THE BLAZAR MAIN SEQUENCE

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ABSTRACT

We propose a sequence (the blazar main sequence: BMS) that links the two main components of the blazar class, namely, flat-spectrum radio quasars (FSRQs) and BL Lac objects, and yields all their distinctive features in a correlated way. In this view, both types of sources are centered on a supermassive Kerr hole close to maximal spin and observed pole-on. However, the FSRQs are energized by accretion at rates \( \dot{m} \sim 1-10 \), and are dominated by disk components (thermal and electrodynamic jetlike components) that provide outputs in excess of \( L \sim 10^{46} \text{ ergs s}^{-1} \). On the other hand, accretion levels \( \dot{m} \ll 1 \) are enough to energize BL Lac objects; here the radiation is highly nonthermal, and the power is partly provided by the rotational energy of the central Kerr hole, with the latter and the disk together sustaining a typical \( L \sim 10^{44} \text{ ergs s}^{-1} \) for several gigayears. If so, we expect the BL Lac objects to show quite different evolutionary signatures from the FSRQs, and in particular, number counts close to the Euclidean shape, or flatter if the sources make a transition to a BL Lac from an FSRQ mode. In addition, for lower \( \dot{m} \) along the BMS, we expect the large-scale electric fields to be less screened out and to accelerate fewer particles to higher energies radiating at higher frequencies; so in moving from FSRQs to BL Lac objects, these nonthermal radiations will peak at frequencies inversely correlated with the disk output. For the BL Lac objects, such a dependence implies increased scatter when one tries a correlation with the total output. At its endpoint, the BMS suggests widespread objects that are radiatively silent but still efficient in accelerating cosmic rays to ultrahigh energies.

Subject headings: BL Lacertae objects: general — galaxies: nuclei — quasars: general

1. INTRODUCTION

Blazars are commonly perceived as a class of active galactic nuclei (AGN) that exhibit a range of features: strong, high-frequency radio emission from compact cores, often with superluminal expanding components (see Jorstad et al. 2001); powerful \( \gamma \)-rays extending to energies \( h\nu \sim 10^2 \text{ MeV} \) and beyond (see Mukherjee 1999); rapid multiwavelength variability (see Böttcher 2000); and high and variable optical polarization (see Yuan et al. 2001). Comprehensive reviews and extensive references concerning these sources can be found in Urry & Padovani (1995) and Padovani & Urry (2001, hereafter PU01).

The above features defining the blazar class are widely explained in terms of the view originally proposed by Begelman, Blandford, & Rees (1984). This holds the radiation from all these sources to be produced in a collimated, relativistic jet of particles with bulk Lorentz factor \( \Gamma \sim 5-20 \); when observed at small angles of the order of \( \Gamma^{-1} \), the jet produces the “blazing” effects that provide the class denomination. The intrinsic luminosity emitted by the jet over the entire solid angle and the total jet kinetic power are reviewed by Ghisellini (1999a), whose definitions and beaming factors we adopt in the following.

Within the blazar class, two main subclasses are usually identified, namely, BL Lac objects and flat-spectrum radio quasars (FSRQs). The former differs from the latter subclass on several accounts that we discuss in this paper: (1) lack of emission lines with EW \( \gtrsim 5 \text{ Å} \) and lack of blue-UV bumps; (2) total outputs \( L \lesssim 10^{46} \text{ ergs s}^{-1} \), compared with FSRQs often exceeding this limit and in some cases approaching \( 10^{48} \text{ ergs s}^{-1} \) (see specifically Maraschi 2001); (3) spectral energy distributions peaking at frequencies from optical to X-ray and in the range of 10 GeV, compared with the FSRQ peaks at far-IR to optical frequencies and around \( 10^{-1} \text{ GeV} \); and (4) no signs of cosmological evolution, compared with the strong evolution clearly displayed by the FSRQs in common with other quasars.

These distinctive features stand out from the many selections entangling this field, and even though intermediate objects are currently found (Sambruna, Chou, & Urry 2000; Perlman et al. 2001), the FSRQ/BL Lac object strong bimodality calls for explanation; this is the scope of the present work, which expands some preliminary results reported by D’Elia & Cavaliere (2001).

We base our paper on the accreting black hole paradigm (see Begelman et al. 1984), in the framework of a four-parameter classification similar to that discussed by Blandford (1990, 1993); this comprises the hole mass \( M \), its angular momentum \( J \), the accretion rate \( \dot{M} \), and the viewing angle \( \theta \) from the axis of the jet (if any). In the scheme that we contemplate, radio-quiet AGNs correspond to slowly rotating black holes with low (Seyfert galaxies) or full (quasars) \( \dot{M} \) compared to the Eddington rates; the quasars require large black hole masses \( M \) of the order of \( 10^9 \text{ M}_\odot \), to attain proportionately high Eddington luminosities \( L_E \approx 10^{47} \text{ M}_\odot \text{ ergs s}^{-1} \).

Radio loudness constitutes a debated issue. Radio-loud AGNs are often observed to reside in very bright galaxies. On the one hand, these sources have been inferred to correlate with large black hole masses; for instance, Laor (2000) stresses the case for radio loudness being a consequence of large \( M \). On the other hand, the majority of the optically selected quasars including very bright ones are radio-quiet (for recent data, see Goldschmidt et al. 1999; Hamilton, Turnshek, & Casertano 2000); in addition, Scarpa & Urry (2001) find that the hosts of quasars strong in the radio are...
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no different from giant ellipticals in general, including hosts of radio-quiet quasars. Finally, Ho (2002), from a comprehensive database, finds no simple relation between radio loudness and $M$. Similar data from more limited observations spurred the view (see Blandford 1993) that the other black hole parameter, namely, the spin, should be involved as a necessary, intrinsic condition for directing and launching the jets associated with radio emissions. In the present paper we focus on this view.

In fact, we consider the blazars in the context of supermassive black holes with $M \approx 10^9 M_\odot$, close to the maximal observed values for compact, massive dark objects in galactic nuclei (see Gebhardt et al. 2000; Ferrarese & Merritt 2000), and with high angular momentum $J \sim J_{\text{max}}$ close to the maximal $J_{\text{max}} = G M^2 / c$, observed nearly pole-on within angles $\theta \lesssim \Gamma^{-1}$ (see Sambruna, Maraschi, & Urry 1996). We concentrate on discussing how all blazar properties can be arranged into a blazar main sequence (BMS) in terms of levels of the accretion rate $\dot{m} = M c^2 / L_E$. Levels $\dot{m} \sim \eta^{-1} \approx 1-10$ (the radiative efficiency being up to about 0.4 around a Kerr hole) mark the FSRQs, while values $\dot{m} \lesssim 10^{-2}$ mark the BL Lac objects.

Our plan is as follows. In § 2 we stress how the optical properties of the blazars can be understood in terms of different levels of $\dot{m}$. In § 3 we show that high rates $\dot{m} \sim 1$ can produce the huge thermal and nonthermal outputs featured by many FSRQs, while conditions where $\dot{m} \ll 1$ lead to the moderate but mainly nonthermal outputs of the BL Lac objects. In § 4 we argue that for lower values of $\dot{m}$ along the BMS, the typical particle and photon energies are expected to increase; a secondary physical parameter relevant at low $\dot{m}$ causes considerable variance within the BL Lac object subclass, adding to the effects from the orientation. In § 5 we show how in the same framework, we understand the widely different evolutionary properties observed in FSRQs and in BL Lac objects. Finally, in § 6 we summarize and discuss our conclusions.

2. OPTICAL PROPERTIES

In the standard view (see Frank, King, & Raine 1992; Peterson 1997), all thermal outputs are produced in or around the accretion disk, with only weak anisotropies and with power given by $L_{\text{th}} \approx \eta \dot{m} L_E$.

Here we take up this view, and only stress how from the broad optical emission lines and the blue-UV bump in particular, we derive a first indication toward a BMS in terms of levels of $\dot{m}$. The bump is produced by power reprocessed in a superposition of blackbody emissions from the inner rings of the accretion disk or in a hot corona (see Sun & Malkan 1989; Siemiginowska et al. 1995); the lines are produced by the high UV–soft X-ray continuum reprocessed by distant gas “clouds” (see Netzer 1990). In both cases, the density of the reprocessing material is expected to scale up with increasing $\dot{m}$.

The FSRQs share with other quasars conspicuous bumps and prominent broad emission lines; the strengths of these features are consistent with high accretion rates: $\dot{m} \sim 1$. On the other hand, the weakness or absence of such features in the BL Lac object spectra can be understood if $\dot{m} \lesssim 10^{-2}$. In fact, at such levels of $\dot{m}$, not only is a weaker ionizing/exciting continuum emitted by the disk, but lower gas densities are also expected in the disk and its environ-

...ment out to parsec and larger scales; these conditions concur to account for the weak or absent emission lines.

The other effect in the BL Lac objects that acts to swamp any residual bump and to further reduce the EW of intrinsically weak emission lines is constituted by the blazing continuum from the jet when observed at a small angle (see Vagnetti, Giulilongo, & Cavaliere 1991; Georgopapoulos 2000).

We recall that the relation of low values of $\dot{m}$ to radio sources had been proposed by Begelman et al. (1984). Specifically, the different power levels and optical spectra of the Fanaroff-Riley (FR) II and FR I radio sources have been previously related to high and low values of $\dot{m}$, respectively, by Baum, Zirbel, & O’Dea 1995; this point is further discussed in § 6.

3. THE BLAZAR POWER

As for the jets, we assume them to be powered by variants of the mechanism originally proposed by Blandford & Znajek (1977, hereafter BZ77) for direct extraction of rotational energy from a Kerr hole via the Poynting-like flux associated with the surrounding magnetosphere. The BZ77 power scales as

$$L_K \propto B^2_h r_h \cdot$$

in terms of the magnetic field $B_h$ threading the hole horizon at $r_h$.

Variants are necessary in view of the limitations to $L_K$ recently stressed by Moderski & Sikora (1996), Ghosh & Abramowicz (1997), and Livio, Ogilvie, & Pringle (1999). Such variants involve either high strengths of $B_h$ or the similar electromagnetic output from the disk associated with a larger radius $r_d$.

In the first variant, a very strong $B_h$, as advocated by Meier (1999), is required to account for the huge outputs of some FSRQs. 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 (2001) and Paczyński (2000) discuss why such field values are unlikely in a thin disk. In thick disks, the status of such enhanced fields is still not settled.

The second variant takes up from recent discussions (Ghosh & Abramowicz 1997; Livio et al. 1999) that have stressed the continuity of $B_h$ with the field $B_d$ at the inner rim of a standard $\alpha$-disk; in turn, $B_d$ is bounded by the maximum pressure, following $B_d^2/4\pi \lesssim P_{\text{max}}$. Depending on $\dot{m}$, the inner disk is dominated by gas pressure (GPD) or by radiation pressure (RPD): the pressure scales as $P_{\text{max}} \propto (\alpha M_\odot)^{-9/10} m_4^{-4/5}$ in the first and as $P_{\text{max}} \propto (\alpha M_\odot)^{-1}$ in the second regime. Correspondingly, in the first regime, the maximum power extractable from the hole grows with $\dot{m}$, and in the jet frame, the emission is (see Moderski & Sikora 1996; Ghosh & Abramowicz 1997)

$$L_K = 10^{44} M_9^{11/10} m_4^{4/5} \left( \frac{J}{J_{\text{max}}} \right)^2 \text{ergs s}^{-1} \text{ (GPD)}$$

in terms of the Kerr hole mass $M = M_9 10^9 M_\odot$; but for $m_4 \lesssim 10^{-3}$, the power $L_K$ saturates to

$$L_K = 2 \times 10^{45} M_9 \left( \frac{J}{J_{\text{max}}} \right)^2 \text{ergs s}^{-1} \text{ (RPD)}.$$

This is because the radius $r_c$ defining the RPD region grows
with \( m^{16/21} \) (Novikov & Thorne 1973), and it turns out to exceed the radius \( r_{ms} \) of the last stable orbit when \( m \gtrsim 10^{-3} \) holds; in the latter conditions, an inner RPD region actually exists.

On the other hand, the electrodynamical power \( L_{d} \) contributed by the disk, itself strongly anisotropic, scales as

\[ L_{d} \propto B_d^2 r_d^3, \]

here the effective disk radius \( r_d \) is bounded at several times \( r_h \) either by the value of \( r_b \) or by the radial decline in the disk of the efficiency \( \eta \propto r^{-1} \). We recall that the ratio \( L_d/L_K \) had originally been estimated by BZ77 at values \( \gtrsim 5 \); recent reappraisals (e.g., by Livio et al. 1999) have evaluated its upper bound at \( L_d/L_K \sim (B_d/B_b)^2 (r_d/r_b)^{3/2} \).

We draw the following implications concerning the BMS. Many BL Lac objects can live on accretion rates \( \dot{m} \sim 10^{-2} \), since the power levels \( L_K \) given by equation (3) are adequate, even including the kinetic energy in the jets (Celotti, Padovani, & Ghisellini 1997; Maraschi 2001). A larger but comparable contribution comes from the disk, so that \( L_K \sim L_d \gtrsim L_h \) holds. The disk is coupled to the rotating hole both dynamically and magnetically (see Livio et al. 1999) through the magnetic field lines threading the hole and tethered in the disk.

On the other hand, many FSRQs feature total outputs \( L > 10^{46} \) ergs s\(^{-1} \), with specific sources exceeding \( 10^{47} \) ergs s\(^{-1} \); see Tavecchio et al. (2000) and Maraschi (2001), who include a high proton contribution to the jet energy, and adopt average values of \( \Gamma \approx 10 \) (see also Sikora 2001). Such luminosities require not only a saturated \( L_K \) (see eq. [3]) but also a dominant component up to \( L_d \sim 10^2 L_K \) from the disk corresponding to \( B_d \) a few times larger than \( B_b \) and \( r_d \sim 5 r_h \); this implies an extended region dominated by radiation pressure, and hence conditions where \( \dot{m} \sim 1 \), consistent with the requirements from the optical properties discussed in § 2.

We note that in FSRQ conditions, both \( L_d \) and the thermal emission \( L_{th} \) are fed by the gravitational power supply of the order of \( GMMc^2/2r_\odot \). The balance between \( L_d \) and \( L_{th} \) depends on the power spectrum of the magnetic field inhomogeneities, that is, on the power distribution between two scales: the coherent large-scale versus the turbulent small-scale component. Dominance of the former, such as to yield a large \( L_d \) and a large associated transfer of angular momentum outward, may require modifications of the standard \( \alpha \)-disk model as discussed by Salviati (1997).

The hole output \( L_{K} \), even when it constitutes a minor component of the total, is likely to be important for providing on the jet axis a “high-velocity spine,” instrumental for the outward jet propagation (see Livio 2000; Chiaberge et al. 2000).

4. THE BLAZAR SPECTRAL ENERGY DISTRIBUTIONS

Another feature of the blazars is constituted by their extended spectral energy distribution (SED). This shows a first peak commonly interpreted as synchrotron radiation (see Urry & Padovani 1995). In the FSRQ spectra, the peak frequencies \( \nu_{\text{peak}} \) lie mainly in the range from the far-IR to the optical band; in BL Lac objects, the peaks are generally shifted to higher frequencies, and in some objects, up to the hard X-rays (Costamante et al. 2001).

An additional high-energy component to the radiation (see PU01) is observed into the 10 GeV range for FSRQs, and out to several TeVs for some BL Lac objects.\(^1\) This is likely to be inverse Compton emission produced by substantial numbers of 1 GeV or \( 10^2-10^3 \) GeV electrons, respectively, scattering off external or synchrotron seed photons as discussed by Ghisellini (1999a).

The apparent inverse scaling of \( \nu_{\text{peak}} \) with the radiative \( L \) in moving from FSRQs to (quiescent) BL Lac objects has been pointed out by Fossati et al. (1998), and interpreted as a cooling sequence due to the radiative energy losses being faster in the more powerful sources, so as to control the maximal electron energies. Concerning the acceleration, one view considers weak electric fields over relatively large distances; these conditions may occur in the internal-shock scenario in which, however, the energies produced are of the order of \( \delta \sim 2 \times 10^7 \) GeV and fall short of the top energies required in some BL Lac objects as discussed by Ghisellini (1999b).

Therefore, we are led to consider as an addition or as an alternative particularly relevant to BL Lac objects the electron acceleration due to higher electric fields acting over shorter distances. We shall see that this leads to an acceleration sequence, also linked with the BMS; this is because in BL Lac objects, lower levels of \( \dot{m} \) allow for higher electron energies and so produce SEDs peaked at higher frequencies. Meanwhile, a second intrinsic parameter produces the specific scatter of \( \nu_{\text{peak}} \) within this subclass.

Such high \( E \) fields naturally arise around the BZ77 magnetosphere in association with considerable energy transport via “pointing flux” along the jet, with the magnetic field decreasing outward rather slowly, as \( B = B_d(r_{ms}/r)^{1+n_p} \) with \( p < 1 \); typically \( p = \frac{1}{4} \), in a manner similar to Blandford & Payne (1982). The force-free condition \( \mathbf{E} \cdot \mathbf{B} = 0 \) governing the BZ77 magnetosphere has to break down at the flow boundaries and give way to electric fields \( E \lesssim B \); this is likely to occur time-dependently and inhomogeneously within sheets or filaments located at average distances \( r \sim 10^{16}-10^{18} \) cm. However, such \( E \) fields are electromagnetically screened out beyond distances exceeding a few times \( d = c/\omega_p \propto (\gamma/n)^{1/2} \), where \( \omega_p = (4\pi \epsilon_0 n/m_e c^2)^{1/2} \) is the plasma frequency of the screening particles with Lorentz factor \( \gamma \) and density \( n \).

Lower bounds to the densities can be estimated from the power emitted in the form of synchrotron or inverse Compton radiation; that is, \( L \sim \gamma^2 U R n \), where \( U \) is the total energy density in quiescent conditions. We obtain \( n \sim 1 \) cm\(^{-3} \) for BL Lac objects with \( L \sim 10^{44} \) ergs s\(^{-1} \) and \( n \sim 10^3 \) cm\(^{-3} \) for FSRQs with \( L \sim 10^{47} \) ergs s\(^{-1} \). Correspondingly, we expect many electrons to attain high energies, up to

\[ \gamma_{\text{max}} \lesssim \frac{eBd}{mc^2} \sim 10^8 B_d M_0^{2.25} d_{10^{-17}}^{1.25}, \]

where we have used \( d = 10^{10} d_{10} \) cm and \( r = 10^{17} r_{17} \) cm; we have also expressed as \( B_d = 10^4 B_g G \) the field values at \( r_{ms} \approx 1.5 \times 10^{14} M_0 \) cm, which decreases into the emitting region like \( B(r) = B_d (r_{ms}/r)^{1.25} \), as recalled above.

In equation (5) there is room for variations of \( B \) and \( n \); the former may be down by a factor of 10 or the latter

\(^1\) Note that the \( \gamma \) ray spectra at the sources may extend to higher energies than observed at Earth after the intervening absorption due to the IR background. If so, the argument below concerning the acceleration would be reinforced.
up by a factor of $10^2$ (with $M$ again set at $10^9 M_\odot$), and equation (5) still yields $\gamma \sim 10^7$. This is enough to produce inverse Compton photons up to $\sim 10$ TeV, the highest energy photons observed up to now from BL Lac objects. In FSRQs, densities $10^3$ times larger give electron energies some 30 times smaller, consistent with the parameters derived by Böttcher & Dermer (2002) from advanced spectral modeling. Given $\gamma_{\text{max}}$, we expect less energetic but more numerous electrons to arise naturally when the particles escape before full acceleration or $E < B$ holds, and when the inhomogeneities of $B$ are considered; the latter varies outward following $B \propto r^{-1.25}$, as stated, and this condition by itself produces an energy range over factors of about $10^5$ within a distance range $r \sim 10^{17}\pm1$ cm.

The electron energies given by equation (5) are proportional to $d \propto n^{-1/2}$, and so scale as

$$\gamma_{\text{max}} \propto (\gamma^2 U R^3)^{1/2} L^{-1/2}.$$  

This results in $\gamma_{\text{max}} \propto L^{-1/2}$ if we adopt the empirical relation $\gamma^2 U \sim \text{const}$ reported by Ghisellini (1999a) for the FSRQs. On the other hand, the same author finds that the $\gamma$ values for the BL Lac objects exceed this relation but can be included on modifying it to read $\gamma U \sim U^{-0.2}$; from this we obtain $\gamma_{\text{max}} \propto L^{-3/5}$. Thus, we expect the peaks of the non-thermal emissions, and more clearly the synchrotron $\nu_{\text{peak}} \propto \gamma_{\text{max}}^{-2}$, to anticorrelate strongly with the disk luminosity, following $\nu_{\text{peak}} \propto L^{-6/5}$ or steeper when one compares the FSRQ with the BL Lac object subclass.

In closer detail, the emitting particles are likely to constitute the high-energy subset of the total particle population, but similar results are obtained if all electrons are described as in Ghisellini (1999a) by a power-law energy distribution $\dot{n}(\gamma) \propto \gamma^{-a}$ from $\gamma_{\text{min}} \sim 10^5$; with $a \approx 2.5$, we obtain $\nu_{\text{peak}} \propto \gamma_{\text{max}}^{-2} L^{-4/3}$, while the steeper relation $\nu_{\text{peak}} \propto L^{-2}$ holds when $a \approx 2$. Concerning the full SED, we refer to the complete modeling of the emitting regions by Böttcher & Dermer (2002), who quantitatively treat the spectral shapes radiated by synchrotron and inverse Compton emissions in the jets, also considering the cooling limit to the electron energies provided by the high photon densities in FSRQs; they evaluate detailed parameters agreeing with the orders of magnitude we estimate.

The other outcome from our view is that within the BL Lac object subclass, we also expect the second parameter $L_K/L_d$ to affect the scaling laws provided by equation (6). This is because the total radiative luminosity of the BL Lac objects $L = L_d + L_K$ comprises a disk and a Kerr hole component with comparable power. Of these, only $L_d \propto GM/M c^2$ is directly related to $\dot{m}$ and to $n$, while $L_K$, when considerable, tends to be independent of them, as shown by equation (3). Thus, at a given $L_d$ (hence, at a given $M$ and $n$), higher total luminosities are obtained in BL Lac objects where $L_K$ is important. In other words, $\nu_{\text{peak}}$ scales inversely with the component $L_d$ only, and it is bound to show scatter specific to BL Lac objects when one tries to correlate it with the total luminosity. As a consequence, we do not expect the scaling to extend unblurred from the so-called LBLs to the HBLs (low- and high-energy peaked BL Lac objects, respectively; see Padovani & Giommi 1995). In fact, considerable scatter of $\nu_{\text{peak}}$ at a given $L$ is increasingly found within the BL Lac object subclass (see Giommi et al. 2001).

On the other hand, for FSRQs $L \approx L_d$ holds; that is, $L_K$ is irrelevant to the total power and so is its contribution to the scatter.

The specific BL Lac object scatter discussed here adds to other components common to all blazars because of different values of $B$, $M$, and viewing angles (see Sambruna et al. 1996; Georganopoulos 2000), and of variations of $\nu_{\text{peak}}$ and $L$ arising during flares.

To this point, we have shown how all spectral properties of FSRQs and BL Lac objects are expected to consistently vary along the BMS. In the next section we discuss why we expect the blazar evolutions to also be related to different levels of $\dot{m}$.

5. THE BLAZAR EVOLUTIONS

Strong cosmological evolution is closely shared by FSRQs with the rest of the quasars (see Wall & Jackson 1997; Goldschmidt et al. 1999) and shows up, e.g., in their steep number counts; BL Lac objects instead show no signs of a similar behavior (Giommi, Menna, & Padovani 1999; Padovani 2001).

Here we argue that such an evolutionary peculiarity is related to the following two independent circumstances: (1) At levels $\dot{m} \leq 10^{-2}$, all BL Lac objects shine for several gigayears with only a mild decrease in luminosity (a very slow “luminosity evolution” [LE]), and this implies counts close to Euclidean. (2) A genetic link is conceivable from FSRQs to BL Lac objects; that is, some of the former may switch from a short-lived regime of high $\dot{m}$ to a long-lived regime of low $\dot{m}$, so the BL Lac objects also undergo some negative “density evolution” (negative DE) and their counts are further flattened. Since point 1 has been discussed by Cavaliere & Malquori (1999), we just recall their results below and concentrate on point 2.

The evolution of the bright optically selected (and mainly radio-quiet) quasars is strong (see Boyle et al. 2000), as it also is for X-ray–selected quasars (see Della Ceca et al. 1994; Miyaji, Hasinger, & Schmidt 2000). For the bright sources, this behavior is widely traced back to the exhaustion in the host galaxy of the circumnuclear gas stockpile usable for further accretion onto the central black hole. Such an exhaustion is caused by previous accretion episodes and by ongoing star formation (Cattaneo, Haehnelt, & Rees 1999; Kauffmann & Haehnelt 2000; Cavaliere & Vittorini 2000, hereafter CV00); the ensuing decrease of the average accretion rate $\dot{m}$ is fast and causes the average bolometric luminosities to scale down rapidly for $z < 2.5$ (a strong LE). The radio-loud quasars share this evolutionary behavior, constituting a fraction (not yet quantitatively understood; see §1, and the discussions by Moderski, Sikora, & Lasota 1998 and by Livio 2000) of the order of 10% of the total; the FSRQs in particular are widely held to be the same sources seen pole-on.

However, as the rates $\dot{m}$ and the luminosities $L$ decrease, we also expect a considerable fraction of the underlying hole-disk systems to eventually switch from being overwhelmingly fueled by accretion to being partly fed by the hole rotational supply $E_K$; the latter is stockpiled during the phases of accretion of coherent angular momentum $J$ along with the mass (Bardeen 1970; Moderski et al. 1998). In other words, we expect some radio-loud sources to switch from the FSRQ to the BL Lac object mode. The moderate outputs typical of this mode can be sustained for several giga-
years by the dynamically and magnetically coupled system constituted by the Kerr hole and inner disk, so the decrease of BL Lac object luminosities is expected to be slow (Cavaliere & Malquori 1999), with timescales in the range estimated to a first approximation by \( \tau_L \approx E_k / L_k \approx 5-10 \text{ Gyr} \), rather uniform within the population.

In closer detail, CV00 (see also references therein) trace the accretion episodes feeding the quasars back to interactions of the host galaxies with their companions in a group. These events destabilize the host gas and trigger accretion over times of the order of \( \tau \sim \text{a few } 10^{-1} \text{ Gyr} \) that comprise the duration of a close interaction and a few galactic dynamical times for the inflow to develop and subside; some 3–5 repetitions are expected per host galaxy after \( z \approx 2.5 \). The frequency of such interaction episodes diminishes in time and gives rise to a positive, weak DE of the quasar population over scales \( \tau_D \approx \text{several gigayears} \). Meanwhile, the efficiency of such episodes drops as anticipated above, because of the exhaustion of the host gas; the latter is halved on the scale \( \tau_L \approx 3 \text{ Gyr} \). The result is that the average luminosities drop over the same scale; in other words, a strong LE is produced in the quasar population.

On this basis, CV00 compute the luminosity function (LF) for the optically selected objects at \( z \leq 2.5 \) to be

\[
N(L, z) \approx \frac{\tau N_G(z) L_0(z)}{\tau(z) L_0(z) \left( \frac{1}{t_{c2}^2} + \frac{1}{t_{c3}^2} \right)} .
\]  

(7)

Here \( N_G(z) \) is the space density of groups of galaxies, \( \tau^{-1}(z) \propto (1 + z)^{3/2} \) is the average interaction frequency for a host galaxy in a group, and \( l \equiv L / L_0(z) \) is normalized using the break luminosity that scales as \( L_0(z) \propto (1 + z)^3 \) in the critical universe; we use this simple scaling for numerical evaluations, since CV00 show that the observables do not vary much in the \( \Omega_0 + \Omega_\Lambda = 1 \) cosmology. For the FSRQs, we use equation (7) with a proportionality factor of the order of \( 10^{-1} \).

Our main point here is that the episodes of powerful FSRQ activity feeding on high \( m \) will last some \( 10^{-1} \text{ Gyr} \) and die out over similar scales; the sources may no longer be reactivated after a “last interaction.” This leaves behind a rapidly spinning hole (and a relatively quiescent, although bright, galaxy; see Scarpa 2001) in about one-half of the objects. Thus, the DE timescale \( \tau_D \) for the deaths of the bright FSRQs also constitutes the timescale for BL Lac object births; we evaluate it from equation (7) integrated over \( L \geq L_0 \) to obtain

\[
\tau_D^{-1} = \frac{d}{d t} \ln \left[ \int_1^\infty N(l, t) dl \right] \approx \frac{d}{d t} \ln \left[ \frac{N_G(t)}{\tau(t)} \right] ,
\]  

(8)

with the second equality holding because only the time-dependent amplitude in equation (7) is relevant here. We obtain values of \( \tau_D \) between 7 and 5 Gyr, depending on the form for small \( z \) of \( N_G(z) \), which may scale as \( (1 + z) \) on assuming a Press & Schechter (1974) mass distribution or as \( (1 + z)^2 \) following Lacey & Cole (1993).

One sign of evolution is provided by the integrated source counts, which can be evaluated from the relation (see Cavaliere & Maccacaro 1990)

\[
N(> S) \propto S^{-3/2} \left[ 1 - C \left( \frac{S_0}{S} \right)^{1/2} + \mathcal{O}(S^{-1}) \right] ,
\]  

(9)

This simple relation is limited to high or intermediate fluxes.

On the other hand, it has the advantage of exposing how the evolutionary properties of the two blazar subclasses depend on the two population timescales \( \tau_D \) and \( \tau_L \) (the latter being long for BL Lac objects and short for FSRQs); these appear in the coefficient

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

(10)

For the BL Lac objects counted in the radio band, a relevant value is \( \tau_L \approx 5-10 \text{ Gyr} \) (marking the slow LE of the BL Lac objects). Other quantities involved are the flat spectral index \( \alpha \approx -0.3 \) in the GHz range, the slope \( \beta \approx 2.5 \) of the radio LF, the normalized moments \( \langle l^2 \rangle \) of the LF, and the typical distance to high-flux BL Lac objects \( D_0 = (L_0 / 4\pi S_0)^{1/2} \approx 0.03 R_H \) in Hubble units.

On using only the slow LE on the scale \( \tau_L \approx 8 \text{ Gyr} \), equation (10) with the Hubble constant \( H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1} \) yields \( C = -0.1 \); then, from equation (9) the result is \( N(> S) \propto S^{-1.8} \), as in Cavaliere & Malquori (1999).

In addition, BL Lac object births also imply the occurrence of negative DE, described by the scale \( \tau_D \approx -6 \text{ Gyr} \) evaluated below equation (8). When this scale is also introduced in equation (10), the values of \( C \) increase to \( C \approx 0.1 \). Now the result is \( N(> S) \propto S^{-1.5} \) at high or intermediate fluxes, consistent with the data by Giommi et al. (1999) (see Fig. 1); at 5 GHz, similarly flat counts are both expected (see Jackson & Wall 2001) and observed (see the preliminary data by Padovani 2001). We add that no evidence of evolution has been observed by Caccianiga et al. (2002) from the values of \( \nu_c / \nu_g \) in a large sample of BL Lac objects from the Radio-emitting X-Ray Sources survey.
The count slopes we evaluate for BL Lac objects are in sharp contrast to the result from a similar evaluation for FSRQs. The parameters appropriate for them are recalled above: $\tau_D = +6$ Gyr and $\tau_L = 3$ Gyr (dashed line). The open squares represent FSRQ counts from Wall & Jackson 1997.

Fig. 2.—FSRQ counts evaluated from eqs. (8) and (9) using $\tau_D = +6$ Gyr and $\tau_L = 3$ Gyr (dashed line). The open squares represent FSRQ counts from Wall & Jackson 1997.

6. DISCUSSION AND CONCLUSIONS

We have argued that blazars constitute basically similar sources comprising a supermassive, nearly maximally spinning Kerr hole and its accretion disk; but large systematic and correlated changes are bound to arise in all observational properties when the accretion rate levels vary from $m \sim 1$, which marks FSRQs, to $m \ll 1$, which marks BL Lac objects. Such systematic changes basically arise because lower values of $m$ imply depleted densities in and around the disk; by the same token, these cause both higher energies of the emitting particles with less reprocessing of the emitted photons, and lower total luminosities over longer timescales leading to slower evolution.

Our view outlined here leads us to specifically predict the following correlated features, also summarized in Table 1:

1. Optical properties.—In § 2 we recall that high values of $m$ yield strong thermal features, namely, emission lines and blue bumps. On the other hand, we stress that low values of $m$ imply intrinsic weakness or dumbing of all these features in the presence of a strong beamed continuum.

2. Luminosities.—In § 3 we argue—in view of the limitations to the power directly extractable from a rotating hole—that disks with high values of $m$ are required to produce outputs as strong as those observed in FSRQs. In BL Lac objects, on the other hand, low values of $m$ sustain intermediate or low disk luminosities, comparable to those directly extractable from a Kerr hole, as in equation (3). This yields a limiting power of about $10^{40}$ ergs s$^{-1}$; it is intrinsic to the present view that the top BL Lac object outputs should not considerably exceed such values, as in fact observed (see Maraschi 2001).

3. SEDs.—In addition, the main features of the blazar spectra can be predicted in this picture as shown in § 4. Comparing BL Lac objects with FSRQs, in the former sources we expect lower particle densities in the acceleration region and less effectively screened electric fields. These produce higher electron energies up to some $10^5$ GeV, allowed on the other hand by the lower photon densities; the ensuing synchrotron emission will peak at higher frequencies. From features 2 and 3, we derive the inverse correlation $\nu_{\text{peak}} \propto L_d^{1/3}$ or somewhat steeper (see § 4). However, in BL Lac objects, specific and considerable scatter arises when one tries to correlate $\nu_{\text{peak}}$ with the total luminosity $L$, because this is made up by two comparable components, $L_K$ and $L_d$.

4. Evolution.—Comparing FSRQs with BL Lac objects, much weaker evolution is expected for the latter, as argued in § 5. This is because their output is lower and is partly extracted from the Kerr hole rotational energy, in conditions of low and long-lasting accretion rates; therefore, these sources are long lived, with a slow population evolution of the LE type over scales $\tau_L$ of several gigayears. Using only this scale to predict the source counts from the relations given in § 5, the result is $N(> F) \propto F^{-1.6}$ at fluxes $F > 10^{-2}$ Jy. In addition, we expect a genetic link to also occur; some FSRQs may make a transition to the BL Lac object mode after a “last interaction” of their host with companion galaxies. Such BL Lac object births are equivalent to a negative, although weak, DE on a scale $\tau_D \approx -6$ Gyr, and this competes with the slow LE to yield counts flatter yet, namely, $N(> F) \propto F^{-1.5}$ at intermediate fluxes, as shown in Figure 1; equivalently, we expect values of $V_e / V_a \approx 0.5$ (see Giommi, Menna, & Padovani 1999). This scenario implies the occurrence of transitional objects between FSRQs and BL Lac objects, with $\nu \lesssim 10^{-1}$ and with intermediate luminosities for a few $10^{-1}$ Gyr; in the optical band these sources will still show thermal features (emission lines and bumps), while their nonthermal SEDs will peak at higher $\nu_{\text{peak}}$ compared to canonical FSRQs. On the other hand, similar relations computed with the shorter timescales appropriate for the FSRQs yield much steeper counts, as shown in Figure 2.

We note that if the FR I and FR II radio sources constitute the parent populations of the BL Lac objects and the FSRQs, respectively, then a genetic link between BL Lac object births and FSRQ deaths implies a similar link between the related radio sources. Such a link constitutes a matter of current debate. We recall from § 2 that power levels and optical spectra of the FR II and FR I radio sources have been related to high and low values of $m$, respectively, by Baum, Zirbel, & O’Dea (1995). We stress
that overlapping properties and truly transitional objects are being found (see Bicknell 1995; PU01, and references therein). In addition, similar evolutionary behaviors are observed for the radio sources and for the blazars related to similar values of \( m \); that is to say, strong evolution for the FR II radio sources but weak or even negative evolution for the FR I radio sources (Jackson & Wall 2001). Therefore, there is scope for discussing “grand unification” schemes of radio sources and blazars, as also pointed out by PU01.

We also note that our BMS agrees well with the parallel work by Böttcher & Dermer (2002); this is based on detailed modeling of the blazar-emitting region and concerns the full SEDs evolving from FSRQs to BL Lac objects as the accretion rates decrease and the black hole environments are depleted in gas, dust, and reprocessed photons. In fact, the two papers turn out to be complementary and concur toward the notion of a sequence or even a genetic link between the two subclasses.

Finally, if we carry the above BMS to its extreme, that is, to residual \( m \approx 10^{-4} \), we are led to expect objects with very faint, if any, electromagnetic emission (further suppressed in the advection-dominated accretion flow regime; see Di Matteo et al. 2000), along with nearly unscreened electric fields. These objects would be akin to the cosmic-ray accelerators discussed by Boldt & Ghosh (1999).

Under the widespread, if arguable, assumption that in such conditions a magnetic field \( B \approx 10^{2} - 10^{3} \) G can still be held around a hole with the slow vertical decrease recalled in §4, particles including protons would be accelerated over long distances, at radii that must exceed that of the force-free region (acceleration at small radii has been shown to be untenable by Levinson 2000). These particles—in fact, cosmic rays with ultrahigh energies—are predicted by the analog of equation (5), but in conditions of unscreened fields; that is, large \( d \) due to very low \( n \) (and to consistently large \( \gamma \)). Thus, we recover the long recognized energy limit given by

\[
\varepsilon_{\text{max}} \approx eB_{d}r_{ms}(r_{ms}/r)^{p} \approx 10^{29}B_{d}M_{9}^{5/4}r_{10}^{-1/4} \text{eV} \ .
\]

Tens of these accelerators could lie within 50 Mpc. As noted by Boldt & Ghosh (1999), they would evade in the simplest way the Greisen-Zatsepin-Kuzmin cutoff at ultrahigh energies; as to accounting for the observed particle flux, they only need to produce \( L \approx 10^{42} \) ergs s\(^{-1}\), mostly in energetic particles. Intergalactic magnetic fields of nano-gauss strength would blur to near isotropy the geometrical memory of the actual sources for most such ultrahigh energy cosmic rays.

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**TABLE 1**

| Parameter                       | FSRQs           | BL Lac Objects | Cosmic Ray Accelerators |
|---------------------------------|-----------------|----------------|-------------------------|
| Key parameter ....................| \( m \approx 1 \)| \( m \approx 10^{-2} \)| \( m \approx 10^{-4} \) |
| Optical features .................| Emission lines, bump | ~No lines and bump | None |
| Integrated power (ergs s\(^{-1}\)) | \( L \approx 10^{47} \) | \( L \approx 10^{45} \) | \( L \approx 10^{42} \) |
| Kerr hole vs. disk ..............| \( L_{K} \approx L_{d} \) | \( L_{K} \approx L_{d} \) | \( L_{K} \approx L_{d} \) |
| Top energies ....................| \( h\nu \approx 10 \) GeV | \( h\nu \approx 10 \) TeV | \( \varepsilon_{\text{max}} \approx 10^{42} \) eV |
| Evolution .......................| Strong           | Weak, if any    | Negligible               |

\[
\varepsilon_{\text{max}} \approx eB_{d}r_{ms}(r_{ms}/r)^{p} \approx 10^{29}B_{d}M_{9}^{5/4}r_{10}^{-1/4} \text{eV} .
\]
