The pc-scale radio structure of MIR-observed radio galaxies

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Received 2018 April 3; accepted 2018 April 25

Abstract We investigated the relationship between the accretion process and jet properties by utilizing very long baseline array (VLBA) and mid-infrared (MIR) data for a sample of 45 3CRR radio galaxies selected with a flux density at 178 MHz $>$ 16.4 Jy, 5 GHz very large array (VLA) core flux density $\geq$ 7 mJy and MIR observations. The pc-scale radio structure at 5 GHz is presented by using our VLBA observations for 21 sources acquired in February, 2016, the analysis of archival data for 16 objects and directly obtaining measurements for eight radio galaxies available from literatures. The accretion mode is constrained from the Eddington ratio with a dividing value of 0.01, which is estimated from the MIR-based bolometric luminosity and the black hole masses. While most Fanaroff-Riley type II radio galaxies (FRIIs) have higher Eddington ratio than Fanaroff-Riley type I radio galaxies (FRIs), we found that there is indeed no single correspondence between the FR morphology and accretion mode with eight FRIIs at low accretion rate and two FRIs at high accretion rate. There is a significant correlation between the VLBA core luminosity at 5 GHz and the Eddington ratio. Various morphologies are identified in our sample, including core only, single-sided core-jet and two-sided core-jet structures. We found that the higher accretion rate may be more likely related with the core-jet structure, thus generating a more extended jet. These results imply that the higher accretion rates are likely able to produce more powerful jets. There is a strong correlation between the MIR luminosity at 15 $\mu$m and VLBA 5 GHz core luminosity, in favor of the tight relation between the accretion disk and jets. In our sample, the core brightness temperature ranges from $10^9$ to $10^{13.38}$ K with a median value of $10^{11.09}$ K, indicating that systematically the beaming effect may not be significant. The exceptional cases, FRIs at high accretion rates and FRIIs at low accretion rates, are exclusively at the high and low ends, respectively, of the distribution of the flux ratio for VLBA core to 178 MHz flux density. It is not impossible that the locations of these sources are due to the recent shining or weakening of their central engines (i.e., both accretion and jet).

Key words: galaxies: active — galaxies: structure — galaxies: general — radio continuum: galaxies

1 INTRODUCTION

It has been long found that Fanaroff-Riley type I radio galaxies (FRIs) are edge-darkened, while Fanaroff-Riley type II radio galaxies (FRIIs) are edge-brightened (Fanaroff & Riley 1974). For a given host galaxy luminosity, FRIs have lower radio luminosities than FRIIs (Owen & Ledlow 1994). The primary reason for this difference is still not clear. There are two scenarios to explain this difference, due to either the different physical conditions in the ambient medium (Gopal-Krishna & Wiita 2000), or the difference in central engines, i.e., different accretion modes and/or jet formation processes (Ghisellini & Celotti 2001).
About three decades ago, two different types of central engines were identified based on the analysis of powerful radio sources. Many powerful objects have strong optical and ultraviolet continua, for which one invokes copious and radiatively efficient accretion flows (quasars and broad line radio galaxies) (Begelman et al. 1984). However, many double radio sources, e.g. Cygnus A, lack this radiative signature, which can be instead perhaps explained by Blandford & Znajek (1977) with a mechanism for electromagnetic extraction of rotational energy from a black hole.

Later on, using spectropolarimetric observations, quasar spectra were discovered in many radio galaxies (Antonucci 1984), suggesting that all radio galaxies and radio quasars are powered by similar central engines. While the hidden quasars were detected in many radio galaxies, in some cases, they were not (Singal 1993). Quasars hidden by dusty gas will re-radiate their absorbed energy in the infrared (IR), therefore, extensive observations with infrared spectroscopy were made to search more robustly for the hidden quasars in radio galaxies (e.g., Ogle et al. 2006; Haas et al. 2005; Leipski et al. 2009, etc). The targets were selected by their diffuse radio flux density, to minimize any orientation biases. Spitzer observations indicated that there are two types of central engines for radio galaxies, which do not show a correlation exactly with the FR class. Ogle et al. (2006) demonstrated that about half of narrow-line FRII radio galaxies have a mid-infrared (MIR) luminosity at 15 m of $> 8 \times 10^{43}$ erg s$^{-1}$, indicating strong thermal emission from hot dust in the active galactic nucleus (AGN), just like the matched quasars. However, they also found that another half do not. These MIR-weak sources do not contain a powerful accretion disk, and they may be fit with nonthermal, jet-dominated AGNs, where the jet is powered by a radiatively inefficient accretion flow or black hole spin-energy, rather than energy extracted from an accretion disk. The mismatch with FR class was also found in FRIs. Leipski et al. (2009) reported most FRIs lack a powerful type-1 AGN, but it is not tenable to generalize this result based on associations between FRI galaxies and nonthermal only AGNs, and a fraction of FRIs do have warm dust emission which could be attributed to hidden type-1 nuclei (Antonucci 2002).

The different central engine types in radio galaxies could be constrained from their IR luminosity. On the scales of relativistic jets being produced, the central engines may strongly differ, which calls for investigations to understand how accretion mode affects the innermost radio emission. Very long baseline interferometry (VLBI) is one of the most powerful tools to detect jet properties at pc-scales. In this work, we combine very long baseline array (VLBA) and MIR observations for a sample of radio galaxies, to study the relation between the accretion process and jet properties at pc-scale. Our sample is described in Section 2, and Section 3 highlights the VLBA and MIR data. We present the results and discussions in Section 4, while the conclusion is provided in Section 5. Throughout the paper, we use a cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.30$, $\Omega_\Lambda = 0.70$. The spectral index $\alpha$ is defined as $f_\nu \propto \nu^\alpha$, in which $f_\nu$ is the flux density at frequency $\nu$.

2 SAMPLE

To systematically study the relationship between accretion mode and pc-scale jet properties, we choose a sample from the 3CRR catalogue (Laing et al. 1983). There are 173 sources in the 3CRR catalogue, including 43 quasars, 10 broad-line radio galaxies and 120 narrow-line radio galaxies. The original 3CRR catalogue has a flux limit of 10 Jy at 178 MHz and is the canonical low-frequency selected catalog for bright radio sources. From the 3CRR sample, the MIR observations have been well studied for a well-defined, radio flux-limited sample of 50 radio galaxies with a flux density at 178 MHz $> 16.4$ Jy and 5 GHz very large array (VLA) core flux density $\geq 7$ mJy (e.g. Ogle et al. 2006; Haas et al. 2005; Leipski et al. 2009, etc). The MIR emission enables us to explore the existence of hidden quasars, thus we use this subsample in our study. We carefully searched the VLBI observations for all these 50 objects, and found that 27 sources have already been observed with VLBA. We observed the remaining 23 targets with VLBA at 5 GHz. In two objects, the poor $uv$ data preclude us from making good images. Moreover, in three of the 27 sources with archived VLBA observations, the VLBA data are not useful for generating final images. After excluding these five sources, the final sample consists of 45 radio galaxies with MIR detections and VLBA observations either by us or from the archive. Essential information on the sample is listed in Table 1, in which 30 sources belong to FRIIs, 11 sources are FRIs and the remaining four sources are core-dominated cases (Laing et al. 1983).
| Name    | Alias | ID     | z     | FR | log $M_{BH}$ ($M_\odot$) | $D$ (Mpc) | $f_{VLA}$ (mJy) | $f_{178}$ (mJy) | $f_{MIR}$ (mJy) | log $L_{bol}$ (erg s$^{-1}$) | Calibrator | Distance (deg) |
|---------|-------|--------|-------|----|--------------------------|-----------|----------------|----------------|----------------|-------------------------------|------------|----------------|
| 3C 31   | UGC00689 | Bo015  | 0.0167| I  | 8.65 72.4 92 18.3 17.19 43.82 |
| 3C 33   | BG239 | 0.0595 | II | 8.50 266 24 59.3 75 45.20 |
| 3C 47   | BG239 | 0.425 | II | 9.20 2330 73.6 28.8 34.39 46.32 |
| 3C 48   | ... | 0.367 | C | 8.80 1960 896 60 110.91 43.56 |
| 3C 66B  | UGC01841 | Bo015  | 0.0215| I  | 8.58 93.6 182 26.8 4.76 43.20 |
| 3C 79   | BG239 | 0.2559 | II | 8.80 1294 10 33.2 42.08 46.03 0316+162 2.23 |
| 3C 84   | ... | 0.0177 | I | 8.89 76.8 59600 66.8 1146.04 45.30 |
| 3C 98   | 0356+10 | BG158  | 0.0306| II | 8.21 134 9 51.4 48.8 46.28 |
| 3C 109  | BT065 | 0.3056 | II | 9.30 1586 263 23.5 120.02 46.51 |
| 3C 123  | ... | 0.2177 | II | 7.87 1078 100 206 2.8 44.99 |
| 3C 138  | BC081 | 0.759 | C | 8.70 4700 896 60 110.91 46.62 |
| 3C 147  | ... | 0.545 | C | 8.70 3142 2500 65.9 22.4 46.03 |
| 3C 173.1| BG239 | 0.292 | II | 8.96 1510 7.4 16.8 0.6 44.67 0708+742 0.78 |
| 3C 192  | BG239 | 0.0598 | II | 8.43 268 8 23 3.2 44.13 0759+252 1.19 |
| 3C 208  | BH167 | 1.109 | II | 9.40 7510 51 18.3 5.8 46.38 |
| 3C 212  | BH057 | 1.049 | II | 9.20 7010 150 16.5 26.5 46.68 |
| 3C 216  | ... | 0.668 | II | 7.00 4020 1050 22 28.7 46.58 |
| 3C 219  | BG239 | 0.1744 | II | 8.77 841.7 51 44.9 11.2 45.31 |
| 3C 220.1| BG239 | 0.61 | II | 8.40 3600 25 17.2 2.4 46.66 |
| 3C 226  | BG239 | 0.82 | II | 8.05 5200 7.5 16.4 15.65 46.52 0943+105 0.77 |
| 3C 234  | BG239 | 0.5524 | II | 8.27 3194 13.3 23.8 0.9 45.29 0951+175 3.15 |
| 3C 254  | BG239 | 0.734 | II | 9.30 4510 19 21.7 11.6 46.01 |
| 3C 263  | BG239 | 0.652 | II | 9.10 3910 157 16.6 29.8 46.57 |
| 3C 264  | BK125 | 0.0208 | I | 8.57 90.5 200 28.3 10.32 46.80 |
| 3C 272.1| ... | 0.0029 | I | 8.40 12 180 21.1 27.6 42.76 |
| 3C 274  | J1230+12 | W040  | 0.0041| I | 8.86 18 4000 1144.5 42.96 43.19 |
| 3C 275.1| BG239 | 0.557 | II | 8.30 3230 130 19.9 8.4 46.03 |
| 3C 286  | ... | 0.849 | C | 8.50 5400 5554 27.3 7.64 45.97 |
| 3C 288  | BG239 | 0.246 | I | 9.50 1240 30 20.6 0.6 45.54 |
| 3C 300  | BG239 | 0.272 | II | 8.49 1390 9 19.5 0.7 44.67 1417+172 2.61 |
| 3C 309.1| J1459+71 | BB233 | 0.904 | II | 9.10 5830 2350 24.7 17.2 46.29 |
| 3C 326  | 1549 | BG202 | 0.0895 | II | 8.23 409 13 22.2 0.39 46.69 |
| 3C 338  | BV017 | 0.0303 | I | 9.07 133 105 51.1 2.4 43.56 |
| 3C 380  | BM157 | 0.691 | I | 9.40 4190 7447 64.7 40.4 46.72 |
| 3C 382  | BT065 | 0.0578 | II | 8.75 258 188 21.7 114 45.33 |
| 3C 386  | BG239 | 0.0177 | I | 8.57 76.8 120 26.1 2.47 43.20 |
| 3C 388  | BG239 | 0.0908 | II | 8.81 415 62 26.8 0.84 43.96 |
| 3C 390.3 | ... | 0.0569 | II | 8.92 254 330 51.8 164 45.44 |
| 3C 401  | BG239 | 0.201 | II | 9.18 986 32 22.8 0.8 44.50 |
| 3C 436  | BG239 | 0.2145 | II | 8.66 1060 19 19.4 1.5 44.76 |
| 3C 438  | BG239 | 0.29 | II | 8.74 1490 7.1 48.7 0.45 44.56 2202+363 2.23 |
| 3C 452  | BB199 | 0.0811 | II | 8.46 369 130 59.3 45 45.24 |
| 3C 465  | V018 | 0.0293 | I | 8.77 128 270 41.2 3.17 43.63 |

Notes: Columns (1) – (2): source name and alias name; Col. (3): VLBA project code, b, c - VLBA measurements from Fomalont et al. (2000) and Worrall et al. (2004), respectively; Cols. (4) and (5): redshift and FR types I and II, C represents a core-dominated source; Col. (6): black hole mass; Col. (7): luminosity distance; Cols. (8) – (11): VLA core flux density at 5 GHz, 178 MHz flux density, MIR flux density at 15 µm ( – at 24 µm) and bolometric luminosity; Cols. (12) – (13): phase calibrators for phase-reference observations, and their separation from the source.
3 DATA COMPILATION

In this work, the VLBA and MIR data are essential to study the relationship between accretion mode and pc-scale jets in radio galaxies, which are compiled from our observations and archive data.

3.1 VLBA Observations and Data Reduction

The VLBA observations in our sample consist of three groups. In the first group, we performed VLBA observations at C-band with a total observing time of 20 hours for 23 sources in three blocks for scheduling convenience on 2016 Feb. 13, 14 and 15 (program ID: BG239). For two of these 23 sources, we were not able to make images due to poor uv data quality, thus this group finally consists of 21 objects. Among these 21 sources, 13 radio galaxies can be self-calibrated with observing time of 30 mins for each target, while for the remaining eight sources, phase-referencing is required with on-source time of 40 mins individually. These sources and related phase calibrators are listed in Table 1. Group two has 16 radio galaxies, the VLBA observational data of which can be downloaded from the NRAO archive\(^2\) (see program ID in Table 1). For the other eight sources, the third group, the measurements of jet components can be directly obtained from literatures (Fomalont et al. 2000; Worrall et al. 2004).

Data reduction was performed for the sources in groups one and two. Data were processed with the Astronomical Image Processing System (AIPS) in a standard way. Before fringe fitting, we correct for Earth orientation, remove dispersive delay from ionosphere, and calibrate the amplitude by using system temperature and gain curve. Phase calibration is followed in order by correcting for instrumental phase and delay using pulse-calibration data, and removing the residual phase, delay and rate for relatively strong targets by fringe fitting on the source itself. For weaker targets, the phase-referencing technique is utilized by applying the residual phase, delay and rate solutions from the phase-referencing calibrator to the corresponding target with an interpolation method. Imaging and model-fitting were performed in DIFMAP and the final results are listed in Table 2, in which the measurements of jet components directly adopted from literatures (Fomalont et al. 2000; Worrall et al. 2004).

3.2 Mid-infrared Data

We collected the MIR data for our sample from the NASA/IPAC Extragalactic Database (NED)\(^3\), which was originally compiled from observations using either Spitzer IRS/MIPS or Infrared Space Observatory ISOCAM (e.g. Ogle et al. 2006; Haas et al. 2005; Leipski et al. 2009; Temi et al. 2005). In the sample, the flux densities at 15 µm are available for 39 sources, but only 24 µm flux densities are obtained for the remaining six radio galaxies (i.e., 3C 98, 3C 254, 3C 309.1, 3C 138, 3C 147 and 3C 286, see Table 1).

4 RESULTS AND DISCUSSION

4.1 Accretion Mode

FRIs have lower radio luminosities than FRIIs for a similar host galaxy luminosity (Owen & Ledlow 1994). FRIs and FRIIs have shown a clear dividing line in the radio and optical luminosity plane, which can be re-expressed as a line of constant ratio for the jet or the disk accretion power with Eddington luminosity. This implies the accretion process plays a more important role in the FRI/FRII dichotomy than a different environment (Ghisellini & Celotti 2001).

Quasars hidden by dusty gas will re-radiate their absorbed energy in the infrared. Ogle et al. (2006) investigated the MIR emission using the Spitzer survey of 3C objects, including radio galaxies and quasars, selected by the relatively isotropic lobe emission. They argued that most of the MIR-weak sources may not contain a powerful accretion disk. It is likely that in nonthermal, jet-dominated AGNs, the jet is powered by a radiatively inefficient accretion flow or black hole spin-energy, rather than energy from the accretion disk. Two different central engines are recognized for FRIs or FRIIs in their study, with the dividing value of luminosity at 15 µm of \(8 \times 10^{43}\) erg s\(^{-1}\). The sources with luminosity above it are suggested to contain a radiatively efficient accretion flow.

Instead of a fixed dividing luminosity, the accretion mode is investigated from the Eddington ratio

\(^2\) https://archive.nrao.edu/archive/advquery.jsp

\(^3\) http://ned.ipac.caltech.edu/
### Table 2 Results for the Radio Galaxies

| Name | Comps. | FR | \( S \) (mJy) | \( r \) (mas) | \( \theta \) (deg) | \( a \) (mas) | \( b/a \) | \( \log T_B \) (K) |
|------|--------|----|-------------|-------------|-------------|-------------|---------|----------------|
| 3C 31 | C I | | 80.37 | 0.24 | 178.16 | 0.22 | 1.00 | 11.09 |
| | | | 15.97 | 0.85 | -19.75 | 0.14 | 1.00 |
| | | | 3.09 | 7.79 | -14.43 | 1.55 | 1.00 |
| | | | 5.02 | 3.00 | -13.66 | 1.18 | 1.00 |
| | | | 1.16 | 11.45 | -14.64 | 1.40 | 1.00 |
| 3C 33 | C II | | 20.89 | 0.07 | -149.68 | 0.24 | 1.00 | 10.46 |
| | | | 1.90 | 4.57 | -155.97 | 0.25 | 1.00 |
| | | | 12.94 | 0.26 | 25.18 | 14.18 | 0.05 |
| | | | 2.65 | 15.41 | -158.56 | 5.34 | 0.32 |
| | | | 1.24 | 12.15 | 25.19 | 0.65 | 1.00 |
| | | | 1.69 | 42.71 | 26.19 | 5.78 | 0.33 |
| | | | 0.91 | 16.14 | 21.54 | 1.11 | 1.00 |
| | | | 0.59 | 35.32 | 25.76 | 0.07 | 1.00 |
| | | | 0.60 | 54.06 | 26.83 | 1.77 | 1.00 |
| | | | 0.41 | 4.14 | 27.21 | 0.49 | 1.00 |
| 3C 47 | C II | | 50.97 | 0.05 | 33.95 | 0.14 | 1.00 | 11.57 |
| | | | 5.52 | 2.06 | -149.00 | 0.24 | 1.00 |
| | | | 5.13 | 7.46 | -149.60 | 13.71 | 0.08 |
| | | | 0.78 | 20.88 | -149.04 | 1.09 | 1.00 |
| | | | 1.31 | 4.49 | -146.83 | 0.41 | 1.00 |
| | | | 1.04 | 12.30 | -145.93 | 0.75 | 1.00 |
| | | | 1.10 | 1.58 | 22.11 | 0.42 | 1.00 |
| | | | 0.80 | 7.01 | -153.43 | 0.48 | 1.00 |
| | | | 0.24 | 25.96 | -147.85 | 0.62 | 1.00 |
| 3C 48 | C C | | 56.10 | 0.11 | -130.17 | 2.00 | 0.18 | 9.93 |
| | | | 137.32 | 0.31 | -124.58 | 0.03 | 1.00 | 13.05 |
| 3C 66B | C I | | 84.78 | 0.55 | 56.66 | 0.03 | 1.00 |
| | | | 1.52 | 21.79 | 53.79 | 1.24 | 1.00 |
| | | | 16.05 | 2.43 | 59.46 | 0.36 | 1.00 |
| | | | 5.38 | 4.80 | 55.70 | 0.16 | 1.00 |
| | | | 21.33 | 11.02 | 53.64 | 13.38 | 0.10 |
| | | | 0.66 | 7.23 | 57.92 | 0.41 | 1.00 |
| 3C 79 | C II | | 27.10 | 0.02 | 108.07 | 0.46 | 1.00 | 10.16 |
| | | | 0.98 | 2.41 | -72.30 | 2.50 | 1.00 |
| | | | 0.86 | 7.06 | -71.87 | 2.50 | 1.00 |
| | | | 0.32 | 14.89 | -113.89 | 0.12 | 1.00 |
| | | | 0.30 | 24.28 | -48.36 | 0.16 | 1.00 |
| 3C 84 | C I | | 17752.00 | 154.00 | 4.60 | 0.78 | 10.90 |
| | | | 5833.00 | 170.00 | 6.60 | 0.14 |
| | | | 3084.00 | 161.00 | 5.70 | 0.28 |
| 3C 98 | C II | | 44.87 | 0.01 | 14.63 | 0.21 | 1.00 | 10.88 |
| 3C 109 | C II | | 221.48 | 0.05 | -7.57 | 0.22 | 1.00 | 11.75 |
| | | | 28.37 | 1.91 | 155.42 | 0.11 | 1.00 |
| | | | 6.30 | 8.66 | 150.16 | 1.51 | 1.00 |
| | | | 9.16 | 3.66 | 154.24 | 1.05 | 1.00 |
| | | | 3.72 | 26.09 | 147.10 | 1.25 | 1.00 |
| | | | 5.40 | 13.83 | 152.72 | 2.92 | 1.00 |
| | | | 3.77 | 20.73 | 149.93 | 2.51 | 1.00 |
| | | | 4.47 | 5.37 | 151.00 | 1.01 | 1.00 |
| | | | 4.40 | 10.81 | 150.35 | 1.43 | 1.00 |
| 3C 123 | C II | | 111.00 | 0.39 | 92.00 | 3.90 | 0.77 | 9.00 |
| 3C 138 | C C | | 130.47 | 0.04 | -113.69 | 0.60 | 1.00 | 10.90 |
| | | | 76.55 | 1.64 | -109.71 | 0.16 | 1.00 |
| | | | 47.50 | 3.94 | 112.07 | 3.51 | 0.21 |
| | | | 98.36 | 6.30 | -92.35 | 0.19 | 1.00 |
| | | | 22.17 | 10.83 | 58.89 | 6.77 | 0.25 |
| | | | 38.20 | 14.58 | 27.92 | 8.06 | 1.00 |
| | | | 10.93 | 19.00 | 6.22 | 5.11 | 0.26 |
| | | | 20.80 | 2.69 | -109.01 | 0.54 | 1.00 |
| 3C 147 | C C | | 882.00 | 171.00 | 2.10 | 0.57 | 10.77 |
| | | | 506.00 | 16.00 | 2.80 | 0.18 |
| | | | 676.00 | 146.00 | 5.00 | 0.28 |
| | | | 222.00 | 1.40 | 0.43 |
| 3C 173.1 | C II | | 14.81 | 0.02 | -178.81 | 0.06 | 1.00 | 11.69 |
| 3C 192 | C II | | 13.63 | 0.02 | -150.73 | 0.03 | 1.00 | 12.09 |
| 3C 196 | C II | | 14.25 | 0.02 | -69.89 | 0.18 | 1.00 | 11.03 |
| Name        | Comps. | FR | $S$ (mJy) | $r$ (mas) | $\theta$ (deg) | $a$ (mas) | $b/a$ | \( \log T_\text{jet} \) (K) |
|-------------|--------|----|-----------|-----------|----------------|----------|-------|-----------------|
| 3C 208     | C II   | 72.62 | 0.02     | 170.04    | 0.15           | 0.88     | 11.65 |
|            |        | 9.01  | 3.80     | -96.16    | 0.90           | 0.45     |
|            |        | 4.54  | 2.02     | -35.84    | 0.84           | 1.00     |
| 3C 212     | C II   | 184.40 | 0.04     | 125.47    | 0.16           | 1.00     | 12.14 |
|            |        | 12.87 | 1.80     | -46.29    | 0.07           | 1.00     |
|            |        | 3.41  | 2.02     | -54.32    | 0.84           | 1.00     |
| 3C 206     | C II   | 162.00 | 0.01     | 152.00    | 0.80           | 0.38     | 11.70 |
|            |        | 1.23  | 15.82    | -150.63   | 1.66           | 1.00     |
| 3C 220.1   | C II   | 22.26  | 0.16     | -173.6   | 0.58           | 0.32     | 10.35 |
|            |        | 6.57  | 1.63     | 80.44     | 1.31           | 0.20     |
|            |        | 0.64  | 5.34     | 82.56     | 3.08           | 0.82     |
| 3C 226     | C II   | 17.22  | 1.34     | 148.61    | 0.17           | 1.00     | 12.66 |
|            |        | 0.25  | 1.50     | -25.26    | 0.13           | 1.00     |
| 3C 228     | C II   | 18.41  | 0.03     | 1.36      | 0.05           | 1.00     | 12.10 |
|            |        | 0.90  | 2.20     | -173.6   | 0.09           | 1.00     |
|            |        | 0.30  | 9.45     | -167.45   | 0.36           | 1.00     |
|            |        | 0.25  | 4.34     | -164.92   | 0.26           | 1.00     |
| 3C 234     | C II   | 19.71  | 0.19     | -166.70   | 0.28           | 1.00     | 10.39 |
|            |        | 12.48 | 5.19     | 65.34     | 1.52           | 0.39     |
|            |        | 1.87  | 8.49     | 67.38     | 0.62           | 1.00     |
|            |        | 10.44 | 1.53     | 67.37     | 0.28           | 1.00     |
| 3C 254     | C II   | 18.19  | 0.11     | 86.87     | 0.02           | 1.00     | 12.99 |
|            |        | 3.27  | 1.25     | -71.87    | 0.04           | 1.00     |
|            |        | 2.61  | 3.20     | -71.01    | 1.06           | 1.00     |
|            |        | 0.71  | 5.98     | -66.40    | 0.80           | 1.00     |
|            |        | 0.32  | 9.71     | -70.11    | 1.09           | 1.00     |
| 3C 263     | C II   | 11.60  | 0.10     | -72.97    | 0.01           | 1.00     | 13.38 |
|            |        | 49.77 | 0.91     | 108.43    | 2.09           | 0.18     |
|            |        | 4.06  | 3.15     | 111.08    | 0.06           | 1.00     |
|            |        | 10.64 | 3.15     | 113.84    | 3.31           | 0.16     |
| 3C 264     | C I    | 159.07 | 0.08     | 174.75    | 0.13           | 1.00     | 11.84 |
|            |        | 20.00 | 1.55     | 28.35     | 0.35           | 1.00     |
| 3C 272.1   | C I    | 187.00 | 1.10     | 24.31     | 1.91           | 1.00     | 10.23 |
|            |        | 13.00 | 2.00     | 1.00      | 1.00           |
| 3C 274     | C I    | 850.81 | 1.10     | 24.31     | 1.91           | 1.00     | 11.58 |
|            |        | 390.81| 0.89     | -82.20    | 0.63           | 1.00     |
|            |        | 308.21| 0.89     | 98.28     | 0.46           | 1.00     |
|            |        | 43.08 | 2.00     | 107.23    | 1.17           | 1.00     |
| 3C 275.1   | C II   | 262.91 | 0.19     | 144.58    | 0.72           | 0.08     | 12.03 |
|            |        | 77.80 | 1.38     | -25.10    | 0.44           | 1.00     |
|            |        | 6.56  | 8.06     | -13.82    | 1.68           | 1.00     |
|            |        | 7.16  | 3.16     | -15.05    | 1.22           | 1.00     |
| 3C 286     | C C    | 1723.00 | 1.10    | 33.00     | 4.60           | 0.78     | 10.41 |
|            |        | 978.00| 6.10     | 7.40      | 0.50           | 1.00     |
|            |        | 192.00| 108.00   | 2.60      | 0.58           | 1.00     |
| Name    | Comps. | FR | S (mJy) | r (mas) | θ (deg) | α (mas) | b/α | log \( T_B \) (K) |
|---------|--------|----|---------|---------|----------|---------|-----|------------------|
| 3C 288  | C      | I  | 20.18   | 0.20    | 74.08    | 0.26    | 1.00 | 10.52           |
| 3C 300  | C      | II | 25.12   | 0.02    | 106.06   | 0.50    | 0.10 | 11.06           |
| 3C 309.1| C      | II | 287.32  | 0.38    | −36.12   | 0.16    | 1.00 | 12.46           |
| 3C 452  | C      |    | 95.31   | 0.26    | −95.22   | 0.84    | 1.00 | 10.04           |
| 3C 438  | C      | II | 16.00   | 0.03    | −106.51  | 0.11    | 1.00 | 11.19           |
| 3C 452  | C      | II | 95.31   | 0.26    | −95.22   | 0.84    | 1.00 | 10.04           |
| 3C 436  | C      | II | 16.79   | 0.62    | 3.21     | 0.70    | 0.43 | 9.92            |
| 3C 401  | C      | II | 20.94   | 0.10    | 36.42    | 0.21    | 1.00 | 10.69           |
| 3C 380  | C      | I  | 1083.99 | 0.61    | 149.70   | 1.37    | 0.15 | 11.87           |
| 3C 382  | C      | II | 120.30  | 0.43    | −125.88  | 0.06    | 1.00 | 12.42           |
| 3C 386  | C      | I  | 17.19   | 0.05    | −136.79  | 0.33    | 1.00 | 10.07           |
| 3C 390.3| C      | II | 463.00  | 1.90    | 159.00   | 1.90    | 0.21 | 10.68           |
| 3C 401  | C      | II | 20.94   | 0.10    | 36.42    | 0.21    | 1.00 | 10.69           |
| 3C 438  | C      | II | 16.00   | 0.03    | −106.51  | 0.11    | 1.00 | 11.19           |
| 3C 452  | C      | II | 95.31   | 0.26    | −95.22   | 0.84    | 1.00 | 10.04           |
| 3C 465  | C      | I  | 90.03   | 0.49    | 135.88   | 0.30    | 1.00 | 10.87           |
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Notes: Column (1): source name; \( ^{a} \) at 8 GHz; Col. (2): components; 'C' represents a radio core; Col. (3): FR types I and II, 'C' represents a core-dominated source; Col. (4): flux density; Cols. (5) – (6): component position, and its position angle; Col. (7): major axis; Col. (8): axial ratio; Col. (9): brightness temperature.
Fig. 1 VLBA 5 GHz images for 21 sources from our observations.
$L_{\text{bol}}/L_{\text{Edd}}$ in this work, in which $L_{\text{bol}}$ and $L_{\text{Edd}}$ are the bolometric and Eddington luminosities, respectively. The black hole masses of 17 sources are collected from various literatures (McLure et al. 2006; Wu 2009; McNamara et al. 2011; Mingo et al. 2014). For the other 28 radio galaxies, the black hole masses were estimated by using the relationship between host galaxy absolute magnitude at $R$ band ($M_R$) and black hole mass provided by McLure et al. (2004),

$$\log \left( \frac{M_{\text{BH}}}{M_\odot} \right) = -0.5 M_R - 2.74,$$

in which $M_R$ was calculated from $R$ magnitude in the updated online 3CRR catalogue.
Fig. 2 VLBA 5 GHz images for 15 sources, and 8 GHz image for 3C 208, analyzed from NRAO archival data.
In this work, the bolometric luminosity $L_{\text{bol}}$ is calculated from MIR luminosity either at 15 or at 24 µm, using the relation in Runnoe et al. (2012),

$$\log L_{\text{bol}} = (10.514 \pm 4.390) + (0.787 \pm 0.098) \log (\nu L_{\nu, 15\mu m}),$$

(2)

$$\log L_{\text{bol}} = (15.035 \pm 4.766) + (0.688 \pm 0.106) \log (\nu L_{\nu, 24\mu m}),$$

(3)

in which a spectral index of $\alpha_{\nu} = -1$ is used for k-correction.

We adopted a conventional value of $L_{\text{bol}}/L_{\text{Edd}} = 10^{-2}$ to separate radiatively efficient or inefficient accretion modes (e.g., Hickox et al. 2009). The relationship between VLBA core luminosity at 5 GHz and Eddington ratio is presented in Figure 3. The rest frame 5 GHz luminosity is estimated from the VLBA 5 GHz or 8 GHz (for 3C 208) core flux density using a spectral index of $\alpha = 0$. While most FRII radio galaxies have higher Eddington ratio than FRIs, we found that there is indeed no single correspondence between the FR morphology and accretion mode. The eight out of 30 FRIIs (26.7%) may have low accretion rate with $L_{\text{bol}}/L_{\text{Edd}} < 10^{-2}$, and the other 22 objects (73.3%) are at high accretion mode with $L_{\text{bol}}/L_{\text{Edd}} \geq 10^{-2}$. In contrast, two out of 11 FRIs (18.2%) and 81.8% of FRIs are at radiatively efficient and inefficient accretion modes, respectively. There is a significant correlation between the VLBA core luminosity at 5 GHz and the Eddington ratio, with a Spearman correlation coefficient of $r = 0.820$ at $\gg 99.99$ per cent confidence. This implies that the higher accretion rates are likely able to produce more powerful jets.

The correlation between MIR luminosity at 15 µm and VLBA 5 GHz core luminosity is also investigated in Figure 4. The luminosity at 15 µm in six sources was estimated from 24 µm using a spectral index of $\alpha_{\nu} = -1$. A significant correlation is found between two parameters with a Spearman correlation coefficient of $r = 0.849$ at $\gg 99.99$ per cent confidence. After excluding the common dependence on redshift, the partial Spearman rank correlation coefficient is $r = 0.814$ at $\gg 99.99$ per cent confidence.

Fig. 2 — Continued.
correlation method (Macklin 1982) shows that a significant correlation is still present with a correlation coefficient of \( r = 0.635 \) at \( \geq 99.99 \) per cent confidence. The linear fit gives

\[
\log L_{\text{core,5GHz}} = (0.951 \pm 0.083) \log (\nu L_{\nu,15\mu m}) - (0.263 \pm 3.655).
\]

In a flux-limited low-frequency radio survey like the 3CRR sample, low-frequency emission is mostly dominated by the lobe, which, however, is normally located at the end of the jet, and thus represents past jet activity. In contrast, the MIR and especially the pc-scale VLBA core emission are instantaneously and contemporarily from the central engine. The strong correlation strongly indicates a tight relation between the accretion disk and jets, as found in various works (e.g., Cao & Jiang 1999; Gu et al. 2009).

In the framework of the unification scheme of AGNs, FRIs are unified with BL Lac objects (BL Lacs), and FRIIs with flat-spectrum radio quasars (FSRQs) (Antonucci 1993; Urry & Padovani 1995). Blazars consist of BL Lacs and FSRQs, and are characteristic of the strong beaming effect due to the jets pointing towards us with small viewing angles. The jets in FSRQs are found to have stronger power and higher velocity than those in BL Lacs (e.g., Gu et al. 2009; Chen 2018). On the other hand, the Eddington ratios of BL Lacs are systematically lower than those of radio quasars with a rough division at \( L_{\text{bol}}/L_{\text{Edd}} \approx 0.01 \), which imply that the accretion mode of BL Lacs may be different from that of radio quasars (e.g., Xu et al. 2009). The radio galaxies used in this study have their own advantages in avoiding strong contamination of the jet beaming effect on the VLBA core emission, since the jet viewing angle is usually large in radio galaxies. Our results of higher accretion rate being likely associated with a stronger jet are generally in agreement with the unification scheme.

### 4.2 Pc-scale Radio Morphology

It can be clearly seen from the high-resolution VLBA 5 GHz images in Figures 1 and 2 that there are various morphologies in our sample sources, including 10 core only, 29 one-sided core-jet and 6 two-sided core-jet structures. The two-sided core-jet structure is found in 3C 33, 3C 38, 3C 338, 3C 452 (see Figs. 1 and 2), 3C 147 and 3C 286 (Fomalont et al. 2000).

In this work, we will not distinguish the latter two categories, and instead we call them all core-jet structures. The radio morphologies were further studied with the source fraction of the specified structure in 17 radio galaxies with inefficient accretion flow and 28 efficient ones. At low Eddington ratio (< \( 10^{-2} \)), we found that six out of 17 (35.3%) exhibit core only structure, and the remaining sources (64.7%) have core-jet morphology. In contrast, core only and core-jet cases are present in three (10.7%) and 25 (89.3%) sources, respectively, at high Eddington ratio (\( \geq 10^{-2} \)). It thus seems that the higher accretion rate may be more likely related with the core-jet structure. For a similar distribution of viewing angles likely present in our sample of radio galaxies, radio morphology perhaps can reflect some jet information like strength and speed in different accretion models. A core-jet radio morphology likely indicates the source jet moving at higher speed with relatively large power. However, a naked core may indicate a relatively weaker jet with lower speed. Based on our analysis, we found that the radiatively inefficient accretion flow may perhaps be also inefficient in producing powerful jets moving at lower speed, while the radiatively efficient one shows higher probability of forming strong jets with higher speed. This is consistent with the correlation between VLBA core luminosity at 5 GHz and Eddington ratio shown in Figure 3. In a broader framework, this is also consistent with the radio-quiet populations. LINERs and Seyferts can act as analogs to two accretion systems (Kewley et al. 2006). LINERs seem to have radio cores more optically thick than those of Seyferts, and their radio emission is mainly confined to a compact core or base of a jet, thus the radiatively inefficient accretion flow is likely to host a more compact VLBI pc-scale core than that of a radiatively efficient one.

The pc-scale VLBA projected linear size \( l \) of sources is estimated to be the largest distance between radio components for core-jet sources, which is the major axis for core-only galaxies. The distribution of pc-scale VLBA sizes for all sources is presented in Figure 5, except for eight objects, in which the size is not available in literature. There is a broad range with most sources in 1–100 pc, and the jet extends to about 300–400 pc in several core-jet objects. We find a significant correlation between the linear size and the Eddington ratio with a correlation coefficient of \( r = 0.671 \) at \( \geq 99.99 \) per cent confidence (see Fig. 5). This indicates that the higher accretion rate may have a more extended jet, again supporting our results that there are more powerful jets in higher-accretion systems.
Fig. 3 The VLBA core luminosity at 5 GHz versus the Eddington ratio. The asterisks are for FRIs, triangles for FRIIs and crosses represent core-dominated sources. The Eddington ratio $L_{\text{bol}}/L_{\text{edd}} = 0.01$ is shown as a dotted line which distinguishes the high and low accretion rates.

Fig. 4 The VLBA core luminosity at 5 GHz versus the MIR luminosity at 15 $\mu$m. The solid line is a linear fit. The dotted line is $\nu L_{\nu,15\mu m} = 8 \times 10^{43}$ erg s$^{-1}$, used in Ogle et al. (2006) to distinguish the MIR-weak and MIR-luminous radio galaxies.

4.3 Brightness Temperature

From the high-resolution VLBA images, brightness temperature of radio core $T_B$ in the rest frame can be estimated with (Ghisellini et al. 1993)

$$T_B = 1.77 \times 10^{12} (1+z) \left( \frac{S_\nu}{\text{Jy}} \right) \left( \frac{\nu}{\text{GHz}} \right)^{-2} \left( \frac{\theta_d}{\text{mas}} \right)^{-2} \text{K},$$

in which $z$ is the redshift, $S_\nu$ is core flux density at frequency $\nu$ and $\theta_d$ is the angular diameter such that $\theta_d = \sqrt{ab}$ with $a$ and $b$ being the major and minor axes, respectively. There is an important parameter, Doppler factor $\delta$, which can be restricted by

$$\delta = \frac{T_B}{T_B'},$$

in which $T_B'$ is the intrinsic brightness temperature. The core brightness temperature distribution diagram is presented in Figure 6. In our sample, the core brightness temperature ranges from $10^9$ to $10^{13.38}$ K with a median value of $10^{11.09}$ K (see also in Table 2). Most sources are in the range of $10^{10} - 10^{12}$ K, less than the inverse Compton catastrophic limit $10^{12}$ K (Kovalev et al. 2005). Therefore, systematically the beaming effect may not be significant in our sample, although it may not be trivial in some cases, for example in 3C 263, the source with the highest $T_B$. In comparison, the VLBA core brightness temperatures of blazars typically range between $10^{11}$ and $10^{13}$ K with a median value near $10^{12}$ K, and can even extend up to $5 \times 10^{13}$ K (Kovalev et al. 2005, 2009). These results are basically in agreement in the framework of the unification scheme of AGNs, with FRIs/FRIIs and BL Lacs/FSRQs. The strong beaming effect results in high brightness temperature of the radio cores in blazars.
while it is less pronounced in radio galaxies because of large jet viewing angles.

We have analyzed the correlation between brightness temperature and Eddington ratio in Figure 6. There is no correlation between these two parameters, and the distribution of $T_B$ is similar at high and low accretion rates.

4.4 Comparison with VLA Data

We collected VLA 5 GHz flux density for our sources from the 3CRR catalogue, then we compared the VLBA with VLA flux density. The flux ratio of VLBA core to VLA core, and ratio of VLBA total to VLA core, are plotted with the Eddington ratio in Figure 7. The flux ratio between VLBA and VLA can in principle give information on the source compactness, since they represent the source structure at different scales, with normally the former at pc-scale and the latter at kpc-scale. There are no correlations between the flux ratio and the Eddington ratio. The flux ratio covers more than one order of magnitude, and there is no systematical difference between the high and low accretion regimes. It is interesting to see that the VLBA core flux density is higher than VLA core in many sources. This can be most likely due to variability. This is even more pronounced when considering the VLBA total flux density. In this case, the VLBA total flux is higher than VLA core in the majority of objects, implying variability may be common in our sample.

4.5 Core/lobe Flux Density Ratio

When comparing VLBI pc-scale core flux density with 178 MHz flux density, we would like to investigate the present status of core radio activity. It might be possible that those sources with weak MIR dust emission have just recently started behavior describable by the radiatively inefficient accretion model, while the large scale radio morphology was produced by past activity describable by the radiatively efficient accretion model. Therefore, their core/lobe flux density ratios are expected to be low.
In previous works (e.g., Ogle et al. 2006), the core and lobe luminosity ratios are indeed less in MIR-weak FRIIs than in MIR-luminous FRIIs at VLA.

The ratio of VLBA core to 178 MHz flux density is plotted with the MIR luminosity and the Eddington ratio in Figure 8. While an MIR luminosity at 15 μm of $8 \times 10^{43}$ erg s$^{-1}$ is adopted to distinguish the MIR-weak and MIR-luminous sources in Ogle et al. (2006), we further use the Eddington ratio in recognizing the accretion mode. The flux ratio of VLBA core to 178 MHz covers about two orders of magnitude, and there is no single dependence of the flux ratio on either the Eddington ratio or MIR luminosity. Similar behaviors are seen in the panels showing flux ratio with MIR luminosity and Eddington ratio. Considering solely the high and low accretion rate regime, there is no correlation between the radio flux ratio and MIR luminosity/Eddington ratio. The distribution of flux ratio at high accretion rate is broader than that at low rate, which is mainly concentrated on lower flux ratio and does not extend to very high values. Interestingly, the FRIIs with low MIR luminosity (below $8 \times 10^{43}$ erg s$^{-1}$) or low accretion rate ($L_{bol}/L_{Edd} < 10^{-2}$) are exclusively at the lower end of the distribution of radio flux ratio. In contrast, two MIR-luminous or highly accreting FRIs are all at the high end. It is not impossible that the locations of these sources are due to the recent shining or weakening of the central engine (i.e., both accretion and jet), resulting in a higher or lower VLBA core luminosity, and thus a lower or higher flux ratio of VLBA core to 178 MHz.

5 SUMMARY

We investigated the role of the accretion model in creating VLBI jets by utilizing VLBA and MIR data for a sample of 45 3CRR radio galaxies. The accretion mode is constrained from the Eddington ratio, which is estimated
from the MIR-based bolometric luminosity and the black hole masses. While most FRII radio galaxies have higher Eddington ratio than FRIs, we found that there is indeed no single correspondence between the FR morphology and accretion mode with eight FRIIs at low accretion rate and two FRIs at high accretion rate. There is a significant correlation between the VLBA core luminosity at 5 GHz and the Eddington ratio. We found that the higher accretion rate may be more likely related with the core-jet structure, thus exhibiting a more extended jet. These results imply that the higher accretion rates are likely able to produce more powerful jets. There is a strong correlation between the MIR luminosity at 15 µm and VLBA 5 GHz core luminosity, in favor of the tight relation between the core-jet structure, thus exhibiting a more extended jet. These results imply that the higher accretion rates are likely able to produce more powerful jets. There is a strong correlation between the MIR luminosity at 15 µm and VLBA 5 GHz core luminosity, in favor of the tight relation between the accretion disk and jets. In our sample, the core brightness temperature ranges from $10^3$ to $10^{13.38}$ K with a median value of $10^{11.09}$ K, indicating that the beaming effect may not be systematically significant. The exceptional cases, FRIs at high accretion rate and FRIIs at low accretion rate, are exclusively at the high and low end of the distribution of the flux ratio of VLBA core to 178 MHz flux density. It is not impossible that the locations of these sources are due to the recent shining or weakening of the central engine (i.e., both accretion and jet).

Acknowledgements We thank the anonymous referee for his/her constructive comments that improved the manuscript. We thank Minhua Zhou, Mai Liao and Jiawen Li for their helpful discussions. Special thanks are given to Robert Antonucci for initialization of the project and valuable discussions. This work is supported by the National Natural Science Foundation of China (Grant Nos. 11473054, U1531245, 11763002 and 11590784). This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The VLBA experiment is sponsored by Shanghai Astronomical Observatory through an MoU with the NRAO. The VLBA is operated by the Long Baseline Observatory which is managed by Associated Universities, Inc., under cooperative agreement with the National Science Foundation. The Long Baseline Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Facility: VLBA; Software: IDL, AIPS, DIFMAP.

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