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OPTICAL SPECTROSCOPIC OBSERVATIONS OF GAMMA-RAY BLAZAR CANDIDATES. V. TNG, KPNO, AND OAN OBSERVATIONS OF BLAZAR CANDIDATES OF UNCERTAIN TYPE IN THE NORTHERN HEMISPHERE

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ABSTRACT

The extragalactic γ-ray sky is dominated by emission from blazars, a peculiar class of active galactic nuclei. Many of the γ-ray sources included in the *Fermi*-Large Area Telescope Third Source catalog (3FGL) are classified as blazar candidates of uncertain type (BCUs) because there are no optical spectra available in the literature to confirm their nature. In 2013, we started a spectroscopic campaign to look for the optical counterparts of the BCUs and of the unidentified γ-ray sources to confirm their blazar nature. Whenever possible we also determine their redshifts. Here, we present the results of the observations carried out in the northern hemisphere in 2013 and 2014 at the Telescopio Nazionale Galileo, Kitt Peak National Observatory, and Observatorio Astronómico Nacional in San Pedro Mártir. In this paper, we describe the optical spectra of 25 sources. We confirmed that all of the 15 BCUs observed in our campaign and included in our sample are blazars and we estimated the redshifts for three of them. In addition, we present the spectra for three sources classified as BL Lacs in the literature but with no optical spectra available to date. We found that one of them is a quasar (QSO) at a redshift of $z = 0.208$ and the other two are BL Lacs. Moreover, we also present seven new spectra for known blazars listed in the Roma-BZCAT that have an uncertain redshift or are classified as BL Lac candidates. We found that one of them, 5BZB J0724+2621, is a "changing look" blazar. According to the spectrum available in the literature, it was classified as a BL Lac, but in our observation we clearly detected a broad emission line that led us to classify this source as a QSO at $z = 1.17$.

Key words: BL Lacertae objects: general – galaxies: active – radiation mechanisms: non-thermal

Supporting material: figure set

1. INTRODUCTION

Blazars are radio-loud active galactic nuclei (AGNs) characterized by non-thermal emission over the entire electromagnetic spectrum, from the radio band to γ rays (see, e.g., Urry & Padovani 1995; Giommi et al. 2013). They show rapid variability on timescales from hours in the optical band up to minutes in γ rays (see, e.g., Aharonian 2000; Homan et al. 2002), high linear polarization from radio to optical frequencies (see, e.g., Marscher et al. 2010; Agudo et al. 2014), compact radio emission (see, e.g., Taylor et al. 2007; Lister et al. 2009), flat radio spectra, and superluminal motions (see, e.g., Vermeulen & Cohen 1994; Kellermann et al. 2003 and references therein). The spectral energy distribution (SED) of blazars is characterized by a double bump, the first component peaking in infrared (IR)/optical wavelengths and the second in X-rays (for more details see, e.g., Giommi & Padovani 1994; Inoue & Takahara 1996). They are strong γ-ray emitters, reaching luminosities up to 10^{49} erg s^{-1} as reported in both the *Fermi*-LAT First Source Catalog (Abdo et al. 2010) and the *Fermi*-LAT Second Source Catalog (Nolan et al. 2012). Blazar multifrequency behavior is widely interpreted as emission arising from particles accelerated in relativistic jets pointed along the line of sight (Blandford & Rees 1978).

According to Stickel et al. (1991), blazars are divided into two main subclasses: BL Lac objects, which present featureless optical spectra or which have emission/absorption lines with a rest-frame equivalent width EW of <5 Å; and flat spectrum radio quasars, which show quasar-like optical spectra with broad emission lines (EW > 5 Å; see also Stocke et al. 1991 and Landoni et al. 2013). In the following, we label the former class as BZBs and the latter as BZQs according to the nomenclature adopted in the Roma-BZCAT "Multifrequency Catalog of BLAZARS" (Massaro et al. 2009). In this catalog, BL Lac candidates are listed as sources that are reported as BL Lacs in the literature but for which no optical spectra were found to confirm their classification. There are also sources classified as blazars of uncertain type (BZUs), adopted for sources with peculiar characteristics, similar to those previously mentioned but which also show blazar activity such as the occasional presence/absence of broad spectral lines, transition objects between a radio galaxy and a BL Lac, or galaxies hosting a low luminosity radio nucleus. In the latest version of the Roma-BZCAT (Massaro et al. 2015a), there is one more class, BL Lacs whose optical spectra exhibit a typical elliptical galaxy spectrum with a low Ca H&K break contrast, labeled as BZGs.

With a density of the order of 0.1 sources degree^{-2}, blazars constitute the most numerous population of extragalactic γ-ray sources, about 38%. However, almost 20% of the sources above 100 MeV in the *Fermi*-LAT Third Source Catalog (Acero et al. 2015) are blazar candidates of uncertain type (BCUs). They present flat radio spectra and/or X-ray counterparts and display multifrequency behavior similar to blazars, but there is no optical spectra to precisely allow this classification (Ackermann et al. 2012). In addition, unidentified γ-ray sources (UGSs) represent $\sim$33% of the *Fermi*-LAT Third Source Catalog and a large fraction of these sources can be associated with blazars (Massaro et al. 2012b, 2012c, 2014a). Knowing how much of the emission in γ-rays comes from blazars is important to place constraints on dark matter scenarios (Mirabal et al. 2012; Berlin & Hooper 2014), to discover new classes of γ-ray emitters, to resolve the γ-ray sky, and to determine the origin of the extragalactic γ-ray background (Ajello et al. 2015). For this purpose, several methods for recognizing blazars as low-energy counterparts of UGSs have been developed. For example, in the three-dimensional IR color space generated by *WISE* photometry, γ-ray emitting blazars lie in a region that is distinct from those regions where most of the other extragalactic sources dominated by thermal emission are located (Massaro et al. 2011a, 2013b; D'Abrusco et al. 2012, 2013). In addition, radio follow-up observations of the *Fermi* UGSs (e.g., Kovalev 2009; Hovatta et al. 2012, 2014; Petrov et al. 2013; Schinzel et al. 2015) correlation of the peculiar IR colors with existing radio databases (Massaro et al. 2013a, 2013c) and X-ray follow-up observations looking for X-ray counterparts (Paggi et al. 2013; Takeuchi et al. 2013; Stroh & Falcone 2013) have been performed. Statistical studies based on γ-ray source properties have also allowed us to recognize the nature of the potential counterparts for UGSs (e.g., Ackermann et al. 2012; Mirabal et al. 2012; Hassan et al. 2013; Doert & Errando 2014). However, none of these methods can be conclusive without optical spectroscopic confirmation for both BCUs and UGSs.

Since 2013, we have been carrying out a spectroscopic campaign to observe the blazar-like sources of uncertain classification as well as those selected according to the methods previously listed. In this fifth paper of the series, we present the results of optical spectroscopic observations of BCUs carried out in the northern hemisphere at Kitt Peak National Observatory (KPNO) in Tucson (USA), Telescopio Nazionale Galileo (TNG) in La Palma (Spain), and Observatorio Astronómico Nacional (OAN) in San Pedro Mártir (Mexico) between 2013 October and 2014 July. The exploratory program obtained with TNG, OAN, and Multiple Mirror Telescope (MMT) was described in Paggi et al. (2014); in addition, the results for observations carried out in 2013 with SOAR and KPNO were presented in Landoni et al. (2015), Massaro et al. (2015b, 2015c), and Ricci et al. (2015). In this paper, we focus mainly on BCUs, although we also had the opportunity to observe Roma-BZCAT sources.

The paper is organized as follows. Section 2 contains the sample selection. We present our data set and discuss the data reduction procedures in Section 3. Then, in Section 4, we report the details of the cross-matches with multifrequency databases and catalogs of the observed targets and present the results of our analysis for different types of sources. Finally, Section 5 is devoted to our summary and conclusions. We use cgs units unless otherwise stated. Spectral indices, α, are defined by flux density $S_\nu \propto \nu^{-\alpha}$. Flat spectra are defined as $\alpha < 0.5$.

2. SAMPLE SELECTION

Our final goal is to perform spectroscopic observations of a large sample of γ-ray blazar candidates selected on the basis of IR colors (Massaro et al. 2011a), extracted from the *WISE* Blazar-like Radio-Loud Source (WIBRaLS) Catalog (D'Abrusco et al. 2014). Our observing strategy, successfully employed during the previous years (see e.g., Landoni et al. 2015; Ricci et al. 2015), consists of requesting small subsamples of our main list from different telescopes to minimize the impact on their schedule. A more comprehensive presentation of our observing strategy, a detailed summary of the results of the spectroscopic observations, and their interpretation will be presented in a forthcoming paper (R. D'Abrusco et al. 2016, in preparation).

In Figure 1, we show the IR colors of the selected γ-ray blazar candidates compared with those of known gamma-ray blazars associated with 2FGL that were used when building the training sample (i.e., locus) to perform the all-sky search (see D'Abrusco et al. 2014 for more details).

The main criterion employed for the selection of observed sources from the pool of potential targets was primarily the source visibility during the nights at each telescope. We chose our targets considering optimal conditions of visibility and airmass lower than 1.6. In addition, interesting sources, such as blazars with uncertain redshifts and/or without optical spectra available in the literature, were also observed during gaps in our observing schedule. During our observing nights we also decided to re-observe sources when optimal conditions became available. For this reason, we decided to point at them because, given the optical variability of blazars, there was a chance of observing the source during a low state, and thus of detecting emission and/or absorption features which would enable a redshift measurement (Vermeulen et al. 1995; Falomo et al. 2014).

We updated the γ-ray classification of the selected sources on the basis of the recent release of the 3FGL. Thus, all of our targets are now indicated as BCUs similar to the old class of active galaxies of uncertain type (AGUs) in both 1FGL and 2FGL.

Our sample contains 25 sources that are grouped as follows.

1. Fifteen sources are classified as BCUs in 3FGL which present IR colors similar to blazars, a flat radio spectrum, and/or an X-ray counterpart that appears to have multifrequency behavior similar to blazars, but for which there are no optical spectra to precisely allow these classifications. In particular, 12 are sources that belong to the WIBRaLS Catalog. The remaining 3 are 1 BZB (WISE J173605.25+203301.1), 1 BZQ (WISE J043307.54+322840.7), and 1 AGU (WISE J065340.46+281848.5), respectively, with no optical spectra available in the literature; these 3 are now grouped with the previous 12 since they are all classified as BCUs in 3FGL.
2. Three sources selected from 3FGL are reported as BL Lacs in the literature but without optical spectra available to confirm their classification.
3. Two sources are BL Lac candidates, not necessary γ-ray emitters, classified according to the criteria of ROMA-BZCAT (Massaro et al. 2011a).
4. The remaining five sources are classified in Roma-BZCAT as BZBs, but their redshifts are still uncertain.

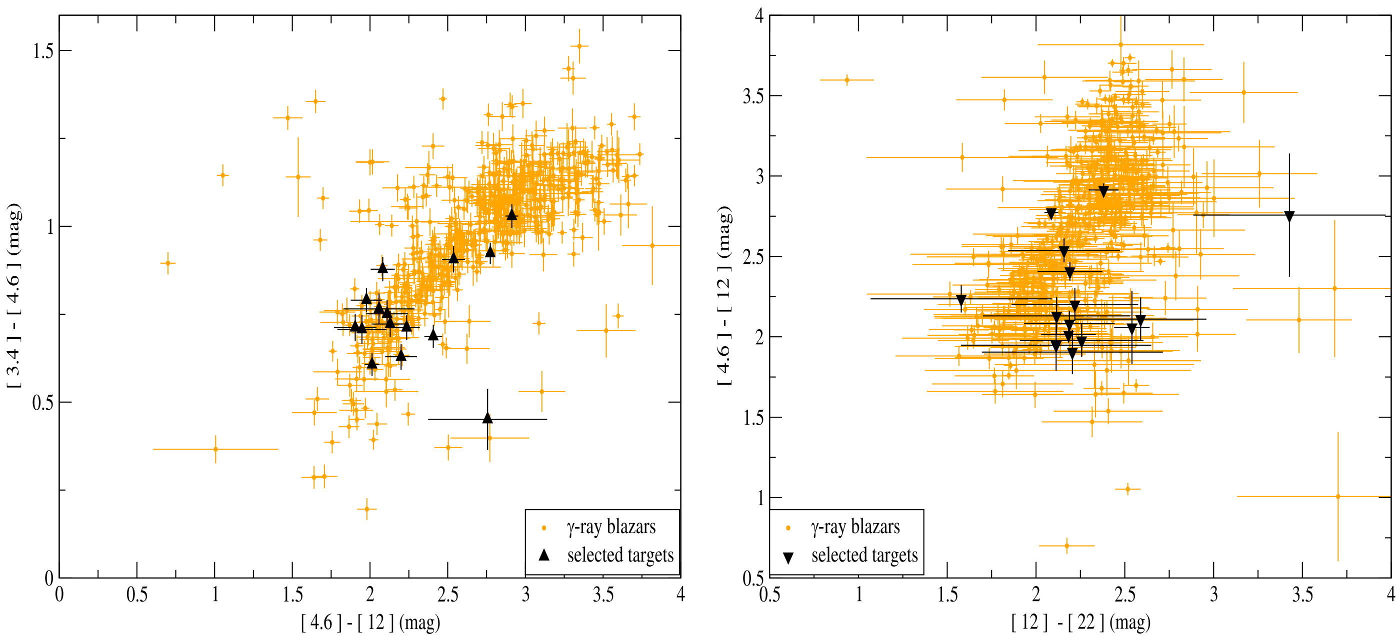

Figure 1. In orange are the gamma-ray blazars from the WIBRaLS catalog that define the so-called *locus* (i.e., the three-dimensional region of the IR color parameter space occupied by the associated gamma-ray blazars in 2FGL with a *WISE* counterpart, see D'Abrusco et al. 2014 for additional details). Left*:* projection of the selected targets in the *WISE* gamma-ray strip in the [3.4]–[4.6] vs. [4.6]–[12] color–color plane. Right*:* projection of the selected targets in the [4.6]–[12] vs. [12]–[22] color–color plane.

In Table 1, we also report the 1FGL and the 2FGL names together with their old classifications and their assigned counterparts. We noted that the latest associations for 3FGL J0653.6+2817 and 3FGL J0433.1+3228 differ from those previously listed in 3FGL. However, for these two cases, the source pointed at during our campaign is the 3FGL source reported in Table 2. On the other hand, for 3FGL J1013.5+3440, the source was unidentified in the 2FGL catalog and we pointed at the potential counterpart WISE J101349.6+344550.8 (listed in Massaro et al. 2015a) instead of the one assigned in 3FGL.

In Table 2, we report our results and multifrequency notes for each source to verify additional information that can support the blazar-like behavior.

3. OBSERVATIONS AND DATA REDUCTION

3.1. Kitt Peak National Observatory

The spectra of 12 objects were obtained in remote observing mode at the KPNO Mayall 4 m class telescope using the R-C spectrograph on the nights of 2014 February 5 and June 4. We adopted a slit width of $1\farcs2$ and low-resolution gratings (KPC10A and BL181 depending on the availability at the telescope) yielding a dispersion of 3 Å pixel^{-1} in both cases. The average seeing during both runs was about $1''$ and conditions were clear. Wavelength calibration was accomplished using the spectra of a helium–neon–argon lamp which guarantees smooth coverage over the entire range. Due to poor long-term stability during each night, we needed to take into account flexures of the instruments and drift, and so we took an arc frame before every target to guarantee a good wavelength solution for the scientific spectra. The accuracy reached is ∼3 Å rms.

3.2. Telescopio Nazionale Galileo

Eight spectra were obtained using the 3.58 m TNG located at La Palma, Canary Islands (Spain). Its imaging spectrograph DOLoReS carried a 2048 × 2048 pixel E2V 4240 CCD; spectra were acquired with the LR-B grism and a $1\farcs5$ slit width which secured a nominal spectra coverage in the 3500–8200 Å range and a dispersion of 2.5 Å pixel^{-1} The TNG data were acquired between 2013 October and 2014 July. We adopted the same data reduction procedure for TNG as for KPNO observations. Wavelength calibration was achieved using spectra of a helium–neon lamp acquired between two exposures of the same object.

3.3. OAN San Pedro Mártir

Five objects were observed with the 2.1 m telescope of the OAN in San Pedro Mártir (Mexico) in 2014 September and October. The telescope carries a Boller and Chivens spectrograph and a 1024 × 1024 pixel E2V 4240 CCD. The slit width was $2\farcs5$. The spectrograph was tuned to ∼4000–8000 Å range with a resolution of 10 Å pixel^{-1}. Wavelength calibration was performed using spectra of a cooper–helium–neon–argon lamp.

Data reduction was performed according to our standard procedures. Further details are given in Masetti et al. (2013), Ricci et al. (2015), and Massaro et al. (2015c).

The set of spectroscopic data acquired was optimally extracted and reduced following standard procedures with IRAF (Horne 1986; Today 1986). For each acquisition, we performed bias subtraction, flat field correction, and cosmic-ray rejection. To remove cosmic rays, we achieved two or three individual exposures for each target and averaged them according to their signal-to-noise ratios (S/Ns). We then exploited the availability of the two individual exposures in the case of dubious detected spectral features to better reject spurious ones.

Table 1
Gamma-ray Classification of the Selected Sample in the Fermi Catalogs

1FGL Name	1FGL Class	1FGL Association	2FGL Name	2FGL Class	2FGL Association	3FGL Name	3FGL Class	3FGL Association
Fermi Active Galaxies of Uncertain Type								
						J0015.7+5552	bcu	GB6 J0015+5551
						J0148.3+5200	bcu	GB6 J0148+5202
						J0145.6+8600	bcu	NVSS J014929+860114
						J0219.0+2440	bcu	87 GB 021610.9+243205
J0433.5+3230	bzq	CRATES J0433+3237	J0433.7+3233	bzq	MG2 J043338+3236	J0433.1+3228	bcu	NVSS J043307+322840
			J0653.7+2818	agu	NVSS J065345+282010	J0653.6+2817	bcu	GB6 J0653+2816
J0659.9+1303	ugs	…	…	…	…	J0700.2+1304	bcu	GB6 J0700+1304
						J0728.0+4828	bcu	GB6 J0727+4827
J1322.1+0838	ugs	…	…	…	…	J1322.3+0839	bcu	NVSS J132210+084231
						J1434.6+6640	bcu	1RXS J143442.0+664031
J1511.8-0513	ugs		J1511.8-0513	ugs		J1511.8-0513	bcu	NVSS J151148-051345
J1647.4+4948	agn	CGRaBS J1647+4950	J1647.5+4950	agn	SBS 1646+499	J1647.4+4950	bcu	SBS 1646+499
J1735.7+2031	ugs		J1735.9+2033	bzb	NVSS J173605+203301	J1736.0+2033	bcu	NVSS J173605+203301
			J1913.4+4440	agu	1RXS J191401.9+443849	J1913.9+4441	bcu	1RXS J191401.9+443849
						J2156.0+1818	bcu	RX J2156.0+1818
Fermi BL Lacs with no Optical Spectra								
			J0103.5+5336	agu	1RXS J010325.9+533721	J0103.4+5336[a]	bll	1RXS J010325.9+533721
			J1013.6+3434	ugs		J1013.5+3440[b]	fsrq	OL 318
			J2021.5+0632	ugs		J2021.9+0630[a]	bll	87 GB 201926.8+061922
BZB Candidates in the Roma-BZCAT								
J0814.5-1011	ugs		J0814.0-1006	bzb	NVSS J081411-101208	J0814.1-1012	bll	NVSS J081411-101208
BZBs Listed in the the Roma-BZCAT with Uncertain z								
J0333.7+299	ugs		J0333.7+2918	agu	TXS 0330+291	J0333.6+2916	bll	TXS 0330+291
			J0941.9-0755	agu	PMN J0942-0800	J0942.1-0756[a]	bll	PMN J0942-0800
J2038.1+6552	ugs		J2036.6+6551	bzb	87 GB 203539.4+654245	J2036.4+6551	bll	87 GB 203539.4+654245
J2323.5+4211	bzb	1ES 2321+419	J2323.8+4212	bzb	1ES 2321+419	J2323.9+4211	bll	1ES 2321+419

Notes. Column description: (1) 1FGL name, (2) 1FGL class, (3) 1FGL association, (4) 2FGL name, (5) 2FGL class, (6) 2FGL association, (7) 3FGL name, (8) 3FGL class, (9) 3FGL association. agu = AGNs of uncertain type, bcu = blazar candidate of uncertain type, ugs = unidentified γ-ray source, bzb = bll = BL Lac, bzq = blazer of QSO type.
[a] These objects are classified as BL Lacs in 3FGL because we provided this information while the present paper was in preparation.
[b] For this source we did not point at the associated 3FGL counterpart but a different radio source that lies within the *Fermi* positional uncertainty region at a 95% level of confidence.

Table 2
Description of the Selected Counterparts, Multifrequency Notes, and Spectroscopic Results

3FGL Name	Alternative Name	R.A. (J2000)	decl. (J2000)	Telescope	Obs. Date (yyyy mm dd)	Exp. (s)	S/N	Multifrequency Notes[a]	z	Class
Fermi Active Galaxies of Uncertain type										
J0015.7+5552	WISE J001540.13+555144.7	00:15:40.1	+55:51:44	KPNO	2014 Feb 05	2 × 1200	10	N, 87, GB, rf, w, M, X, x	?	BL Lac
J0148.3+5200	WISE J014820.33+520204.9	01:48:20.2	+52:02:06	OAN	2014 Oct 01	3 × 1800	26	L, N, 87, GB, rf, w	?	BL Lac
J0145.6+8600	WISE J014935.28+860115.4	01:49:29.8	+86:01:14	TNG	2013 Oct 12	2 × 1200	55	W, N, w	0.15	BL Lac/galaxy
J0219.0+2440	WISE J021900.40+244520.6	02:19:00.4	+24:45:20	OAN	2014 Oct 02	3 × 1800	43	N, w	?	BL Lac
J0433.1+3228	WISE J043307.54+322840.7	04:33:07.7	+32:28:40	KPNO	2014 Feb 05	2 × 600	5	N, 87, GB, w, rf	?	BL Lac
J0653.6+2817	WISE J065340.46+281848.5	06:53:40.2	+28:18:49	TNG	2014 Mar 26	2 × 1200	77	N, w	>0.45	BL Lac/galaxy
J0700.2+1304	WISE J070014.31+130424.4	07:00:14.3	+13:04:24	KPNO	2014 Feb 05	2 × 1350	12	N, w	?	BL Lac
J0728.0+4828	WISE J072759.84+482720.3	07:27:59.9	+48:27:20	TNG	2014 May 07	2 × 1200	39	L, N, 87, GB, w	?	BL Lac
J1322.3+0839	WISE J132210.17+084232.9	13:22:10.2	+08:42:33	KPNO	2014 Feb 05	2 × 1350	13	N, w, s, g	?	BL Lac
J1434.6+6640	WISE J143441.46+664026.5	14:34:41.8	+66:40:27	TNG	2014 Mar 26	2 × 1200	38	N, w, X	?	BL Lac
J1511.8-0513	WISE J151148.56-051346.9	15:11:48.6	-05:13:45	TNG	2014 Jul 02	2 × 1200	49	N, w, SED in Takeuchi+13	?	BL Lac
J1647.4+4950	WISE J164734.91+495000.5	16:47:34.9	+49:50:00	KPNO	2014 Jun 05	2 × 300	22	N, 87, GB, c, rf, w, M, s, g, X, (z = 0.047 Falco+98)	0.049	QSO
J1736.0+2033	WISE J173605.25+203301.1	17:36:05.3	+20:33:01	TNG	2014 May 31	2 × 1200	41	N, w, U, g, X	?	BL Lac
J1913.9+4441	WISE J191401.88+443832.2	19:14:01.9	+44:38:33	OAN	2014 Sep 30	3 × 1800	23	N, w	?	BL Lac
J2156.0+1818	WISE J215601.64+181837.1	21:56:01.6	+18:18:39	OAN	2014 Oct 02	3 × 1800	12	N, U, g, X	?	BL Lac
Fermi BL Lacs with no Optical Spectra										
J0103.4+5336	WISE J010325.89+533713.4	01:03:25.9	+53:37:13	KPNO	2014 Feb 05	2 × 600	10	N, 87, w, rf, X	?	BL Lac
J1013.5+3440	WISE J101336.51+344003.6	10:13:36.0	+34:40:06	TNG	2014 Mar 26	2 × 1200	18	N, w, X	0.208	QSO
J2021.9+0630	WISE J202155.45+062913.6	20:21:55.5	+06:29:14	KPNO	2014 Feb 05	2 × 1200	35	Pm, N, 87, w	?	BL Lac
BZB Candidates in the Roma-BZCAT										
	5BZB J0724+2621	07:24:42.7	+26:21:31	KPNO	2014 Feb 05	2 × 1800	20	N, w, M, (White+2000)	1.17	QSO
J0814.1-1012	5BZB J0814-1012	08:14:11.7	−10:12:10	KPNO	2014 Feb 05	2 × 1200	35	N, A, w, 6	?	BL Lac
BZBs Listed in the the Roma-BZCAT with Uncertain z										
J0333.6+2916	5BZB J0333+2916	03:33:49.0	+29:16:31	TNG	2013 Oct 12	2 × 1200	96	T, N, 87, GB, rf, U, X, ($z > 0.14$ Shaw+13)	?	BL Lac
J0942.1-0756	5BZB J0942-0759	09:42:00.6	−07:55:17	KPNO	2014 Feb 05	2 × 1350	9	N, w, ($z > 0.46$ Shaw+13)	?	BL Lac
	5BZG J1414+3430	14:14:09.3	+34:30:57	KPNO	2014 Feb 05	2 × 600	5	N, F, w, M, s, X, (z = 0.275 Bauer+00)	?	BL Lac
J2036.4+6551	5BZB J2036+6553	20:36:19.9	+65:53:14	KPNO	2014 Feb 05	2 × 3000	10	N, 87, w, ($z > 0.3$ Shaw+13)	?	BL Lac
J2323.9+4211	5BZB J2323+4210	23:23:52.1	+42:10:58	OAN	2014 Oct 25	3 × 1800	32	N, w, M, X, (z = 0.059 Padovani+95, Shaw+13, Massaro+15c)	?	BL Lac

Notes. Our sources are divided in 4 subsamples: (1) sources classified as active galaxies of uncertain type according to the 3LAC; (2) *Fermi* sources classified as BL Lacs in the literature without optical spectra available; (3) BZB candidates in the Roma-BZCAT. (4) BL lac candidates, both detected and not detected by *Fermi* for which no optical spectroscopic information were found in the literature or BZBs with uncertain/unknown redshift estimate. Column description: (1) 3FGL name, (2) Alternative name, (3) R.A. (Equinox J2000), (4) decl. (Equinox J2000), (5) Telescope: Kitt Peak National observatory (KPNO); Telescopio Nazionale Galileo (TNG); Observatorio Astronómico Nacional San Pedro Mártir (OAN), (6) Observation Date, (7) Exposure time, (8) signal-to-noise ratio, (9) multifrequency notes (see Table 3), (10) redshift (symbol ? indicates uncertain/unfeasible measurement), (11) source classification.

[a] Symbols used for the multifrequency notes are all reported in Table 3 together with the references of the catalogs/surveys.

Table 3
List of Catalogs in which We Searched for Additional Multifrequency Information

Survey/Catalog Name	Acronym	Reference	Symbol
VLA Low-frequency Sky Survey Discrete Source Catalog	VLSS	Cohen et al. (2007)	V
Westerbork Northern Sky Survey	WENSS	Rengelink et al. (1997)	W
Parkes-MIT-NRAO Surveys	PMN	Wright et al. (1994)	Pm
Texas Survey of Radio Sources	TEXAS	Douglas et al. (1996)	T
Low-frequency Radio Catalog of Flat-spectrum Sources	LORCAT	Massaro et al. (2014a)	L
NRAO VLA Sky Survey	NVSS	Condon et al. (1998)	N
VLA Faint Images of The Radio Sky at 20 cm	FIRST	Becker et al. (1995), White et al. (1997)	F
87 Green Bank catalog of radio sources	87 GB	Gregory & Condon (1991)	87
Green Bank 6 cm Radio Source Catalog	GB6	Gregory et al. (1996)	GB
WISE all-sky survey in the Allwise Source catalog	*WISE*	Wright et al. (2010), Cutri et al. (2012)	w
Two Micron All Sky Survey	2MASS	Skrutskie et al. (2006)	M
Sloan Digital Sky Survey Data Release 9	SDSSS DR9	Ahn et al. (2012)	s
Six-degree-field Galaxy Redshift Survey	6dFGS	Jones et al. (2004, 2009)	6
ROSAT Bright Source Catalog	RBSC	Voges et al. (1999)	X
ROSAT Faint Source Catalos	RFSC	Voges et al. (2000)	X
XMM-Newton Slew Survey	XMMSL	Saxton (2008), Warwick et al. (2012)	x
Deep *Swift* X-Ray Telescope Point Source Catalog	1XSPS	Evans et al. (2014)	x
Chandra Source Catalog	CSC	Evans et al. (2010)	x

Note. Column description: (1) Survey/Catalog name, (2) Acronym, (3) Reference, (4) Symbol used in multifrequency notes in Table 2.

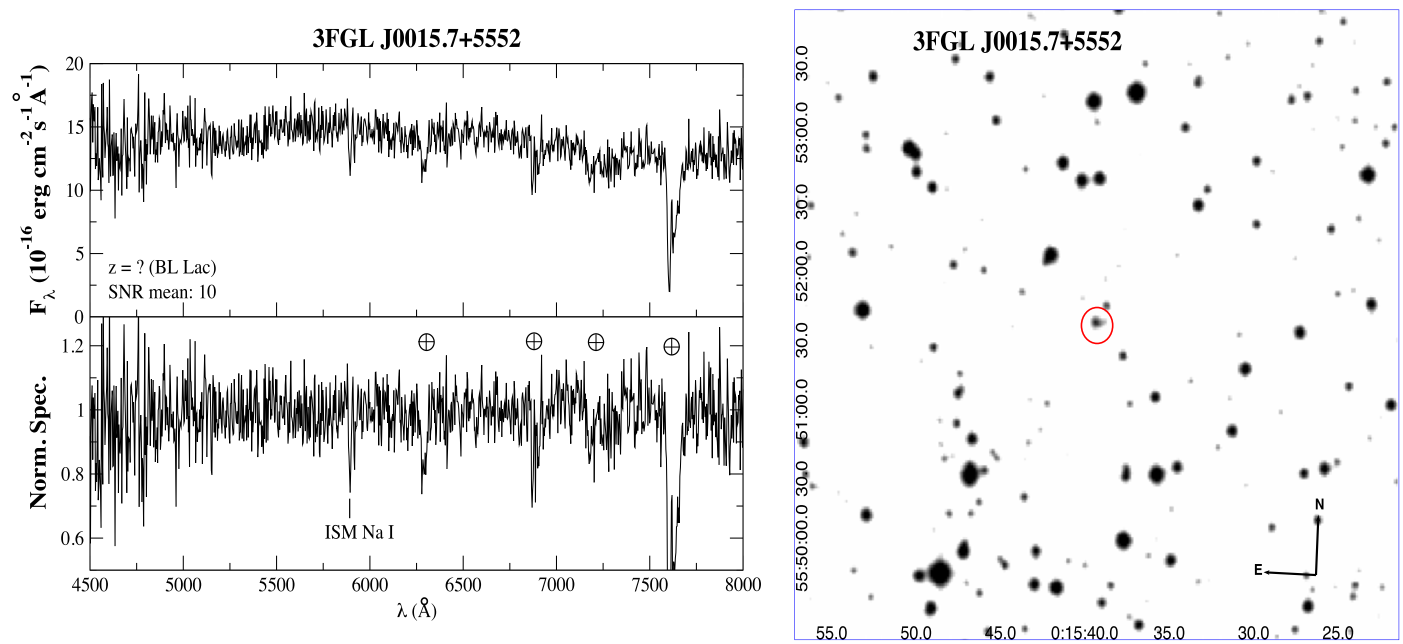

Figure 2. Left: (Upper panel) The optical spectra of WISE J001540.13+555144.7, potential counterpart of 3FGL J0015.7+5552. It is classified as a BL Lac on the basis of its featureless continuum. The average signal-to-noise ratio (SNR) is also indicated in the figure. (Lower panel) The normalized spectrum is shown here. Telluric lines are indicated with a symbol. Right The $5' \times 5'$ finding chart from the Digital Sky Survey (red filter). The potential counterpart of 3FGL J0015.7+5552 pointed during our observations is indicated by the red circle.

(The complete figure set (25 images) is available.)

We dereddened the spectra for galactic absorption assuming E_{B-V} values taken using the Schlegel et al. (1998) relation. Although our program did not require precise photometric calibration, we observed a spectrophotometric standard star to perform relative flux calibration on each spectrum. The overall spectral shape is correct but the absolute calibration may suffer from sky condition issues, such as seeing and transparency. To detect faint spectral features, especially since our targets might be BL Lac objects, aimed at estimating redshifts, we also present normalized spectra.

4. RESULTS

Here we report all of the results from our optical analysis of the selected sources divided in four groups. We have searched for additional multifrequency information that can support the blazar-like nature in radio, IR, optical, and X-ray surveys and in both the NASA Extragalactic Database (NED) and the SIMBAD astronomical database. All of the selected sources with their corresponding multifrequency notes are listed in Table 2. There is also a note in cases where the SED of the source is presented in Takeuchi et al. (2013) and if the radio counterpart has a flat radio spectrum (marked as "rf"). The surveys and catalogs used to search for the counterparts to our targets are listed in Table 3. Note that we use the same symbol for the X-ray catalogs of *XMM-Newton Chandra* and *Swift* because these X-ray observatories perform only pointed observations. There is the possibility that the pointed observation related to the field of the *Fermi* source was not requested as follow up but for another reason. Therefore, the discovery of the X-ray counterpart for an associated and/or identified source could be serendipitous.

4.1. Gamma-ray AGUs

Details of the 15 BCUs observed in our sample are listed below. Multifrequency notes relative to each source are reported in Table 2. The spectra of the whole sample are shown in Figures 2.1–2.23 together with their finding charts. Our spectroscopic observations allow us to confirm that all of these sources are BL Lac objects and we have been able to determine the redshift in one case in which the BL Lac shows absorption features from the host elliptical galaxy. For another source we were able to fix a lower redshift limit due to the presence of an intervening system seen along the line of sight.

The spectra of WISE J014935.28+860115.4 associated with 3FGL J0145.6+8600 is dominated by the emission of the host elliptical galaxy rather than by non-thermal continuum arising from the jet; the features distinguished are the G band, doublet Ca H+K ($EW_{obs} = 0.4–0.7$ Å), and Mg I ($EW_{obs} = 0.6$ Å). These features enable us to estimate a redshift of $z = 0.15$ (see Figure 2.2). In the case of the optical counterpart WISE J065344.26+281547.5 associated with 3FGL J0653.6+2817, the presence of an intervening doublet system of Mg II ($EW_{obs} = 1.3 - 1.0$ Å) allows us to set a lower limit on its redshift of $z > 0.45$ (see Figure 2.4). The spectra of WISE J164734.91+495000.5, counterpart of 3FGL J1647.4+4950, shows a broad emission line that we tentatively identify with Hα ($EW_{obs} = 27.7$). On the basis of our optical spectra and the radio data, we classify the source as a FSRQ at a redshift of $z = 0.049$ (see Figure 2.11). This redshift is consistent with the previous value published by Falco et al. (1998) where the spectrum is described. In the rest of the BCUs, only featureless continuum spectra are shown so we can conclude that they are BL Lacs but we did not fix any redshift (Figures 2.7–2.14).

4.2. Fermi BL Lacs With No Optical Spectra

During our northern campaign, we observed three sources claimed in the literature as BL Lacs but with no optical spectra available at the time of observation. For the optical counterparts of the sources 3FGL J0103.4+5336 and 3FGL J2021.9+0630, we were able to confirm the BL Lac nature but not to estimate the redshift because in neither of our spectra are features present (see Figures 2.15 and 2.17, respectively). On the basis of our optical spectra, we classify the counterpart of 3FGL J1013.5+3440 as a QSO at a redshift of $z = 0.208$, which was possible due to the identification of the lines [O II] ($EW_{obs} = 17.2$ Å), [Ne III] ($EW_{obs} = 4.1$ Å), Hβ ($EW_{obs} = 4.5$ Å), the doublet [O III] ($EW_{obs} = 14.3–15.8$ Å), and Hα ($EW_{obs} = 48.5$ Å; see Figure 2.16). This is consistent with a BZQ classification but the lack of radio data did not permit us to verify the flatness of the radio spectrum as expected for BZQs.

4.3. BL Lac Candidates in the Roma-BZCAT

Here, we discuss the BZB candidates in Roma-BZCAT in our observed sample. Table 2 reports their Roma-BZCAT name as an alternative name for the counterpart associated with a γ-ray source in the 3FGL. The spectra of this sample are shown in Figures 2.18 and 2.19 together with their finding charts. We classify 5BZB J0724+2621 as a QSO, not as a BZQ, again because of the lack of radio data. It shows a broad emission line ($EW_{obs} = 26.8$ Å) that we tentatively identify as Mg II, yielding a redshift estimate of $z = 1.17$ (see Figure 2.18). The other source 5BZB J0814-1012 (also known as 3FGL J0814.1-1012) shows a featureless continuum which allows us to confirm its classification as a BL Lac (see Figure 2.19).

4.4. Roma-BZCAT Sources with Uncertain Nature or Unknown Redshifts

In this subsample of five sources, we confirmed the BL Lac nature for all of them but, unfortunately, it was not possible to establish their redshifts. In particular, we re-observed 5BZB J0333+2916 (also known as 3FGL J0333.6+2916) and confirm its BL Lac nature but not the lower limit of the redshift set before as $z > 0.14$ in Shaw et al. (2013) because our observations show only a featureless continuum (see Figure 2.20). The same situation occurs for 5BZB J0942-0759 (also known as 3FGL J0942.1-0756), the spectra is dominated by a featureless continuum and it is not possible to determine the redshift ($z > 0.46$ in Shaw et al. 2013, see Figure 2.21). In the case of the source 5BZG J1414+3430 we have not been able to confirm the previous redshift value of $z = 0.275$ in White et al. (2000; see Figure 2.22). For the source 5BZB J2036+6553 (also known as 3FGL J2036.4+6551) we do not see any features on top of the non-thermal continuum and the confirmation of $z > 0.30$ given in Shaw et al. (2013) was not possible (see Figure 2.23). Finally, for the last source 5BZB J2323+4210 (also known as 3FGL J2323.9+4211) the spectra is featureless and so it was not possible to confirm the value $z = 0.059$ given by Padovani & Giommi (1995). A featureless spectra of this source was also presented also by Shaw et al. (2013) and Massaro et al. (2015c; see Figure 2.24).

5. SUMMARY AND CONCLUSIONS

We present the results of our 2013 and 2014 optical spectroscopic campaign in the northern hemisphere with the TNG, KPNO, and OAN in San Pedro Mártir. The main goal of our program is to use optical spectroscopy to confirm the nature of sources selected from BCUs because they have low radio frequency spectra (i.e., below ~1 GHz) or peculiar IR colors.

Confirmation of blazar nature among these objects will improve and refine future associations for the *Fermi* catalog.

Also, once our campaign is completed, this will allow us to understand the efficiency and completeness of the association method based on IR colors. One more aim is to search for redshift estimates of the potential UGS counterparts.

During our campaign we also observed several AGUs as defined according to the *Fermi* catalogs (Ackermann et al. 2011; Nolan et al. 2012; Acero et al. 2015) to verify if they are blazars. In addition, we observed several sources that already belong to Roma-BZCAT because either there were no optical spectra available in the literature or their estimated redshifts were still uncertain when the catalog was released.

The total number of targets presented is 25. The results of this part of the spectroscopic campaign can be reported as follows.

1. In the BCU subsample, all of the sources have a blazar nature. One of them, namely, WISE J014935.28+860115.4, is dominated by the absorption of the host galaxy, and we were able to detect absorption lines in the optical spectrum leading to a redshift measurement of $z = 0.15$. We have also been able to set a lower limit for WISE J065344.26+281547.5 of 0.45 thanks to the detection of an Mg II intervening system.
2. We obtained spectra of three sources classified as BL Lacs in the literature but with no spectra published at the time of the observations. We found that two of them are indeed BL Lacs, but the optical spectrum of WISE J101336.51+344003.6 shows that this source is a QSO at $z = 0.208$.
3. For the 5 BZBs listed in Roma-BZCAT with uncertain redshift estimation, we were not able to obtain any z value with our observations.
4. We also analyzed two BL Lac candidates listed in Roma-BZCAT. According to our results, 5BZB J0814-1012 is confirmed as a BZB. The spectra of the source 5BZB J0724+2621 observed by White et al. (2000) showed a featureless continuum corresponding to the classification as a BL Lac, but in our observations we detected a broad emission line. This strongly indicates that the source was previously observed during a state dominated by non-thermal radiation that did not allow the detection of emission lines. During our observation, we observed this previously classified BL Lac showing a broad emission line that led to a QSO classification.

   It is a "changing look" blazar (see, e.g., Giommi et al. 2012), and we classify it as a QSO at redshift $z = 1.17$. It has been suggested that this transition could happen due to a change in the bulk Lorentz factor of the jet (Bianchin et al. 2009). Another interpretation is that these blazars are instead FSRQs, whose emission lines are swamped by the relativistically boosted jet flux (Ghisellini et al. 2012).

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