The Radio/Gamma Connection of Blazars from High to Low Radio Frequencies

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Abstract

We construct a large sample of γ-ray blazars with low-frequency radio data using the recently released TGSS AD1 catalog at 150 MHz. The radio/gamma connections of blazars are compared from 143 GHz to 150 MHz. The radio flux density at all radio frequencies shows strong correlation with γ-ray flux for blazars, as well as for the two subclasses, flat-spectrum radio quasars (FSRQs) and BL Lacs. But the correlations get worse from high to low radio frequencies, which indicates that the low-frequency radio emission is the mixture of extended and core components for blazars. In addition, we find that the correlation between 150 MHz radio flux density and γ-ray flux is more significant for BL Lacs than that for FSRQs. The slope for the luminosity correlation between radio and γ-ray flux also gets flatter than unity at 150 MHz. These results indicate that the core dominance at 150 MHz for BL Lacs is larger than that for FSRQs. We also compare the radio luminosity from direct TGSS observations and the extended radiation at 150 MHz for blazars. The results show that the ratio between core and extended components at 150 MHz is about 1:1 on average.

Key words: BL Lacertae objects: general – gamma rays; galaxies – radiation mechanisms: non-thermal – radio continuum; galaxies

1. Introduction

Blazars are active galactic nuclei (AGNs) whose radiation is dominated by the non-thermal emission from aligned relativistic jets. The spectral energy distribution (SED) of blazars is characterized by two bumps, where the low-energy bump is widely accepted to be produced by synchrotron radiation of relativistic electrons. The radiation mechanism of the high-energy bump is under debate. The possible mechanisms include the inverse Compton (IC) emission of relativistic electrons (leptonic model), and the hadronic model with protons and pions (Böttcher et al. 2013). The IC process, including synchrotron-self Compton (SSC) and external Compton (EC) processes, can usually be successful to reproduce the high-energy SEDs of blazars (Ghisellini & Tavecchio 2009; Abdo et al. 2010). Based on the peak frequency of the low-energy bump, blazars are usually divided into three subclasses, low synchrotron peaked blazars (LSPs), intermediate synchrotron peaked blazars, and high synchrotron peaked blazars (HSPs; Abdo et al. 2010; Fan et al. 2016a). In general, the peak frequency of both low and high-energy bumps are corresponding to each other. That is the LSPs have lower high-energy peaks, while the high energy spectra is hard for HSPs (Fossati et al. 1998). The γ-ray photon spectral index is also found to be correlating with the peak frequency (Ackermann et al. 2011a, 2015). According to whether the line emission is present or not, blazars can be divided into flat-spectrum radio quasars (FSRQs) and BL Lac objects (BL Lacs), respectively. In general, most FSRQs are LSPs, while BL Lacs can span a much broader range of peak frequency. There are also some researches suggesting that FSRQs and BL Lacs stay in distinct accretion regimes (Ghisellini et al. 2009, 2010; Sbarrato et al. 2014).

The radio emission of blazars at GHz frequency is characterized by a flat power-law spectrum with \( \alpha < 0.5 \) \((S_\nu \propto \nu^{-\alpha};\) Healey et al. 2007). The radio/gamma connection of blazars has been explored since the era of the Energetic Gamma Ray Experiment Telescope on board the Compton Gamma-Ray Observatory (Jorstad et al. 2001; Lähteenmäki & Valtaoja 2003). Tight correlations between radio and γ-ray flux are found for most works based on the Fermi/LAT observations, where the radio data at various GHz frequencies are applied (Kovalev et al. 2009; Ghirlanda et al. 2010, 2011; Ackermann et al. 2011b; Linford et al. 2011; Nieppola et al. 2011; Fan et al. 2012). These correlations are usually explained by that the radio and γ-ray emission are generated by the same population of relativistic electrons. This is also supported by the weakened trend of the radio/gamma connection from low to high γ-ray bands (Ackermann et al. 2011b; Fan et al. 2012; Lico et al. 2017). In spite of many explorations with GHz band or high-frequency radio data, the radio/gamma connection at low frequency (hundreds MHz) is less explored. Several attempts showed that the radio/gamma connection at low frequency was worse than that at high frequencies (Massaro et al. 2013a, 2013b; Giroletti et al. 2016).

Due to the Doppler-boosted emission from the core region, the origin of low-frequency radio emission in blazars is under debate. Similar with large-scale radio galaxies, it is believed to be dominated by the extended jet structure, as the low-frequency radio emission from the core should be absorbed by synchrotron-self absorption (SSA). However, the spectra between MHz and GHz show a signature of flat spectra for blazars (Massaro et al. 2013a, 2013b). The low-frequency spectra of blazars around hundreds of MHz are also flatter than other radio objects (Giroletti et al. 2016), which supports that the low-frequency radio emission of blazars is the mixture of extended and core radiation (Massaro et al. 2014; Giroletti et al. 2016).

In recent years, several new all-sky surveys with much higher sensitivity and angular resolution at low radio frequency (around 150 MHz) have been proposed (see Figure 1 of Shimwell et al. 2017). Several early catalogs of these surveys at low frequency have been released, such as the Low-Frequency Array (LOFAR) Two-meter Sky Survey (LoTSS; Shimwell et al. 2017), the
GaLactic and Extragalactic All-sky Murchison widefield array (GLEAM; Hurley-Walker et al. 2017) survey, and the Tata Institute of Fundamental Research (TIFR) Giant Metrewave Radio telescope (GMRT) Sky Survey (TGSS; Intema et al. 2017). These new and deeper surveys provide good opportunities to explore the radio emission properties of blazars at low radio frequency. Meanwhile, they are also useful for clarifying the nature of unidentified γ-ray sources (Massaro et al. 2013a, 2013b, 2014).

In this paper, we compare the radio/gamma connection of blazars from high to low radio frequencies with the new low-frequency radio survey, and discussed the origin of the low-blazars from high to low radio frequencies with the new low-frequency radio emission. Section 3 gives the results of the radio/gamma connection and other correlations for different radio bands. In Section 4, we explore whether the low-frequency radio luminosity can be used to estimate jet power for blazars. The main conclusions are summarized in Section 5. Throughout this paper, we use a ΛCDM cosmology with $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.27$, and $\Omega_{\Lambda} = 0.73$.

2. Sample Properties

The 0.1–100 GeV γ-ray energy flux of the third Fermi/LAT AGN catalogs (3LAC; Ackermann et al. 2015) clean sample is taken from the third Fermi/LAT source catalog (3FGL), which is based on the first 48 months of data of the Fermi/LAT (Acero et al. 2015). The clean sample of 3LAC contains 1420 blazars, where only 760 sources have redshift measurements (Ackermann et al. 2015). The radio data are derived from three catalogs. For low-frequency radio data, we use the catalog of the TGSS AD1 (Intema et al. 2017). The TGSS survey has covered 90% of all of the sky between $-53^\circ$ and $+90^\circ$ decl. The median sensitivity limit is about 3.5 mJy beam$^{-1}$. The astrometric accuracy is about 2" in R.A. and decl. (Intema et al. 2017). The GHz radio data are taken from the Radio Fundamental Catalog (RFC; L. Petrov & Y. Y. Kovalev 2018, in preparation; Petrov et al. 2019). The RFC provides precise positions with milliarcsecond accuracies, and correlated flux densities at baselines of 1000–8000 km for more than 14,000 compact radio sources based on very long baseline interferometry (VLBI) observations. 3 The 143 GHz high-frequency data are derived from the fifth edition of the Roma-BZCAT catalog (Massaro et al. 2009, 2015), which is based on the observations of Planck Compact Source Catalogue Public Release 1 (PLANCK; Planck Collaboration et al. 2014).

These three radio samples are cross-matched with the 3LAC clean sample. The coordinates of the low-energy counterparts for the γ-ray sources in 3LAC are used to cross-match with the radio catalogs. As the associations of γ-ray sources are mostly based on the radio catalogs (such as NVSS, SUMSS, CRATES, and CGRaBs; Ackermann et al. 2015), the expected separations are small. We compare the association results for different matching radius from 1″ to 15″ with a 0′′.5 step. The results are shown in Figure 1. The counts of the associated sources are generally less variable when the matching radius is larger than 5″. To avoid the spurious associations, we choose 5″ for all of the source associations in our work.4

3 http://astrogeo.org/rfc/
4 Note that the selection of the matching radius has little impact on our final samples for statistic analysis, as most sources without radio flux density and redshift data in the cross-matched samples are excluded for statistic analysis.

Within 5″ of the TGSS AD1, 983 γ-ray sources are found. The detection rate is about 74.0% compared with the 1328 γ-ray objects within the TGSS field. As the luminosity is needed in our analyses below, we only consider the sources with redshift measurements. Among the 983 sources, there are 603 sources with redshift measurements, including 364 FSRQs, 197 BL Lacs, and 42 AGNs of other types.

Benefiting from the VLBI observations of the RFC, the total and unresolved (core) emission at gigahertz can be treated individually. Three frequencies of K-band (22 GHz), C-band (5 GHz), and S-band (2.2 GHz) radio data are applied in this work. There are 127, 315, and 498 sources with redshift measurements after cross-matching with the 3LAC clean sample for 22 GHz, 5 GHz, and 2.2 GHz, respectively.

For 143 GHz data, there are 281 blazars with redshift measurements in BZCAT within 5″ of the associations in the 3LAC clean sample, including 222 FSRQs and 46 BL Lacs. The construction of each sample is also summarized in Table 1. For the K-correction when the luminosity is calculated, the spectral index is assumed to be 0.7 for 150 MHz and 0.0 for the high frequencies.
Table 1
Results of Correlation Analysis

| Radio Frequency | Par A | Par B | All | FSRQ | BL Lac |
|-----------------|-------|-------|-----|------|--------|
|                 | N     | $\rho$ | $P$ | N    | $\rho$ | $P$ |
| 143 GHz         |       |       |     |      |        |
| $F_{143\,GHz}$  | 281   | 0.50  | 3.4e-19 | 222 | 0.49 | 8.6e-15 | 46 | 0.59 | 1.7e-05 |
| $L_{143\,GHz}$  | $\Gamma_7$ |       | 2.2e-04 | 222 | 0.10 | 0.14 | 46 | 0.23 | 0.13 |
| $F_{\gamma}/F_{143\,GHz}$ | 281 | -0.28 | 1.9e-06 | 222 | -0.25 | 1.9e-04 | 46 | -0.54 | 9.0e-05 |
| 22 GHz core     |       |       |     |      |        |
| $F_{\gamma}/F_{22\,GHz}$ | 127 | 0.39 | 4.4e-06 | 94 | 0.36 | 3.6e-04 | 24 | 0.19 | 0.38 |
| $L_{22\,GHz}$   | $\Gamma_7$ |       | 0.16 | 94 | -0.006 | 0.95 | 24 | 0.09 | 0.69 |
| $F_{\gamma}/F_{22\,GHz}$ | 127 | -0.25 | 0.004 | 94 | -0.20 | 0.06 | 24 | -0.69 | 1.7e-04 |
| 22 GHz total    |       |       |     |      |        |
| $F_{\gamma}/F_{22\,GHz}$ | 127 | 0.40 | 2.8e-06 | 94 | 0.41 | 4.7e-05 | 24 | 0.10 | 0.64 |
| $L_{22\,GHz}$   | $\Gamma_7$ |       | 0.09 | 94 | 0.009 | 0.93 | 24 | 0.13 | 0.56 |
| $F_{\gamma}/F_{22\,GHz}$ | 127 | -0.31 | 3.8e-04 | 94 | -0.29 | 0.005 | 24 | -0.71 | 1.2e-04 |
| 5 GHz core      |       |       |     |      |        |
| $F_{\gamma}/F_{5\,GHz}$ | 315 | 0.46 | 4.0e-18 | 216 | 0.46 | 1.8e-12 | 83 | 0.64 | 5.3e-11 |
| $L_{5\,GHz}$    | $\Gamma_7$ |       | 1.8e-15 | 216 | 0.15 | 0.03 | 83 | 0.41 | 1.3e-04 |
| $F_{\gamma}/F_{5\,GHz}$ | 315 | -0.45 | 6.1e-17 | 216 | -0.29 | 1.8e-05 | 83 | -0.60 | 2.8e-09 |
| 5 GHz total     |       |       |     |      |        |
| $F_{\gamma}/F_{5\,GHz}$ | 315 | 0.52 | 4.2e-23 | 216 | 0.52 | 1.1e-16 | 83 | 0.64 | 6.9e-11 |
| $L_{5\,GHz}$    | $\Gamma_7$ |       | 9.4e-15 | 216 | 0.12 | 0.08 | 83 | 0.41 | 1.2e-04 |
| $F_{\gamma}/F_{5\,GHz}$ | 315 | -0.45 | 2.2e-17 | 216 | -0.29 | 2.0e-05 | 83 | -0.59 | 3.4e-09 |
| 2.2 GHz core    |       |       |     |      |        |
| $F_{\gamma}/F_{2.2\,GHz}$ | 498 | 0.41 | 5.4e-22 | 329 | 0.40 | 5.0e-14 | 132 | 0.55 | 7.4e-12 |
| $L_{2.2\,GHz}$  | $\Gamma_7$ |       | 4.8e-27 | 329 | 0.10 | 0.08 | 132 | 0.51 | 4.6e-10 |
| $F_{\gamma}/F_{2.2\,GHz}$ | 498 | -0.45 | 2.1e-26 | 329 | -0.30 | 2.3e-08 | 132 | -0.67 | 2.9e-18 |
| 2.2 GHz total   |       |       |     |      |        |
| $F_{\gamma}/F_{2.2\,GHz}$ | 498 | 0.43 | 2.2e-24 | 329 | 0.42 | 8.2e-16 | 132 | 0.54 | 1.8e-11 |
| $L_{2.2\,GHz}$  | $\Gamma_7$ |       | 3.5e-27 | 329 | 0.09 | 0.11 | 132 | 0.51 | 4.3e-10 |
| $F_{\gamma}/F_{2.2\,GHz}$ | 498 | -0.47 | 7.3e-29 | 329 | -0.32 | 2.1e-09 | 132 | -0.65 | 3.9e-17 |
| 150 MHz         |       |       |     |      |        |
| $F_{150\,MHz}$  | 603   | 0.35  | 6.4e-19 | 364 | 0.29 | 2.6e-08 | 197 | 0.50 | 1.2e-13 |
| $L_{150\,MHz}$  | $\Gamma_7$ |       | 7.9e-43 | 364 | 0.06 | 0.27 | 197 | 0.42 | 9.8e-10 |
| $F_{\gamma}/F_{150\,MHz}$ | 603 | -0.29 | 5.4e-13 | 364 | -0.11 | 0.03 | 197 | -0.27 | 1.6e-04 |

Note. Column 1 gives the frequency for radio data, where the core and total components are treated individually for the RFC. Columns 2 and 3 are the two parameters that are applied for the correlation analysis, respectively. $N$ is the sample number. $\rho$ is the correlation coefficient of the Spearman correlation test. $P$ is the probability of no correlation.

Figure 2. Radio/gamma connection for different radio frequencies. The orange open circles represent FSRQs, the blue triangles are BL Lacs, and the black squares are blazars of uncertain types.
3. Results and Discussions

Figure 2 shows the flux correlation between radio and $\gamma$-ray luminosities for different radio frequencies. The results of the Spearman correlation test for each radio band are given in Table 1. The core and total flux densities of VLBI observations from RFC are treated individually. We also examine the correlation for FSRQs and BL Lacs individually. The 150 MHz radio flux density shows significant correlation with the $\gamma$-ray flux, although the correlation coefficient is smaller than that for higher frequencies. The 143 GHz and 5 GHz radio flux densities show the strongest correlation with the $\gamma$-ray flux with the correlation coefficient of 0.50 and 0.52. In addition, the correlation of BL Lacs is generally better than that of FSRQs, except the 22 GHz radio flux density. No correlation is found between the 22 GHz radio flux density and the $\gamma$-ray flux for BL Lacs. This may be caused by the small sample (24 objects). In particular, the flux correlation at 150 MHz for BL Lacs is much better ($\rho = 0.50$) than that for FSRQs ($\rho = 0.29$). As the radio/$\gamma$-ray connection is originated from the related physical processes of radio and $\gamma$-ray emission (e.g., Ackermann et al. 2011b), the more significant correlation for BL Lacs indicates that the core component is more dominant in BL Lacs.

The correlations for core and total emission from VLBI observations show no obvious differences. Fractional reason is that the total VLBI flux density is dominated by the core component. The tight connection between the flux density of the radio core and $\gamma$-ray flux indicates that the $\gamma$-ray emission is related to the VLBI cores.

To clarify the origin for the weaker correlation at low radio frequencies further, we compare the linear relation between radio and $\gamma$-ray luminosity for different radio bands (Figure 3) with $\log L_\gamma = A \log L_{\text{radio}}$ (where $\sigma$ is the intrinsic scatter for the linear relation). The Bayesian approach for linear regression proposed by Kelly et al. (2007) is applied to find the linear relations between radio and $\gamma$-ray luminosity. The results of linear fit are summarized in Table 2. The linear relations get flatter from high to low radio frequencies with similar intrinsic scatters. The slopes for GHz (from several to tens) radio luminosity are well consistent with unity (Lister et al. 2011), which suggests the common origin from the same group of electrons. The slope for low-frequency radio luminosity is about 0.88, which suggests a different origin of low-frequency radio emission.

Considering the radio luminosity at the GHz and MHz band, if the spectral index is constant for all of the sources, the slope would be similar between the different bands. The flatter trend indicates that radio luminosity difference at the low-luminosity end is larger than that at the high luminosity part, i.e., the spectral index between high and low frequency of the low-luminosity sources is flatter than that of the high-luminosity sources. This is supported by the direct analyses of blazar spectra at low frequency. The spectral index of FSRQs is slightly larger than that of BL Lacs (Giroletti et al. 2016). The flatter spectra of BL Lacs indicates that the core emission is more dominant, which is also supported by the results of the flux correlation. The more dominant extended emission, combined with the higher total luminosity of FSRQs at 150 MHz, indicates that the luminosity of extended structures of FSRQs is also higher than that of BL Lacs. This is consistent with their unified version—radio galaxies, where FR IIs are more luminous than FR Is (Fanaroff & Riley 1974). For the steepening trend between the GHz and 143 GHz band, a possible explanation is that the variability at high frequency is

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Table 2

| Radio Frequency | A      | B      | $\sigma$ |
|----------------|--------|--------|----------|
| 143 GHz        | 1.18 ± 0.03 | −6.39 ± 1.40 | 0.41     |
| 22 GHz core    | 0.98 ± 0.05 | 3.44 ± 2.33 | 0.52     |
| 22 GHz total   | 1.01 ± 0.05 | 2.05 ± 2.30 | 0.51     |
| 5 GHz core     | 0.91 ± 0.02 | 7.15 ± 0.97 | 0.50     |
| 5 GHz total    | 0.93 ± 0.02 | 6.01 ± 0.98 | 0.48     |
| 2.2 GHz core   | 0.97 ± 0.02 | 5.03 ± 0.75 | 0.45     |
| 2.2 GHz total  | 0.97 ± 0.02 | 5.06 ± 0.75 | 0.46     |
| 150 MHz        | 0.88 ± 0.02 | 9.38 ± 0.80 | 0.57     |

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Figure 3. Linear correlation between radio and $\gamma$-ray luminosity for different radio frequencies. The symbols are same as those in Figure 2. The solid lines show the best fits.
more intense and the variability amplitude of high-luminosity sources, i.e., LSPs is larger than that of the low-luminosity ones (Richards et al. 2014; Fuhrmann et al. 2016).

We also explore the correlation between the \(\gamma\)-ray photon spectral index, \(\Gamma_{\gamma}\), and the radio properties of blazars for different radio frequencies. The results for radio luminosity \(L_{\text{radio}}\) and flux ratio \(F_{\gamma}/F_{\text{radio}}\) are plotted in Figures 4 and 5, respectively. As the \(\gamma\)-ray spectral index is well correlated with the peak frequency (Ackermann et al. 2011a, 2015), the correlation between radio luminosity and \(\Gamma_{\gamma}\) can be used to explore the so-called blazar sequence (Fossati et al. 1998; Ghisellini et al. 1998). The other is the position at the SED for a certain observed frequency. For the SEDs with constant shape, the separation between the observed frequency and the peak is larger for HSPs. Thus the higher-peaked (smaller \(\Gamma_{\gamma}\)) sources would have lower radio luminosity at a certain radio frequency. This effect can also explain why the correlation between radio luminosity and \(\Gamma_{\gamma}\) only exists for BL Lacs, as the peak frequency range of FSRQs is much smaller. The correlations disappear at the highest radio frequencies (143 GHz and 22 GHz) even for BL Lacs.

The flux ratio between \(\gamma\)-ray and radio emission \(F_{\gamma}/F_{\text{radio}}\), also named \(\gamma\)-ray dominance or \(\gamma\)-ray loudness (Lister et al. 2011; Nieppola et al. 2011), shows negative correlation with the \(\gamma\)-ray spectral index. The correlation is best for 2.2 GHz and 5 GHz. Similar with the flux correlation, the correlations for BL Lacs is better than those for FSRQs (Figure 5, Table 1). The similar correlations with 15 GHz and 37 GHz data have been

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**Figure 4.** Correlation between radio luminosity and the \(\gamma\)-ray index for different radio frequencies. The symbols are same as those in Figure 2.

**Figure 5.** Correlation between the flux ratio \(F_{\gamma}/F_{\text{R}}\) and the \(\gamma\)-ray index for different radio frequencies. The symbols are same as those in Figure 2.
explored by Lister et al. (2011) and Nieppola et al. (2011), respectively. The $\gamma$-ray loudness is different from the Compton dominance, which is defined by the flux/luminosity ratio between the IC bump and the synchrotron bump. As mentioned above, the radio flux density at a certain frequency is not only dependent on the blazar sequence, but also on the position at the SED. Similarly, the $\gamma$-ray flux is also dependent on the $\gamma$-ray spectra, which results in the similar range of $\gamma$-ray flux between FSRQs and BL Lacs (Figure 2, also see Figure 8 and 9 of Ackermann et al. 2015). Thus the negative correlation between $\gamma$-ray loudness and $\Gamma_{-\gamma}$, which seems to contradict with the blazar sequence (reflected by the negative/positive correlation between Compton dominance and peak frequency/$\Gamma_{-\gamma}$), is comprehensible. As suggested by Lister et al. (2011), the significant correlations between the peak frequency/$\Gamma_{-\gamma}$ and the $\gamma$-ray loudness indicate that the intrinsic shapes of SEDs are similar for all blazars, including not only the Compton dominance, but also the frequency ratio between the two bumps and width of each bump. Another factor affecting the $\gamma$-ray loudness is the different Doppler transformation for EC and SSC processes (Dermer 1995; Meyer et al. 2012). However, all of these parameters seem correlate with the peak frequency (Fossati et al. 1998; Finke 2013; Chen 2014; Fan et al. 2016b). These extra connections bring in large scatters for the correlation with $\gamma$-ray loudness.

4. Is the 150 MHz Radio Luminosity a Good Tracer of the Jet Power for Blazars?

Based on the radio and X-ray observations of radio lobes, several empirical relations between kinetic jet power and 151 MHz radio luminosity have been constructed (Willott et al. 1999; Punsly 2005; Cavagnolo et al. 2010; Wu et al. 2011; Godfrey & Shabala 2013; Ineson et al. 2017). These empirical relations are dependent on the assumption that the low-frequency radio emission is dominated by the extended radio structures (Willott et al. 1999; Hardcastle 2018). The radio/gamma connection and the spectral index properties (Massaro et al. 2013a, 2013b; Giroletti et al. 2016) suggest that the blazar emission at 151 MHz is the combination of core and extended components. Thus, can 151 MHz radio luminosity be used to estimate the jet power for blazars?

In order to clarify this, we compare the extended radio luminosity from Meyer et al. (2011) with the 150 MHz data from direct TGSS observations. A spectral index of 0.7 is assumed to convert the 300 MHz radio luminosity into 150 MHz. We find that the 150 MHz luminosity from the TGSS observation is about 2.1 times higher than that from the extrapolation of the extended 300 MHz luminosity. This indicates that about half of the radio emission at 150 MHz comes from the extended radio structures, i.e., the ratio between core and lobe is about 1:1. Figure 6 shows the comparison between the extended radio luminosity of 150 MHz extrapolated from 300 MHz and observed 150 MHz radio luminosity corrected by a factor of 2.1. A linear regression gives the best fit $\log(L_{150}/2.1) = 0.96 \pm 0.03 (\log(L_{300}^{2.1} - 40)) + 40.09 \pm 0.07$. The slope is well consistent with unity. We also find that this correction makes good unification of jet power distributions between blazars and radio galaxies (Urry & Padovani 1995) for both FSRQs/FR IIs and BL Lacs/FR Is (X.-L. Fan et al. 2018, in preparation).

Giroletti et al. (2016) decomposed the total flux density as the combination of core and lobe components between 120 MHz and 180 MHz, $S_\nu = k_c \nu^{-\alpha_c} + k_l \nu^{-\alpha_l} \propto \nu^{-\alpha_{low}}$. By substituting $\alpha_c = 0.096$, $\alpha_l = 0.866$, and $\alpha_{low} = 0.57$, they derived $k_l/k_c = 75$ and the core dominance of about 0.63 at 150 MHz. This value is slightly lower than the value here (1.1 on average). The core dominance derived with this method is dependent on the applied spectral index at low radio frequency $\alpha_{low}$ (from 120 MHz to 180 MHz in their case). If the spectral index of 0.5 of $\gamma$-ray blazars is applied (see their Table 3), the core dominance at 150 MHz becomes about 0.93, which is generally consistent with our estimations.

It needs to be noted that the correction with a constant factor is only valid statistically, as the ratio between the core and the extended component at 150 MHz is variable for a single object due to variable Doppler factors, or for various subclasses of blazars (see Section 3). The scatter of low-luminosity sources is roughly larger than that of high-luminosity sources in Figure 6. This also can be speculated if the core component is more obvious at the low-luminosity end, and the high luminosity sources are more dominated by the extended component at 150 MHz. Merloni & Heinz (2007) explored the connection between jetic jet power and the radio core luminosity of AGNs. They found a significant correlation with a flatter slope of $A = 0.54$. After considering the Doppler boosting effect, the slope changed to 0.81. Their results suggest that both the core and extended emission of radio-loud AGNs has a tight connection with the kinetic jet power. Thus it is expected that the extended radio luminosity can have a tight relation with the mixture of core and extended radio luminosity, except for a scatter from a constant correction factor (2.1 in our case).

5. Summary

The radio/gamma connection of blazars was explored widely in the literature. In this paper, we compare this connection between five different radio frequencies from 143 GHz to 150 MHz. The results confirm that the radio emission at low frequency (150 MHz) is correlated with the high energy emission for blazars, which was found with smaller samples in previous works (Massaro et al. 2014; Giroletti et al. 2016). We confirm that the radio/gamma
connection at 150 MHz is worse when compared with higher frequencies, indicates the combination of extended and core emission for blazars at 150 MHz.

The tighter radio/gamma connection for BL Lacs, combined with the flatter slope of luminosity correlation at 150 MHz, suggest that the core emission at 150 MHz for BL Lacs is more dominant than that for FSRQs.

We compare the 150 MHz radio luminosity of blazars from direct radio observations and extended radio luminosity extrapolated from 300 MHz, and find the fraction of core to extended radio emission is about 1:1 on average. After a correction of a factor of about 2.1, the 150 MHz radio luminosity can be a good tracer of jet power for blazars statistically.

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