \( \gamma \)-ray blazars from the WIBRaLS catalog that define the so called locus (peculiar position of blazars in the IR color-color space, D'Abrusco et al. 2014). The BZQs are located in the redder part of the locus, and the BL Lacs on the bluer part.

For those sources consistent with being a BL Lac or a FSRQ, we searched for archival optical spectra in both surveys SDSS DR12 (Alam et al. 2015) and 6dFGS DR3 (Jones et al. 2009) to confirm their nature and whenever possible to estimate their redshifts.

Based on the spectra of both surveys, we classified 28 sources as BL Lacs and determined the redshift for 3 of them, as a FSRQ for which there was radio information available in the literature and 6 BZGs. We corrected the automatic classification and redshift measurements for 3FGL J1315.4+1130. It is classified as a QSO as SDSS, but measuring the \( \text{EW}_{\text{rest}} \) of the emission lines we detected it is indeed a BL Lac, and we were able to measure a redshift of \( z=0.73 \) instead of the \( z=1.56 \) given by their automated classification.

We emphasize that our analysis will be useful not only to reduce the number of unclassified sources in the future release for the Fermi catalogs, but to improve our knowledge on the luminosity function of each of the different blazar classes (see e.g., Ajello et al. 2012) and thus help determine their contributions to the extragalactic background (see e.g., Ajello et al. 2014). This will translate into more stringent limits on the dark matter annihilation (Ajello et al. 2015, Ackermann et al. 2015) as well as on the imprint of the extragalactic background light on BL Lac spectra (see e.g., Ackermann et al. 2012). Our investigation will also be useful to select of potential targets for the Cherenkov Telescope Array (CTA) (Massaro et al. 2013d, Arsioli et al. 2015) in the near future.
known γ-ray emitting BZBs
new BZBs identified from the BCU sample

Fig. 1.— Projection of the BZBs of our sample in the WISE gamma-ray strip in the $[3.4] - [4.6]$ versus $[4.6] - [12]$ color-color plane.

known γ-ray emitting BZQs
new BZQs identified in the BCU sample

Fig. 2.— Projection of the BZQs of our sample in the WISE gamma-ray strip in the $[3.4] - [4.6]$ versus $[4.6] - [12]$ color-color plane.
Fig. 3.— The optical spectrum of WISE J131532.62+113331.7 from the SDSS, potential counterpart of 3FGL J1315.4+1130. It is classified as a BZB at $z=0.7$ on the basis of its featureless optical spectrum, dominated by non-thermal emission from the jet. The average signal to noise is 36.

Fig. 4.— The optical spectrum of WISE J002829.81+200026.7 from the SDSS, potential counterpart of 3FGL J0028.8+1951. Classified as a BZQ at $z=1.5517$ because of the identification of the lines C IV, He II, [C III], Mg and [O II]. The average signal to noise is 16.
Fig. 5.— The optical spectrum of WISE J141149.44+524900.2 from the SDSS, potential counterpart of 3FGL J1412.0+5249. The spectrum is dominated by the emission of the host elliptical galaxy and shows the doublet Ca H+K, the G band, [O III], Mg, He I, Na, Hα and Ar III. These features corresponds to a redshift of $z = 0.07649$. The average signal to noise is 41.
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| J0008.9+0635 | bli | CRATES J0008+0628 | J0009.0+0632 | bli | CRATES J0009+0628 |
| J0028.8+1951 | bcu | TXS 0028+197 |
| J0050.2+1646 | bcu | J0050 080 |
| J0063.5+0444 | bcu | J0063 120 |
| J0063.5+0444 | bcu | J0063 120 |
| J0146.5-5206 | agn | PKS 0146-522 |
| J0258.8-0552 | bcu | J0258 200 |
| J0339.1-1754 | agn | PKS0339-1754 |
| J0403.5-0329 | agn | PKS 0403-032 |
| J0403.5-0329 | agn | PKS 0403-032 |
| J0439.9-1858 | bcu | J0439 300 |
| J0521.6+0103 | bcu | J0521 300 |
| J1040.3+0616 | bcu | J1040 300 |
| J1256.5-1148 | agn | CRATES J1256-1148 |
| J1322.1+0838 | bcu | J1322 300 |
| J1340.5-0413 | bcu | J1340 300 |
| J1656.9-2008 | agn | J1656 200 |
| J2108.8-0636 | agn | PKS 2108-063 |
| J2118.3-3237 | agn | PKS 2118-323 |

**Table 1: Gamma-ray Name, Classification and Counterparts in the Fermi Catalogs**

| 1FGL | 1FGL | 1FGL | 2FGL | 2FGL | 2FGL | 3FGL | 3LAC | 3FGL |
|------|------|------|------|------|------|------|------|------|
| name | class | ctp | name | class | ctp | name | class | ctp |
| FRG 1FGL | FRG 1FGL | FRG 1FGL | FRG 2FGL | FRG 2FGL | FRG 2FGL | FRG 3FGL | FRG 3LAC | FRG 3FGL |

- bcu = AGN of uncertain type; bli = BL Lac; bq = Blazar of QSO type
- Column description: (1): 1FGL name, (2): 1FGL classification, (3): 1FGL assigned counterpart, (4): 2FGL name, (5): 2FGL classification, (6): 2FGL assigned counterpart, (7): 3FGL name, (8): 3LAC classification, (9): 3FGL assigned counterpart.
### TABLE 2

| 3FGL name | WISE name | Survey/telescope name | Q | SN classification | z |
|-----------|-----------|------------------------|---|------------------|---|
| J0000.6-3211 | J000353.55-321636.8 | 6dFGS | 4 | bzb | 0.02 |
| J0028.4-1931 | J002829.81+200026.7 | SDSS | - | 24 | bqb | 1.55 |
| J0031.2-1646 | J003119.40-164711.7 | 6dFGS | 1 | - | bzb | 1.63 |
| J0156.9-4742 | J015646.03-474417.5 | 6dFGS | 1 | - | bzb | 0.06 |
| J0255.6-0532 | J025549.51+053350.0 | SDSS | - | 32 | bzb | 1.55 |
| J0339.2-1736 | J033917.70+173608.6 | 6dFGS | 4 | - | bzb | 0.02 |
| J0439.9-1859 | J043949.72-190101.5 | 6dFGS | 2 | - | bzb | 1.55 |

### TABLE 3

| 3FGL name | WISE name | Survey/telescope name | Q | SN classification | z | Notes |
|-----------|-----------|------------------------|---|------------------|---|-------|
| J0003.8-1151 | J000404.91-114858.3 | 6dFGS | 4 | bzb | 0.02 | 5BZB J0004-1148 |
| J0147.0-5204 | J014648.38-520211.7 | 6dFGS | 4 | bzb | 0.09 | 5BZG J0146-5202 |
| J0501.6-7157* | J050118.47-715634.5 | GemN | bzb | 0.82 | 5BZG J0501-7156 |
| J0543.4+3822* | J054328.94+382212.4 | Palomar | bzb | 1.48 | 5BZG J0543+3822 |
| J0645.7-6028* | J064534.59-602101.5 | GemN | bzb | 0.93 | 5BZG J0645-6030 |
| J0648.4-2343* | J064828.59-234205.5 | NTT | bzb | 0.30 | 5BZG J0648-2343 |
| J1256.5-1146 | J125619.85-114537.5 | 6dFGS | 4 | bzb | 0.06 | 5BZG J1256-1146 |
| J1210.9+0658* | J121058.60+065727.2 | 6dFGS | 4 | bzb | 0.93 | 5BZG J1210+0658 |
| J1320.6-4059 | J132019.26-405939.8 | GemN | bzb | 1.97 | 5BZG J1320-4059 |

### Notes

- Column description: (1): 3FGL name (*) indicates sources in the Roma-BZCAT, (2): WISE name, (3): Survey/telescope: Six-Degree Field Galaxy Survey Database (6dFGS), Sloan Digital Sky Survey (SDSS), (4): quality of the spectra in 6dFGS, (5): signal to noise ratio in the telescopes, (6): source classification, (7): redshift.