A new multiwavelength census of blazars[★]

A. Paggi^{1,2}, M. Bonato^{3,4}, C. M. Raiteri¹, M. Villata¹, G. De Zotti⁴, and M. I. Carnerero¹

¹ INAF, Osservatorio Astrofisico di Torino, Via Osservatorio 20, 10025 Pino Torinese, Italy
e-mail: alessandro.paggi@inaf.it

² INFN – Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Via Pietro Giuria 1, 10125 Turin, Italy

³ INAF, Istituto di Radioastronomia, Via Piero Gobetti 101, 40129 Bologna, Italy

⁴ INAF, Osservatorio Astronomico di Padova, Vicolo dell-Osservatorio 5, 35122 Padova, Italy

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ABSTRACT

Context. Blazars are the rarest and most powerful active galactic nuclei. They play a crucial and expanding role in the multifrequency and multimessenger astrophysics of today. Dominating the high-energy extragalactic sky, they have been recently associated with high-energy astrophysical neutrinos and they may be among the accelerators of the ultra-high energy cosmic rays. Current blazar catalogs, however, are incomplete and they are depleted, in particular, at low Galactic latitudes.

Aims. Our study is aimed at augmenting the current blazar census, starting from a sample of ALMA calibrators that provides more homogeneous sky coverage, especially at low Galactic latitudes, to build a catalog of blazar candidates that can provide candidate counterparts to unassociated γ -ray sources and sources of high-energy neutrino emission or ultra-high energy cosmic rays.

Methods. Based on the ALMA Calibrator Catalog, we compiled a selection of 1580 ALMA Blazar Candidates (ABCs) for which we collected multiwavelength information, including *Gaia* photometric, parallax, and proper motion data, as well as SDSS and LAMOST photometric and spectral data, WISE photometric data, X-ray (*Swift*-XRT, *Chandra*-ACIS and *XMM-Newton*-EPIC) count-rates and spectra, and *Fermi*-LAT fluxes and spectral slopes. We also compared our ALMA Blazar Candidates with existing blazar catalogs, such as 4FGL, 3HSP, W1BRLS2, and the KDEBLACS.

Results. The ABC catalog fills in the gaps with regard to low Galactic latitude sources in current blazar catalogs. By cross-matching this catalog with *Gaia* DR2, SDSS DR12, LAMOST DR5, AllWISE, and 4FGL catalogs, we obtained 805, 295, 31, 1311, and 259 matches, respectively. ALMA Blazar Candidates are significantly dimmer than known blazars in the *Gaia* g band, while the difference in the *Gaia* $b - r$ color between the two populations is less pronounced. Also, ABC sources appear bluer in SDSS than known blazars, although with low statistical significance. Most ABCs classified as QSO and BL Lac fall into the SDSS color regions of low redshift quasars, with some QSOs entering the regions of higher redshift quasars. We collected 110 optical spectra in SDSS DR12 and LAMOST DR5, which mostly classify the corresponding sources as QSO (98), while 12 sources turned out to be galactic objects. Regarding the WISE colors, we found that ABC sources are significantly bluer than known blazars in the $w2-w3$ and $w3-w4$ colors. In X-ray, we detected 173 ABCs and we were able to extract X-ray spectra for 92 of them. Our sources are, on average, similar in the X-ray band to known blazars in terms of count rates and spectral slopes, implying that our sample covers the same region of the blazar parameter space in this band. A comparison of γ -ray properties shows that the ABCs are, on average, dimmer and that their γ -ray spectra are softer than known blazars, indicating a significant contribution on the part of FSRQ sources. Making use of WISE colors, we classified 715 ABCs as candidate γ -ray blazar of different classes.

Conclusions. We built a new catalog of 1580 candidate blazars with a rich multiwavelength data-set, filling in the gaps for low Galactic latitude sources in current blazar catalogs. This will be particularly important for the identification of the source population of high-energy neutrinos or ultra-high energy cosmic rays, or to verify the *Gaia* optical reference frame. In addition, ALMA Blazar Candidates can be investigated both through optical spectroscopic observation campaigns or through repeated photometric observations for variability studies. In this context, the data collected by the upcoming LSST surveys will provide a key tool for investigating the possible blazar nature of these sources.

Key words. catalogs – galaxies: active

1. Introduction

Blazars are the rarest and most powerful active galactic nuclei. Their emission is characterized by variable, non-thermal radiation that extends over the entire electromagnetic spectrum, flat radio spectra, high and variable polarization, apparent superluminal motion, and high luminosities characterized by intense and rapid variability (e.g., Urry & Padovani 1995; Giommi et al. 2013). These observational properties are generally interpreted in terms

of a relativistic jet aligned within a small angle to our line of sight (Blandford & Rees 1978). Traditionally blazars have been classified in two main subclasses: BL Lac objects and flat spectrum radio quasars (FSRQs). The former exhibit featureless optical spectra, while the latter are characterized by strong quasar emission lines and higher radio polarization. More specifically, if the only spectral features observed are emission lines with a rest-frame equivalent width of $EW < 5 \text{ \AA}$, the object is classified as a BL Lac (Stickel et al. 1991; Stocke & Rector 1997), otherwise it is classified as a FSRQ (Laurent-Muehleisen et al. 1999). The blazar spectral energy distributions (SEDs) typically show two peaks: one in the range of infrared-soft X-rays due to

[★] Full Tables 1, 2, 4, C.1 and C.2 are only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/cat/J/A+A/641/A62>

synchrotron emission by highly relativistic electrons within the jet, and another one at hard X-ray or γ -ray energies. The latter is interpreted as inverse Compton upscattering by the electrons in the jet on the seed photons provided by the synchrotron emission (synchrotron self-Compton, SSC, see, e.g., Inoue & Takahara 1996) which dominates the high energy output in BL Lacs. The possible addition of seed photons from outside the jets yields contributions to the non-thermal radiations in the form of external inverse Compton scattering (EC, see Dermer & Schlickeiser 1993; Dermer et al. 2009) often dominating the γ -ray outputs in FSRQs (Aharonian et al. 2009; Ackermann et al. 2011).

Blazars play a crucial and expanding role in the multifrequency and multimessenger astrophysics of today. They dominate the high-energy (from MeV to TeV) extragalactic sky (Massaro et al. 2015a; Di Mauro et al. 2018; Chang et al. 2019; Chiaro et al. 2019) and they have recently been associated with high-energy astrophysical neutrinos (IceCube Collaboration 2018; Garrappa et al. 2019). In turn, these neutrinos arise from interactions of ultra-high energy cosmic rays (UHECR; Sarazin et al. 2019) via charged pion decay. Thus, blazars jets may also be among the long-sought accelerators of the UHECR.

The 5th edition of the Roma-BZCAT Multifrequency Catalogue of Blazars (Roma-BZCAT, Massaro et al. 2015b) is the most comprehensive list of blazars confirmed by means of published spectra. This catalog contains 3561 entries and for each source it lists radio coordinates obtained from very-long-baseline interferometry measurements (VLBI, Titov & Malkin 2009; Titov et al. 2011; Petrov & Taylor 2011), augmented with the available multiwavelength information, such as optical magnitude from USNO B1 or SDSS DR10, radio flux density from NVSS (Condon et al. 1998), FIRST (White et al. 1997), SUMSS (Mauch et al. 2003), GB6 (Gregory et al. 1996), or PMN (Wright et al. 1994), the microwave flux density from *Planck* (Planck Collaboration XXVIII 2014), the soft X-ray flux from ROSAT archive or *Swift*-XRT catalogs, the hard X-ray flux from Palermo BAT Catalogue (Cusumano et al. 2010), the γ -ray flux from the first (1FGL, Abdo et al. 2010a), as well as the Second *Fermi* catalog (2FGL, Nolan et al. 2012) and the redshift. Confirmed blazars listed in the Roma-BZCAT are subdivided into:

- 1059 BZBs: BL Lac objects,
- 1909 BZQs: Flat spectrum radio quasars.

In addition, the 5th edition of Roma-BZCAT lists 92 BL Lac candidates, that is, sources classified as BL Lac in the literature, but without published optical spectra. In the following, we consider these sources as BZBs. The other kind of sources listed in Roma-BZCAT are:

- 274 BZGs: sources classified as BL Lacs in the literature but with a host galactic emission dominating the nuclear one,
- 227 BZUs: blazars of uncertain type.

Blazar catalogs that are as large and complete as possible are necessary to provide candidate counterparts to unassociated γ -ray sources that have been detected by the *Fermi* satellite (D’Abrusco et al. 2013; Massaro et al. 2013) and to sources of high-energy neutrino emission or UHECRs. In particular, a complete sky coverage of such catalogs is critically important in the case of rare events, such as detections of high-energy neutrinos. The identification of the neutrino-emitting source population requires to fully exploit the all-sky neutrino sample by stacking analyses towards candidates. To this end, we obviously need blazar catalogs that cover the whole sky.

The Atacama Large Millimeter Array (ALMA) calibrators are compact sources bright at mm and sub-mm wavelengths. They were primarily drawn from “seed” catalogs, such as those

of the Very Long Array (VLA), the SubMillimeter Array (SMA), the Australia Telescope Compact Array (ATCA), and the Combined Radio All-Sky Targeted Eight-GHz Survey (CRATES)¹. The ALMA Calibrator Catalogue (ACC; Bonato et al. 2019) contains 3364 sources, whose distribution in Galactic coordinates is presented in the left panel of Fig. 1. Because of the ALMA location in the Southern Hemisphere, its calibration sources have declination lower than $\sim +60^\circ$; this explains the “hole” centered at about $l = -120^\circ$ and $b = 30^\circ$ in the left panel of the figure.

The distribution of the Galactic latitude of ACC sources is presented in the upper part of the right panel of the same figure. The Galactic north-south asymmetry in latitude distribution is evident, with $\sim 50\%$ of the ACC sources having $b < -10^\circ$ and $\sim 35\%$ having $b > 10^\circ$. In particular, we note that we have $\sim 15\%$ of the sources at low Galactic latitudes, that is, $|b| < 10^\circ$. This is at variance with the sources listed in the Roma-BZCAT, whose Galactic latitude distribution is shown in the lower part of the right panel of Fig. 1. In this case we have $\sim 40\%$ of the Roma-BZCAT sources with $b < -10^\circ$ and $\sim 57\%$ with $b > 10^\circ$, while only $\sim 3\%$ of the Roma-BZCAT sources have $|b| < 10^\circ$. This is mainly due to the fact that the firm blazar classification adopted in the Roma-BZCAT catalog is based on optical spectroscopy, which tends to be problematic along the Galactic plane due to strong absorption and source crowding.

The ALMA Calibrator Catalogue therefore represents an excellent starting point from which we can build a new catalog of blazar candidates, with the goal of completing the census of blazars, especially at low galactic latitudes where the current blazar catalogs are depleted.

In this paper, following an analysis of the sample of ALMA calibrators to select bona fide blazar candidates in Sect. 2, we compare the sample of selected sources, compiled into the ALMA Blazar Candidates (ABC) catalog, with other blazar catalogs in Sect. 3. In Sect. 4, we collect multiwavelength data on ABC sources by cross-matching our catalog with public infrared, optical, and γ -ray catalogs, and by performing an extensive X-ray analysis of available data. In Sect. 5, following D’Abrusco et al. (2019), we use data from the Wide-Field Infrared Survey Explorer (WISE, Wright et al. 2010) to select ABC sources whose mid-infrared colors are consistent with those of confirmed γ -ray emitting blazars and to assign them to blazar sub-classes. Finally, in Sect. 6, we summarize our conclusions.

2. Sample selection

In this section, we compare the radio properties of ACC sources with those of Roma-BZCAT source and compile a sample of ACC sources that are not included in Roma-BZCAT in order to build a catalog of ALMA blazar candidates.

As mentioned before, the ACC contains 3364 sources, with a declination of ($\delta < 60^\circ$). The sources in Roma-BZCAT below such a declination are 3340. Cross-matching them with the ACC using a search radius of $10''$ we find 1391 matches. The comparison between the radio flux densities at 1.4 or 0.843 GHz (as listed in the Roma-BZCAT) for these 1391 matches and the remaining 1949 Roma-BZCAT sources with declination $< 60^\circ$ without a match in the ACC catalog is presented in the left panel of Fig. 2, from which it is evident that the ACC sources represent the brightest radio end of the blazar population. A similar result is found when comparing the average ALMA band 3 (65–90) GHz

¹ <https://almascience.eso.org/alma-data/calibrator-catalogue>

Fig. 1. *Left panel:* white circles indicate the Galactic coordinates of the ACC sources. Grey crosses in the background represent the Galactic coordinates of the Roma-BZCAT sources. Black lines represent equatorial coordinates with declinations from -60° to 60° with increment of 20° . *Right panel:* normalized Galactic latitude distribution of ACC (*top*) and Roma-BZCAT (*bottom*) source.

Fig. 2. *Left panel:* comparison of the normalized distributions of the radio fluxes densities at 1.4 or 0.843 GHz (as listed in the Roma-BZCAT) for the Roma-BZCAT sources with a match in the ACC catalog (blue) and for the Roma-BZCAT sources below $< 60^\circ$ of declination without a match in the ACC catalog (red). *Right panel:* comparison of the normalized distributions of the average ALMA band 3 radio flux densities for the ACC sources with a match in the Roma-BZCAT (blue) and for the ACC sources without a match in the Roma-BZCAT (red).

flux density of 1391 ACC sources that have a match with Roma-BZCAT, with the remaining 1973 ACC sources without a Roma-BZCAT match, as shown in the right panel of Fig. 2.

Then we excluded the 1391 sources with a match in the Roma-BZCAT from the sample of 3364 ACC sources, narrowing our selection down to 1973 sources. For the sources in ACC Bonato et al. (2019), the authors evaluated the low frequency spectral index, α_{low} , between 1 and 5 GHz using the 1.4 GHz flux densities from NVSS, SUMSS, GB6, and PMN survey catalogs. We then considered only the sources classified in the ACC that are likely to be blazars, that is, sources with $\alpha_{\text{low}} < -0.5$ or demonstrating evidence of variability or γ -ray emission. This narrows our sample to 1646 sources. To get a preliminary characterization of these sources, we searched in the SIMBAD² database (Wenger et al. 2000) for information from the literature and collected it in Table 1. In this table, in addition to the

source name (Col. 1) and coordinates (Cols. 2 and 3), we list the source alternate name (Col. 4), the redshift (Col. 5), the source class given in literature according to SIMBAD object classification (Col. 6; see Table 1 note for more details), and the relative reference (Col. 7). We note that some sources are listed in the SIMBAD as “candidates” (AGN candidates: 2 sources; BL Lac candidates: 1 source; blazar candidates: 169 sources; quasar candidates: 3 sources). For the sake of simplicity, in the following, we consider candidates along with their respective sources that have a secure classification.

The composition of this sample of 1646 sources in terms of source class is presented in Fig. 3. It is evident that the three main contributors to the sample are generic radio sources (RS, 43.1%), quasars (QSO, 26.3%), and blazars (11.7%).

Since we are interested in selecting a sample of blazar candidates, in the following, we exclude from our analysis the sources classified as galaxies (labeled as “G” in Fig. 3), galaxies in clusters, planetary nebulae, Seyfert galaxies, stars, etc. (labeled as

² <http://simbad.u-strasbg.fr/simbad/>

Table 1. ALMA sources with flat radio spectrum without counterparts in the Roma-BZCAT (see Sect. 2).

Name ALMA	RA	Dec	Name NED	Redshift	Object type	Reference
J0002–2153	00:02:11.98	−21:53:09.87	WISEA J000211.98−215310.0		BLL	D’Abrusco et al. (2014)
J0003–1941	00:03:15.95	−19:41:50.40	WISEA J000315.94−194150.1		QSO	Mignard et al. (2016)
J0004–4345	00:04:07.26	−43:45:10.15	PKS 0001–440		rG	Titov et al. (2017)
J0006–2955	00:06:01.12	−29:55:50.10	PKS 0003–302		QSO	Mignard et al. (2016)
J0008+1144	00:08:00.84	+11:44:00.77	WISEA J000800.80+114400.9		Rad	
J0008–1329	00:08:28.02	−13:29:30.57	PMN J0008–1329		Rad	
J0008–3945	00:08:09.20	−39:45:22.96	WISE J000809.17−394522.8		Rad	
J0010–0433	00:10:00.39	−04:33:48.51	WISEA J001000.38−043348.4		Rad	
J0011+0823	00:11:35.27	+08:23:55.59	WISEA J001135.27+082355.5		QSO	Mignard et al. (2016)
J0011–1434	00:11:40.46	−14:34:04.63	LQAC 002–014 001		QSO	Mignard et al. (2016)

Notes. For each source we present the source name (Name ALMA), coordinates (RA and Dec), the source alternate name (Name NED), the redshift (Redshift), the source type given in literature (Object type, see note for more details) and the reference (Reference). SIMBAD object classification. AGN: Active Galaxy Nucleus, AG?: Possible Active Galaxy Nucleus, BCG: Brightest galaxy in a Cluster, BLL: BL Lac object, BL?: BL Lac candidate, Bla: Blazar, Bz?: Blazar candidate, G: Galaxy, gam: γ -ray source, GiC: Galaxy in cluster of galaxies, IR: infrared source, PaG: Pair of galaxies, PN: Planetary nebula, pr*: Pre-main sequence star, QSO: Quasar, Q?: Quasar candidate, Rad: Radio source, rG: Radio Galaxy, Sy1: Seyfert 1 galaxy, Sy2: Seyfert 2 galaxy, SyG: Seyfert galaxy, X: X-ray source. The full table is available in electronic form at the CDS.

Fig. 3. Composition of the sample of 1646 ALMA calibrators with a flat radio spectrum and without a Roma-BZCAT counterpart in terms of their SIMBAD type. In blue: we present BL Lacs, in red: quasars (QSO), in violet: blazars, in green: radio sources (RS), in purple: active galactic nuclei (AGN), in brown: radio galaxies (RG), in yellow: sources without classification (No Type), in pink: galaxies (G), and in white: other type of sources (including galaxies in clusters, planetary nebulae, Seyfert galaxies, stars, etc).

“Other” in Fig. 3). In addition, we also include the only source with a γ -ray source classification (GAM in SIMBAD), namely J0055–1217, since its position at high Galactic latitude $\sim -75^\circ$ indicates that it is likely to be a blazar. As this is only one source, in the following, we include it in the RS group. This narrows our sample to 1580 sources, which represents about $\sim 96\%$ of the ACC sample, referred to ALMA Blazar Candidates (ABC).

In Fig. 4, we compare the redshift distribution of sources in Roma-BZCAT (top panel) and ABC (lower panel). We note that redshift estimates are available for 706 ABC sources ($\sim 46\%$) and for 2566 Roma-BZCAT sources ($\sim 72\%$)³. We see that BZQ

Fig. 4. Upper panel: redshift distribution of sources. The colored bars represent the different source classes indicated in the legend, while the white bars in the background show the redshift distribution of the whole Roma-BZCAT catalog. Lower panel: same as the upper panel, but for ABC sources.

sources extend up to $z \sim 5.5$, with BZG and BZB showing smaller redshifts $z \leq 0.6$ and $z \leq 1.3$, respectively. On the other hand, ABC sources only reach $z \sim 3.5$, with BL Lacs extending up to $z \leq 2.6$, and sources without classification reaching $z \leq 1.8$, while the other source types extend up to $z \leq 3.5$.

3. Comparisons with other blazar candidate catalogs

In this section, we compare the ABC catalog with other catalogs of blazar sources. The full results of this comparison are presented in Table C.1.

We start from the *Fermi* Large Area Telescope Fourth Source Catalog (4FGL, Abdollahi et al. 2020), the most recent release

shows that this estimate based on tentative detections of Ly- α and NV λ 1240 lines is doubtful.

³ We exclude from this analysis the redshift estimate $z = 6.802$ of Roma-BZCAT source 5BZQJ1556+3517, since its SDSS spectrum

Fig. 5. *Left panel:* distribution of the 4FGL (Abdollahi et al. 2020) source types in the ABC source classes. Blue rectangles indicate BLLs, red rectangles indicate FSRQs, violet rectangles indicate BCUs, and white rectangles indicate other kind of sources (including compact steep spectrum radio sources, radio galaxies, starburst galaxies, generic active galactic nuclei, or unknown sources). *Right panel:* distribution of the WIBRaLS2 (D’Abrusco et al. 2019) source types in the ABC source classes. Blue rectangles indicate BZBs, red rectangles indicate BZQs and violet rectangles indicate MIXED sources.

of the *Fermi* mission γ -ray source catalog. Blazars represent the largest population of identified γ -ray sources. The 4FGL contains 5065 sources in the 50 MeV–1 TeV energy band, including 3915 sources associated with lower-energy counterparts with the Bayesian source association method (Abdo et al. 2010a) and the Likelihood Ratio method (Ackermann et al. 2011, 2015), both based on the spatial coincidence between the γ -ray sources and their potential counterparts, and 358 sources identified basing on periodic variability, correlated variability at other wavelengths, or spatial morphology.

Sources in 4FGL are classified as BLL (BL Lac objects), FSRQs, BCU (blazar of uncertain type), RDG (radio galaxies), AGNs, etc., according to the properties of their counterpart at other wavelengths. In particular, 3137 sources in the 4FGL are classified as blazars, which therefore represents $\sim 62\%$ of the whole 4FGL and $\sim 80\%$ of the identified sources.

We therefore cross-matched the catalog of ABC with the associated or identified sources in the 4FGL, adopting a search radius of $3''$ around the coordinates of the associated counterparts, finding 259 matches. We then looked for ABCs that would fall into the 90% uncertainty ellipse of unassociated unidentified sources in the 4FGL and found no matches.

The distribution of these matches in the different source classes of ABC is shown in the left panel of Fig. 5. In this figure, each rectangle represents an ABC class and the colored bars inside it represent the distribution of sources in this class among the 4FGL types.

We see that all ABC types are dominated by *Fermi* BCUs, which represent most ($\sim 73\%$) of the 4FGL sources matching ABC sources. On the other hand, the majority of sources classified as BLL in the 4FGL fall in the BL Lac class, while FSRQs mainly fall in QSO and blazar classes. In addition, we note that six AGN and four RDG sources fall in the QSO class, while the ABC AGN type contains two BLLs, two FSRQs, five BCUs, and three RDGs.

We then compared the catalog of ABC with the Third catalog of extreme and High-Synchrotron Peaked blazars (3HSP, Chang et al. 2019). This is a catalog containing 2013 high-synchrotron peaked blazars (HSPs), that is, BL Lacs with the

synchrotron component of their SED peaking at frequencies larger than 10^{15} Hz. They were selected through multiwavelength analysis and 657 of these sources also appear in the 5th edition of Roma-BZCAT

We note that the Galactic latitude distribution of sources in 3HSP is similar to that of Roma-BZCAT (see Fig. 1), that is, peaking outside of the Galactic plane ($|b| > 10^\circ$). By cross-matching the ABC and the 3HSP catalogs adopting a search radius of $3''$ we find 9 matches. In particular, one object has no classification in the ABC catalog, one object is classified as Radio Galaxy, and seven are classified as BL Lacs.

Next we considered two catalogs of blazar candidates presented in D’Abrusco et al. (2019), namely, the second WISE Blazar-like Radio-Loud Sources (WIBRaLS2) catalog and the KDEBLACS. The WIBRaLS2 catalog includes 9541 blazar candidates selected on the basis of their radio-loudness and of their WISE colors. Candidates were required to be detected in all four WISE bands. Their radio-loudness was defined on the basis of the ratio between the mid-infrared $22\mu\text{m}$ flux density $S_{22\mu\text{m}}$ and the radio flux density S_{Radio} , defined as $q_{22} = \log(S_{22\mu\text{m}}/S_{\text{Radio}})$. Radio flux densities were taken from NVSS (Condon et al. 1998), FIRST (White et al. 1997) and SUMSS (Mauch et al. 2003).

D’Abrusco et al. (2012) discovered that blazar listed in the second edition of Roma-BZCAT (Massaro et al. 2009) and associated with γ -ray sources listed in the *Fermi* Large Area Telescope Second Source Catalog (2FGL, Nolan et al. 2012) occupy a specific region of the two-dimensional WISE color-color planes. D’Abrusco et al. (2019) defined the region of the three-dimensional principal component space generated by the three independent WISE colors occupied by blazars listed in the 5th edition of Roma-BZCAT and associated with γ -ray sources listed in the *Fermi* Large Area Telescope Third Source Catalog (3FGL, Acero et al. 2015). The WIBRaLS2 catalog contains radio-loud sources located in this region. Such sources are classified as candidates BZB and BZQ depending on whether they are compatible with the region occupied by BL Lacs or FSRQs. In the cases where they are compatible with both, they are classified

as MIXED candidates⁴. Finally, blazar candidates in WIBRaLS2 are assigned a class going from D to A depending on how compatible a source is with the respective blazar WISE color region.

By cross-matching the ABC catalog with WIBRaLS2, adopting a search radius of 3'0, we find 381 matches. The distribution of WIBRaLS2 source types among the various ABC classes is presented in the right panel of Fig. 5. Again, each rectangle in this figure represents an ABC class and the colored bars inside it represent the amount of sources in this class falling the WIBRaLS2 class types, according to the color code indicated in the legend. BZB sources are found mostly among BL Lacs, while other classes are dominated by BZQs which represent ~64% of the WIBRaLS2 sources associated with ABC catalog.

KDEBLACS is a catalog of BL Lac candidates selected among radio-loud sources using criteria that are analogous to those of the WIBRaLS2 catalog, except for the requirement of detection taking place in only the first three WISE bands and, consequently, for redefining the radio-loudness on the basis of their $S_{12\mu\text{m}}$ 12 μm flux density, that is, on the ratio $q_{12} = \log(S_{12\mu\text{m}}/S_{\text{Radio}})$, where S_{Radio} is the radio flux density⁵. BL Lac candidates are located in the region of the two dimensional w_1-w_2 versus w_2-w_3 WISE color-color plane occupied by BL Lacs listed in the 5th edition of Roma-BZCAT and associated with γ -ray sources listed in the 3FGL. This region is bounded by the isodensity contour, obtained with kernel density estimation (KDE), containing 90% of Roma-BZCAT γ -ray BL Lacs. Finally, the KDEBLACS catalog is restricted to the sources outside the Galactic plane ($|b| > 10^\circ$). By cross-matching the ABC catalog with KDEBLACS adopting a search radius of 3'0, we find only one match, namely the source J0835–5953, which is classified in the ABC catalog as a blazar.

4. Multiwavelength analysis

In this section, we aim to offer an improved characterization of our ABC sources by looking for their multiwavelength counterparts in the available catalogs obtained from major surveys.

4.1. Optical data

Optical observations of blazars both in photometry (e.g., Marchesini et al. 2016a; Raiteri et al. 2019; Abeysekara et al. 2020) and spectroscopy (e.g., Landoni et al. 2015; Ricci et al. 2015; Álvarez Crespo et al. 2016; Peña-Herazo et al. 2019; de Menezes et al. 2020) provide an excellent tool to characterize their broad band emission and a to pinpoint their classification through the detection (or lack of it) of strong emission lines. In this section, we collect the photometric and spectroscopic data available in public catalogs with the goal of obtaining a better characterization of the ABC sources.

4.1.1. Galactic extinction

As we saw in Sect. 2, nearly one-fourth of the ABC sources are located close to the Galactic plane, where extinction is a major issue. We used the Galactic Dust Reddening and Extinction

tool of the NASA/IPAC Infrared Science Archive⁶ to obtain the value of Galactic absorption along the line of sight of our ABC sources, according to the analysis by Schlafly & Finkbeiner (2011).

In Fig. 6, we show the distribution of the Galactic extinction in the V band $A(V)$ (left panel) and the distribution of $A(V)$ as a function of the Galactic latitude (right panel) for both the ABC and Roma-BZCAT sources. We see that Roma-BZCAT objects have, on average, lower $A(V)$ values than ABC ones, confirming that an important percentage of ABC sources are probable blazars that have so far gone unrecognized because they lie close to the Galactic plane, where strong absorption makes optical observations difficult.

4.1.2. Gaia

The *Gaia* satellite (Gaia Collaboration 2016a) was launched in 2013 with the aim of performing the largest, most precise 3D map of our Galaxy. A first data release (DR1) was issued in 2016, covering the first 14 months of observations (Gaia Collaboration 2016b). A second data release (DR2) followed in 2018, including 22 months of observations (Gaia Collaboration 2018). *Gaia* DR2 contains high-precision parallaxes and proper motions for over 1 billion sources together with precise multiband photometry.

As stressed by Bailer-Jones et al. (2019), *Gaia* selects point-like sources, so most galaxies have been missed. Moreover, parallaxes and proper motions of galaxies are liable to incorrect fitting by the astrometric model. Therefore, most BL Lac sources with dominant host galaxies (i.e., BZGs) may have no *Gaia* counterparts or may suffer for overestimates of parallaxes and proper motions.

We looked for *Gaia* counterparts of the ABC sources in DR2 using the standard 3'0 search radius and found 1137 matches. However, we expect that the *Gaia* counterparts can be shifted by no more than a fraction of arcsec with respect to the ALMA position. Therefore, in Fig. 7 we plot the distribution of the separations between the ABC source positions and its closest *Gaia* match. The separation distribution was fitted with Expectation-Maximization algorithm for mixtures of univariate normals (NORMALMIXEM⁷ R package). We can clearly see that this distribution is adequately represented by two gaussians, the smallest one with mean $\mu_1 = \sim 1''.5$ and the largest one with mean $\mu_2 = \sim 2$ mas, indicating that the majority of these matches are accurate to the sub-arcsecond scale. We therefore select as reliable only the matches that show a separation smaller than $\sim 0''.1$, that corresponds to a deviation of 3 sigmas from μ_2 , narrowing down the number of associations to 1030.

In addition, extragalactic objects should ideally have null parallaxes and proper motions (even though not all sources with null parallax and proper motion are necessarily extragalactic objects). We then consider as possible identifications all associations where the proper motion and parallaxes are compatible with zero at a three-sigma level, narrowing down the number of associations to 805 possible identifications. These are shown in the left panel of Fig. 8 in the RA Dec proper motion plane, where we see that there is no significant difference between the proper motions of all possible identifications and sources close to the Galactic plane ($|b| < 10^\circ$).

In the right panel of the same figure we show *Gaia* parallaxes of the possible associations versus the separation between

⁴ The thresholds on radio loudness are selected as $q_{22} \leq -0.61$, $q_{22} \leq -0.97$ and $q_{22} \leq -0.79$ for BZB, BZQ and MIXED candidates, respectively.

⁵ In particular, BL Lac candidates are selected with $-1.85 < q_{12} < -1$, $-1.64 < q_{12} < -1.01$ and $-1.64 < q_{12} < -1$ for sources with NVSS, FIRST and SUMSS counterparts, respectively.

⁶ <https://irsa.ipac.caltech.edu/applications/DUST/>

⁷ <https://www.rdocumentation.org/packages/mixtools/versions/1.0.4>

Fig. 6. *Left panel:* distribution of the Galactic extinction in the V band $A(V)$ at the coordinates of ABC sources (blue bars) and at the coordinates of Roma-BZCAT sources (red bars). *Right panel:* galactic extinction in the V band $A(V)$ versus Galactic latitude for ABC sources (blue circles) and for Roma-BZCAT sources (red circles).

Fig. 7. Distribution of the separations between the ABC source positions and its closest *Gaia* match. The dashed lines represent the two gaussians fitting the separation distribution. The vertical dot-dashed line represents the three-sigma deviation from the mean of the largest gaussian, chosen as the boundary for reliable matches (see Sect. 4.1.2).

the ABC sources and their *Gaia* matches. We note that negative parallaxes are a consequence of how *Gaia* data are treated and can be safely used (Gaia Collaboration 2018). Again, we do not see a significant difference between the parallaxes of all possible identifications and sources close to the Galactic plane.

In Fig. 9, we compare the distribution of ABC sources (blue circles) and Roma-BZCAT sources (red circles) in the *Gaia* g versus $b - r$ color-magnitude plot. The great majority ($\sim 98\%$) of the *Gaia* counterparts selected for ABC sources are detected in g , b , and r bands. *Gaia* counterparts for Roma-BZCAT sources have been selected adopting the same matching criteria used for ABC sources. All magnitudes have been corrected for Galactic absorption using reddening estimates from Schlafly & Finkbeiner (2011) and the extinction model from Fitzpatrick & Massa (2007). In the same plot we show with gray points in the background $\sim 5 \times 10^4$ random *Gaia* sources, together

with KDE isodensity curves containing 60%, 70%, 80%, and 90% of these *Gaia* random sources. On top and on the right of the main panel of this figure, we show the normalized distributions of the $b - r$ color and g magnitude, respectively, for the ABC, Roma-BZCAT and random sources. It is evident that neither ABC nor Roma-BZCAT sources are clearly separated on the color-magnitude diagram from the random *Gaia* sources. ABC sources are, on average, slightly bluer and dimmer than the Roma-BZCAT ones, although spanning a similar range of magnitudes. A Kolmogorov-Smirnov (KS; Kolmogorov 1933; Smirnov 1939) test shows that the distributions of the *Gaia* g magnitudes of ABC sources and Roma-BZCAT sources have a p -chance $p = 3.0 \times 10^{-11}$ of having been randomly sampled from a common parent distribution, while for the $b - r$ color distributions this value is $p = 1.1 \times 10^{-5}$.

We can then conclude that ABC sources are significantly dimmer than Roma-BZCAT sources in *Gaia* g band, while the difference in the *Gaia* $b - r$ color between the two populations is less pronounced, while still significant.

4.1.3. SDSS DR12 and LAMOST DR5

The 12th data release of the Sloan Digital Sky Survey (SDSS DR12, Alam et al. 2015) covers over $14\,000 \text{ deg}^2$ of the sky, providing optical multiband photometric information for more than 450 millions unique objects and optical spectra for more than 5 million sources.

To determine the optimal cross-match radius of ABC sources with the SDSS DR12 catalog, we considered values from $0''.1$ to $3''.0$ in steps of $0''.1$. We then repeated the same procedure around random positions in the sky. In the left panel of Fig. 10, we compare the increase of sources with at least one SDSS counterpart (Δn) with increasing search radius for the ABC sources (black line) and for the random positions (red line). Since these variations are rather noisy, for better visualization we smoothed Δn using the SMOOTH.SPLINE R tool with a smoothing parameter 0.4. For ABC sources, the majority of matches can already be found with a search radius of $0''.6$, and further increases in the search radius only add few matches, while for the random positions Δn is initially 0, and then it increases after $1''.0$. We therefore chose, as an optimal search radius for the SDSS DR12

Fig. 8. *Left panel:* distribution of the 805 possible *Gaia* identifications in the motion plane (see Sect. 4.1.2). The white circles represent all possible *Gaia* identifications, and the red circles represent the sources close to the Galactic plane ($|b| < 10^\circ$). The ellipses in the lower-right corner represent the average uncertainties for possible *Gaia* identifications (white ellipse) and for the sources close to the Galactic plane (red ellipse). *Right panel:* *Gaia* parallaxes of the possible associations versus separation between the ABC sources and their *Gaia* matches. The vertical bars represent the 1- σ errors on parallax, the white circles represent all possible *Gaia* identifications, and the red circles represent the sources close to the Galactic plane.

Fig. 9. Comparison of ABC sources (blue circles) and Roma-BZCAT sources (red circles) in the *Gaia* g versus $b-r$ color-magnitude plot. Gray points in the background represent random *Gaia* sources, and the black continuous lines indicate KDE isodensity curves containing 60%, 70%, 80%, and 90% of the *Gaia* random sources. On top and on the right of the main panel: we present the normalized distributions of the $b-r$ color and g magnitude, respectively, for the ABC, Roma-BZCAT and random sources.

counterpart, the radius of $1''.1$ at which the increase of matches at random positions in the sky becomes larger than that at the positions of ABC sources. As shown in the right panel of Fig. 10, at this radius we have a total of 295 SDSS DR12 matches for the ABC sources, without multiple matches. All these 295 sources are detected in the five SDSS bands.

The Large sky Area Multi-Object fiber Spectroscopic Telescope (LAMOST, Cui et al. 2012) survey is a large-scale spectroscopic survey which follows completely different target selection algorithms than SDSS, and is therefore complementary

to the latter. The fifth data release of the LAMOST survey (DR5) provides optical spectra for more than 9 million sources.

We adopted the same approach to determine the optimal radius to cross-match ABC sources with the LAMOST DR5 catalog. We looked for matches in the latter with search radii, increasing from $0''.1$ to $3''.0$, with increments of $0''.1$, around both the coordinates of ABC sources and random positions in the sky. We find that for ABC sources, the majority of matches is already found with a search radius of $0''.3$. Due to the difference in surface density of sources between SDSS DR12 (~ 470 million sources) and LAMOST DR5 (~ 7 million sources), we start finding some matches around random sources only around $4''$. We then choose as an optimal search radius for LAMOST DR5 counterpart the radius of $0''.5$ at which Δn reaches 0, and above which fluctuations in Δn for ABC sources and random positions are similar. At this radius, we have a total of 31 LAMOST DR5 matches for the ABC sources, without multiple matches. Of these, 29 have also SDSS DR12 counterparts.

In Fig. 11, we compare ABC sources (blue circles) and Roma-BZCAT sources (red circles) in the SDSS color-color plots, namely $g-r$ versus $u-g$ (left panel), $r-i$ versus $g-r$ (central panel), and $i-z$ versus $r-i$ (right panel). SDSS counterparts for Roma-BZCAT sources have been selected adopting the same matching radius used for ABC sources. Again, all magnitudes have been corrected for Galactic absorption. Like for Fig. 9, in the panels of Fig. 11 we show with gray points in the background $\sim 5 \times 10^4$ random SDSS sources together with KDE isodensity curves containing 60%, 70%, 80%, and 90% of these random sources. Again, on the top and on the right of the main panels of this figure we show the normalized distributions of the SDSS color for the ABC, Roma-BZCAT and random sources. The ellipses in the panels indicate the average uncertainties on the SDSS colors.

We see that neither ABC nor Roma-BZCAT sources can be easily separated from random SDSS sources, with the possible exception of $g-r$ color, in which ABC and Roma-BZCAT sources appear bluer than the majority of random sources, however there is significant contamination. In general, ABC sources

Fig. 10. *Left panel:* increase of sources with at least one SDSS counterpart (Δn) plotted versus the search radius for ABC sources (black line) and for random positions in the sky (red line). Lines representing (Δn) were smoothed for better visualization. The optimal search radius is represented with a vertical dashed line. *Right panel:* number of matches between ABC sources and SDSS DR12 sources plotted versus the search radius. The number of ABC sources with at least one match in SDSS DR12 is indicated with a black line, while the number of ABC the sources with a single match in SDSS DR12 is indicated with a blue line. As in the right panel, the optimal search radius is represented with a vertical dashed line.

Fig. 11. Comparison of ABC sources (blue circles) and Roma-BZCAT sources (red circles) in the SDSS $g-r$ versus $u-g$ (left panel), $r-i$ versus $g-r$ (central panel), and $i-z$ versus $r-i$ (right panel) color-color diagrams. Gray points in the background represent random SDSS sources and the black continuous lines indicate KDE isodensity curves containing 60%, 70%, 80%, and 90% of the random sources. On the top and on the right of each main panel: we show the normalized distributions of the SDSS colors for the ABC, Roma-BZCAT, and random sources. The ellipses in the panels indicate the average uncertainties on the SDSS colors.

appear bluer than Roma-BZCAT sources, however, the KS test for the distributions of the SDSS colors of ABC sources and Roma-BZCAT sources have p -chances of $p = 5.7 \times 10^{-3}$, $p = 5.5 \times 10^{-3}$, $p = 4.4 \times 10^{-3}$ and $p = 9.2 \times 10^{-5}$ for the $u-g$, $g-r$, $r-i$, and $i-z$ colors, respectively. Therefore, we can conclude that although ABC sources are on average bluer than Roma-BZCAT sources, these differences are not statistically significant.

In Fig. 12, we show the Roma-BZCAT (left panel) and ABC (right panel) sources on the SDSS $g-r$ versus $u-g$ color-color plane, superimposing the three regions defined by Butler & Bloom (2011) to select low ($z < 2.5$), intermediate ($2.5 < z < 3$), and high ($z > 3$) redshift quasars. For Roma-BZCAT sources, we see that the majority of BZBs and BZQs fall into the region of low redshift quasars, with some BZQs falling into the regions of higher redshift quasars.

The BZGs, on the other hand, represent the majority of the Roma-BZCAT sources falling outside the quasar regions from Butler & Bloom (2011), with some of the $u-g$ redder BZGs

turning into the region of $z > 3$ quasars. For ABC sources we have a similar situation, with most QSOs and BL Lacs falling into the region of low redshift quasars, and some QSOs entering the regions of higher redshift quasars. Sources outside the quasar regions from Butler & Bloom (2011) are a mixed bag without a clear predominant class.

We then looked for available SDSS DR12 and LAMOST DR5 spectra for the previously identified counterparts, selecting only spectra without analysis flags. In SDSS DR12 we found 98 spectra, and in LAMOST DR5 we found 28 spectra (16 of which were already found in SDSS), for a total of 110 sources with available optical spectra; they are presented in Figs. B.1 and B.2. These spectra are classified either as QSO (98) or GALAXY (12) spectra, and the distribution of these spectral classes in ABC sources types is presented in Fig. 13. The majority of spectral classes in all ABC sources types is of course represented by QSOs, because these represent more than 90% of the sources with optical spectral classification. We can see, however, that one of the two ABC sources classified as blazars and as AGN have

Fig. 12. Distribution of Roma-BZCAT (left panel) and ABC (right panel) sources in the SDSS $g - r$ versus $u - g$ color-color plane. The three colored rectangles represent the regions indicated by [Butler & Bloom \(2011\)](#) to select low ($z < 2.5$), intermediate ($2.5 < z < 3$), and high ($z > 3$) redshift quasars. Roma-BZCAT and ABC subclasses are represented with circles of different colors, as indicated in the legend.

Fig. 13. Distribution of the spectral classes (QSO or GALAXY) of the 110 sources with an optical spectra in SDSS DR12 or LAMOST DR5 in the ABC sources types.

a GALAXY optical classification, just as the two ABC sources classified as RG and the one without literature classification. The optical properties of ABC sources are summarized in Table C.2, including the LAMOST and SDSS counterpart, spectral classification, and redshift.

4.2. Infrared data: WISE

WISE was launched in 2009, completing its double survey of the whole sky in 2011. The data were acquired with a 40 cm telescope in four filters, $w1$, $w2$, $w3$, and $w4$, with the central wavelength at 3.4, 4.6, 12, and $22\mu\text{m}$, respectively. As mentioned previously, WISE data have been extensively used to select blazar candidates and study their properties (see also [Massaro et al. 2012, 2015c](#); [Plotkin et al. 2012](#); [Capetti & Raiteri 2015](#); [Raiteri & Capetti 2016](#)). Released in 2013, the AllWISE catalog ([Cutri et al. 2013](#)) offers a compilation of the data from

the cryogenic and post-cryogenic survey phases of the WISE mission, containing more than 700 million celestial objects.

The optimal search radius for cross-matching ABC and AllWISE catalogs was determined using the same procedure as for SDSS. In the left panel of Fig. 14, we compare the increase of sources with at least one AllWISE counterpart (Δn) with an increasing search radius for the ABC sources (black line) and for the random positions (red line). Again, Δn was smoothed for improved visualization. For ABC sources, the majority of matches was already found with a search radius of $1''.5$, while for the random positions, Δn is initially 0 and then increases after $1''.0$. We therefore chose as an optimal search radius for the WISE counterpart, a radius of $2''.4$, at which the increase of matches at random positions in the sky becomes larger than that at the positions of ABC sources. As shown in the right panel of Fig. 14, at this radius, we have a total of 1311 AllWISE matches for the ABC sources, without any multiple matches.

Specifically, we have 906 source with a detection in all four WISE bands, 739 of which ($\sim 82\%$) have a detection with a signal to noise ratio of at least 3 in all four WISE bands. The distribution of the 906 ABC sources with a detection in all four WISE bands in the WISE color-color diagrams is presented with blue circles in Fig. 15, where the distribution of the Roma-BZCAT sources (red circles) is also shown for comparison. WISE counterparts for Roma-BZCAT sources were selected adopting the same matching radius used for ABC sources. The $w1-w2$ versus $w2-w3$ and $w2-w3$ versus $w3-w4$ color-color diagrams are presented in the left and right panel of the figure, respectively. The ellipses in the panels indicate the average uncertainties on the WISE colors. As usual, all magnitudes have been corrected for Galactic absorption. We note, however, that the average Galactic absorption is smaller than the average photometric uncertainties for $|b| > 35^\circ$ and $|b| > 20^\circ$ for $w1$ and $w2$ bands, respectively; and in these two bands, it becomes larger than 0.1 mag for $|b| < 20^\circ$. On the other hand, Galactic absorption becomes relevant in $w3$ and $w4$ bands only very close to the Galactic center ($|b| < 4^\circ$, see also [D'Abrusco et al. 2012](#)). Again, on the top and on the right of the main panels we show the normalized distributions of the WISE color for the ABC and Roma-BZCAT sources. Sources from ABC have similar $w1-w2$ colors to Roma-BZCAT sources, while they appear bluer in the $w2-w3$ and $w3-w4$ colors. This

Fig. 14. Same as Fig. 10, but for matches between ABC sources and AllWISE source.

Fig. 15. Distribution of ABC sources (blue circles) and Roma-BZCAT sources (red circles) in the WISE $w1-w2$ versus $w2-w3$ (left panel) and $w2-w3$ versus $w3-w4$ (right panel) color-color diagrams. On the top and on the right of each main panel: we show the normalized distributions of the WISE colors for the ABC and Roma-BZCAT sources. The ellipses in the panels indicate the average uncertainties on the WISE colors.

is confirmed by the KS test for the distributions of the WISE colors of ABC sources and Roma-BZCAT sources that yields p -chances of $p = 0.04$, $p = 4.0 \times 10^{-4}$ and $p = 8.9 \times 10^{-11}$ for the $w1-w2$, $w2-w3$, and $w3-w4$ colors, respectively. Therefore, we can conclude that the difference is significant only in the $w2-w3$ and $w3-w4$ colors.

4.3. X-ray data

Blazars are known X-ray sources since ROSAT DXRBS (Perlman et al. 1998; Landt et al. 2001) and *Einstein* IPC (Elvis et al. 1992; Perlman et al. 1999) surveys (see also Perlman 2000). Since then, the X-ray properties of blazars have been investigated in depth by numerous authors (see, e.g., example Giommi & Padovani 1994; Padovani & Giommi 1995; Comastri et al. 1997; Rieger et al. 2000; Donato et al. 2001; Massaro et al. 2011a,b).

The nature of X-ray emission in blazar is essentially non-thermal and the physical processes responsible for this emission vary in the different blazar subclasses. For HSPs, the synchrotron peak frequency ν_p is larger than 10^{15} Hz and, therefore, the X-ray

emission in these sources is dominated by the synchrotron radiation from the relativistic electrons in the jets. As the synchrotron peak frequency moves to lower energies the SSC component enters the X-ray band, and for low-synchrotron peaked blazars (LSPs) with $\nu_p < 10^{14}$ Hz, this is the dominant contribution to the observed X-ray emission. This is even more true in FSRQs, where the synchrotron peak frequency is $\nu_p < 10^{13}$ Hz and the X-ray emission is dominated by the inverse Compton components (SSC and EC). To study the X-ray emission from the ABC sources, we made use of the data available for this sample in the archives of *Swift*, *Chandra* and *XMM-Newton* missions.

4.3.1. *Swift*-XRT

Swift has proven to be an excellent multifrequency observatory for blazar research, having so far observed hundreds of sources (e.g., Moretti et al. 2007, 2012; Dai et al. 2012) and providing an extremely rich and unique database of multifrequency (optical, UV, X-ray), simultaneous blazar observations. Several papers on samples selected with different criteria have already been published, including: blazars detected at TeV energies

(e.g., Massaro et al. 2008, 2011a,b), simultaneous optical-to-X-ray observations of flaring TeV sources (e.g., Perri et al. 2007; Tramacere et al. 2007), as well as the investigation of low- and high-frequency peaked BL Lacs (e.g., Maselli et al. 2010; Giommi et al. 2012). *Swift* has also been used for UV-optical and X-ray follow-up observations of TeV flaring blazars (e.g., Aliu et al. 2011; Aleksić et al. 2012; H.E.S.S. Collaboration 2013) and in the framework of broad-band multiwavelength campaigns (e.g. Raiteri et al. 2011, 2013; Carnerero et al. 2017). It has also been useful in obtaining photometric redshift constraints for many *Fermi*-detected BL Lacs (Rau et al. 2012).

Data collected by *Swift* X-Ray Telescope (XRT) were downloaded from the HEASARC⁸ data archive and processed using the XRTDAS software (Capalbi et al. 2005) developed at the ASI Science Data Center and included in the HEASoft package (v. 6.26.1) distributed by HEASARC, using a procedure similar to the one illustrated in Paggi et al. (2013) and Marchesini et al. (2019). *Swift*-XRT photon counting (PC) data were available for 325 ABC sources. For each observation, calibrated and cleaned PC mode event files were produced with the XRTPIPELINE task (ver. 0.13.5), generating exposure maps for each observation. In addition to the screening criteria used by the standard pipeline processing, we applied a further filter to screen background spikes that can occur when the angle between the pointing direction of the satellite and the bright Earth limb is low. In order to eliminate this so-called bright Earth effect, due to the scattered optical light that usually occurs towards the beginning or the end of each orbit, we used the procedure proposed by Puccetti et al. (2011) and D’Elia et al. (2013). We monitored the count-rate on the CCD border and, through the XSELECT package, we excluded time intervals when the count-rate in this region exceeded 40 counts s⁻¹. In addition, we selected only time intervals with CCD temperatures less than -50°C (instead of the standard limit of -47°C) since contamination by dark current and hot pixels, both of which increase the low energy background, are strongly temperature dependent (D’Elia et al. 2013).

To detect X-ray sources in the XRT images, we made use of the XIMAGE detection algorithm DETECT, which locates the point sources using a sliding-cell method. The average background intensity is estimated in several small square boxes that are uniformly located within the image. The position and intensity of each detected source are calculated in a box whose size maximizes the signal-to-noise ratio. The algorithm was set to work in bright mode, which is recommended for crowded fields and fields containing bright sources since it can reconstruct the centroids of very nearby sources. We then evaluated the net count-rates for the detected sources with the SOSTA algorithm that, besides the net count-rates and the respective uncertainties, yields the statistical significance of each source. We note that SOSTA requires the positions of the sources detected by DETECT, and the uncertainties in the count-rates returned by SOSTA are purely statistical – meaning that do not include systematic errors – and they are, in general, smaller than those given by DETECT. We used count-rates produced by SOSTA because these are in most cases more accurate since DETECT uses a global background for the entire image, whereas SOSTA uses a local background. Finally, we refined the source position and relative positional errors by using the task XRTCENTROID of the XRTDAS package, considering only the sources detected at a position that is compatible with the ABC sources. In this way, we detected X-Ray counterparts for 101 sources.

Generally, XRT-PC source spectra – with the corresponding arf and rmf files – were obtained from events extracted with XRTPRODUCTS task, using a 30 pixel radius circle centered on the detected source coordinates, while background spectra were estimated from a nearby source-free circular region of 60 pixel radius. When the source count-rate is above 0.5 counts s⁻¹, the data are significantly affected by pileup in the inner part of the point spread function (PSF, Moretti et al. 2005). To remove the pile-up contamination, we extracted only those events contained in an annular region centered on the source (Perri et al. 2007). The inner radius of the region was determined by comparing the observed profiles with the analytical model derived by Moretti et al. (2005) and typically has a four or five pixel radius. In this way, we were able to obtain X-ray for spectra 43 ABC sources.

4.3.2. *Chandra*-ACIS

Chandra X-ray telescope has been used in the past years to provide important information about the high-energy emission of blazars (e.g. Ighina et al. 2019). In addition, thanks to its unmatched angular resolution, *Chandra* has been used to resolve and study the X-ray jets of several blazars (e.g., Jorstad & Marscher 2004; Tavecchio et al. 2007; Marscher & Jorstad 2011; Hogan et al. 2011).

Data collected by the *Chandra* Advanced CCD Imaging Spectrometer (ACIS) were available for fields containing 62 ABC sources. These were retrieved from the *Chandra* Data Archive⁹ and analyzed with CIAO (Fruscione et al. 2006) data analysis system version 4.12 and *Chandra* calibration database CALDB version 4.9.1, adopting standard procedures. We then ran the ACIS level 2 processing with CHANDRA_REPRO CIAO task to apply up-to-date calibrations (CTI correction, ACIS gain, bad pixels) and then excluded time intervals of background flares exceeding 3 σ with the DEFLARE task. We produced full-band exposure maps, PSF maps to evaluate the PSF size across the ACIS detector, and pileup maps with the PILEUP_MAP task. We then run the WAVDETECT task to identify point sources in each observation with a $\sqrt{2}$ sequence of wavelet scales (i.e., 1 1.41 2 2.83 4 5.66 8 11.31 16 pixels) and a false-positive probability threshold of 10⁻⁶. We then considered only the sources detected at positions compatible with the ABC sources and extracted count-rates, making use of the SRCFLUX task. In this way, we detected X-ray counterparts for 56 ABC sources.

ACIS source spectra and the corresponding arf and rmf files were extracted with the SPEXTRACT tool from the source regions generated from WAVDETECT, excluding the inner pixels with pileup larger than 5% as estimated from the pileup maps, while background spectra were extracted from source-free circular regions with typical radii of 80''. In this way, we were able to extract spectra for 46 ABC sources.

4.3.3. *XMM-Newton*-EPIC

The *XMM-Newton* space observatory, thanks to its large collecting area the ability to make long uninterrupted observations, has provided important information for the multiwavelength study of blazars (e.g., Raiteri et al. 2006; Fidelis et al. 2009; Kalita et al. 2015; Bhagwan et al. 2016).

Data collected by *XMM-Newton* European Photon Imaging Camera (EPIC), available for fields containing 64 ABC sources,

⁸ <https://heasarc.gsfc.nasa.gov/>

⁹ <http://cda.harvard.edu/chaser>

Table 2. X-ray properties of ABC sources.

Name ALMA	Detector	EXP ks	Count rate 10^{-3} s^{-1}	S/N	Flux _{0.1–2.4} $10^{-13} \text{ erg cm}^2 \text{ s}^{-1}$	Γ_X	K $10^{-4} \text{ keV cm}^{-2} \text{ s}^{-1}$	χ^2 (d.o.f.)
J0010–0433	XRT	1.3						
J0011–8706	XRT	4.9	2.55 ± 0.84	3.0	0.87 ± 0.29			
J0019–5641	XRT	2.9						
J0024–6820	XRT	0.7	13.25 ± 5.00	2.6	3.82 ± 1.44			
J0025+3919	ACIS	19.7	15.70 ± 1.00	15.7	2.04 ± 0.35	$1.36^{+0.22}_{-0.22}$	$0.53^{+0.11}_{-0.10}$	0.8(24)
J0028+2000	XRT	3.0						
J0029+3456	EPIC	28.2	66.77 ± 3.08	21.7	2.15 ± 0.10			
J0034–0054	ACIS	2.0	14.60 ± 2.90	5.0	2.54 ± 0.50			
J0039–2220	XRT	0.8	12.42 ± 4.30	2.9	3.51 ± 1.21			
J0045–3705	XRT	2.2						

Notes. For each source we list the name (Name ALMA), the X-ray detector (Detector) and the observation exposure (EXP). If the source is detected we also list the count-rate (Count rate) and the signal to noise ratio (S/N). We then list the unabsorbed source flux (Flux_{0.1–2.4}) in the 0.1–2.4 KeV band, obtained from the count-rate assuming a power-law model with a spectral index 1.8 or, if a spectrum is available, from the spectral fit. For the sources adequately fitted with a power-law model, we also list the power-law spectral index Γ_X and normalization K , together with the fit χ^2 and degrees of freedom (χ^2 , d.o.f.). The full table is available in electronic form at the CDS.

were retrieved from the *XMM-Newton* Science Archive¹⁰ and reduced with the SAS¹¹ 18.0.0 software.

Following Nevalainen et al. (2005) we filtered EPIC data for hard-band flares by excluding the time intervals where the 9.5–12 keV (for MOS1 and MOS2) or 10–12 keV (for PN) count-rate evaluated on the whole detector FOV was more than 3σ away from its average value. To achieve a tighter filtering of background flares, we iteratively repeated this process two more times, re-evaluating the average hard-band count-rate and excluding time intervals away more than 3σ from this value. The same procedure was applied to soft 1–5 keV band restricting the analysis to an annulus with inner and outer radii of 12' and 14' (excluding sources in the field) where the detected emission is expected to be dominated by the background.

When possible, we merged data from MOS1, MOS2 and PN detectors from all observations using the MERGE task, in order to detect the fainter sources that wouldn't have been detected otherwise. Sources were detected on these merged images following the standard SAS sliding box task EDETECT_CHAIN that mainly consist of three steps: (1) source detection with local background, with a minimum detection likelihood of 8; (2) removal of sources found in step 1 and creation of smooth background maps by fitting a 2D spline to the residual image; (3) source detection with the background map produced in step 2 with a minimum detection likelihood of 10. The task EMLDETECT was then used to determine the parameters for each detected source – including the count rate – by means of a maximum-likelihood fit to the input images, selecting sources with a minimum detection likelihood of 15 and a flux in the 0.3–7 keV band larger than $10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ (assuming an energy conversion factor of $1.2 \times 10^{-11} \text{ cts cm}^2 \text{ erg}^{-1}$). An analytical model of the PSF was evaluated at the source position and normalized to the source brightness. The source extent was then evaluated as the radius at which the PSF level equals half of local background. We then considered only the sources detected at position compatible with the ABC sources. In this way, we detected X-ray counterparts for 55 ABC sources.

The source spectra were extracted with the EVSELECT task from the regions obtained with EMLDETECT. The inner regions of high pileup were estimated using the EPATPLOT task through

the distortion of pattern distribution, following the procedure explained in the SAS Data Analysis Threads¹². The corresponding arf and rmf files were generated with the RMFGEN and ARFGEN tasks to take into account time and position-dependent EPIC responses, and background spectra were extracted from source free regions of the sky. We were able to extract spectra for 51 ABC sources.

4.3.4. X-Ray Spectral Fitting

In total, we detected X-ray counterparts for 173 ABC sources and we were able to extract a total of 140 spectra for 92 ABC sources. Spectral fitting was performed with the Sherpa¹³ modeling and fitting application (Freeman et al. 2001) in the 0.3–7 KeV energy range, adopting Gehrels weighting (Gehrels 1986). Source spectra were binned to a minimum of 20 counts/bin to ensure the validity of χ^2 statistics. For the EPIC spectra we excluded from the spectral fitting the 1.45–1.55 KeV band due to variable Al K lines, and fitted simultaneously the MOS1, MOS2, and PN spectra.

For the spectral fitting, we used a model comprising an absorption component fixed to the Galactic value (Kalberla et al. 2005) and a power law, as expected in studies of blazars. This model proved to adequately fit the majority (109) of the extracted spectra. The results of the power-law model fitting are presented in Table 2, where errors correspond to the 1- σ confidence level for one interesting parameter ($\Delta\chi^2 = 1$). The X-ray spectra fitted with power-law models are presented in Figs. A.1–A.3. The intrinsic (i.e., unabsorbed) fluxes listed in Table 2 are estimated from the spectral fitting when a spectra was available, otherwise they are estimated from the measured count-rates assuming a power-law model with a spectral index of 1.8.

We note that 31 spectra for 24 ABC sources were not adequately fitted by a simple power-law model but they required, instead, more complex models comprising intrinsic absorption, thermal components, reflections components, or emission lines. They are presented in Figs. A.4–A.6. The results of the fit procedure on these spectra are summarized in Table 3. Interestingly, only one of these 24 sources showing complex X-ray spectra

¹⁰ <http://nxsas.esac.esa.int/nxsas-web>

¹¹ <http://www.cosmos.esa.int/web/xmm-newton/sas>

¹² <https://www.cosmos.esa.int/web/xmm-newton/sas-thread-epatplot>

¹³ <http://cxc.harvard.edu/sherpa>

Table 3. Results of the X-ray spectral fitting for ABC sources with a complex (non power-law) model.

Name ALMA	Other name	Object type	Detector	Model	N_H	Γ_X	K	Γ_R	K_R	kT	K_T	E_1	K_1	E_2	K_2	χ^2 (d.o.f.)
J0029+3456	B2 0026+34	AGN	EPIC	A * PL	$0.88^{+0.37}_{-0.30}$	$1.38^{+0.21}_{-0.19}$	$0.40^{+0.12}_{-0.08}$									0.47(28)
J0057+3021	NGC 0315	AGN	ACIS	PL+T		$1.04^{+0.06}_{-0.06}$	$0.47^{+0.03}_{-0.03}$				$0.69^{+0.03}_{-0.03}$					0.83(115)
			EPIC	PL+T		$1.30^{+0.04}_{-0.04}$	$1.08^{+0.06}_{-0.06}$				$0.72^{+0.01}_{-0.01}$					0.79(356)
J0111-7302	PMN J0111-7302	AGN	EPIC	PL+T		$1.72^{+0.43}_{-0.44}$	$0.19^{+0.07}_{-0.07}$				$0.56^{+0.18}_{-0.25}$					0.81(14)
J0242-2132	PKS 0240-217	QSO	ACIS	A * PL	$0.27^{+0.08}_{-0.08}$	$2.36^{+0.15}_{-0.14}$	$2.46^{+0.32}_{-0.28}$									0.88(37)
			EPIC	A * (PL+L)	$0.09^{+0.01}_{-0.01}$	$2.03^{+0.02}_{-0.01}$	$9.52^{+0.15}_{-0.15}$					$6.71^{+0.02}_{-0.02}$	$0.15^{+0.02}_{-0.02}$			0.80(969)
J0702-2841	NGC 2325	AGN	EPIC	PL+T		$1.54^{+0.04}_{-0.04}$	$0.28^{+0.01}_{-0.01}$				$0.76^{+0.03}_{-0.03}$					0.64(323)
J0758+3747	NGC 2484	QSO	EPIC	PL+T		$2.16^{+0.03}_{-0.03}$	$0.66^{+0.02}_{-0.02}$				$0.83^{+0.03}_{-0.03}$					0.57(360)
J0928-0409	PKS J0928-0408	QSO	EPIC	PL+L		$1.53^{+0.22}_{-0.22}$	$0.29^{+0.06}_{-0.06}$					$1.05^{+0.06}_{-0.06}$	$0.32^{+0.13}_{-0.13}$			1.18(8)
J1044+0655	PKS 1042+071	QSO	ACIS	PL+L		$2.40^{+0.28}_{-0.25}$	$0.33^{+0.04}_{-0.04}$					$0.67^{+0.05}_{-0.05}$	$12.89^{+13.19}_{-6.34}$			0.94(115)
J1109-3732	NGC 3557	AGN	ACIS	PL+T		$1.99^{+0.52}_{-0.34}$	$0.38^{+0.19}_{-0.11}$				$0.31^{+0.35}_{-0.21}$					0.60(9)
J1215-1731	PKS 1213-17	Blazar	XRT	A * (PL+R)	$2.48^{+0.23}_{-0.30}$	>7.79	$19.34^{+5.53}_{-4.44}$	<-2.63								0.86(9)
J1230+1223	M 87	AGN	XRT	PL+T		$1.67^{+0.07}_{-0.09}$	$18.98^{+4.71}_{-4.71}$				$1.85^{+0.07}_{-0.08}$					1.05(212)
			ACIS	PL+T		$1.86^{+0.05}_{-0.05}$	$0.73^{+0.07}_{-0.07}$				$1.75^{+0.19}_{-0.12}$					0.87(141)
J1305-4928	NGC 4945	RS	EPIC	A * (PL+T)	$0.05^{+0.01}_{-0.01}$	$2.51^{+0.08}_{-0.07}$	$280.33^{+19.12}_{-18.54}$				$1.66^{+0.01}_{-0.01}$					1.14(1153)
			ACIS	A * (T+R+L+L)	$2.07^{+0.16}_{-0.17}$						$0.86^{+0.06}_{-0.04}$	$6.42^{+0.01}_{-0.01}$	$0.34^{+0.02}_{-0.02}$	$6.77^{+0.03}_{-0.02}$	$0.10^{+0.02}_{-0.02}$	1.08(183)
J1319-1239	NGC 5077	AGN	EPIC	PL+T	$0.06^{+0.05}_{-0.05}$						$0.79^{+0.06}_{-0.05}$	$6.42^{+0.01}_{-0.01}$	$0.88^{+0.08}_{-0.07}$	$6.82^{+0.08}_{-0.06}$	$0.21^{+0.04}_{-0.05}$	0.90(227)
J1321-4342	NGC 5090	RG	EPIC	A * (T+R)		$1.63^{+0.33}_{-0.36}$	$0.08^{+0.02}_{-0.02}$				$0.71^{+0.13}_{-0.13}$					0.27(6)
J1336-3357	IC 4296	AGN	ACIS	PL+T		$0.82^{+0.08}_{-0.09}$	$0.39^{+0.04}_{-0.04}$				$0.71^{+0.03}_{-0.11}$					0.66(189)
J1347+1217	PKS 1345+12	QSO	ACIS	A * (PL+L)		$1.01^{+0.05}_{-0.05}$	$0.85^{+0.05}_{-0.05}$				$0.76^{+0.01}_{-0.01}$					0.78(89)
J1553+2348	PKS 1551+23	QSO	XRT	A * PL	$2.24^{+0.44}_{-0.40}$	$0.94^{+0.20}_{-0.20}$	$1.10^{+0.40}_{-0.38}$				$0.82^{+0.01}_{-0.01}$					0.69(392)
J1558-1409	PKS 1555-140	AGN	ACIS	T	$2.13^{+0.71}_{-0.62}$	$2.84^{+0.56}_{-0.49}$	$36.64^{+36.20}_{-17.27}$					$0.76^{+0.04}_{-0.04}$	$183.11^{+837.27}_{-141.83}$			0.82(53)
			EPIC	PL+T		$1.62^{+0.03}_{-0.03}$	$60.21^{+5.70}_{-5.70}$				$4.27^{+0.57}_{-0.57}$					0.84(7)
J1627-2426	PMN J1626-2426	AGN	ACIS	R+L+L							$3.74^{+0.13}_{-0.14}$					0.85(75)
J1711-3744	PMN J1711-3744	No type	ACIS	A * PL	$36.08^{+13.35}_{-4.40}$	$8.02^{+7.43}_{-4.40}$	$<28.93^{e4}$	-1.72^*	<0.01			3.11^*	<0.01	$4.35^{+0.27}_{-0.27}$		0.90(1434)
J1723-6500	NGC 6328	QSO	EPIC	A * PL	$0.11^{+0.02}_{-0.02}$	$1.90^{+0.05}_{-0.05}$	$1.08^{+0.05}_{-0.05}$									0.90(11)
J2033+2146	PKS 2031+21	QSO	XRT	A * PL	$0.40^{+0.12}_{-0.10}$	$1.55^{+0.14}_{-0.13}$	$32.32^{+5.70}_{-4.70}$									1.10(22)
J2157-6941	PKS 2153-69	QSO	ACIS	PL+T		$1.67^{+0.02}_{-0.02}$	$2.70^{+0.08}_{-0.08}$	$0.20^{+0.02}_{-0.01}$	$0.64^{+0.12}_{-0.12}$							0.65(309)
J2212-2518	CRATES J221220.71-251828.4	AGN	ACIS	P+T		$1.94^{+0.20}_{-0.20}$	$0.25^{+0.03}_{-0.03}$				$0.74^{+0.10}_{-0.11}$	$0.08^{+0.02}_{-0.02}$				0.98(55)
																0.88(272)
																0.30(16)

Notes. For each source we list the ALMA name (Name ALMA), the alternate name (Other name), the ABC type (Object type), and the X-ray detector (Detector). The column Model shows the model components used to fit the spectrum, namely an intrinsic photoelectric absorption component ZWABS (A), a power-law component (PL), a thermal component APEC (T), a gaussian line ZGAUSS (L), and a power law spectrum reflected from neutral material PEXRAV (R). We then list the intrinsic hydrogen column density (N_H), the power-law spectral index (Γ_X) and normalization K , the reflection component spectral index Γ_R and normalization K_R , the thermal component temperature (kT) and normalization K_T , and the line(s) rest-frame energy (E_1 , E_2) and normalization(s) (K_1 , K_2). Finally, we list the fit χ^2 and degrees of freedom (χ^2 , d.o.f.). N_H is in 10^{22} cm^{-2} . K is $10^{-4} \text{ keV cm}^{-2} \text{ s}^{-1}$. K_R is $10^{-2} \text{ keV cm}^{-2} \text{ s}^{-1}$. kT , E_1 , and E_2 are in keV. K_T is 10^{-4} cm^{-5} . K_1 and K_2 are in $10^{-4} \text{ cm}^{-2} \text{ s}^{-1}$. Parameters indicated with an asterisk (*) are unconstrained and fixed to their best fit value.

Fig. 16. *Left panel:* normalized distributions of the 0.3–7 KeV count-rate for Roma-BZCAT (*top*) and ABC (*bottom*) sources. The various subclasses of Roma-BZCAT sources and types of ABC sources are presented with the colors indicated in the legend, and the white histograms on the background represent the distribution of the whole samples. For Roma-BZCAT sources, gaussian fits to the subclass distributions are indicated with dashed lines of the respective colors, while for ABC sources a gaussian fit to the distribution of the whole sample is indicated with a black dashed line. *Right panel:* same as the right panel, but for the distributions of the X-ray slope Γ_X .

(namely J1215–1731) has a blazar classification in SIMBAD, while the others are AGNs (11 sources), QSOs (9), RSs (1), RGs (1), and objects without SIMBAD classification (1).

It is useful to compare the X-ray properties of ABC and Roma-BZCAT sources. To this end, we obtained and reduced *Swift*-XRT, *Chandra*-ACIS and *XMM-Newton* data for Roma-BZCAT sources in the same way as we did for ABC sources. In the left panel of Fig. 16, we compare the normalized distributions of the X-ray count-rates for Roma-BZCAT (*top*) and ABC (*bottom*) sources. When count-rates for a source were available for more than one instrument, we picked the count-rate corresponding to the detection with the higher signal to noise ratio. The Roma-BZCAT sources of the different subclasses (BZB, BZQ, BZU, and BZG) are presented with different colors, and gaussian fits to the count-rate distributions of each subclass are indicated with dashed lines of the respective color. The peak logarithmic count-rates (in units of s^{-1}) of BZBs and BZQs are at -1.6 and -1.7 , respectively, while BZUs and BZGs are slightly brighter on average, peaking at -1.3 and -1.1 , respectively. For ABC sources, the different source types are indicated with different colors presented in the legend. Due to the lower statistics with respect to the Roma-BZCAT we overplot only a gaussian fit to the distribution of the whole sample, presented with a dashed black line. ABC sources show similar count-rates in X-rays compared to Roma-BZCAT sources, at variance with what is observed at radio wavelengths (see Fig. 2). In particular, the distribution of logarithmic count-rates for Roma-BZCAT sources peaks at -1.6 , while that of ABC sources peaks at -1.7 . In addition, the KS test shows that these two distributions have a p -chance, $p = 0.44$, of having been randomly sampled from a common parent distribution and are, therefore, statistically indistinguishable.

The right panel of Fig. 16 shows the comparison of the power-law slopes, Γ_X , of the X-ray spectra in terms of count rates. Again, when Γ_X slopes for a source were available for more than one instrument, we picked the slope corresponding to the detection with the higher signal to noise ratio. BZBs and BZGs are the softer subclasses in X-rays, with their Γ_X distributions peaking at 2.1 and 2.0, respectively, while BZQs and BZUs are harder, both peaking at 1.6. The ABC sources have a

Fig. 17. ABC (blue circles) and Roma-BZCAT (red circles) sources represented on the X-ray slope versus X-ray count-rate plot. The ellipses of the relative color indicate the average uncertainties. On *top* and on the *right* of the main panels: we show the normalized distributions of the X-ray count-rate and slope for ABC and Roma-BZCAT sources, with the same colors used in the main panel.

Γ_X distribution similar to that of the Roma-BZCAT as a whole. The ABC distribution peaks at $\Gamma_X = 1.7$, while that of Roma-BZCAT sources as whole peaks at 1.8. Also, the KS test shows that these two distributions have a p -chance, $p = 0.10$, of having been randomly sampled from a common parent distribution, making them, therefore, similar.

In Fig. 17, we present on a X-ray slope versus X-ray count-rate plot the ABC and Roma-BZCAT sources that have an estimate for both count-rate and X-ray slope. On the top and right of this figure, we present the normalized distributions of the X-ray count-rate and slope Γ_X for ABC and Roma-BZCAT sources. Both count-rate and Γ_X distributions are similar among ABC and Roma-BZCAT sources, and this is confirmed by the KS test, which yields a p -chance of 0.11 and 0.10 for the count-rate and Γ_X distributions, respectively.

Fig. 18. *Left panel:* normalized distributions of the 100 MeV–100 GeV flux for Roma-BZCAT (*top*) and ABC (*bottom*) sources. The various subclasses of Roma-BZCAT sources and types of ABC sources are presented with the colors indicated in the legend, and the white histograms on the background represent the distribution of the whole samples. For Roma-BZCAT sources, gaussian fits to the subclass distributions are indicated with dashed lines of the respective colors, while for ABC source a gaussian fit to the distribution of the whole sample is indicated with a black dashed line. *Right panel:* same as the right panel, but for the distributions of the γ -ray slope Γ_γ .

4.4. γ -ray data: *Fermi*-LAT

In this section, we compare the γ -ray properties of ABC and Roma-BZCAT sources, as reported in 4FGL catalog. In Sect. 3, we explain our finding of 259 4FGL counterparts (mainly BCUs) for ABC sources. In addition, we find 1506 Roma-BZCAT sources with a counterpart in the 4FGL catalog. For each of these sources, we collected from the 4FGL the photon index obtained fitting the *Fermi* Large Area Telescope (LAT) spectra with a power-law (PL_INDEX PHOTON) and the energy flux in the range 100 MeV–100 GeV obtained from the spectral fitting (ENERGY_FLUX100), mostly ($\sim 70\%$) with a power-law model. Although these two quantities are not independent, it is instructive to compare their distributions in Roma-BZCAT and ABC sources.

As in Fig. 16, in the left panel of Fig. 18, we compare the normalized distributions of the γ -ray flux for Roma-BZCAT (*top*) and ABC (*bottom*) sources. The Roma-BZCAT of the different subclasses (BZB, BZQ, BZU, and BZG) are presented with different colors and gaussian fits to the flux distributions of each subclass are indicated with dashed lines of the respective color. The peak logarithmic fluxes (in cgs units) of these fits are similar for BZQs and BZUs, being, -11.1 and -11.0 , respectively, while BZGs are on average dimmer, peaking at -11.5 . BZBs sit somewhat in between, peaking at -11.2 . For ABC sources the different source types are indicated with different colors. Again, due to lower statistics with respect to the Roma-BZCAT, we overplot just a gaussian fit to the distribution of the whole sample. We see that Roma-BZCAT sources extend to larger fluxes with respect to ABC sources, which is at variance with what is observed at radio wavelengths (see Fig. 2). We note that both distributions of γ -ray logarithmic flux peak at similar values, with the Roma-BZCAT sources peaking at -11.3 , and the ABC sources peaking at -11.3 , between BZG and BZB peaks. However a KS test shows that the two distributions have a p -chance, $p = 1.3 \times 10^{-5}$, of having been randomly sampled from a common parent distribution, making them, therefore, significantly different from the statistical point of view.

The right panel of Fig. 18 shows a similar comparison, but for the power-law slopes Γ_γ of the *Fermi*-LAT spectra. Roma-BZCAT subclasses are clearly separated on the basis of their spec-

Fig. 19. ABC (blue circles) and Roma-BZCAT (red circles) sources represented on the γ -ray slope versus γ -ray flux plot. The ellipses of the relative color indicate the average uncertainties. The black full and dot-dashed lines represent the 90% KDE isodensity contours for ABC sources and Roma-BZCAT sources, respectively. On the *top* and *right* panels, we present the normalized distributions of the γ -ray flux and slope for ABC and Roma-BZCAT sources, with the same colors used in the main panel.

tral shape, with BZQs and BZUs being softer in γ -rays (their Γ_γ distribution peaks at 2.5 and 2.4, respectively) than BZB and BZG (both peaking at 2.0). The ABC sources are on average softer than average Roma-BZCAT sources, with their Γ_γ distribution peaking at 2.4 and 2.2, respectively. The KS test confirms, however, that the two distributions are completely different, with a p -chance, $p = 4.0 \times 10^{-13}$, of having been randomly sampled from a common parent distribution. This p -chance is, instead, $p = 3.7 \times 10^{-2}$, when comparing ABC sources and BZUs from Roma-BZCAT, indicating that ABC sources are probably a mixture of different sub-populations possibly dominated by softer FSRQs.

In Fig. 19, we plot ABC and Roma-BZCAT sources with counterparts in 4FGL catalog on a γ -ray slope versus γ -ray flux

Fig. 20. *Left panel:* ABC sources with a WISE counterpart detected in all four WISE bands (white circles) represented in the $w1-w2$ versus $w2-w3$ color-color plane. KDE isodensity contours containing 90% of the Roma-BZCAT sources detected in γ -rays (as reported in 4FGL catalog) are presented with lines of different colors for the different Roma-BZCAT subclasses, as indicated in the legend. Filled circles of the respective colors mark the γ -ray blazar candidates of the different subclasses (see main text). The ellipse indicates the average color uncertainties. *Right panel:* same as the left panel, but for the $w2-w3$ versus $w3-w4$ projection.

plot. Again, we note that these two quantities are not independent (since the flux is evaluated from a spectral fit), however this representation is useful for the visualization of the general properties of the sources. On the top and right of this figure, we present the normalized distributions of the γ -ray flux and slope Γ_γ for ABC and Roma-BZCAT sources. As noted before, ABC sources are on average softer and dimmer in γ -rays with respect to the blazar in Roma-BZCAT. This is highlighted by the 90% KDE isodensity contours for ABC sources and Roma-BZCAT sources represented with a black full and dot-dashed lines, respectively, that suggest that ABC sources occupy the same region of the γ -ray slope versus γ -ray flux space, although clustering in the softer-dimmer region.

5. γ -ray blazar candidate selection

In this section, we make use of the WISE data collected in Sect. 4.2 to select candidate γ -ray blazars in the ABC sample. As discussed by D’Abrusco et al. (2019), WISE data provide an effective way to select γ -ray blazars through a comparison of their colors with those of known γ -ray blazars.

Here we take an approach that is somewhat halfway between those adopted for the compilation of WIRaLS2 and KDE-BLLACS catalogs. First, we selected all Roma-BZCAT sources detected in γ -rays, that is, with a counterpart in 4FGL catalog (1506 sources) and with a WISE counterpart detected in all four WISE bands (selected as explained in Sect. 4.2), for a total of 1237 sources. Then, for each source subclass (BZB, BZQ, BZU and BZG), we evaluated the KDE isodensity contours containing 90% of the sources in both $w1-w2$ versus $w2-w3$ and $w2-w3$ versus $w3-w4$ color-color planes. We then compared the position of the 906 ABC sources with a WISE counterpart detected in all four bands in the two color-color planes, as shown in Fig. 20. Here, the KDE isodensity contours for different Roma-BZCAT subclasses are indicated with lines of the relative color indicated in the legend. To select γ -ray blazar candidates among these ABC sources, we proceeded as follows:

- since the regions occupied by BZBs and BZQs have a significant overlap, if a source is compatible with both the 90%

KDE isodensity contours of BZBs and BZQs on both color-color planes, it is classified as γ -ray blazar candidate of MIXED class,

- if a source is compatible with the 90% KDE isodensity contours of BZBs on both color-color planes but not with the 90% KDE isodensity contours of BZQs on both color-color planes, it is classified as γ -ray blazar candidate of BZB class,
- if a source is compatible with the 90% KDE isodensity contours of BZQs on both color-color planes but not with the 90% KDE isodensity contours of BZBs on both color-color planes, it is classified as γ -ray blazar candidate of BZQ class,
- if a source is compatible with the 90% KDE isodensity contours of BZUs on both color-color planes but not with the 90% KDE isodensity contours of BZBs nor BZQs on both color-color planes, it is classified as γ -ray blazar candidate of BZU class,
- if a source is compatible with the 90% KDE isodensity contours of BZGs on both color-color planes but not with the 90% KDE isodensity contours of BZBs, BZQs, or BZUs on both color-color planes, it is classified as γ -ray blazar candidate of BZG class,
- if a source is not compatible with the 90% KDE isodensity contours of BZBs, BZQs, BZUs, or BZGs, it is not classified as γ -ray blazar candidate.

We stress that to consider a source position on the color-color plane compatible with a KDE isodensity contour, we take into account the WISE color uncertainties, that is, the color-color uncertainty ellipse of the source must have an overlap with the isodensity contours. In this way, we select 715 γ -ray blazar candidates, subdivided in 42 candidates BZBs, 247 candidates BZQs, 334 candidates MIXED, 46 candidates BZUs, and 28 candidates BZGs, indicated in Fig. 20 with circles of the respective color. The properties of γ -ray blazar candidates are summarized in Table C.2, including the WISE counterpart and its blazar candidate classification.

As mentioned before, this selection criterion is intermediate between those presented by D’Abrusco et al. (2019) for the WIRaLS2 catalog, such that selected sources are detected in all four WISE bands based on their position in the

Fig. 21. *Left panel:* comparison of our classification method and the one proposed by D’Abrusco et al. (2019) for the WIBRaLS2 catalog. The black rectangles represent the γ -ray blazar candidate classes selected by our method, while the colored bars in each rectangle represent the percentage of sources also classified in WIBRaLS2 catalog. *Right panel:* same as left panel, but with black rectangles representing the γ -ray blazar candidate classes of WIBRaLS2 catalog, and with the colored bars representing the percentage of sources also classified in the present work.

three-dimensional principal component space generated by the three independent WISE colors, and for KDEBLACS, that selects sources detected in the first three WISE bands based on their compatibility with the 90% KDE isodensity contours of BZBs in the two-dimensional $w1-w2$ versus $w2-w3$ color-color plane. In addition, the WIBRaLS2 method only selects BZB, BZQ, and MIXED candidates, while we use our method to select also BZU and BZG candidates. In addition, we note that D’Abrusco et al. (2019) based their selection methods on the third release of the *Fermi*-LAT catalog, 3FGL, the latest that was available at the time of the publication, while for our method, we used the results of the updated 4FGL. It is for these reasons that the two methods are not equivalent and we expect differences in the classification of the ABC sources.

These differences are summarized in Fig. 21. In the left panel of this figure we present the 715 ABC γ -ray blazar candidates we selected with our method, 361 of which are also selected in the WIBRaLS2 catalog. For each subclass our classification method (BZB, BZQ, MIXED, BZU and BZG) we indicate with colored rectangles the percentage of sources that have a WIBRaLS2 classification (BZB, BZQ and MIXED). We see that $\sim 70\%$ of our candidates BZBs are also selected as candidate BZBs in WIBRaLS2, while the remaining $\sim 30\%$ of this subclass is not classified in WIBRaLS2 catalog. About $\sim 50\%$ of our BZQ candidates is also classified as BZQ candidate in WIBRaLS2, while three are classified as BZBs and 8 as MIXED in WIBRaLS2. Only $\sim 13\%$ of the sources we classify as MIXED candidates have the same classification in WIBRaLS2, while $\sim 34\%$ and $\sim 6\%$ of these sources are classified as BZQ and BZB candidate in WIBRaLS2, respectively. Finally, $\sim 26\%$ and $\sim 21\%$ of the sources that we classify as BZU and BZG, respectively (two classes non-present in WIBRaLS2), are classified as BZB candidates in WIBRaLS2 catalog.

In the right panel of the same figure, we present the reverse comparison, that is, we study how the 361 ABC sources listed in the WIBRaLS2 catalog are classified according to our selection method. The sources classified as BZB candidates in WIBRaLS2 catalog are a mixed bag of different classifications for our method, while $\sim 51\%$ and $\sim 47\%$ of the sources classified as BZQ candidates in WIBRaLS2 are classified as candidate BZQs

Fig. 22. Summary of the 715 γ -ray blazar candidates selected according to the method presented in Sect. 5. The black rectangles represent the different ABC source types and the colored bars in each rectangle represent the percentage of each source type classified as γ -ray blazar candidates of the different classes, with the colors indicated in the legend.

and MIXED according to our method, respectively. Finally, $\sim 14\%$ and $\sim 80\%$ of sources classified as candidate MIXED in WIBRaLS2 are classified as BZQs and MIXED candidates in our method.

In Fig. 22, we summarize the results of our γ -ray blazar candidates selection in terms of ABC source types. We see that most BZB candidates belong to the BL Lac source type, while the other source types are mainly composed of candidate BZQs and MIXED candidates, which represent the majority ($\sim 35\%$ and $\sim 47\%$ respectively) of our γ -ray blazar candidates.

To conclude this section, in Fig. 23 we see how the sources for which we have an optical spectroscopic classification (see Sect. 4.1.3) compare with the regions occupied in the WISE color-color diagrams by the different classes of Roma-BZCAT

Fig. 23. *Left panel:* ABC sources with a WISE counterpart detected in all four WISE bands (white circles) represented in the $w1-w2$ versus $w2-w3$ color-color plane. The same KDE isodensity contours of Fig. 20 are presented with lines of different colors for the different Roma-BZCAT subclasses, as indicated in the legend. Filled red and black circles mark sources with an optical spectroscopic classification of QSO and GALAXY, respectively. *Right panel:* same as the left panel, but for the $w2-w3$ versus $w3-w4$ projection.

γ -ray blazars, represented as they are in Fig. 20. Of the 110 sources for which we have an optical spectroscopic classification, 89 have a WISE counterpart detected in all four WISE bands and they are presented in this figure with red circles for sources with an optical spectroscopic classification of QSO, then with black circles for sources with an optical spectroscopic classification of GALAXY. We see that most QSO objects, as expected, lie in the region occupied by BZQs. The GALAXY objects, on the other hand, mostly lie in the region of BZBs – especially in the $w1-w2$ versus $w2-w3$ projection – and in the region of BZGs (whose emission is dominated by the galactic one), extending toward the color-color region occupied by old elliptical galaxies (see e.g. Raiteri et al. 2014), suggesting that these objects are BL Lac objects whose host galaxy dominates the optical emission.

6. Conclusions

We built a new catalog of candidate blazars, dubbed ABC, derived from the ALMA Calibrator Catalogue by Bonato et al. (2019). The ABC catalog fills, at least partly, the lack of $|b| < 10^\circ$ blazars in Roma-BZCAT, providing low Galactic latitude candidate counterparts to unassociated high-energy sources. This is particularly important in the case of rare events, such as detections of high energy neutrinos for which a full exploitation of all-sky data is essential to identify the source population. Some of the ABC sources at low Galactic latitudes may also be useful to verify the *Gaia* optical reference frame (Mignard et al. 2016).

The ABC catalog contains 1580 sources not included in the Roma-BZCAT. It was cross-matched with *Gaia* DR2, SDSS DR12, LAMOST DR5, AllWISE, and 4FGL catalogs, finding 805, 295, 31, 1311, and 259 matches, respectively. These data were used for the classification of our sources and a comparison with the population of known blazars in Roma-BZCAT.

ABC sources are significantly dimmer than Roma-BZCAT sources in the *Gaia* g band, while the difference in the *Gaia* $b-r$ color between the two populations is less pronounced. Also, ABC sources appear bluer in SDSS than Roma-BZCAT sources, but with low statistical significance. When comparing with the results of Butler & Bloom (2011), we see that most ABC sources

classified as QSO and BL Lac fall into the region of low redshift quasars, with some QSOs entering the regions of higher redshift quasars. Regarding WISE colors, we find that ABC sources are significantly bluer than Roma-BZCAT sources in the $w2-w3$ and $w3-w4$ colors. In addition, we collected 110 optical spectra in SDSS DR12 and LAMOST DR5, which mostly classify the corresponding sources as QSO (98), while 12 sources resulted in classifications as galactic objects.

A fraction of ABC sources are located in fields covered by *Swift*-XRT, *Chandra*-ACIS and *XMM-Newton*-EPIC observations. We have retrieved the X-ray archive data and made our own source extraction, achieving the detection of 101, 56 and 55 ABC sources, respectively, extracting spectra for 43, 46, and 51 of them, respectively. Our sources are, on average, similar in X-rays to Roma-BZCAT blazars in terms of count-rates and spectral slopes, implying that our sample is covering the same region of the blazar parameter space in this band. A comparison of γ -ray properties of ABC sources with Roma-BZCAT blazars has shown that ABC sources are, on average, dimmer, and their γ -ray spectra are, on average, softer, consistent with the ABC containing a significant fraction of FSRQs.

About 57% (906 out of 1580) of ABC sources are detected in all four WISE bands. This has allowed us to re-examine the selection of γ -ray blazars by means of mid-IR colors discussed by D’Abrusco et al. (2019). Making use of the KDE contours in the WISE color-color diagrams containing 90% of WISE-detected 4FGL blazar subclasses, we were able to classify about 80% (715 out of 906) of the ABC WISE-detected sources as candidate γ -ray blazar. A comparison with the classification by D’Abrusco et al. (2019) for common sources has shown that these two methods yield different results and may, therefore, be used in a complementary way.

The main properties of the 879 ABC sources for which we were able to collect additional information are summarized in Table 4, including their inclusion in other blazar catalogs (see Sect. 3), the optical spectroscopic classification (see Sect. 4.1.3), the X-ray properties (see Sect. 4.3.4), and the blazar candidate classification (see Sect. 5).

The ABC provides a large sample of candidate blazars that can be investigated both through dedicated optical spectroscopic

Table 4. Main properties of ABC sources.

Name ALMA	RA	Dec	Object type	Redshift	Type WISE	Type optical	4FGL	3HSP	WIBRaLS2	KDEBLLACS	X-ray
J0002–2153	00:02:11.98	–21:53:09.87	BL Lac		MIXED						
J0006–2955	00:06:01.12	–29:55:50.10	QSO	0.683	BZU						
J0008–3945	00:08:09.20	–39:45:22.96	RS	1.9	MIXED		BCU		BZQ		
J0011+0823	00:11:35.27	+08:23:55.59	QSO	1.35	MIXED	QSO			BZQ		
J0011–4105	00:11:52.40	–41:05:45.17	RS		MIXED						
J0011–8443	00:11:45.91	–84:43:20.01	RS	0.6	MIXED				BZQ		
J0011–8706	00:11:51.48	–87:06:25.45	RG	3.292							det
J0019–5641	00:19:26.61	–56:41:42.46	RS				BCU				
J0024–0811	00:24:00.67	–08:11:10.05	QSO	2.067	BZQ	QSO			BZQ		
J0024–4202	00:24:42.99	–42:02:03.95	QSO	0.937	BZQ				BZQ		

Notes. For each source we list the name (Name ALMA), the coordinates (RA, Dec), the ABC source type (Object type), the redshift (Redshift), the blazar candidate class obtained from WISE colors (Type WISE), the source type obtained from optical spectra (Type optical), the source class listed in the 4FGL catalog (4FGL), if the source is present in the 3HSP catalog (3HSP), the blazar candidate class as reported in the WIBRaLS2 catalog (WIBRaLS2), if the source is present in the KDEBLLACS catalog (KDEBLLACS), and the X-ray information (X-ray), namely a source detection (det), a power-law spectrum (PL) or a more complex spectrum (COMPLEX). The full table is available in electronic form at the CDS.

Fig. 24. White circles: Galactic coordinates of the ABC sources. Colored circles: ABC sources falling in the area covered by the planned WFD survey, with the exception of the Galactic center indicated with a dark lozenge. In particular, blue circles represent ABC sources for which we were able to collect additional information (see Table 4), while the red circles represent ABC sources for which we could not collect additional information. The black lines represent equatorial coordinates with declinations from -60° to 60° with increment of 20° .

observation campaigns or through repeated photometric observations for variability studies. An ideal tool for performing the latter investigation will be the ten-year Legacy Survey of Space and Time (LSST) which, starting from 2022, will be performed at the *Vera C. Rubin* Observatory (Ivezić et al. 2019). The LSST will repeatedly scan the whole southern sky, providing multi-epoch observations in six optical photometric bands (*ugrizy*) for more than 35 billions objects. The main LSST survey will be the Wide, Fast, Deep (WFD) survey, observing the sky between -65° and $+5^\circ$ of declination, with an observation cadence of ~ 3 days. In Fig. 24 we show the ABC sources in Galactic coordinates with white circles. The colored circles represent the ABC sources falling in the area covered by the planned WFD survey, with the exception of the Galactic center indicated with a dark lozenge. In particular, in the WFD survey area, we have 556 ABC sources with additional information contained in Table 4 (blue circles) and 529 ABC sources without additional information (red circles). Among the 125

ABC sources in the WFD survey area with an SDSS DR12 counterpart, 114 (more than 90%) have a r magnitude between the median single-visit 5σ point sources depth of $r = 24.16$ for the planned WFD survey and the nominal LSST saturation limit of $r \sim 16$ for 15 s exposures¹⁴. The data collected by the WFD survey will therefore provide a key tool for the investigation of the possible blazar nature of these sources.

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¹⁴ See the [white paper](#) on the LSST Observing Strategy.

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Appendix A: X-ray spectra

In this appendix we collect the results of the spectral fitting discussed in Sect. 4.3.4. In particular, in Figs. A.1–A.3 we show the spectra fitted with a power-law model, while in Figs. A.4–A.6 we show spectra fitted with the models listed in Table 3.

Fig. A.1. *Swift*-XRT spectra with their best-fit power law models (*upper panels*) and residuals (*lower panels*).

Fig. A.1. continued.

Fig. A.2. *Chandra-ACIS spectra with their best-fit power law models (upper panels) and residuals (lower panels).*

Fig. A.2. continued.

Fig. A.3. XMM-Newton-EPIC spectra with their best-fit power law models (*upper panels*) and residuals (*lower panels*). Lines and points in blue, red and green indicates models and data of MOS1, MOS2 and PN detectors, respectively.

Fig. A.3. continued.

Fig. A.4. *Swift*-XRT spectra listed in Table 3 with their best-fit models (*upper panels*) and residuals (*lower panels*).

Fig. A.5. *Chandra*-ACIS spectra listed in Table 3 with their best-fit models (*upper panels*) and residuals (*lower panels*).

Fig. A.6. *XMM-Newton-EPIC* spectra listed in Table 3 with their best-fit models (*upper panels*) and residuals (*lower panels*). Lines and points in blue, red and green indicates models and data of MOS1, MOS2 and PN detectors, respectively.

Fig. B.1. continued.

Fig. B.1. continued.

Fig. B.1. continued.

Fig. B.1. continued.

Fig. B.1. continued.

Fig. B.1. continued.

Fig. B.2. continued.

Appendix C: Optical spectra

In this appendix we present tables collecting properties of ABC sources. In particular in Table C.1 we show the properties of

the ABC sources found in other blazar catalogs (4FGL, 3HSP, WIBRaLS2 and KDEBLACS), while in Table C.2 we present the infrared and optical properties of ABC sources.

Table C.1. ABC sources found in other blazar catalogs.

Name ALMA	Redshift	Object type	Name 4FGL	Type 4FGL	Name 3HSP	Name WIBRaLS2	Type WIBRaLS2	Class WIBRaLS2	Name KDEBLACS
J0008–3945	1.9	RS	4FGL J0008.0–3937	BCU		J000809.17–394522.8	BZQ	D	
J0011+0823	1.35	QSO				J001135.27+082355.5	BZQ	D	
J0011–8443	0.6	RS				J001145.90–844320.0	BZQ	C	
J0019–5641		RS	4FGL J0019.2–5640	BCU					
J0024–0811	2.067	QSO				J002400.67–081109.8	BZQ	D	
J0024–4202	0.937	QSO				J002442.99–420203.9	BZQ	D	
J0024–6820	0.354	AGN	4FGL J0023.7–6820	BCU		J002406.72–682054.5	BZQ	A	
J0025–4803		RS	4FGL J0025.7–4801	BCU		J002545.81–480355.1	BZQ	D	
J0028+2000	1.552	QSO	4FGL J0028.4+2001	FSRQ		J002829.81+200026.7	BZQ	D	
J0030–0211	2.1	QSO	4FGL J0030.6–0212	BCU					

Notes. For each source we list the name (Name ALMA), the redshift (Redshift), the ABC source type (Object type), the name (Name 4FGL) and source class (Type 4FGL) as listed in the 4FGL catalog, the name of the source as listed in the 3HSP catalog (Name 3HSP), the name (Name WIBRaLS2) and blazar candidate class (Type WIBRaLS2) as listed in the WIBRaLS2 catalog, and the name of the source as listed in the KDEBLACS catalog (Name KDEBLACS). The full table is available in electronic form at the CDS.

Table C.2. Infrared and optical properties of ABC blazar candidates.

Name ALMA	Redshift	Object type	Name WISE	Type WISE	Name LAMOST	Type OST	LAM-Redshift LAMOST	Name SDSS	Type SDSS	Redshift SDSS
J0002–2153		BL Lac	J000211.98–215310.0	MIXED						
J0006–2955	0.683	QSO	J000601.12–295550.0	BZU						
J0008–3945	1.9	RS	J000809.17–394522.8	MIXED						
J0011+0823	1.35	QSO	J001135.27+082355.5	MIXED	J001135.27+082355.6	QSO	1.40175(0.0004989)			
J0011–4105		RS	J001152.39–410545.1	MIXED						
J0011–8443	0.6	RS	J001145.90–844320.0	MIXED						
J0024–0811	2.067	QSO	J002400.67–081109.8	BZQ				J002400.67–081110	QSO	2.071(0.00032)
J0024–6820	0.354	AGN	J002406.72–682054.5	BZQ						
J0024–4202	0.937	QSO	J002442.99–420203.9	BZQ						
J0025+3919	1.946	QSO	J002526.13+391935.6	MIXED						

Notes. For each source we list the name (Name ALMA), the redshift (Redshift), the ABC source type (Object type), the name of WISE counterpart (Name WISE), the blazar candidate class obtained from WISE colors (Type WISE), the name of the LAMOST DR5 counterpart (Name LAMOST), the redshift as evaluated from the LAMOST spectrum (Redshift LAMOST) with the error in parenthesis, the name of the SDSS DR12 counterpart (Name SDSS), and the redshift as evaluated from the SDSS spectrum (Redshift SDSS) with the error in parenthesis. The full table is available in electronic form at the CDS.