The Connection between BL Lacs and FSRQs

V. D’Elia, A. Cavaliere

Astrofisica, Dip. Fisica, Universitá Tor Vergata, Roma, I-00133

Abstract. We discuss the features that mark the Flat Spectrum Radio Quasars from the BL Lacertae objects. We propose that FSRQs exceeding $L \sim 10^{46}$ erg s$^{-1}$ are powered by black hole accreting at rates $\dot{m} \sim 1 \div 10$; their power is dominated by the disk components, thermal and BZ. Instead, sources accreting at rates $\dot{m} \sim 10^{-2} \div 10^{-3}$ radiate in the BL Lac mode; here the power is mainly non-thermal, and is driven by the rotational energy stored in a Kerr hole which sustains $L \lesssim 10^{46}$ erg s$^{-1}$ in the jet frame for Gyr. The two populations may be even linked if around the same objects $\dot{m}$ drops in time; then some negative cosmological evolution is expected for the newborn BL Lacs fed by the dying FSRQs. Further implications are discussed.

1. Introduction

Within the AGNs, the Blazars are singled out by their flat-spectrum GHz emission, powerful $\gamma$ rays into the GeV band and beyond, rapid variability, high and variable optical polarization.

These common properties are widely explained (see Urry & Padovani 1995) in terms of beamed emissions from a relativistic jet, with Lorentz bulk factors $\Gamma \approx 5 \div 20$ (in the following, we will concentrate on the debeamed e.m. power).

Within the Blazars, the Flat Spectrum Radioloud Quasars (FSRQs) differ from the BL Lac objects on the following accounts: 1) optical features 2) integrated power 3) top spectral energies 4) cosmological evolution. The specific features of the two classes are collected in the following Table 1:

| Feature               | FSRQs                  | BL Lacs                |
|-----------------------|------------------------|------------------------|
| optical features      | em. lines, bump        | no lines, no bump      |
| integrated power      | $L \sim 10^{46}$ erg s$^{-1}$ | $L \lesssim 10^{40}$ erg s$^{-1}$ |
| evolution             | strong                 | weak if any            |
| top energies          | $h\nu \sim 10$ GeV     | $h\nu \sim 10$ TeV     |

These differences stand out of selections and call for explanation. Within the accreting black hole paradigm for the primary power source, we shall order all these features in a sequence primarily marked by one parameter, the accretion rate $\dot{m}$ (Eddington units). We propose that the FSRQs, like other quasars, accrete at rates $\dot{m} \sim 1 \div 10$, while the BL Lacs radiate in conditions of $\dot{m} \ll 1$. 
2. The Blazar Luminosities

We begin with the thermal luminosities, including the optical-UV bumps; in the standard view these are produced in the accretion disk and are given by \( L_{th} \approx \dot{m} L_E \). Then the absence or weakness of bumps in the BL Lac spectra can be simply understood in terms of \( \dot{m} \ll 1 \). If so, low gas densities are also expected around the hole, and these concur to account for the other optical feature of the BL Lacs, namely, the weak or absent emission lines. The FSRQs instead, in spite of their “blazing” non-thermal component, share with other quasars the bumps and the broad emission lines; these features are consistent with values \( \dot{m} \sim 1 \div 10 \).

As to the jets, we state our guideline: jets are powered by variants of the mechanism originally proposed by Blandford & Znajek (1977) for extraction of rotational energy from a Kerr hole via the Poynting-like flux associated with the surrounding magnetosphere. Variants are necessary in view of the limitations recently discussed to the power extractable from the hole. Since the BZ power scales as \( B_h^2 (r_c/r_h)^2 \), such variants involve either high strengths of the magnetic fields \( B_h \) threading the hole horizon at \( r_h \), or the MHD contribution of the disk from a radius \( r_c \) larger than \( r_h \).

Recent discussions (Modersky & Sikora 1996; Ghosh & Abramowicz 1997; Livio, Ogilvie & Pringle 1999) have stressed the continuity of \( B_h \) with the field \( B_d \) rooted in the inner stable region of the disk; in turn, \( B_d \) is bounded after \( B_d/8\pi \lesssim P_{\text{max}} \) by the maximum pressure. In a standard \( \alpha \)-disk the latter scales as \( P_{\text{max}} \propto (\alpha M_9)^{-9/10} \dot{m}_4^{4/5} \) if it is gas dominated, or as \( P_{\text{max}} \propto (\alpha M_9)^{-1} \) if it is radiation dominated; in the latter case the hole power attains its maximum

\[
L_K = 2 \times 10^{45} M_9 (J/J_{\text{max}})^2 \text{ ergs}^{-1}.
\] (1)

But to have an inner disk region dominated by radiation pressure, accretion rates \( \dot{m} \gtrsim 10^{-3} \) are required. This is because the radius \( r_c \) bounding the region grows with \( \dot{m}^{16/21} \) (Novikov & Thorne 1973), and exceeds the last stable orbit only if \( \dot{m} \gtrsim 10^{-3}(\alpha M_9)^{-1/8} \) holds. In such conditions, the hole output can exceed the disk thermal luminosity as given by \( L_K/L_{th} = 3.3 \times 10^{-2} \dot{m}^{-1} (J/J_{\text{max}})^2 \).

With \( \dot{m} \) increasing, \( L_K \) saturates and its ratio to \( L_{th} \) decreases, but the radiation pressure region tends to broaden. Then a larger power component may be extracted from the disk, up to \( L_d \sim L_K (r_c/r_h)^2 \).

Within this framework, we draw the following implications concerning the Blazar sequence. BL Lac jets can live with accretion rates \( \dot{m} \sim 10^{-2} \), since the rotational power levels \( L_K \) given by eq. (1) are often adequate even considering the kinetic power remaining in the jets (see Celotti 1999). The most powerful BL Lacs require very massive BHs and/or a larger but still comparable contribution from the dynamically entrained and magnetically connected inner rings of the disk. In all such cases one expects \( L_d \sim L_K \gtrsim L_{th} \) to hold.

On the other hand, many FSRQs feature outputs exceeding \( 10^{46} \text{ erg s}^{-1} \) considerably, with specific sources approaching a total of \( 10^{48} \text{ erg s}^{-1} \) (Tavecchio et al. 2000). Such outputs require dominant components \( L_d \sim L_{th} \gg L_K \) from a wider disk region dominated by radiation pressure, and so require conditions where \( \dot{m} \sim 1 \div 10 \). The hole contribution, though minor, is likely to provide a “high-velocity spine” instrumental for the jet propagation, see Livio 1999.
Alternatively, to account for such huge outputs one needs very strong $B_h$, as advocated by Meier 1999; fields up to $B_h^2/8\pi \sim \rho c^2$ in the plunging orbit region have been argued by Krolik 1999; Armitage, Reynolds & Chiang 2000 and Paczynski 2000 discuss how and why such enhancements are unlikely inside a thin disk. In thick disks the status of such enhanced fields is still uncertain; we note they would require high $\dot{m}$ anyway.

In this section we have shown how different values of the key parameter $\dot{m}$ mark thermal and non-thermal features together along the Blazar sequence. We summarize our discussion by adding to the previous Table 1 the following lines:

| Kerr hole vs. disk | FSRQs | BL Lacs |
|--------------------|-------|--------|
| key parameter: $\dot{m}$ | $\dot{m} \sim 1 \div 10$ | $\dot{m} \sim 10^{-3} \div 10^{-2}$ |

3. The Blazar Evolutions

Strong cosmological evolution is closely shared by the FSRQs with the rest of the quasars (Goldschmidt et al. 1999), and shows up, e.g., in their steep number counts; the BL Lacs, instead, show no signs of a similar behavior (Giommi, Menna & Padovani 1999; Padovani 2000).

The quasar behavior includes a strong component of luminosity evolution (see Boyle et al. 2000 for the optical and Della Ceca et al. 1994 for the X-ray band). This is widely traced back to the exhaustion in the host galaxy of the gas stockpile usable for accretion, due to previous accretion episodes and to star formation (Cattaneo, Haehnelt & Rees 1999; Haehnelt & Kauffmann 2000; Cavaliere & Vittorini 2000). With the average rate $\dot{m}$ so decreasing, we expect many objects to switch from being mostly fueled by accretion to being mostly fed by the Kerr hole rotational supply $E_K$ (stored by accretion of angular momentum $J$ along with mass, Bardeen 1970); so we expect many sources to switch from the FSRQ to the BL Lac mode. The moderate BL Lac powers can be sustained for several Gyrs by the coupled system Kerr hole - disk, so the BL Lac luminosity evolution is expected to be slow (Cavaliere & Malquori 1999), with time scales around $\tau_L \approx E_K/L_K \approx 8$ Gyr.

In more detail, Cavaliere & Vittorini 2000 trace back the bright quasar evolution to the diminishing rate of the interaction episodes of the host galaxies with their neighbors in a group. These events destabilize the host gas and trigger accretion; they last some $10^{-1}$ Gyr, a galactic dynamical time, and produce a weak density evolution on a time scale $\tau_D \approx 6$ Gyr. But the efficiency of such episodes drops, due to the exaustion of the gas available in the hosts over times $\tau_L \approx 3$ Gyr; this produces a strong luminosity evolution.

Our point is that the powerful FSRQ activity based on high $\dot{m}$ will die out over times of some $10^{-1}$ Gyr after a “last interaction”; but in many instances this will leave behind a maximally spinning hole, and so a long lived BL Lac. Thus the scale $\tau_D$ for bright FSRQ deaths is also the scale for BL Lac births.

One sign of evolution is provided by the integrated counts, which at high/medium fluxes may be evaluated from the crude but explicit expression

$$N(> S) \propto S^{-3/2}[1 - C(S_0/S)^{1/2} + O(S^{-1})] , \quad (2)$$
with the key time scales directly appearing in the coefficient

\[ C = 3D_0(l^2)[2(1 + \alpha) - 1/H_0 \tau_D - (\beta - 1)/H_0 \tau_L]/4R_H(l^{3/2}). \]  (3)

For the BL Lacs counted in the radio band such time scales are: \( \tau_D \approx -6 \) Gyr (BL Lac births imply negative density evolution); \( \tau_L \approx 8 \) Gyr (marking the slow BL Lac luminosity evolution). Other quantities involved are: the spectral index \( \alpha = 0.3 \) in the GHz range; the slope \( \beta \approx 2.5 \) of the radio LF; the normalized moments \( \langle l^n \rangle \) of the LF; the distance \( D_0 = (L_0/4\pi S_0)^{1/2} \approx 0.05R_H \) in Hubble units of typical high flux BL Lacs.

For example, in the critical universe with \( t_0 \approx 13 \) Gyr the result is \( C \approx 0.1 \). This means \( N(> S) \propto S^{-1.5} \) or flatter at high fluxes, consistent with the data by Giommi et al. 1999, see fig. 1.

In contrast, the values appropriate for the FSRQs, namely: \( \tau_D = +6 \) Gyr, \( \tau_L = 3 \) Gyr, \( D_0 \approx 0.5R_H \) and still \( \beta = 2.5 \), yield \( C \approx 4 \) and produce radio counts \( N(> S) \) steepening well above \( S^{-1.5} \).

Note that \( C \) includes \( \beta \) and \( \langle l^2 \rangle/\langle l^{3/2} \rangle \), which both act to flatten the counts for flatter LFs. In fact, the beaming effect (Urry & Padovani 1995) does flatten the LF at the faint end, which contributes to the flattening of the faint counts; however, the similarly affected FSRQ counts show a bright steep section indicative of intrinsically stronger evolution.

To summarize this discussion, we add to Table 1 the following line:

|        | FSRQs | BL Lacs |
|--------|-------|---------|
| evolution | strong | weak if any |

4. The Blazar Spectra: \( \gamma \) rays

Another feature of the Blazars is their SED that extends into the 10 GeV range for the FSRQs, and into the TeV range for the BL Lac objects. Such high energy photons are likely produced via inverse Compton (Ghisellini 1999) by GeV and by \( 10^2 \) GeV electrons, respectively. Can the parameter \( \dot{m} \) also explain this difference?

To such energies the particles may be accelerated in two ways: either by weak electric fields \( (E \sim 10^{-8} \) cgs units) over large distances \( (\sim 10^{16} \) cm) as in the internal shock scenario which, however, falls short of the top energies required in BL Lacs (Ghisellini 1999); or by higher fields (associated with energy transport via “Pointing flux” along the jet) effective over shorter distances.

In pursuing the latter way, we expect the force-free condition \( E \cdot B = 0 \) governing the BZ magnetosphere to break down at average distances \( R \sim 10^{17} \) cm, but to do it inhomogeneously within bubbles or filaments; however, fields with natural values \( E \sim 1 \) cgs units still would be screened out over distances exceeding some \( c/\omega_p \propto (\gamma/n)^{1/2} \). The densities may be estimated from the emissions which scale as \( L \sim \gamma^2 U R^3 n \) with \( \gamma^2UR^3 \) roughly constant (Fossati et al. 1999; Ghisellini 1999). So in comparing BL Lacs as a class with the FSRQs, values of \( n \) smaller by \( 10^{-5} \) obtain; then the top electron (and \( \gamma \)-ray) energies ought to scale like \( E_{\text{max}} \propto (\gamma^2UR^3)^{1/2} \gamma_{\text{min}}^{1/2} L^{-1/2} \). The scatter of \( \nu_{\text{peak}} \) in
Figure 1. The BL Lac counts evaluated from eqs. (2) and (3) using \( \tau_D = -7 \) Gyr (dashed) and \( \tau_D = -5 \) Gyr (solid). The dotted line represents the “Euclidean” slope. Data for extreme BL Lacs from Giommi, Menna, & Padovani 1999.

the BL Lac class expected from the second parameter \( L_d/L_K \) will be discussed elsewhere.

After this discussion we may add to Table 1 the line:

| top energies | FSRQs | BL Lacs |
|--------------|-------|---------|
| \( h\nu \sim 10 \text{ GeV} \) | \( h\nu \sim 10 \text{ TeV} \) |

5. A Link with Accelerators of UHECR?

If we carry the Blazar sequence to its extreme, we may expect endpoint objects (dead BL Lacs) with very low residual \( \dot{m} \lesssim 10^{-4} \), which would feature very faint if any e.m. emission, along with nearly unscreened electric fields. These would accelerate particles including protons, and make ultra high energy cosmic rays up to the long recognized limit given by \( E_{\text{max}} \sim e B_D \tau_{\text{ms}} (r_{\text{ms}}/R)^p/p \sim 10^{20} \text{ M}_8 \text{ B}_4 \text{ eV} \); after Blandford & Payne 1982, the magnetic fields are assumed to decrease outwards like \( r^{-(1+p)} \) with \( p = 1/4 \).

Several tens of these accelerators could lie within some 100 Mpc (Boldt & Ghosh 1999). As to ultra high energies, these accelerators would evade in the simplest way the GZK cutoff (if it exists); as to accounting for the particle flux, they need to produce only \( L \sim 10^{42} \text{ erg s}^{-1} \). Note that nG intergalactic fields would blur the geometrical memory of the sources for most but not all UHECRs.
6. Conclusions

The lines added to Table 1 as a summary of each of the Sects. 2, 3, 4, 5 lead us to propose the overall Table 2:

Table 2 - The Blazar sequence

|                | FSRQs | BL Lacs | → CR accelerators |
|----------------|-------|---------|-------------------|
| optical features | em. lines, bump | no lines, no bump | none |
| integrated power | $L \sim 10^{47+48}$ erg s$^{-1}$ | $L \lesssim 10^{46}$ erg s$^{-1}$ | $L \lesssim 10^{42}$ erg s$^{-1}$ |
| evolution       | strong | weak if any | negligible |
| top energies    | $h\nu \sim 10$ GeV | $h\nu \sim 10$ TeV | $E_{max} \sim 10^{21}$ eV |
| Kerr hole vs. disk | $L_K \ll L_D$ | $L_K \gtrsim L_D$ | very low $L_K$ and $L_D$ |
| key parameter: $\dot{m}$ | $\dot{m} \sim 1 \div 10$ | $\dot{m} \sim 10^{-2}$ | $\dot{m} \lesssim 10^{-4}$ |

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References

Armitage, P.J., Reynolds, C.S. & Chiang, J., 2000, astro-ph/0007042
Bardeen, J., 1970, Nature, 226, 64
Blandford, R. D. & Payne, D. G. 1982, MNRAS, 199, 883
Blandford, R.D. & Znajek, R. 1977, MNRAS, 179, 473
Boldt, E. & Ghosh, P. 1999, MNRAS, 307, 491
Boyle, B.J. et al. 2000, astro-ph/0005368
Cattaneo, A., Haehnelt, M.G., & Rees, M.J. 1999, MNRAS, 308, 77
Cavaliere, A. & Malquori, D. 1999, ApJ, 516, L9
Cavaliere, A. & Vittorini, V. 2000, astro-ph/0006194
Celotti, A., 1999, Mem SAIt, 70, 169 and references therein
Della Ceca, R. et al. 1994, ApJ, 430, 533
Fossati G. et. al., 1999, MNRAS, 299, 433
Ghisellini, G. 1999, astro-ph/9906111 and references therein
Ghosh, P. & Abramowicz, M. 1997, MNRAS, 292, 887
Giommi, P., Menna, M.T. & Padovani, P., 1999, astro-ph/9907014
Goldschmidt, P., Kukula, M.J., Miller, L., & Dunlop, J.S. 1998, ApJ, 511, 612
Kauffmann, G. & Haenelt, M.G., 2000, MNRAS, 311, 576
Livio, M., 1999, preprint Astrophysical Jets: a Phenomenological Examination
Livio, M., Ogilvie, G., & Pringle, J. 1998, Astrophys. J., 512, 100
Krolik, J.H., 1999, ApJ, 515, L73
Meier, D.L., 1999, astro-ph/9908283
Modersky, R. & Sikora, M. 1996, MNRAS, 283, 854
Novikov, I.D. & Thorne, K.S., 1973 in Black Holes, ed. De Witt C. & De Witt D. (New York: Gordon & Breach), 343
Paczynski, B., 2000, astro-ph/0004129
Padovani, P., et al. 2000, these Proceedings
Salvati, M., 1997, Mem. SAIt 68, 23
Tavecchio et al., 2000, astro-ph/0006443
Urry, M. & Padovani, P. 1995, PASP, 107, 83