Unification of Blazars

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Blazars have been discovered mainly based on X-ray and radio surveys. While in the beginning of the Blazar research X-ray and radio selected Blazars seemed to belong to different classes of objects, it is now mainly believed that the differences are only due to different peak frequencies of their synchrotron and inverse Compton emission. This is shown in the dependency of several physical parameters (such as luminosity, spectral shape, and spectral energy distribution) to the synchrotron emission peak. It is also possible to explain the different evolutionary behaviour in a unified scheme. Finally, implications on the existence of ultra high frequency peaked BL Lac objects can be made. These objects have their synchrotron peak at frequencies higher than 100 keV and make them possible targets for observations in Gamma-rays. First encouraging results from studying a large and complete Blazar sample and from follow-up observations in the optical domain and with BeppoSAX will be presented.

1 Introduction

BL Lac objects are a rare type of Active Galactic Nuclei (AGN), which are observationally distinguished mainly by the absence of strong emission lines. They have strong X-ray and radio emission, and they often show strong variability and optical polarization. Their observational properties are usually explained by a particular line of sight toward the galaxy nucleus, which in BL Lacs is thought to be parallel to a jet emerging from this nucleus. Two search strategies are commonly used to find BL Lacs. The first is a search for strong X-ray sources with a high ratio of X-ray to optical flux, yielding X-ray selected BL Lacs (XBL). The second is to search among flat spectrum radio sources to find radio selected ones (RBL). As the radio and X-ray surveys got more and more sensitive, the properties of both groups started to overlap, raising the question of how they are related. Padovani & Giommi [13] noticed that the spectral energy distribution (quantified by $\log \nu L_\nu$) of radio and X-ray selected BL Lacs shows peaks at different frequencies, and suggested that this is the basic difference between the two classes of BL Lacs. They introduced the notation of *high-energy cutoff BL Lacs* (HBLs) and *low-energy cutoff BL Lacs* (LBLs). Most, but not all, XBLs are HBLs, while the group of LBLs is preferentially selected in the radio region. Unlike all other AGNs, and different from RBLs also, the space density or the luminosity of XBLs is increasing with time. This is called negative evolution. To study this effect we use the HRX-BL Lac sample presented here, which comprises 77 BL Lacs and is the largest complete XBL sample so far.

Recent models tried to explain the different evolutionary behaviour of HBLs and LBLs by assuming that BL Lacs start as LBLs and evolve into HBLs as they grow older. As described by Ghisellini [9] the spectral energy distributions (SED) of BL Lacs are characterized by two components, both consisting of beamed continuum emission from the plasma of the jets. The first component is synchrotron emission, peaking in the mm to far IR for LBLs. The second component is inverse Compton (IC) emission peaking at MeV energies. HBLs have SEDs peaking in the keV and in the GeV-TeV band respectively.

The HRX-BL Lac sample contributes to the discussion with a large and complete sample of X-ray selected BL Lac objects. This sample can also be used to determine candidates for the extreme high frequency peaked BL Lac objects (UHBL).

2 The HRX-BL Lac sample

The HRX-BL Lac sample is based on ROSAT X-ray sources. It has been shown that X-ray bright BL Lac objects are also radio sources; to the authors knowledge, all known BL Lac objects do have radio counterparts down to the ~ 2.5 mJy level. We concluded therefore that for the high X-ray count-rates used we can include radio detection in the NVSS (Condon et al.[7]) as selection criterium without loosing BL Lac objects. As X-ray input we used the ROSAT Bright Source Catalog (RASS-BSC; Voges et al.[16]) with a count-rate limit ($0.5 - 2.0\,\mathrm{keV}$) of $hcps \geq 0.09\,\mathrm{sec}^{-1}$. The selection was done on a sky area of $4768\,\mathrm{deg}^2$ on the northern hemisphere. The cross-correlation yielded 223 matches between X-ray and radio sources. These candidates were classified in a two-step process. First we searched for known optical counterparts in the NASA/IPAC Extragalactic Database (NED)and in the SIMBADdatabase. Special care was taken to avoid confusion of BL Bac objects with normal galaxies and other types of AGNs. For the remaining candidates follow-up observations were obtained.

Spectroscopic observations to classify the remaining BL Lac candidates and to determine their redshifts were made with the 3.5m telescope on Calar Alto and with the 4.2m WHT on La Palma. BL Lac objects by definition have no or very weak emission lines. Integration times of $\approx 1000 \ldots 2000\,\mathrm{sec}$ were needed to detect the weak absorption lines of the host galaxy, which is often out-shined by the non-thermal continuum of the point-like central synchrotron source.

The optical identification of the 223 BSC/NVSS objects leads to the following distribution of object classes within the radio/X-ray correlation: 35% are BL Lac objects, 36% are other AGNs (QSO, Seyfert 1/2, FSRQs), 11% galaxies (including starburst galaxies and LINERs), 13% cluster of galaxies, and 4% stars (including 2 supernova remnants). Only a fraction of 1% of the 223 candidates is yet not identified. In comparison to the EMSS BL Lac sample, this sample probes a population of objects with lower α_{RO} and α_{OX} values and contains therefore more radio quiet and stronger X-ray dominated objects. The HRX-BL Lac sample is the largest complete sample of X-ray selected BL Lac objects.

For studying the spectral energy distribution (SED), additional near infrared data from the Two-Micron All-Sky Survey (2MASS) were used, when available.

3 Spectral Energy Distribution

To study the spectral energy distribution (SED) of the HRX-BL Lac objects, overall spectral indices were calculated to derive general correlations within the sample. As reference frequencies we used 1.4 GHz in the radio ($\lambda \simeq 21\,\mathrm{cm}$), 4400 Å in the optical ($\sim B$), and $1\,\mathrm{keV}$ ($\lambda \simeq 12.4$ Å) in the X-ray region to derive the optical-X-ray α_{OX}, the radio-X-ray α_{RX}, and the radio-optical α_{RO} spectral index.

The HRX-BL Lac sample shows typical values for the mean overall spectral indices: $<\alpha_{OX}>= 0.94 \pm 0.23$, $<\alpha_{RX}>= 0.55 \pm 0.08$, $<\alpha_{RO}>= 0.37 \pm 0.09$. The center of the area covered by this sample is similar to that of the EMSS BL Lacs (see Padovani & Giommi[13]) though a larger range in α_{OX} and α_{RO} is covered.

Table 1: Correlation of luminosity with peak frequency in the HRX-BL Lac sample

region	r_{xy} Pearson coefficient	confidence level of correlation	linear regression[a]
radio (1.4 GHz)	-0.23	$> 97\%$	$\log L_R = -0.09 \cdot \log \nu_{\rm peak} + 26.4$
near IR (K-band)	-0.28	$> 95\%$	$\log L_K = -0.14 \cdot \log \nu_{\rm peak} + 25.9$
optical (B-band)	-0.37	$> 99.9\%$	$\log L_B = -0.13 \cdot \log \nu_{\rm peak} + 25.1$
X-ray (1 keV)	+0.51	$> 99.9\%$	$\log L_{\rm X} = +0.19 \cdot \log \nu_{\rm peak} + 17.3$
total (radio – X-ray)	-0.12		$\log L_{sync} = -0.04 \cdot \log \nu_{\rm peak} + 22.0$

[a] Luminosities in [W/Hz]

3.1 Peak frequency

In order to get a more physical description of the spectral energy distribution of the BL Lac objects, we used a simple model to fit the synchrotron branch of the BL Lac. This has the advantage of describing the SED with one parameter (the peak frequency) instead of a set of three parameters ($\alpha_{\rm OX}$, $\alpha_{\rm RO}$, and $\alpha_{\rm RX}$). It has been shown by several authors that the synchrotron branch of the BL Lac SED is well approximated by a parabolic fit in the $\log \nu - \log \nu f_\nu$ plane (cf. Fossati et al. [8]).

If only three data points were given (one in the radio, optical, and X-ray band), the parabola was definite. When more than three data points were available (i.e. the K, H, and J near infrared measurements from the 2MASS), a χ^2 minimization was used to determine best fit parameters. $\nu_{\rm peak}$ is sensitive for the f_x/f_{opt}-relation, and is therefore strongly correlated with $\alpha_{\rm OX}$.

The relation can be approximated by a polynomial of third degree. Thus the peak frequency can also be determined, in the case no radio data is available by applying

$$\log \nu_{\rm peak} = -11.0 \cdot \alpha_{\rm OX}^3 + 43.0 \cdot \alpha_{\rm OX}^2 - 58.3 \cdot \alpha_{\rm OX} + 42.1(\pm 0.54) \qquad (1)$$

3.2 Correlation of luminosities with the SED

A set of physical parameters which are correlated to the peak frequency are the luminosities in the different wavelength regions. While the luminosities L_R in the radio, L_K in the near infrared, and L_B in the optical region are decreasing with increasing peak frequency, the situation at X-ray energies is the other way round (as reported by Beckmann [3]).

The details about the correlation analysis are listed in Table 1, including the confidence level of the correlations. The total luminosity L_{sync} within the synchrotron branch has been derived by integrating the spectral energy distribution between the radio and the X-ray band. This is a reasonable approximation as long as the peak frequency is below 1 keV ($\log \nu = 17.4$), but systematically underestimates L_{sync} if the peak frequency is shifted beyond 1 keV.

The non-detection of the correlation between total luminosity and $\nu_{\rm peak}$ might be due to the fact that for a fraction of $\sim 20\%$ the redshift information is still missing and a redshift of z=0.3 was assumed. But, omitting these objects do not alter the results.

4 Distribution in space

Redshifts are available for 64 (83%) of the 77 BL Lac objects. Therefore it is possible to study the evolution by application of an $V_{\rm e}/V_{\rm a}$-test. The $V_{\rm e}/V_{\rm a}$-test is a simple method developed by Avni & Bahcall [1] based on the $V/V_{\rm max}$ test. $V_{\rm e}$ stands for the volume, which is enclosed by the object, and $V_{\rm a}$ is the accessible volume, in which the object could have been found (e.g. due to a

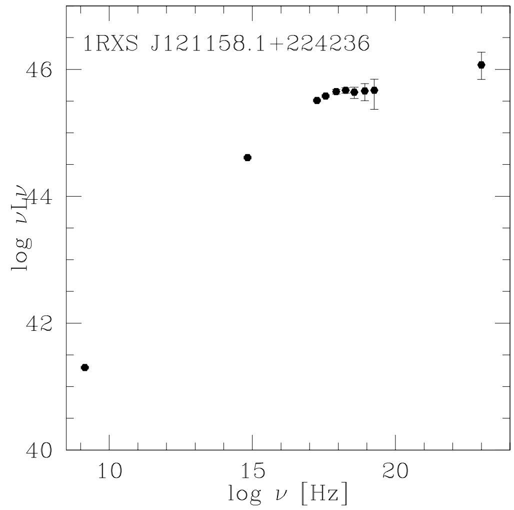

Figure 1: Spectral energy distribution of 1RXS J121158.1+224236 which is the possible counterpart of the unidentified EGRET source 3EG 1212+2304

flux limit of a survey). We computed the accessible volume $V_{a,i}$ for each object by applying the survey limits. In most cases this volume is determined by the X-ray flux limit, only $\sim$ 10% of the objects have a smaller $V_{a,i}$ for the radio data, due to the radio flux limit of 2.5 mJy. Applied to the HRX-BL Lac sample the test yields $\langle V_{\rm e}/V_{\rm a}\rangle = 0.42 \pm 0.04$. This result shows that HBLs have been less numerous and/or less luminous in the past, but the significance is only 2σ. The negative evolution of X-ray selected BL Lac objects has been reported several times before (e.g. for the EMSS sample), but is less significant for the HRX-BL Lac sample.

Thanks to the large number of objects with known redshifts within the HRX-BL Lac sample it is possible to examine dependencies of the evolution on other parameters, like the overall spectral indices. Dividing the HRX-BL Lac sample we get for the HBLs ($\alpha_{\rm OX} < 0.9$) $\langle V_{\rm e}/V_{\rm a}\rangle = 0.45 \pm 0.05$ (N=34) and for the IBLs $\langle V_{\rm e}/V_{\rm a}\rangle = 0.40 \pm 0.06$ (N=30). There seems to be no difference between the two groups as was reported by Bade et al. [2] and we are not able to confirm the different types of evolution for the HBLs and the IBLs.

5 Ultra high frequency peaked objects in the HRX-BL Lac sample

16 HBLs within the HRX-BL Lac sample show peak frequencies $\nu_{peak} > 10^{18}$ Hz from the parabolic fit to the synchrotron branch.even $\nu_{peak} > 10^{19}$ Hz. 1RXS J121158.1+224236 might even be a UHBL with a peak frequency of the synchrotron branch at $\nu_{peak} \simeq 10^{22}$ Hz. To confirm the high peak frequency for this extreme source, observations with the BeppoSAX satellite have been performed in January 2002. The combined LECS, MECS, and PDS spectrum can be well fitted with one single power law from 1 keV up to 100 keV, showing a spectral slope of $\Gamma \simeq 1.96 \pm 0.03$. This results in a still slightly rising synchrotron branch in the $\log \nu L_\nu$ vs. $\log \nu$ diagram, as shown in Figure 1. This object is even more interesting, as it could be the counterpart of the up to now unidentified EGRET source 3EG J1212+2304. Investigations in the gamma region ($\sim$ 1 MeV) are needed to decide whether these energies are dominated by the synchrotron emission or if already the inverse Compton branch is rising. The SPI spectrograph on-board the INTEGRAL mission will allow to do spectroscopy in this energy region (20 keV $-$ 8 MeV).

6 Discussion

The large number of objects included in the HRX-BL Lac sample enabled us to study in detail a number of BL Lac properties in different wavelength regions. In the following, we will discuss these properties with special emphasis on their compatibility with the most recent models trying to unify the HBL and LBL objects.

The concept to characterize the energy distributions of blazars and in particular of BL Lacs by a parabolic function seems to be quite successful to link samples selected by different techniques. In the case of the HRX BL Lac sample we find that the X-ray luminosity is correlated and the optical, radio, and probably the near-infrared luminosities are anti-correlated with peak frequency over eight decades in frequency. Quite a number of our BL Lacs have peak frequencies close to those typical for LBLs. We have therefore divided our sample into IBLs and HBLs to study the transition to the LBLs. The energy distributions of our intermediate BL Lacs, the IBLs, peak longwards the X-ray band and those of the HBLs shortwards up into the γ-ray region.

Sambruna et al. [15] found for blazars an increasing bolometric luminosity with decreasing peak frequency, e.g. a decrease of the luminosity from the radio selected to the X-ray selected objects. We found no correlation of the total luminosity L_{sync} attributed to the synchrotron branch with peak frequency among our X-ray selected sample, although many BL Lacs have as low peak frequencies as the RBLs of Sambruna et al.. These results do not need to be contradictory, instead it may suggest that the increase of the bolometric luminosity is mostly due to the luminosity contribution of the inverse Compton component. As has been shown by Ghisellini [9], the ratio between the emitted radiation in the IC and synchrotron branch as function of the peak frequency is relatively small for HBLs, while in LBLs the Compton emission makes up for most of the bolometric luminosity. We predict therefore that IBLs will have a stronger inverse Compton component than HBLs, and hence also their bolometric luminosity will be higher.

Beckmann et al. [5] showed that also the curvature and slope of the X-ray spectra are related to the peak frequency in a way that the higher peaked objects show flatter and less curved X-ray spectra. This can be explained by the fact that in HBLs the peak of the synchrotron branch falls in or near to the X-ray region. Thus the spectrum is flat and shows weak curvature.

We found negative evolution using the HRX-BL Lac sample, but we did not find differences in evolution, if we divide the sample by α_{OX} (or peak frequency). The $V_{\rm e}/V_{\rm a}$ values presented here are consistent (albeit higher) with the $\langle V_{\rm e}/V_{\rm a}\rangle = 0.36 \pm 0.05$ found for the EMSS BL Lacs by Wolter et al. [17], and are in good agreement with those of FR-I galaxies ($\langle V_{\rm e}/V_{\rm a}\rangle = 0.40 \pm 0.06$) within the 3CR sample. This supports the assumption that the FR-I galaxies build the parent population of BL Lac objects (see e.g. Padovani & Urry [12]).

In contrast to HBLs, the LBLs show weak or positive evolution ($\langle V_{\rm e}/V_{\rm a}\rangle = 0.61 \pm 0.05$) as shown for the 1Jy sample by Rector & Stocke [14]. Also FR-II radio galaxies, FSRQs, and "normal" quasars seem to be more numerous and/or luminous at cosmological distances than in the neighborhood, leaving the question for the reasons of the HBL/LBL evolutionary dichotomy of relevance also in future.

6.1 A unifying model for LBL and HBL

The different evolutionary behaviour of HBLs and LBLs is a challenge for all theories to unify both BL Lac types into one class. However, the existence of transition objects and the numerous similar properties of LBLs and HBLs make it plausible that both classes belong to the same parent population.

As described by Böttcher & Dermer [6] one way to unify both classes would be a transformation of LBLs into HBLs as the BL Lac objects grow older. BL Lacs would start as LBLs with jets of high energy densities. Strong cooling limits the electron energies leading to cutoff frequencies for the synchrotron component at optical wavelengths and for the IC component in the GeV energy range. This results in steep X-ray spectra with strong curvature (Beckmann et al. [5]).

When by the time the source of the jet gets less powerful the energy density within the jet decreases. The cooling efficiency decreases as well resulting in higher cutoff frequencies for HBLs. The shift of the cutoff frequencies to higher energies is therefore accompanied by decreasing bolometric luminosities, which is evident from the decrease of the luminosities in the radio, near IR and optical bands. Due to the increasing peak frequencies of the synchrotron branch more energy is released in the X-ray band and the X-ray luminosity increases quite in contrast to the luminosities at shorter frequencies. The X-ray spectra are correspondingly flatter and less curved than in the LBL state.

With decreasing jet power the emission from the BL Lac core gets less powerful compared to the host galaxy, making the light of the host galaxy more and more dominant and making the calcium break values increase to values close to those of non-active elliptical galaxies. Objects which do not fit into this scenario are doubtlessly the extremely luminous HBLs, like 1ES 1517+656 (Beckmann et al. [4]). These objects may be evidence for the need of orientation related parameters in addition to jet evolution, to unify the different blazar classes.

A transformation of the BL Lacs from LBLs to HBLs would result in a dominance of LBLs in the past, e.g. at cosmological distances, while at present in the local universe, when for most of the BL Lacs the jets have a lower energy density, the HBLs would be more numerous. It naturally explains the more positive evolution of LBLs compared to HBLs. The failure to find evolutionary differences among HBLs and IBLs may indicate either a still insufficient size of the HRX BL Lac sample to detect the intermediate character of IBLs also in evolution or a very rapid decrease of jet power during the transition from LBLs to IBLs in comparison to their later evolution.

The HRX-BL Lac sample could be the basis to study the extreme end of the HBL population, the ultra high frequency peaked BL Lac objects (UHBL). Sambruna et al. [15] argued that objects with cutoff frequencies higher than 10^{18} Hz would be detected only in hard X-ray surveys but should be faint at lower frequencies, which would make their discovery difficult. Nevertheless we found 16 promising candidates for UHBLs, from which one object could already be confirmed being an UHBL by applying a BeppoSAX observation.

References

1. Y. Avni and J.N. Bahcall, *ApJ* **235**, 694 (1980)
2. N. Bade, V. Beckmann, N.G. Douglas, et al., *A&A* **334**, 459 (1998)
3. V. Beckmann, 1999, in: PASPC Vol. 159, eds. L. O. Takalo, A. Silanpää
4. V. Beckmann, N. Bade, O. Wucknitz, *A&A* **352**, 395 (1999)
5. V. Beckmann, A. Wolter, A Celotti, et al., *A&A* **282**, 410 (2002)
6. M. Böttcher and C.D. Dermer, *ApJ* **564**, 86 (2002)
7. J.J. Condon, W.D. Cotton, E.W. Greisen, et al., *AJ* **115**, 1693 (1998)
8. G. Fossati, L. Maraschi, A. Celotti, et al., *MNRAS* **299**, 433 (1998)
9. G. Ghisellini, 1999, in: PASPC Vol. 159, eds. L. O. Takalo, A. Sillanpää, p. 311
10. L. Maraschi and F. Rovetti, *ApJ* **436**, 79 (1994)
11. M.J.M. Marchã, I.W.A. Browne, C.D. Impey, P.S. Smith, *MNRAS* **281**, 425 (1996)
12. P. Padovani and C.M. Urry, *ApJ* **356**, 75 (1990)
13. P. Padovani and P. Giommi, *ApJ* **444**, 567 (1995)
14. T.A. Rector and J.T. Stocke, *AJ* **122**, 565 (2001)
15. R.M. Sambruna, L. Maraschi, C.M. Urry, *ApJ* **463**, 444 (1996)
16. W. Voges, B. Aschenbach, Th. Boller, et al. *A&AS* **349**, 389 (1999)
17. A. Wolter, A. Caccianiga, R. Della Ceca, T. Maccacaro, *ApJ* **433**, 29 (1994)