Investigating Orientation Effects Considering Angular Resolution for a Sample of Radio-loud Quasars Using VLA Observations

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Abstract

Radio core dominance measurements, an indicator of jet orientation, sometimes rely on core flux density measurements from large-area surveys like Faint Images of the Radio Sky at Twenty cm (FIRST) that have an angular resolution of only 5″. Such low-resolution surveys often fail to resolve cores from the extended emission, resulting in an erroneous measurement. We focus on investigating this resolution effect for a sample of 119 radio-loud quasars. We obtained continuum observations from NSF’s Karl G. Jansky Very Large Array (VLA) at 10 GHz in A configuration with a 0″2 resolution. Our measurements show that at FIRST spatial resolution, core flux measurements are indeed systematically high even after considering the core variability. For a handful of quasars, 10 GHz images reveal extended features, whereas the FIRST image shows a point source. We found that the resolution effect is more prominent for quasars with smaller angular sizes. We further computed two radio core dominance parameters $R$ and $R_{5100}$ for use in statistical orientation investigations with this sample. We also present the spectral energy distributions between 74 MHz and 1.4 GHz, which we used to measure the spectral index of the extended emission of these quasars. Our results empirically confirm that determination of radio core dominance requires high spatial resolution data. We highlight the practical issues associated with the choice of frequency and resolution in the measurement of core and extended flux densities.

1. Introduction

Quasars are the most luminous form of active galactic nuclei (AGNs), powered by the release of gravitational potential energy of material accreting onto the supermassive black holes at their centers. The axisymmetric nature of quasars makes orientation to the line of sight (LOS) an essential quantity for comprehending their observed properties. Not only does orientation play a pivotal role in unifying type 1 and type 2 AGNs, e.g., Seyfert 1 and Seyfert 2 galaxies (Antonucci & Miller 1985), but it is also fundamental in unifying classes of radio-loud quasars. When the radio jet axis of a quasar is aligned close to the LOS, the core radiation gets Doppler boosted and we observe a flat-spectrum radio-loud quasar, whereas when the quasar is observed at larger angles to the LOS, little Doppler boosting takes place and we observe a steep-spectrum radio-loud quasar (Orr & Browne 1982) dominated by the optically thin synchrotron radiation of the extended radio lobes. Properties of the optical spectra differ between these classes. The FWHM of broad emission lines, such as Hβ, correlates with orientation: quasars aligned close to the LOS show lower values of FWHM, whereas the quasars at larger angles to the LOS (∼60° in type 1 AGNs; Marin 2016) show systematically higher values (Wills & Browne 1986).

Orientation not only governs classifications but also impacts the quantitative determination of fundamental properties like black hole mass and luminosity. The optical Hβ line emitted from what is likely a flattened broad-line region is most commonly used to derive the mass of the black hole. As FWHM Hβ correlates with the orientation (Wills & Browne 1986), the derived mass is also orientation dependent (e.g., Runnoe et al. 2013a). Bolometric luminosity determination also depends on orientation (Nemmen & Brotherton 2010). Face-on radio-loud quasars have brighter optical–UV continuum and X-rays (Jackson et al. 1989), and also the near-infrared emission is brighter by a factor of 2–3 (Runnoe et al. 2013b). This anisotropy needs to be understood, and ideally corrected for, in order to obtain the actual bolometric luminosity. Orientation also affects the luminosity functions of quasars (DiPompeo et al. 2014). For these reasons, orientation introduces scatter into the measurement of the fundamental properties of quasars. In order to fully understand the growth of black holes and their relationship to the evolution of galaxies, we require a better understanding and quantification of orientation, an essential parameter for axisymmetric quasars.

1.1. Orientation Indicators for Radio-loud Quasars

Quasars are generally too distant to have their inner structure spatially resolved for direct measurements of their orientation (although see the amazing results for 3C 273 by the Gravity Collaboration et al. 2018 and for M87 by the Event Horizon Telescope Collaboration et al. 2019). However, radio-loud
quasars have large-extent radio structures that can be used to determine orientation. The unresolved compact jets observed as cores undergo Doppler boosting in the direction of motion (Orr & Browne 1982; Wills & Brotherton 1995; Van Gorkom et al. 2015). Hence, the core emission is orientation dependent and dominates in face-on quasars, whereas the isotropic diffuse emission from lobes dominates in the case of more edge-on quasars.

The core emission also depends on the power of the central engine. So to account for the power of the central engine, the core emission is normalized, often by the extended emission. Hence, the ratio of the flux density of the core to the extended emission at 5 GHz rest-frame is defined as the core dominance $R$ (Orr & Browne 1982) and serves as an orientation indicator. But using extended flux density to normalize the central engine power has its own shortcomings. First, extended emission includes the contribution from hot spots, which are formed when highly collimated jets hit material in the intergalactic (or intracluster) medium. Hence, the extended flux density depends on the gaseous environment in which these quasars reside, which can differ from source to source and with redshift. Second, the extended emission is representative of the time-averaged power of the central engine, i.e., it depends on the history of the source and does not correspond directly to the current power, which governs the core emission.

Likely a better way to normalize the radio core is to use V-band optical luminosity because it is emitted from the contemporaneous accretion of material into the black hole whose rotation powers the jet. Therefore, a better quasar orientation indicator is $R_{\text{V}}$, the ratio of radio core luminosity and optical V-band luminosity (Wills & Brotherton 1995; Van Gorkom et al. 2015). Evidence supporting the V-band optical luminosity as a better normalization factor includes its correlation with the emission-line luminosity (Yee & Oke 1978) and the proportionality of jet power with the luminosity of the narrow-line region (Rawlings & Saunders 1991). Although the optical emission is anisotropic, between face-on and edge-on quasars, it varies only by a factor of about two, which is negligible in contrast to a factor of $\sim 10^4$ in the case of core flux density emission.

Other ways to determine core dominance are as follows. Rawlings & Saunders (1991) use the luminosity of the narrow-line region based on luminosities of $[O\text{ II}]$ and $[O\text{ III}]$ lines to define $R_{\text{SLR}}$. Willott et al. (1999) define $R_{\text{OX}}$ using total luminosity at 151 MHz to normalize the core luminosity. At this frequency, the total luminosity measures the luminosity of lobes.

Van Gorkom et al. (2015) performed two tests to determine the best orientation indicator among the four discussed above. The first test uses geometric rank as a proxy for orientation. Each object is assigned a rank as a sum of rank in ascending order of projected linear size and in decreasing order of the angle between the core and two hot spots. They found that only $R$ and $R_{\text{V}}$ show high correlation with geometric rank. They also performed line regression to fit the data and calculate the data variance. They find that $R_{\text{V}}$ has the lowest variance, i.e., optical luminosity introduces the least amount of scattering in the core dominance parameter. They conducted another test by randomizing the normalization factor and obtained the distribution of the variance. They shuffled the denominator of each core dominance parameter by the value of the different source and obtained its variance against the best-fit line calculated earlier. They repeated this 100,000 times to obtain a distribution of variance. They find that normalizing the core luminosity by a measurement from the same source only matters in the case of $R_{\text{V}}$, when dividing by optical luminosity. Hence, their work confirms that $R_{\text{V}}$ is a better orientation indicator, as previously claimed by Wills & Brotherton (1995). In this paper, we examine only the extended radio and the optical emission for normalization to determine core dominance.

### 1.2. Selection Biases in Past Orientation Studies

Few past orientation studies of radio-loud quasars have employed ideally selected samples. The widely used 3C/3CR catalog at 178 MHz, with a flux limit of 10 Jy, provides a nearly orientation-independent sample, as at this low frequency the emission is dominated by the extended optically thin component. However, the high-flux limit makes this catalog biased toward high-luminosity sources, which may not be typical. Orr & Browne (1982) use a flux-limited sample of 3C quasars, with no redshift constraints, to study their radio core dominance $R$. Their results on the quasar counts indicate that samples selected at high frequencies, above 1 GHz, have more high-redshift quasars in comparison to samples selected at lower frequencies of a few hundred megahertz. High-redshift quasars will go through higher Doppler boosting and will have flatter spectra on average. Hence, the sample will be biased toward flat-spectrum quasars.

On the other hand, an optical magnitude limit also introduces a bias toward flat-spectrum radio quasars (Kapahi & Shastri 1987; Jackson & Browne 2013). For example, the Wills & Browne (1986) sample is a collection of quasars from different catalogs based on their optical brightness cutoff ($< 17$ mag) and a redshift cutoff of 0.7. The anticorrelation between $R$ and optical magnitude (Browne & Wright 1985) means that quasars with jet close to the LOS have enhanced optical emission. Hence, their sample includes quasars that are intrinsically fainter than 17 mag but optically beamed. The combination of magnitude, orientation, and redshift results in a sample that lacks faint quasars and is biased against low-$R$ quasars.

Runnoe et al. (2013a) studied the effects of orientation on determining the mass of black holes. Their sample consists of 52 radio-loud quasars from the radio-loud subsample of Shang et al. (2011), excluding blazars. These objects have extended radio luminosities in a range of $26.5 < \log L_{\text{ext}} < 27.6$, measured at 5 GHz in units of erg s$^{-1}$ Hz$^{-1}$. Hence, the selected objects are similar in nature but differ by their orientation. For our sample, we performed a luminosity cut allowing a range in $L_{\text{ext}}$ down to 33.0 erg s$^{-1}$ Hz$^{-1}$ measured at a low frequency (325 MHz) that is dominated by emission from the lobe component.

### 1.3. Selection and Resolution Bias Associated with FIRST

Recent studies are based on samples selected by matching Sloan Digital Sky Survey (SDSS; York 2000) and Faint Images of the Radio Sky at Twenty cm (FIRST; Becker et al. 1995) survey data. A sample selected at high frequency, such as 1.4 GHz in the case of FIRST, is expected to be biased toward core-dominated quasars that have flat spectra in comparison to the less orientation-biased lobe-dominated quasars that have steep spectra.
Irrespective of the sample selection, it is quite common to use FIRST measurements to determine core dominance. Jackson & Browne (2013) claim that FIRST measurements do not have the spatial resolution to reliably distinguish the core from more extended components. So the core flux densities obtained from the FIRST survey will therefore likely have excess flux density coming from the extended emission, thus overestimating the radio core dominance. Thus, orientation studies based on FIRST survey radio data are biased by selection and resolution effects (e.g., Brotherton et al. 2015).

In order to improve the radio core dominance measurements, we need high-resolution data that can separate core from extended emission. For instance, for radio data with 5″ resolution, we will not be able to distinguish a 1″ core from any extended emission within the resolution element. In the absence of high-resolution data, we would then likely overestimate the core flux densities and poorly identify their orientation.

To test this idea, we proposed for NSF’s Karl G. Jansky Very Large Array (VLA) 10 GHz A configuration observations of a well-selected and relatively orientation-unbiased sample of quasars. We selected 10 GHz because at this frequency measurements are still efficient and the cores will stand out against extended emission. Using the A configuration we can achieve an angular resolution of 0″2, a factor of 25 times smaller than FIRST. From our results, we have confirmed that high-resolution data (better than the ~5″ of FIRST) are generally required to correctly estimate the core flux density of quasars.

The outline of this paper is as follows: Section 2 discusses the sample selection, followed by Section 3 about our VLA observations and the reduction procedures used to derive the core flux densities. We catalog all the radio and optical flux densities in Section 4. Next, we define the two core dominance parameters, R and R3500, and the groups we determined on the basis of extended radio spectra in Section 5. Finally, we present our results in Section 6, followed by discussion and conclusion in Sections 7 and 8. Appendix A shows the spectral energy distribution (SED) of our targets. Appendix B shows radio images of sources with resolved structure at 10 GHz in contrast to their point-like FIRST images. It also tabulates the statistical properties of the 10 GHz images presented in this paper. Lastly, Appendix C lists the additional targets we observed with VLA. For our calculations we have used a cosmology with \( H_0 = 70 \text{ km s}^{-1} \text{Mpc}^{-1}, \Omega_\Lambda = 0.7, \) and \( \Omega_m = 0.3. \) We have defined radio spectral index \( \alpha \) by the relation \( S_\nu \propto \nu^\alpha, \) where \( S \) stands for the flux density and \( \nu \) is the frequency.

### 2. Sample Selection

We used a relatively unbiased sample (Runnoe & Boroson 2020, ApJ, submitted) that is likely largely representative of the full range of quasar orientations. These objects were selected from the SDSS Data Release 7 (DR7) quasar catalog (Schneider et al. 2007) within a redshift range of 0.1 < \( z < 0.6 \) to attain high-quality optical spectra for the measurements of the Hβ emission line. The sample was then matched with the low-frequency 325 MHz Westerbork Northern Sky Survey (WENSS; de Bruyn et al. 2000; Rengelink et al. 1997), which has a resolution of 54″ × 54″ cosec(\( \delta \)). WENSS covers the whole sky north of 30°, about 1/3 of the larger SDSS DR7 quasar catalog covering \( \approx 9380 \text{ deg}^2. \) A total radio luminosity cutoff \( \log(L_{325}) > 33.0 \text{ erg s}^{-1} \text{Hz}^{-1} \) was applied. This luminosity cutoff is generally above the WENSS flux limit of 18 mJy (5\( \sigma_{\text{beam}} \)) and also above the transition between Fanaroff–Riley class I and II sources at \( \log(L_{325}) \sim 32.5 \text{ erg s}^{-1} \text{Hz}^{-1}. \) At 325 MHz, the isotropic extended emission dominates in nearly every object and hence produces a quasar sample largely unbiased by orientation.

Core and lobe candidates were matched separately because each object may appear as separate entries in the WENSS catalog. Core candidates were matched within a search radius of 30″, whereas lobe candidates were matched within 1100″. To associate lobes with a core candidate, three criteria were used: the two lobes should be within 30″ of being opposite to each other, their ratio of the distance from SDSS position should be within a factor of two, and their flux ratio should also be within a factor of two. As a result, 142 sources were selected and visually inspected in SDSS, WENSS, FIRST, and the NRAO VLA Sky Survey Catalog (NVSS; Condon et al. 1998) to ensure correct matching of all the components. Furthermore, 16 sources were removed based on visual inspection of the match at multiple wavelengths and a subsequent reevaluation of the luminosity cut.

The Runnoe & Boroson final sample consists of 126 objects. We excluded seven objects that do not have black hole masses from the \( M-\sigma \) relationship (e.g., McConnell & Ma 2013), as one of the original goals of our study was to address the orientation effect in black hole mass (e.g., Brotherton et al. 2015). Here \( \sigma_\ast \) is the stellar velocity dispersion of the host galaxy, and mass estimated using the \( M-\sigma \) relationship is independent of orientation of quasar axis. Those seven objects have problematic optical spectra. Either the broad Hβ line was too weak and a reliable width could not be measured, or the optical continuum was unreliable (e.g., because it was weak).

Our final sample consists of 119 objects, with a mean redshift \( z = 0.46. \) See Section 4 of Runnoe & Boroson (2020) for further discussion on sample properties.

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\( \mu = 0.46 \)  
\text{median} = 0.48  
\( \sigma = 0.10 \)

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\( ^7 \) We list additional objects that were proposed for VLA observation but are no longer part of the Runnoe & Boroson sample in Appendix C.
3. VLA Observations and Data Reduction

The VLA continuum observations were carried out at 10 GHz (X band) with the A configuration to achieve 0.2\degree resolution, 25 times smaller than FIRST to separate the unresolved core from extended emission. The VLA project ID of the observations is 16B-329. We used the 3-bit digital samplers appropriate for X-band wideband observations with basebands of 2 \times 2 GHz and a total bandwidth of 4 GHz. The dynamical observations occurred in two scheduling blocks (SBs), on 2016 October 29 (SBID 32533323; total elapsed time = 10,508 s) and 2016 November 13 (SBID 32713722; total elapsed time = 9232 s). For both blocks, the flux calibrator was 3C 286. Each block included a scan of a phase calibrator at the beginning and the end. Some of our targets were already standard phase calibrators, so we also used them for phase calibration. The time on source varies between 88 and 286 s. The mean time on source is 199 s.

Data were reduced using the Common Astronomy Software Applications (CASA; McMullin et al. 2007) version 4.7.0. The initial 6 s of the data from each scan were flagged to take into account the stabilizing time for the array. We did not flag our data for shadowing, as the A configuration does not suffer from this effect. Antennas reported with bad baselines in the observer’s log were flagged wherever corrections were unavailable. By making plots of amplitude versus time for the flux calibrator, we found that spectral windows 12 and 31 in the first block had an error, so we excluded these spectral windows while applying further calibrations.

The visibilities of the flux calibrator were modeled using the Perley–Butler 2013 (Perley & Butler 2013) model for X band. The initial phase calibration was performed to look for the time variation from scan to scan for the bandpass calibrator before deriving the bandpass solution. Then, we solved for the antenna-based delay relative to the reference antenna. These phase and delay solutions were used to determine the bandpass solution that best determines the variation of the gain with frequency. Next, we derived the correction for the complex antenna gain for the flux calibrator and phase calibrators. The absolute flux densities of the phase calibrators were obtained assuming that the gain amplitude for the phase calibrators is the same as for the flux calibrator, for which we have taken the gain amplitude from the measured and modeled visibilities. The calibration solutions derived earlier were then applied to the flux and phase calibrators. We matched the targets to the neighboring phase calibrator and applied the solutions. Image synthesis was performed using the CLEAN task with multifrequency synthesis imaging mode, Clark (Clark 1980), as the method of point-spread function calculation, and the Cotton-Schwab clean algorithm (Schwab 1984) with one term and Briggs weighting (Briggs 1995).

4. Essential Radio and Optical Data

The newly synthesized 10 GHz images were visually inspected to ensure matching of the core position, i.e., the position of the pixel with maximum flux density, with the SDSS position. There were five quasars with poor-quality images due to bad radio data (J134303.59+521626.7, J154620.98+539161.7, J170441.38+604430.5) or high positional uncertainty (J105232.74+612520.9, J141858.85+394638.7) that we dropped from further analysis. We used the CASA task instat to measure the 10 GHz core flux densities from the peak flux density at the optical position. The standard deviations in the residual images produced by the CLEAN task provided the rms noises.

Table 1 presents the properties of our final set of 119 quasars. Columns (1) and (2) list the SDSS object names and their redshifts, respectively. We list the optical flux densities at 5100 Å in Column (3), obtained from the SDSS spectra of these quasars. We adopted these measurements from Runnoe & Boroson (2020). They corrected the spectra for Galactic extinction. The model used to fit the AGN power-law continuum also takes into account the contribution from the host galaxy and the optical Fe II.

Core flux densities at 10 and 1.4 GHz are listed in Columns (4) and (5) of Table 1, respectively. For the 1.4 GHz core flux densities we adopt measurements from Runnoe & Boroson (2020). They matched to the FIRST survey by manually determining the search radius. They visually determined the core and used the FIRST peak flux. For objects with core detections, they used the peak flux density as the core flux density. For 12 objects with no core detections they used the FIRST rms and adopted a 5σ limit on the core flux density (J080754.50+494627.6, J081540.84+394334.7, J085341.18+405221.7, J090501.55+533907.5, J105141.16+591305.3, J110726.92+361612.2, J134303.59+521626.7, J141054.05+584655.3, J150455.56+564920.3, J151936.72+534255.5, J154620.98+539161.7, J170334.99+391735.6).

The extended, steep-spectrum emission in quasars dominates at MHz frequencies. Hence, to measure the extended flux densities and the spectral indices of extended emission, we matched our sources with the WENSS (discussed in Section 2), 7th Cambridge (7C; Hales et al. 2007), TIFR GMRT Sky Survey Alternative Data release (TGSS ADR; Intema et al. 2017), and VLA Low-Frequency Sky Survey redux (VLSSr; Lane et al. 2012, 2014) surveys. The total flux densities are listed in Columns (6), (7), (8), and (9) of Table 1, respectively. We report the relative error in flux densities of WENSS using Equation (9) of the catalog paper. The 7C survey covers an area of about 1.7 sr at 151 MHz and has a resolution of 70′′ × 70′′ cosec(δ). We used the formula given in the appendix of the catalog paper to convert the cataloged signal-to-noise ratio to the rms (σ) error in the flux densities. TGSS ADR is a recently available radio survey at 150 MHz with 20′′ resolution and covers 90% of the full sky with median rms noise of 3.5 mJy beam−1. The catalog also reports the flux density error for each target. For both the surveys, we started with a search radius of 70′′. We then visually matched images with WENSS and subsequently increased the search radius to 5′′ for some targets to collect all the components. We used the same approach to match our targets with the VLSSr survey. It is a low-frequency counterpart of the NVSS at 74 MHz with 75′′ resolution and ≈0.1 Jy beam−1 rms sensitivity. We report the cataloged error estimates in flux densities. The radio spectral index of extended emission, \(\alpha_{\text{ext}}\), is listed in Column (10). The last column lists the group assigned to these objects on the basis of their radio SED. We will address the reason for choosing two surveys at 150 MHz, the method used to calculate \(\alpha_{\text{ext}}\), and the group assignment in the next section.

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8 https://www.cv.nrao.edu/vlss/VLSSlist.shtml
Table 1  
SDSS Names, Redshifts, Optical and Radio Flux Densities, and Spectral Indices of Extended Emission of 119 Radio-loud Quasars

| Object Name | Redshift | **F5100** | $S_{\text{core}}^{10}$ GHz (mJy beam$^{-1}$) | $S_{\text{core}}^{1.4}$ GHz (mJy beam$^{-1}$) | $S_{\text{total}}^{\text{WENSS}}$ (mJy) | $S_{\text{total}}^{\text{TNGS}}$ (mJy) | $S_{\text{total}}^{\text{VLSSr}}$ (mJy) | $\alpha_{\text{ext}}$ | **Group** |
|-------------|---------|-----------|----------------|----------------|----------------|----------------|----------------|-------------|---------|
| J073422.19+472918.8 | 0.382 | 9.67 ± 0.25 | 12.39 ± 0.06 | 6.47 ± 0.14 | 766 ± 31 | 991.9 ± 99.8 | 1257 ± 87 | 2020 ± 300 | −0.71 ± 0.049 | 2 |
| J074125.22+333319.9 | 0.364 | 19.38 ± 0.22 | 8.61 ± 0.03 | 3.01 ± 0.22 | 1853 ± 74 | 3683.1 ± 261.3 | 2789 ± 146 | 5330 ± 470 | −0.754 ± 0.04 | 2 |
| J074541.66+314256.6 | 0.461 | 94.04 ± 0.12 | 449.4 ± 0.42 | 614.6 ± 0.15 | 3458 ± 138 | 6802 ± 484.7 | 5948 ± 296 | 15370 ± 1340 | −0.716 ± 0.045 | 2 |
| J075145.14+341555.8 | 0.429 | 5.24 ± 0.29 | 94.16 ± 0.41 | 202.6 ± 0.14 | 460 ± 19 | 533.1 ± 53.6 | 457 ± 48 | 730 ± 100 | −0.748 ± 0.105 | 3 |
| J080413.87+470442.8 | 0.510 | 0.30 ± 0.29 | 107.5 ± 0.43 | 847.18 ± 0.21 | 2574 ± 103 | 4586.6 ± 459.5 | 3644 ± 184 | 3720 ± 450 | −0.64 ± 0.049 | 2 |
| J080644.42+484149.2 | 0.370 | 23.09 ± 0.27 | 81.08 ± 0.25 | 43.32 ± 0.24 | 3099 ± 124 | 6867.8 ± 519 | 6071 ± 298 | 1210 ± 160 | −0.766 ± 0.044 | 2 |
| J080754.50+494627.6 | 0.575 | 2.65 ± 0.29 | 1.7 ± 0.02 | 1.05 ± 0.21 | 1452 ± 59 | 3061.4 ± 306.5 | 2787 ± 157 | 5000 ± 630 | −0.897 ± 0.051 | 2 |
| J080814.70+475244.7 | 0.546 | 14.00 ± 0.26 | 3.26 ± 0.03 | 26.39 ± 0.15 | 226 ± 11 | 365.4 ± 41.9 | 610 ± 76 | 540 ± 100 | −0.827 ± 0.08 | 2 |

Notes. Table 1 is published in its entirety in the machine-readable format. A portion is shown here for guidance regarding its form and content.

a **F5100** is in units of $10^{-17}$ erg s$^{-1}$ Å$^{-1}$ cm$^{-2}$.

b Quasars are assigned group 1, 2, 2-flag (2f), or 3 on the basis of their radio spectrum. See Section 5 for details.

(This table is available in its entirety in machine-readable form.)
5. Core Dominance Determinations

We derived two radio orientation indicators: (1) $R$, radio core dominance, defined as the ratio of the observed core flux density and the observed extended flux density $k$-corrected to 5 GHz rest-frame (Equation (1)), and (2) $R_{5100}$, defined as the ratio of the core flux density and the optical 5100 Å flux density (Equation (2)). We derive both orientation indicators using core flux densities at observed frequencies, $\nu_{\text{obs}}$, of 1.4 GHz (from FIRST) and 10 GHz:

$$R_{\nu_{\text{obs}}} = \left( \frac{S_{\text{core},\nu_{\text{obs}}}}{S_{\text{ext},\nu_{\text{obs}}}^k} \right)_{\text{GHz, rest}}$$  \quad (1)$$

$$R_{5100,\nu_{\text{obs}}} = \frac{S_{\text{core},\nu_{\text{obs}}}}{S_{5100,\lambda}}.$$  \quad (2)

The flux densities ($S_{\text{obs}}$) observed at frequency $\nu_{\text{obs}}$ are $k$-corrected to 5 GHz rest frame using

$$S_{5\text{GHz, rest}}^\nu_{\text{obs}} = S_{\text{obs}} (1 + z)^{-(1+\alpha)} \left( \frac{\nu_{\text{5GHz, rest}}}{\nu_{\text{obs}}} \right)^{\alpha},$$  \quad (3)

where $z$ is the redshift and $\alpha$ is the radio spectral index. We assumed the radio spectral index of the cores to be zero, as quasar cores have flat spectra (Bridle et al. 1994; Kimball et al. 2011), so $S_{5\text{GHz, rest}}^\nu_{\text{obs}} = S_{\text{core,obs}}^\nu_{\text{obs}}/(1 + z)$. The observed extended flux density is the difference of total flux density at the observed frequency ($\nu_{\text{obs}}$) and the core flux density at the observed frequency ($\nu_{\text{obs}}$), i.e., $S_{\text{obs}}^\nu_{\text{ext}} = S_{\text{obs}}^{\text{total}} - S_{\text{obs}}^{\text{core}}$. To calculate $S_{5\text{GHz, rest}}^\nu_{\text{ext}}$, we need to measure the extended radio spectral index, $\alpha_{\text{ext}}$.

The best way to calculate $\alpha_{\text{ext}}$ is to fit a power-law slope to the total flux densities obtained from simultaneous observations at two low radio frequencies, where the emission is dominated by the lobes. In practice, observations are not available at low enough frequency, and one still needs to know whether an object is core dominated or lobe dominated. If an object is core dominated, total flux density will be dominated by the core emission rather than the lobe emission, giving an inaccurate measure of $\alpha_{\text{ext}}$. Hence, to determine the most accurate $\alpha_{\text{ext}}$, we plotted the radio SED of our targets. We plotted the total flux densities from VLSSr, TGSS, 7C, WENSS, NVSS, and FIRST. The NVSS and FIRST total flux densities are taken from Table 1 of Runnoe & Boroson (2020). We also included the core flux densities from FIRST and the new 10 GHz observations (Appendix A). By visually inspecting these radio SEDs, we were able to distinguish flat-spectrum sources (core dominated) from the steep-spectrum sources (lobe dominated).

For a significant number of quasars, we found that the total flux densities from TGSS were falling below the overall slope (e.g., J080814.70+475244.7, J080833.36+424836.3, J085341.18+405221.7, J110313.30+301442.7, etc.). This is the reason why we included the 7C survey in our analysis, despite being at a frequency so close to that of TGSS. Figure 2 compares the total flux densities from TGSS and 7C in log scales. The plot shows an agreement between the two surveys only for $S_{\text{TGSS}} \geq 580$ mJy. The difference between TGSS and 7C at lower flux densities is because of the resolution bias, 7C having a larger beam of 70″. The ratio of flux densities of the two surveys matches to almost unity for sources brighter than 2 Jy (see Section 4.5 of Interna et al. 2017). We therefore made a cut at $S_{\text{TGSS}} = 580$ mJy and discarded TGSS measurements that are below the cut while plotting radio SEDs. The total flux densities between WENSS, 7C, TGSS, and VLSSr agree well with a consistent power law in a majority of our sources.
we plot the histogram of the logarithm of the ratio of the two flux densities in the top right panel of Figure 4. The distribution is asymmetric around the dashed line representing equal fluxes. A Gaussian fit to the distribution has a mean of 0.25 and a standard deviation of 0.68. The core variability contributes to the negative tail of the distribution. The standard deviation of a symmetric Gaussian around the dashed line fitting the negative tail is 0.43. Hence, a change of a factor of $\approx 2.69$ in the core flux density can be attributed to the core variability. This is an upper limit, as the objects with FIRST core flux density limit are also included. Without them, the standard deviation is 0.35, implying a factor of $\approx 2.24$ core variability.

The assumption of a flat radio core spectra could introduce scatter around the 1:1 line that represents $\alpha_{\text{core}} = 0$. Hovatta et al. (2014) found the mean $\alpha_{\text{core}} = 0.22 \pm 0.04$ for a sample of 133 flat-spectrum radio quasars using VLBA observations. Their mean core spectral index also shows an anticorrelation with the linear size of the core, implying that the measurements for high-redshift sources were contaminated by the jet emission. To quantify the effect of inverted core spectral index, we generated 10,000 samples of $\alpha_{\text{core}}$ from a Gaussian distribution with a mean of 0.22 and standard deviation of 0.04 and calculated the mean flux density of the sample scaled between 1.4 and 10 GHz. We found that the change in flux density is a factor of 1.54 owing to nonzero core spectral index. This is the largest effect that could be induced owing to an inverted core spectral index that is still smaller than the apparent factor of $\approx 2.69$ resulting from core variability.

The scatter plot of 1.4 GHz versus 10 GHz core flux densities also shows that the majority of our targets are above the 1:1 dashed line, indicating that many FIRST core measurements are contaminated by poorly resolved extended emission. We found 41 objects for which FIRST fluxes are above the dotted line representing the core variability limit; this is 36% of the sample. Excluding the targets within the FIRST core flux density limit, the percentage increases to 41%. In a few of them we have detected extended features in the 10 GHz images at the scale of a few arcseconds or less (see Appendix B).

If the FIRST core measurements are contaminated by the extended emission, we expect larger contamination as the angular size of the target in FIRST image decreases. Figure 5 plots the largest angular size (LAS) from FIRST against the ratio of flux densities at 1.4 GHz (from FIRST) and 10 GHz in log–log scale. The LASs were taken from Table 1 of Runnoe & Boroson (2020). It was determined by plotting the FIRST elliptical Gaussian fits to all components associated with a source and calculating the largest associated size scale among them. We find that the ratio increases as the FIRST angular size decreases. The anticorrelation has a Pearson’s $r$-coefficient of $-0.465$.

These results clearly demonstrate that the cores were unresolved at the FIRST resolution and their core flux density measurements were contaminated with extended emission. With our new X-band observations, we were able to resolve these sources and hence improved the core flux density measurements.

Since the core flux densities were systematically higher in the case of the FIRST measurements, we expect the radio core dominance calculated from the FIRST survey to have higher values too. Figure 4 (middle panel) compares $R$ using the FIRST core and 10 GHz core measurements and shows a
prominent excess. We observed the same excess in the $R_{S100}$ in Figure 4 (bottom panel) while using FIRST core measurements. We have plotted the error bars accounting for uncertainties in flux densities and $\alpha_{opt}$. The histogram of the ratio of $R_{S100}$ from FIRST and 10 GHz is the same as the ratio of core flux densities from them.

Our results confirm the Jackson & Browne (2013) claim about resolution effects, and that radio core dominance calculated from FIRST maps is often compromised and biased high. With our current high-resolution radio images, we have determined improved core flux densities and hence improved the radio orientation indicators $R$ and $R_{S100}$.

### 7. Discussion

There are a number of choices to make when determining the radio core dominance of a quasar. Observations are conducted at a particular frequency and resolution given available facilities and/or surveys. There are distinctly different issues when it comes to measuring radio core flux density compared to that of the total or extended radio emission.

The radio core stands out against extended emission best at higher frequencies, making 10 GHz a better choice compared to lower frequencies. Similarly, radio cores are better distinguished from extended emission at higher angular resolution. These considerations make our choice of VLA A-configuration 10 GHz observations among the best to measure quasar radio cores. As previously discussed, the FIRST Survey using the VLA at B configuration and 1.4 GHz suffers shortcomings that can compromise the results for individual objects.

The core flux density of the group 2-flag objects suffers most owing to the resolution effect. These sources appear as point-like sources in both GHz and MHz frequency surveys. One can misclassify them as core-dominated sources, but they are CSS quasars. The CSS sources are likely young AGNs that have an intrinsically compact radio structure and exhibit a steep spectral index. For example, J080413.87+472918.8, J074541.66+314256.6, and J075145.14+411535.8 are 2.25, 1.04, and 1.26, respectively, at a particular frequency and resolution given available facilities and surveys. There are distinctly different issues when it comes to measuring radio core flux density compared to that of the total or extended radio emission.

In the future, surveys like the VLA Sky Survey (VLASS) will provide a better source of archival core flux densities than the FIRST. VLASS will cover the entire sky above $40^\circ$ at $2-4$ GHz with a resolution of $2^\circ.5$ (Lacy et al. 2020). This will provide radio cores at double the frequency and resolution of the FIRST. There may still be issues of core contamination, but they will be much reduced, although A-configuration 10 GHz observations remain the optimal choice when possible.

Even after making the best choices for measuring radio cores, our measurements are affected by intrinsic core variability. The cores exhibit a variability factor of up to about two over timescales of a few years (Barthel et al. 2000; Verschuur et al. 1988). Our 10 GHz VLA and FIRST measurements are separated by years to decades, as the FIRST survey includes observations from 1993 to 2011; our measurements are affected by variability too. Our analysis suggests that the quasars in our sample have variability of about a factor of two and a half over the time period considered. This is true for both core-dominated and lobe-dominated quasars. Approximately two-fifths of our sample show excess core flux density in FIRST measurements beyond the amount ascribable to variability. Hence, our results demonstrate statistically that the contamination of FIRST core measurements by the extended emission is apparent, as discussed by Jackson & Browne (2013).

Also important in the determination of radio core dominance is the choice of the normalization factor. We have reported radio core dominance measurements by normalizing the radio cores by both the extended radio flux density and the optical. The optical normalization of $R_{S100}$ is preferred. Wills & Brotherton (1995) first defined an alternative way to normalize core luminosity by the V-band optical luminosity as a measure of intrinsic jet power. They claimed that $R_V$ is a better orientation indicator than $R$, as it shows a better correlation with the jet angle and FWHM H$\beta$ compared to the more traditional $R$. While the optical continuum likely has an orientation dependence (e.g., Nemmen & Brotherton 2010), it is relatively small compared to the variation in radio cores seen within the beaming angle. The optical luminosity is also

### Table 2

| Object Name (1) | log($R_{1.4\,GHz}$) (2) | log($R_{10\,GHz}$) (3) | log($R_{S100,1.4\,GHz}$) (4) | log($R_{S100,10\,GHz}$) (5) |
|-----------------|------------------------|------------------------|----------------------------|----------------------------|
| J073422.19+472918.8 | $-1.33 \pm 0.056$ | $-1.04 \pm 0.052$ | $1.89 \pm 0.034$ | $2.17 \pm 0.026$ |
| J074125.22+333319.9 | $-2.00 \pm 0.084$ | $-1.54 \pm 0.042$ | $1.25 \pm 0.074$ | $1.71 \pm 0.012$ |
| J074541.66+314256.6 | $0.07 \pm 0.046$ | $-0.09 \pm 0.046$ | $2.87 \pm 0.001$ | $2.73 \pm 0.002$ |
| J075145.14+411535.8 | $1.26 \pm 0.043$ | $0.93 \pm 0.043$ | $3.65 \pm 0.055$ | $3.32 \pm 0.055$ |
| J080413.87+470442.8 | $0.34 \pm 0.049$ | $-0.72 \pm 0.050$ | $4.63 \pm 0.124$ | $3.73 \pm 0.124$ |
| J080644.42+481414.2 | $-1.04 \pm 0.046$ | $-0.77 \pm 0.046$ | $2.33 \pm 0.012$ | $2.61 \pm 0.012$ |
| J080754.50+494627.6 | $-2.25 \pm 0.206$ | $-2.04 \pm 0.052$ | $1.66 \pm 0.228$ | $1.87 \pm 0.109$ |

(This table is available in its entirety in machine-readable form.)
Figure 4. Left panels: scatter plots of core flux density measured at 1.4 GHz and 10 GHz and the corresponding $R$ and $R_{5100}$ measurements on log scales. The points are color-coded according to the groups defined by the radio spectra of their extended emission. Points in the bottom left panel with downward-pointing arrows represent the objects with FIRST flux limits. The dashed lines show where the two quantities are equal. Top left: scatter plot with the logarithm of 1.4 GHz core flux density on y-axis and the logarithm of 10 GHz core flux density on the x-axis. The dotted line represents $y = x \pm 0.43$, an estimate of the 1σ scatter introduced by the core variability. Middle left: scatter plot of log $R$ calculated from the 1.4 GHz FIRST cores on the y-axis and from the 10 GHz cores on the x-axis normalized by the extended flux densities scaled to 5 GHz rest-frame according to the groups as discussed in Section 5. Bottom left: scatter plot of $R_{5100}$ values calculated from the ratio of 10 GHz vs. 1.4 GHz core flux densities and 5100 Å flux density. The point with a black open circle (top right) represents a quasar with a bad 5100 Å flux density measurement. Right panels: histograms of the corresponding ratio of the quantities in the x-axis and y-axis of the left panels. The dashed lines in these histograms show where the ratios are equal.
representative of the power of the AGN at the present epoch, while the extended radio emission represents some time averaging of the power of past activity. The extended radio luminosity is also affected by the jet’s interaction with the environment, introducing additional scatter. Van Gorkom et al. (2015) present a comparative study of several different radio-based radio core dominance normalizations, using complementary tests, also finding the optical continuum to be a superior normalization choice.

The extended radio flux density normalization of $R$ is laborious. Low-frequency observations are preferred since extended emission has a steep spectrum compared to the relatively flat spectrum of cores. We adopted the WENSS total flux density at observed-frame 325 MHz. Even lower-frequency observations would be better in principle, as the degree of core contamination will be increasingly negligible, although there are other considerations. The lowest-frequency sky survey we use is the VLSSr at 74 MHz. It fails to detect fainter sources because of its low sensitivity. Also, at this frequency, the slope of CSS sources shows flattening. The TGSS at 150 MHz is the highest-resolution and highest-sensitivity radio survey available for obtaining the total flux density measurements. It has a resolution of 25″ at which the extended emission may be resolved. Figure 7 demonstrates the resolving power of these surveys. J074541.66+314256.6 appears as a single source at the resolution of VLSSr and WENSS, but it is a resolved two-component source in TGSS. Therefore, the search radius to match lobe candidates should be carefully chosen to make sure that all components are collected; otherwise, one may end up underestimating the flux densities. Using the lobe-matching technique that Runnnoe & Boroson (2020) performed for WENSS could be very taxing for TGSS, as a search radius of 1100″ would result in a large number of detections to match to a core. Another downside with TGSS is that it suffers with a resolution bias. It has a higher resolution power but a poor low surface brightness sensitivity. This leads to lower total flux densities for objects fainter than 2 Jy when compared to a lower-resolution survey like 7C (Intema et al. 2017). However, for our sample we found this threshold to be $\sim$580 mJy by comparing with the 7C survey. Plotting SEDs with total flux densities from other low-resolution surveys like WENSS and NVSS shows that 7C measurements comply with the overall trend, whereas TGSS measurements for the fainter objects fall below because of the resolution bias. For a small set of objects, TGSS is the preferred survey for extended flux densities given that the objects are bright enough and the matching is done carefully. For a large set of objects, this would be difficult, in which case WENSS falls at the sweet spot of frequency and resolution good for extended flux density measurements. Several orientation studies used NVSS extended flux densities, as it is at the same frequency as FIRST. Being at 1.4 GHz, the NVSS total flux density is often beamed and suffers from core variability; hence, it is not a good choice for normalization.

The extended flux densities needs to be k-corrected (Hogg et al. 2002) and scaled to 5 GHz for the measurement of $R$. When using low-frequency data like those from TGSS and WENSS, $\alpha_{\text{ext}}$ should be chosen carefully. As the frequency difference is very large, a small change in $\alpha_{\text{ext}}$ can significantly affect your $R$ measurements. We took the approach of determining the extended slope for individual objects by fitting their SEDs from TGSS, 7C, WENSS, and NVSS (Appendix A). In lobe-dominated quasars this gives a fair measurement of the radio spectral index for extended emission, and we can account for variability concerns separately. For core-dominated sources, $\alpha_{\text{ext}}$ is not well measured in this way and requires simultaneous measurements. Hence, we adopted the mean spectral index of our sample for them.

The actual utility of radio core dominance is as an indicator of the orientation of the radio jet to the LOS, and it is desirable to be able to relate it to a physical angle. Marin & Antonucci (2016) provide such a quantitative prescription, deriving a semiempirical function between core dominance and inclination angle by numerically fitting a polynomial regression relation to sources within an equally distributed solid angle. Their relation provides a measurement of inclination from log $R$ of radio-loud AGNs with an accuracy of $\approx 10^\circ$ or less. AGN inclination angle ($i$) can be obtained from the log $R$ (LR) at 5 GHz using

$$i = g + h(LR) + j(LR)^2 + k(LR)^3 + l(LR)^4 + m(LR)^5,$$

where $g = 41.799 \pm 1.190$, $h = -20.002 \pm 1.429$, $j = -4.603 \pm 1.347$, $k = 0.706 \pm 0.608$, $l = 0.633 \pm 0.226$, and $m = 0.062 \pm 0.075$ (see Section 3 of Marin & Antonucci 2016 for details).

The assumption that radio core dominance may be used as a statistical orientation indicator is based in part on the notion that the structure of the source is constant for a very long time. The jet axis of AGNs is known to exhibit precession and can lead to an irregular radio morphology in a fraction of objects experiencing significant torques. The time period of jet precession in binary supermassive black holes is in the range of $10^5$–$10^6$ yr (Gower et al. 1982; Dunn et al. 2006). In a study of X-shaped radio galaxies, 21% are known to be genuinely formed by mergers and only 1.3% are formed by the spin-flip mechanism (Roberts et al. 2015). There are few cases in which jet precession in seen in quasars. QSO 2300–189 is one such
Figure 6. TGSS, FIRST, and VLA 10 GHz images (see Table 3 for image statistics) of two known CSS sources in our sample that are either (a) resolved or (b) unresolved at 10 GHz. In both cases the contamination of core flux density due to extended emission is removed in the 10 GHz observation. Their SEDs show that VLSSr flux density (at 74 MHz) falls below the steep slope, expected in the case of CSS quasars.
example where an S-shaped radio morphology is attributed to jet precession due to a merger with a nearby galaxy (Hunstead et al. 1984). The bending of jets at kiloparsec scale may not be from time-dependent precession but rather from an environmental change such as a density gradient. Precession, environment, or episodic nuclear activity can all potentially contribute to unusual behavior in individual objects and create outliers in plots involving radio core dominance against other parameters that can be orientation dependent.

There are several immediate applications of our work to recent investigations. For instance, Brotherton et al. (2015) use a sample of radio-loud quasars selected using the FIRST survey to examine and offer corrections to orientation biases for black hole mass estimates, as well as propose a radio-quiet quasar orientation indicator. Because of the high frequency of FIRST, their sample is deficient in lobe-dominant quasars and biased toward flat-spectrum sources. Moreover, their radio core dominance values are from FIRST and have contaminated cores. A similar investigation based on our sample and the new VLA observations would be superior. Runnoe & Boroson (2020) use a subset of this sample to investigate the dependence of quasar optical spectral properties on orientation. They focus on updating the Wills & Browne (1986) plot of H/β FWHM against radio core dominance, finding that the sharp envelope of previous studies where only edge-on sources display the broadest lines is absent. Again, they use FIRST for their radio core measurements, and a revised study would benefit from our 10 GHz observations to determine core flux densities. There are many additional applications, for instance, such as the investigation of the association of orientation with quasar spectral principal components (e.g., Ma et al. 2019). Such follow-ups will be the subject of a future paper.

8. Conclusions

In this paper, we have used a relatively unbiased sample designed for studying orientation effects in radio-loud quasars. The sample is based on matching 0.1 < z < 0.6 SDSS quasars with the WENSS survey at 325 MHz with a total radio luminosity cutoff \( \log(L_{325}) > 33.0 \text{ erg s}^{-1} \text{ Hz}^{-1} \). At this low frequency the isotropic extended emission dominates, which enables selecting representative quasars relatively unbiased by orientation. In the case of quasar cores, we expect a flat radio spectrum over a broad range of frequencies. Jackson & Browne (2013) pointed out that most survey measurements of core flux densities, like FIRST, often do not have the spatial resolution to always distinguish cores from the extended regions. We present observational evidence for this claim by comparing FIRST measurements of core flux densities with newly obtained 10 GHz VLA A-configuration measurements. We discern a systematically higher core brightness in the case of FIRST measurements for about two-fifths of our sample, even after taking into account core variability (Figure 4). We present examples in Appendix B showing resolved structure in the 10 GHz image as compared to point-like structure in FIRST images.

We compared the two core dominance parameters \( R \) and \( R_{5100} \) using core flux densities from FIRST and the new observations (Figure 4). Use of FIRST measurements resulted in a systematically higher value of core dominance; hence, more quasars appeared core dominated. Overall we recommend using our optically normalized core dominance parameter \( R_{5100,10 \text{ GHz}} \) based on other studies in the literature.

Our results provide improved measurements of the core flux densities and the core dominance parameters that have potential implications in understanding accurate correlation between radio and optical properties of the quasars. This sample will also serve to update several past studies that employed FIRST-based core dominance measurements.

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*Facility:* VLA.

*Software:* CASA.

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### Appendix A

#### Radio Spectral Energy Distributions

We plot the total flux densities versus frequency for VLSSr, TGSS, 7C, WENSS, NVSS, and FIRST. The SEDs also include core flux densities from FIRST and the new 10 GHz measurements. Figure 8(a) shows the SEDs of group 1 and group 3 sources that are likely core-dominated or intermediate quasars. Figure 8(b) shows the SEDs of group 2 sources that are likely lobe-dominated quasars and group 2-flag sources that are likely CSS quasars. The total flux densities from VLSSr, 7C, TGSS, WENSS, and NVSS are fitted with a slope to calculate $\alpha_{\text{ext}}$. The error in slope is given by the fitting algorithm as described in the main text.
Figure 8. (a) Log–log plot of the radio flux density vs. frequency for core-dominated and intermediate (groups 1 and 3) quasars. The data points include total flux densities from VLSSr, 7C, TGSS, WENSS, FIRST, and NVSS. It also includes core flux densities from FIRST and the new 10 GHz measurement. Spectral slopes are not plotted as they would be affected by core variability. (b) Log–log plot of the radio flux density vs. frequency for group 2 and group 2-flag quasars. The data points include total flux densities from VLSSr, 7C, TGSS, WENSS, FIRST, and NVSS. It also includes core flux densities from FIRST and the new 10 GHz measurement. The dashed line shows the spectral index of the extended emission obtained by fitting a slope to the total flux densities from VLSSr, 7C, TGSS, WENSS, and NVSS.
Figure 8. (Continued.)
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Appendix B

Sources with Resolved 10 GHz Images

Figure 9 presents half a dozen targets with an extended structure in the 10 GHz images compared to an unresolved point-like source in the FIRST images. Table 3 gives the rms, mean, and dynamical range of the 10 GHz resultant maps.
Figure 9. FIRST image (on the left) of half a dozen targets compared to the new observation at 10 GHz (on the right). The high-resolution 10 GHz images show extended structures that are unresolved at FIRST resolution.
Figure 9. (Continued.)
Appendix C
Additional Objects

We proposed VLA observations on a preliminary version of the Runnoe & Boroson sample, consisting of 147 radio-loud quasars. They excluded 28 targets after a revision in the luminosity cut. In the spirit of publicizing all available VLA data, we present the measurements in Table 4, available as a machine-readable table. The optical spectra of these targets were analyzed together; thus, their spectral properties were calculated identically to the final Runnoe & Boroson sample. One of the additional 28 objects has bad 10 GHz data. The remaining 27 were assigned groups based on their SEDs. Two targets are in group 1, 17 in group 2, five in group 2-flag, and three in group 3.

We redid the whole analysis with the additional targets included. Figure 10 compares the core flux densities, $R$, and $R_{5100}$ measurements. The core variability is a factor of 2.45 for the larger sample. For 53 targets the FIRST core flux density is above the dotted line representing the core variability limit. The mean extended radio slope of $\alpha_{\text{ext}} = -0.746 \pm 0.130$ is used to $k$-correct the extended flux density to 5 GHz for group 1 and group 3 targets. The radio core dominance calculated using FIRST measurements suffers from the resolution effect.

Table 3
The rms, Mean, and Dynamical Range of the Resultant Maps of VLA 10 GHz Presented in This Paper

| Object Name       | rms (Jy beam$^{-1}$) | Mean (Jy beam$^{-1}$) | Dynamical Range |
|-------------------|----------------------|-----------------------|-----------------|
| SDSS J080413.87+470442.8 | 2.4E-03              | 1.1E-04               | 44.05           |
| J085128.92+600320.1  | 8.6E-05              | 1.3E-05               | 21.06           |
| J100611.67+294027.0  | 1.3E-04              | 5.6E-06               | 60.59           |
| J124159.10+431624.7  | 1.1E-04              | 1.2E-05               | 28.89           |
| J125226.35+563419.6  | 1.54E-02             | 2.08E-03              | 20.62           |
| J164311.34+315618.4  | 2.61E-04             | 5.74E-05              | 13.72           |
| J170334.99+391735.6  | 2.72E-05             | 6.0E-07               | 22.13           |

Table 4
Data for 28 Additional Objects Observed with VLA

| Object Name       | Redshift $z$ | F5100 | $S_{\text{core}10\,\text{GHz}}$ (mJy beam$^{-1}$) | $S_{\text{core}1.4\,\text{GHz}}$ (mJy beam$^{-1}$) | $S_{\text{total}1.4\,\text{GHz}}$ (mJy) | $S_{\text{total}5\,\text{GHz}}$ (mJy) | $S_{\text{VLSS}r}^{\text{total}}$ (mJy) | $S_{\text{WENSS}}^{\text{total}}$ (mJy) |
|-------------------|--------------|-------|-----------------------------------------------|-----------------------------------------------|----------------------------------|---------------------------------|----------------------------------|---------------------------------|
| SDSS J081432.11+560956.6 | 0.5093       | 7.23 ± 0.25 | 19.7 ± 0.07 | 69.18 ± 0.16 | 67 ± 6 | 124.2 ± 13.2 | ... | ... |
| J084925.89+564132.1  | 0.5882       | 5.71 ± 0.27 | 1.02 ± 0.02 | 1.42 ± 0.15 | 62 ± 7 | 119.5 ± 12.1 | ... | ... |

| $\alpha_{\text{ext}}$ | $\delta$Group | log(R$_{1.4\,\text{GHz}}$) | log(R$_{10\,\text{GHz}}$) | log(R$_{5100,1.4\,\text{GHz}}$) | log(R$_{5100,10\,\text{GHz}}$) |
|----------------------|---------------|-----------------|----------------|-----------------|----------------|
| −0.746 ± 0.130       | $g$3          | 1.08 ± 0.053    | 0.53 ± 0.053 | 3.04 ± 0.03    | 2.50 ± 0.03   |
| −0.688 ± 0.194       | $g$2          | −0.95 ± 0.226   | −1.10 ± 0.201 | 1.46 ± 0.12    | 1.31 ± 0.05   |

Notes.

a F5100 is in units of $10^{-17}$ erg s$^{-1}$ Å$^{-1}$ cm$^{-2}$.

b Quasars are assigned group 1, 2, 2-flag (2f), or 3 on the basis of their radio spectrum. See Section 5 for details.

(This table is available in its entirety in machine-readable form.)
Figure 10. Left panels: scatter plots of core flux density measured at 1.4 GHz and 10 GHz and the corresponding $R$ and $R_{5100}$ measurements on log scales. The points are color-coded according to the groups defined by the radio spectra of their extended emission. Points in the bottom left panel with downward-pointing arrows represent the objects with FIRST flux limits. The dashed lines show where the two quantities are equal. Top left: scatter plot with the logarithm of 1.4 GHz core flux density on the $y$-axis and the logarithm of 10 GHz core flux density on the $x$-axis. The dotted line represents $y = x \pm 0.39$, an estimate of the $1\sigma$ scatter introduced by the core variability. Middle left: scatter plot of log $R$ calculated from the 1.4 GHz FIRST cores on the $y$-axis and from the 10 GHz cores on the $x$-axis normalized by the extended flux densities scaled to 5 GHz rest frame according to the groups as discussed in Section 5. Bottom left: scatter plot of $R_{5100}$ values calculated from the ratio of 10 GHz vs. 1.4 GHz core flux densities and 5100 Å flux density. The point with a black open circle represents a quasar with a bad 5100 Å flux density measurement. Right: panels show the histograms of the corresponding ratio of the quantities in the $x$-axis and $y$-axis of the left panels. The dashed lines in these histograms show where the ratios are equal.
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