PROCEEDINGS OF SCIENCE

New blazars from the cross-match of recent multi-frequency catalogs

Alessandro Maselli[*a], **Giancarlo Cusumano**[a], **Valentina La Parola**[a], **Alberto Segreto**[a], **Francesco Massaro**[b,c], **Raffaele D'Abrusco**[d], **Gino Tosti**[e,f]

[a]*INAF-IASF Palermo, via Ugo La Malfa 153, I-90146 Palermo, Italy*
[b]*Dipartimento di Fisica, Università degli Studi di Torino, via Pietro Giuria 1, I-10125 Torino, Italy*
[c]*Yale Center for Astronomy and Astrophysics, Physics Department, Yale University, PO Box 208120, New Haven, CT 06520-8120, USA*
[d]*Harvard-Smithsonian Astrophysical Observatory, 60 Garden Street, Cambridge, MA 02138, USA*
[e]*Dipartimento di Fisica, Università degli Studi di Perugia, Piazza dell'Università 1, I-06123 Perugia, Italy*
[f]*Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, Via A. Pascoli, I-06123 Perugia, Italy*

E-mail: maselli@ifc.inaf.it, cusumano@ifc.inaf.it, laparola@ifc.inaf.it, segreto@ifc.inaf.it, f.massaro@unito.it, rdabrusco@cfa.harvard.edu, tosti@pg.infn.it

Blazars are peculiar radio-loud active galactic nuclei (AGNs) emitting over the whole electromagnetic spectrum. We performed the cross-match of several catalogs obtained from recent surveys at different frequencies to search for new blazars to be included in the *Roma*-BZCAT catalog which is, to date, the most comprehensive list of such sources. To exclude generic active galactic nuclei from the preliminary list of objects that we obtained, and focus on authentic blazar-like sources, we carefully investigated additional properties such as their morphology and the slope of their spectral energy distribution in the radio domain, the features shown in their optical spectrum, and the luminosity in the soft X rays. At the end of our screening we obtained a list of 15 objects with firmly established blazar properties.

Swift: 10 Years of Discovery
2-5 December 2014
La Sapienza University, Rome, Italy

*Speaker.

PoS(SWIFT 10)148

1. Blazars and their classification criteria

Blazars are radio-loud active galactic nuclei (AGNs) well known for their non thermal emission spanning a wide range of frequencies from the radio band to the MeV–GeV range of γ rays, and extending towards the TeV range in the most extreme cases. This class of extragalactic sources is one of the most widely detected by *Fermi*-LAT. Traditionally, two main classes of blazars are distinguished: the BL Lac objects (BL Lacs) and the flat-spectrum radio quasars (FSRQs). The shape of their spectral energy distribution (SED) is similar, with two main broad components: a low-energy one peaking in the range from the IR to the X-ray band, and a high-energy one peaking from MeV to GeV energies (*e.g.* [1]). However, they reveal differences in their optical spectrum depending on the width and strength of the emission lines: missing or very narrow for BL Lacs, strong and broad for FSRQs [2, 3]. The criteria adopted in the *Roma*-BZCAT catalog [4] for their classification are: 1) detection in the radio band down to mJy flux densities at 1.4 GHz; 2) for FSRQs, a radio spectral index α lower than 0.5 ($F(\nu) \propto \nu^{-\alpha}$) measured between 1.4 GHz and 5 GHz (condition that is not required for BL Lacs, although most of them have flat spectra); 3) compact radio morphology or, when extended, with a dominant core and a one-sided jet; 4) optical identification and analysis of the optical spectrum to establish the type of blazar; 5) isotropic X-ray luminosity $L_X > 10^{43}$ erg s^{-1} from a point-like source.

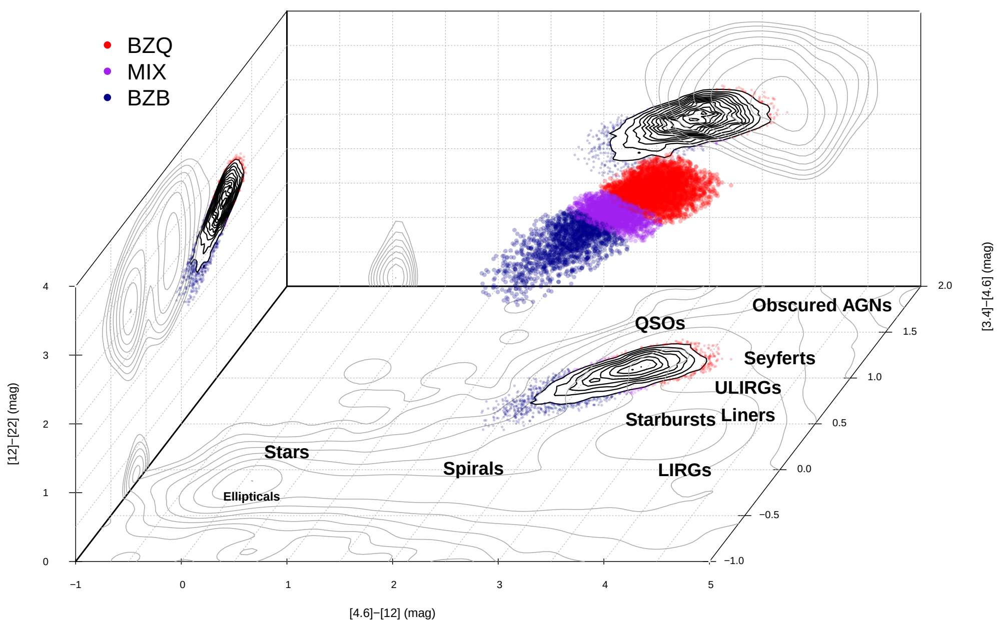

Figure 1: Three-dimensional distribution of the WIBRaLS sources in the space generated by the WISE [3.4]-[4.6] μm, [4.6]-[12] μm, and [12]-[22] μm colors. Each source is color-coded according to the WISE spectral classification and labeled according to the *Roma*-BZCAT nomenclature (BZB for BL Lacs and BZQ for FSRQs). The approximate location of different typical classes of objects in the [3.4]-[4.6] μm vs [4.6]-[12] μm color-color plane is also shown (from [5]).

Table 1: The list of validated blazars.

(1) SDSS name	(2) d_{OX} (")	(3) R_X (")	(4) d_{OR} (")	(5) d_{OI} (")	(6) $S_{1.4\ GHz}$ (mJy)	(7) $S_{5\ GHz}$ (mJy)	(8) α_r	(9) r (mag)	(10) z	(11) $F_X \cdot 10^{-12}$ (erg cm^{-2} s^{-1})	(12) $L_X \cdot 10^{44}$ (erg s^{-1})	(13) classification
J003931.58−111102.4	1.2	4.2	0.41	0.24	296	237	+0.18	19.0	0.553	6.30	75.1	FSRQ
J082438.99+405707.7	2.1	4.7	0.51	0.09	175	138	+0.19	17.0	0.612	0.10	1.5	FSRQ
J082753.69+521758.3	2.6	3.8	0.68	0.14	181	292	−0.38	18.9	0.338	2.50	9.2	FSRQ
J095906.96+050958.9	1.5	4.4	0.42	0.09	47	73	−0.35	18.0	0.996	0.38	19.5	FSRQ
J100033.84+132410.8	1.7	3.9	0.20	0.13	53	34	+0.36	16.7	1.355	0.74	82.2	FSRQ
J103045.22+255522.1	3.1	5.1	0.18	0.04	49	50	−0.02	17.1	0.692	0.24	5.0	FSRQ
J104031.62+061721.7	1.1	3.9	0.12	0.13	39	49	−0.18	19.9	0.735	0.66	15.9	BL Lac
J110838.98+255613.2	0.3	3.8	0.20	0.31	68	73	−0.06	17.5	0.732	0.80	19.0	FSRQ
J133631.44+031423.5	5.4	4.3	0.32	0.75	62	111	−0.47	18.9	1.303	0.12	12.1	FSRQ
J141238.66+484447.1	1.6	3.8	0.16	0.13	58	74	−0.20	18.6	0.906	0.39	15.8	FSRQ
J142114.05+282452.8	3.4	4.1	0.68	0.03	49	40	+0.16	17.8	0.538	0.46	5.1	FSRQ
J153458.41+575625.6	2.5	4.6	0.08	0.29	7	17	−0.71	19.0	1.129	0.17	11.9	FSRQ
J161541.21+471111.7	2.9	4.6	0.23	0.09	98	175	−0.46	17.2	0.199	1.28	1.4	BL Lac
J162805.20+252636.8	1.8	4.7	0.14	0.08	100	59	+0.42	18.4	0.995	0.31	15.9	FSRQ
J170634.12+361508.0	4.9	4.4	0.37	0.14	19	27	−0.28	17.9	0.917	1.06	44.2	FSRQ

1) SDSS designation of the source; 2) angular separation d_{OX} between the SDSS and the 1SXPS sources; 3) 90% error radius of the 1SXPS source; 4) and 5) angular separation d_{OR} and d_{OI} of the SDSS source from the corresponding FIRST and WISE associated counterparts, respectively; 6) and 7) radio flux density at 1.4 GHz and 5 GHz, respectively; 8) radio spectral index α_r; 9) magnitude in the r filter; 10) redshift z; 11) unabsorbed flux F_X over the 0.3–10 keV band; 12) corresponding luminosity L_X; 13) our classification.

2. Cross-match of recent multifrequency catalogs

The large amount of data from recent all-sky surveys in different energy bands is very helpful for blazar research. Considering the criteria adopted in the *Roma*-BZCAT we searched for new blazars by cross-matching recent multi-frequency catalogs and carrying out further investigation on their properties reported in the literature. We started from the cross-match of the 1st Swift-XRT Point Source catalog (1SXPS, [6]) with the spectroscopic sample of the 9th Data Release of the Sloan Digital Sky Survey (SDSS-DR9, [7]). We used as matching radius the error radius (at 90% confidence level) of the soft X-ray source reported in the 1SXPS, incremented by 2" to take into account the typical seeing of the SDSS. As a result we obtained 5012 SDSS objects provided with an optical spectrum and a point-like X-ray counterpart. Then, we cross-matched this list with the all-sky catalog of WISE blazar-like radio-loud sources (WIBRaLS, [5]). This includes all the radio-loud infrared sources, detected in all the WISE four filters, that occupy a well defined region in the infrared colour space (see Figure 1), the so-called *blazar strip*. This region has been defined [8] using the infrared colours of certified blazars detected by the *Fermi*-LAT during the first two years of this mission. We used an overall matching radius of 3.3" as determined by [9] in their search for the optimal value of the spatial association between blazars in the *Roma*-BZCAT and WISE sources, and obtained 214 objects. Although all the WIBRaLS sources have a radio counterpart, we kept for further investigation only objects also included in the Faint Images of the Radio Sky at Twenty centimeters (FIRST, [10]) survey since the angular resolution of this survey allows one for a better evaluation of the radio morphology. Therefore we finally obtained 201 SDSS objects including 152 blazars already reported in the 4th version of the *Roma*-BZCAT: the properties of the remaining 49 blazar candidates were investigated in greater detail.

3. Deeper investigation of multifrequency properties

A few additional aspects need to be taken into account to confirm the blazar nature of a candidate, such as the radio morphology, the slope of the spectral energy distribution in the radio band and the features shown in the optical spectra. Blazars are in fact characterized by a core-dominated radio morphology; as an alternative, the additional presence of a one-sided jet can be accepted. Moreover, unlike the BL Lac objects, a flat radio spectrum is required when broad emission lines are evident in the optical spectrum. Therefore we excluded from our sample of blazar candidates: a) 11 objects with an extended radio morphology characteristic of radio galaxies; b) 10 objects with no measurements at radio frequencies different from 1.4 GHz, for which we could not estimate the slope of the radio spectrum; c) 13 objects with both a steep radio spectrum and broad emission lines in their optical spectra.

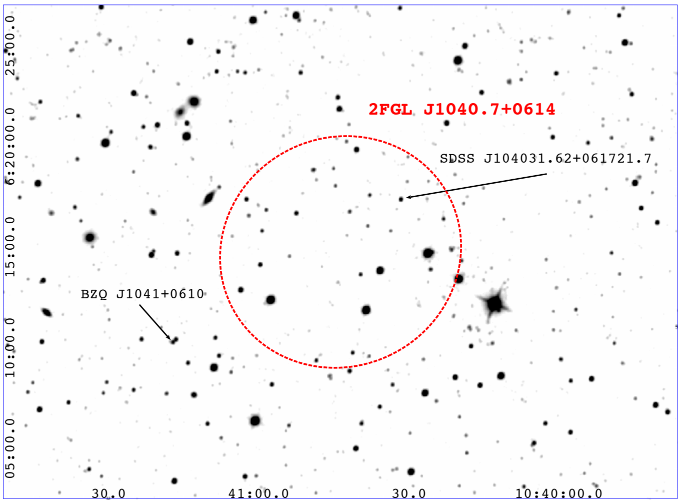

Figure 2: WISE 3.4 μm sky map centered at the position of 2FGL J1040.7+0614. The BL Lac object found by our procedure, SDSS J104031.62+061721.7, is within the error region of the γ-ray source (red line) at variance with BZQ J1041+0610, the counterpart associated in the 2LAC.

4. Sample of certified blazars

We finally obtained a list of 15 blazars, that is reported in Table 1. Among them there are 13 FSRQs and 2 BL Lacs; the X-ray luminosity is always higher than 10^{43} erg s^{-1} by at least an order of magnitude. The two BL Lac objects are also possible counterparts to γ-ray sources. SDSS J104031.62+061721.7 is within the 95% error circle (Θ_{95} = 5.88") of the γ-ray source 2FGL J1040.7+0614. We note that the counterpart 4C +06.41 (named BZQ J1041+0610 in the *Roma*-BZCAT) associated to this γ-ray source in the Second LAT AGN Catalog (2LAC, [11]) is outside of the 2FGL error circle, at a distance of 9.45" (see Figure 2); their association is given with a low probability. Therefore, we consider the possibility that a contribution to the γ-ray emission corresponding to 2FGL J1040.7+0614 might be attributed to SDSS J104031.62+061721.7, possibly in addition to BZQ J1041+0610. The second BL Lac object, SDSS J161541.21+471111.7, was reported by [12] as a possible counterpart to the unidentified γ-ray source 2FGL J1614.8+4703.

Considering the group of 167 blazars obtained by our method, including those already classified in the 4th version of the *Roma*-BZCAT, we found 72 BL Lacs (43.1%), 85 FSRQs (50.9%) and 10 blazars with uncertain classification (6.0%), in agreement with the corresponding fractions in the BZCAT (38.8%, 54.2%, and 7.0%).

References

[1] P. Giommi et al., *The sedentary survey of extreme high energy peaked BL Lacs*, *A&A* **434** (2005) 385

[2] M. Stickel et al., *The complete sample of 1 Jansky BL Lacertae objects. I - Summary properties*, *ApJ* **374** (1991) 431

[3] J.T. Stocke et al., *The Einstein Observatory Extended Medium-Sensitivity Survey. II - The optical identifications*, *ApJS* **76** (1991) 813

[4] E. Massaro et al., *Roma-BZCAT: a multifrequency catalogue of blazars*, *A&A* **495** (2009) 691

[5] R. D'Abrusco et al., *The WISE Blazar-like Radio-loud Sources: An All-sky Catalog of Candidate gamma-ray Blazars*, *ApJS* **215** (2014) 14

[6] P.A. Evans et al., *1SXPS: A Deep Swift X-Ray Telescope Point Source Catalog with Light Curves and Spectra*, *ApJS* **210** (2014) 8

[7] C.P. Ahn et al., *The Ninth Data Release of the Sloan Digital Sky Survey: First Spectroscopic Data from the SDSS-III Baryon Oscillation Spectroscopic Survey*, *ApJS* **203** (2012) 21

[8] F. Massaro et al., *The WISE Gamma-Ray Strip Parameterization: The Nature of the Gamma-Ray Active Galactic Nuclei of Uncertain Type*, *ApJ* **750** (2012) 138

[9] R. D'Abrusco et al., *Unveiling the Nature of Unidentified Gamma-Ray Sources. I. A New Method for the Association of Gamma-Ray Blazars*, *ApJS* **206** (2013) 12

[10] R.H. Becker et al., *VizieR Online Data Catalog: The FIRST Survey Catalog, Version 12Feb16* **VIII/90** (2012)

[11] M. Ackermann et al., *The Second Catalog of Active Galactic Nuclei Detected by the Fermi Large Area Telescope*, *ApJ* **743** (2011) 171

[12] F. Massaro et al., *Unveiling the Nature of Unidentified Gamma-Ray Sources. II. Radio, Infrared, and Optical Counterparts of the Gamma-Ray Blazar Candidates*, *ApJS* **206** (2013) 13