The Power form BL Lacs

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Blazars are among the brightest Active Galactic Nuclei (AGNs) observed with inferred (isotropic) luminosities up to \( L_{\text{iso}} \sim 10^{47} \text{ erg s}^{-1} \). Emission from these sources is widely held to originate from a relativistic jet closely aligned to the observer line of sight, with bulk Lorentz factor \( \Gamma \sim 10 \div 20 \). Taking into account related relativistic effects the intrinsic jet powers are actually much lower, \( L \sim \Gamma^{-2} L_{\text{iso}} \). A physical reference is provided by the power extractable from a central rotating Kerr Hole spun up by past accretion via the electromagnetic interaction with the magnetic field of the accretion disc, the Blandford-Znajek (BZ) mechanism. The limiting power reads \( L_{\text{BZ}} \sim 2 \times 10^{45} (\text{M}_{\odot}/10^9 \text{ M}_{\odot}) \) erg s\(^{-1}\) in an equilibrium magnetic field \( B \sim 10^9 \) G.

We study in particular gas-poor BL Lacs, which show no evidence of current accretion or well developed accretion disk, and can therefore provide a simple benchmark for this model. A study of several such BL Lacs across the entire electromagnetic spectrum allows robust estimates of the source parameters and energetics, showing that these sources comply with the BZ limit or just exceed it, within the uncertainties on black hole (BH) masses estimation.

In particular, powerful BL Lacs like 0716+714 close to the BZ limit appear to be constrained in the evolution of their flaring activity. It is therefore exciting to look for sources sharply exceeding the BZ limit. If any, they could involve orbits plunging into the BH horizon in a region with very intense magnetic field \( B > 10^9 \) G and dominated by strong gravity effects.

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I. INTRODUCTION

Blazars rank among the brightest Active Galactic Nuclei (AGNs) on the basis of their luminosities up to \( L_{\text{iso}} \sim 10^{48} \text{ erg s}^{-1} \) inferred from isotropic flux distribution. Actually, these sources are widely held to be radiating from a relativistic jet closely aligned to the observer line of sight; this emits highly beamed non-thermal radiations, with observed fluxes enhanced by relativistic effects so as to match or overwhelm other, thermal or reprocessed emissions into wider solid angles. Thus, due to special relativistic effects in the emitting jets, the luminosities \( L_{\text{iso}} \) are far larger than the intrinsic radiated powers \( L_{\nu} \); for small viewing angles one easily has \( L_{\nu} \approx 10^{-3} L_{\text{iso}} \).

Among Blazars, BL Lacs are in particular those showing no or just weak emission lines. Their spectra may be represented as a continuous spectral energy distribution (SED) \( S_{\nu} = \nu F_{\nu} \) marked by two peaks: the one at lower frequency is widely interpreted as synchrotron emission by highly relativistic electrons in the jet; the higher frequency counterpart is believed to be inverse Compton (IC) upscattering by the same electron population of the seed photons either emitted by source external to the jet (external Compton, EC \([1]\)), or provided by the synchrotron emission itself (synchrotron-self Compton, SSC \([2], [3]\)). BL Lac Objects also show rapid variability on timescales of days or shorter, during which they undergo strong flux variations often named “flares”, with intrinsic timescales longer than the apparent ones again by relativistic effects.

BL Lacs are conveniently classified in terms of the frequency of their synchrotron peak \([1]\): for the low frequency BL Lacs (LBLs) the peak lies in the infrared-optical bands, while the IC component peaks at MeV photon energies; instead, high frequency BL Lacs (HBLs) feature a first peak in the X-ray band and the second one at energies of about \( 10^2 \) GeV or beyond.

Here we focus on “dry” BL Lacs, that is, sources with no (evidence of) surrounding gas and related current accretion. They provide an appropriate benchmark for comparing their intrinsic luminosity with the top power extractable from a maximally rotating supermassive black hole (SMBH) via the electromagnetic Blandford-Znajek (BZ) mechanism \([5], [6], [7], [8]\); this can emit up to \( L_{\text{BZ}} \leq 2 \times 10^{45} (\text{M}_{\odot}/10^9 \text{ M}_{\odot}) \) erg s\(^{-1}\), given of a SMBH.
mass \( M_\bullet \) and a magnetic field \( B \sim 10^4 \) G threading the hole horizon and held by the kinetic or radiation pressure in the disk.

II. SSC MODEL

To account for the BL Lac SEDs we adopt the simple homogeneous SSC model, assuming the radiations to be produced in a region containing relativistic electrons in a magnetic field, moving toward the observer with bulk Lorentz factor \( \Gamma \); they emit primary synchrotron photons, and radiate secondary ones upon IC scattering of the former.

We begin with representing the source by a spherical homogeneous topology of radius \( R \), containing non-relativistic protons and highly relativistic electrons at uniform density \( n \), sharing a bulk Lorentz factor \( \Gamma \sim 10 \div 20 \); the electrons, however, are given random Lorentz factors \( \gamma \) up to \( 10^6 \).

To match the observed BL Lac spectra we make use of log-parabolic electron energy distributions; such distributions are obtained in the presence of stochastic adding to systematic acceleration processes as shown by [3] and computed in detail by [10]. So we write for the particle differential energy distribution

\[
N(\gamma) = N_0 \left( \frac{\gamma}{\gamma_0} \right)^{-s-r\log\left( \frac{\gamma}{\gamma_0} \right)},
\]

where \( s \) is the constant contribution to the slope, \( r \) is the distribution curvature and \( \gamma_0 \) is the initial injection energy. The energetic content of the electron population can be expressed in terms of the root mean square (hereafter rms) Lorentz factor

\[
\langle \gamma \rangle = \gamma_p 10^{-1/4r}
\]

while \( \langle \gamma \rangle = \gamma_p \) \( 10^{-1/4r} \) is the distribution mean energy.

The emitted synchrotron SED will correspondingly read [11]

\[
S_\nu = S_0 \left( \frac{\nu}{\nu_0} \right)^{-a-b\log\left( \frac{\nu}{\nu_0} \right)},
\]

with a constant contribution \( a = (s-3)/2 \) to the spectral index, a spectral curvature \( b \approx r/5 \), and a peak frequency \( \xi \propto B\gamma_p^2 \). For the IC an analogous SED holds: in the Thomson regime one has \( a = (s-3)/2, b \approx r/10 \) and a peak frequency \( \epsilon \propto B^2\gamma_p^2 \); in the Klein-Nishina (KN) regime one has \( a = s, b \approx r \) and a peak frequency \( \epsilon \propto \gamma_p \). Proton radiations will be quite lower due to the much smaller cross section and lower kinetic energies, and therefore will be neglected here.

Note that observed (primed) frequencies and fluxes are related to rest frame (unprimed) quantities via \( \nu' = \nu \delta \) and \( F' = F \delta^4 \) [12], where \( \delta = [\Gamma(1-\beta \cos \theta)]^{-1} \) is the beaming factor, \( \theta \) being the angle between the jet and the line of sight. For small viewing angles \( \theta \sim 1/\Gamma \), one obtains \( \delta \approx 2\Gamma \).

We focus on the flaring activity of dry BL Lacs for which sufficient, multi-wavelength data are published, namely 0716+714 in 2009 [13], Mrk501 in 1997 [14], Mrk421 in 2000 [15] and 2008 [16, 17] (see Figure 1).

As showed by [10], an homogeneous single zone SSC model can be fully constrained by five key observational quantities: synchrotron peak frequency \( \xi \) and flux \( S \), IC peak frequency \( \epsilon \) and flux \( C \), and the observed variation time \( \Delta t \). Then one obtains in the Thomson regime

\[
\gamma_p \propto \epsilon^{\frac{1}{2}} \xi^{-\frac{3}{2}}
\]

\[
R \propto \epsilon^{\frac{1}{2}} S^{\frac{1}{2}} \Delta t^{\frac{1}{2}} \xi^{-\frac{3}{2}} C^{-\frac{1}{2}}
\]

\[
B \propto \xi^3 C^{\frac{3}{2}} \Delta t^{\frac{3}{2}} \epsilon^{-\frac{1}{2}} S^{-\frac{1}{2}}
\]
\[ \delta \propto e^{\frac{1}{\gamma}} S^{\frac{1}{2}} \xi^{-1} C^{-\frac{1}{2}} \Delta t^{\frac{1}{2}} \]  \hspace{1cm} (7)

\[ n \propto \xi^2 C^2 \epsilon^{-\frac{1}{2}} S^{-\frac{1}{2}} \Delta t^{-\frac{1}{2}}, \]  \hspace{1cm} (8)

while for the extreme KN regime we have

\[ \gamma_p \propto \xi^2 \epsilon^{\frac{1}{2}} C^{\frac{1}{2}} \Delta t^{\frac{1}{2}} S^{-\frac{1}{2}} \]  \hspace{1cm} (9)

\[ R \propto e^{\frac{1}{\gamma}} S^{\frac{1}{2}} \Delta t^{\frac{1}{2}} \xi^{\frac{1}{2}} C^{-\frac{1}{2}} \]  \hspace{1cm} (10)

\[ B \propto \xi^2 S^{\frac{1}{2}} \xi^{-\frac{1}{2}} C^{-\frac{1}{2}} \Delta t^{-\frac{1}{2}} \]  \hspace{1cm} (11)

\[ \delta \propto e^{\frac{1}{\gamma}} S^{\frac{1}{2}} \xi^{-\frac{1}{2}} C^{-\frac{1}{2}} \Delta t^{-\frac{1}{2}} \]  \hspace{1cm} (12)

\[ n \propto \xi^2 C^2 \epsilon^{-\frac{1}{2}} S^{-\frac{1}{2}} \Delta t^{-\frac{1}{2}}. \]  \hspace{1cm} (13)



It is possible to evaluate a threshold for the synchrotron peak frequency when the transition between the two IC regimes occurs, that is, for example,

\[ \xi_T \approx 7.15 \times 10^{15} \left( \frac{B}{0.1} \text{ G} \right) \left( \frac{\delta}{10} \right) \left( 1 + z \right)^{-1} \text{ Hz}. \]  \hspace{1cm} (14)

So, in LBL sources the majority of photons of IC peak are upscattered in the Thomson regime, while in HBL sources the majority of photons of IC peak are upscattered in the KN regime, as also supported by the more curved IC spectra with respect to the synchrotron ones observed in HBL sources (see Figure 11).

In [10] it is also shown that spectra from a single electron population are expected to irreversibly broaden under the action of stochastic acceleration process, after \( b \propto 1/t \); so, a sudden increase in the spectral curvature clearly marks the emergence of a second electron population, as may be the case for 0716+714 [13].

**III. JET ENERGETICS**

We denote by \( L_{iso} = 4\pi D_L^2 F_{obs} \) the luminosity inferred from assuming an isotropic distribution of the flux \( F_{obs} \) observed at the luminosity distance \( D_L \).

We are instead interested in the intrinsic luminosities in the jet frame; assuming one cold proton per electron (satisfying \( \langle \gamma \rangle \leq m_p/m_e \)), we follow [18] in writing for the radiative luminosity and for the related powers transported by the jet

\[ L_r = L_{iso} \frac{\Gamma^2}{\delta^4}, \]  \hspace{1cm} (15)

\[ L_c = \frac{4}{3} \pi R^2 c n_e e^2 \langle \gamma \rangle \Gamma^2, \]  \hspace{1cm} (16)

\[ L_p = \frac{4}{3} \pi R^2 c n_p e^2 \Gamma^2, \]  \hspace{1cm} (17)

\[ L_B = \frac{1}{6} R^2 c B^2 \Gamma^2. \]  \hspace{1cm} (18)

Here \( L_r \) is the radiated luminosity contributed by synchrotron and IC radiation, \( n \) is the particle number density, \( m_e \) and \( m_p \) are electron and proton masses, respectively. The total jet luminosity will therefore be \( L_{tot} = L_r + L_c + L_p + L_B \), but is dominated by \( L_r \) and next by \( L_c \), with \( L_B < L_p \leq L_c \).

So, in order to evaluate luminosities robust estimates of source parameters are required. These can be achieved with simultaneous, multiwavelength observations that allow solid spectral reconstructions and evaluation of five the key parameter (beside spectral curvature \( b \)), namely synchrotron peak frequency and flux, IC peak frequency and flux, and variation time: these five parameters can be used in Eqs. [14] - [18] to obtain the five source parameters \( n, R, B, \gamma_B \) (and therefore \( \langle \gamma \rangle = 10^{-1/4} \), \( r \approx 5b \)) and \( \delta \) (and therefore \( \Gamma \) on assuming a viewing angle of a few degrees).

**IV. THE BLANDFORD-ZNAJEK POWERHOUSE**

Intrinsic luminosities evaluated via Eqs. [15] - [18] for our sources turns out to top some \( 10^{45} \text{ erg s}^{-1} \); moreover the absence of gas evidences for these sources points to very small current accretion rates \( \dot{m} < 10^{-2} \) in Eddington units.

Thus an enticing benchmark for these luminosities is provided by the BZ process for extracting energy electrodynamically from a rotating Kerr hole. This yields

\[ L_{BZ} = 2 \times 10^{45} \left( \frac{M_\bullet}{10^6 M_\odot} \right) \text{ erg s}^{-1} \]  \hspace{1cm} (19)

for a hole spun up to maximal rotation by past accretion episodes, with horizon threaded by a poloidal magnetic field produced in the inner
disk, and held after $B^2/4\pi \lesssim p_{\text{disk}}$ by kinetic or radiation pressure in the disk to yield $B \sim 10^8$ G.

The hole mass constitutes a key parameter in Equation (13) to estimate it we make use of its correlation with the red luminosity of the host galactic bulge [19, 20, 21], that reads

$$\log \left( \frac{M_\bullet}{M_\odot} \right) = -0.5 M_R - 2.61,$$

(20)

with a scatter of ±0.4 dex. For the host galaxy of 0716+714 measurements of the bulge magnitude at $M_R = 18.3 \pm 0.5$ have been recently reported by Nilsson et al. [22]; these yield a mass $M_\bullet \simeq 5.5^{+0.9}_{-3.3} \times 10^8 M_\odot$; such values are also supported by micro-variability of the optical flux [23, 24].

**V. FLARING PATTERNS**

Flaring activity of our BL Lacs is reported in Figure 2. In flares, all sources increase their electron r.m.s. energy (and so their peak frequency) as well as their luminosity, but the powerful source 0716+714 is apparently constrained to move sideways, so as to skim the BZ limit.

We note that during flare activity the sources move in the $L_{\text{tot}} - \gamma_p$ plane to higher $\gamma_p$ and $L_{\text{tot}}$ almost perpendicularly to the locus of the bright BL Lacs (see Figure 3); this indicates that the flares are not due to disk activity, but rather to emitting electrons acceleration.

Moreover, during their flaring activity, sources move into the region of faster radiative cooling; this implies short-lived flares with timescales $\sim 1$ day, or requires more structured jets than the homogeneous SSC model, e.g., de-celerating jets [25], spine-sheath layer jet [26] or jets in a jet [27].

**VI. CONCLUSIONS**

The SSC radiation model provides a robust evaluation of the jet luminosity for 0716+714 and for other “dry” BL Lacs ($\dot{m} < 10^{-2}$). During the observed flare activity this appears to be effectively constrained by the power extractable from the central rotating black hole after BZ process.

We add that higher luminosities may be provided in “wet” Blazars by the disk contribution enhanced in the Blandford-Payne regime ($\dot{m} \sim 10^{-1}$) [28]; this, however, involves substantial current accretion and would imply related gas evidence, that is missing in 0716+714. The next step in this sequence, as extrapolated from Figure 3 is represented by FSRQs with Eddington-accreting disk with $\dot{m} \sim 1$.

If the benchmark will be found to be substantially exceeded, and intrinsic luminosities $L > 10^{46}$ erg s$^{-1}$ detected in dry BL Lacs (especially at higher redshifts), with $M_{BH} < 10^9 M_\odot$...
in Equation\[19\] they will require $B > 10^4$ G at the BH horizon; these fields may relate to the larger dynamical stresses up to $B^2/4\pi \leq \rho c^2$ associated with orbits plunging from the disk toward the BH horizon into a region dominated by strong gravity effects; these conditions will provide a powerful test for GR at work. All that will represent exciting test ground for available FERMI data.

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