THE JET-DISK CONNECTION AND BLAZAR UNIFICATION

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ABSTRACT

We discuss the relation between the power carried by relativistic jets and the nuclear power provided by accretion for a group of blazars, including flat-spectrum radio quasars (FSRQs) and BL Lac objects. They are characterized by good-quality broadband X-ray data provided by the BeppoSAX satellite. The jet powers are estimated using physical parameters determined from uniformly modeling their spectral energy distributions. Our analysis indicates that for FSRQs the total jet power is of the same order as the accretion power. We suggest that blazar jets are likely powered by energy extraction from a rapidly spinning black hole (BH) through the magnetic field provided by the accretion disk. FSRQs must have large BH masses ($10^8$–$10^9 M_\odot$) and high, near-Eddington accretion rates. For BL Lac objects, the jet luminosity is larger than the disk luminosity. This can be understood within the same scenario if BL Lac objects have masses similar to FSRQs but accrete at largely subcritical rates, whereby the accretion disk radiates inefficiently. Thus, the “unification” of the two classes into a single blazar population, previously proposed on the basis of a spectral sequence governed by luminosity, finds a physical basis.

Subject headings: accretion, accretion disks — BL Lacertae objects: general — galaxies: jets — galaxies: nuclei

1. INTRODUCTION

The formation of highly relativistic jets in active galactic nuclei is one of the most fundamental open problems in astrophysics. It is currently assumed that jets are produced close to the central black hole (BH), involving power extraction from the BH spin (Blandford & Znajek 1977) and/or from the accretion disk (Blandford & Payne 1982). In both scenarios the magnetic field must play a major role in channeling power from the BH or from the disk into the jet; in both cases, it should be sustained by matter accreting onto the BH, leading one to expect a relation between the accretion power and the jet power.

Estimates of the power of jets and of the associated accretion flows can therefore be crucial to shed light on the jet-disk connection. In a pioneering work, Rawlings & Saunders (1991) addressed this question by studying a large sample of radio galaxies. They used the narrow-line luminosity as indicative of the accretion power and estimated the power transported by the jet from the energy content and lifetime of the radio lobes, finding a good correlation between the two. This result has been confirmed with larger and deeper samples and with different power “estimators” (e.g., Willot et al. 1999; Xu, Livio, & Baum 1999). However, because of the indirect nature of the estimators used, the “calibration” of the relation in terms of jet power and accretion power remains uncertain. Celotti, Padovani, & Ghisellini (1997, hereafter CPG97) first investigated the relation between jet and disk using the direct radio emission of the jet close to the nucleus, as resolved by VLBI, for the jet power estimation. They considered a large sample of objects (55), mostly blazars (including 12 BL Lac objects), and derived the accretion luminosity from the broad emission lines when available. They found a suggestive hint of correlation between these two quantities, although the statistical significance was too low to draw a firm conclusion.

Blazars are in fact the best laboratories in which to study the physics of relativistic jets. Their emission (from radio to gamma rays) is dominated by the beamed nonthermal continuum produced in the jet (Urry & Padovani 1995). Their spectral energy distributions (SEDs) are in general well understood as synchrotron plus inverse Compton (IC) emission. When observations of both components are available, the basic physical quantities of the emission region can be derived in a robust way, allowing one to estimate the jet power in the region closest to its origin (e.g., Tavecchio et al. 2000, hereafter Paper I). Particularly interesting for the study of the jet-disk connection are those blazars showing thermal features directly related to the central accretion flow, such as the so-called “blue bump” and/or the bright emission lines produced in the broad-line region.

In the present work, we consider a relatively small group of bright blazars (11 flat-spectrum radio quasars [FSRQs] and five BL Lacs) with good wavelength coverage, basing jet power estimates on physical parameters derived from uniformly modeling the observed SEDs (Tavecchio et al. 2002, hereafter Paper II). All these objects have broadband X-ray spectra (0.1–100 keV) from BeppoSAX observations. As discussed below (§ 2), the information on the X-ray continuum is crucial in order to have reliable estimates.

The plan of the paper is as follows: In § 2 we describe the objects and the adopted method for estimating the power of the jet. We then compare the jet powers with their luminosities (integrated over angles), deriving the jet radiative efficiencies, and the jet luminosities with the accretion luminosities estimated from the blue bump or line strengths (§ 3). The derived relation between jet luminosity and accretion luminosity is discussed in § 4, taking into account the radiative efficiencies and comparing them with the expectations of current models. Implications for a scenario of blazar unification are considered. The conclusions are presented in § 5. Throughout the paper we assume $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0$.

Preliminary results were presented in Maraschi & Tavecchio (2001a, 2001b) and Maraschi (2001).
2. SAMPLE AND GENERAL MODEL

In view of a reliable estimate of the power carried by the relativistic jet, we require uniform "good-quality" data on their SEDs. These are commonly modeled with synchrotron and IC radiation from a uniform emission region. Both components must be observationally constrained in order to derive the physical parameters of the emitting region (Tavecchio et al. 1998; see further discussion below).

In practice, the broadband coverage (0.1–100 keV) allowed by the BeppoSAX satellite is essential. In fact, in the case of FSRQs the X-ray emission derives from the IC mechanism (with seed photons external to the jet [EX] and, in some cases, an additional contribution from the synchrotron self-Compton photons [SSC]). The X-ray data then fall on the low-energy branch of the IC component, constraining the electron spectrum at low energies, which is particularly important in the power estimate (see below). In the case of BL Lacs, whose SEDs peak at higher frequencies, the X-ray data constrain the position of the synchrotron peak, while information on the IC peak is provided by observations in the gamma-ray (GeV range) or in the TeV domain.

Specifically, the selection criteria for the sources considered are the following: The FSRQs belong to a subsample of the 2 Jy catalog by Padovani & Urry (1992, 50 sources), with a threshold of $F_{\text{1 keV}} > 0.5$ mJy (19 objects) chosen in order to obtain good BeppoSAX spectra up to 100 keV. Twelve objects have been observed until now. In Paper I we discussed three of them, namely, 0836+710, 1510–089, and 2230+114; another six sources are analyzed in Paper II (0208-512, 0521–365, 1641+399, 2223–052, 2243+365, and 2251+158), and two sources (3C 279, PKS 0537–441) are discussed elsewhere (Maraschi et al. 1999a, 1999b; Ballo et al. 2002; Pian et al. 2002, submitted). For 0528+134, for which good data on the SED are available (Ghisellini et al. 1999), we were unable to find the line luminosity in the literature, and for this reason it was excluded from our sample.

The five BL Lac objects were chosen so as to have a well-measured SED near the synchrotron peak, complemented by information on the IC peak. They are the two TeV sources Mrk 421 and Mrk 501 (for which simultaneous observations are used: Maraschi et al. 1999a, 1999b; Tavecchio et al. 2001), PKS 2155–304 (Chiappetti et al. 1999), ON 231 (Tagliaferri et al. 2000), and BL Lac itself (Ravasio et al. 2002). Other BL Lacs with BeppoSAX data and gamma-ray information (from EGRET) are 0716+714 and 0235+164, but for 0716+714 the redshift is unknown, while 0235+164 shows a peculiar phenomenology, possibly resulting from gravitational lensing (e.g., Webb et al. 2000). Therefore, both were excluded from the present analysis.

The observational information on the SEDs is given in the above papers. The physical parameters of the jets were rederived uniformly reproducing all the SEDs with a synchrotron + IC model including both the synchrotron and external photons as seed photons (SSC + external Compton).

We adopt a one-zone model in which the radiation is produced in a homogeneous emitting region by a single electron population. One-zone models are supported by a number of observational evidences, at least for the spectral range from the gamma-ray band down to the optical-IR band. In particular, the observations of correlated variability at different frequencies suggest cospatial production of low- and high-energy photons via the two mechanisms (synchrotron + IC) by the high-energy branch of the electron population (e.g., Ulrich, Maraschi, & Urry 1997; Urry 1999; Giommi et al. 1999; Maraschi et al. 1999a, 1999b; Sambruna 2000; Sikora & Madejski 2001). In general, the one-zone model predicts synchrotron self-absorption in the FIR/submillimeter range. Thus, it cannot account for the radio emission, which is thought to be due to the superposition of self-absorbed synchrotron components produced farther out ($d \geq 0.1$ pc) along the jet (e.g., Blandford & Konigl 1979). The one-zone model considered here naturally appears as the innermost component of the inhomogeneous jet model.

As shown in Tavecchio et al. (1998) for the case of a one-zone synchrotron + SSC model, the knowledge of the frequency and luminosity of both the synchrotron and IC peaks, together with the upper limit on the size of the emission region derived from variability, allows us to univocally determine the model parameters. In the case, particularly relevant for the present work, in which the IC component is dominated by scattering of external radiation, the model involves an additional parameter, that is, the energy density of the external radiation field. However (see, e.g., Paper I and the discussion below), the latter quantity can be estimated with reasonable confidence from the available luminosities of the emission lines and/or the UV bump. Therefore, given sufficient observational information on both peaks, in both the SSC and EX models reliable estimates of the basic physical quantities of the jet can be derived.

For a complete description of the model, we refer to the Appendix. We just recall that a phenomenological description of the electron spectrum was adopted (analogous to a broken power law),

$$N(\gamma) = K \gamma^{-n_2} \left(1 + \frac{\gamma}{\gamma_c}\right)^{n_2 - n_1}, \quad \gamma_{\text{min}} < \gamma < \gamma_{\text{max}},$$

where $K$ is the normalization factor, $\gamma_c$ is the Lorentz factor of electrons at the spectral break, $n_1$ and $n_2$ are the spectral indices below and above the break, respectively, and $\gamma_{\text{min}}$ and $\gamma_{\text{max}}$ are the minimum and maximum energies of the relativistic electrons. For Mrk 501 we used a slightly modified electron energy distribution (see Tavecchio et al. 2001), with the addition of an exponential high-energy cutoff.

The viewing angle is assumed to be $\theta \sim 1/\Gamma$, where $\Gamma$ is the bulk Lorentz factor of the emitting plasma; in these conditions, the Doppler factor $\delta \sim \Gamma$. This choice, which eliminates the angle to the line of sight as an independent parameter, may appear arbitrary for individual objects; however, it can be justified for a group of objects. In fact, for fixed $\delta$ (derived from the spectral modeling), the probability of observing a source at an angle $\theta$ is maximal around $\theta \sim 1/\Gamma$, since this is the maximum angle allowed for a given $\delta$; thus, for a group of sources, as in the case discussed here, we expect that the average viewing angle is close to $1/\Gamma$. A known exception is the case of 0521–365, for which various indicators suggest that the jet forms a relatively large angle with the line of sight (Pian et al. 1996). Assuming that the bulk Lorentz factor of the emitting plasma is similar to that of the other blazars, $\Gamma_b \sim 10$, this implies that the emission from 0521–365 is weakly boosted. Here, we assumed $\Gamma = 10$ and $\theta = 15^\circ$, implying $\delta = 3$.

The external radiation field is described as a blackbody with temperature $T \approx 10^4$ K and energy density $U_{\text{ext}}$. 
Uncertainties in the temperature (to within factors of a few) do not strongly affect the determination of other physical parameters. The most important parameter is the energy density $U_{\text{ext}}$. The latter can be derived from the luminosity of the broad-line region (BLR) and/or of the accretion disk by $U_{\text{ext}} = L_{\text{BLR}} / 4\pi R_{\text{BLR}}^2$ and $L_{\text{BLR}} = \pi L_{\text{disk}}$ (where $\tau$, usually assumed to be $\sim 0.1$, represents the fraction of the central emission reprocessed by the BLR and $R_{\text{BLR}}$ represents its radius). For sources showing a clear UV bump, we used $L_{\text{disk}} = L_{\text{UV}}$, while for the other cases $L_{\text{BLR}}$ was derived from the luminosity of the observed broad emission lines, applying correction factors as used by CPG97. $R_{\text{BLR}}$ was adjusted in the fits, but the derived values were found to agree within a factor of 2 with those predicted by the correlation of Kaspi et al. (2000) between $R_{\text{BLR}}$ and $L_{\text{BLR}}$.

In the case of BL Lac, ON 231, 0836+710, 1510–089, and 2230+114, the models for the SEDs presented in the original papers (Ravasio et al. 2002; Tagliaferri et al. 2000; Paper I) were computed with different hypothesis on the electron energy distribution (Ghisellini et al. 1998). Electrons were assumed to be continuously injected in the emitting region, with a power-law distribution with index $n_{\text{inj}}$, extending from $\gamma_{\text{min}}$ to $\gamma_{\text{max}}$. The equilibrium distribution reached as a result of cooling then has a double power-law shape, with energy indices $n_1 = 2$ for $\gamma < \gamma_{\text{min}}$ and $n_2 = n_{\text{inj}} + 1$ for $\gamma > \gamma_{\text{min}}$. Therefore, in this model the spectral index of the low-energy portion of the emitted spectrum is fixed to be $\alpha_1 = 0.5$, and the peak of the SED corresponds to electrons with $\gamma = \gamma_{\text{min}}$, which plays the same role as $\gamma_\text{b}$ in the model adopted in the present paper. Notably, although some of the parameters obtained with the two versions of the model are different, important derived quantities such as powers and luminosities (see the following sections) appear to be rather stable (within a factor of 2–3) against the details of the model adopted, supporting the consistency of our results. Table 1 reports the list of sources, their redshifts and the values of the parameters derived from modeling the SEDs.

3. RADIATIVE JET LUMINOSITY AND POWER

The kinetic power of the jet, i.e., the energy flux of the relativistic flow through a section $\pi R^2$ of the jet, is given by $P_{\text{jet}} = \pi R^2 \beta c U T^2$ (e.g., CPG97), where $U = U_B + U_e + U_p$ is the total energy density in the jet frame, caused by magnetic field, relativistic electrons, and, if present, protons ($L_{\text{jet}} = L_B + L_e + L_p$). The energy density in particles is given by $U_e + U_p = n_e m_e c^2 \left[ (\gamma_e) + (n_p/n_e)(m_p/m_e) \right]$, where $n_e = \int_{\text{min}}^{\gamma_{\text{max}}} N(\gamma) d\gamma$ is the electron density and $\langle \gamma_e \rangle$ is the average Lorentz factor of electrons.

The critical parameter determining $P_{\text{jet}}$ is the total number of particles, which in turn depends on the energy spectrum of the electrons below $\gamma_{\text{b}}$ and on the value of $\gamma_{\text{min}}$. For FSRQ, both quantities can be inferred from the shape of the X-ray spectrum. In particular, values of $\gamma_{\text{min}} > 1$ would produce an unobserved break in the X-ray continuum (e.g., Paper I). Moreover, in several cases our data exclude an important contribution from cold pairs, whose presence should produce a "bump" in the soft X-ray spectrum (Sikora et al. 1997).

We will assume that the jet is composed by a normal plasma with one (cold) proton per relativistic particle. This hypothesis is justified below. For uniformity, we evaluate $P_{\text{jet}}$ with $\gamma_{\text{min}} = 1$ for all the objects; the power should then be considered as an upper limit to the actual power of the jet. An increase of a factor of 10 in $\gamma_{\text{min}}$ (which cannot be excluded in all cases) would lower the estimated powers by a factor of 5–10, depending on the value of $n_1$.

For BL Lac objects, X-rays can derive from the synchrotron component or from IC emission produced through SSC. In both cases, the emission is produced by high-energy electrons, $\gamma > 1000$ in the case of synchrotron, and $\gamma \approx 100$ for SSC. Thus, the SEDs contain less stringent information on the amount of low-energy particles in the jet, in particular on the value of $\gamma_{\text{min}}$ and on the index $n_1$. Because we work in the perspective of a unified model, we will assume also for BL Lacs an equal number of protons and electrons and $\gamma_{\text{min}} \sim 1$.

### TABLE 1

| Source       | $z$   | $R$      | $B$ | $\delta$ | $\gamma_\text{b}$ | $n_1$ | $n_2$ | $K$     | $U_{\text{BLR}}$ |
|--------------|------|---------|-----|----------|-------------------|------|------|-------|-------------|
| 0208–512 (PKS) | 1.003 | 1.5     | 1.5 | 18       | 100               | 1.4  | 3.8  | $2 \times 10^4$ | 15           |
| 0521–365 (PKS) | 0.035 | 2.0     | 0.3 | 3$^\mu$ | $8.8 \times 10^3$ | 1.25 | 4 $^\mu$ | $3 \times 10^3$ | 0.1          |
| 0537–441 (PKS) | 0.039 | 4.65    | 2.1 | 10       | 400               | 1.6  | 3.4  | $3.5 \times 10^3$ | 33           |
| 0836+710 (4C71.07) | 2.172 | 4       | 3   | 16       | 50                | 1.6  | 4.0  | $5 \times 10^4$ | 54           |
| 1253–055 (3C279) | 0.539 | 5       | 0.5 | 12.3     | 600               | 1.6  | 4.2  | $4.5 \times 10^3$ | 0.1          |
| 1510–089 (PKS) | 0.036 | 1       | 1.5 | 19       | 50                | 1.7  | 3.6  | $6 \times 10^3$ | 0.8          |
| 1641+399 (3C243) | 0.593 | 4.0     | 2.9 | 9.75     | 200               | 1.5  | 4.2  | $2.8 \times 10^3$ | 30           |
| 2223–052 (3C446) | 1.4   | 2.45    | 5.6 | 17       | 135               | 1.6  | 4.3  | $1.7 \times 10^3$ | 18           |
| 2230–014 (CTA102) | 1.037 | 3       | 1.65| 18       | 55                | 1.9  | 3.4  | $3 \times 10^4$ | 6.5          |
| 2243–123 (PKS) | 0.064 | 3.5     | 2.5 | 15       | 250               | 1.6  | 4.3  | $1.7 \times 10^3$ | 18           |
| 2251+158 (3C454.4) | 0.089 | 4.0     | 1.5 | 12       | 60                | 1.8  | 3.4  | $5 \times 10^4$ | 10           |
| 1101+384 (Mkn 421) | 0.03  | 1       | 0.06| 20       | $3 \times 10^4$  | 2.2  | 5.3  | $4 \times 10^4$ | ...          |
| 1219+285 (ON231) | 0.102 | 0.7     | 0.8 | 14       | $5 \times 10^4$  | 2    | 3.9  | $5 \times 10^3$ | ...          |
| 1652+398 (Mkn 501) | 0.03  | 0.19    | 0.32| 10       | $1.1 \times 10^4$| 1.5  | 7.5  | ...               | ...          |
| 2155–304 (PKS) | 0.117 | 0.3     | 1   | 18       | $3.2 \times 10^4$| 2    | 4.85 | $5 \times 10^4$ | ...          |
| 2200+420 (BL Lac) | 0.07  | 0.2     | 1.5 | 20       | $10^4$            | 1.9  | 3.8  | $2 \times 10^5$ | ...          |

* See text.
The derived jet powers are reported in Table 2. Table 2 shows that the magnetic field tends to be close to equipartition with the relativistic particles in FSRQs but largely below equipartition in BL Lacs, especially in TeV sources ($U_e/U_B \sim 10$–100). The latter result has been recently independently found by other authors and appears to be rather robust (see in particular the discussion of Kino et al. 2002). Clearly, in all cases the total jet power is dominated by protons, while the magnetic field and relativistic electrons give minor contributions.

An important quantity is the total radiative luminosity ($L_{\text{jet}}$) of the jet, integrated over the whole solid angle in the observer frame. This is derived from the observed apparent luminosity correcting for beaming (e.g., Sikora et al. 1997), $L_{\text{jet}} = (L_{\text{obs}}/6^4)T^2 \simeq (L_{\text{obs}}/T^2)$. $L_{\text{jet}}$ represents the minimum power that must be associated with the jet in order to produce the observed luminosity, i.e., a lower limit to $P_{\text{jet}}$.

In Figure 1 we compare the radiative luminosities of jets with the powers provided by the electron component only. The dotted line indicates the relation $L_e = L_{\text{jet}}$. In most cases, the power associated with the electron component alone is insufficient or at best marginally sufficient to sustain the jet beyond the inner emission region. Analogously, the Poynting flux associated with the transport of magnetic field is too small, unless other components or complex geometries for the magnetic field are invoked. Thus, a proton contribution seems the most natural to explain the transport of energy to large distances.

In Figure 2 $L_{\text{jet}}$ is compared with the total power estimated including protons $P_{\text{jet}}$. There is a well-defined correlation between the two quantities (probability greater than 99.9%, slope = 1.12 ± 0.17), extending over a range of about 4 orders of magnitude. Notably, BL Lac objects appear to lie on the same (linear) correlation with powerful quasars, supporting the view that these two classes of blazars have similar jets.

The radiative efficiency, $\eta = L_{\text{jet}}/P_{\text{jet}}$, turns out to be in the range 1%–10%. It is interesting to note that similar values are naturally predicted by the internal shock scenario, recently proposed for blazars by Spada et al. (2001).

4. THE JET-DISK CONNECTION

The disk luminosity $L_{\text{disk}}$ was estimated either directly from the optical-UV luminosity of the blue bump attributed to an optically thick accretion disk (e.g., Sun & Malkan 1989) or from the luminosity of the broad emission lines (assuming $\tau = 0.1$), using the relations proposed by CPG97. For 3C 279 we used the luminosity of...
the blue bump identified in the IUE data by Pian et al. (1999); we checked that this luminosity is close to 10 times the luminosity estimated from the emission lines. For BL Lacs, except for BL Lac itself, for which a broad emission line has been observed (Corbett et al. 2000), one can only derive upper limits to the luminosity of the (putative) accretion disk (CPG97).

Figure 3 shows the radiative luminosity of the jet, \( L_{\text{jet}} \), against the disk luminosity \( L_{\text{disk}} \). A dotted line represents the equality of the two. It is apparent that for high-luminosity blazars (FSRQ) \( L_{\text{jet}} \), which represents the minimal power transported by the jet, is of the same order as the luminosity released in the accretion disk. The situation is different for low-luminosity blazars (BL Lac objects). For the latter objects, the jet luminosity is higher than the estimated/upper limits on their disk luminosity. Because \( L_{\text{jet}} \) is obtained from the observed SED with only a beaming correction, the results above are largely independent of the theoretical model adopted and in particular of the assumptions concerning the proton component, which enter in the estimate of \( P_{\text{jet}} \).

In view of a more quantitative discussion, however, it is essential to convert the derived luminosities into powers, taking into account radiative efficiencies for both the jet and the disk. Let us define \( L_{\text{jet}} = \eta P_{\text{jet}} \) and \( L_{\text{disk}} = \epsilon P_{\text{acc}} \). As discussed in § 3, \( \eta \sim 0.1-0.01 \), where the higher value holds for high-luminosity jets. On the other hand, for high-luminosity blazars in which the blue bump and/or broad lines are observed, the accretion disk is also extremely luminous (see Fig. 3). It is then natural to assume that the disk should have efficiency close to standard, that is \( \epsilon \sim 0.1 \); otherwise, implausibly high accretion rates, as large as \( 10 \ M_\odot \text{ yr}^{-1} \), would be required. The radiative efficiencies for the jet and disk are then of the same order so that comparable luminosities \( L_{\text{jet}} \sim L_{\text{disk}} \) imply comparable powers, \( P_{\text{jet}} \sim P_{\text{acc}} \). This near equality, although difficult to achieve according to presently available models (see below), represents the main result of our analysis.

For low-luminosity blazars, \( \eta \sim 0.01 \) and \( L_{\text{jet}} > L_{\text{disk}} \). Assuming that the relation \( P_{\text{jet}} \sim P_{\text{acc}} \) is verified for all blazars, in order to account for a jet luminosity larger than the disk luminosity a very low radiative efficiency for the disk is implied. This can be explained naturally if the accretion flow in these systems has the structure of an “ion torus” (Rees et al. 1982) or advection-dominated accretion flow (ADAF) (Narayan, Mahadevan, & Quataert 1998), whereby the inefficient cooling keeps the flow geometrically thick, supported by the pressure of hot ions. Such configurations are possible if the accretion rate is largely sub-Eddington.

This scenario then suggests that the range of powers observed in blazars is essentially due to a range in accretion rate onto BHs of equally large masses.

### 4.1. Discussion

Two main classes of models for the formation of jets consider either extraction of rotational energy from a rapidly spinning BH, the Blandford & Znajek (1977) (BZ) process, or magnetohydrodynamic winds arising from the inner regions of accretion disks (MHD) (Blandford & Payne 1982). In the latter scenario, jets would be powered solely from the accretion process through the action of the magnetic field. Livio, Ogilvie, & Pringle (1999) show that the power extracted through the latter mechanism can be important. For reasons of global consistency, however, it would seem difficult that in this type of model a large fraction (of order 1) of the accretion power could be channeled into a highly relativistic outflow.
The complex analysis of BZ can be summarized in the well-known expression

$$P_{BZ} \simeq \frac{1}{128} B_0^2 r_g^2 a^2 c,$$

(2)

where $r_g$ is the gravitational radius and $a = j/j_{\text{max}}$ is the adimensional angular momentum of the BH, $a = 1$, for a maximally rotating BH (e.g., Thorne, Price, & MacDonald 1986). The critical problem is the estimate of the intensity reached by the magnetic field threading the event horizon, which must be provided by the surrounding matter.

Let us take as reference an extreme approximation, i.e., a spherical free-fall accretion flow. Assuming equipartition of magnetic and kinetic energy density ($B_0/8\pi \approx \rho c^2$) as a zero-order approximation to the physical picture envisaged for the “plunging” region (Krolik 1999), it is easy to find that

$$P_{\text{acc}} = g a^2 \dot{m} 10^{47} M_{\odot} a^2 \text{ erg s}^{-1},$$

(3)

where $P_{\text{acc}} = \dot{M} c^2$ is the accretion power and $g = 1/64$; $\dot{m} = \dot{M} c^2/L_{\text{edd}}$ is the accretion rate in Eddington units, and $M_0$ is the BH mass in units of $10^9 M_{\odot}$. This simple formula shows clearly that even when the jet is produced at the expense of the BH rotational energy, the generated power is closely linked to the accretion rate. Equation (3) is shown as a dashed line in Figure 3 (assuming $\eta \approx \epsilon \approx 10^{-1}$) and is clearly insufficient to account for our results.

In the case of disk accretion, one expects higher densities and plausibly higher fields. Ghosh & Abramowicz (1997) (GA) discussed the possible field strengths threading the BH horizon on the basis of the disk model of Shakura & Sunyaev (1973). Their results are shown in Figure 3 as continuous lines (efficiencies as above). It is interesting to note that when the disk is in the gas pressure–dominated regime ($f < 10^{-3}$), ratios $L_{\text{jet}}/L_{\text{disk}}$ not far from unity are indeed obtained ($g \approx 1$). However, because of the pressure saturation introduced by the formation in the disk of a radiation pressure–dominated region (horizontal branches in Fig. 3), the model fails to explain the large powers observed in the jets of bright quasars, even for maximal rotation and large BH masses ($g \ll 1$ for $m > 10^{-3}$).

Our results, pointing to a high yield for the jet production mechanism, underline the need of further investigations of the BZ process in more general conditions, both for the disk model (e.g., $\beta$ disk models; Sakimoto & Corroniti 1981) and for its interaction with a fast-spinning BH. In fact, it has been suggested that dynamical effects and frame dragging by the rotating hole may restore $g$ to values of order 1 or even larger (Krolik 1999; Merin 1999, 2001).

The scenario indicated by our results involves a substantial equality of the jet and accretion powers, which could hold for all blazars. High-luminosity blazars including highly polarized, optically violently variable quasars (HPQ, OVV) or more generically quasars with flat spectrum radio cores (FSRQ) owe their properties to a high, near-critical accretion rate, which accounts at the same time for the presence of bright accretion disks and of powerful jets. Low-luminosity blazars (otherwise called BL Lacs), in which clear signatures of an accretion disk are not found, can be explained by largely subcritical accretion rates, giving rise to radiatively inefficient accretion flows and low-power jets. Thus there is no “genetic” difference between FSRQs and BL Lac objects, and the blazar population can be “unified” and described in terms of a single parameter ($m$).

The idea that the power scale of blazars corresponds to a scale of accretion rates in objects with essentially similar (large) masses and high angular momentum ($a \sim 1$) also provides a physical basis to understand the “spectral sequence” of blazars proposed by Fossati et al. (1998). The latter paper showed that the spectral energy distributions (SED) of blazars change systematically with luminosity in the sense of a shift of the emission peaks toward higher frequencies with decreasing luminosity. The modeling of Ghisellini et al. (1998) showed that the particles radiating at the peaks have lower energies in higher luminosity objects, which was interpreted as being due to a larger density of ambient photons, resulting in a larger cooling rate. The scaling proposed here supports this view, in the sense that, because of the ADAF-like accretion flow, less powerful jets find a much cleaner ambient in the transition region from the BH to the parsec scale.

The evolutionary aspects of this scenario have been explored by Cavaliere & D’Elia (2002) and found to be in agreement with present data on the number counts. Moreover, Cavaliere & D’Elia (2002) also discuss reasons for the correlation between luminosity and the average shapes of the SEDs. Within a closely similar scenario, Böttcher & Dermer (2002) developed a specific model of the expected SEDs, introducing a number of hypotheses and parameters.

In particular, Cavaliere & D’Elia (2002) and Böttcher & Dermer (2002) proposed that the blazar spectral sequence also traces an evolutionary sequence, from young FSRQs to the older BL Lac objects. FSRQs are rich in gas and therefore are characterized by large accretion rates, while BL Lac objects represent evolved sources depleted of gas, with faint nuclear emission and low-power jets. Our results provide a solid basis for these speculations.

This scenario can be observationally tested, taking advantage of the correlations between the mass of the central BH and the host galaxy properties (e.g., Merritt & Ferrarese 2002) for estimating the BH masses in blazars of different types. Treves et al. (2001) measured the host galaxies around a large number of BL Lacs. Their results (see also Urry et al. 2000; Scarpa et al. 2000) show that the magnitudes of the host galaxies have relatively little scatter and are independent of the luminosity of the BL Lac. Assuming (e.g., Ferrarese & Merritt 2000) that the central BH mass correlates with the mass of the bulge and therefore with the magnitude of the galaxy, one can derive (to zero order) that the BH mass is similar in all these objects. More accurate estimates are possible, measuring the stellar velocity dispersions of the host galaxies for which the intrinsic correlation with BH mass is thought to be much tighter. Using the latter method, Barth, Ho, & Sargent (2002) derived a BH mass of $10^{9} M_{\odot}$ for Mrk 501, yielding for this object a highly subcritical accretion rate, in complete agreement with our expectations.

5. CONCLUSIONS

Estimates of the powers transported by the jets of a small group of FSRQs and BL Lac objects, for which broadband spectra have been obtained with BeppoSAX, were derived by modeling their overall SEDs with the widely accepted synchrotron/IC emission model. Comparing jet powers and luminosities with estimates of the accretion luminosity...
derived from the optical-UV spectra, we find that for the most powerful blazars the power carried by the jet is of the same order as the accretion power. Moreover, comparing the respective jet and accretion luminosities of FSRQ with those of BL Lacs with data of comparable quality on their SEDs, we find that for the latter the jet luminosity is higher than the upper limits on the accretion luminosity.

Taking into account the radiative efficiencies of both the jet and the accretion disk, we infer that the mechanism of jet production must have high efficiency (in terms of $M c^2$) favoring energy extraction from a Kerr hole, rather than a hydromagnetic wind generated by an accretion disk.

In view of the various approximations used, the conclusions above can only be regarded as tentative. Nevertheless, the available evidence suggests that the main parameter governing the total power and the ratio between jet and accretion luminosity is the accretion rate. In FSRQs, the accretion rate must be high, near Eddington. This can explain the large powers and the contemporaneous presence of thermal signatures associated with efficient disk accretion. The absence of thermal signatures in BL Lac objects (and in low-power radio galaxies) can be ascribed to a highly subcritical accretion disk with low radiative efficiency.

The unification of the two classes of sources into a single blazar population, previously proposed on the basis of a spectral sequence governed by luminosity (Fossati et al. 1998; Ghisellini et al. 1998) and recently revisited by Cavaliere & D’Elia (2002) and Böttcher & Dermer (2002) therefore finds a physical basis.

The scenario is testable through measurements of the properties of the host galaxies of blazars of different types, leading to estimates of the central BH mass.

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APPENDIX

THE HOMOGENEOUS SYNCHROTRON-INVERSE COMPTON MODEL

We give here the full description of the model used to reproduce the SED of blazars adopted in our work.

The emission region is assumed to be a sphere ("blob") with radius $R$, uniformly filled by a tangled magnetic field with intensity $B$ and isotropic relativistic electrons with energy distribution $N(\gamma)$. The region is in motion with velocity $\beta c$ and bulk Lorentz factor $\Gamma$ at an angle $\theta$ with respect to the line of sight. Relativistic effects in the emitted radiation are then taken into account by the relativistic Doppler factor $\delta$, defined by

$$\delta = \frac{1}{\Gamma(1 - \beta \cos \theta)} .$$

The electron distribution is described (for $\gamma_{\text{min}} < \gamma < \gamma_{\text{max}}$) by the law (in the following, physical quantities are expressed in the comoving frame)

$$N(\gamma) = K \gamma^{-n_1} \left( 1 + \frac{\gamma}{\gamma_b} \right)^{-n_2} ,$$

where $K$ (cm$^{-3}$) is a normalization factor (it represents the density of electrons with $\gamma = 1$), $\gamma_b$ is the break Lorentz factor, and $n_1$ and $n_2$ are the spectral indices below and above the break, respectively. This law represents a double power-law distribution with a smooth connection. This particular form for the distribution function has been assumed on a purely phenomenological basis in order to describe the curved shape of the SED.

Once the parameters are specified, the outstanding spectrum is calculated using the standard single-electron synchrotron emissivity (e.g., Rybicki & Lightman 1979) and the IC emissivity including the full Klein-Nishina cross section given by Jones (1968). Specifically:

1. In the case of the synchrotron emission the emissivity at a given frequency $\nu_s$ is calculated using the relation

$$j_s(\nu_s) = \frac{1}{4\pi} \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} N(\gamma) P(\nu_s, \gamma) d\gamma ,$$

where $P(\nu_s, \gamma)$ is the standard specific power emitted by a single electron with Lorentz factor $\gamma$. The spectrum is calculated between the two limit frequencies $\nu_{s,1}$ and $\nu_{s,2}$, where $\nu_{s,1}$ is the self-absorption frequency (calculated using the approximation obtained for the slab geometry given in Ghisellini et al. 1985) and $\nu_{s,2}$ is the maximum frequency, evaluated as the typical synchrotron frequency of electrons with energy $\gamma_{\text{max}}$, $\nu_{s,2} \sim 3 \times 10^9 B_{\text{max}}^{-2}$.

2. For the calculation of the IC spectrum we adopt the single-electron emissivity $j_C(\nu_C; \gamma, \nu_I)$ (function of the electron energy $\gamma m c^2$ and of the soft photon frequency $\nu_I$) calculated by Jones (1968) (see also Blumenthal & Gould 1970). The total emissivity $j_C(\nu_C)$ is calculated by integrating the single-electron emissivity over the soft photon spectrum and the electron energy distribution (from $\gamma_{\text{min}}$ to $\gamma_{\text{max}}$),

$$j_C(\nu_C) = \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} N(\gamma) \int_{\nu_{s,\text{min}}}^{\nu_{s,\text{max}}} n_s(\nu_I) j_C(\nu_C; \gamma, \nu_I) d\nu_I d\gamma ,$$

where $n_s(\nu_I)$ is the soft photon distribution.
where $n_t(\nu_t)$ is the numerical density of target photons, $n_e(\nu_e) = U(\nu_e)/\hbar \nu_e$. The energy density $U(\nu_e)$ of the soft target photons is calculated as follows:

1. In the case of SSC emission, the energy density of the synchrotron target photons is calculated with (e.g., Ghisellini et al. 1998)

$$U(\nu_e) = \frac{4\pi R^2}{3c} j(\nu_e),$$

(A5)

where $\nu_{1,\text{max}}$ and $\nu_{2,\text{max}}$ are fixed to $\nu_{1,\text{min}}$ and $\nu_{2,\text{min}}$, respectively.

2. For the calculation of the EX spectrum, we need a prescription to model the external radiation field. We assume that the spectrum of the external radiation is characterized by a blackbody-like spectrum with temperature $T$ and total luminosity $L_{\text{ext}}$ diluted in a spherical region with radius $R_{\text{BLR}}$ (typically of the order of the radius of the broad-line region). The external radiation energy density (in the observer frame) is

$$U_{\text{ext}}(\nu_{\text{obs}}) = \frac{L_{\text{ext}}(\nu_{\text{obs}})}{4\pi R_{\text{BLR}}^2}.$$  

(A6)

Because of relativistic amplification effects the (angle-averaged) energy density seen in the blob’s reference frame will be

$$U^\Gamma(\nu) = \Gamma U_{\text{ext}}(\nu_{\text{obs}}) = \frac{\nu_{\text{obs}}}{\Gamma}.$$  

(A7)

Comoving emissivities are used to calculate the observed fluxes as follows:

1. Synchrotron and SSC emissions are transformed according to the standard relations (e.g., Lind & Blandford 1985),

$$F_{\text{obs}}(\nu_{\text{obs}}) = \frac{\delta^3}{D^2} j(\nu = \nu_{\text{obs}}/\delta) V,$$

where $D$ is the luminosity distance and $V$ is the comoving emitting volume.

2. As pointed out by Dermer (1995), the beaming of the external radiation field in the source frame introduces a supplementary $\delta$ term in the calculation of the final flux. Dermer’s (1995) calculation assumed a number of approximations, namely, a single power-law electron distribution, the Thomson cross section, a monochromatic external radiation field, and extreme beaming (assuming that photons enter the source only head-on); thus, we cannot directly apply his results (expressed by the supplementary term $\delta^3/\delta^2$, where $\delta$ is the power-law index of the IC spectrum) to our more complex model. However, in the case $\delta = 1$ (as assumed in the present work), the effect of the anisotropy is taken into account simply assuming equation (A8) and using equation (A7) for the energy density.

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