RELATIVISTIC JET PROPERTIES OF GeV–TeV BLAZARS AND POSSIBLE IMPLICATIONS FOR THE JET FORMATION, COMPOSITION, AND CAVITY KINEMATICS

JIN ZHANG\textsuperscript{1}, XIAO-NA SUN\textsuperscript{2}, EN-WEI LIANG\textsuperscript{3}, RUI-JING LU\textsuperscript{2}, YE LU\textsuperscript{1}, AND SHUANG-NAN ZHANG\textsuperscript{1,3,4}

\textsuperscript{1} National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China; zhang.jin@hotmail.com
\textsuperscript{2} Department of Physics and GXU-NAOC Center for Astrophysics and Space Sciences, Guangxi University, Nanning 530004, China; lew@gxu.edu.cn
\textsuperscript{3} Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
\textsuperscript{4} Physics Department, University of Alabama in Huntsville, Huntsville, AL 35899, USA

ABSTRACT

We fit the spectral energy distributions of a GeV–TeV flat spectrum radio quasar (FSRQ) sample with the leptonic model. Their $\gamma_{\min}$ of the relativistic electron distributions, which significantly affect the estimate of the jet properties, are constrained, with a typical value of $\sim 48$. Their jet power, magnetized parameter, radiation efficiency, and jet production and radiation rates per central black hole (BH) mass are derived and compared with those of BL Lacertae (BL Lac) objects. We show that the FSRQ jets may be dominated by the Poynting flux and have a high radiation efficiency, whereas the BL Lac object jets are likely dominated by particles and have a lower radiation efficiency than FSRQs. Being different from BL Lac objects, the jet powers of FSRQs are proportional to their central BH masses. The jet production and radiation rates of the FSRQs distribute in narrow ranges and are correlated with each other, whereas no similar feature is found for the BL Lac objects. We also show that the jet power is correlated with the cavity kinetic power: the magnetic field energy in the jets may provide the cavity kinetic energy of FSRQs, and the kinetic energy of cold protons in the jets may be crucial for the cavity kinetic energy of BL Lac objects. We suggest that the dominating formation mechanism of FSRQ jets may be the Blandford–Znajek process, but BL Lac object jets may be produced via the Blandford–Payne and/or Blandford–Znajek processes, depending on the structures and accretion rates of accretion disks.

Key words: BL Lacertae objects: general – galaxies: jets – quasars: general – radiation mechanisms: non-thermal

Online-only material: color figures

1. INTRODUCTION

Most confirmed extragalactic GeV–TeV emitters are blazars, a sub-sample of radio-loud active galactic nuclei (AGNs). They are the main targets for studying the cosmic $\gamma$-ray horizon (e.g., Dominguez et al. 2013), the intergalactic magnetic field (e.g., Maraschi et al. 1995), the contributions to the extragalactic background radiation (Giommi et al. 2006b), etc. Their observed emission is dominated by a relativistic jet, which is generally believed to be beamed toward to the Earth. Their broadband spectral energy distributions (SEDs) from the radio to gamma-ray band are usually bimodal, which can be well explained with the synchrotron radiation and the inverse Compton scattering by the photons from broad-line regions (BLRs) and/or torus (Sikora et al. 1994, 2009) usually dominate the emission of the IC peak of FSRQs, being different from BL Lac objects. It was also proposed that the existence of a BLR in a blazar may associate with the accretion rate (Nicastro et al. 2003; Ho 2008; Elitzur & Ho 2009). Therefore, the intrinsic differences between the jets of FSRQs and the jets of BL Lac objects may be related to their central black holes (BHs), accretion disks, and the mechanisms of jet formation (e.g., Ghisellini et al. 2013).

The formation of a relativistic jet from an accreting BH system is still not well understood. It has long been speculated that the physics in different BH jet systems may be essentially the same (Mirabel 2004; Zhang 2007). It is generally believed that jet launching is connected with the central BH, accretion disk, and corona in a source (Armitage & Natarajan 1999; Merloni & Fabian 2002; Cao 2004; Wang et al. 2004; Chen et al. 2012) via either the Blandford–Payne (BP; Blandford & Payne 1982) and/or Blandford–Znajek (BZ; Blandford & Znajek 1977) mechanisms. The BP mechanism may power a jet by releasing the gravitational energy of accreting matter that moves toward the BH. The rotational energy of a rapidly rotating BH is essential for the BZ process. Jets may be made of several components, but the basic makeup of jets is still largely unknown. Most models of jet formation predict a Poynting flux dominating energy transport. However, the observations
of polarized radio and optical emission indicate that at least some of jet should be made of relativistic electrons that radiate through synchrotron emission (Harris & Krawczynski 2006).

Broadband SEDs are critical for revealing the radiation mechanisms and the properties of the radiation regions. Powerful blazars are usually high energy photon emitters. The IC bumps of the observed SEDs of blazars typically peak at the GeV–TeV gamma-ray band. The Large Area Telescope (LAT) on board the Fermi satellite, which covers an energy band from 20 MeV to ∼300 GeV, presents an unprecedented opportunity to explore the nature of blazars (e.g., Abdo et al. 2010a). We systematically model the observed SEDs for Fermi/LAT blazars to investigate their jet properties. We derive the physical parameters of the jets with the single-zone leptonic model, using the minimization χ2 technique. Our results for Fermi/LAT GeV–TeV BL Lac objects are reported in Zhang et al. (2012). It can be found that with the observed broadband SEDs, the model parameters of some BL Lac objects are well constrained (see also Cerruti et al. 2013).

In this paper, we extend our analysis to the Fermi/LAT FSRQs and present a comparison of the jet properties for FSRQs and BL Lac objects. We also investigate the jet composition and jet launching mechanism of the two kinds of blazars, as well as the kinetic properties of the cavity.

Our sample and the observed SEDs are presented in Section 2. The model and results of SED fitting are described in Section 3. A comparison of jet power and cavity kinetic power is given in Section 4. Jet composition and radiation efficiency are presented in Section 5, and jet bulk motion and electron spectrum are discussed in Section 6. The connection between the jet power and the central BH mass is shown in Section 7, and a discussion on the jet production, the jet composition, and the cavity kinematics is given in Section 8. A summary of our results is presented in Section 9.

2. SAMPLE AND DATA

Fermi/LAT bright blazars are selected for our analysis. The BL Lac object sample data and the results of their SED fits are available in Zhang et al. (2012). All the FSRQs in Abdo et al. (2010a) that have confirmed redshift are included in our sample, and there are 23 sources. The observed SEDs of these FSRQs are shown in Figure 1. Note that more than one observational campaign with Swift was made during the LAT observation period for some sources (3C 279, PKS 0208-512, PKS 0528+134, and 3C 454.3). We thus take the average flux of the data from these campaigns for the SEDs of these sources.

3. MODELS AND RESULTS OF SED FITS FOR THE FSRQs

The single-zone syn+SSC+EC model is used to fit the SEDs of FSRQs in our sample. Although some groups proposed that the radiation regions of some objects may be outside of the BLR in some states (e.g., Tavecchio et al. 2013), some works for an individual source also indicate that the gamma-ray emitting region is inside the BLR (for 3C 279, Bai et al. 2009; for 3C 454.3, Isler et al. 2013). Since the energy density of torus photon field is much lower than that of BLR, which is ∼10−4 erg cm−3 (Ghisellini & Tavecchio 2008), and since the EC process of the BLRs may dominate the IC peaks of the SEDs (e.g., Sikora et al. 1994; Ghisellini et al. 2009b, 2010; Chen et al. 2012), we consider only the EC/BLR process. The Klein–Nashina (KN) effects and the absorption of high energy gamma-ray photons by extragalactic background light (Franceschini et al. 2008) are also taken into account in our model calculations. The KN effects are not significant for most of the sources, as shown in Figure 1, but the highest energy points in the SEDs of five sources are only marginally fitted with our model. Although a more complex model with more parameters may present a better fit to the SEDs, we prefer to use a simple model to fit the SEDs and to perform a statistical analysis of the jet properties on the basis of fitting results.

In order to calculate the energy density of the BLR photon field (U_{\text{BLR}}) in the comoving frame, one needs to estimate the radius (R_{\text{BLR}}) and total luminosity of the BLR. The radius is usually estimated with the continuum luminosity at 5100 Å (L_{5100}) or the luminosities of emission lines of Hβ and Hα (L_{Hβ} and L_{Hα}), such that R_{\text{BLR}} = \frac{2.23 \pm 2.1}{L_{5100}}/10^{44} \text{erg s}^{-1}.\frac{10^{-0.1 \beta}}{0.69 + 0.061} (Kaspi et al. 2005), R_{\text{BLR}} = (30.2 \pm 1.4)(L_{5100}/10^{44} \text{erg s}^{-1})^{0.64 \pm 0.02} (Greene & Ho 2005), log R_{\text{BLR}} = −21.3^{+0.8}_{−0.6} + 0.519 \pm 0.063 log L_{5100}/10^{44} \text{erg s}^{-1} (Bentz et al. 2009), log R_{\text{BLR}} = (2.22 \pm 0.02) + (0.51 \pm 0.02) log(L_{Hα}/10^{44} \text{erg s}^{-1}) (Wang & Zhang 2003), and log R_{\text{BLR}} = (1.381 \pm 0.080) + (0.684 \pm 0.106) log(L_{Hβ}/10^{44} \text{erg s}^{-1}) (Wu et al. 2004), where R_{\text{BLR}} is in unit of light-days. The R_{\text{BLR}} of eight FSRQs in our sample for which the data of emission line are available in literature are estimated with these correlations. The results are listed in Table 1. The estimated U_{\text{BLR}} values among these sources vary with a factor of 2–3, with an average of 2.07 × 10^{-2} erg cm^{-3}. Note that Ghisellini & Tavecchio (2008) suggested that R_{\text{BLR}} ∼ L_{\text{disk}}^{1/2} and L_{\text{BLR}} = 0.1 L_{\text{disk}}, and they obtained U_{\text{BLR}} = 2.65 × 10^{-2} erg cm^{-3} at rest frame, which is close to the mean of U_{\text{BLR}} in Table 1. Since the BLR is not uniform and has an angle to the disk, a corrected factor of 17/12 for U_{\text{BLR}} is also proposed (Ghisellini & Madu 1996). The observed energy density in the jet is boosted by a factor of \Gamma^{2}, where \Gamma is the bulk Lorentz factor of the radiating region. Therefore, the estimated U_{\text{BLR}} is about 3.76 × 10^{-2} \Gamma^{2} erg cm^{-3} in the comoving frame (Ghisellini & Tavecchio 2008; Ghisellini et al. 2009b). In our calculations, we also take U_{\text{BLR}} = 3.76 × 10^{-2} \Gamma^{2} erg cm^{-3} for all FSRQs in our sample. We assume \Gamma = \delta since the relativistic jets of blazars are close to the line of sight, where \delta is the beaming factor.

The radiation region is assumed to be a sphere with radius R, which is obtained with R = \delta c \Delta t / (1 + z), where \Delta t is the variability timescale. Blazars usually have flux variations with timescales from one year to several hours and sometimes even shorter than one hour (Kartaltepe & Balonek 2007; Fossati et al. 2008). The timescales for a source at different energy bands may be different (such as for 3C 279, Collmar et al. 2010, Abdo et al. 2010b; for 3C 454.3, Giommi et al. 2006a). It was suggested that the rapid variations on timescales shorter than one hour are from an emission blob smaller than the jet cross section, which moves much faster than the surrounding relativistic jet material (Zacharias & Schlickeiser 2013). It implies that the rapid flares should originate from local disturbance. Therefore, we do not adopt the observed minimum timescales to estimate the radiating region size. Considering the great uncertainty of the variation timescales and the statistical analysis purpose, we take \Delta t = 12 hr for all sources, which is the median of the previous BL Lac object sample (Zhang et al. 2012).
Figure 1. Observed SEDs (scattered data points) with our best model fits (solid lines) for the FSRQs in our sample. The highest energy points in the SEDs of five sources are only marginally fitted because of the KN effect (dashed lines). The radio data are not considered in our fits because of the synchrotron self-absorption effect. The blue bumps observed in 3C273 and PKS 1510-089 are also not included since they may be the emission from the accretion disk.

Table 1

Data of the BLRs for Eight FSRQs in Our Sample

| Source   | Flux_{H\beta}^a | log \(L_{BLR}^a\) | \(R_{BLR}^b\) | \(R_{BLR}^c\) | \(R_{BLR}^7\) | \(U_{BLR}^b\) | \(U_{BLR}^c\) | \(U_{BLR}^7\) |
|----------|----------------|--------------------|---------------|---------------|---------------|----------------|----------------|---------------|
| 3C 279   | 0.8            | 44.78              | 83.01         | 89.61         | 78.00         | 3.45           | 2.96           | 3.91          |
| 3C 273   | 154.8          | 45.82              | 329.02        | 310.72        | 238.29        | 2.41           | 2.70           | 4.60          |
| 3C 454.3 | 4.3            | 45.94              | 413.70        | 382.10        | 286.93        | 1.47           | 1.48           | 4.18          |
| 4C 29.45 | 1.8            | 45.16              | 197.80        | 196.27        | 157.73        | 1.46           | 1.48           | 2.30          |
| PKS 1510-089 | 5.3           | 44.87              | 141.00        | 144.59        | 119.86        | 1.47           | 1.40           | 4.04          |
| PKS 0208-512 | 1.2           | 45.17              | 245.51        | 238.55        | 187.94        | 0.96           | 1.02           | 1.64          |
| PKS 0454-234 | 0.2           | 44.42              | 92.74         | 99.05         | 85.34         | 1.20           | 1.06           | 1.42          |
| PKS 0420-01 | 0.8           | 44.92              | 178.82        | 179.18        | 145.33        | 1.04           | 1.03           | 1.57          |

Notes.

\(^a\) The data are taken from Celotti et al. (1997), in units of \(10^{-14}\ \text{erg s}^{-1}\ \text{cm}^{-2}\). The fluxes of emission line H\(\beta\) in PKS 0208-512, PKS 0454-234, and PKS 0420-01 are derived from the fluxes of the emission line M\(\gamma\)II by using the relative flux in Francis et al. (1991).

The luminosities of BLRs for the three sources are also calculated with the luminosities of emission line M\(\gamma\)II (Equation (1) in Celotti et al. 1997).

\(^b\) \(R_{BLR}\) (in units of light-days) and the corresponding energy densities (\(U_{BLR}\), in units of \(10^{-2}\ \text{erg cm}^{-3}\)) estimated with the relations of \(L_{5100}\) to \(R_{BLR}\) and \(L_{H\beta}\) (Equations (2) and (4) in Greene & Ho 2005).

\(^c\) The same as (b) but using Equation (2) in Wang & Zhang (2003) with the relative flux between H\(\beta\) and H\(\alpha\).

\(^d\) The same as (b) but using the \(R_{BLR}–L_{5100}\) correlation in Bentz et al. (2009) and the H\(\beta\)–\(L_{5100}\) correlation in Greene & Ho (2005).
The electron distribution is taken as a broken power law as used in the community (Ghisellini et al. 2009b, 2010; Chen et al. 2012; Aharonian et al. 2009), which is characterized by an electron density parameter \( N_0 \), a break energy \( \gamma_b \), and indices \( p_1 \) and \( p_2 \) in the range of \( \gamma_e \) to \( [\gamma_{\text{min}}, \gamma_{\text{max}}] \). In the case of \( \gamma_e = 1/\sqrt{1 - v^2/c^2} = 1 \), where \( v \) is the velocity of electron, the electron is at rest. Therefore, \( \gamma_{\text{min}} \) should be \( \geq 1 \). The \( \gamma_{\text{max}} \) is usually poorly constrained, but it does not significantly affect our results and is fixed at a large value. Note that \( \gamma_b \) is not exactly the same as the cooling break since \( \gamma_b \) results from a complex physical process, including the adiabatic losses, the particle escape, and the cooling (Ghisellini et al. 2009b). We are not concerned with the physical reasons that make the break in the electron spectrum. The \( p_1 \) and \( p_2 \) are derived from the spectral indices of the observed SEDs as reported by Zhang et al. (2012). The \( N_0 \) and \( \gamma_b \) depend on the synchrotron peak frequency \( \nu_s \) and peak flux \( \nu_s f_{\nu s} \) as well as other model parameters. We set \( \nu_s \) and \( \nu_s f_{\nu s} \) as free parameters instead of \( N_0 \) and \( \gamma_b \) (see Equations (2) and (5) in Zhang et al. 2009). We use the minimization \( \chi^2 \) technique to perform the SED fits. The free parameter set of our SED modeling is \{ \( B \), \( \delta \), \( \nu_s \), \( \nu_s f_{\nu s} \), \( \gamma_{\text{min}} \) \}, where \( B \) is the magnetic field strength of the radiating region. We randomly generate a parameter set in broad spaces and measure the consistency between the model result and the observation data with a probability \( p \propto e^{-\chi^2/2} \), where \( \chi^2 \) is the reduced \( \chi^2 \). Note that no errors are available for some data points. We estimate their errors with the average relative errors of the data points whose errors are available. Since the relative errors of the data for the synchrotron bump and synchrotron self-Compton (SSC) bump are usually much smaller than those for the EC bump, we derive the average relative errors of the data for the two bumps separately (with a separation at \( \nu = 10^{20} \) Hz; e.g., Zhang et al. 2012). For PKS 1510-089, no error of observation data below \( 10^{20} \) Hz is available, and we take 10% of the observation flux as the errors (Zhang et al. 2012). A significant bump at the ultraviolet band is observed in the SEDs of some sources, which may be the thermal radiation of the accretion disk. We do not include these data in our SED modeling.

Taking source B2 1520+31 as an example, Figure 2 shows the probability distributions of \( B \), \( \delta \), \( \nu_s \), \( \nu_s f_{\nu s} \), and \( \gamma_{\text{min}} \). The center values and 1\( \sigma \) confidence level of these parameters are derived from Gaussian fits to the profiles of the \( p \) distributions. Note that the low energy data of the SSC bumps are sensitive to the \( \gamma_{\text{min}} \) values that have been reported by Tavecchio et al. (2000) and Ghisellini et al. (2009b), as shown in Figures 3(a) and (c). The probability distribution profiles of \( \gamma_{\text{min}} \) for the FSRQ SEDs in our sample are classified into two kinds as shown in Figures 3(b) and (d). The \( p \) profiles of five FSRQs (3C 279, 3C 273, PKS 0454-234, S4 0917+44, and PKS 1502+106) are a one-sided Gaussian function with a cutoff at \( \gamma_{\text{min}} = 1 \). This cutoff is due to the physical limit, i.e., \( \gamma_{\text{min}} \) should be \( \geq 1 \). Their \( p \) profiles peak at \( \gamma_{\text{min}} = 2 \) or remain almost constant in the range of

---

**Figure 2.** Probability distributions of \( \delta, B, \nu_s, \nu_s f_{\nu s} \), and \( \gamma_{\text{min}} \) for B2 1520+31. Gaussian function fits to the profiles of distributions are shown with solid lines. The vertical dashed lines mark the 1\( \sigma \) ranges of the parameters.

---

**Figure 3.** Observed SEDs with model fitting lines at different \( \gamma_{\text{min}} \) values for B2 1520+31 (a) and 3C 279 (c) and the corresponding probability distributions of their \( \gamma_{\text{min}} \) with Gaussian function (b) and one-sided Gaussian function (d) fits. The vertical dashed lines mark the 1\( \sigma \) ranges of \( \gamma_{\text{min}} \).

(A color version of this figure is available in the online journal.)
Table 2 of Zhang et al. (2013). We also calculate the bolometric shown in Figure 1, and the model parameters are reported in ranges from 2 to 86, with a median of \( \sim \)\( \gamma \min \). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativis-
Note that blazars are violently variable. The model parameters derived from the fit to an SED are only for a given state of the sources (e.g., Zhang et al. 2012, 2013). The conventional method of the SED fits is by artificially adjusting the model parameters to make an acceptable fit. With the minimization \( \chi^2 \) technique, we not only can present a nice fit to the data, we also can yield the statistical confidence level of the parameters. We should emphasize that the derived 1\( \sigma \) confidence level for the parameters with the minimization \( \chi^2 \) technique is not the observational errors of the parameters but rather the confidence level in regards to what extent the parameters can reproduce the observed SEDs.

4. JET POWER AND CAVITY KINETIC POWER

The jet power (\( P_{\text{jet}} \)) is essential for understanding the production and composition of the jets. There is no way to directly measure the ratio of protons to electrons in the jets. The proton–electron pair assumption\(^6\) is widely adopted in the calculations of jet power in blazars (e.g., Ghisellini et al. 2009b, 2010). We assume that the jet power is carried by relativistic electrons, cold protons, magnetic fields, and radiation, i.e., \( P_{\text{jet}} = \sum \pi R^2 c U_i \), where \( U_i \) is the energy density associated with the emitting electrons (\( U_e \)), cold protons (\( U_p \)), magnetic fields (\( U_B \)), and radiation (\( U_r \)).

\(^6\) We further discuss this issue and examine another extreme case of the positron–electron pairs in Section 8.2.

\(^7\) Note that the radiation power \( P_r \) should be a part of \( P_{\text{jet}} \) before radiation, since \( P_r \) is only the power carried by the electrons after radiation. We did not take the radiation power \( P_r \) into account when we calculated the total jet power \( P_{\text{jet}} \) in our previous work (Zhang et al. 2012). Here we add the radiation power to the total jet powers of BL Lac objects.
in the comoving frame (Ghisellini et al. 2010), which are given by

\[ U'_e = m_e c^2 \int N(\gamma) \gamma d\gamma, \]

(1)

\[ U'_p = m_p c^2 \int N(\gamma) d\gamma, \]

(2)

\[ U'_B = B^2 / 8\pi, \]

(3)

\[ U'_r = \frac{L_{\text{obs}}}{4\pi R^2 c^2} \approx \frac{L_{\text{bol}}}{4\pi R^2 c^2}. \]

(4)

We calculate the total jet powers and the powers carried by each component with our SED fitting parameters. The results are reported in Table 2.

The jet power also can be derived from the lobe low frequency radio emission under the assumption of minimum energy arguments (e.g., Rawlings & Saunders 1991; Willott et al. 1999). This approach is now widely used to estimate the jet kinetic energy in AGNs. It is also believed that the observed X-ray cavities are evidence for AGN feedback and provide a direct measurement of the mechanical energy released by AGNs (Birzan et al. 2008; Cavagnolo et al. 2010). It is found that the cavity kinetic power is correlated with the radio extended power of galaxies (Birzan et al. 2004, 2008; Cavagnolo et al. 2010; O’Sullivan et al. 2011), and the scaling relationship is roughly consistent with the theoretical relation presented in Willott et al. (1999; Cavagnolo et al. 2010; Meyer et al. 2011). We thus also estimate the cavity kinetic power \( L_{\text{kin}} \) by using the relation between \( L_{\text{kin}} \) and radio luminosity (Meyer et al. 2011), i.e.,

\[ \log L_{\text{kin}} = 0.64(\pm 0.09)(\log L_{300} - 40) + 43.54(\pm 0.12) \quad (\text{erg s}^{-1}), \]

(5)

where \( L_{300} \) is the extended luminosity at 300 MHz. Since the values of \( L_{300} \) are not available for the sources in our sample, we estimated their values with the 5 GHz core luminosity. Meyer et al. (2011) defined a core dominance parameter with \( R_{\text{CE}} = \log(L_{\text{core}}/L_{\text{ext}}) \) at 1.4 GHz. As shown in Figure 5 of Meyer et al. (2011), the typical \( R_{\text{CE}} \) for blazars is 0.5, which is adopted in our calculations, i.e., \( L_{\text{core}}/L_{\text{ext}} = 3 \). We first use the spectral index of \( \alpha = 0.5 \) (radio spectral index for the core region, Urry & Padovani 1995) to derive the core luminosity at 1.4 GHz, and then we employ the core dominance parameter \( R_{\text{CE}} \) to obtain the extended luminosity at 1.4 GHz for the FSRQs and BL Lac objects in our samples. We finally obtain \( L_{300} \) by using a radio spectral index of \( \alpha = 1.2 \) (radio spectral index for extended region, Meyer et al. 2011). We also derive the errors of \( L_{\text{kin}} \) by considering the uncertainty of the correlation in Equation (5).

A comparison between \( P_{\text{jet}} \) and \( L_{\text{kin}} \) for the FSRQs and BL Lac objects in our sample is shown in Figure 5. Note that the values of \( \gamma_{\text{min}} \) for some BL Lac objects are poorly constrained by the observed SEDs (Zhang et al. 2012). We took \( \gamma_{\text{min}} = 2 \) in the calculations of \( P_e \) and \( P_p \) for those BL Lac objects whose \( \gamma_{\text{min}} \) values cannot be constrained with the data (Zhang et al. 2012). This may lead to significant overestimate of their \( P_{\text{jet}} \), mainly \( P_p \), if their true \( \gamma_{\text{min}} \) values are much larger than 2. We mark these sources as different symbols in the figures, but we do not take these sources (10 data points) into account for the statistical analysis hereafter. One can observe that \( P_{\text{jet}} \) and \( L_{\text{kin}} \) are correlated. The best linear fit yields \( \log P_{\text{jet}} = (13.7 \pm 2.9) + (0.70 \pm 0.06) \log L_{\text{kin}} \), with a Pearson correlation coefficient of \( r = 0.90 \) and a chance probability of \( p = 3.9 \times 10^{-14} \).

![Figure 5. Comparison of \( P_p \) and \( L_{\text{kin}} \) for FSRQs and BL Lac objects. The solid line is the best fits for FSRQs and BL Lac objects (without considering the opened triangles data points). The dashed lines indicate the 3σ confidence bands for the best fits. The dotted line is the equality line.](image)

(A color version of this figure is available in the online journal.)

5. JET COMPOSITION AND RADIATION EFFICIENCY

Whether the jets are matter or Poynting flux dominating is essential for understanding the radiation physics and jet formation of blazars. We first compare the distributions of \( B \) for the two kinds of sources in Figure 6(a). The magnetic field strengths of the FSRQs are larger than that of the BL Lac objects by 1–2 orders of magnitude, i.e., from 3.1 G to 15.1 G for FSRQs and from 0.09 G to 1.1 G for BL Lac objects. The medians of the distributions are 6.9 G for FSRQs and 0.2 G for BL Lac objects. We then compare the powers carried by the jet ingredients for the FSRQs and BL Lac objects in Figure 7. One can find that the jet powers of FSRQs are systematically larger than that of BL Lac objects. The values of \( P_{\text{jet}} \) for the FSRQs are from 2.6 \times 10^{45} \text{ erg s}^{-1} to 3.6 \times 10^{46} \text{ erg s}^{-1}, \) with a median of 9.6 × 10^{45} \text{ erg s}^{-1}, and the median is 8.1 × 10^{44} \text{ erg s}^{-1} for the BL Lac objects. Similarly, the medians of the \( P_e \) and \( P_p \) distributions are 2.0 \times 10^{44} \text{ erg s}^{-1} and 3.0 \times 10^{45} \text{ erg s}^{-1} for FSRQs, whereas they are 1.9 \times 10^{44} \text{ erg s}^{-1} and 5.1 \times 10^{44} \text{ erg s}^{-1} for BL Lac objects, respectively. However, the medians of the \( P_B \) and \( P_t \) distributions for FSRQs are much larger than that for BL Lac objects by almost three orders of magnitude, i.e., 3.0 \times 10^{45} \text{ erg s}^{-1} and 2.4 \times 10^{45} \text{ erg s}^{-1} for FSRQs and 1.1 \times 10^{43} \text{ erg s}^{-1} and 1.3 \times 10^{43} \text{ erg s}^{-1} for BL Lac objects, respectively.

We calculate the ratios of the power carried by each ingredient to \( P_{\text{jet}} \), i.e., \( \epsilon_i = P_i/P_{\text{jet}} \), and show their distributions in Figure 7. It is found that the medians of \( \epsilon_e \) and \( \epsilon_p \) distributions for FSRQs are 0.02 and 0.34, respectively, being smaller than that of the BL Lac objects, which are 0.24 and 0.67, respectively. However, the medians of the \( \epsilon_B \) and \( \epsilon_t \) distributions for FSRQs are 0.37 and 0.22, being much larger than that of BL Lac objects, which are 0.02 and 0.04, respectively. In addition, as shown in Figure 8(a), \( P_{\text{jet}} \) of FSRQs is tightly correlated with \( P_B \), i.e., \( P_{\text{jet}} \propto P_B^{0.76 \pm 0.10} \), with a Pearson correlation coefficient of \( r = 0.77 \) and chance probability of \( p = 1.8 \times 10^{-5} \); however, this is not so for the BL Lac objects. We also show \( P_e + P_p \) as a function of \( P_B \) in Figure 8(b). One can observe that \( P_B \) is
larger than $P_e + P_p$ for half of the FSRQs, implying that the jets of FSRQs may be dominated by Poynting flux, but this is not so for the case of BL Lac objects, which may be dominated by particles.

We measure the magnetization of a jet with a parameter of $\sigma = P_B/(P_p + P_e + P_{\gamma})$ (Zhang et al. 2013). We show the distributions of $\sigma$ for FSRQs and BL Lac objects in Figure 6(b). One can observe that the FSRQs tend to have a higher $\sigma$ than the BL Lac objects, sometimes even close to or exceeding unity. The radiation efficiencies $\epsilon_i$ for most of the FSRQs are greater than 0.1 and even close to 0.5 as shown in Figure 7. For BL Lac objects, $\epsilon_i$ distributes in a very broad range but always smaller than 0.1 and sometimes even lower than $10^{-3}$. As reported in Zhang et al. (2013), the FSRQ jets are likely highly magnetized and the BL Lac object jets have lower radiation efficiency and are matter dominating. The radiation power of a jet, $P_t$, as a function of $P_B$ is shown in Figure 8(c). FSRQs and BL Lac objects form a clear sequence in which a jet with higher $P_B$ tends to have higher $P_t$. The best linear fit in log scale gives $P_t \propto P_B^{0.78 \pm 0.03}$, with a Pearson correlation coefficient of $r = 0.86$ and chance probability of $p = 7.5 \times 10^{-12}$. It seems that a jet with higher $P_B$ tends to be very tightly correlated with its $P_t$. These results indicate that the high radiation efficiency of FSRQ jets could be due to their high magnetization of jets.

6. JET BULK MOTION AND ELECTRON SPECTRUM

We compare the distributions of $\delta$ and the parameters of the electron spectrum for FSRQs and BL Lac objects in Figure 9. It is found that $\delta$ for FSRQs ranges from 10 to 27, with the same median as BL Lac objects, $\sim 15$. We test whether the two distributions show any statistical difference with the Kolmogorov–Smirnov test (K-S test), which yields a chance probability, $p_{KS}$. A K-S test probability larger than 0.1 would strongly suggest no statistical difference between the two distributions. We get $p_{KS} = 0.63$, indicating that the distributions of $\delta$ for the two kinds of blazars have no statistical difference. We do not find any relation between $\delta$ and $B$, hence the magnetic field is not related to the bulk motion of the emitting regions for both FSRQs and BL Lac objects.

The electron spectrum may signal the acceleration of the electrons in the radiation region. We also compare the parameter distributions of the electron spectra and the two peak frequencies of SEDs for the FSRQs and BL Lac objects in Figures 9(b)-(e). The distributions of $p_2$ for the two kinds of blazars\textsuperscript{8} are consistent with the same mean of $p_2 = 3.8$. The $p_1$ for BL Lac objects is around 2, roughly consistent with the prediction of the Fermi acceleration mechanism (Gallant 2002; Wang 2002; Cao & Wang 2013a; Zhou et al. 2014). The distribution of $p_1$ for FSRQs is bimodal; half are consistent with that for BL Lac objects and half have $p_1 \sim 1.2$, implying the different acceleration process (Yan et al. 2013). The electron acceleration is likely not related to the bulk motion of the jets since no statistical difference is observed between the $\delta$ distributions for FSRQs and BL Lac objects, but the distributions of $\gamma_b$ are dramatically different for FSRQs and BL Lac objects. The $\gamma_b$ ranges from $10^3$ to $10^6$ for BL Lac objects. However, $\gamma_b$ narrowly clusters around several hundreds for FSRQs. This results in very narrow distributions of both $\nu_c$ and $\nu_e$, i.e., $\nu_c = 10^{12} \sim 10^{13}$ Hz and $\nu_e = 10^{22} \sim 10^{23}$ Hz, as shown in Figure 9(e), which are also consistent with the results of Şentürk et al. (2013). Note that the IC bumps of the SEDs for FSRQs are dominated by the EC process and the energy of seed photons is $2 \times 10^{15}$ $\Gamma$ Hz in the comoving frame. The peak frequencies of EC bumps are $\nu_c \sim 2 \times 10^{15}$ $\Gamma \gamma_b^2 \delta$. We find a tentative anticorrelation between $\gamma_b$ and $\delta$ with $r = -0.54$ (Pearson correlation coefficient) and $p = 0.008$ (chance probability) for FSRQs as shown in Figure 9(f). The narrow distributions of $\gamma_b$ and $\delta$ result in the narrow distribution of $\nu_e$ for the FSRQs. This anticorrelation may also imply that the relativistic electrons in the emission region with a larger $\delta$ suffer more cooling by the EC process. Therefore, the lower $\gamma_b$ in FSRQs may be due to the strong cooling of relativistic electrons by both the SSC and EC processes. Ghisellini et al. (2010) also found a similar feature for bright Fermi blazars. The observed blazar spectral sequence (e.g., Fossati et al. 1998; Donato et al. 2001) should be due to the different electron cooling efficiency

\textsuperscript{8} The K-S tests yield $p_{KS} = 2 \times 10^{-3}$ and $p_{KS} = 0.51$ for the distributions of $p_1$ and $p_2$ between FSRQs and BL Lac objects.
Figure 7. Distributions of the powers associated with relativistic electrons $P_e$, cold protons $P_p$, Poynting flux $P_B$, radiation component $P_r$, and the total power $P_{jet}$ of the jets (left panels), together with the distributions of the ratios of these powers to $P_{jet}$ (right panels). The line styles are the same as in Figure 6. (A color version of this figure is available in the online journal.)

(Ghisellini et al. 1998, 2009b, 2010; Sbarrato et al. 2012) or the increasing importance of the external radiation field along with the sequence of HBLs–LBLs–FSRQs.

7. CONNECTION BETWEEN THE JET PROPERTIES AND THE CENTRAL BLACK HOLES

AGN jets may be driven by both the accretion process and the spin of the central BH (Fanidakis et al. 2011; Zhang et al. 2012). We further investigate the connection between the jet properties and the central BHs. We search the BH masses from literature and obtain a sub-sample of 14 FSRQs with BH masses available, as reported in Table 2. Although the BH masses for FSRQs are collected from different papers, 13 FSRQs from these papers were obtained using the same assumption that broad-line clouds are virialized. A sub-sample of BL Lac objects with the BH mass available is from Zhang et al. (2012). As reported in Zhang et al. (2012), a weak relation of $P_{jet} \propto M_{BH}^{-1.2}$ was found in
Figure 8. $P_{\text{jet}}$, $P_{e}$, $P_{p}$, and $P_{r}$ as a function of $P_{B}$ for FSRQs and BL Lac objects. The solid lines are the best fits and the dashed lines indicate the $3\sigma$ confidence bands for the best fits. The dotted line in panel (b) is the equality line.

(A color version of this figure is available in the online journal.)

Figure 9. Distributions of the beaming factor $\delta$, the break Lorentz factor of electrons $\gamma_b$, the indices $p_1$ and $p_2$ of the electron distribution, and the two peak frequencies $\nu_s$ and $\nu_c$ for the 23 FSRQs with the BL Lac object data from Zhang et al. (2012). (f) $\gamma_b$ as a function of $\delta$. The solid line is the best fit for FSRQ data and the dashed lines indicate the $3\sigma$ confidence bands of the best fit.

(A color version of this figure is available in the online journal.)

both the high and low states of BL Lac objects. We also examine the $P_{\text{jet}}-M_\text{BH}$ relation for FSRQs. Dramatically different from BL Lac objects, a tentative positive correlation between $P_{\text{jet}}$ and $M_\text{BH}$ is found for FSRQs as shown in Figure 10. The best linear fit in log scale gives $P_{\text{jet}} \propto M_\text{BH}^{1.96\pm0.02}$, with $r = 0.53$ and $p = 0.05$, where the errors of BH masses are assumed to be $\Delta(\log M_\odot) = 0.3$ for all the FSRQs in our sample.

We measure the jet production and radiation rates per central BH mass with $P_{\text{jet}}/L_{\text{Edd}}$ and $P_{r}/L_{\text{Edd}}$ of FSRQs narrowly range from 0.01 to 0.09 and from 0.02 to 0.23, with averages of $P_{\text{jet}}/L_{\text{Edd}}$ and $P_{r}/L_{\text{Edd}}$ ~0.04 and ~0.008, respectively. This likely indicates the universal jet production and radiation rates per central BH mass for FSRQs, hence the same dominating jet formation mechanism may work at these FSRQs. As shown in Figure 11(b), $P_{r}/L_{\text{Edd}}$ is tightly correlated with $P_{\text{jet}}/L_{\text{Edd}}$ for FSRQs, i.e., $P_{r}/L_{\text{Edd}} \propto (P_{\text{jet}}/L_{\text{Edd}})^{1.24\pm0.16}$ derived from the best linear fit in log scale with a Pearson correlation coefficient of $r = 0.89$ and a chance probability of $p = 1.8 \times 10^{-5}$. For the BL
8. DISCUSSION

8.1. Jet Formation Mechanisms

It is generally believed that the jet formation occurs via either the BP (Blandford & Payne 1982) and/or BZ (Blandford & Znajek 1977) mechanisms. Besides the BH spin and the accretion rate, the dramatically different $P_{\text{jet}}-M_{\text{BH}}$ relations shown in Figure 10 between the FSRQs and BL Lac objects may also signal that the BH mass would be also an essential factor for the jet radiation efficiency and jet power (see also Davis & Laor 2011).

The different $P_{\text{jet}}-M_{\text{BH}}$ relations may indicate the different dominating jet formation mechanisms in the two kinds of blazars. The anticorrelation between $P_{\text{jet}}$ and $M_{\text{BH}}$ observed in the BL Lac objects may disfavor the scenario that the jets are purely powered by the accretion process and imply that the spin energy release of the central BH may also play a significant role in jet formation for these objects (Zhang et al. 2012). The mix of the two contributions may lead to a broad jet production rate among sources, hence there is no universal jet production efficiency among BL Lac objects. This is supported by the broad $P_{\text{jet}}/L_{\text{Edd}}$ distribution of BL Lac objects, which spans from $10^{-4}$ to 0.3. It was proposed that the different structures and accretion rates of accretion disks may result in the different dominating mechanisms of jet launching (Ghisellini & Celotti 2001; Pu et al. 2012; Zhang 2013). The accretion disk of a BL Lac object with a low accretion rate may consist of an outer thin disk and an inner advection-dominated accretion flow (e.g., Zhang 2013). In such a combined disk, which has a large inner radius, the accreted materials in the accretion disk would be ejected along with the line of magnetic force, and a relativistic jet with moderate luminosity and speed would be launched by the BP process. When the accretion rate and the BH spin increase, the inner radius of the disk becomes smaller and is closer to the BH. The dominating jet formation mechanism then may transfer to the BZ mechanism. Therefore, it is possible that there is no universal jet production mechanism at work among these BL Lac objects.

The highly magnetized jets in FSRQs may be powered by the BZ mechanism. It was suggested that the magnetic flux...
threading the BH is important for launching a powerful jet (Sikora & Begelman 2013). The efficiency of extracting the BH rotational energy via the BZ mechanism depends on the magnetic flux dragged in (Tchekhovskoy et al. 2011; McKinney et al. 2012). It requires a geometrically thick disk to transport a large amount of flux into the center (Lubow et al. 1994; Rothstein & Lovelace 2008; Beckwith et al. 2009; Cao 2011; McKinney et al. 2012). The observed narrow distribution of the jet production rates of FSRQs implies a universal jet production efficiency among these sources. It remains a problem whether the accretion flow can accumulate adequate magnetic fields in the inner region to power the jet. More recently, Cao & Spruit (2013) reported that this problem can be overcome if the angular momentum of the disk is removed predominantly by the magnetically driven outflows. The thin disk of a FSRQ may extend to around the innermost stable circular orbit. The so-called magnetically choked accretion flow can form by flux accumulation during a hot, low-accretion rate phase prior to the cold accretion event (Sikora et al. 2013), and then a powerful jet for FSRQs is produced via the BZ mechanism.

The difference between the jet production mechanisms may also manifest in the observed luminosity, which has been proposed to unify the subclasses of blazars as a blazar sequence (Fossati et al. 1998; Ghisellini et al. 1998). It was suggested that the distinction between BL Lac objects and FSRQs may be associated with different accretion rate (Ghisellini et al. 2009a, 2010), since a very weak BLR may form if the accretion rate is lower than $10^{-2}L_{\text{Edd}}$ (e.g., Ho 2008). Thus, the BLR is also related to the accretion disk structure and the disk radiative efficiency. The division between BL Lac objects and FSRQs may be observationally controlled by the luminosity of the BLR measured in Eddington units (Ghisellini et al. 2011; Sbarrato et al. 2012).

8.2. Jet Composition and Cavity Kinematics

It is generally believed that the X-ray cavities are direct evidence of AGN feedback (Birzan et al. 2008; Cavagnolo et al. 2010), and the cavity kinetic power is correlated with the radio extended power of galaxies (Rawlings & Saunders 1991; Willott et al. 1999; Birzan et al. 2004, 2008; Cavagnolo et al. 2010; O’Sullivan et al. 2011; Meyer et al. 2011). Therefore, in the systems where the X-ray cavities are lacking or not observed, the radio extended luminosity is used to estimate the cavity kinetic power. However, the formation mechanism and composition of the cavity are still unclear. As described in Section 4, we find a strong correlation between $P_{\text{jet}}$ and $L_{\text{kin}}$ for the blazars in our sample, indicating that the cavity results from the interaction between AGN jets and the surrounding medium. We further investigate the relation of $L_{\text{kin}}$ to $P_{\text{e}}$, $P_{\gamma}$, $P_{B}$, $P_{r}$, $P_{e} + P_{r}$, and $P_{B} + P_{e}$ for the FSRQs and BL Lac objects in our sample. As shown in Figure 12, one can observe that $P_{B}$ is comparable with $L_{\text{kin}}$ for FSRQs but $P_{e}$ is comparable with $L_{\text{kin}}$ for BL Lac objects, indicating that the magnetic field energy in the jets may provide the cavity kinetic energy for FSRQs and the kinetic energy of cold protons in the jets may contribute to the cavity kinetic energy of BL Lac objects. The kinetic energy of relativistic electrons is not important to produce the cavity for both FSRQs and BL Lac objects. This is reasonable since electrons cool off effectively by radiation rather than collisions. Hence, FSRQs and BL Lac objects adequately form a sequence along the equality line in the $P_{e} + P_{r} \sim L_{\text{kin}}$ panel of Figure 12.

The jet composition is also a debated issue. It was suggested that the jets for both FSRQs and BL Lac objects are dominated by particles (e.g., Ghisellini et al. 2009b, 2010). We examine the discrepancy between our results with that of Ghisellini et al. (2010), in which they derived the lepton model parameters for a sample of 53 FSRQs and 31 BL Lac objects. As reported in their Table 4, the average values of the parameters are $B = 2.6$ G, $\Gamma = 13$ (or $\delta = 17.8$), $\gamma_{B} = 300$, $p_{1} = 1$, and $p_{2} = 2.7$ for FSRQs and $B = 0.8$ G, $\Gamma = 15$ ($\delta = 18.6$), $\gamma_{B} = 1.5E4$, $p_{1} = 1$, and $p_{2} = 3.3$ for BL Lac objects. These results are statistically consistent with ours, i.e., $B = 7.4$ G, $\delta = 16$, $\gamma_{B} = 274$, $p_{1} = 1.6$, and $p_{2} = 3.8$ for FSRQs and $B = 0.33$ G, $\delta = 18.8$, $\gamma_{B} = 1.5E5$, $p_{1} = 2.0$, and $p_{2} = 3.8$ for BL Lac objects. The main difference between our results and theirs is the $\gamma_{\text{min}}$ values. In Ghisellini et al. (2010), $\gamma_{\text{min}}$ is taken as 1 for most of the sources. As shown in Figure 4, the derived $\gamma_{\text{min}}$ for 23 FSRQs ranges from 2 to 86, with a median of 48. Note that the estimates of $P_{p}$ and $P_{e}$ are significantly affected by the $\gamma_{\text{min}}$ values. We use the derived $\gamma_{\text{min}}$ values to calculate the jet powers for the FSRQs in our sample. This significantly lowers both $P_{p}$ and $P_{e}$ values of FSRQ jets in comparison with those reported in Ghisellini et al. (2010). As a result, both the radiation efficiency and the magnetized parameter of FSRQs derived in our work are significantly higher than those derived in Ghisellini et al. (2010). As described in Section 4, we take $\gamma_{\text{min}} = 2$ for those BL Lac objects whose $\gamma_{\text{min}}$ cannot be constrained by the SED data. The derived jet powers for most of those BL Lac objects tend to be larger than the typical values and significantly deviate from the fitting line, as also shown in Figures 5, 8, 11, and 12.

Therefore, the powers carried by particles may be overestimated in Ghisellini et al. (2010). Our results show that the jet radiation efficiencies of FSRQs are much higher than that of BL Lac objects and the jets of FSRQs may be dominated by the Poynting flux, whereas the jets of BL Lac objects may be dominated by particles.

Note that the above results are based on the traditional assumption of one cold proton for one relativistic electron in the calculations of jet powers. We check another extreme case in which the jet power is carried by positron–electron pairs, magnetic fields, and radiation, but no protons. In this scenario, the correlation between jet power $P_{\text{jet}}$ and cavity kinetic power $L_{\text{kin}}$ becomes tighter with $r = 0.93$ and $p = 2.2 \times 10^{-16}$, which is $P_{\text{jet}} \propto L_{\text{kin}}^{0.83 \pm 0.08}$, as shown in Figure 13(a). Under this extreme scenario, all the FSRQ jets would be dominated by the Poynting flux and most of BL Lac object jets are still dominated by the relativistic electrons as shown in Figure 13(b).

9. SUMMARY

On the basis of the systematic SED fits with the single-zone leptonic models for the given observed SEDs of GeV–TeV blazars, we have made a comparison of the jet properties for the FSRQs and BL Lac objects. Our results are summarized below.

1. We derive the $\gamma_{\text{min}}$ value with a 1σ confidence level for the given observed SEDs of the FSRQs in our sample and find a typical value of $\sim 48$.

2. The magnetic field strengths of the FSRQ jets are larger than those of the BL Lac objects by 1–2 orders of magnitude, and the $\gamma_{B}$ values of FSRQs are clustered at several hundreds, being dramatically different from those of BL Lac objects, which range from $10^{3}$ to $10^{6}$, but no statistical difference between the Doppler factors of the FSRQs and BL Lac objects is found.
Figure 12. Comparisons of \( P_e \) (a), \( P_p \) (b), \( P_b \) (c), \( P_r \) (d), \( P_e + P_p \) (e), and \( P_b + P_p \) (f) with \( L_{\text{kin}} \) for FSRQs and BL Lac objects. The dotted lines are the equality lines.

(A color version of this figure is available in the online journal.)

3. Assuming that the total jet power is carried by electron–proton pairs, magnetic fields, and radiation, we calculate the powers carried by these ingredients and show that the total jet power \( P_{\text{jet}} \) is correlated with the cavity kinetic power \( L_{\text{kin}} \) of the jets. Under this assumption, we show that the jet radiation efficiencies of FSRQs are much higher than that of BL Lac objects and the jets of FSRQs may be dominated by the Poynting flux, whereas the jets of BL Lac objects may be dominated by particles.

4. Different from BL Lac objects, a tentative positive correlation between \( P_{\text{jet}} \) and \( M_{\text{BH}} \) is found for FSRQs. The jet production and radiation rates per central BH mass for FSRQs, \( P_{\text{jet}}/L_{\text{Edd}} \) and \( P_r/L_{\text{Edd}} \), narrowly range from 0.01 to 0.09 and from 0.002 to 0.023, respectively. These likely indicate the universal jet production and radiation rates per central BH mass for FSRQs, hence a dominating jet formation mechanism via the BZ process may work at these sources. For the BL Lac objects, both \( P_{\text{jet}}/L_{\text{Edd}} \) and \( P_r/L_{\text{Edd}} \)
span for several orders of magnitude, which may indicate that there is no universal jet production efficiency among these BL Lac objects. Therefore, there is no universal jet production mechanism at work among these BL Lac objects, i.e., the BP and/or BZ processes, depending on the structures and accretion rates of accretion disks, should operate in BL Lac objects.

5. By comparing $L_{\text{kin}}$ with $P_e$, $P_B$, $P_e + P_B$, and $P_B + P_{\text{kin}}$ for the FSRQs and BL Lac objects in our sample, we find that the magnetic field energy may provide the cavity’s kinetic energy for FSRQs, whereas the kinetic energy of cold protons may power the cavities of the BL Lac objects.

The topic of the differences between BL Lac objects and FSRQs was extensively covered and discussed (e.g., Ghisellini et al. 2011; Sbarrato et al. 2012). In contrast to previous papers, we constrain $\gamma_{\text{min}}$ with the observed SEDs and show that the FSRQ jets may be dominated by the Poynting flux and have a high radiation efficiency, whereas the BL Lac object jets may be dominated by particles and have a lower radiation efficiency than FSRQs. More essentially, the observed difference between FSRQs and BL Lac objects may signal the different jet production mechanisms. The difference in the jet production mechanisms may also manifest in the observed luminosity, as that was proposed to unify the subclasses of blazar sequences (Fossati et al. 1998; Ghisellini et al. 1998).

We thank the anonymous referee for valuable suggestions. We appreciate helpful discussion with Bing Zhang, G. Ghisellini, Wei Cui, Zi-Gao Dai, Wei-Min Gu, Xin-Wu Cao, Jian-Min Wang, and Yuan Liu. This work is supported by the National Basic Research Program (973 Programme) of China (grant 2014CB848500), the National Natural Science Foundation of China (grants 11078008, 11025313, 11363002, 11373036, and 11133002), the Strategic Priority Research Program “The Emergence of Cosmological Structures” of the Chinese Academy of Sciences (grant XDB09000000), the Guangxi Science Foundation (2013GXNSFFA019001), and the Key Laboratory for the Structure and Evolution of Celestial Objects of Chinese Academy of Sciences. Shuang-Nan Zhang acknowledges support from the Qianren start-up grant 292012312D117210.

REFERENCES

Abdo, A. A., Ackermann, M., Aguado, I., et al. 2010a, ApJ, 716, 30
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010b, Natur, 465, 919
Ackermann, M., Ajello, M., Allafort, A., et al. 2011, ApJ, 743, 171
Aharonian, F., Akhperjanian, A. G., Anton, G., et al. 2009, ApJL, 696, L150
Armitage, P. J., & Natarajan, P. 1999, ApJL, 523, L7
Bai, J. M., Liu, H. T., & Ma, L. 2009, ApJ, 707, 428
Bentz, M. C., Peterson, B. M., Netzer, H., Pogge, R. W., & Vestergaard, M. 2009, ApJ, 697, 160
Birzan, L., McNamara, B. R., Nulsen, P. E. J., Carilli, C. L., & Wise, M. W. 2008, ApJ, 686, 859
Birzan, L., Rafferty, D. A., McNamara, B. R., Wise, M. W., & Nulsen, P. E. J. 2004, ApJ, 607, 800
Blandford, R. D., & Payne, D. G. 1982, MNRAS, 199, 883
Blandford, R. D., & Znajek, R. L. 1977, MNRAS, 179, 433
Cao, G., & Wang, J. 2013a, PASJ, 65, 109
Cao, G., & Wang, J.-C. 2013b, MNRAS, 436, 2170
Cao, X. 2004, ApJ, 613, 716
Cao, X. 2011, ApJ, 737, 94
Cao, X., & Jiang, D. R. 2002, MNRAS, 331, 111
Cao, X., & Spruit, H. C. 2013, ApJ, 765, 149
Cavagnolo, K. W., McNamara, B. R., Nulsen, P. E. J., et al. 2010, ApJ, 720, 1066
Celotti, A., Padovan, P., & Ghisellini, G. 1997, MNRAS, 286, 415
Cerruti, M., Boisson, C., & Zech, A. 2013, A&A, 558, A47
Chen, L., Cao, X., & Bai, J. M. 2012, ApJ, 748, 119
Chen, Z.-Y., Gu, M.-F., Fan, Z.-H., & Cao, X.-W. 2009, RAA, 9, 1192
Collmar, W., Böttcher, M., Krichbaum, T. P., et al. 2010, A&A, 522, A66
Dai, Z. G., Zhang, B., Gou, L. J., Mészáros, P., & Waxman, E. 2002, ApJL, 580, L7
Davis, S. W., & Laor, A. 2011, ApJ, 728, 98
Dominguez, A., Finke, J. D., Prada, E. et al. 2013, ApJ, 770, 77
Donato, D., Ghisellini, G., Tagliaferri, G., & Fossati, G. 2001, A&A, 375, 739
Elitzur, M., & Ho, L. C. 2009, ApJL, 701, L91
Falomo, R., Carangelo, N., & Treves, A. 2003, MNRAS, 343, 505
Fan, Z.-H., & Cao, X. 2004, ApJ, 602, 103
Fanidakis, N., Baugh, C. M., Benson, A. J., et al. 2011, MNRAS, 410, 53
Fossati, G., Buckley, J. H., Bond, I. H., et al. 2008, ApJL, 677, 906
Fossati, G., Maraschi, L., Celotti, A., Comastri, A., & Ghisellini, G. 1998, MNRAS, 299, 433
