ON THE SELECTION EFFECT OF RADIO QUASARS IN THE SLOAN DIGITAL SKY SURVEY

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ABSTRACT

We identify a large sample of radio quasars, including those with complex radio morphology, from the Sloan Digital Sky Survey and the Faint Images of the Radio Sky at Twenty cm (FIRST). Using this sample, we inspect previous radio quasar samples for selection effects resulting from complex radio morphologies and adopting a positional coincidence between radio and optical sources alone. We find that 13.0% and 8.1% of the radio quasars do not show a radio core within 1.2′′ and 2′′, respectively, of their optical position and thus are missed in such samples. Radio flux is underestimated by a factor of more than 2 for an additional 8.7% of the radio quasars. These missing radio-extended quasars are more radio-loud, with a typical radio-to-optical flux ratio, namely, radio loudness RL ≥ 100 and radio power P ≥ 10^{25} W Hz^{-1}. They account for more than one-third of all quasars with RL > 100. The color of radio-extended quasars tends to be bluer than that of radio-compact quasars. This suggests that radio-extended quasars are more radio-powerful sources, e.g., Fanaroff-Riley type 2 sources, rather than the compact sources viewed at larger inclination angles. By comparison with the radio data from the NRAO VLA Sky Survey, we find that for sources with total radio flux less than 3 mJy, low surface brightness components tend to be underestimated by FIRST, indicating that lobes in these faint radio sources are still missed.

Key words: galaxies: jets — quasars: general — techniques: high angular resolution

Online material: color figures

1. INTRODUCTION

In past decades we have witnessed a rapid growth in the number of radio-selected active galactic nuclei resulting from large and deep radio surveys such as the Faint Images of the Radio Sky at Twenty cm (FIRST; Becker et al. 1995) and the NRAO VLA Sky Survey (NVSS; Condon et al. 1998) coupled with optical spectroscopy follow-ups or dedicated spectroscopic surveys such as the Two Degree Field (2dF; Maddox 1998; Boyle et al. 2001) and the Sloan Digital Sky Survey (SDSS; York et al. 2000; Stoughton et al. 2002). However, some fundamental issues regarding the origin of radio emission remain hotly debated: Is the radio-loudness dichotomy true (Kellermann et al. 1989; Miller et al. 1990; Hewett et al. 2001; Ivezić et al. 2002)? Are radio jets in radio-quiet/radio-intermediate quasars relativistic (Readhead et al. 1988; Wilson & Colbert 1995; Meier 2001)? Which physical parameters control the large range of radio strength despite their great similarity in the spectral energy distribution at other wave-lengths for various quasars (Barthel 1989; Urry & Padovani 1995; Jackson & Wall 1999; Boroson 2002; Aars et al. 2005)?

Concerning the first question, the ambiguity is caused largely by various selection biases introduced by the survey limits and by the incompleteness in the radio sample due to their complex morphologies or in the optical sample due to various color selections (Ivezić et al. 2002; Cirasuolo et al. 2003a; Best et al. 2005). The traditional radio surveys were carried out at shallow flux density limits (0.1–1 Jy), and primarily radio-loud quasars were detected (e.g., Bennett 1962; Smith & Spinrad 1976; Colla et al. 1972; Fanti et al. 1974; Large et al. 1981). Only the two latest radio surveys, NVSS and FIRST, have enough sensitivity and positional accuracy to allow for the detection of a large number of radio-intermediate and radio-quiet quasars in conjunction with moderately deep, large-area optical surveys such as 2dF and SDSS. However, by taking advantage of the accuracy in the position of the radio sources, most authors constructed the radio quasar or quasar candidate sample solely using the position match between radio and optical sources (Gregg et al. 1996; White 1999; Lacy & Rigby 2001; McMahon et al. 2002; Richards et al. 2002; Cirasuolo et al. 2003a). This process introduces a bias against lobe-dominated radio quasars; either they were missed or their radio flux was underestimated.

White et al. (2000) argued that this incompleteness is not severe in the FIRST Bright Quasar Survey (FBQS), which was selected by matching optical counterparts within a 1.2′′ position offset to the radio sources in the FIRST catalog. Using a matching radius of 2′′, Ivezić et al. (2002) estimated that less than 10% of the SDSS-FIRST associations have complex radio morphology, and core-lobe and double-lobe sources together represent only about 5% in the radio quasars and galaxy sample. Using a novel technique, de Vries et al. (2006) constructed a Fanaroff-Riley type 2 (FR II) quasar sample and found that 27% of the FR II quasars do not show cores at the FIRST flux limit. These authors also compared the emission-line properties and optical colors of these FR II quasars with radio-quiet quasars. It should be noted that these missing quasars are not random but are all extended sources and tend to be more radio-loud (Falcke et al. 1996; Ivezić et al. 2002; Best et al. 2005). As a result, the statistical properties of the sample, such as radio loudness and radio luminosity distribution, will be affected by this selection effect.

In this paper we study in detail the selection effects in the SDSS radio quasar samples. We identify a large sample of radio quasars from SDSS and FIRST, including those with complex radio morphology. Besides using positional coincidence as a primary selection criterion, we manually examine the FIRST images for all of the candidates with extended radio morphology. Through this less efficient process, we obtain a sample of 3641 spectroscopically
confirmed quasars with secure radio identification. A detailed comparison of this sample with other radio quasar samples is given. Various selection effects are quantified. Throughout this paper we adopt a concordant cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$.

2. THE RADIO QUASAR SAMPLE

2.1. Optical Data

Our starting point is the SDSS quasar catalog constructed by Schneider et al. (2005). The catalog consists of quasars that contain at least one broad emission line (FWHM $\geq 1000$ km s$^{-1}$) or are unambiguously broad absorption line quasars. These quasars, selected from the SDSS photometric catalog either by their colors or for their positional coincidence with radio sources in the FIRST catalog (within $2\alpha$ of a FIRST source) or with ROSAT X-ray sources (within $10''-20''$ of a ROSAT source), were spectroscopically confirmed to meet the above criteria and their absolute optical magnitudes at the $i$ band, $M_i \leq -22.0$. The sample also includes some supplementary quasars that meet the above criteria but were initially selected as galaxy targets (Eisenstein et al. 2001; Strauss et al. 2002). Note that the magnitude limits for various candidates are different: $i < 19.1$ for color-selected low-$z$ ($z < 3.0$) quasars, $i < 20.2$ for color-selected high-$z$ quasars, $i < 19.1$ for FIRST and ROSAT sources, and $i < 17.7$ for the main galaxy sample. The final sample contains 46,420 quasars in the redshift range $0.078 \leq z \leq 5.414$, absolute magnitude range $-30.2 \leq M_i \leq -22.0$, and $i$-band optical magnitude range $15.10 \leq i \leq 21.78$.

We use a subsample of this catalog in order to minimize the bias introduced in the selection of quasar candidates. The SDSS sources with the target flags QSO\_FIRST\_CAP or QSO\_FIRST\_SKIRT only (hereafter “FIRST-only sources”) are biased against the lobe-dominated radio sources and are redder than the color-selected quasars (Richards et al. 2002). Therefore, they are excluded from the sample. Since radio and X-ray emission from quasars is well correlated (Shastri et al. 1993; Padovani et al. 2003), the ROSAT-only selected quasars are biased toward radio-strong sources, and as such they are excluded from the subsample.

2.2. Radio Data

Radio counterparts to the SDSS quasars are found using the FIRST survey. The survey covers about 10,000 deg$^2$ and is 95% complete to 2 mJy and 80% complete to 1 mJy (Becker et al. 1995). The source surface density in this survey is $\sim 90$ deg$^{-2}$. At the 1 mJy source detection threshold, the resolution is better than 5$''$. Individual sources down to the 1 mJy threshold have 90% confidence error circles with radii of $\lesssim 1''$.

The FIRST catalog was produced by fitting a two-dimensional Gaussian to each source to generate major axes, minor axes, and peak and integrated flux densities from the co-added images. The major axes have been deconvolved to remove blurring by the elliptical Gaussian fitting. For bright sources, the size was determined down to about one-third of the beam size, 5.4$''$. The FIRST survey also provides clean radio images.

2.3. Compact Radio Quasars

Most radio quasars are compact sources in the FIRST images, and as such they can be identified through cross-correlation of the FIRST catalog with the SDSS quasar catalog by adopting a small matching radius in the position offset.

The matching radius is a trade-off between completeness and random association; i.e., higher completeness necessarily implies higher random contamination. Knapp et al. (2002) showed that random association increases with matching radius at $\leq 2.5''$. Magliocchetti & Maddox (2002) found that a 2$''$ matching radius could include $\sim 97\%$ of the true matches above the 1 mJy level. Gregg et al. (1996) estimated that more than 95% of the FBQS I quasars with magnitude $E \leq 17.8$ are within a 1.1$''$ offset between the POSSI I and FIRST positions, while White et al. (2000) showed that an $\sim 1''-1.1''$ matching radius eliminates most false quasar candidates at the expense of only 5% incompleteness, and the fraction of optical candidates found to be quasars declines steadily from 80% near 0$''$ offset to $\sim 20\%$ at 1.2$, and is constant farther out. Ivezic et al. (2002) estimated that a 1$''$ matching radius produces 72% completeness and 1.5% random contamination and a 1.5$''$ matching radius produces 85% completeness and a contamination of 3%. For their photometric SDSS quasar sample, they estimated that a 3$''$ matching radius will cover almost all counterparts, but with 9% random contamination.

Following Richards et al. (2002) we used a matching radius of 2$''$ for compact FIRST sources and obtained 2782 matches with a false rate$^5$ of $\sim 0.15\%$. In addition, we found 71 SDSS quasars located within the ellipses of FIRST sources with core-jet or diffuse structure but with their optical-radio offset larger than the 2$''$ matching radius. We added these quasars to our sample after visual confirmation of the true association.

2.4. Extended Radio Quasars

The two-point angular correlation function (Cress et al. 1995) can be used to define an appropriate scale for searching for radio matches with complex radio morphologies. The correlation function in 0.02$''-2$ can be well fitted by a power law $A\theta^\gamma$, where the angle $\theta$ is in degrees, $A \sim 3 \times 10^{-3}$, and $\gamma \sim 1 - 1.1$. At $\theta \sim 0.1$ (6$'$) it drops to a value of only 0.038, which means that double and multicomponent FIRST sources are shown to have little clustering amplitude beyond that angular limit; i.e., intrinsic correlated double and multiple components are mostly clustered under that scale. We also note that the physical size of the 6$'$ angle at $z = 0.05$ is $\sim 353$ kpc, approximately the scale of most radio jets and lobes ($\sim 100$ kpc; Readhead et al. 1988; Jackson 1999; Krolik 1999). All quasars in the SDSS Data Release 3 (DR3) have redshifts above 0.05. Therefore, we use the 6$'$x6$'$ FIRST map surrounding the quasar to determine possible complex structure.

The extended radio quasars are extracted in two steps. First, the candidate radio quasars are selected with one of the following two simple criteria: (1) two radio sources are located nearly symmetrically around the quasar position, i.e., the angle between optical-radio connections lies in the range 150$'' \leq \theta \leq 210''$, and the ratio of their distances to the quasar is 1/3 $\leq d_1/d_2 \leq 3$; and (2) more than two radio sources are scattered around the SDSS quasars. The first criterion allows us to detect radio sources with symmetric lobes of either FR II or FR I type (Fanaroff & Riley 1974), similar to the criterion used by de Vries et al. (2006). The FR I sources are core-dominated sources with a bright nucleus and two extended lobes with surface brightness decreasing toward the edges. In contrast, the FR II sources are generally lobe-dominated sources and always show brighter lobes, usually with a hot spot and with or without a weak core (see Fig. 1). However, when viewed at an extreme angle, the FR II sources

$^5$ The fraction of chance coincidence is estimated as $\rho r^2 N_s/N_m$, where $\rho$ is the surface density of the FIRST sources, $r$ is the matching radius, $N_s$ is the number of quasars in the SDSS DR3, and $N_m$ is the number of matches.
may be dominated by the brighter core (Barthel 1989; Hoekstra et al. 1997; Hardcastle et al. 1998). Based on the first criterion, sources with distorted asymmetric lobes may be missed. The second criterion is designed for more complex radio morphologies, such as sources with distorted asymmetric lobes and a compact core, or for cases in which extended lobes are resolved into complex structure in the FIRST image (see Fig. 1).

With these criteria, we selected 3115 radio quasar candidates. Among them, 1035 sources are selected by the first criterion and 2080 by the second criterion. A $6' \times 6'$ cutout of the FIRST image centered at the quasar candidate was extracted for each SDSS source and visually checked. We used the radio morphologies in the Third Cambridge Revised Catalog of Radio Sources (3CR) as the reference for the true matches. We found that about 70% of these radio components in the $6' \times 6'$ cutouts are likely not related to the SDSS quasars; i.e., they are isolated radio components or radio components related to other SDSS sources, or they have no convincing evidence for their connection to the quasar. They are excluded either from the radio flux estimation or from the sample.

In the end, 859 extended sources are selected (with unambiguous radio lobes or jets) from the initial 3115 candidates. Of these, about half (409) show FR II morphologies and 564 have radio core components (within the $2''$ circle of the optical quasar position) in the FIRST catalog. In comparison, de Vries et al. (2006) found 422 FR II quasars using the Abazajian et al. (2005) DR3 quasar sample (44,984 sources), of which 359 are in common. There are 63 radio counterpart members in the de Vries et al. sample that are not included in our sample. Most of these “lost” objects (41 out of 63) are not included in the SDSS DR3 quasar catalog of Schneider et al. (2005). Another 18 are excluded by us due to their “FIRST-only” or “ROSAT-only” target flag. The remaining four are excluded by us for their unconvincing connection between radio and optical sources. We also note that, for 83 of the 359 common quasars in both samples that show more complex radio structure than simply “double lobes,” i.e., the lobes resolved in the FIRST image, we account for the radio fluxes of all components. As a comparison, de Vries et al. (2006) only considered the radio fluxes of the two components located symmetrically around the quasar; thus, the total radio fluxes are systematically underestimated for these sources. The flux difference between the two components ranges from 2% to 86%, with a typical value of 31.2%.

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Fig. 1.—Top panels: FIRST images of typical FR II–type radio quasars. Bottom panels: FIRST images of multicomponent radio quasars.

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6 Available at http://archive.stsci.edu/vlafirst/.

7 See http://www.jb.man.ac.uk/atlas/sample.html.
The maximum projected physical distance of the lobe component is independent of the radio power (Fig. 2, left), while the rest-frame peak intensity increases with radio power (Fig. 2, right). The former is expected if the radio power does not vary significantly during the quasar activity phase while the lobe pushes farther outward. The latter may result from the interaction of powerful radio jets with the interstellar medium, which produces more relativistic electrons and thus high intrinsic brightness.

By merging the compact and extended radio quasar samples after eliminating duplicate sources, we obtain a sample of 3641 radio quasars. Of these, 859 are multicomponent sources (hereafter "extended sources"), and the remaining 2782 are single-component sources (hereafter "compact sources"). The average apparent magnitude of this sample is $m_i \sim 18.78$, and the median redshift is $\sim 1.36$ (see Fig. 3). The distributions of the optically selected and optical+radio-selected subsamples are significantly different. As noticed by Richards et al. (2006), radio-selected and optically selected quasars show different redshift distributions in the sense that the optically selected quasars show a deeper deficit at $z \sim 2.7$, while the optical+radio quasars are distributed more smoothly at $z > 2$. This is due to the selection effect of the optically selected SDSS quasars based on optical colors. We can also see that radio quasars peak at a slightly lower redshift and are more abundant between redshifts of 2.2 and 3.0. This may be due to the comparatively shallower survey depth of FIRST, so that we can find more radio counterparts of optically selected quasars at lower redshift.

Note that the redshift distribution of extended sources peaks at a lower redshift than that of the compact quasars; i.e., the fraction of extended sources decreases with redshift. The median radio flux is 5.49 mJy for compact quasars and 48.31 mJy for extended quasars.

3. ON THE SELECTION EFFECT OF THE RADIO QUASAR SAMPLE

3.1. The Incompleteness of Extended Sources Caused by the Surface Brightness Limit

FIRST is not sensitive to low surface brightness emission due to its small beam size; as such, diffuse emission, if present, will be missed in the FIRST survey. It should be noted that the surface brightness is lowered due to cosmological expansion [$I \propto (1+z)^{-4-\alpha'}$]; as such, lobes may fall below the detection limit (0.75 mJy beam$^{-1}$) of the FIRST survey at large redshifts (see below). In the worst case, if the source is dominated by a diffuse component, it may escape detection completely in the FIRST.
survey. We use cross-correlation between SDSS and NVSS to constrain this.

The 1.4 GHz NVSS (Condon et al. 1998) provided a catalog containing $2 \times 10^6$ sources stronger than 2.5 mJy. It is 90% complete at an integrated flux density of $S_{1.4 \text{GHz}} = 3$ mJy and 99% complete at $S_{1.4 \text{GHz}} = 3.5$ mJy. With a synthesized beam of 45" (FWHM), NVSS is much more sensitive to lower surface brightness components than FIRST. Therefore, it can be used to check the fraction of quasars with only diffuse emission. For a typical redshift of the quasars in this sample, the radio emission should be unresolved by NVSS.

In the following we consider radio sources with an NVSS flux density larger than 3 mJy. The matching radius used in the cross-correlation of DR3 quasars and NVSS sources is a trade-off between random contamination and completeness. First, we estimate that the fractions of chance coincidence corresponding to a 15", 20", and 25" matching radius are $\sim 3.95\%$, $\sim 6.68\%$, and $\sim 9.64\%$, respectively. Second, we check 775 extended sources with FIRST fluxes above 3 mJy in our FIRST-DR3 quasar sample. Of these, NVSS counterparts are found for 719 quasars ($\sim 92.8\%$) within a 20" offset of the quasars. The fraction decreases to $87.65\%$ with a 15" matching radius and increases to $95.6\%$ with a 25" matching radius. We take 20" as the matching radius for the NVSS-SDSS match.

With a 20" matching radius, we extracted 3029 NVSS radio counterparts to SDSS DR3 quasars in the overlapping area of FIRST, SDSS DR3, and NVSS, with the NVSS flux density limit of 3 mJy. In this DR3-NVSS sample, 227 sources are not present in our DR3-FIRST radio quasar sample; 208 of these "lost" sources are located at a distance from the quasar greater than the NVSS major axis. We found that the NVSS-SDSS offset distribution of these "lost" sources is significantly different from that of the "found" sources (see Fig. 4, bottom), indicating that most of them are due to chance coincidence. This number is close to the expected rate of chance coincidence ($\sim 6.68\%$). Note in passing that four sources are found in our DR3-FIRST sample, but their NVSS flux densities are less than 3 mJy. Therefore, no more than 19 extended radio quasars may be missed due to the higher FIRST resolution at the NVSS flux density limit of 3 mJy. This lost fraction is $\sim 19/(775 + 19) \sim 2.3\%$. Therefore, above the 3 mJy flux density limit, radio quasars with only diffuse radio sources are rare.

However, weak diffuse emission is likely to be overlooked by FIRST. We plotted the distribution of $k = \log (F_{\text{NVSS}}/F_{\text{FIRST}})$ at FIRST fluxes $>3$ and $<3$ mJy (Fig. 4, top left), where $F_{\text{FIRST}}$ is the sum of all the radio sources within the NVSS beam size. The value of $k$ is peaked at zero with a tail toward $\langle k \rangle \sim 0.04$ above 3 mJy, which suggests that most of the NVSS flux has been detected by FIRST. But below the 3 mJy limit, $\langle k \rangle$ increases to 0.24. This indicates that some diffuse radio flux, such as the weak lobes of extended sources, can be underestimated by FIRST as the flux density decreases. As a result, some extended sources with low

![Fig. 4](https://example.com/fig4.png)
surface brightness may be misidentified as compact sources. This may explain why most of the extended sources have a flux greater than 3 mJy (see Fig. 4, top right).

3.2. The Selection Effects of a Radio Quasar Sample

In this section we address the selection effects introduced by the positional coincidence alone using our radio quasar sample. This includes the lost fraction of lobe-only objects and the underestimation of the extended flux. In the following we divide the radio quasars into extended and compact sources according to whether one or more extracore components are present or not. The core component is defined as the single component within the $2''$ radius of the optical quasar.

The distribution of the position offsets of the closest radio components to the SDSS quasars is shown for our radio quasar sample in Figure 5 (left). We find that 13.0% of the quasars are lost with a matching radius in the position offset of $1.2''$, 10.4% with $1.5''$, and 8.1% with $2''$. With these numbers we conclude that the fraction of radio quasars missed due to lack of detectable radio cores is low.

Using the positional coincidence will underestimate the radio flux density if there are one or more off-core components, even if a radio core is present. This is particularly important in lobe-dominated quasars. To quantify this bias, we calculate $q$ as the flux ratio of the core component to the total radio flux (the summation over all radio counterparts that associate with the radio quasar).

The result remains the same for the core-only and lobe-only sources and for quasars with unresolved and resolved cores [resolved core: $\log (f_{\text{int}}/f_{\text{peak}})^2 > 0.1$, with $f_{\text{int}} > 3$ mJy in order to gain sufficient signal-to-noise ratio (Ivezić et al. 2002); see Fig. 7]. However, the core-lobe sources and the lobe-only sources are indistinguishable. These results are in line with that of de Vries et al. (2006), who found that the composite spectrum of FR II quasars is flatter than that of radio-compact quasars.

Next, we calculate the $k$-corrected radio power at 2500 Å at the rest frame of the quasars by interpolating or extrapolating the five SDSS apparent magnitudes using a spline function. Extrapolation is required for only a small number of quasars at low redshift ($z < 0.5$). The radio loudness is defined as the flux ratio of $k$-corrected radio flux at 20 cm and the UV flux at 2500 Å. An average of the radio spectral index $\alpha_r = -0.5$ for quasars is assumed. We plot the average UV absolute magnitudes versus redshift in Figure 8 (left).

We find that the average UV absolute magnitudes of extended and compact sources are similar, as they are for resolved and unresolved sources. Next, we calculate the $k$-corrected radio power at 20 cm as $P_{\text{radio}} = 4\pi D_L^2 f_{\text{int}}/D_{\text{m}}^2 (1+z)^{\alpha_r}$, where the radio spectral index $\alpha_r$ is assumed to be $-0.5$ for all the objects. The radio power and the radio-loudness distribution are shown in Figure 9, and the radio power as a function of $z$ is shown in Figure 8 (right). Evidently, extended radio quasars are much more powerful in the radio than compact radio quasars, despite their similar optical luminosity.

The difference in the radio power between the extended and compact sources decreases with increasing redshift, from a factor of more than 10 at redshifts less than 0.5 to a factor of $\approx 2$ or
so at redshifts larger than 2 (Fig. 8). This might be caused by a combination of the survey limit, with which only powerful radio sources can be detected at high $z$, and an increase in the detection limit of intrinsic brightness for the extended lobes at high redshift; i.e., only very bright lobes are detected, and thus only very powerful FR II sources. At redshifts less than 0.5, the radio power of compact radio quasars is close to the border of the FR I/FR II division.

It was proposed that strong radio emission from extended quasars may be enhanced by the interaction of the radio jet with the

Fig. 6.—Left: Intrinsic brightness of the lobes vs. redshift. The solid line represents the surface brightness at the detection limit as 0.75 mJy beam$^{-1}$. Right: Physical size of the extended sources at different redshifts. The size is the physical distance of the furthest radio component associated with the quasar. The solid line marks the minimum distance that can be resolved in the FIRST survey at the corresponding redshift (on scales down to about one-third of the beam size of 5.4$''$.)

Fig. 7.—Median-subtracted $g-i$ color distribution for quasars with redshifts $0 < z < 3$ (see the text for definition). A comparison between extended (gray line) and compact (black line) radio quasars is shown in the top left panel, between resolved (gray line) and unresolved (black line) compact radio quasars in the bottom left panel, between extended quasars with (black line) and without (gray line) cores in the top right panel, and between lobe-only (gray line) and core-only (black line) quasars in the bottom right panel. [See the electronic edition of the Journal for a color version of this figure.]
Fig. 8.— *Left*: Average absolute magnitude at 2500 Å vs. redshift. The gray line represents the extended sources, and the black line represents the compact sources. *Right*: Average radio power of extended (thick line) sources and compact (thin line) sources at 1.4 GHz vs. redshift. The dashed line indicates the FIRST detection limit of 1 mJy. Error bars are shown at 1 σ scatter around the average. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 9.— *Left*: Radio luminosity (left) and radio loudness \(F_{1.4\text{GHz}}/F_{2500\text{Å}}\) in rest frame; *right* distributions. The light-gray line represents extended radio quasars, the black line represents compact radio quasars, and the dark-gray line represents all radio quasars. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 10.— *Left*: Conditional radio-loudness distribution for compact sources and for all cores (component within 20' offset from quasar). The thin and thick solid lines represent compact sources and cores with \(15 < m_{2500} < 19\); the thin and thick dashed lines represent compact sources and cores with \(19 < m_{2500} < 21\). *Right*: Conditional distribution of extended sources with \(15 < m_{2500} < 19\) (dashed line) and \(19 < m_{2500} < 21\) (solid line). [See the electronic edition of the Journal for a color version of the left panel.]
dense intergalactic/interstellar medium (Bridle et al. 1994; Wills & Brotherton 1995). As such, the difference in the radio power of core-dominated and extended quasars is due to their different environment, rather than their different central engine. To check this point, we compare the core radio power for those quasars with detected cores and find that extended quasars have more powerful cores. Therefore, our result does not support this interpretation.

The radio and optical flux limits introduce another selection effect on the radio-loudness distribution of quasars. At a given optical magnitude limit, only quasars with a radio loudness above a certain limit can be detected in the FIRST survey due to its flux limit; i.e., the sample is complete above a certain radio loudness. Using a strip in the log RL-i plane similar to that of Ivčič et al. (2004), we estimate the conditional radio-loudness distribution under a different photometric limit. As shown in Figure 10, the distribution of log RL for compact sources peaks at ∼2 for 19 < i < 21, consistent with Ivčič et al. (2004). Adding the core flux of the extended sources, the radio-loud peak becomes more significant, with the amplitude of the dip at log RL ∼ 2 increasing from 24% to 37% due to their contribution to the large radio-loudness portion. As shown in Figure 10, the distribution for extended quasars stays at a peak of log RL ≥ 2.7 at different i-magnitude bins, while the compact sources show a peak at log RL ≤ 2.3. Furthermore, the compact source distribution peaks at a lower radio loudness when i is decreased.

By plotting the radio loudness under different redshifts, we find that the peak of the compact radio quasars moves to small radio loudness as the redshift decreases, while the distribution of the extended radio quasars remains the same (peaked at ∼3) for all redshifts (see Fig. 11). This radio-loudness distribution of the extended (and more radio-loud) radio quasars is consistent with Cirasuolo et al. (2003b), who modeled the radio-loudness distribution with a double-Gaussian function by fitting the FIRST-selected 2dF quasars and found that the intrinsic radio loudness of radio quasars peaks at log RL = 2.7 ± 0.2 and −0.5 ± 0.3.

4. CONCLUSION AND DISCUSSION

We have constructed a relatively unbiased large radio quasar sample using the SDSS quasar catalog (Schneider et al. 2005) and the FIRST catalog and images. In addition to the positional coincidence of radio sources within 2° of the quasars, we also identify the radio counterparts of quasars with complex radio morphologies, such as lobe-dominated quasars, by visual inspection of their radio images. We find that using the positional coincidence alone misses ∼8% of the radio counterparts that do not show a radio core at the FIRST flux limit of 1 mJy and underestimates the radio flux by a factor of more than 2 in another ∼9% of the objects. By comparing the radio flux from the FIRST survey with that from NVSS, we find that the lobes in weak radio sources tend to be missed in this sample. Therefore, these numbers are only lower limits.

Quasars with extended radio emission show both larger radio powers and radio loudness, and they appear somewhat bluer than radio-compact quasars despite their indistinguishable optical luminosity. As such, the radio-extended quasars account for nearly one-third of the radio-loud quasars at log RL > 2.2. Naturally, including the extended emission and weak core radio sources increases the fraction of radio-loud objects and the significance of the radio-loud peak in the distribution of radio loudness.

At first glance, our results are not consistent with the simple unification scheme in which radio-compact quasars are extended quasars viewed along the radio jet, for which the relativistic beaming enhances the core radio emission and, as such, the total radio power (Wills & Browne 1986; Hough & Readhead 1988; Readhead et al. 1988; Barthel 1989; Falcke et al. 2004) when the projection effect would make the apparent size smaller. Within such a scheme, the unresolved core is enhanced because of the beaming effect. That the lobe-dominated radio quasars are more luminous in radio seems to contradict this model. However, there are at least two selection effects that make the average radio power in the core-dominated sources smaller.

First, as we showed in § 3, the peak brightness of the radio-lobe component is correlated with radio power, and FIRST is not able to detect the lobe component in lower radio power sources, especially at high redshift (see also Fig. 2). Second, if most core-dominated quasars are intrinsically radio-weak (Wang et al. 2006), and if their radio luminosity function is steep, their average apparent luminosity can be lower even if the radio power is boosted.

The relative number density of the extended and compact sources also suggests that a majority of compact sources are either of beamed, intrinsically much weaker radio quasars or of intrinsically compact radio sources, such as compact steep spectrum objects (CSSs) or gigahertz-peaked sources (GPSs). With a typical Lorentz factor of 10–15 for the jets in the FR II radio quasars, the boosted emission can be viewed only in a relatively small fraction of the solid angle between the line of sight and the jet, θ < 7°, whereas at other angles the core is weakened due to
the Doppler effect. If the power of the unbeamed radio cores is near 0.005 of that of the lobes, as determined for 3CR sources (Urry & Padovani 1995), the intrinsic radio-loudness distribution follows Cirasuolo et al. (2003b), and with a luminosity distribution like that of the DR3 quasar sample, we can estimate that ~62% of the beamed intrinsic radio-quiescent sources could be detected by FIRST. Since GPSs and CSSs are all powerful radio sources, it is likely that most of these compact quasars are beamed radio-intermediate quasars, as proposed by Falcke et al. (1996).

Our results suggest that lobe-dominated sources are not particularly reddened, in agreement with the finding by de Vries et al. (2006). This is valid even for quasars without detectable radio cores at fluxes down to the FIRST limit. The line of sight does not intercept the dusty torus in those lobe-dominated quasars. However, Backer et al. (1997) found that most lobe-dominated quasars in the Molonglo quasars are reddened by \( Y \approx 2 \text{-} 4 \), and CSSs are the most reddened. It should be pointed out that quasars reddened by this amount cannot be found in the color-selected sample, particularly at high redshift, due to strong attenuation in the UV. The slightly bluer color for lobe-dominated quasars in this sample could be due to the inclusion of CSS-like objects in the core-dominant objects or a selection effect by which reddened “extended” radio quasars are lost.

If Backer et al. (1997) are correct, we might miss a large number of heavily reddened lobe-dominated quasars. Although most such quasars are likely below the magnitude limit of the spectroscopic quasar sample, in principle the FIRST-selected sample is able to detect some of these reddened quasars, particularly in the lower redshifts, if a weak core is present. We look at the spectroscopic sources that are selected as FIRST sources only and find that the FIRST-only selected spectroscopic sources are indeed much redder. But the fraction of quasars with extended lobes in FIRST-only sources is very low (~0.2%), probably due to large extinction. Thus, whether a large number of such reddened lobe-dominated quasars does exist is not conclusive.

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REFERENCES

Aars, C. E., Hough, D. H., Yu, L. H., Linick, J. P., Beyer, P. J., Vermeulen, R. C., & Readhead, A. C. S. 2005, AJ, 130, 23
Abazajian, K., et al. 2005, AJ, 129, 1755
Backer, D. C., Dexter, M. R., Zepka, A., Ng, D., Werthimer, D. J., Ray, P. S., & Readhead, A. C. S. 2005, AJ, 124, 2364
Hough, D. H., & Readhead, A. C. S. 1988, in IAU Symp. 129, The Impact of VLBI on Astrophysics and Geophysics, ed. M. J. Reid & J. M. Moran (Dordrecht: Kluwer), 65

Colla, G., et al. 1972, A&AS, 7, 1
Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1998, AJ, 115, 1693
Cress, C. M., Heller, D. J., Becker, R. H., & White, R. L. 1995, BAAS, 27, 1364
de Vries, W. H., Becker, R. H., & White, R. L. 2006, AJ, 131, 666
Eisenstein, D. J., et al. 2001, AJ, 122, 2267
Falcke, H., Kürkling, E., & Markoff, S. 2004, A&A, 414, 895
Falcke, H., Sherwood, W., & Patnaik, A. R. 1996, ApJ, 471, 106
Fanaroff, B. L., & Riley, J. M. 1974, MNRAS, 167, 31P
Fanti, C., Fanti, R., Ficarra, A., & Padrielli, L. 1974, A&AS, 18, 147
Gregg, M. D., Becker, R. H., White, R. L., Helfand, D. J., McMahon, R. G., & Hook, I. M. 1996, AJ, 112, 407
Harcastle, M. J., Alexander, P., Pooley, G. G., & Riley, J. M. 1998, MNRAS, 296, 445
Hewett, P. C., Foltz, C. B., & Chaffee, F. H. 2001, AJ, 122, 518
Hoekstra, H., Barthel, P. D., & Hes, R. 1997, A&A, 319, 757
Hough, D. H., & Readhead, A. C. S. 1988, in IAU Symp. 129, The Impact of VLBI on Astrophysics and Geophysics, ed. M. J. Reid & J. M. Moran (Dordrecht: Kluwer), 99
Ivezic, Z., et al. 2002, AJ, 124, 2364
—. 2004, in ASP Conf. Ser. 311, AGN Physics with the Sloan Digital Sky Survey, ed. G. T. Richards & P. B. Hall (San Francisco: ASP), 347

Jackson, C. A. 1999, Publ. Astron. Soc. Australia, 16, 124
Jackson, C. A., & Wall, J. V. 1999, MNRAS, 304, 160
Kellermann, K. I., Sramek, R., Schmidt, M., Shaffer, D. B., & Green, R. 1989, AJ, 98, 1195
Knapp, G. R., et al. 2002, BAAS, 34, 1180
Krolik, J. H. 1999, Active Galactic Nuclei: From the Central Black Hole to the Galactic Environment (Princeton: Princeton Univ. Press)
Lacy, M., & Ridgway, S. E. 2001, BAAS, 33, 1520
Large, M. I., Mills, B. Y., Little, A. G., Crawford, D. F., & Sutton, J. M. 1981, MNRAS, 194, 693
Maddox, S. 1998, in ASP Conf. Ser. 146, The Young Universe: Galaxy Formation and Evolution at Intermediate and High Redshift, ed. S. D’Odorico, A. Fontana, & E. Giallongo (San Francisco: ASP), 198
Magliocchetti, M., & Maddox, S. J. 2002, MNRAS, 330, 241
McMahon, R. G., White, R. L., Helfand, D. J., & Becker, R. H. 2002, ApJS, 143, 1
Meier, D. L. 2001, ApJ, 548, L9
Miller, L., Peacock, J. A., & Mead, A. R. G. 1990, MNRAS, 244, 207
Padovani, P., Costamante, L., Ghisellini, G., Giovannini, P., & Perlman, E. 2003, in ASP Conf. Ser. 299, High Energy Blazar Astronomy, ed. L. O. Takalo & E. Valtaoja (San Francisco: ASP), 63
Readhead, A. C. S., Pearson, T. J., & Barthel, P. D. 1988, in IAU Symp. 129, The Impact of VLBI on Astrophysics and Geophysics, ed. M. J. Reid & J. M. Moran (Dordrecht: Kluwer), 65
Richards, G. T., et al. 2002, AJ, 123, 2945
—. 2006, AJ, 131, 2766
Schneider, D. P., et al. 2005, AJ, 130, 367
Shastry, P., Wilkes, B. J., Elvis, M., & McDowell, J. 1993, ApJ, 410, 29
Smith, H. E., Smith, E. O., & Spinrad, H. 1976, PASP, 88, 621
Stoughton, C., et al. 2002, AJ, 123, 485
Strauss, M. A., et al. 2002, AJ, 124, 1810
Urry, C. M., & Padovani, P. 1995, PASP, 107, 803
Wang, T.-G., Zhou, H.-Y., Wang, J.-X., Lu, Y.-J., & Lu, Y. 2006, ApJ, 645, 856
White, R. 1999, HST Proposal 8382 (Baltimore: STScI)
White, R. L., et al. 2000, ApJS, 126, 133
Wills, B. J., & Brotherton, M. S. 1995, ApJ, 448, L81
Wills, B. J., & Browne, I. W. A. 1986, ApJ, 302, 56
Wilson, A. S., & Colbert, E. J. M. 1995, ApJ, 438, 62
York, D. G., et al. 2000, AJ, 120, 1579