A new unifying model for X–ray and radio–selected BL Lacs

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ABSTRACT.

We discuss alternative interpretations of the differences in the Spectral Energy Distributions (SEDs) of BL Lacs found in complete Radio or X–ray surveys.

In order to explain the different properties of radio and X–ray selected within the assumption of a single population we propose a new approach (Fossati et al. 1997). The model is based on the idea that the BL Lacs constitute a “parameterized family” and that the physical parameter which governs the shape of the SEDs, is (or is associated with) the bolometric luminosity. Assuming an empirical relation between spectral shape and luminosity the observational properties of the two surveys, including the redshift distributions, can be reasonably well reproduced.

1. Different energy cut–off hypothesis

BL Lacs have been almost exclusively discovered through radio or X–ray surveys. However the properties of objects selected in the two spectral bands are systematically different, posing a question as to whether there are two “types” of BL Lacs. The first difference to be recognized and perhaps still the most striking is the shape of the SED. The differences show up in broad band spectral indices and color–color diagrams, e.g. \(\alpha_{RO}\) vs \(\alpha_{OX}\) (Sambruna, Maraschi and Urry 1996).

On the basis of the X-ray to radio flux ratio we adopt an objective criterion separating two (putative) classes of objects: we define XBLs the objects with \(\log(F_{1\text{keV}}/F_{5\text{GHz}}) \geq -5.5\) and RBLs those with a ratio smaller than this dividing value, where the fluxes are monochromatic and expressed in the same units.

The spread in spectral shapes was originally attributed to orientation effects, associated with different strength of the relativistic boosting and widths of the beaming cones of the radio and X–ray radiation emitted by a relativistic jet, in the sense of weaker boosting and wider cone for X–ray than for radio emission (Maraschi et al. 1986). The different beaming affecting the various bands could be due to an accelerating (Ghisellini & Maraschi 1989) or an increasingly collimated jet (Celotti et al. 1993).

Substantial progress in the knowledge of the broad band spectra of BL Lacs suggests that the SEDs of XBLs differ from those of RBLs mainly in having a (synchrotron) spectral cut–off (or break) at much higher frequency. Sambruna et al. (1996) showed that it is difficult to model the detailed transition from an XBL to an RBL like in terms of orientation only and suggested rather a continuous change in the physical parameters of the jet.
Giommi & Padovani (1994) introduced the idea that BL Lacs are a single population of objects whose SED can be characterized phenomenologically by the distribution of the values of the frequency at which the peak in the emission occurs (i.e. the peak in the $\nu F_\nu$ representation of the broad band energy distribution) for the putative synchrotron component. In particular they propose that a single luminosity function in the radio band describes the full BL Lac population. For each radio luminosity X–ray bright BL Lacs (i.e. XBLs) are intrinsically a minority following a fixed (luminosity independent) distribution of X–ray to radio flux ratios. According to this approach the intrinsic fraction of the two types of BL Lac would be objectively reflected in radio surveys.

In addition to this “radio leading” model we considered the “symmetric” alternative, “X–ray leading”, namely that the X-ray luminosity function represents the whole BL Lac population. In this case the objective survey would be in X–ray band. Starting from these hypothesis, one can again derive the statistical properties of a sample of BL Lacs simply by assuming a radio (X–ray) luminosity function and a probability distribution, $P$, of the X–ray to radio luminosity ratio.

Given the above assumptions, we computed the predictions of both models. We used a Monte Carlo technique to simulate the distribution of sources in space and luminosity. This method is very convenient because it allows us to store “single source” attributes and not only to compute sample integrated average properties.

The predictions were compared in detail with the best BL Lac samples nowadays available, i.e. the 1 Jy sample (Stickel et al. 1991) and the one derived from the Einstein Slew survey sample (Perlman et al. 1996). The quantities compared with the predictions of the models are the number of sources of the two types and their respective average radio and X–ray luminosities, and also the redshift distribution, for both surveys.

In terms of source numbers and average luminosities both models are in fairly good agreement with the observed properties of the reference samples, showing only minor discrepancies which however correspond to quantities only weakly constrained due to poor statistics of the “real” samples. The redshift distribution instead appears badly reproduced by both models. In particular they are not able to account for the flatness of the “$z$” distribution of RBLs in the 1Jy sample (Fossati et al. 1997).

2. Unified bolometric approach

Because of the implications of these issues for physical models of relativistic jets and the understanding of the physical conditions within the emission region, we tried a different approach.

Partly based on the observational indication of a possible link, along a continuous sequence, between the SED shape and the source luminosity (e.g. Sambruna et al. 1996), we propose that XBLs and RBLs are different representatives of a spectral sequence that can be described in terms of a single parameter. We identify this fundamental quantity with the bolometric luminosity of the synchrotron component, $L_{\text{bol.\,sync}}$. Both “flavours” of BL Lac objects share the same bolometric luminosity function and the SED properties strongly depend on it.

The main positive feature of this approach is that it offers a more direct interpretation
in terms of the physical properties of BL Lacs. In fact: (a) the assumptions are largely independent of the biases of the observed statistical samples; (b) there is a more direct connection between the parameters of solutions “acceptable” from a statistical point of view and the physical conditions of the emitting plasma.

The relation between the bolometric luminosity and the SED has been based on observed trends. More luminous objects seem to have RBL–type spectral properties, with the peak of the energy distribution in the mm–IR range and Compton dominated soft X–ray spectra. Therefore, if we characterize the SED with the frequency at which the (synchrotron) energy distribution has a maximum, a fundamental (inverse) relation must exist between the bolometric luminosity and this frequency.

Interestingly, note that the different redshift distributions of the two kinds of BL Lacs could be a natural outcome of this scenario. XBLs objects come from the lower (and richer) part of the luminosity function and so they would dominate at low redshift, but they would disappear at large distances despite the increase of the available volume. On the contrary, RBLs, even though coming from the poorer part of the luminosity function, would become predominant at higher redshifts, being still detectable.

In order to reproduce the basic features of the observed SEDs, we consider a simple “geometric” parameterization. The synchrotron radio to soft X–ray component is represented with a power law in the radio domain, smoothly connecting with a parabolic branch ranging up to \( \nu_{\text{peak}} \). Beyond \( \nu_{\text{peak}} \) the synchrotron component steepens parabolically. The hard X–ray Compton component is simply represented with a single power law. This schematic description of the SEDs well reproduces the basic properties of the observed BL Lacs broad band spectra.

We then specify the relation between \( \nu_{\text{peak}} \) and the value of \( L_{\text{bol, sync}} \). This is the key physical relation of the proposed model. For simplicity we consider a simple power law dependence: \( \nu_{\text{peak}} \propto L_{\text{bol, sync}}^{-\eta} \) (\( \eta > 0 \)).

Despite the number of parameters, there is only a limited freedom in the choice of their values, which are tightly constrained by observations.

We adopt a luminosity function for \( L_{\text{bol, sync}} \) inspired to that calculated by Urry & Padovani (1995) (see their Fig. 13) for the 1 Jy and EMSS BL Lacs.

Even a “first attempt” set of input model parameters gives a surprisingly good results. Basically, all observational quantities are correctly predicted by the model, except an excessive radio luminosity for RBL detected in radio surveys. Furthermore, a very positive consequence of this scenario is that it implies a qualitatively correct redshift distribution. There is still a problem with RBLs in the radio survey. In fact, even though the shape of the distribution is correctly flat, and this is the major difficulty of the two other models, it extends beyond \( z = 1 \). This is likely connected with the excessive average radio luminosity of RBLs. However, we suggest that the excess of objects predicted at higher redshift (and/or their overestimated radio power) could be understood in an even broader unifying picture.

3. Discussion and conclusions

We propose (Fossati et al. 1997) a new unified bolometric model, whose key feature is the link of the bolometric luminosity with the energy of the synchrotron cut–off. This
scenario is based on a schematic parameterization of the BL Lac SED, constrained by observational trends, and adopts a semi-empirical bolometric luminosity function. Despite the rigid formulation of the one-to-one correspondence between the SED properties and the luminosity, in this scenario all the main observational data can be successfully reproduced. The only discrepancy of the model seems to be the prediction of a radio luminosity for RBLs detected in radio surveys higher than observed, and the related problem with their redshift distribution.

We note, however, that Highly Polarized Quasars (HPQ) show an interesting continuity of properties with those of BL Lacs (e.g. Sambruna et al. 1996; Comastri et al. 1997). There seems to be a remarkable progression in properties, in a luminosity sequence XBL→RBL→HPQ, which is also a sequence of increasing importance of emission lines. In this picture, if a fraction of the RBL with the highest bolometric luminosities were indeed HPQ, this fact could explain the discrepancies of the model in the predictions of the high radio luminosity and redshift distribution.

As already stressed, a very interesting aspect of the “bolometric” approach is that it is based on the relative dependence of two quantities which are directly related to the properties of the emitting plasma, namely the luminosity and the cut-off of the synchrotron spectrum. One can therefore speculate on the physical origin of this dependence. Probably the most simple interpretation of this link is that it is related to the particle cooling. The more radiation is emitted the more particles loose energy, with consequent decrease of the cut-off frequency (which depends the maximum energy of the emitting particles).

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