In the frame of unification schemes for radio-loud active galactic nuclei (AGNs), FR I radio galaxies are believed to be BL Lacertae (BL Lac) objects with the relativistic jet misaligned to our line of sight, and FR II radio galaxies correspond to misaligned radio quasars. The Ledlow–Owen dividing line for the FR I/FR II dichotomy in the optical absolute magnitude of the host galaxy–radio luminosity ($M_R$–$L_{\text{Rad}}$) plane can be translated to the line in the black hole mass–jet power ($M_{\text{bh}}$–$Q_{\text{jet}}$) plane by using two empirical relations: $Q_{\text{jet}}$–$L_{\text{Rad}}$ and $M_{\text{bh}}$–$M_R$. We use a sample of radio quasars and BL Lac objects with measured black hole masses to explore the relation of the jet power with black hole mass, in which the jet power is estimated from the extended radio emission. It is found that the BL Lac objects are clearly separated from radio quasars by the Ledlow–Owen FR I/II dividing line in the $M_{\text{bh}}$–$Q_{\text{jet}}$ plane. This strongly supports the unification schemes for FR I/BL Lac object and FR II/radio quasar. We find that the Eddington ratios $L_{\text{bol}}/L_{\text{Edd}}$ of BL Lac objects are systematically lower than those of radio quasars in the sample with a rough division at $L_{\text{bol}}/L_{\text{Edd}} \sim 0.01$, and the distribution of Eddington ratios of BL Lac objects/quasars exhibits a bimodal nature, which imply that the accretion mode of BL Lac objects may be different from that of radio quasars.

Key words: black hole physics – BL Lacertae objects: general – galaxies: active – galaxies: nuclei – quasars: emission lines

1. INTRODUCTION

FR I radio galaxies (defined by an edge-darkened radio structure) have lower radio power than FR II galaxies (defined by an edge-brightened radio structure due to compact jet-terminating hot spots; Fanaroff & Riley 1974). Relativistic jets are observed in many radio-loud active galactic nuclei (AGNs). In the frame of unification schemes of radio-loud AGNs, FR I radio galaxies are believed to be misaligned BL Lacertae (BL Lac) objects, and FR II radio galaxies correspond to misaligned radio quasars (see Urry & Padovani 1995 for a review). Most BL Lac objects have featureless optical and ultraviolet (UV) continuum spectra, and only a small fraction of BL Lac objects show very weak broad emission lines, while quasars usually have strong broad-line emission. The broad emission lines of quasars are produced by distant gas clouds in broad-line regions (BLRs) which are photoionized by the optical/UV continua radiated from the accretion disks surrounding massive black holes. The difference of the broad-line emission between radio-loud quasars and BL Lac objects may be attributed to their different central engines (e.g., Cavaliere & D’Elia 2002; Cao 2002, 2003).

The unified scheme of BL Lac objects and FR I radio galaxies has been extensively explored by many previous authors with different approaches, such as comparisons of spectral energy distributions (SEDs) in different wavebands (e.g., Owen et al. 1996; Capetti et al. 2000; Bai & Lee 2001), radio morphology, radio luminosity functions (LFs; e.g., Padovani & Urry 1991; Kollgaard et al. 1992; Laurent-Muehleisen et al. 1993), and optical line emission (e.g., Marchã et al. 2005). Padovani & Urry (1992) derived the radio LFs of flat-spectrum radio quasars (FSRQs) and FR II galaxies from a sample of radio-loud AGNs. They considered a two-component model in which the total luminosity is the sum of an unbeamed part and a beamed jet luminosity. The beamed LFs of FR II radio galaxies are consistent with the observed LFs of FSRQs and steep-spectrum radio quasars (SSRQs), which strengthens the unification of FR II galaxies and radio quasars (see Padovani & Urry 1992 for details). Similar analyses were carried out on the relation between FR I galaxies and BL Lac objects (Padovani & Urry 1991; Urry & Padovani 1995), which is also consistent with the unification of FR Is and BL Lac objects. Even though the main observational features of different types of radio-loud AGNs can be successfully explained in the frame of the unification schemes, some authors have found observations indicating that the unification may be more complex than usually portrayed in these schemes (e.g., Marchã et al. 2005; Landt & Bignall 2008). Landt & Bignall (2008) found that a considerable number of BL Lac objects can be identified with the relativistically beamed counterparts of FR II radio galaxies in a sample of BL Lac objects selected from the Deep X-ray Radio Blazar Survey (DXRBS).

Ledlow & Owen (1996) found that FR I and FR II radio galaxies can be clearly divided in the host galaxy optical luminosity–radio luminosity ($M_R$–$L_{\text{Rad}}$) plane by a dividing line showing that radio power is proportional to the optical luminosity of the host galaxy. What causes the FR I/FR II division is still unclear, and there are two categories of models to explain it: (1) the morphological differences being caused by the interaction of jets with the ambient medium of different physical properties (e.g., Gopal-Krishna & Wiita 2000), and/or (2) different intrinsic nuclear properties of accretion and jet formation processes (e.g., Baum et al. 1995; Bicknell 1995; Reynolds et al. 1996; Ghisellini & Celotti 2001; Marchesini et al. 2004; Hardcastle et al. 2007). Ghisellini & Celotti (2001) used the optical luminosity of the host galaxy to estimate the central black hole masses of FR I/FR II radio galaxies, and estimated the bolometric luminosity from the radio power of jets in FR I/FR II galaxies. They suggested that most FR I radio galaxies are accreting at lower rates compared with FR IIs.
which could correspond to different accretion modes in FR I and FR II radio galaxies. If the black hole is spinning rapidly, the rotational energy of the black hole is expected to be transferred to the jets by the magnetic fields threading the holes, namely the Blandford–Znajek (BZ) mechanism (Blandford & Znajek 1977). The jet can also be accelerated by the large-scale fields threading the rotating accretion disk (i.e., the Blandford–Payne (BP) mechanism; Blandford & Payne 1982). Cao & Rawlings (2004) found that the BZ mechanism for rapidly spinning black holes surrounded by advection-dominated accretion flows (ADAFs; Narayan & Yi 1995) provides insufficient power to explain the jets in some 3CR FR I radio galaxies. Wu & Cao (2008) calculated the maximal jet power available from ADAFs around Kerr black holes as a function of black hole mass with a hybrid jet formation model (i.e., BP+BZ mechanism). They found that it can roughly reproduce the dividing line of the Ledlow–Owen relation for the FR I/FRII dichotomy in the black hole mass–jet power ($M_{bh}$-$Q_{jet}$) plane with mass accretion rate $M \sim 0.01M_{Edd}$ if the black hole spin parameter $a \sim 0.9$–0.99 is adopted. This accretion rate indicates that FR I and FR II galaxies have different accretion modes, supporting the results of Ghisellini & Celotti (2001) and suggesting that FR I sources are in the ADAF mode. Wu & Cao’s (2008) results imply that the black hole spin may play an important role in jet formation at least for FR I radio galaxies (see also Sikora et al. (2007) for a discussion of the impact of black hole spin on jet formation in AGNs).

In this work, we use a sample of BL Lac objects and radio quasars with measured radio power, black hole masses, and Eddington ratios to explore the relationship between BL Lac objects and radio quasars, and to compare it with the FR I/FRII division. The sample and the estimates of black hole mass/jet power are described in Sections 2 and 3. We show the results in Section 4, and Section 5 contains the discussion. The cosmological parameters $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$ have been adopted in this work.

2. THE SAMPLE

The host galaxies of 132 BL Lac objects have been observed with the Hubble Space Telescope WFPC2 by Urry et al. (2000), among which there are 48 sources with measured redshifts and extended radio emission. We add 18 additional BL Lac objects compiled in the work of Wu et al. (2008) to the sample of Urry et al. (2000), which leads to 66 BL Lac objects (including 28 low-energy-peaked BL Lac objects (LBLs) and 38 high-energy-peaked BL Lac objects (HBLs)) with measured redshifts and extended radio emission data for our present investigation. We search the literature for the emission line data of these sources, and find 44 sources including 23 LBLs and 21 HBLs. We use the luminosity of the narrow [O iii] line at 3727 Å to estimate the bolometric luminosity. For sources where the emission line data of [O iii] are unavailable, we estimate the [O iii] luminosity using other narrow emission lines.

In order to compare the difference between BL Lac objects and radio quasars, we need a sample of radio quasars. In this work, we adopt the sample of radio quasars compiled by Liu et al. (2006), which is selected from the 1 Jy, S4, and S5 radio source catalogs. Their sample consists of 146 radio quasars including 79 FSRQs (with $\alpha_{2-8\text{GHz}} < 0.5$) and 67 SSRQs (with $\alpha_{2-8\text{GHz}} > 0.5$). All quasars in their sample have estimated black hole masses and jet power (see Liu et al. 2006 for details of the quasar sample).

3. THE BLACK HOLE MASS AND JET POWER

The relation between black hole mass $M_{bh}$ and host galaxy luminosity $L_h$ at the K band (Equation (1) in McLure & Dunlop 2004) is derived from $M_{bh}$—$M_*$ by using an average color correction of $R - K = 2.7$ for the same cosmology adopted in this letter. We convert this relation back to $M_{bh}$—$M_*$ as

$$\log_{10}(M_{bh}/M_\odot) = -0.50(\pm 0.02)M_R - 2.75(\pm 0.53) \quad (1)$$

to estimate the central black hole masses of BL Lac objects in this sample. For a few BL Lac objects, their black hole masses can also be estimated from their stellar dispersion velocity $\sigma$ with the empirical $M_{bh}$—$\sigma$ relation. It is found that the black hole masses of three BL Lac objects estimated with the $M_{bh}$—$\sigma$ relation are roughly consistent with those estimated with Equation (1) (see Cao 2004 for details, and references therein).

The jet power can be estimated from the relationship between jet power and radio luminosity proposed by Willott et al. (1999),

$$Q_{jet} \simeq 3 \times 10^{38} f^{3/2} L_{ext,151}^{6/7} \text{Watt}, \quad (2)$$

where $L_{ext,151}$ is the extended radio luminosity at 151 MHz in units of $10^{28}$ W Hz$^{-1}$ sr$^{-1}$. Willott et al. (1999) have argued that the normalization is uncertain and introduced the factor $f (1 \leq f \leq 20)$ to account for these uncertainties. This relation was proposed for FR II radio galaxies and quasars. Cao & Rawlings (2004) compared the power of the jet in M87 (a typical FR I radio galaxy) derived with different approaches, and found that Equation (2) may probably be suitable even for FR Is (see Cao & Rawlings 2004 for details, and references therein). Following Cao (2003), we adopt this relation to estimate the power of jets in BL Lac objects; this is believed to be a good approximation if BL Lac objects can be unified with FR Is.

For most BL Lac objects, their radio/optical continuum emission is strongly beamed to us due to their relativistic jets and small viewing angles of the jets with respect to the line of sight (e.g., Fan & Zhang 2003; Gu et al. 2006). The low-frequency radio emission (e.g., 151 MHz) may still be Doppler beamed. We therefore use the extended radio emission detected by VLA to estimate the jet power, as adopted in Cao (2003). The observed extended radio emission is $K$-corrected to 151 MHz in the rest frame of the source assuming $\alpha_e = 0.8$ ($f_e \propto \nu^{-\alpha_e}$; Cassaro et al. 1999).

We take the black hole masses of radio quasars from Liu et al. (2006), which are estimated from the broad-line widths of Hβ, Mg ii, or C iv, as well as the line luminosities of these lines (see Liu et al. 2006 for details). In Liu et al.’s (2006) work, the jet power is estimated from the extended radio emission at 151 MHz with the formula derived by Punsly (2005), which is slightly different from Equation (2) proposed by Willott et al. (1999). To be self-consistent, we estimate the jet power of quasars in Liu et al.’s (2006) sample from their extended radio luminosities with Equation (2), which is the same as the estimates of jet power for BL Lac objects in this work.

For BL Lac objects, the observed optical continuum emission may be dominated by the beamed synchrotron emission from relativistic jets (e.g., Gu et al. 2006). The narrow-line regions (NLRs) are believed to be photoionized by the radiation from the accretion disk, and the narrow-line emission can be used to estimate the bolometric luminosity for BL Lac objects. We convert the luminosity of the narrow-line [O iii] to bolometric luminosity using the relation proposed by Willott et al. (1999),

$$L_{bol} = 5 \times 10^3 L_{[O\text{III}]\text{Watt}}, \quad (3)$$
for the BL Lac objects in this sample. For the objects which lack [O iii] line emission data, we convert the luminosities of other narrow lines ([O iii] or Hα+[N ii]) to the luminosity of [O iii] using the ratios suggested by Zirbel & Baum (1995) for FR I galaxies. The narrow-line emission data for the BL Lac objects are taken from the literature (Sharufutti et al. 2006; Carangel et al. 2003; Rector et al. 2000; Rector & Stocke 2001; Stickel et al. 1993; Marchá et al. 1996; Morganti et al. 1992). We note that Equation (3) is derived for FR IIs/quasars, while ADAFs may be present in these BL Lac objects. The SED of an ADAF is significantly different from that of a standard thin disk (e.g., Narayan et al. 1995). Nagao et al. (2002) calculated the emission of NLRs photoionized by two different SED templates, i.e., a standard thin disk SED template with a bump in UV/soft X-ray bands and a hot ADAF SED template described by a power-law continuum in hard X-ray bands with an exponential cutoff. They found that the NLRs are more efficiently photoionized by the ADAF SED template than the standard thin disk case (see the bottom panel of Figure 5 in Nagao et al. 2002), which implies that the present estimates on the bolometric luminosity with Equation (3) may be overestimated to some extent (a factor of ~2–3 for the NLRs with hydrogen column density \( \lesssim 10^{20} \text{cm}^{-2} \)).

For radio quasars, we estimate their bolometric luminosities from the total broad-line luminosities \( L_{\text{BLR}} \) calculated by Liu et al. (2006) as the optical continua for most radio-loud quasars are probably contaminated by the beamed emission from relativistic jets. Liu et al. (2006) derived a tight correlation: \( \lambda L_{\lambda}(5100 \text{ Å}) = 84.3 L_{\text{H}\alpha}^{0.998} \), for the sample of radio-quiet AGNs in Kaspi et al. (2000). Given that the luminosity of the broad-line H\( \beta \) corresponds to ~4% of \( L_{\text{BLR}} \) (see Liu et al. 2006 and references therein) and using the relation \( \lambda L_{\lambda} = 9 \lambda L_{\lambda}(5100 \text{ Å}) \) (Kaspi et al. 2000), the bolometric luminosity can be estimated as \( L_{\text{bol}} \simeq 30L_{\text{BLR}} \).

4. RESULTS

The division between FR I and FR II radio galaxies is clearly shown by a line in the plane of total radio luminosity and optical luminosity of the host galaxy (Ledlow & Owen 1996). The optical luminosity of the host galaxy can be converted to black hole mass \( M_{\text{bh}} \) by using the empirical relation (1), while the jet power \( Q_{\text{jet}} \) can be estimated from the radio luminosity with relation (2). Thus, the dividing line between FR I and II radio galaxies is translated to

\[
\log Q_{\text{jet}}(\text{erg s}^{-1}) = 1.13 \log M_{\text{bh}}(M_{\odot}) + 33.18 + 1.50 \log f
\]

in the \( M_{\text{bh}}-Q_{\text{jet}} \) plane (see Wu & Cao 2008 for details), which is modified for the cosmology adopted in this Letter. In Figure 1, we plot the relation between the black hole masses \( M_{\text{bh}} \) and jet power \( Q_{\text{jet}} \) for radio quasars and BL Lac objects. It is found that BL Lac objects can be roughly separated from quasars by the FR I/II dividing line.

The distributions of Eddington ratios for BL Lac objects and quasars are plotted in Figure 2, where only the BL Lac objects with measured line emission have been included, because the bolometric luminosity is derived from the emission lines for these sources. We estimate the statistical significance of a possible bimodal distribution of Eddington ratios for BL Lac objects and quasars using the KMM algorithm (Ashman et al. 1994). The distribution for the entire sample is strongly inconsistent with being unimodal (\( P \)-value < 0.001), and the KMM algorithm separates the entire sample into two groups.

No significant difference is found in the distributions of black hole masses for BL Lac objects and radio quasars.

5. DISCUSSION

Figure 1 shows that the FR I/FR II dividing line given by Ledlow & Owen (1996) roughly separates the radio-loud quasars from BL Lac objects in the \( M_{\text{bh}}-Q_{\text{jet}} \) plane, which strongly supports the FR I/BL Lac objects and FR II/radio quasars unification schemes. This conclusion is independent of the value of the uncertainty factor \( f \) in Equation (2).

We find that only a small fraction of LBLs/quasars are above/below the dividing line, which is similar to the FR I/II division (see, e.g., Figure 1 in Ledlow & Owen 1996). The HBLs have relatively lower jet power than LBLs, and only one HBL appears above the dividing line. This means that BL Lac objects/quasars and the FR I/II divisions may be true only in a statistical sense.

![Figure 1](image1.png)

Figure 1. Relation between black hole mass \( M_{\text{bh}} \) and jet power \( Q_{\text{jet}} \) for the BL Lac objects and quasars. The open squares and filled squares represent FSRQs and SSRQs, respectively, while the circles and triangles represent BL Lac objects. The filled circles/triangles represent the LBLs/HBLs with measured line emission, while the open circles/triangles represent the LBLs/HBLs without measured line emission. The dashed line represents the Ledlow–Owen dividing line between FR I and FR II radio galaxies given by Equation (4).

![Figure 2](image2.png)

Figure 2. Distributions of Eddington ratios (\( L_{\text{bol}}/L_{\text{Edd}} \)) for BL Lac objects (dashed line) and quasars (solid line).
The exceptional sources in the $M_{bh}$–$Q_{bol}$ plane may provide useful clues to investigations on the central engines in radio-loud AGNs (e.g., Cao & Rawlings 2004; Landt & Bignall 2008). In Figure 2, we show that the distributions of Eddington ratios for BL Lac objects and quasars are bimodal. The BL Lac objects are roughly separated from the quasars at $L_{bol}/L_{Edd} \sim 0.01$, with most BL Lac objects having $L_{bol}/L_{Edd} \lesssim 0.01$ and almost all the quasars having $L_{bol}/L_{Edd} \gtrsim 0.01$. We suggest that this bimodal behavior of the distribution may imply different accretion modes in BL Lac objects and quasars, and furthermore the transition between the accretion states happens at $L_{bol}/L_{Edd} \sim 0.01$ according to Figure 2. Since this is roughly the critical luminosity above which ADAFs are not possible (e.g., Narayan & Yi 1995), this suggests that ADAFs are present in BL Lac objects and standard thin disks are in quasars. We note that a similar explanation is invoked to explain the FR I/II division, in which ADAFs would be present in FR I galaxies while standard thin disks are in FR II galaxies (e.g., Ghisellini & Celotti 2001; Wu & Cao 2008). Interestingly enough, Marchesini et al. (2004) found a similar bimodal distribution of Eddington ratios for a sample of FR I and FR II radio galaxies.

As discussed in Section 3, the bolometric luminosities of BL Lac objects may be overestimated if ADAFs are present in these sources. This would strengthen the bimodality in the distribution of Eddington ratios of BL Lac objects and quasars.

The similarity between the division of BL Lac objects/quasars and FR I/II found in this Letter strongly supports the unification schemes for FR I/BL Lac object and FR II/radio quasar.

We thank the anonymous referee for helpful comments/suggestions. This work is supported by the NSFC (grants 10778621, 10703003, 10773020, 10821302, and 10833002), the CAS (grant KJCX2-YW-T03), and the National Basic Research Program of China (grant 2009CB824800).

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