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OPTICAL SPECTROSCOPIC OBSERVATIONS OF GAMMA-RAY BLAZAR CANDIDATES. VI. FURTHER OBSERVATIONS FROM TNG, WHT, OAN, SOAR, AND MAGELLAN TELESCOPES

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ABSTRACT

Blazars, one of the most extreme classes of active galaxies, constitute so far the largest known population of γ-ray sources, and their number is continuously growing in the *Fermi* catalogs. However, in the latest release of the *Fermi* catalog there is still a large fraction of sources that are classified as blazar candidates of uncertain type (BCUs) for which optical spectroscopic observations are necessary to confirm their nature and their associations. In addition, about one-third of the γ-ray point sources listed in the Third *Fermi*-LAT Source Catalog (3FGL) are still unassociated and lacking an assigned lower-energy counterpart. Since 2012 we have been carrying out an optical spectroscopic campaign to observe blazar candidates to confirm their nature. In this paper, the sixth of the series, we present optical spectroscopic observations for 30 γ-ray blazar candidates from different observing programs we carried out with the Telescopio Nazionale Galileo, William Herschel Telescope, Observatorio Astronómico Nacional, Southern Astrophysical Research Telescope, and Magellan Telescopes. We found that 21 out of 30 sources investigated are BL Lac objects, while the remaining targets are classified as flat-spectrum radio quasars showing the typical broad emission lines of normal quasi-stellar objects. We conclude that our selection of γ-ray blazar candidates based on their multifrequency properties continues to be a successful way to discover potential low-energy counterparts of the *Fermi* unidentified gamma-ray sources and to confirm the nature of BCUs.

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

Supporting material: figure set

1. INTRODUCTION

Unidentified γ-ray sources (UGSs) have been known to constitute a large fraction of the γ-ray sources since the observations of the Energetic Gamma Ray Experiment Telescope (EGRET) survey on board the *Compton Gamma-Ray Observatory* (Mukherjee et al. 1997; Hartman et al. 1999). For this reason "resolving" the γ-ray sky, i.e., searching for the counterparts of the UGSs, was listed as one of the four key scientific objectives of the *Fermi* mission launched in 2008 (Atwood et al. 2009).

Given the large position uncertainty of *Fermi* sources (of the order of 0°.1) compared to the density of potential optical counterparts, there is no simple procedure to assign them a potential counterpart, and a multifrequency approach is thus necessary, in particular to decrease the number of UGSs. Consequently, a large number of follow-up observations have been carried out since the launch of *Fermi* to decrease the number of UGSs, mostly focused on searching for blazars, the most numerous class of active galaxies detected in the γ-rays, and pulsars (see, e.g., Ackermann et al. 2012; Nolan et al. 2012; Abdo et al. 2015). Both low and high radio frequency observations (such as the All-sky Survey of Flat-Spectrum Radio Sources CRATES [Healey et al. 2007] and the All-sky Survey of Gamma-ray Blazar Candidates CGRaBS [Healey et al. 2008]) have been successfully used in recent years to select compact radio sources as blazar candidates (see, e.g., Petrov et al. 2013; Schinzel et al. 2015). The discovery of the peculiar infrared (IR) colors of the known γ-ray blazar population (Massaro et al. 2011; D'Abrusco et al. 2012) led to the development of several methods to search for sources with similar proprieties within the UGS sample (Massaro et al. 2012; D'Abrusco et al. 2013; Massaro et al. 2013a, 2013b). In addition, a dedicated X-ray survey of all the UGSs is currently being carried out by the *Swift* satellite[15] (see Stroh & Falcone 2013 and also Paggi et al. 2013; Takeuchi et al. 2013; Acero et al. 2015), aiming at the determination of the X-ray counterpart of the *Fermi* sources. Finally, statistical analyses have been also performed trying to characterize the nature of the γ-ray sources by their γ-ray

[15] http://www.swift.psu.edu/unassociated/

spectral properties and temporal behaviors (see, e.g., Ackermann et al. 2012; Doert & Errando 2014).

In addition, 20% of the sources above 100 MeV in the *Fermi*-LAT Third Source Catalog, (3FGL; Acero et al. 2015) are listed as blazar candidates of uncertain type (BCUs). They present flat radio spectra and/or X-ray counterparts and have a multifrequency behavior similar to blazars, as defined according to the 3FGL and the Third Catalog of Active Galactic Nuclei Detected by the *Fermi*-LAT (Ackermann et al. 2015).

Definitive confirmation of the blazar-like nature of candidates selected as potential counterparts of UGSs comes from optical spectroscopy (see Massaro et al. 2014 for more details). In 2012 we started an optical spectroscopic campaign to follow up and confirm the nature of the blazar-like sources selected on the basis of their IR colors or their low-frequency (i.e., below ~1 GHz) flat radio spectrum (Massaro et al. 2013b, 2013c) to confirm their nature. Using the results achieved to date, the fraction of UGSs listed in the First *Fermi*-LAT source catalog (1FGL; Abdo et al. 2010) and the Second *Fermi*-LAT source catalog (2FGL; Nolan et al. 2012) is decreased by ~10%–20%.

Sources observed during our campaign were classified as BL Lac objects, labeled as BZBs according to the nomenclature of the Roma-BZCAT catalog (Massaro et al. 2009), whenever the optical spectrum is featureless or shows only optical emission/absorption features with equivalent widths smaller than 5 Å (Stickel et al. 1991), or as blazars of quasar type (i.e., BZQs) if they have a typical quasar-like optical spectrum with broad emission lines. The members of this last class are also known as flat-spectrum radio quasars (FSRQs) since they present the same optical spectra as quasars and a flat radio spectra. We also considered sources classified according to the latest release of the Roma-BZCAT (Massaro et al. 2015a); in this catalog, BL Lacs exhibiting optical spectra of a typical elliptical galaxy (nonthermal continuum with a low Ca H&K break contrast) are classified as BZGs that stands for BL Lac of galaxy type (Marchã et al. 1996; Landt et al. 2002).

In this sixth paper of the series we present 30 additional optical spectra collected during observational gaps in different programs or in service mode. The data were collected at Telescopio Nazionale Galileo (TNG) in La Palma (Spain), William Herschel Telescope (WHT), Observatorio Astronómico Nacional (OAN) in San Pedro Mártir (Mexico) for the Northern Hemisphere, and at the Southern Astrophysical Research Telescope (SOAR) and at the Magellan Telescopes at the Carnegie Observatories for the Southern Hemisphere. Results from our exploratory program were presented in Paggi et al. (2014); while those results for observations carried out in 2013 with SOAR and KPNO, together with additional OAN spectra, are discussed in Landoni et al. (2015), Massaro et al. (2015b, 2015c), and Ricci et al. (2015) respectively, and a release of ~25 γ-ray BCUs has been recently presented in Álvarez-Crespo et al. (2016).

The paper is organized as follows: Section 2 describes the sample analyzed. Section 3 is dedicated to the data reduction procedures, while Section 4 details the results of our spectral analysis. Finally, the summary and conclusions are presented in Section 5. We use cgs units unless otherwise stated. Spectral indices, α, are defined by flux density $S_\nu \propto \nu^{-\alpha}$, and flat spectra are considered for sources with $\alpha < 0.5$.

2. SAMPLE SELECTION

The aim of our campaign is to perform spectroscopic observations of a large number of γ-ray blazar candidates selected on the basis of their characteristic IR colors (Massaro et al. 2011). The observing strategy, successfully applied in recent years (see, e.g., Álvarez-Crespo et al. 2016; Ricci et al. 2015), is to request small subsamples of our main list from different telescopes to minimize the impact on their individual schedules. More details on the observing strategy and a summary of the observations performed on the γ-ray blazar candidates found for the 2FGL catalog will be presented in a forthcoming paper (R. D'Abrusco et al. 2016, in preparation).

Our present sample lists 30 sources; a large fraction of them (i.e., 23 out of 30) lie within the positional uncertainty region of the corresponding *Fermi* source listed in the 3FGL, while four of the sources that do not appear in the 3FGL are included in the 2FGL (Nolan et al. 2012), one is listed in the first catalog release 1FGL (Abdo et al. 2010), and the remaining two are reported in the First *Fermi*-LAT Catalog of Sources above 10 GeV (1FHL; Ackermann et al. 2013). All their pointed counterparts lie within the *Fermi* position uncertainty at 95% level of confidence.

The sample selection was mainly driven by source visibility during the nights obtained at each telescope. We chose our targets considering the optimal conditions of visibility and airmass lower than 1.5. Our sample of 30 sources was selected as follows:

1. Nine targets belong to the *WISE* Blazar-like Radio-Loud Source (WIBRaLS; D'Abrusco et al. 2014). This is a catalog of radio-loud candidate γ-ray-emitting blazars with *WISE* mid-infrared colors similar to the colors of confirmed γ-ray blazars. Details of the sources are reported in Table 1.
2. Seven objects are included in Massaro et al. (2015b), which reports refined associations of the 1FGL and 2FGL catalogs based on multifrequency properties.
3. Twelve targets are selected because they are radio sources lying within the positional uncertainty region of UGSs. This is because all the *Fermi* blazars associated up to date have a radio counterpart, as highlighted by the radio–gamma-ray connection (Abdo et al. 2010; Ghirlanda et al. 2010; Mahony et al. 2010). To search for potential blazar-like objects, these radio sources are the primary candidates for optical spectroscopic observations.

In addition to the above selection, we also pointed at serendipitous objects based on opportunity. The reasons for the selection of these targets are described in the following list:

1. 3FGL J0721.5–0221 was selected for being an active galaxy of uncertain type (AGU) in the 2FGL.
2. The bright flat-spectrum radio source, PMN J1038–5311, was proposed as the counterpart of the LAT-detected flaring source 3FGL J1038.9–5311 in 2012 March by Ciprini et al. (2012). The first appearance of the γ-ray source in a *Fermi*-LAT catalog is in the 3FGL, associated with the PMN source.
3. 3FGL J1221.5–0632 is unassociated in all existing *Fermi*-LAT catalogs. We observed the optical source, USNO B1.0 0835–0232187, coincident with the brightest X-ray source found within the 1FGL J1221.4–0635 and

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

1FGL Name	1FGL Class	2FGL Name	2FGL Class	2FGL Assoc	1FHL Name	1FHL Class	3FGL Name	3FGL Class	3FGL Assoc	*WISE*/2MASS Counterpart Name
					J0030.1–1647	UGS				J003020.44–164713.1
					J0044.0–1111	UGS				J004348.66–111607.2[c]
		J0103.8+1324	UGS				J0103.7+1323	BCU	NVSS J010345+132346	J010345.74+132345.3[a]
J0105.7+3930	UGS	J0105.3+3930	BLL	GB6 J0105+3928			J0105.3+3928	BLL	GB6 J0105+3928	J010509.19+392815.1[a]
J0307.5+4916	UGS	J0307.4+4915	UGS		J0307.4+4915		J0307.3+4916	UGS		J030727.21+491510.6[b]
		J0332.5–1118	AGU	NVSS J033223–111951						J033223.25–111950.6[c]
J0352.8+5658	UGS	J0353.2+5653	UGS				J0352.9+5655	BCU	GB6 J0353+5654	J035309.54+565430.7[a]
J0411.6+5459	UGS									J041203.78+545747.2[b]
		J0508.1–1936	AGU	PMN J0508–1936			J0508.2–1936	BCU	PMN J0508–1936	J050818.99–193555.7[c]
							J0618.2–2429	BCU	PMN J0618–2426	J061822.65–242637.7[a]
		J0700.3+1710	AGU	TXS 0657+172			J0700.0+1709	BCU	TXS 0657+172	J070001.49+170921.9[a]
							J0720.0–4010	BCU	1RXS J071939.2–401153	J071939.18–401147.4[a]
		J0721.2–0223	AGU	1RXS J072114.5–022047			J0721.5–0221	UGS		J072113.90–022055.0
		J0819.6–0803	BLL	RX J0819.2–0756						J081917.58–075626.0[b]
							J0828.8–2420	BCU	NVSS J082841–241850	J082841.74–241851.1[c]
							J0917.3–0344	BCU	NVSS J091714–034315	J091714.61–034314.2[c]
							J1038.9–5311	BCU	MRC 1036–529	J103840.66–531142.9
							J1042.0–0557	BCU	PMN J1042–0558	J104204.30–055816.5[c]
J1141.8–1403	UGS	J1141.7–1404	AGU	1RXS J114142.2–140757			J1141.6–1406	BCU	1RXS J114142.2–140757	J114141.80–140754.6[c]
J1221.4–0635	UGS	J1221.4–0633	UGS				J1221.5–0632	UGS		J122127.20–062847.8
							J1331.1–1328	BCU	PMN J1331–1326	J133120.35–132605.7[a]
J1548.6+1451	UGS	J1548.3+1453	UGS		J1548.3+1455	UGS	J1548.4+1455	UGS		J154824.38+145702.8[b]
	UGS	J1624.4+1123	AGU	MG1 J162441+1111						J162444.79+110959.3[b]
		J1704.3+1235	UGS				J1704.1+1234	UGS		J170409.58+123421.7[b]
		J1803.6+2523c	AGU	TXS 1801+253						2MASS J18031240+2521185[b]
		J1818.7+2138	AGU	MG2 J181902+2132			J1819.1+2134	BCU	MG2 J181902+2132	J181905.22+213233.8[a]
J1844.1+1547	UGS	J1844.3+1548	UGS				J1844.3+1547	BCU	NVSS J184425+154646	J184425.36+154645.8[a]
					J2015.3–1432	UGS	J2015.3–1431	UGS		J201525.02–143203.9[c]
J2037.0–3329	UGS				J2036.9–3325	UGS	J2036.6–3325	BCU	1RXS J203650.9–332817	J203649.49–332830.7[c]
J2134.5–2130	UGS	J2134.6–2130	UGS		J2134.6–2130	UGS	J2134.5–2131	UGS		J213430.18–213032.8[c]

Notes. bcu = AGN of Uncertain Type; ugs = Unidentified γ-ray Source; bzb = bll = BL Lac; bzq = Blazar of QSO Type. Column description. (1): 1FGL name; (2): 1FGL class; (3): 2FGL name; (4): 2FGL class; (5): 2FGL association; (6): 1FHL name; (7): 1FHL class; (8): 3FGL name; (9): 3FGL class; (10): 3FGL association; (11): *WISE*/2MASS counterpart name.

[a] Reported in the WIBRaLS catalog.

[b] Reported in Refined associations paper.

[c] Radio counterpart pointed sources.

2FGL J1221.4–0633 error circles (XRT Src#1 in Takeuchi et al. 2013). Interestingly, Takeuchi et al. (2013) found no radio emission from the optical/X-ray source in the FIRST survey data.

It is worth noting that the γ-ray class of BCUs in the 3FGL corresponds to the old class AGU in both the 1FGL and 2FGL catalogs. Gamma-ray information and classification are shown in Table 1, while in Table 2 we report the log of the observations together with results of our analysis and the multifrequency notes collected for each source. We note that since all but one of our sources have an IR counterpart in the *WISE* catalog (Wright et al. 2010; Cutri et al. 2012), we decide to use the *WISE* name to label/identity them in both tables. For 2FGL J1803.6+2523c, the *WISE* counterpart is contaminated by a nearby star, so instead we report the name of its counterpart in the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006).

3. OBSERVATIONS AND DATA REDUCTION

Here we describe the telescopes and the instruments used to carry out our spectroscopic campaign and provide the basic details of the data reduction procedures adopted.

3.1. TNG

The spectra of five objects were obtained using the TNG, a 3.58 m telescope located at La Palma, Canary Islands (Spain). Its imaging spectrograph DOLoReS carries a 2048×2048 pixel E2V 4240 CCD. We used a slit width of 1″.5, which secured a nominal spectral coverage in the 3500–8200 Å and a dispersion of 2.5 Å pixel^{-1}. The TNG data were acquired on the nights 2013 October 12, 2014 February 1, and March 27. Wavelength calibration was accomplished using the spectra of a helium–neon–argon lamp, which guarantees a smooth coverage over the entire range. Owing to poor long-term stability during each night, we needed to take into account flexures of the instruments and drift, so we took an arc frame before every target to guarantee a good wavelength solution for the scientific spectra.

3.2. William Herschel Telescope

Four objects were observed with the 4.2 m WHT in La Palma, Canary Islands (Spain), on three different nights between 2013 November and 2014 March. We adopted a slit of 2″ and used the low-resolution imaging spectrograph ACAM with a detector E2V EEV4482. The spectrograph was tuned in the ~4000–8000 Å range. Wavelength calibration was done using the spectra of a helium–neon–argon lamp.

3.3. Observatorio Astronómico Nacional San Pedro Mártir

Seven spectra were taken between 2014 October and 2015 April with the 2.1 m telescope of the Observatorio Astronómico Nacional (OAN) in San Pedro Mártir (Mexico). The telescope carries a Boller & Chivens spectrograph and a 1024×1024 pixel E2V-4240 CCD. The slit width was 2″, and the spectrograph was tuned in the ~4000–8000 Å range with a dispersion of 10 Å pixel^{-1}. Wavelength calibration was done using the spectra of a cooper–helium–neon–argon lamp.

3.4. Southern Astrophysical Research Telescope

The spectra of 10 objects were observed with the SOAR, a 4.1 m telescope situated in Cerro Pachón (Chile). The objects were observed on nine different nights between 2013 November and 2015 May using the Goodman High Throughput spectrograph (Clemens et al. 2004). We used the 400 line mm^{-1} grating centered at 5000 Å, which gave wavelength coverage between 3000 and 7000 Å. Resolution is ~830, with a dispersion of 1 Å pixel^{-1}. Slit width was 1″, and wavelength calibration was accomplished using the spectra of an Fe–Ar lamp.

3.5. Magellan Telescopes at the Carnegie Observatories

Four additional observations were made in 2015 January with the 6.5 m Baade Magellan Telescope (Cerro Manqui, Chile) using the Inamori Magellan Areal Camera and Spectrograph. The f/2 camera was used in combination with the 300 line mm^{-1} grism (blaze angle 17°.5) and a 0″.7 slit to yield spectra with dispersion of 1.34 Å pixel^{-1} and FWHM resolution of ~4 Å.

3.6. Data Reduction Procedures

The data reduction has been performed according to our standard procedures, and it is similar for all the telescopes. Further details are given in Masetti et al. (2013) and Massaro et al. (2015c).

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

We dereddened the spectra for the galactic absorption assuming E_{B-V} values taken by the Schlegel et al. (1998) relation. Although our program does not require precise photometric calibration, we observed a spectrophotometric standard star to perform relative flux calibration on each spectrum. Even though the spectral shape is correct, the absolute calibration may suffer from sky condition issues, such as poor seeing and/or transparency. We also present normalized spectra, dividing them to a fit of the continuum to better show faint spectral features.

4. RESULTS

We have explored several catalogs, surveys, and databases such as the NASA Extragalactic Database (NED) and SIMBAD Astronomical Database searching for the multifrequency information of the sources listed in our sample. All the multifrequency notes collected in our analysis are listed in Table 2, and surveys and catalogs are listed in Table 3. There is also a note when the spectral energy distribution (SED) of a source is presented in Takeuchi et al. (2013) and when the radio counterpart has a flat radio spectrum (marked as “rf”). For the *XMM-Newton*, *Chandra*, and *Swift* catalogs we decided to use the same symbol to indicate whether the blazar candidate has an X-ray counterpart because these X-ray observatories

Table 2
Description of the Selected Sample

WISE/2MASS Name	R.A. (J2000)	decl. (J2000)	Telescope	Obs. Date yyyy-mm-dd	Exposure (s)	S/N	Notes	z	Class
J003020.44–164713.1	00:30:19.674	−16:47:13.114	SOAR	2013 Nov 28	2 × 600	59	N, w	0.237	BL Lac
J004348.66–111607.2	00:43:47.798	−11:15:52.999	SOAR	2014 Aug 02	2 × 600	51	N, w, 6, X	0.264	BL Lac
J010345.74+132345.3	01:03:48.993	+13:24:15.016	TNG	2014 Feb 01	2 × 1200	27	N, w	0.49	BL Lac
J010509.19+392815.1	01:05:13.009	+39:28:31.931	TNG	2014 Feb 01	2 × 1200	35	N, 87, GB, w, g (z = 0.083 Marlow+00) (z = 0.44 Shaw13)	0.44	BL Lac
J030727.21+491510.6	03:07:26.467	+49:15:11.810	TNG	2013 Oct 12	2 × 1200	38	N, GB, w	?	BL Lac
J033223.25–111950.6	03:32:22.812	−11:19:52.090	SOAR	2014 Jan 11	2 × 600	28	N, A, w, X	0.2074	FSRQ
J035309.54+565430.7	03:53:09.588	+56:54:31.09	WHT	2013 Nov 16	2 × 1576	15	N, 87, GB, w	?	BL Lac
J041203.78+545747.2	04:13:10.3	+54:59:44.0	SPM	2014 Oct 02	1800	11	N, w, M	?	BL Lac
J050818.99–193555.7	05:08:18.294	−19:35:55.154	SOAR	2014 Mar 03	2 × 600	10	Pm, N, A, c, rf, w	1.88	FSRQ
J061822.65–242637.7	06:17:51.9	−24:31:59.5	Magellan	2015 Jan 15	2 × 600	43	Pm, N, A, c, rf, w	0.2995	FSRQ
J070001.49+170921.9	07:00:55.7	+17:08:0.0	SPM	2015 Apr 20	3 × 1800	4	T, N, 87, GB, c, rf, w	1.08	FSRQ
J071939.18–401147.4	07:20:16.0	−40:06:25.7	Magellan	2015 Jan 16	2 × 600	31	w, X	?	BL Lac
J072113.90–022055.0	07:21:13.403	−02:20:57.541	SOAR	2014 Nov 26	2 × 600	19	N, w	?	BL Lac
J081917.58–075626.0	08:18:48.9	−08:01:43.0	Magellan	2015 Jan 17	2 × 600	13	N, w, M, 6, g, X (z = 0.85115 Jones+09) (SED Takeuchi+13)	?	BL Lac
J082841.74–241851.1	08:28:03.1	−24:19:56.6	Magellan	2015 Jan 17	2 × 1200	22	N, w	?	BL Lac
J091714.61–034314.2	09:18:03.7	−03:46:55.0	SPM	2015 Feb 27	3 × 1800	18	N, w, g, X	0.308	BL Lac/galaxy
J103840.66–531142.9	10:38:40.038	−53:11:43.973	SOAR	2014 Nov 26	2 × 600	32	Pm, A, c, rf, w	1.45	FSRQ
J104204.30–055816.5	10:42:53.9	−06:02:46.0	SPM	2015 Feb 27	1800	8	Pm, N, w,	0.39	BL Lac/galaxy
J114141.80–140754.6	11:41:41.844	−14:07:53.56	WHT	2014 Mar 14	2 × 1800	18	N, w, X (SED Takeuchi+13)	?	BL Lac
J122127.20–062847.8	12:21:26.849	−06:28:48.140	SOAR	2015 May 28	2 × 100	9	w, g	0.44	QSO
J133120.35–132605.7	13:31:20.363	−13:26:05.70	WHT	2014 Mar 13	2 × 1500	60	Pm, N, c, rf, w	0.25	FSRQ
J154824.38+145702.8	15:48:26.024	+14:56:30.628	TNG	2014 Mar 27	2 × 1200	21	S, N, w	0.23	BL Lac/galaxy
J162444.79+110959.3	16:24:44.372	+11:10:01.10	WHT	2014 Mar 13	2 × 1500	24	S, N, 87, c, rf, w	2.1	FSRQ
J170409.58+123421.7	17:04:11.504	+12:33:39.840	TNG	2014 Mar 27	2 × 1200	50	N, w	0.45	BL Lac
2MASS J18031240+2521185	18:03:12.4	+25:21:18.8	SPM	2015 Apr 17	2 × 1800	17	T, N, 87, c, rf	0.77	FSRQ
J181905.22+213233.8	18:19:45.7	+21:33:28.0	SPM	2015 Apr 19	2 × 1800	16	N, 87, c, rf, w	?	BL Lac
J184425.36+154645.8	18:45:04.7	+15:48:37.0	SPM	2015 Apr 21	2 × 1200	19	N, w	?	BL Lac
J201525.02–143203.9	20:15:24.246	−14:32:14.107	SOAR	2014 Aug 03	2 × 600	16	N, w, g	?	BL Lac
J203649.49–332830.7	20:36:49.097	−33:28:30.259	SOAR	2014 Aug 03	2 × 600	53	N, w, g, X	0.23	BL Lac
J213430.18–213032.8	21:34:28.556	−21:30:29.531	SOAR	2014 Aug 02	2 × 300	13	N, w (SED Takeuchi+13)	?	BL Lac

Notes. Our sources are divided into four 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 was found in the literature, or BZBs with uncertain/unknown redshift estimate. Column description. (1): *WISE*/2MASS name; (2): R.A. (Equinox J2000); (3): decl. (Equinox J2000); (4): telescope: Telescopio Nazionale Galileo (TNG), William Herschel Telescope (WHT), Observatorio Astronómico Nacional (OAN), Southern Astrophysical Research Telescope (SOAR), Magellan Telescopes at the Carnegie Observatories (Magellan); (5): observation date; (6): exposure time; (7): signal-to-noise ratio, (8): multifrequency notes (see Table 3); (9): redshift; (10): 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	References	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
Sydney University Molonglo Sky Survey	SUMSS	Mauch et al. (2003)	S
Parkes-MIT-NRAO Surveys	PMN	Wright et al. (1994)	Pm
Texas Survey of Radio Sources	TXS	Douglas et al. (1996)	T
Low-frequency Radio Catalog of Flat-spectrum Sources	LORCAT	Massaro et al. (2014)	L
Combined Radio All-Sky Targeted Eight-GHz Survey	CRATES	Healey et al. (2007)	c
NRAO VLA Sky Survey	NVSS	Condon et al. (1998)	N
VLA Faint Images of The Radio Sky at Twenty-Centimeter	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
Australia Telescope 20 GHz Survey	AT20G	Murphy et al. (2010)	A
WISE all-sky survey in the Allwise Source catalog	*WISE*	Wright et al. (2010)	w
Two Micron All Sky Survey	2MASS	Skrutskie et al. (2006)	M
Sloan Digital Sky Survey Data Release 9	SDSS DR9	Ahn et al. (2012)	s
Six-degree-Field Galaxy Redshift Survey	6dFGS	Jones et al. (2004)	6
GALaxy Evolution eXplorer All-Sky Survey Source Catalog	*GALEX*	Seibert (2012)	g
ROSAT Bright Source Catalog	RBSC	Voges et al. (1999)	X
ROSAT Faint Source Catalog	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	1SXPS	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.

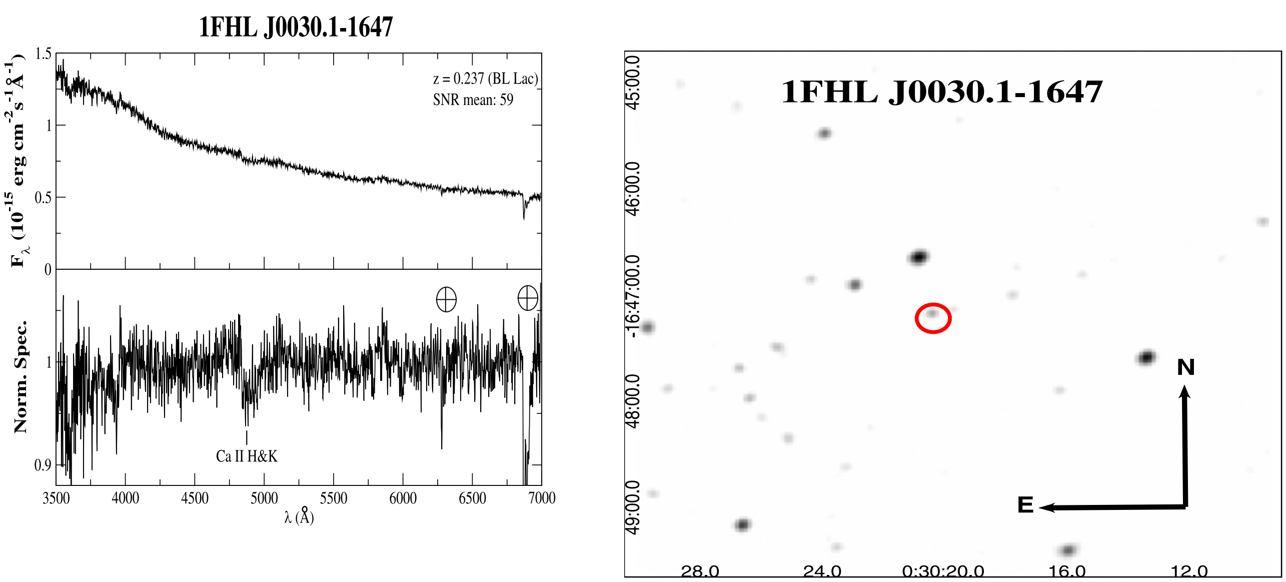

Figure 1. Left (upper panel): the optical spectrum of WISE J003020.44–164713.1, potential counterpart of 1FHL J0030.1–1647. It is classified as a BL Lac on the basis of its continuum dominated by non-thermal emission, but the absorption feature Ca II H+K ($\lambda_{obs} = 4867$–4928 Å) seen in the normalized spectra gives us a redshift $z = 0.237$. The average signal-to-noise ratio (S/N) is also indicated in the figure. Left (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 1FHL J0030.1–1647 pointed toward during our observations is indicated by the red circle.

(The complete figure set (29 images) is available.)

performed only pointed observations that could have been done serendipitously in the field of the *Fermi* source. In the following we provide the description of the results divided in subsections according to the classification in the *Fermi* catalogs. The spectra of the individual targets, together with their finding charts, are shown in the figure set of Figure 1.

4.1. Unidentified γ-ray Sources

Here we discuss the spectra obtained in our sample for the 10 UGSs selected as having blazar-like characteristics. Our spectroscopic observations allow us to confirm that eight of these sources are BL Lacs, and we have been able to determine the redshifts for four of them. The remaining two sources are QSOs, and the redshifts are given for these cases. A source is classified as a QSO and not as an FSRQ if there are no radio data available.

We classify the sources WISE J030727.21+491510.6, WISE J041203.78+545747.2, WISE J072113.90–022055.0, WISE J201525.02–143203.9, and WISE J213430.18–213032.8 (optical counterparts of 3FGL J0307.3+4916, 1FGL J0411.6+5459 and 3FGL J0721.5–0221, 3FGL J2015.3–1431, and 3FGL J2134.5–2131, respectively) as BL Lacs based on their featureless optical spectra.

In the case of WISE J170409.58+123421.7, the optical counterpart of 3FGL J1704.1+1234, there are emission features, [O II] ($EW_{obs} = 3.1$ Å), [O III] ($EW_{obs} = 1.5$–3.8 Å), and Ca H+K ($EW_{obs} = 2.2$–0.4 Å). Because these emission lines have rest-frame EWs smaller than 5 Å, the source is classified as a BL Lac at a redshift $z = 0.45$.

The spectrum of WISE J003020.44–164713.1, associated with 1FHL J0030.1–1647, is a BL Lac dominated by nonthermal optical emission. Nonetheless, the tentative identification of the doublet Ca H+K ($EW_{obs} = 0.2$–3 Å), which is evident only in the normalized spectra, allows us to estimate a redshift of $z = 0.237$. In the case of the optical counterpart WISE J004348.66–111607.2, associated with 1FHL J0044.0–1111, again it is a BL Lac dominated by nonthermal emission, but in the normalized spectra we tentatively identify the doublet Ca H +K ($EW_{obs} = 1.5$–0.7 Å) that would correspond to a redshift of $z = 0.264$.

The spectrum of WISE J154824.38+145702.8 associated with 3FGL J1548.4+1455 is dominated by the emission of the host elliptical galaxy rather than by nonthermal continuum arising from the jet, the features identified are doublet Ca H+K ($EW_{obs} = 9.2$–6.8 Å), G band, and Mg I ($EW_{obs} = 4.5$ Å). These features enable us to estimate a redshift of $z = 0.23$.

Finally, we classify the optical counterpart of 3FGL J1221.5–0632, WISE J122127.20–062847.8, as a QSO at a redshift $z = 0.44$ on the basis of its optical spectra. It shows a broad emission line that we tentatively identify as Mg II ($EW_{obs} = 44.8$ Å).

4.2. Blazar Candidates of Uncertain Type

Details of the 18 BCUs observed in our sample are listed below. The results obtained allow us to confirm the BL Lac nature of 10 of them, and for 8 of the sources we confirm that they are FSRQs.

The optical counterparts of 3FGL J0352.9+5655, 3FGL J0720.0–4010, 3FGL J0828.8–2420, 3FGL J1141.6–1406, 3FGL J1819.1+2134, and 3FGL J1844.3+1547 (WISE J035309.54+565430.7, WISE J071939.18–401147.4, WISE J082841.74–241851.1, WISE J114141.80–140754.6, WISE J181905.22+213233.8, and WISE J184425.36+154645.8, respectively) are classified as BL Lacs because of their featureless spectra, and we were not able to determine any redshift for these sources. For the source WISE J181905.22 +213233.8 there was a problem with the calibration star, so the calibration in flux is not reliable, but since the spectrum is featureless, it is a BL Lac.

The spectrum of WISE J010345.74+132345.3, counterpart of 3FGL J0103.7+1323, shows an absorption doublet that we tentatively identify with Ca H+K ($EW_{obs} = 2.3$–9.1 Å), and we classify this source as a BL Lac at $z = 0.49$. The spectrum of WISE J203649.49–332830.7, associated with 3FGL J2036.6–3325, is a BL Lac dominated by nonthermal emission. The doublet feature of Ca H+K ($EW_{obs} = 3.5$ Å) appears evidently only on the normalized spectra, allowing an estimate of the redshift of $z = 0.237$ (see Figure 1).

The spectrum of WISE J091714.61–034314.2, associated with 3FGL J0917.3–0344, is dominated by the emission of the host elliptical galaxy rather than by nonthermal continuum arising from the jet. The features identified are doublet Ca H +K ($EW_{obs} = 1.2$–1.9 Å) and G band. These features enable us to estimate $z = 0.308$. Also for the source 3FGL J1042.0–0557 (aka WISE J104204.30–055816.5) it is possible to see absorption features from the host galaxy, such as Ca H+K ($EW_{obs} = 2.4$–5.0 Å), that lead us to a redshift $z = 0.39$.

On the basis of our optical spectra and radio data available, we classify WISE J033223.25–111950.6, the optical counterpart of 2FGL J0332.5–1118, as an FSRQ at a redshift $z = 0.2074$. This was possible owing to the identification of the lines [O II] ($EW_{obs} = 3.1$ Å), [Ne III] ($EW_{obs} = 6.1$ Å), Hδ ($EW_{obs} = 12.9$ Å), Hγ ($EW_{obs} = 31.4$ Å), Hβ ($EW_{obs} = 42.8$ Å), and the doublet [O III] ($EW_{obs} = 14.2$–48.9 Å). In the case of WISE J050818.99–193555.7, optical counterpart of 3FGL J0508.2–1936, the optical and radio data available allow us to confirm that this is an FSRQ. Given the emission lines Lyα ($EW_{obs} = 173.2$ Å), C IV ($EW_{obs} = 139.3$ Å), and C III ($EW_{obs} = 11.35$ Å), we estimated a redshift of $z = 1.88$. With the optical and radio data of the optical counterpart of 3FGL J0618.2–2429, WISE J061822.65–242637.7, we can deduce this source is an FSRQ at a redshift $z = 0.2995$. The emission features identified are [O II] ($EW_{obs} = 10.3$ Å), the doublet [O III] ($EW_{obs} = 2.1$–6.1 Å), Hα ($EW_{obs} = 18.9$ Å), and [S II] ($EW_{obs} = 4.2$ Å). The optical counterpart of the following source 3FGL J0700.0+1709 (WISE J070001.49+170921.9) is also an FSRQ. In this source we detected a broad emission line that we tentatively identify as Mg II ($EW_{obs} = 44.8$ Å) and correspondent to $z = 1.08$. In the case of the optical counterpart WISE J103840.66–531142.9 associated with 3FGL J1038.9–5311, its optical and radio data indicate that it is an FSRQ at $z = 1.45$. The features presented are C IV ($EW_{obs} = 53.9$ Å), [C III] ($EW_{obs} = 28.2$ Å), and Mg II ($EW_{obs} = 11.0$ Å). For the source WISE J133120.35–132605.7 associated with 3FGL J1331.1–1328, the features observed are Hγ ($EW_{obs} = 3.1$ Å), Hβ ($EW_{obs} = 5.3$ Å), and the doublet [O III] ($EW_{obs} = 3.3$–9.6 Å). These and the available radio data enable us to classify the source as an FSRQ at $z = 0.25$. According to the data in optical and radio, WISE J162444.79+110959.3 associated with 2FGL J1624.4 +1123 is an FSRQ. The spectral features are C IV ($EW_{obs} = 23.43$ Å) and [C III] + S II ($EW_{obs} = 23.0$ Å), yielding a redshift of $z = 2.1$. We could see the presence of a doublet intervenient system of Mg II ($EW_{obs} = 3.1$ Å) at $z = 0.895$. For the optical counterpart of 2FGL J1803.6+2523c (aka 2MASS J18031240+2521185), we see an emission feature that we tentatively identify with Mg II ($EW_{obs} = 17.6$ Å), so we classify this source as an FSRQ at $z = 0.77$ given both optical and radio data.

4.3. Reobservations of Fermi BL Lac Objects

In the case of WISE J081917.58–075626.0, the optical counterpart of 2FGL J0819.6–0803, we have not been able to confirm the previous value of the redshift $z = 0.85115$ given in Jones et al. (2009) because of its featureless spectrum. That value of the redshift is claimed in the survey paper, but the image of the spectrum does not allow any clear line identification.

We reobserved WISE J010509.19+392815.1, associated with 3FGL J0105.3+3928. For this source there were two different redshift values in the literature. In Marlow et al. (2000) they measure a redshift of $z = 0.083$ owing to a tentative association of [O II] and Hα that we do not see in our spectrum. This could be due to variability. In Shaw et al. (2013) they classify the source as a BL Lac at $z = 0.44$ owing to identification of absorption lines from the host galaxy. According to our observations, there is an emission line that we tentatively identify as Mg II ($EW_{obs} = 5.9$ Å) and that allows us to measure a redshift of $z = 0.44$, in agreement with the value given by Shaw et al. (2013). Since our spectrum is dominated by nonthermal emission from the jet rather than emission from the host galaxy as in Shaw et al. (2013), this source might be a transition object.

5. SUMMARY AND CONCLUSIONS

Our main goal was to confirm the nature of the counterparts for the UGSs and BCUs selected on the basis of their low radio frequency spectra and their peculiar IR colors (Massaro et al. 2012b, 2013d).

In addition, we reobserved two sources already classified as BL Lacs at uncertain redshift in the literature because of the optimal conditions at the moment of the observation for these sources. We aim to find a variation of the continuum emission that enables us to estimate their redshifts.

The total number of sources presented is 30, and the results can be summarized as follows:

1. In the UGS subsample all the sources have a blazar nature. Five of them are BL Lacs whose redshifts could not be determined owing to their featureless continuum, while three others (even though they have a BL Lac nature) have features in their optical spectra that led to the possibility of determining their redshifts. These sources are WISE J003020.44–164713.1, which was detected at $z = 0.237$, WISE J004348.66–111607.2 at $z = 0.264$, and WISE J170409.58+123421.7 at $z = 0.45$. The source WISE J154824.38+145702.8 is a BZG, dominated by absorption from the host galaxy, and we were able to detect absorption lines in the optical spectrum leading to a redshift measurement of $z = 0.23$. There is a QSO, WISE J122127.20–062847.8, at $z = 0.44$. Since there is no radio emission for this optical source, it is possible that this QSO is not the real counterpart.
2. We analyzed the spectra of 18 sources classified as BCUs. We found that six of them are BL Lacs, and their featureless spectra made it impossible to measure their redshifts. Even though the source WISE J010345.74+132345.3 was found to be a BL Lac dominated by nonthermal emission, some spectral features enabled us to determine its redshift of $z = 0.49$. The same situation was found for the source WISE J203649.49–332830.7, a BL Lac dominated by nonthermal emission at $z = 0.237$. The emissions of the sources WISE J091714.61–034314.2 at $z = 0.308$ and WISE J104204.30–055816.5 at $z = 0.39$ were both dominated by the host galaxy rather than by the jet continuum. Finally, because of the radio and optical data available, eight of them were classified as FSRQs, and we measured their redshifts: WISE J033223.25–111950.6 was determined to be at $z = 0.2074$, WISE J050818.99–193555.7 at $z = 1.88$, WISE J061822.65–242637.7 at $z = 0.2995$, WISE J070001.49+170921.9 at $z = 1.08$, WISE J103840.66–531142.9 at $z = 1.45$, WISE J133120.35–132605.7 at $z = 0.25$, WISE 162444.79+110959.3 at $z = 2.1$, and 2MASS J18031240+2521185 at $z = 0.77$.
3. We reobserved the spectra of two sources previously characterized as BL Lacs and confirmed this classification for both of them. The spectra of the source WISE J010509.19+392815.1 observed by Shaw et al. (2013) showed emission dominated by the host galaxy rather than by nonthermal emission. In our observations, instead, the spectrum is dominated by continuum emission arising from the jet; it might be a transition object.

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[16] http://www.star.bris.ac.uk/~mbt/topcat/
[17] http://aladin.u-strasbg.fr/aladin.gml

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