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Ultra High Frequency Peaked BL Lac objects

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Abstract. The unification of the BL Lac sequence is based on the observation that the differences between radio and X-ray selected BL Lacs are due to different peak frequencies of their synchrotron and inverse Compton emission. Based on the large and complete HRX-BL Lac sample, dependencies of several physical parameters (such as luminosity, spectral shape, and spectral energy distribution) on the synchrotron emission peak are shown. 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 (UHBL) 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 UHBL candidates of the HRX-BL Lac sample and from follow-up observations in the optical domain and with BeppoSAX will be presented. One recently discovered UHBL is likely to be the counterpart of an unidentified EGRET source.

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 (1995) noticed that the spectral energy distribution (SED) 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.

As described by Ghisellini et al. (1998) 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. Based on the knowledge about the relations between the two components of the SED, this sample can be used to determine candidates for the extreme high frequency peaked BL Lac objects (UHBL). These BL Lac objects have their synchrotron peak at $\nu_{peak} \gtrsim 10^{19}$ Hz and the maximum of the inverse Compton branch in the TeV range. At present, only a few of these objects have been detected by Cherenkov telescopes (Catanese & Weekes 1999; Aharonian et al. 2002; Horns & Konopelko 2002). But recent studies have shown that it should br possible to detect more of them based on the connection between the synchrotron and inverse Compton emission (Costamante & Ghisellini 2002).

2. The HRX-BL Lac sample

The Hamburg/RASS X-ray Bright (HRX) BL Lac sample (Beckmann 2000) 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. 1998) as selection criterium without loosing BL Lac objects. As X-ray input we used the ROSAT Bright Source Catalog (Voges et al. 1999) 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 SIMBAD database. 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

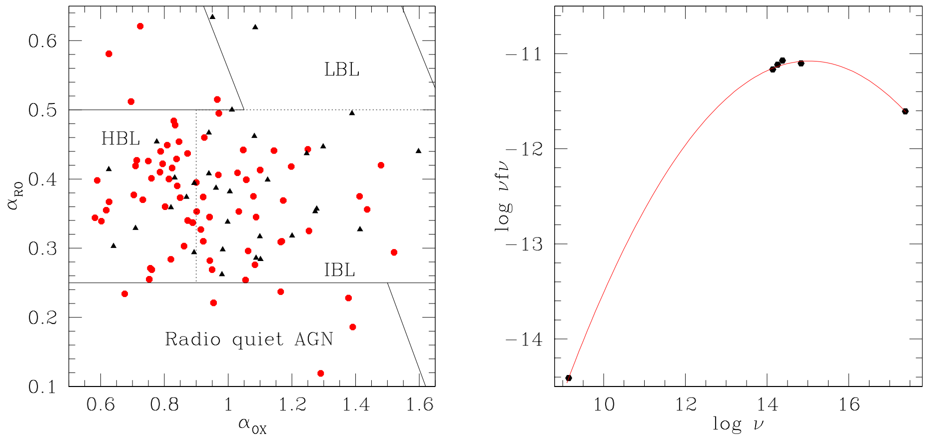

Figure 1. The $\alpha_{\rm OX} - \alpha_{\rm RO}$ plane covered by the HRX-BL Lac objects. The points refer to the *complete sample*, the triangles mark additional objects found within the course of the work. Objects with $\alpha_{\rm RO} < 0.2$ are called radio quiet.
Right panel: Parabolic fit to the data of B2 0912+29

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, 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. Ledden and O'Dell (1985) defined the overall spectral index between two frequencies:

$$\alpha_{1/2} = -\frac{\log(f_1/f_2)}{\log(\nu_1/\nu_2)} \tag{1}$$

Here f_1 and f_2 are the fluxes at two frequencies ν_1 and ν_2. As reference frequencies we used 1.4 GHz in the radio ($\lambda \simeq 21\,$cm), 4400 Å in the optical ($\sim B$), and 1 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: $<\alpha_{OX}>= 0.94 \pm 0.23$, $<\alpha_{RX}>= 0.55 \pm 0.08$, $<\alpha_{RO}>= 0.37 \pm 0.09$, if compared to Wolter et al. (1998), Laurent-Muehleisen et al. (1999), and Beckmann et al. (2002).

The region in the $\alpha_{\rm OX} - \alpha_{\rm RO}$ plane, which is covered by the HRX-BL Lac sample, is shown in the left panel of Figure 1. The center of the area covered by this sample is similar to that of the EMSS BL Lacs (see Padovani & Giommi 1995) though a larger range in $\alpha_{\rm OX}$ and $\alpha_{\rm RO}$ is covered.

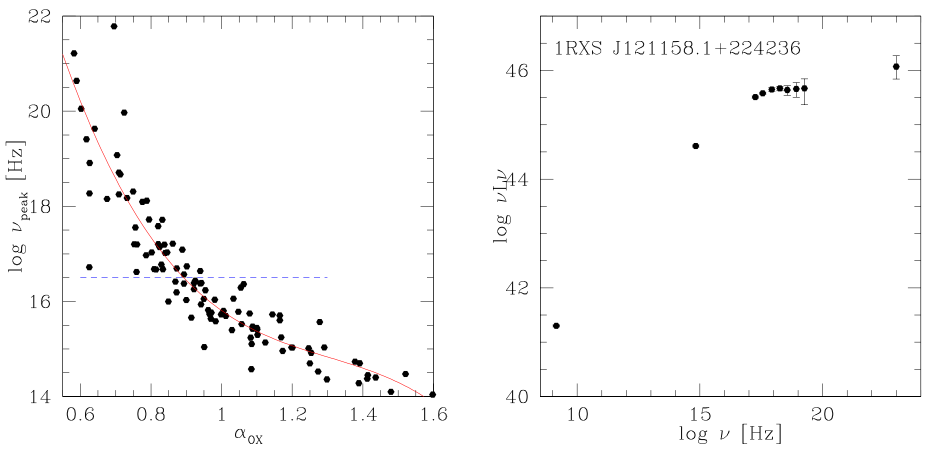

Figure 2. Left panel: Logarithm of the peak frequency vs. α_{OX}. The relation was approximated by a polynomial of third degree. The horizontal line marks the distinction between HBLs (above the line) and IBLs.
Right panel: Spectral energy distribution of 1RXS J121158.1+224236 which is the possible counterpart of the unidentified EGRET source 3EG J1212+2304. The SED shown here includes radio, B-band, X-ray, and γ-ray data.

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 (α_{OX}, α_{RO}, and α_{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. Landau et al. 1986, Sambruna et al. 1996, Fossati et al. 1998). In this way the peak position (ν_{peak}), the total luminosity and the total flux of the synchrotron emission can be derived. We chose the parameterization using fluxes $\log \nu f_\nu = a \cdot (\log \nu)^2 + b \cdot \log \nu + c$. Using luminosities instead of fluxes would change the absolute constant c only, leaving the position of the peak frequency unaffected.

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, a χ^2 minimization was used to determine best fit parameters. An example for a parabolic fit is shown in the right panel of Figure 1. ν_{peak} is sensitive for the f_x/f_{opt}-relation, and is therefore strongly correlated with α_{OX}. This is shown in the left panel of Figure 2. 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

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

This result is comparable to that found by Fossati et al. (1998) when studying the dependency of α_{RO} and α_{RX} on the peak frequency.

4. UHBL candidates

The knowledge about the correlation between the peak frequency in the synchrotron branch and the one of the inverse Compton emission can now be used to select candidates with extremely high peak frequencies from our sample. From the parabolic fit described in Section 3.1 we derived a peak frequency for all objects of the HRX-BL Lac sample. We then selected those objects which showed a peak frequency of $\nu_{\rm peak} > 10^{19}$ Hz (above 41 keV). This selection resulted in 8 UHBL candidates listed in Table 1.

Table 1. UHBL candidates within the HRX-BL Lac sample

Name	z	f_R[mJy]	B[mag]	f_X^a	α_X
1RXS J071030.0+590808	0.125	159	18.4	10.2	0.93
1RXS J091324.6+813318	0.639	4.9	20.7	2.3	0.65
1RXS J092804.2+744714	0.638	85.8	20.8	1.1	0.66^b
1RXS J100811.5+470526	0.343	4.7	19.9	4.4	0.93^b
1RXS J111131.2+345212	0.212	8.4	19.7	2.7	1.13
1RXS J121158.1+224236	0.455	20.2	19.6	2.6	0.96
1RXS J123705.6+302002	0.700	5.6	20.0	3.2	0.94
1RXS J145827.3+483250	0.539	3.1	20.4	2.7	0.88

^{a} PSPC flux $(0.5 - 2.0\,\mathrm{keV})$ in $[10^{-12}\mathrm{erg\,cm^{-2}\,sec^{-1}}]$

^{b} PSPC spectral slope derived from pointed observation

One object from this selection is the BL Lac 1RXS J121158.1+224236, which falls into the 95% confidence radius (53 arcmin) of the EGRET object 3EG1212+2304. The BL Lac could be the counterpart to the gamma-ray source. The redshift of the UHBL candidate is $z = 0.455$ as derived from absorption lines within the optical spectrum. Checking the NED we found 134 objects inside the 53 arcmin circle. Most of them (130) are normal galaxies which should not produce any detectable gamma-ray emission.

Other identifications included a compact group, a galaxy cluster, and an unidentified X-ray source. From these three objects only the unidentified X-ray source RX J1212+2232 could be a possible gamma-ray bright counterpart. The galaxy cluster and also the compact group could produce thermal X-ray emission up to a few keV but cannot be a relevant gamma-ray source.

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 the right panel of Figure 2.

5. Conclusions

It has been shown that by selecting high energy peaked BL Lac objects based on the information from radio to X-ray data, it is possible to effectively select candidates for Ultra High Frequency BL Lac objects (UHBL). Applying a BeppoSAX observation to one of the UHBL candidates showed that the hard X-ray spectrum was still slightly rising. Thus the peak frequency of the synchrotron branch of this object is at $\nu_{\rm peak} \gtrsim 10^{19}$ Hz. In case this object is the counterpart of the up to now unidentified EGRET source 3EG J1212+23, we expect the transition from the synchrotron to the inverse Compton branch in the $0.1 - 50\,\mathrm{MeV}$ region. Further investigations on this energy range are foreseen, i.e. by doing spectroscopy in the $30 - 8000\,\mathrm{keV}$ range using INTEGRAL/SPI (Jean et al. 2000, Beckmann 2002). Confirmed UHBL objects can then be targets for studies at highest energies, i.e. in the TeV range, as their inverse Compton branch will peak in this range. Unfortunately the TeV emission of 1RXS J121158.1+224236 ($z = 0.455$) will probably be suppressed by interaction with the extragalactic infrared background (Stecker et al. 1996).

References

Aharonian, F., Akhperjanian, A., Barrio, J., et al. 2002, A&A 384, L23

Beckmann, V. 2000, PhD thesis, Hamburg University, `http://www.sub.uni-hamburg.de/disse/330/vbdiss.html`

Beckmann, V., Wolter, A., Celotti, A., et al. 2002, A&A 383, 410

Beckmann, V. 2002, to appear in: proceedings of the XXII Moriond Astrophysics Meeting, eds. Goldwurm, Neumann, and Tran Thanh Van, `astro-ph/0206506`

Catanese, M., Weekes, T. C. 1999, PASP 111, 1193

Condon, J.J., Cotton, W. D., Greisen, E. W., et al. 1998, AJ 115, 1693

Costamante, L., Ghisellini, G. 2002, A&A 384, 56

Fossati, G., Maraschi, L., Celotti, A., et al. 1998, MNRAS 299, 433

Ghisellini, G., Celotti, A., Fossati, G., et al. 1998, MNRAS 301, 451

Horns, D., Konopelko, K. 2002, ATel 96, 1

Jean, P., Vedrenne, G., Schönfelder, V., et al. 2000, Proc. 5th Compton Symposium 510, 708

Landau, R., Golisch, B., Jones, T. J., et al. 1986, ApJ 308, 78

Laurent-Muehleisen, S. A., Kollgaard, R. I., Feigelson I. D., et al. 1999, ApJ 525, 127

Ledden, J. E., & O'Dell, S. L. 1985, ApJ 298, 630

Padovani, P., & Giommi, P. 1995, ApJ 444, 567

Sambruna, R. M., Maraschi, L., & Urry, C. M. 1996, ApJ 463, 444

Stecker, F. W., De Jager, O. C., & Salomon, M. H. 1996, ApJ 473, L75

Voges, W., Aschenbach, B., Boller, Th., et al. 1999, A&AS 349, 389

Wolter, A., Comastri, A., Ghisellini, G., et al. 1998, A&A 335, 899