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X-ray selected BL Lacertae objects: catalogue and statistical properties

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The present work focuses on the statistical properties of X-ray selected BL Lacertae objects (XBLs) whose catalogue has been compiled. It consists of 312 sources from different X-ray surveys, unambiguously identified to mid-2010. Results of the statistical research of different observational quantities (redshift, multiwavelength luminosities, host/nucleus absolute magnitudes, central black hole masses, synchrotron peak frequencies, broadband spectral indices) are also provided and existence of the correlation between them is proved. Overall flux variability shows an increasing trend towards larger frequencies. XBLs are found to be much less active in sense of intra-night optical variability as compared to radio-selected BL Lacs (RBLs). A separate list of 106 XBL candidates including the same characteristics for each source as in the case of XBL catalogue was also created.

Key words: BL Lacertae objects: general

INTRODUCTION

BL Lacertae objects form one of the extreme subclasses of active galactic nuclei (AGN). The prototype of these sources, BL Lacertae, was detected by [11] who classified it as a short-period variable star of 13-15 stellar magnitude and named the object as "363.1929 Lac". The name "BL Lacertae" was given by van Schewick in 1941. On the basis of the photographic plates, taken at the Sonnenberg observatory during 1927–1933, he deduced that there is an irregular variable star the apparent magnitude of which varies between 13.5 mag and 15.1 mag (see [2]). After almost three decades, it was reported [21] that BL Lacertae coincides with the radio source VRO 42.22.01. This was followed by the detection of high and variable radio/optical polarization [15, 23], rapid optical variability with 0.1 mag over a few hours and flicker with the amplitude $\Delta V = 0.03$ mag per 2 minutes [19], steep optical spectrum following a single power law similar to quasars but showing no emission lines [17].

On the basis of the absorption features, detected in the optical spectra obtained with the 5m Hale telescope the redshift of BL Lacertae was determined [18]. The obtained value ($z = 0.07$) revealed that it is an extragalactic source hosted by an elliptical galaxy. During 1970–1978 up to 30 sources with similar properties were detected. At the Pitsburgh Conference on BL Lacertae Objects in 1978 it was suggested that the extreme properties of these objects should be caused by a Doppler-boosted emission pointed to the observer [3]. During that conference Ed Speigel introduced a term "blazars" to denote an independent class of the extragalactic sources, including BL Lacertae objects (BLLs) and flat spectrum radio-quasars (FSRQs, showing the same features with additional presence of emission lines). X-ray satellite Einstein and Energetic Gamma-Ray Experimental Telescope (EGRET) introduced a new era in investigation of these sources. It was revealed that blazars constitute the most observed class of extragalactic sources through $\gamma-$rays up to the TeV frequencies.

BLLs are thus the extragalactic sources with the features listed below:
a) quasi-featureless spectra, lack of prominent emission lines;
b) strong radio sources with a core-dominant morphology;
c) strong and variable optical/radio polarization;
d) violent flux variability through all spectral bands;
e) apparent superluminal motions;
f) broad continuum extending from radio to very high-energy γ-rays.

Up to now, more than 900 BLLs are unambiguously identified (see the second edition of the Roma-BZCAT[1]). Bulk of them are originally detected either through radio or X-ray bands. Due to this reason they were subdivided broadly into the radio-selected (RBLs) and X-ray selected BLLs (XBLs).

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[1] `http://www.asdc.asi.it/bzcat`

However, these subclasses differ from each other by their spectral energy distributions. According to [25] BLL is assumed to be a XBL if

$$\log F_x/F_r \geq -5.5,$$

where the X-ray flux density F_x is measured at 1 keV (2.42×10^{17} Hz) and the radio one F_r at 5 GHz (both in Janskys). Otherwise one deals with an RBL source.

THE CATALOGUE

The XBL catalogue consists of 312 sources [13], containing their equatorial coordinates, redshifts, multiwavelength flux values and isotropic luminosities, X-ray-to-radio flux ratios etc. It was compiled on the basis of the following X-ray surveys:

1) HEAO-1 Large Area Sky Survey [24] (16 sources);
2) Einstein Observatory Medium Sensitivity Survey [8, 14] (25 sources);
3) Einstein Observatory Extended Medium Sensitivity Survey [9] (42 sources);
4) EXOSAT High Galactic Latitude Survey [10] (10 sources);
5) Einstein Slew Survey [6] (61 sources);
6) ROSAT All-Sky Survey [1] (306 sources);
7) XMM-Newton Bright Serendipitous Survey [5] (3 sources).

A great deal of the XBLs belongs to the different surveys. A separate list of 106 XBL candidates including the same characteristics for each source as in the XBL catalogue was also compiled. We cannot consider them as BLL sources mainly due to lack of the optical spectroscopy. Their spectra are either not published or they are of bad quality and we thus cannot exclude the existence of the emission lines. Their observational features are in fact the same as for confirmed BLLs and we expect that high signal-to-noise ratio spectroscopy will boost the number of XBLs.

STATISTICAL PROPERTIES OF XBLs

Fig. 1 gives the distributions of different observational quantities: redshift, 1.4 GHz/V-band/ROSAT-band luminosities, host and nucleus R band absolute magnitudes, host V-R indices etc. Correlations between different quantities are shown in Fig. 2.

Redshifts. Only 207 XBLs (66.3% of the total sample) have confirmed redshifts. They range from $z = 0.031$ (Mrk 421) to $z = 0.702$ (H151+660) with a peak of the distribution at $z = 0.23$ (Fig. 1a). About 37% of the sources are concentrated within $z = 0.1 - 0.3$, and 88% of the sources have $z < 0.5$. Redshifts of 105 sources remain still either undetermined or not confirmed due to absence or extremal weakness of the spectral lines in these sources.

Luminosities. Common logarithms of 1.4 GHz isotropic luminosities (in erg/s) are distributed from 39.57 to 42.15 peaking at $\nu L_r = 40.85$ erg/s (Fig. 1b). The optical V-band luminosities are distributed from $\nu L_o = 43.31$ erg/s to $\nu L_o = 46.07$ erg/s with a peak at $\nu L_o = 44.20$ erg/s (Fig. 1c). Finally, $\nu L_x = 42.78 - 46.21$ erg/s for ROSAT-band X-ray luminosity that peaks at $\nu L_x = 45.10$ erg/s (Fig. 1d). Radio/optical/X-ray luminosities are found to be correlated with the redshift above the 99% confidence level: correlation coefficient r is equal to 0.53, 0.47, 0.58, respectively (Fig. 2a,b,c). In that case, we deal with an evolution from distant ellipticals with powerful nuclei to normal elliptical galaxies. However, there is a significant scatter in the correlations that are probably caused by the scatter in jet directions (leading to the scatter in Doppler boosting of the emission) and different brightness state.

Hosts/nuclei. Up to now, the hosts of only 94 XBLS are detected. As a rule, they are elliptical galaxies with effective radius $r_{eff} = 3.26 - 25.40$ kpc and ellipticity $\epsilon = 0.04 - 0.52$. R-band absolute magnitude ranges from -21.11 mag to -24.72 (Fig. 1e). The distribution peaks at $M_R = -22.80$ mag and its mean is -22.83 mag. The nuclei show much broader range of R-band absolute magnitudes: they are distributed from -19.21 mag to -27.24 mag with a peak at $M_R = -22.20$ mag (Fig. 1f). There is a negative correlation with a redshift ($r = -0.52$) above 99% confidence level (Fig. 2e) indicating thus a trend of increasing luminosities towards greater redshifts.

V-R indices of the hosts. This quantity ranges from 0.61 to 1.52 and shows three different peaks at $V - R = 0.73$, $V - R = 1.08$, and $V - R = 1.50$ (Fig. 1g). If confirmed, it might be may related to the three "waves" in a birth of elliptical galaxies. However, it may be caused by poor dataset: V-R indices are available for only 59 sources. They show a strong positive correlation with the redshift ($r = 0.97$, $> 99\%$ confidence level; Fig. 2f) explained with a redshifted emission of passively evolving elliptical galaxies with an old stellar population [22]. This correlation, fitted well with a third-order polynomial [13] may be used to evaluate the redshifts of that XBLs whose V-R indices are derived photometrically but their z values remain either unknown or controversial.

Masses of central BHs. According to the widely accepted scenario, BLL contain in their nuclei supermassive BHs whose masses are estimated mainly via the velocity dispersions in their hosts. $\log M_{BH}/M_{\odot}$ values are currently estimated for 47 XBLs and range from 7.39 to 9.30 (Fig. 1h). A peak of the distribution is found to be at $\log M_{BH}/M_{\odot} = 8.30$. These values do not show a correlation with a redshift. However, there are weak but statistically significant correlations between $logM_{BH}/M_{\odot}$ and 1.4 GHZ/V-band luminosities (Fig. 2g,h).

Synchrotron peak frequencies. Peak frequencies of synchrotron SEDs (radio to UV/X-ray frequencies) are currently determined for 187 XBLs. They range from $\log\nu_{peak} = 14.56$ Hz to $\log\nu_{peak} = 21.46$ Hz with a peak of the distribution at $\log\nu_{peak} = 16.60$ Hz (Fig. 1i). It seems that a subclass of ultra-high peaked BLLs (UHBLs) with $\log\nu_{peak} > 19.00$ should be an artefact of the poor datasets of multi-frequency flux values used for constructing the SEDs of these sources. Among 22 UHBLs, provided in [16], 13 sources are proven to have much lower peak frequencies [13]. ROSAT band X-ray luminosity shows a positive correlation ($r = 0.40$) with synchrotron peak frequencies while those for 1.4 GHz and V-band do not reveal any trend (Fig. 2j,k,m, respectively). This means a trend of increasing bolometric luminosity towards greater $\log\nu_{peak}$ values. This result is in contradiction with [7] about the decreasing power along the sequence LBLs → IBLs → HBLs that is explained in [4] as a cosmological result of gradual depletion of circumnuclear material causing a decreasing jet power along this sequence.

Broadband spectral indices. Radio-to-optical indices are distributed from 0.17 to 0.59, peaking at $\alpha_{ro} = 0.40$. The range of optical-to-X-ray indices is much broader: $\alpha_{ox} = 0.56 - 1.48$ with a peak of the distribution at $\alpha_{ox} = 0.98$. As for radio-to-X-ray indices, they span from $\alpha_{rx} = 0.41$ to $\alpha_{rx} = 0.75$ and peak at $\alpha_{rx} = 0.56$. The corresponding plots are in Fig. 1j, Fig. 1k, and Fig. 1m, respectively.

Flux variability. Almost 60% of the XBLs are not investigated for multiwavelength flux variability. The best studied are only brightest XBLs 1ES 2155-304 (since 1890) and Mrk 421 (since 1900). Only several sources have a history of observations greater than three decades. XBLs show basically erratic variability — changing duration, amplitude and base flux level from flare to flare. Periodical changes are reported very rarely, e.g. flares with 420 d period in 1ES 2321+419 through 1.5-12 keV band was reported in [20]; quasi-periodical flares with 3.2 yr duration in 1ES 1028+511 through optical R- band, reported in [12] etc. There is a trend of increasing overall range of optical variability towards shorter wavelengths [13]: $\langle\triangle m_R\rangle = 1.22$ mag (18 sources), $\langle\triangle m_V\rangle = 1.52$ mag (66 sources), $\langle\triangle m_B\rangle = 1.65$ mag (28 sources). On the intra-night time-scales XBLs are less active compared to RBLs in the optical domain: flickerings with $\triangle m \sim 0.1$ mag/night were recorded for several times while there are much more occasions and higher amplitudes in the case of RBLs. The reason is still unclear and cannot be simply related to the different jet orientation to the observer of these two BLL subclasses that could lead to the different boosting in the observed flux.

SUMMARY AND CONCLUSIONS

In the present paper a catalogue of 312 XBLs, updated to mid-2010, is presented. In the future, we may expect the number of XBLs to grow on the expense of XBL candidates (106 sources) which may not be assumed as BLL sources mainly due to the lack of high signal-to-noise ratio optical spectra. XBLs are the extragalactic sources with $0.031 < z < 0.702$ and with the common logarithms of radio/optical/X-ray luminosities of $39-42$, $43-45$, and $42-46$ erg/s order, respectively. These sources show a trend of increasing luminosity towards distant objects that has a deep cosmological implication: there is an evolution from distant elliptical galaxies with powerful nuclei into the ellipticals without active nuclei. However, this correlation may be related simply to the selection effect — great number of distant BLLs, whose apparent fluxes are below the detection threshold of current observing technique, may exist. XBL hosts are elliptical galaxies with effective radii of $3.26 - 25.40$ kpc and $M_R = -21.11.. - 24.86$ while the nuclei reveal much broader range of optical absolute magnitude of $(-19.93.. - 27.24)$. $V - R$ indices of the hosts reveal a third order polynomial relationship with z. $\log M_{BH}/M_\odot$ values range with almost two order of masses up to maximum value of 9.30 and do not show any correlation with redshift. But they show positive correlations with radio and optical luminosities that may serve as an argument of the Blandford-Znajek mechanism of jet production. Bolometric luminosities do not show an decreasing trend towards higher synchrotron peak frequencies, as it was shown in some previous works, and the blazar sequence may not be simply explained by the hypothesis of depleting circumnuclear material along this sequence. As for Synchrotron peak frequencies, $\log\nu_{peak} \sim 15 - 21$ Hz with a mean value of 16.76. We are also far from perfect understanding both of the character of multiwavelength flux variability and the nature of unstable processes, responsible for these variations.

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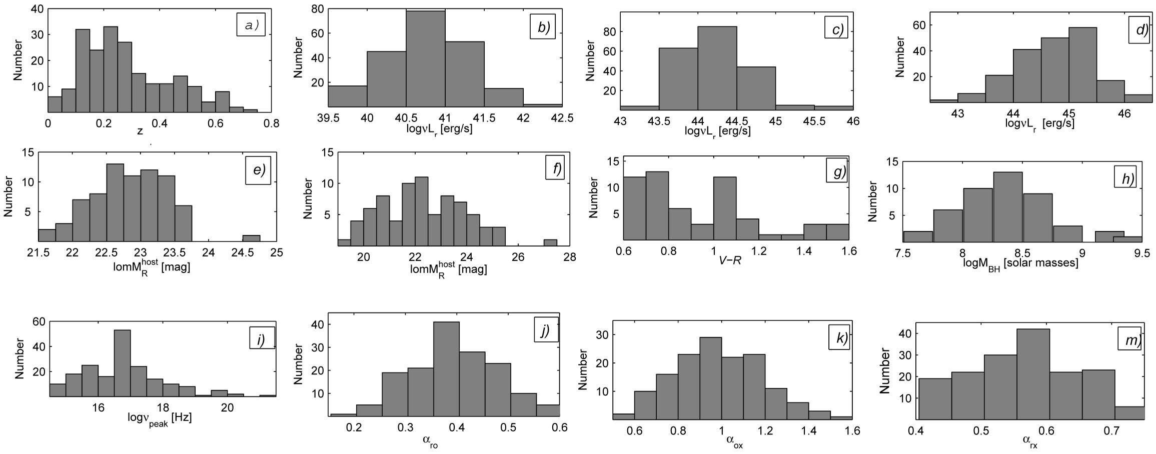

Fig. 1: Distribution of the observational quantities of XbLs.

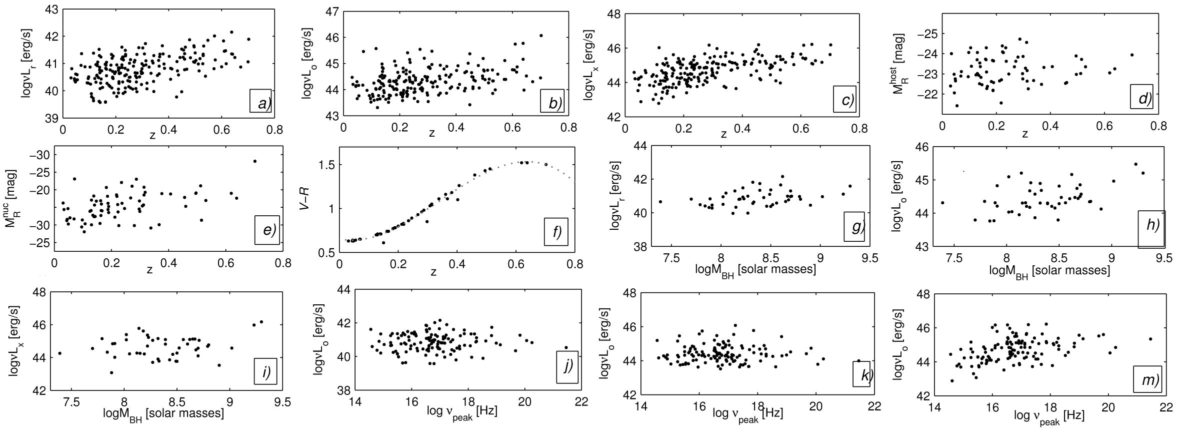

Fig. 2: Correlation between the different observational quantities of XBLs.

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