ASTRONOMIA E ASTROFISICA
SCIENTIFICA

COLLANA DIRETTA DA ENRICO COSTA ED ENRICO MASSARO

3

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La più sublime, la più nobile tra le Fisiche scienze ella è senza dubbio l'Astronomia. L'uomo s'innalza per mezzo di essa come al di sopra di se medesimo, e giunge a conoscere la causa dei fenomeni più straordinari.

Giacomo Leopardi

Negli ultimi anni si è assistito ad una grande crescita di libri dedicati alla descrizione dei primi istanti dell'universo e delle sue complicate proprietà fisiche o alla scoperta di un sempre crescente numero di pianeti in rotazione attorno a stelle vicine.

Gli argomenti trattati nelle ricerche astronomiche spaziano in un panorama molto più ampio, spesso poco noto alla maggioranza dei lettori. Molti dei risultati recenti devono essere confermati ed ampliati e ciò richiede un numero sempre più grande di osservazioni e di accurate analisi dei dati così ottenuti. Accade spesso che le tecniche i dettagli di questi lavori non riescono ad essere descritti come meriterebbero nel ristretto spazio di un articolo su rivista.

Questa collana si prefigge di colmare in parte questa lacuna pubblicando testi che forniscano agli specialisti, come a coloro che affrontano queste impegnative ricerche, una documentazione che ne descriva i diversi aspetti.

Ad essi si affiancheranno anche cataloghi e raccolte di dati, un fondamentale *thesaurus* per le ricerche astrofisiche, e testi più semplici di livello introduttivo.

La collana si divide in due sezioni: in questa sono ospitati i volumi con un taglio e un orientamento scientifico.

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Multifrequency Catalogue of Blazars

5^{th} edition

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Foreword

This volume presents the 5th Edition of the Multifrequency Catalogue of Blazars, shortly named Roma-BZCAT. This catalogue was initially assembled with the aim of providing a useful tool for the identification of the counterparts to the many gamma-ray sources detected by Fermi-GST. The list was actually used for that purpose in the redaction of the 1FGL and 2FGL catalogues, and of 1LAC and 2LAC catalogues. However, blazars are important observational targets for a number of other space missions like e.g., AGILE, PLANCK, INTEGRAL, WISE, Swift, XMM, and NuSTAR. The Roma-BZCAT *should therefore be considered as a contribution to the scientific activities of several observatories, as well as to other general research projects.*

We are pleased that our catalogue has been, and still is, considered by several colleagues a good and practical tool for research activity in high-energy, as well as other branches of astrophysics. Despite the great amount of work carried out to discover new blazars in several surveys, only a relative small number of blazars have been studied intensively so far. Therefore there is still a very large amount of observational work to do in the coming years to gain a deeper insight into the physics of Blazars. We are confident that the Roma-BZCAT *will be useful to help choose the best suited sources for these deep investigations and to select blazar samples useful to test their properties. The source list for the entire sky is available online at the ASDC web site of* http://www.asdc.asi.it/bzcat *where it is frequently updated to add new blazars and to improve the database.*

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Contents

THE Roma-BZCAT CATALOGUE

(From the Presentation to the 3rd Edition)

The *Roma-BZCAT* is a list of carefully checked blazars originally conceived as a tool for the identification of counterparts of high energy sources. The Fermi-LAT collaboration, in fact, has been using it for this purpose in various γ-ray source catalogues, like 1FGL, 1LAC (Fermi LAT AGN Catalog) and the new 2FGL and 2LAC.

The complete 1st Edition of the *Roma-BZCAT*, only available on-line, included 2728 sources (Massaro et al. 2009). The first two volumes of a printed version covering the RA intervals 0h-6h (Volume I) and 6h-12h (Volume II) have also been published (Massaro et al. 2005, Massaro et al. 2008). In addition to the catalogue tables, these two volumes presented a large collection of multi-frequency data, and the Spectral Energy Distributions (SED) of over one hundred sources.

The 2nd Edition, including more than 250 new sources, was made available as an on-line table in May 2010. A brief description of this version was published in the arXiv preprint database (Massaro et al. 2010).

This book presents the 3rd Edition of the catalogue that will also be available on line. The differences with respect to previous editions are the addition of new data at different frequencies (radio, microwaves and γ rays) derived from recent catalogues and compilations, and a deep revision of sources that, in some cases, led to a revised classification, or to the elimination from the lists of previous editions because their blazar nature was not confirmed.

Traditionally, blazars come in two main flavors: BL Lac objects (BL) and Flat Spectrum Radio Quasars (FSRQ), depending on the width and strength of the emission lines in their optical spectrum. Variability and other uncertainties, however, raised the problem of an accurate blazar definition, an issue that is still open. For this reason, in this Introduction, we briefly discuss how blazars were discovered and originally classified.

1. The discovery of blazars: a brief historic outline

Before radio astronomical observations became available, only a few BL Lac objects had been noticed as irregular variable stars with peculiar spectra, and nobody was aware of their extragalactic nature. In 1941 the photographic magnitude of the star-like object BL Lac was observed to vary between 13.0 and 16.0 (van Schewick, 1941), and large and fast brightness changes were also reported for W Com, AP Lib and BW Tau.

Later, in the sixties, radio astronomers conducted the first surveys and started programs aimed at the identification of many newly discovered radio sources. In 1965 MacLeod et al. (1965) published in *The Astronomical Journal* the first list of sources detected in a 610 MHz radio survey performed with the 400-ft radio telescope of the Vermillion River Observatory (VRO). The radio source VRO 42.22.01, with a flux density of 4.0 Jy, was further studied by MacLeod and Andrew (1968) who discovered that its radio spectrum was unusual and its centimetric emission was linearly polarised. VRO 42.22.01 was identified by Schmitt (1968) with the "star" BL Lac from a positional agreement, however images revealed a bright core inside a nebulous object. Subsequent optical observations (DuPuy et al. 1969, Oke et al. 1969, Visvanathan 1969, Bertaud et al. 1969) showed large and rapid variability, with intensity changes of 0.7 mag in 74 minutes, a high linear polarisation of about 10% and an unusual spectral distribution. Visvanathan (1969) suggested that BL Lac could be a synchrotron source because its spectrum was in a good agreement with the computations by Matthews and Sandage (1963), but the absence of spectral lines made it quite different from recently discovered quasars and its nature remained obscure. Racine (1970) confirmed the fast changes of the BL Lac brightness with a rate of about 0.03 mag in 2 minutes and again noticed the similarities with the N-type galaxies and Seyfert nuclei. Pigg and Cohen (1971) studied the 21 cm absorption spectrum of BL Lac and concluded that its distance *"is certainly more than 200 parsecs ... the absorption spectrum is consistent with this object being extragalactic"*.

In the same year Bond (1971) identified the optically variable object AP Lib, discovered by Ashbrook (1942) at the Harvard College Observatory, with the radio source PKS 1514-24 which was previously associated with a 16-mag elliptical galaxy by Bolton, Clarke and Ekers (1965), and classified by Westerlund and Wall (1968) as an N-type galaxy. Searle and Bolton (1968) reported that its optical spectrum did not exhibit emission lines. The possibility that these peculiar sources could be the prototypes of a new class of extragalactic objects was first proposed by Strittmatter et al. (1972) in a famous paper that marked the beginning of blazar research.

The number of BL Lac objects continued to grow, and when Stein, O'Dell & Strittmatter (1976) published the first review paper, it reached the level of 32, with only four sources in the southern hemisphere. Two years later the first conference on BL Lac objects was held in Pittsburg. On that occasion Blandford and Rees (1978) presented their model where the very peculiar properties of BL Lac objects were explained as the effect of relativistic Doppler boosting occurring in the the jet of source pointing at small angle with respect to the line of sight. Other major conferences on BL Lac objects (excluding, of course, several other workshops) were held at the distance of 10 years in Como (Italy, 1988) and Turku (Finland, 1998). In 2008 a workshop focused on variability was held at Palaiseau (Paris).

The advent of Einstein observatory, the first X-ray imaging telescope, in 1979 led to the discovery a new type of BL Lac objects, typically characterised by a high X-ray to radio flux ratio, which were named X-ray selected BL Lacs (Stocke et al. 1982, 1983, 1985).

The discovery that some radio-loud quasars exhibiting characteristics similar to BL Lac objects, with the exception of the occurrence of broad spectral lines, completed the definition of the blazar population. Moore and Stockman (1981) gave an important contribution when performed a polarisation survey in which discovered 17 high polarisation quasar (HPQ) and discussed their relation with BL Lacs. Before they work only four radio quasar were known to show high variable optical linear polarisation. Some years later, Impey and Tapia (1988) performed optical polarisation measurements on a sample of radio sources and discovered 31 new blazars.

The division of blazars into the two main classes of BL Lacs and Flat Spectrum Radio

Quasars was then firmly established.

After the first list of 32 BL Lac objects given by Stein, O'Dell and Strittmatter (1976), Angel and Stockman (1980) increased the number to 57. A further catalogue of BL Lac objects was prepared by Burbudge and Hewitt (1987), containing 87 sources, but it did not include all the sources listed by Angel and Stockman. At that epoch the total number of blazar was 103. Since 1984 Veron-Cetty and Veron published a general catalogue of Active Galactic Nuclei including, starting from the 2nd Edition (Veron-Cetty and Veron 1985), a table of BL Lac objects, whose number is continuously increasing from that epoch to the most recent editions.

2. Blazar selection criteria

As stated above, blazars are a peculiar class of radio loud AGN selected on the basis of the presence of strong non-thermal radiation, on large and rapid variability and on high polarisation. Their unusual observational properties are explained by non-thermal emission from small size regions moving with a velocity close to the speed of light and observed at a small angle with respect to the line of sight. The relativistic Doppler boosting that results from these very special circumstances strongly amplify the non-thermal emission that often becomes dominant compared to all other components of thermal origin, like those from the accretion disk, the dust heated by the AGN flux or that from the stars and interstellar matter of the host galaxy.

In very general terms we can define a blazar as an extragalactic source characterized by *i*) a spectral energy distribution (SED) showing strong non-thermal emission over the entire electromagnetic spectrum, from radio waves to γ-rays, and *ii*) the presence of some evidence for relativistic beaming.

It is clear that both requirements can be secured only making use of rich observational data sets, involving either polarimetric or variability studies and VLBI imaging to detect compact cores and superluminal motions. Such data sets are available only for a limited number of, usually bright, sources and therefore the majority of known blazars have been recognized only on the basis of some spectral properties. Moreover, in most cases the data available are not simultaneous and are often derived from catalogues; this situation sometimes makes it very difficult to establish whether an AGN is a genuine blazar or not.

The main objective of the present catalogue is to provide the largest available sample of identified blazars that could be of interest for the present and next generation of space observatories such as Swift, Fermi, NuSTAR, Planck etc. For this reason, we adopted a rather wide set of acceptance criteria as described below:

1.– Detection in the radio band, down to mJy flux densities at 1.4 GHz (*NVSS*, Condon et al. 1998 or *FIRST*, White et al. 1997) or 0.84 GHz (*SUMSS*, Mauch et al. 2003);

2.- optical identification and knowledge of the optical spectrum to establish the blazar type;

3.– isotropic X-ray luminosity larger than $\sim 10^{43}$ erg/s;

4.– for FSRQs, we require a radio spectral index measured between 1.4 GHz (or 0.843 GHz) and 5 GHz, $\alpha_r < 0.5$ ($F(\nu) \propto \nu^{-\alpha_r}$), while for BL Lacs, although most of them have flat spectra, this condition is not required, mainly because of lack of high frequency data;

5.– compact radio morphology, or, when extended, with a dominant core and a one-sided jet.

We recall that X-ray detection cannot be required as a criterium since for blazars with synchrotron peak located at frequencies lower than $\approx 10^{14}$ Hz, the emission around 1 keV is generally due to the inverse Compton component and can be well below the detection threshold of the *RASS* (Voges et al. 1999), the most sensitive all sky X-ray survey presently available. For this reason, many blazars, in particular a large fraction of FSRQs, are included in the catalogue despite they are undetected in the X-ray band. To confirm the validity of our choice a sample of such sources was observed with the Swift X-Ray Telescope and in all cases a positive detection was always achieved (Giommi et al. 2007).

There is, however, a relative small number of sources that do not entirely satisfy the criteria listed above but nevertheless do show some blazar features. In particular, some nearby galaxies exhibit a nuclear activity resembling that of a low-luminosity blazar core: for instance, some galaxies have a flat spectrum radio emission from a nuclear compact source with a luminosity larger than that expected from a normal or nearby active galaxy. Taking into account that little is generally known about them, and that these sources could be blazars in a particular status (e.g. new born or dying blazars), we decided to include the most interesting of these sources in a separate class named "Blazar of Uncertain Classification" (see the description of the catalogue).

3. The thorny issue of blazar classification

This classification of blazars in the two classical categories of BL Lacs and FSRQs, although very simple, is not unambiguous. The former type are characterized by the lack of broad emission features in their optical spectrum, namely the equivalent width (EW) of any emission line must be lower than 5 Å in the blazar rest frame (Stickel et al. 1991, Stocke et al. 1991), while FSRQs display the prominent emission lines that are typical of QSOs. However, well established BL Lac objects like OJ 287 and BL Lac itself, on some occasions, clearly exhibited emission lines with EW well above the 5 Å limit (Vermeulen et al. 1995, Corbett et al. 1996). The recent detection of broad Lyman-α emission in the UV spectrum of classical BL Lacs like MKN 421 and MKN 501 also points towards a common nature of the two types of blazars. In addition, several other BL Lac objects show luminous emission lines of EW just below the 5 Å threshold (see e.g. Lawrence et al. 1996, Ghisellini et al. 2010 and references therein), and well known FSRQs like 3C279 appear nearly featureless during bright states (Pian et al. 1999). The boundary between BL Lac objects and radio galaxies is also fragile as BL Lacs are distinguished from radio galaxies when the 4000 Å Ca H&K break (a stellar absorption feature in the host galaxy) is diluted by non-thermal radiation more than a certain amount first quantified by Stocke et al. (1991) and then revised by Marchã et al. (1996) and Landt et al. (2004). The level of non-thermal blazar light around 4000 Å reflects the intrinsic radio power of the jet, it can be highly variable and strongly depends on the position of the peak of the synchrotron emission (see below) thus making the classification as BL Lac or radio galaxy quite uncertain.

Another problem concerns variability: on some occasions blazars showed large brightness changes on time scales of a day or of a few hours, whereas sometimes they remain in a quasi-quiescent state for years. Such different behaviour can hide blazar properties and can lead to misidentification.

BL Lac objects are also classified into different types based on their physical properties, and precisely on the basis of the peak frequency of their synchrotron component. The two main BL Lac types were defined by Padovani and Giommi (1995) as Low-

Energy peaked BL Lacs (LBL), when the peak is between $\sim 10^{13}$ and $\sim 10^{14}$ Hz, and High-Energy peaked BL Lacs (HBL) when it lies above 10^{15} Hz. In this last case the synchrotron component dominates the observed emission in the soft X-ray band. The inverse Compton peak of the former type is in the range 10 MeV and 1 GeV, whereas that of HBL objects is located at higher energies, sometimes reaching the TeV energy band (e.g. Abdo et al. 2010c). The presently known LBL objects are typically much brighter in the radio band than HBLs, whose radio fluxes can be as low as a few mJy. Conversely, in the X-ray band LBL objects are fainter than HBLs and go undetected in shallow surveys. For this reason, our knowledge on the radio emission of many HBL objects is rather poor, with the exception of a few nearby sources like e.g. Mrk 421 (see, for instance, Giroletti et al. 2006). The majority of HBL objects have little amount of radio data and often only fluxes at a single frequency (typically 1.4 GHz) are available. It is an open problem how observational effects are relevant in this dichotomy. In this framework it is certainly worth studying the population of the so called Intermediate BL Lac objects with the synchrotron peak in the UV range (two relevant examples are ON 231 and S5 0716+71), whose X-ray emission is characterized by a flattening towards the high energies due to the onset of the inverse Compton component.

The fact the radio emission from distant HBL objects can be close or below the flux limits of the majority radio survey raises the problem of the existence of “radio-quiet” (or rather “radio-silent”) BL Lacs. Londish et al. (2002) considered a sample of “optically selected” BL Lac candidates, as a by product of the much wider *2QZ* sample of QSOs (Croom et al. 2001). Nesci et al. (2005) searched for optical variability of a subsample of the *2QZ-BL* sources and found that only few of them have significant brightness changes, including all the radio loud ones. In a subsequent paper, Londish et al. (2007) reported a further analysis of an expanded and revised sample of potential optically identified BL Lacs and concluded that there can be no significant population of truely “radio-quiet” BL Lac objects.

The selection criteria for BL Lac objects have also been discussed in several papers (e.g. Marchã et al. 1996, Landt et al. 2002) and, particularly, the relevance of the nuclear emission to that of the host galaxy, measured by the strength of the Ca H&K break. Although some of the proposed criteria led to the identification of many true blazars, a new study of some sources’ samples from the present catalogue is providing a good evidence that some non-blazar objects could satisfy these criteria and that more stringent conditions must be adopted (Massaro, Nesci & Piranomonte 2012).

Another problem concerns the nature of a class of radio sources whose nature is still a matter of debate. We refer to the so called High-Frequency Peakers (HFP) (Dallacasa et al. 2000) and GHz-Peaked Sources (GPS) (O’Dea et al. 1991), whose optical counterparts are a mixture of galaxies and quasars together with a few BL Lacs. Broad-band monitoring campaigns have shown that many of these sources are indeed variable and that their spectra can change from the characteristic convex shape to a flat frequency distribution (Torniainen et al. 2005). Such a complex behavior suggests a relation between GPS-HFP objects and blazars that may depend upon either the beaming or other physical parameters. Moreover, the spectral coverage of many radio sources is poor, both in frequency and time, and several sources with non simultaneous spectra could have been classified as FSRQ while they are GPS-HFP and vice-versa. In other cases, some SEDs indicate the occurrence of a convex radio component superposed onto a power-law spectrum. We decided therefore to include in the catalogue also this type of radio sources, adding a specific note if they are GPS or HFP, using as reference the recent master list by Labiano et al. (2007) and other literature.

4. Blazar surveys

Starting from the late 1980's several sizable blazar samples were produced as a result of a number of systematic searches in large radio or X-ray surveys. These highly organised efforts were initially carried out following a standard approach involving the optical identification of all sources above the survey's flux limit. However, when the necessity to assemble deeper and larger samples pushed the need for optical telescope time to hardly manageable amounts, multifrequency (usually radio, optical and X-ray) pre-selection techniques were developed in order to significantly reduce the number of candidates requiring optical spectroscopy.

Table I gives a list of all the major surveys of both types that led to the discovery of most of the blazars known today and included in this catalogue.

After the first list of 32 BL Lac objects given by Stein, O'Dell and Strittmatter (1976), Angel and Stockman (1980) increased the number to 57. A further catalogue of BL Lac objects was prepared by Hewitt and Burbidge (1987), containing 87 sources, but it did not include all the sources listed by Angel and Stockman. At that epoch the total number of blazar was 103. Since 1984 Veron-Cetty and Veron published a general catalogue of Active Galactic Nuclei including, from the 2nd Edition (Veron-Cetty and Veron 1985), a table of BL Lac objects whose number is continuously increasing from that epoch to the most recent editions.

In the past years new surveys have become available and the number of blazar candidates has grown rapidly. A clear indication of this increase is that in the present volume the number of catalogued blazars is 3061, although not all firmly confirmed. An important multifrequency sample is the Radio-Optical-X-ray built at ASDC (*ROXA*, Turriziani et al. 2007), that was obtained by means of a cross-correlation between large radio (*NVSS*, *ATCAPMN* Taker 2000) and X-ray surveys (*RASS*) together with the *SDSS-DR4* and *2dF* data to spectroscopically identify the candidates. The *ROXA* sample consists of 816 objects and includes 173 newly discovered blazars. As for the other sources all the ROXA objects were examined to decide if they actually satisfy the *Roma-BZCAT* acceptance criteria, and only a small percentage of them was not accepted. Note that the relatively high threshold of the X-ray flux of the RASS survey preferentially selects objects with high F_X/F_{radio} ratio, hence HBL objects.

Recent samples of BL Lac and candidates, based on the *SDSS* spectroscopic database, were obtained by Collinge et al. (2005), Plotkin et al. (2008), and Plotkin et al. (2010). The objects selected by Collinge et al. (2005) were divided into the two groups of 240 "probable" and 146 "possible" BL Lac candidates, the former selected by colours unlike those of DC white dwarf stars and some evidence of extragalactic nature, such as a redshift estimate and/or a radio/X-ray counterpart. The majority of these BL Lac candidates are, as for the *ROXA* sample, of the HBL type. In this sample there are several sources without a radio counterpart, and this possibility raises the problem of the existence of radio-quiet (or optically selected) BL Lacs.

Plotkin et al. (2010) presented a sample of 723 optically selected BL Lac candidates based on the Sloan Digital Sky Survey Data Release 7 (Abazajian et al. 2009). However, only 106 of these objects have been added so far to the *Roma-BZCAT* catalogue as we decided to adopt rather severe selection criteria. In our first approach, we considered only sources with a radio flux larger than 5 mJy at 1.4 GHz and preferentially with an optical spectrum indicating a strong nuclear activity. Fainter sources, in fact, could not be safely distinguished from other types of AGNs, like weak radio galaxies. An accurate analysis of these objects is in progress and should be considered for a further edition of our catalogue.

Another very important survey aimed to blazar identification is the Candidate Gamma Ray blazar Survey (*CGRaBS*) (Healey et al. 2008). This sample is essentially based on the *CRATES* (Combined Radio All-Sky Targeted Eight GHz Sources) catalogue (Healey et al. 2007), which extended the *CLASS* (Cosmic Lens All-Sky Survey, Myers et al. 2003) to obtain observations at 8.4 GHz of flat spectrum sources with $|b| > 10°$ and brighter than 65 mJy at 4.8 GHz, with the exclusion of the region with declination $\delta > 75°$ where the flux limit is 250 mJy. The *CRATES* catalogue contains 11,131 sources, many of them without optical counterpart.

The *CGRaBS* sample was selected in such a way to identify sources having the greatest similarity to the EGRET blazars, and for the majority of them an optical follow-up provided the counterpart identification and spectroscopy. For the sake of completeness, we decided to add to the *Roma-BZCAT* all *CGRaBS* sources classified as FSRQs, although their spectra are not available in literature and/or online. Sources of unknown type and without redshift were not included.

Other new blazars and blazar candidates come from lists of possible associations with γ-ray sources discovered in the LAT survey (Abdo et al. 2010b). New optical observations, most of which still unpublished, have been used to distinguish between BL Lac objects and FSRQs. We accepted this classification, but we list the BL Lacs without an available spectrum in the candidate section.

Other radio discovered blazar candidates, characterised by flat spectra, without a firmly established optical counterpart, were not considered as confirmed blazars and therefore are not included in this version of the catalogue.

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