

Unification of Radio Galaxies and their Accretion Jet Properties

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Abstract. We investigate the relation between black hole mass, M_{bh} , and jet power, Q_{jet} , for a sample of BL Lacs and radio quasars. We find that BL Lacs are separated from radio quasars by the FR I/II dividing line in $M_{\text{bh}}-Q_{\text{jet}}$ plane, which strongly supports the unification scheme of FR I/BL Lac and FR II/radio quasar. The Eddington ratio distribution of BL Lacs and radio quasars exhibits a bimodal nature with a rough division at $L_{\text{bol}}/L_{\text{Edd}} \sim 0.01$, which imply that they may have different accretion modes. We calculate the jet power extracted from advection-dominated accretion flow (ADAF), and find that it requires dimensionless angular momentum of black hole $j \simeq 0.9 - 0.99$ to reproduce the dividing line between FR I/II or BL Lac/radio quasar if dimensionless accretion rate $\dot{m} = 0.01$ is adopted, which is required by the above bimodal distribution of Eddington ratios. Our results suggest that black holes in radio galaxies are rapidly spinning.

Key words. Black hole physics—accretion—galaxies: jets.

1. Introduction

FR I radio galaxies (defined by edge-darkened radio structure) have lower radio power than FR II galaxies (defined by edge-brightened radio structure) (Fanaroff & Riley 1974). In the frame of unification schemes of radio-loud AGNs, low-power FR I radio galaxies are believed to be misaligned BL Lacertae (BL Lac) objects, and high-power FR II radio galaxies correspond to misaligned radio quasars (Urry & Padovani 1995). The unified scheme of radio galaxies have been extensively explored by many authors previously with different approaches, such as the comparisons of the spectral energy distributions in different wavebands (e.g., Capetti *et al.* 2000, the radio morphology and luminosity functions (e.g., Padovani & Urry 1991), etc. Most BL Lacs have featureless optical/UV continuum spectra, and only a small fraction of BL Lacs show very weak broad emission lines, while quasars usually have strong broad line emission (e.g., Véron-Cetty & Véron 2000). The broad emission lines of quasars are produced by distant gas clouds in broad-line regions, which are photo-ionized by the optical/UV continua radiated from the accretion disks. The difference of the broad line emission between radio-loud quasars and BL Lacs may be attributed to their different central engines (e.g., Cao 2003).

FR I/II dichotomy is a famous observational result, which can be clearly divided in the host galaxy optical luminosity and radio luminosity plane (Ledlow & Owen 1996). The physical reason for the FR I/II division is still unclear, and there are two categories of models to explain it:

- their ambient medium are different (e.g., Gopal-Krishna & Wiita 2000); and/or
- intrinsic difference of their central engines, i.e., different accretion modes and/or jet formation processes (e.g., Meier 1999; Ghisellini & Celotti 2001).

2. Unification of BL Lacs/radio quasars and FR I/II

Our sample includes 66 BL Lacs (28 low-energy-peaked BL Lacs, LBLs and 38 high-energy-peaked BL Lacs, HBLs) and 146 radio quasars (79 flat-spectrum radio quasars, FSRQs, and 67 steep-spectrum radio quasars, SSRQs) (see Xu *et al.* 2009). Figure 1 shows the relation between the black hole (BH) mass, M_{bh} , and jet power, Q_{jet} for both BL Lacs and radio quasars. It is found that the BL Lacs can be well separated from radio quasars by the FR I/II dividing line. This result strongly supports the unification schemes for FR I/BL Lac and FR II/radio quasar.

3. Bimodal distribution of Eddington ratios for radio galaxies

The distribution of Eddington ratios for BL Lacs and radio quasars are shown in Fig. 2, where the bolometric luminosities of BL Lacs are derived from the [O II]

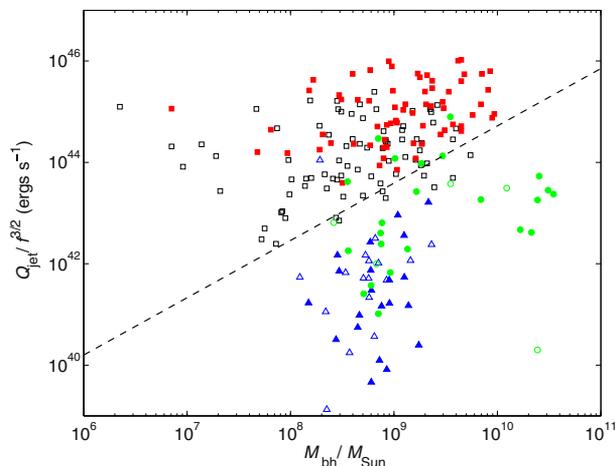


Figure 1. The relation between M_{bh} and Q_{jet} , for the BL Lacs and quasars. The open squares and filled squares represent FSRQs and SSRQs respectively, while the circles and triangles represent BL Lacs. The filled circles/triangles represent the LBLs/HBLs with measured line emission, while the open circles/triangles the LBLs/HBLs without measured line emission. The dashed line represents the Ledlow–Owen dividing line between FR I and FR II radio galaxies in the $M_{\text{bh}}-Q_{\text{jet}}$ plane. Parameter f describe the uncertainties in deriving the jet power (see Wu & Cao 2008).

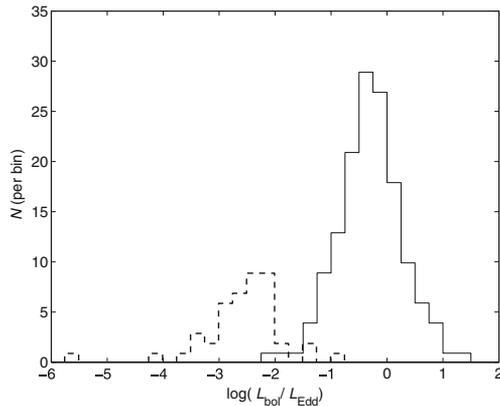


Figure 2. The $L_{\text{bol}}/L_{\text{Edd}}$ distributions for BL Lacs (dashed line) and quasars (solid line).

narrow line luminosities, while they are calculated from the broad line luminosities for radio quasars, since the continuum spectrum of radio galaxies may be contaminated by the beaming emission from the relativistic jets (see Xu *et al.* 2009). We find that the Eddington ratio distributions for BL Lacs and quasars in our sample exhibit a bimodal nature. The BL Lacs are roughly separated from the quasars at $L_{\text{bol}}/L_{\text{Edd}} \sim 0.01$, with most BL Lac objects having $L_{\text{bol}}/L_{\text{Edd}} \leq 0.01$, while almost all radio quasars have $L_{\text{bol}}/L_{\text{Edd}} \geq 0.01$. We suggest that this bimodal behaviour of the distribution may imply different accretion modes in BL Lacs and radio quasars. The critical Eddington ratio of $L_{\text{bol}}/L_{\text{Edd}} \sim 0.01$ is roughly consistent with the theoretical prediction for accretion mode transition from a standard accretion disk to an advection-dominated accretion flow (ADAF, e.g., Narayan & Yi 1995). Therefore, our results suggest that ADAFs may be present in BL Lacs and standard thin disks in radio quasars. A similar explanation is invoked to explain the FR I/II dichotomy (e.g., Ghisellini & Celotti 2001).

4. Jet power extracted from ADAF and FR I/II or BL Lac/radio quasar dichotomy

We calculate the global structure of an accretion flow surrounding a spinning BH (see Wu & Cao 2008 for more details, and references therein). Then we calculate the maximal jet power as a function of black hole mass with the hybrid jet formation model, which was proposed by Meier (2001) as a variant of the classical Blandford–Znajek model (BZ model, Blandford & Znajek 1977). We find that it can roughly reproduce the dividing line of the FR I/II dichotomy (also the BL Lac and radio quasars as in Fig. 1) in $Q_{\text{jet}}-M_{\text{bh}}$ plane, if the dimensionless accretion rate $\dot{m} \sim 0.01$ and BH spin parameter $j \sim 0.9 - 0.99$ are adopted (see Fig. 3). We note that $\dot{m} \sim 0.01$ is required to reproduce the bimodal distribution of Eddington ratios (Fig. 2). Our result suggests that the BHs in radio galaxies are rapidly spinning.

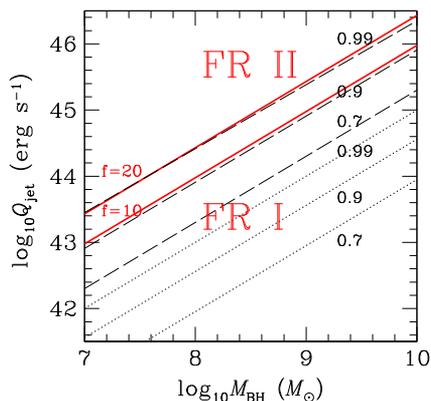


Figure 3. Jet power versus BH mass. The red solid lines represent the dividing line of FR I/II or BL Lac/radio quasar, where the jet power is calculated from 151 MHz radio luminosity with two different correction factors $f=20$ (upper) and $f=10$ (lower), respectively. The dashed and dotted lines are the jet power of the hybrid model and pure BZ model extracted from the ADAFs with $j=0.99, 0.9$ and 0.7 (from top to bottom), respectively.

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