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The ROSAT X-ray spectra of BL Lacertae objects

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ABSTRACT

We study the X-ray spectra of 85 BL Lacertae objects using the hardness ratios as given in the WGA catalogue of *ROSAT* sources. This sample includes all WGA BL Lacs with high-quality data and comprises about 50 per cent of presently known BL Lacs. We find that BL Lacs have energy power-law spectral indices between 0 and 3 with a mean value $\alpha_{\rm x} \sim 1.4$. Significant differences, however, are present between high-energy cutoff BL Lacs (HBLs), normally selected in the X-ray band, and low-energy cutoff BL Lacs (LBLs), generally found in radio surveys. HBLs have steeper X-ray spectral slopes ($\alpha_{\rm x} \sim 1.5$) well correlated with $\alpha_{\rm ox}$, and anti-correlated with the X-ray-to-radio flux ratio and cutoff frequency, with convex overall broad-band spectra. LBLs, on the other hand, have flatter X-ray spectra ($\alpha_{\rm x} \sim 1.1$) and concave optical-X-ray continuum. We interpret these results in terms of different mechanisms being responsible for the X-ray emission in the two classes, namely synchrotron and inverse Compton for HBLs and LBLs respectively. The observed differences are consistent with the hypothesis that HBLs and LBLs are powered by essentially the same non-thermal engines differing mainly in their synchrotron cutoff energy.

Key words: galaxies: active – BL Lacertae objects: general – X-rays: galaxies

1 INTRODUCTION

BL Lacertae objects constitute a relatively rare class of active galactic nuclei (AGN), distinguished by their almost complete lack of emission lines. At present, only about two hundred BL Lacs are known (Padovani & Giommi 1995b) as compared, for example, to the thousands of quasars listed in the most recent AGN catalogues (Véron-Cetty & Véron 1993; Hewitt & Burbidge 1993).

Despite their small numbers and other somewhat extreme and non-typical properties (radio core-dominance, superluminal motion, rapid variability, high polarization: e.g., Kollgaard 1994; Urry & Padovani 1995) BL Lacs are nevertheless an important AGN subgroup, as the broad-band emission in these objects is most likely completely dominated by non-thermal processes. Their multifrequency spectra are in fact fairly smooth over a wide frequency range, suggestive of a common emission process, and lack the thermal features characteristic of the other, more common, AGN, like dust emission in the infrared and (possibly) disk emission in the ultraviolet band (e.g., Bregman 1990).

Historically, BL Lacertae objects have been divided into RBLs (radio-selected BL Lacs) and XBLs (X-ray-selected BL Lacs), depending on the discovery band. The two classes showed in fact somewhat different properties, RBLs being more extreme, for example, in their optical polarization, core-dominance, and variability properties (e.g., Jannuzi, Smith & Elston 1994; Perlman & Stocke 1993). This division was clearly not satisfactory, as it was not based on intrinsic physical properties but solely on the selection band, and did not characterize uniquely a source. Recent all-sky X-ray surveys (Laurent-Muehleisen et al. 1993; Brinkmann et al. 1995; Perlman et al. 1995a), in fact, include many BL Lacs previously selected at radio frequencies, which could now then be classified both as XBLs or RBLs.

It has been known for some time (e.g., Ledden & O'Dell 1985) that the broad-band spectra of the two classes are also different (with the likely exception of the radio to millimetre band: Gear 1993). Recently, Giommi, Ansari & Micol (1995a) have studied the multifrequency spectrum of a large sample of BL Lacs, arguing that there may be only one population of objects, characterized by a wide range of energy cutoffs (or alternatively energy peaks in a νf_ν vs. ν plot): at infrared-optical energies for most RBLs, at ultraviolet/X-ray or higher energies for most XBLs, with the latter constituting only $\sim$ 10 per cent of all BL Lacs. The X-ray-to-radio flux ratios ($f_{\rm x}/f_{\rm r}$) for the two classes are also different, as a result of the different break frequencies. Note that within this hypothesis there is a continuum of cutoff energies, with different selection bands picking up objects with different spectra.

We (Giommi & Padovani 1994; Padovani & Giommi 1995a) have then proposed a division based on $f_{\rm x}/f_{\rm r}$ (as the break frequency at present can be derived directly from the spectra only for a small number of objects: see Sect. 3), classifying as HBLs (or high-energy cutoff BL Lacs) and LBLs (or low-energy cutoff BL Lacs) sources respectively above or below the value of $f_x/f_r \sim 10^{-11}$ (where X-ray fluxes cover the $0.3 - 3.5$ keV range and are in units of erg cm^{-2} s^{-1} and radio fluxes refer to 5 GHz and are expressed in janskys). We have also shown that the hypothesis that HBLs (that is, so far, most XBLs) are the minor component of the BL Lac population with high-energy cutoffs can explain most of their properties at least as well as the alternative (and more diffuse) explanation for the existence of two classes of BL Lacs, which posits that XBLs are intrinsically more numerous as they are viewed significantly off their beaming axis (e.g., Stocke et al. 1985; Maraschi et al. 1986; Padovani & Urry 1990).

A study of the puzzling distribution of BL Lacs on the $\alpha_{\rm ro}, \alpha_{\rm ox}$ plane (Padovani & Giommi 1995a) has led us to suggest that the observed bimodality can also be explained by an energy break ranging from high (X-ray) to low (far-infrared) energies for HBLs and LBLs respectively. This assumes a different origin of the X-ray emission for HBLs and LBLs: namely, an extension of the synchrotron emission likely responsible for the lower energy continuum in the former and inverse Compton (SSC: synchrotron self-Compton) emission in the latter. This would be consistent with the peak of the emitted power being at lower energies for LBLs, suggestive of an extra component taking over at higher frequencies (see Bregman 1990 and references therein). A crucial test of our hypothesis (and in general of any other model wishing to explain the existence of two BL Lac classes) is then the analysis of the spectral shape of the X-ray emission of a large sample of BL Lacs including both HBLs and LBLs. In the X-ray band, in fact, Compton emission is expected to be flatter than the synchrotron component (e.g., Ghisellini & Maraschi 1989).

The study of X-ray spectral indices of BL Lacs has given various and sometimes contradicting results, even considering only the most recent papers dealing with possible differences between the two classes (references to earlier papers can be found in Sambruna et al. 1994). Sambruna et al. (1994) have analyzed the EXOSAT spectra of 21 BL Lacs (only five of which were RBLs) and found similar spectral indices in the LE ($0.04 - 2.0$ keV) and ME ($1 - 20$ keV) bands for the two classes, with indications of a steepening at higher energies for XBLs. Ciliegi, Bassani & Caroli (1995) have studied the X-ray spectra of 42 BL Lacs (mostly RBLs) observed with various (pre-*ROSAT*) X-ray telescopes in different energy ranges and found that XBLs and RBLs have similar (within the rather large errors) spectral indices in the soft ($0.2 - 4$ keV) and possibly also in the hard ($2 - 10$ keV) band. However, there were indications that XBLs and RBLs have different global X-ray spectra, with the former and the latter steepening and flattening, respectively, at higher energies. Urry et al. (1996; see also Sambruna 1994) have examined more recent *ROSAT* spectral data for 32 out of the 34 radio-selected BL Lacs in the 1 Jy sample (Stickel et al. 1991). They find that 1 Jy RBLs have spectra similar to those of the *Einstein Observatory* Extended Medium Sensitivity Survey (EMSS) XBLs (Perlman et al. 1995b), with an indication for the subsample with *Einstein* IPC data of a flattening of the spectra at higher ($\gtrsim$ 1 keV) energies. Comastri, Molendi & Ghisellini (1995) analyzed the *ROSAT* spectra of twelve 1 Jy BL Lacs (i.e. a subsample of the objects studied by Urry et al. 1996) dividing the objects according to the X-ray-to-radio flux ratio, as proposed by Padovani & Giommi (1995a), with the result that the average spectrum of the (3) HBLs was steeper than that of the (9) LBLs. Urry et al. (1996) reached similar conclusions.

It is clear that at least some of the different results can be explained by poor statistics and the use of the RBL/XBL classification, which as we have discussed above is not physical. However, it is also probably true that the differences between the X-ray spectra of HBLs and LBLs are not that strong and require better statistics to be singled out.

The purpose of this paper is to analyze the X-ray spectra of all BL Lacs observed (as pointed or serendipitous sources) by *ROSAT* to check for any differences between HBLs and LBLs, coupling for the first time a large statistics with what we think is a meaningful distinction between the two classes. Our data have been taken from the WGA catalogue (White, Giommi & Angelini 1994), a large list of X-ray sources generated from all the *ROSAT* PSPC pointed observations, with which is now possible to study the X-ray properties of large numbers of objects in an homogeneous and relatively simple way. The selection of the objects was done by cross-correlating the first revision of the WGA catalogue (restricting ourselves to sources with quality flag ≥ 5, which excludes problematic detections) with our recent catalogue of BL Lacs (Padovani & Giommi 1995b). This produced 163 observations of 85 distinct BL Lacs (58 HBLs and 27 LBLs: see Sect. 2), which correspond to $\simeq 46$ per cent of confirmed BL Lacs presently known. This represents the largest number of BL Lacs for which homogeneous X-ray spectral information is available and the largest BL Lac sample ever studied at X-ray frequencies (cf. Ciliegi et al. 1993 who collected information on the spectra of 42 BL Lacs observed with various X-ray telescopes).

The structure of the paper is as follows: Section 2 describes the observational data and the data analysis, Section 3 studies the X-ray spectral properties of BL Lacs while Section 4 discusses our results and presents our conclusions. Throughout this paper spectral indices are written $f_\nu \propto \nu^{-\alpha}$.

2 DATA ANALYSIS

Spectral indices for the WGA BL Lacs were obtained from the count rates given in the catalogue in the $0.1 - 0.4$ keV range (soft band: S), $0.4 - 0.86$ keV range (mid band: M) and $0.87 - 2.0$ keV range (hard band: H) combined into hardness (HR) and softness (SR) ratios (see Giommi et al. 1995b). Briefly, the count rates were combined to construct one $SR = S/M$ and two HRs, $HR_1 = H/M$ and $HR_2 = H/(M + S)$. Initially we converted the hardness ratios into energy spectral indices both assuming Galactic $N_{\rm H}$ derived from 21 cm measurements (Stark et al. 1992; Shafer et al., private communication) and with $N_{\rm H}$ derived from the softness ratio through an iterative procedure. The spectral indices derived from the two approaches were found to be similar and well correlated in the $0.4 - 2.0$ keV range, while considerable scatter was present when the total *ROSAT* band was considered, with a sizeable number of objects having $\alpha_{\rm x,NH}$ significantly different from $\alpha_{\rm x,Galactic\ NH}$, suggestive of a change of the spectrum at lower energies. In this paper we will adopt as X-ray spectral index the value obtained with $N_{\rm H}$ fixed to the Galactic value, which is better determined than the $N_{\rm H}$ derived from the softness ratios, and in the $0.4-2.0$ keV range, i.e. the mid to hard band (spectral indices in the whole *ROSAT* range were used for the comparison between the values obtained with our method and those derived by other authors from detailed spectral fits: see below).

The choice of this energy range stems from two facts: first, our method *assumes* a single power-law; given the evidence of a change of spectral shape at lower energies in some sources, as described above (see also Comastri et al. 1995 and Urry et al. 1996), this assumption might be incorrect in the whole *ROSAT* range while it is probably more acceptable in the narrower $0.4-2.0$ keV range (as shown by the similarity of the spectral indices obtained with Galactic $N_{\rm H}$ and $N_{\rm H}$ derived from the softness ratio); second, the method used in the WGA catalogue to estimate the source intensity uses the counts detected in a box whose size optimises the signal to noise (S/N) ratio. This size is calculated assuming an average point spread function (PSF) that is too sharp for very soft photons. For weak sources near the field center the "optimum" box size is small and consequently includes a small, energy-dependent, fraction of the source photons causing an underestimation of the counts in the soft band. The effects of the dependence of energy response with off-axis angle have been taken into account using different conversion matrices in five different off-axis ranges: $0-20$, $20-30$, $30-40$, $40-50$, and $50-60$ arcminutes.

Errors on the spectral indices (1σ) were derived from the uncertainties on the hardness ratios. We included in our analysis only observations with values of hardness ratios relative to their uncertainties > 3.5, which corresponds roughly to 1σ errors on $\alpha_{\rm x} \lesssim 0.5$ (Giommi et al. 1995b). All objects in this study are "bona fide" BL Lacs: we excluded eight sources classified as uncertain BL Lacs or BL Lac candidates (Padovani & Giommi 1995b). We are then left with 163 observations of 85 BL Lacs.

Figure 1 compares the X-ray energy spectral indices derived from our method in the whole *ROSAT* band (i.e. obtained from HR_2) with those obtained by other authors (Perlman et al. 1995b; Maraschi et al. 1995; Urry et al. 1996) through a detailed spectral fitting procedure, using the same *ROSAT* data for 44 BL Lacs. The comparison is between spectral indices derived under the same assumption regarding the absorbing column density, i.e. either assuming Galactic $N_{\rm H}$ (Stark et al. 1992; Shafer et al., private communication) or with $N_{\rm H}$ derived from the softness ratio. Figure 1 shows that most objects cluster around the line $\alpha_{\rm x,hr} = \alpha_{\rm x,fit}$ with a linear relationship between the spectral indices derived with the two methods. Overall the agreement is then very good, especially considering the underestimate of soft photons in the WGA data. The mean values for the two derivations are $\alpha_{\rm x,hr} = 1.18 \pm 0.08$ and $\alpha_{\rm x,fit} = 1.24 \pm 0.08$ (here and in the following we give the error of the mean), which clearly indicates the statistical robustness of our approach.

A few sources in the PSPC field of famous objects have many X-ray observations: for example, 1E 1415+2557 (in the field of NGC 5548) has been observed in 29 different occasions! Inclusion of all these data in statistical studies (means, correlations, Kolmogorov-Smirnov [KS] tests etc.) would clearly bias them: the resulting mean, for example, would represent more the typical X-ray spectrum of 1E 1415+2557 than that of BL Lacs as a class. Therefore, although we plot in the figures all the 163 X-ray spectral indices, in all statistical tests we have kept only one observation (and therefore one spectral index) per object, selected on a one-to-one basis taking the best combination of offset from the field center and S/N ratio. When more than two observations with comparable offset and S/N ratios were available, we selected as most representative the one with $\alpha_{\rm x}$ nearest to the mean value for that source.

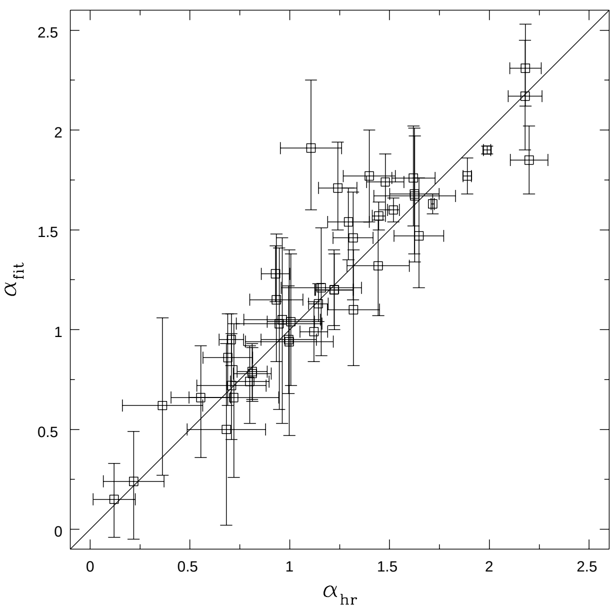

Figure 1. *ROSAT* band energy spectral indices of BL Lacs derived from our approach based on the hardness ratios, $\alpha_{\rm hr}$, compared to the values obtained by other authors from a detailed spectral fitting procedure of the same *ROSAT* data, $\alpha_{\rm fit}$. The solid line indicates the locus of points with $\alpha_{\rm hr} = \alpha_{\rm fit}$. Error bars represent 1σ errors for our values and 90 per cent errors for those obtained by other authors.

3 THE X-RAY SPECTRA

3.1 $\alpha_{\rm x}$ versus $f_{\rm x}/f_{\rm r}$

The main purpose of this paper is to study the X-ray spectral indices of HBLs and LBLs. To this aim, it is important to define the value of the $f_{\rm x}/f_{\rm r}$ ratio which divides the two classes. (We prefer the use of broad-band X-ray fluxes in the X-ray-to-radio flux ratios instead of, for example, 1 keV fluxes, because the latter are more dependent on the precise value of $\alpha_{\rm x}$ and therefore require spectral fitting, which is at present not possible for all BL Lacs.) In Padovani & Giommi (1995a), based on the energy distributions given by Giommi et al. (1995a), we suggested a ratio $f_{\rm x}/f_{\rm r} \sim 10^{-11}$. It should be noted, though, that very few BL Lacs in the compilation by Giommi et al. (1995a) had $10^{-11.5} \lesssim f_{\rm x}/f_{\rm r} \lesssim 10^{-10.5}$, because this intermediate zone is not favoured either by radio or X-ray selection and is therefore poorly populated both in X-ray and radio surveys. The dividing $f_{\rm x}/f_{\rm r}$ value was then not well determined.

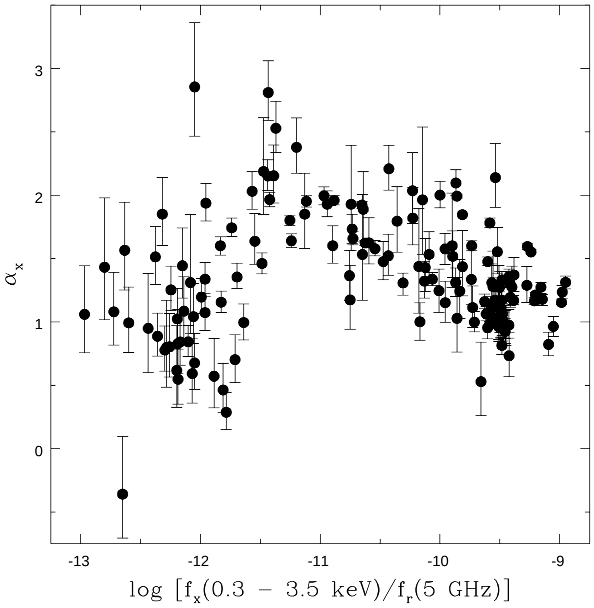

Figure 2. The X-ray spectral index of BL Lacs versus their X-ray-to-radio flux ratio (with X-ray fluxes in the 0.3 – 3.5 keV range in units of erg cm^{-2} s^{-1} and radio fluxes at 5 GHz expressed in janskys). Error bars represent 1σ errors.

In Fig. 2 we plot α_x versus f_x/f_r for all the objects in our sample, with radio data from Padovani & Giommi (1995b and references therein) and X-ray fluxes in the 0.3 – 3.5 keV band derived from the Galactic N_H and α_x values. (Ideally the radio and X-ray observations should be simultaneous; although variability in the radio is not very strong, this undoubtedly introduces some "noise" in our plots.) Within our hypothesis on the difference between HBLs and LBLs (Padovani & Giommi 1995a), described in the Introduction, the X-ray emission of HBLs should be dominated by synchrotron emission. HBLs near the transition region, in which the break is just below the X-ray band and where we see the steep tail of the synchrotron emission but not yet the inverse Compton component, should then be characterized by the steepest X-ray spectra (see also Sect. 3.3). Figure 2 shows this to happen for $10^{-11.5} \lesssim f_x/f_r \lesssim 10^{-11}$, where all objects have $\alpha_x \gtrsim 1.5$ and reach values up to ~ 3. A better dividing line between the two classes is then $f_x/f_r \sim 10^{-11.5}$, which is the value at which there is a *discontinuity* in α_x. We stress that our results (and those obtained in Padovani & Giommi 1995a) are unaffected by the precise value of this parameter. (One object has $\alpha_x \sim 3$ but $f_x/f_r \sim 10^{-12}$. This is 1WGA J1202.1+444, which appears three times in the WGA catalogue and only in its faintest state crosses the HBL/LBL boundary to become an LBL with an unusually steep X-ray spectrum, albeit with large errors, following the $\alpha_x - f_x$ anti-correlation normally observed in HBLs [e.g., Giommi et al. 1990; Sambruna et al. 1994]. We note however that a decrease in radio flux by a factor of $2-3$ as compared to the value we used, which we cannot rule out, would have kept this object within the HBL limits.)

The mean value of the X-ray spectral index for the 85 BL Lacs under study is $\langle\alpha_x\rangle = 1.37 \pm 0.05$. Figure 2, however, already shows that the X-ray spectral indices of the 58 HBLs (BL Lacs with $f_x/f_r \geq 10^{-11.5}$) are *steeper* than those of the 27 LBLs (BL Lacs with $f_x/f_r < 10^{-11.5}$). In fact, $\langle\alpha_{x,\mathrm{HBL}}\rangle = 1.52 \pm 0.06$ while $\langle\alpha_{x,\mathrm{LBL}}\rangle = 1.06 \pm 0.09$, different at the 99.99 per cent level according to a Student's t-test. The two α_x distributions, shown in Fig. 3, are also different at the 99.9 per cent level according to a KS test. (Had the dividing line been drawn at the value $f_x/f_r = 10^{-11}$, against the evidence presented in Fig. 2, one would have found $\langle\alpha_{x,\mathrm{HBL}}\rangle = 1.43 \pm 0.05$ and $\langle\alpha_{x,\mathrm{LBL}}\rangle = 1.27 \pm 0.11$, with the two distributions different at the 95.4 per cent level according to a KS test.)

Another notable feature of Fig. 2 is the anti-correlation between α_x and f_x/f_r for HBLs, significant at the 99.99 per cent level (Spearman rank-order test), independently of the precise value of the dividing f_x/f_r ratio, and not present in LBLs. A linear fit to the HBL data gives $\alpha_x = -(0.41 \pm 0.07)\log(f_x/f_r) - (2.65 \pm 0.66)$. In HBLs, in other words, the smaller the X-ray to radio flux ratio, (i.e., the steeper the effective radio-X-ray spectral index), the steeper is the X-ray spectral index, which points to a connection between the radio and X-ray bands and/or to the effects of a break in the energy distribution (see Sect. 3.3).

3.2 α_x versus α_{ox}

A similar and related connection for HBLs exists between the optical and X-ray bands. Figure 4 plots the X-ray spectral slope versus α_{ox}, the effective optical-X-ray spectral index evaluated between the rest-frame frequencies of 5000 Å and 1 keV. Optical fluxes were derived from the V magnitudes collected by Padovani & Giommi (1995b), correcting for Galactic absorption following Giommi et al. (1995a), while 1 keV fluxes have been obtained from the *ROSAT* counts and the derived spectral indices and have also been corrected for Galactic absorption. The k-correction has been derived assuming an optical index $\alpha_o = 1.05$ for LBLs and $\alpha_o = 0.65$ for HBLs (Falomo, Scarpa & Bersanelli 1994). For k-correction purposes objects with no redshift have been assigned the mean redshift of the corresponding sub-sample, i.e. $z_{\mathrm{mean,LBL}} = 0.60$ and $z_{\mathrm{mean,HBL}} = 0.25$. Note that optical fluxes are not simultaneous with X-ray data (although for most of the 1 Jy BL Lacs in our sample they should be representative of their "typical" optical state: see Padovani & Giommi 1995b), which will certainly introduce a scatter: a variation ΔV in magnitude, in fact, translates into a change $\Delta\alpha_{ox} = 0.15\Delta V$.

From the data presented in Fig. 4 we infer that: 1. for HBLs the X-ray spectral index is correlated with α_{ox} at the 99.99 per cent level (Spearman rank-order test) with a best fit $\alpha_x = (1.38 \pm 0.20)\alpha_{ox} - (0.01 \pm 0.22)$; 2. no correlation is present for LBLs; 3. the two classes separate extremely well on this plane, that is all HBLs apart from one have $\alpha_x \geq \alpha_{ox}$ (within the errors), while the majority of LBLs have $\alpha_x < \alpha_{ox}$.

This separation is better appreciated in Fig. 5, which plots $\alpha_x - \alpha_{ox}$ versus f_x/f_r. This plane can be divided into four quadrants, out of which one is basically unpopulated and another one is only marginally populated. The remaining ones are the HBL–convex-spectrum quadrant ($f_x/f_r \geq 10^{-11.5}$ and $\alpha_x > \alpha_{ox}$) and the LBL–concave-spectrum quadrant ($f_x/f_r < 10^{-11.5}$ and $\alpha_x < \alpha_{ox}$). The only HBL with possibly concave spectrum is MS0122.1+0903,

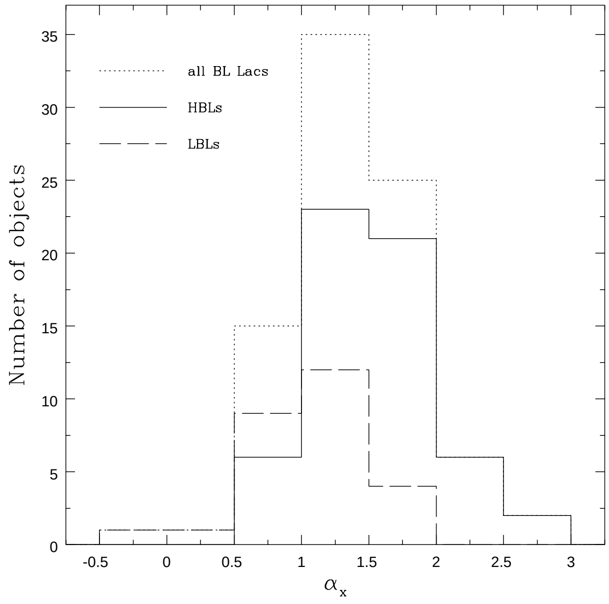

Figure 3. The X-ray spectral index distribution of all BL Lacs in our sample (dotted line), and of HBLs ($f_x/f_r \geq 10^{-11.5}$: solid line) and LBLs ($f_x/f_r < 10^{-11.5}$: dashed line) separately. Only one X-ray spectrum per object is used, as described in Sect. 2. The distributions of HBLs and LBLs are different at the 99.9 per cent level according to a KS test.

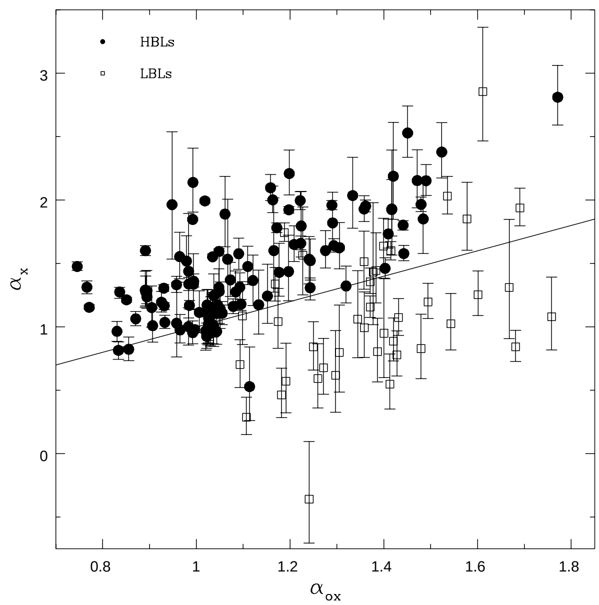

Figure 4. The X-ray spectral index versus α_{ox} for BL Lacs. Filled points indicate HBLs ($f_x/f_r \geq 10^{-11.5}$), while open squares indicate LBLs ($f_x/f_r < 10^{-11.5}$). The solid line represents the locus of points having $\alpha_x = \alpha_{ox}$. Error bars represent 1σ errors.

which is however consistent with having $\alpha_x > \alpha_{ox}$ at the $\sim 2\sigma$ level, especially considering that errors on $\alpha_x - \alpha_{ox}$ do not include errors on α_{ox}. As regards the twelve LBL spectra with possibly convex optical-X-ray continuum, only four of them have $\alpha_x > \alpha_{ox}$ at the $\gtrsim 2\sigma$ level. These correspond to four different objects: one is 1WGA J1202.1+444, discussed above, while the other three have f_x/f_r values within a factor of two of the HBL/LBL dividing line, which, as far as we know, could have well been crossed had there been a decrease in radio flux by a factor of 2 (compared to the values we used) at the time of the *ROSAT* observation.

The difference between HBLs and LBLs in $\langle \alpha_x - \alpha_{ox} \rangle$ is striking, this parameter being equal to 0.40 ± 0.04 for HBLs and -0.33 ± 0.09 for LBLs (0.17 ± 0.06 for the whole sample). This is simply an amplification of the different X-ray and effective optical-X-ray spectral indices. While, as we have seen, HBLs have α_x steeper than LBLs, the opposite is true as regards α_{ox} (see Fig. 4), for which $\langle \alpha_{ox,HBL} \rangle = 1.11 \pm 0.03$ and $\langle \alpha_{ox,LBL} \rangle = 1.39 \pm 0.03$.

Sambruna (1994; see also Maraschi et al. 1995) has found a significant difference between the $\alpha_{ox} - \alpha_x$ distributions of 1 Jy RBLs and EMSS XBLs, with mean values, however, apparently less different than ours. This difference can be explained by her smaller statistics and inclusion of three 1 Jy HBLs with the RBL sample.

Perlman et al. (1995b) have compared the *ROSAT* X-ray spectral indices of 22 EMSS BL Lacs (all HBLs) to the slope of the tangent at 1 keV to a parabola fitted to the radio, optical, and X-ray fluxes. They find that the X-ray spectra have similar or slightly steeper slopes than the tangent slope in most cases, a somewhat different result from ours. This might be due to our larger sample and also to their use of the tangent slope instead of the effective optical-X-ray index. Brunner et al. (1994) have studied the *ROSAT* spectra of five 1 Jy BL Lacs and derived a mean value for $\alpha_x - \alpha_{ox}$ consistent with zero, unlike our result for LBLs. Despite their small statistics, exclusion of the HBL object in their sample (S5 0716 + 714), which has the largest value of $\alpha_x - \alpha_{ox}$, makes their mean value consistent with ours.

3.3 α_x versus ν_{break}

The anti-correlation between α_x and f_x/f_r and the correlation between α_x and α_{ox} for HBLs are both related to what we think is the most interesting correlation, that between α_x and ν_{break}.

In theory, one should infer the break frequency ν_{break} from the observed energy distribution of the objects. In practice, however, the available spectral coverage is far from complete and the measurements are generally non-simultaneous. In particular, far-ultraviolet and far-infrared data are missing for the large majority of the sources, and these are the bands where the peak of the emission is most likely located for HBLs and LBLs respectively (Giommi et al. 1995a). The break frequency has then been derived as follows: Padovani & Giommi (1995a), using a triple power-law approximation to the spectra, have shown that the distribution of BL Lacs on the α_{ro}, α_{ox} plane (where α_{ro} is the effective radio-optical spectral index evaluated between the rest-frame frequencies of 5 GHz and 5000 Å) can be easily explained by an energy break migrating from high (X-ray) to low (far-infrared) energies (see their Fig. 12). Here we use their results to infer ν_{break} from the α_{ro} and α_{ox} values. The former were derived from the radio and optical data collected by Padovani & Giommi (1995a), using optical indices and mean redshifts (when necessary) as described above. As regards the radio spectral index, necessary for the k-correction of α_{ro}, for the

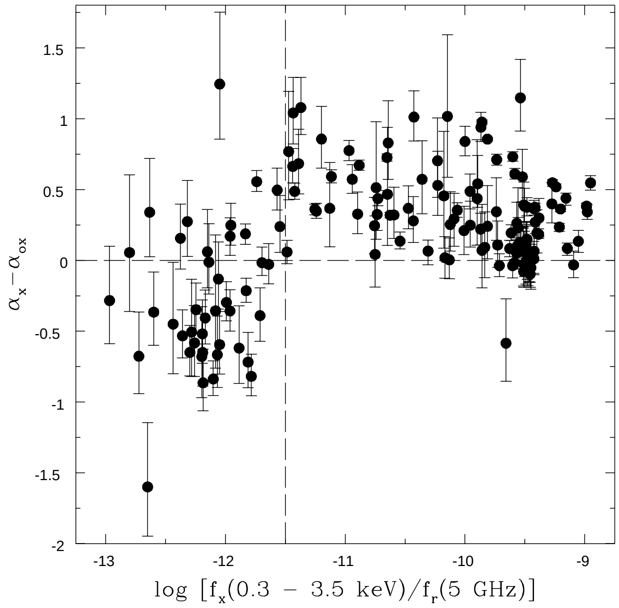

Figure 5. α_x minus α_{ox} versus f_x/f_r for BL Lacs. The horizontal dashed line represents the locus of points with $\alpha_x = \alpha_{ox}$, while the vertical dashed line represents the dividing line between LBLs and HBLs at $f_x/f_r = 10^{-11.5}$. Error bars represent 1σ errors and include *only* the uncertainties on α_x.

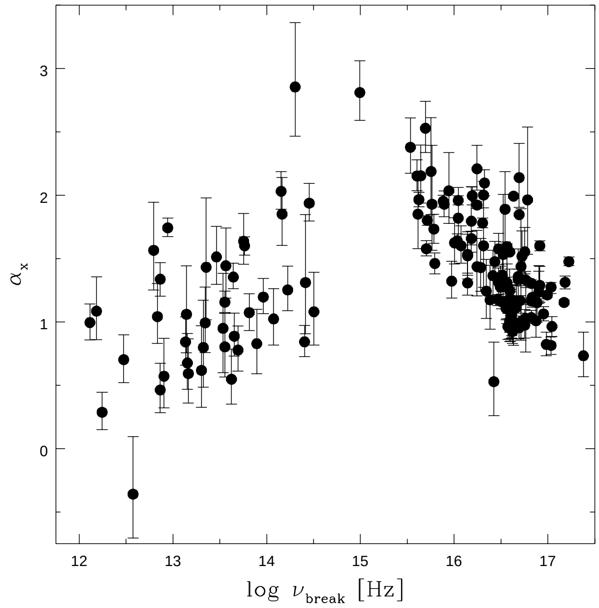

Figure 6. The X-ray spectral index versus the logarithm of the break frequency for BL Lacs. Objects with $\nu_{break} \gtrsim 10^{15}$ Hz have $f_x/f_r > 10^{-11.5}$ and are, by definition, HBLs, while the remaining objects are LBLs. Error bars represent 1σ errors. See text for the derivation of ν_{break}.

BL Lacs lacking this parameter it was assumed equal to the mean value for the two sub-classes, that is $\alpha_r = 0.2$ for HBLs and $\alpha_r = -0.2$ for LBLs.

Operationally, we projected the points on the α_{ro}, α_{ox} plane on the predicted relationship between the two parameters derived by Padovani & Giommi (1995a), namely on that of HBLs for $f_x/f_r \geq 10^{-11.5}$ and on that of LBLs for $f_x/f_r < 10^{-11.5}$ (see Fig. 12 of Padovani & Giommi 1995a). We then read off the corresponding values of the break frequency. Although this method gives only an approximate estimate of ν_{break}, the values derived this way agree well with those inferred from an inspection of the plots, for example, in Giommi et al. (1995a) for the (few) objects with enough data to permit a direct determination of the break. Moreover, our values are typically consistent within ~ 0.2 dex with the peak frequencies obtained by Comastri et al. (1995) from polynomial fits to the broad band spectra of twelve 1 Jy BL Lacs.

Figure 6 clearly shows the strong anti-correlation (significant at the 99.99 per cent level: Spearman rank-order test) between X-ray spectral index and break frequency for HBLs. A linear fit gives $\alpha_x = -(0.63 \pm 0.09) \log \nu_{break} + (11.87 \pm 1.50)$: i.e., the highest ν_{break}, the flattest α_x. As regards LBLs, here the situation is not clear: a fit to the "compressed" data as done for all the correlations studied in this paper (i.e., using only one spectrum per object, selected as described in Sect. 2) gives no correlation between α_x and ν_{break} for the 27 LBLs (Pcorr $\simeq 61$ per cent). However, Fig. 6 shows an apparent positive correlation between the two parameters ($\alpha_x \propto 0.41 \log \nu_{break}$) when all (42) spectra are included, significant at the 99.6 per cent level (Spearman rank-order test; this reduces to 98.2 per cent, with $\alpha_x \propto 0.26 \log \nu_{break}$, if one excludes the two outliers with the largest and smallest spectral index). This might suggest that LBLs display a (weak) positive correlation, possibly diluted by the relatively small statistics and larger error bars (the LBL sample is less than half the size the HBL one and on average the LBLs studied in this work are weaker X-ray sources than HBLs).

3.4 Interpretation

The negative correlation between α_x and ν_{break} observed for HBLs is expected if the emission of these objects is due to the synchrotron process all the way up to the X-ray band, as shown in Fig. 7: when the break is near the X-ray band ($\sim 10^{17}$ Hz: dotted line) the X-ray spectrum will be relatively flat, but as soon as the peak shifts to lower energies ($\sim 10^{16}$ Hz: dashed line) the steep tail of the synchrotron emission moves in. When ν_{break} is at much lower energies (e.g., $\sim 10^{14}$ Hz: solid line) so that the synchrotron component is no more dominant, Compton emission starts to be important: at this point one has crossed the HBL/LBL dividing line. For even smaller break frequencies, two effects compete: first, the smaller ν_{break}, the smaller is the product $B\gamma^2_{max,e}$, where B is the magnetic field and $\gamma_{max,e}$ is the maximum Lorentz factor of the electrons (e.g., Rybicki & Lightman 1979); this should not affect the lower energies, thereby leaving unchanged the shape of the Compton component; second, a lower ν_{break} means a weaker steep X-ray synchrotron component, which should result in a flatter spectrum in objects with still a non-negligible synchrotron emission. The sum of the two effects is not easy to quantify but the fact that in LBLs the X-ray spectral index is not strongly dependent on ν_{break} suggests that the Compton component might dominate completely the X-ray band in at least some objects.

This ties in nicely with the study of the $\alpha_{\rm ox}$ index, which shows that the X-ray band connects smoothly to the optical one in HBLs, with a steepening of the broad-band spectrum, supporting a common emission mechanism for the two bands, while in the great majority of LBLs $\alpha_{\rm x}$ is flatter than $\alpha_{\rm ox}$, indicative of a different component entering the X-ray range. Also, the anti-correlation between $\alpha_{\rm x}$ and $f_{\rm x}/f_{\rm r}$ in HBLs is simply related to that between $\alpha_{\rm x}$ and $\nu_{\rm break}$ as objects with larger $\nu_{\rm break}$ have also larger values of $f_{\rm x}/f_{\rm r}$.

In objects with very low break frequencies, for which the X-ray emission should be pure inverse Compton, the X-ray spectral indices should be similar to those in the radio–far-infrared region, obviously up to $\nu \lesssim \nu_{\rm break}$. Unfortunately, very few BL Lacs have been detected by *IRAS* so the statistics is quite poor: we find that the 5 GHz – 60μ spectral index for about ten 1 Jy BL Lacs is $\alpha_{\rm ri} \sim 0.3$ (see also Giommi et al. 1995a), which roughly corresponds to the lower bound of $\alpha_{\rm x}$ for LBLs. Clearly a detailed study of the far infrared spectra of LBLs would be extremely valuable in this respect: this project will be carried out with *ISO*.

We predict that the observed anti-correlation between $\alpha_{\rm x}$ and $\nu_{\rm break}$ observed for HBLs cannot continue indefinitely. Since the synchrotron spectrum steepens with frequency (e.g., Ghisellini & Maraschi 1989), if $\nu_{\rm break}$ moves to larger and larger values, the X-ray spectral index at minimum will be as flat as the effective radio-optical spectral index $\alpha_{\rm ro}$. In that case, then, one will have $\alpha_{\rm x} \sim \alpha_{\rm ox} \sim \alpha_{\rm ro} \sim 0.3 - 0.5$, the typical values for HBLs. Extrapolating the observed anti-correlation, one should find $\alpha_{\rm x} \sim 0.4 \sim$ constant for $\nu_{\rm break} \gtrsim 10$ keV. As this requires very high electron energies, it is not surprising that no BL Lac in our sample has such a high $\nu_{\rm break}$. If such objects exist they are probably quite rare but should be detected by future hard-X-ray missions.

We note that the paucity of objects with break frequencies in the optical/ultraviolet band ($\sim 10^{14.5} - 10^{15.5}$ Hz) is simply a selection effect, as these objects have intermediate values of $f_{\rm x}/f_{\rm r}$ which make them difficult to detect both in radio and X-ray surveys. Optical surveys, which in principle do not discriminate against this sort of objects, are at present very inefficient (e.g., Green, Schmidt & Liebert 1986; Jannuzi, Green & French 1993) and have so far led to the selection of only about ten BL Lacs (Padovani & Giommi 1995b).

4 DISCUSSION AND CONCLUSIONS

The data presented in this paper allow us to draw a consistent picture of HBLs and LBLs. Namely, the correlations of the X-ray spectral indices with $\alpha_{\rm ox}$, $f_{\rm x}/f_{\rm r}$, and break frequency all point to a common, likely synchrotron, origin for the radio/optical/X-ray emission in HBLs, with an overall convex spectrum. On the other hand, as hinted by the lower cutoff energies, in LBLs a second, harder, most likely inverse Compton, component appears in the X-ray band. The *ROSAT* spectral indices of the two classes are different, with HBLs displaying on average steeper spectra which show a strong anti-correlation with break frequency, while LBL spectra might show a *positive* dependence on this parameter. These are yet other differences between the two BL Lac classes, which add to the previously known ones, and might be helpful in selecting BL Lac candidates from the WGA catalogue, for example.

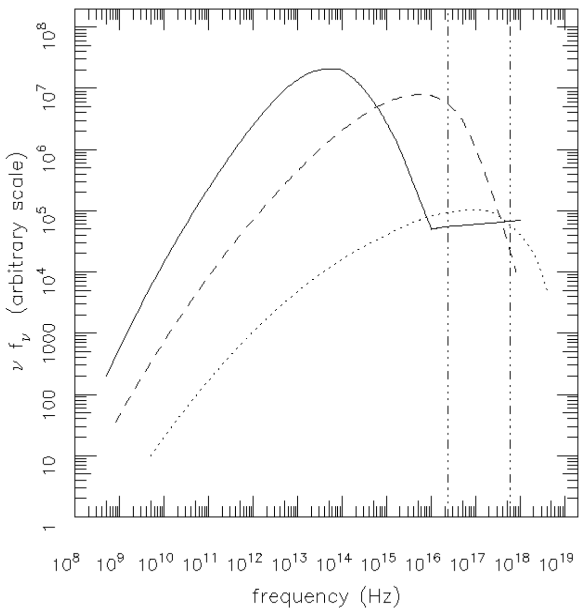

Figure 7. Examples of multifrequency spectra of BL Lacs with different peak (or break) frequencies: $\sim 10^{17}$ Hz (~ 0.4 keV: dotted line), $\sim 10^{16}$ Hz (dashed line), $\sim 10^{14}$ Hz (solid line). The two parallel (dot-dashed) lines represent the *ROSAT* band. Note how the X-ray spectrum steepens with decreasing break frequency until Compton emission becomes the dominant process. The normalizations of the different curves have been chosen to best illustrate the spectral differences in the X-ray band and do not reflect intrinsic properties.

Based on the additional information presented here, we can better pinpoint the borderline between HBLs and LBLs, and therefore propose a refined dividing line between the two classes at $f_{\rm x}/f_{\rm r} \sim 10^{-11.5}$, which corresponds to $\alpha_{\rm rx} \sim 0.8$ between 1 keV and 5 GHz and a break frequency $\sim 10^{15}$ Hz (see Fig. 6). Our results agree with the hypothesis we put forward that the cutoff energy is the fundamental parameter giving rise to two different classes of BL Lacs (Giommi & Padovani 1994; Padovani & Giommi 1995). Oddly enough, our results are also consistent with the other explanation for the existence of two BL Lac classes based on orientation. Ghisellini & Maraschi (1989), in fact, have shown that in objects at larger angles with respect to the line of sight (i.e., XBLs/HBLs in their view) synchrotron emission should be the main radiation mechanism in the X-ray band, while inverse Compton should be more important for more aligned sources (i.e., RBLs/LBLs), in agreement with our findings. The main problem of that model, however, apart from other ones discussed by Padovani & Giommi (1995a), is that a change in viewing angle does not seem to be able to explain the large difference in cutoff energies between the two classes, as exemplified by Fig. 4 of Ghisellini & Maraschi (1989) (Sambruna 1994; Sambruna et al. 1995, in preparation).

Our results explain the peculiar spectral variability of XBLs (i.e., HBLs) and RBLs (i.e., LBLs). Various studies have shown that in XBLs higher flux states are associated with flatter spectra (e.g., Giommi et al. 1990; Sambruna et al. 1994). Little is known about spectral variability in RBLs but Urry et al. (1996) have shown that the handful of

1 Jy BL Lacs with suitable data seem to show the opposite trend, that is steeper spectra in brighter states (the exception, PKS 2005 − 489, is an HBL). If X-ray variability in BL Lacs is accompanied by a change in break frequency (e.g., George, Warwick & Bromage 1988: MKN 421; Sambruna 1994: S5 0716+714, PKS 2005−489), this behaviour is easily explained: when an object brightens and the break moves to higher energies, in HBLs the spectrum hardens, as shown in Fig. 8 for a single source and in Figs. 2 and 6 for the HBL population. The opposite effect for RBLs can be explained in those cases where synchrotron emission in the X-ray band is not negligible in the high state: when the break moves to higher energies, the steep synchrotron component moves in the X-ray band therefore steepening the spectrum (Fig. 8). This would be in agreement with the (weak) correlation between α_x and $\nu_{\rm break}$ for LBLs, discussed in Sect. 3.3 (see Fig. 6). Figure 8 also shows that a spectral variability similar to that observed in the X-ray band for HBLs, that is flatter spectra at higher states, should be mirrored by LBLs in the infrared band, as in fact observed (e.g., Gear et al. 1986).

Our results seem in contradiction with those of Urry et al. (1996), who found that the α_x distribution for 1 Jy RBLs was consistent with that of the EMSS XBLs. As discussed in the Introduction, however, most previous work on the study of spectral indices of BL Lacs was limited by smaller statistics and the use of the RBL/XBL classification, which can be misleading. In particular, the result of Urry et al. (1996) can be explained as follows: 1. three of the 1 Jy RBLs are HBLs (S5 0716 + 714, MKN 501, PKS 2005 − 489), whose inclusion in the RBL sample certainly shifted the α_x distribution to steeper values (the mean value of α_x for these three objects is significantly different, i.e., steeper, than that of the rest of the sample: see also Comastri et al. 1995 and Urry et al. 1996); 2. the EMSS BL Lacs (all HBLs) have values of $f_x/f_r \gtrsim 10^{-10.5}$ (Padovani & Giommi 1995a), partly because, being a serendipitous survey, the EMSS excludes by definition well-know BL Lacs with considerable radio emission which have lower f_x/f_r values but more importantly because objects with relatively low values of f_x/f_r have a small probability of being detected and large-area X-ray surveys are needed. (This interpretation is supported by the fact that the Slew survey HBLs reach lower f_x/f_r values: see Perlman et al. 1995a). Given the anti-correlation between α_x and f_x/f_r (Fig. 2), this implies that EMSS HBLs are bound to have α_x flatter than average, thereby reducing any difference between the two classes. In fact, if we compare our LBL sample with the EMSS HBLs, we also find no significant difference between the spectral indices of the two samples.

One could argue that our sample is not complete in a statistical sense. However, it is the largest sample for which homogeneous X-ray data are available and includes 50 per cent of known BL Lacs. We needed a large enough sample to maximize the coverage of the parameter space to be able to test for any differences in the X-ray spectra of the two BL Lac classes. Previous results, even those based on complete (and therefore not very large) samples, were in fact not clear-cut. We are not aware of selection effects which could possibly alter our results significantly. Furthermore, considering only the complete sub-sample of 22 EMSS BL Lacs (all HBLs: Perlman et al. 1995b) we still reproduce one of our most important results, i.e. we find an anti-correlation between α_x and $\nu_{\rm break}$, significant at the 99.3 per cent level (Spearman rank-order test), consistent with the one we obtained for the whole HBL sample.

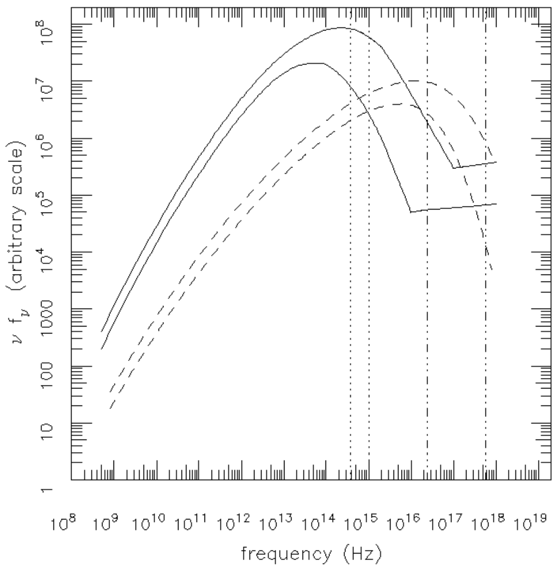

Figure 8. The effect of a change in break frequency on the flux and spectral variability of BL Lacs: in HBLs (dashed lines), when the object brightens and the break moves to higher energies, the X-ray spectrum hardens. In LBLs (solid lines), the opposite effect might apply (i.e., spectral steepening at higher fluxes) when synchrotron emission in the X-ray band is not negligible in the high state. Incidentally, note also the much larger flux variability, at fixed radio variability, expected for LBLs in the optical band (parallel dotted lines), as compared to that of HBLs, as effectively observed (e.g., Jannuzi et al. 1994). As in Fig. 7, the normalizations of the different curves have been chosen only for illustrative purposes and do not reflect intrinsic properties.

Comastri et al. (1995) have found a *positive* correlation between α_x and $\nu_{\rm break}$ in their sample of twelve 1 Jy BL Lacs (which includes nine LBLs and three HBLs). This is consistent with our results. If we consider all objects irrespective of the HBL/LBL classification, in fact, we also detect a positive correlation between α_x and $\nu_{\rm break}$, because on average HBLs have steeper spectra. Our much better statistics, however, allows us to examine this relation in more detail and to see that the dependence of α_x on break frequency is different for the two BL Lac classes, in particular HBLs exhibit a *negative* correlation between the two parameters.

The main conclusions of this paper, which studies the *ROSAT* X-ray spectra of about half the known BL Lacs, can be thus summarized:

BL Lacs are characterized by energy power-law spectral indices ranging between ~ 0 and 3, with an average value ~ 1.4. The X-ray spectral properties of BL Lacs with high ($\gtrsim 10^{15}$ Hz) frequency cutoffs (HBLs) are significantly different from those with lower frequency cutoffs (LBLs). HBLs have on average steeper X-ray spectral indices ($\alpha_x \sim 1.5$) which correlates with the effective radio-X-ray and optical-X-ray spectral indices. The overall spectrum is convex from radio to X-ray energies, and gets steeper with frequency. A strong anti-correlation is also present between X-ray spectral index and break frequency, with sources having cutoffs at larger energies displaying harder X-ray spectra. In LBLs, on the other hand, which have $\alpha_x \sim 1.1$, the X-ray spectrum shows no correlation with the effective spectral indices and the optical-X-ray continuum has a concave shape. These differences might also explain the peculiar X-ray spectral variability of HBLs and LBLs.

These findings strongly support the hypothesis that the main radiation mechanism in HBLs is synchrotron emission from the radio to the X-ray band, while in LBLs an inverse Compton component dominates the X-ray emission, and are consistent with the view that the apparent dichotomy between the two BL Lac classes is mainly due to different cutoff energies. They would also be consistent with the predictions of an inhomogeneous SSC model in which the main difference is the orientation of the beaming axis, but this model appear not to be able to reproduce the observed large differences in cutoff energies.

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NOTE ADDED IN PROOF

After this paper was accepted for publication, it came to our knowledge that Lamer, Brunner & Staubert (1996), A&A, in press, have independently analysed most of the data presented in this paper, reaching similar conclusions.