Extended extragalactic radio sources have traditionally been classified into Fanaroff & Riley (FR) I and II types, based on the ratio $r_s$ of the separation $S$ between the brightest regions on either sides of the host galaxy and the total size $T$ of the radio source ($r_s \equiv S/T$). In this paper, we examine the distribution of various physical properties as a function of $r_s$ for 1040 luminous ($L > 10^{26} L_\odot$) extended radio galaxies (RGs) at $z < 0.3$ selected with well-defined criteria from the SDSS, NVSS, and FIRST surveys. About 2/3 of the RGs are lobe dominated (LD) and 1/3 have prominent jets. If we follow the original definition of the FR types, i.e., a division based solely on $r_s$, FR I and FR II RGs overlap in their host galaxy properties. However, the rare LD sources with $r_s > 0.8$ and $[O III] \lambda 5007$ line luminosity $> 10^6 L_\odot$ are markedly different on average from the rest of the RGs, in the sense that they are hosted in lower mass galaxies, live in relatively sparse environments, and likely have higher accretion rates onto the central supermassive black hole (SMBH). Thus, these high emission line luminosity, high-$r_s$ LD RGs, and the rest of RGs form a well-defined dichotomy. Motivated by the stark differences in the nuclear emission line properties of the RG subsamples, we suggest that the accretion rate onto the SMBH may play the primary role in creating the different morphologies. At relatively high accretion rates, the accretion system may produce powerful jets that create the “classical double” morphology (roughly corresponding to the LD sources with $r_s > 0.8$ and emission lines); at lower accretion rates, the jets from a radiatively inefficient accretion flow generate radio lobes without apparent “hot spots” at the edge (corresponding to the majority of LD sources). At slightly lower accretion rates and in galaxies with dense galactic structure, sources with prominent jets result. It is possible that while the high accretion rate systems could affect sub-Mpc scale environments, the jets from lower accretion rate systems may efficiently suppress activity within the host galaxies.

**Key words:** galaxies: active – galaxies: elliptical and lenticular, cD – radio continuum: galaxies

**Online-only material:** color figures, machine-readable table

1. INTRODUCTION

Ever since the seminal work by Fanaroff & Riley (1974, hereafter FR), radio galaxies (RGs) have been broadly categorized into two types according to their large-scale radio morphology (e.g., De Young 2002). FR proposed a simple binary classification scheme, based on the ratio $r_s$ of the separation between the brightest regions on either sides of the RG and the total size of the radio source. If $r_s > 0.5$, the source was considered type II (“edge brightened”); otherwise the source belonged to type I (“edge darkened”). FR found that nearly all 3CR (Mackay 1971) radio sources with power ($P$) at 178 MHz greater than $1.3 \times 10^{28}$ W Hz$^{-1}$ were type II, while nearly all of those weaker than this power were type I.

Subsequent studies have found an overlap in radio power (about 2 orders of magnitude) for the transition from one type to the other (e.g., Baum & Heckman 1989). In a series of papers, Owen and collaborators suggested this division between type I and II RGs was a function of the optical luminosity ($L$) of the host galaxies, in the sense that the division was at higher radio power for more luminous galaxies ($P \propto L^{1.8}$; Owen & Laing 1989; Owen & White 1991; Owen 1993; Ledlow & Owen 1996). A corollary is that, at fixed radio power, type I sources are hosted in more optically luminous galaxies than the type IIs. At a given optical luminosity, Owen et al. suggested that the transition as a function of radio power was quite abrupt.

It was also found that the two types of sources exhibit differences other than the radio power. Type IIs are usually found in less dense environments, and strong emission lines can often be seen in their optical spectra (e.g., Zirbel & Baum 1995; Zirbel 1997; Kauffmann et al. 2008); type IIs, on the other hand, are usually hosted by giant elliptical galaxies, and on average have weaker or no optical nuclear emission lines, which puts them on a different radio power–emission line luminosity correlation than that of FR IIs (Hine & Longair 1979; Zirbel & Baum 1995, see below). The cosmological evolution of the two types may also differ significantly (e.g., Willott et al. 2001; but see Gendre et al. 2010). Collectively, these differences are usually referred to as the FR I/II dichotomy, which has been the focus of numerous studies (e.g., Heckman et al. 1994; Baum et al. 1995; Hardcastle et al. 2007; Kauffmann et al. 2008; Baldi & Capetti 2010, and references therein).

Larger samples and better observations have led to several proposals for refinement/alternatives of radio source classification schemes (e.g., Owen & Laing 1989; Leahy 1993; Laing 1993). In particular, Owen & Laing (1989, hereafter OL89) categorized RGs into three types based on their radio morphologies: classical double (CD) sources are those with “compact outer hot spots and elongated, diffuse lobes extending from the hot spots back toward the nucleus;” fat double (FD) objects have “bright outer rims of radio emission and roundish diffuse radio lobes;” while twin jet (TJ) RGs “can be described by symmetric jets originating in the nucleus and extending on both sides” of the host. OL89 suggested that the hosts of FD and TJ sources have similar optical properties, and regarded both types, together with the narrow-angle tail (NAT) objects, as FR I (see also
Owen & White 1991). The CD objects were considered to be equivalent to FR II.

In addition to the radio morphologies, RGs have been classified based on their nuclear optical narrow emission line properties (e.g., Laing et al. 1994; Hardcastle et al. 2006). Objects with weak emission lines were generally referred to as low-excitation (LE) RGs, while their counterparts with strong lines were known as high-excitation (HE) RGs. Such a scheme is believed to better reflect any differences in the central supermassive black hole (SMBH), or/and the physical conditions of the accretion flow onto the central engine (e.g., Kauffmann et al. 2008). On the other hand, classification based on radio morphology is likely more intimately connected to interactions of the jets with the (large-scale) environments (e.g., De Young 1993; Kawakatu et al. 2009). As such, the correspondence between HE/LE and FR II/I is not perfect: a large fraction of FR IIs have an LE nucleus (e.g., Laing et al. 1994), while some FR Is are HE RGs (see Heywood et al. 2007). This suggests that a hybrid classification system that incorporates both radio morphology and nuclear emission line activity may perform better in revealing distinct populations of RGs, which in turn would lead to a fuller understanding of the onset of radio activity, as well as the unification of radio-loud (RL) active galactic nuclei (AGNs; e.g., Barthel 1989; Urry & Padovani 1995; Falcke & Biermann 1995; Hardcastle et al. 2006).

The samples used by many of the previous studies on the FR I/II dichotomy were limited by the available data at the time, and thus often have heterogeneous origins and did not have well-defined selection criteria (e.g., Owen 1993; Zirbel & Baum 1995). Furthermore, it is inevitable that classification of extended radio sources will be subject to the classifiers’ experience and preference. Both factors may make it difficult to uncover the origin of the dichotomy.

Our primary goal is to understand the origin of the different radio morphology schemes based on radio morphology or/nuclear activity. In addition, we will use $r_{s}$ as a continuous parameterization of the radio morphology to study the transition from FR I to FR II, and to quantify any bimodality in the physical properties of the host galaxies on the radio power–optical luminosity plane. We will mainly use our own terminology to refer to the RG populations identified in this paper; unless specifically noted, we adopt the original definition of FR when we refer to the FR I/II types of extended RGs.

We have constructed a large RG sample with well-defined criteria (see Section 2), and paid particular attention to the measurements of the total size ($T$) of an RG, as well as the separation ($S$) between the highest surface brightness (HSB) spots (Section 3). From these quantities, we define the ratio $r_{s}$ objectively and reproducibly, and present a classification system that is purely based on radio morphologies (Section 3). In Section 4, we examine the distribution of RGs on the radio power–optical luminosity plane as a function of $r_{s}$, while in Section 5 we study dependences of various physical properties of host galaxies as a function of $r_{s}$. Comparisons between RL and radio-quiet (RQ)$^{5}$ galaxies are made in Section 5.4. Discussion of the FR dichotomy, a proposal for an improved classification scheme based on both $r_{s}$ and nuclear emission line strengths, comparison of our scheme with those of FR and OL89, and the possible origin of the morphological differences, are presented in Section 6. We summarize our main results in Section 7. Possible systematics due to the limitations of the radio data we use, and the uncertainties in the measurement of $r_{s}$, are discussed in the Appendices.

Most of the radio sources in the local universe are compact or barely resolved at ~5” resolution (see Section 2); this paper concentrates on extended radio sources, and we will study the physical properties of the host galaxies of compact sources in future publication.

Throughout this paper, we adopt a flat ΛCDM cosmological model where $\Omega_{M} = 1 - \Omega_{b} = 0.3$ and $H_{0} = 100$ km s$^{-1}$ Mpc$^{-1}$ with $h = 0.70$. As our sources are at $z < 0.3$, the small differences between the adopted cosmology and the current best concordance model (e.g., Komatsu et al. 2010) have a negligible effect on our results.

2. THE PARENT RADIO GALAXY SAMPLE

We construct the RG sample by cross-matching the Sloan Digital Sky Survey (SDSS; York et al. 2000) main galaxy spectroscopic sample (Strauss et al. 2002) with the NRAO VLA Sky Survey (NVSS; Condon et al. 1998) and Faint Images of the Radio Sky at Twenty-Centimeters (FIRST; Becker et al. 1995) surveys. We start with the DR6 (Adelman-McCarthy et al. 2008) version of the NYU Value-Added Galaxy Catalog$^{6}$ (VAGC; Blanton et al. 2005), selecting from the large-scale structure bright5 subsample$^{7}$ 229,379 galaxies with $0.02 < \alpha < 0.3$ and $M_{r,0}^{0.1} \leq -21.27$ (i.e., more luminous than the characteristic magnitude $M_{r}^{0}$ in the galaxy luminosity function; Blanton et al. 2003. $M_{r,0}^{0.1}$ or $r_{0.1}$ denotes the SDSS r band shifted blueward by a factor of 1.1 in wavelength. Similarly, $g_{0.1}^{0.1}$ and $i_{0.1}^{0.1}$ refer to the shifted $g$ and $i$ bands, respectively). Selecting RGs with a uniform absolute magnitude limit makes it easy to compute the fraction of RL objects in volume-limited galaxy samples. Since the parent VAGC galaxy sample excludes quasars, our sample does not contain radio quasars. Our survey area covers 6008 deg$^{2}$.

As the first step, automatic matching to the radio source catalogs is carried out following the prescription of Best et al. (2005b). In short, if a galaxy has only one NVSS source projected within 3′, the pair would be matched depending on their angular separation as well as the properties of the FIRST source(s) (if present) in the vicinity of the galaxy. If there are at least two NVSS sources within 3′ of a galaxy, the matching depends on the spatial distribution and the fluxes of the NVSS and FIRST sources. We then visually inspect all galaxies with at least one NVSS source within 3′ (irrespective of the results of auto-matching), correcting for any mismatch, keeping only RGs with total flux density $f_{1.4} \geq 3$ mJy at 1.4 GHz, and recording their morphological and structural information wherever possible (see Section 3). The radio flux from the NVSS catalog is in general adopted, as fluxes from extended sources may be resolved out by the FIRST survey. For complicated sources that are blended/ unresolved in the NVSS images, we make use of both NVSS and FIRST data to assign proper fluxes to individual RGs. More details on the construction of the RG sample will be presented in a future publication where we study the large-scale clustering properties of RGs.

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5 We do not use an optical-to-radio luminosity ratio to distinguish between RL and RQ galaxies; by RL we refer to galaxies with 1.4 GHz power $P > 10^{23}$ W Hz$^{-1}$, while by RQ we mean galaxies not detected by the NVSS survey (i.e., 20 cm flux density <3 mJy; see Section 2).

6 http://sdss.physics.nyu.edu/vagc/

7 This subsample is defined by a constant, extinction-corrected Petrosian (1976) magnitude limit of $r = 17.6$, together with no fiber collision corrections.
Our RG catalog contains about 10,500 objects. Of these, 1040 have extended morphology with roughly aligned lobes/jets; this is the RG sample we study in this paper. The details of the selection and morphology measurement are described in Section 3. Our sample is constructed to be complete in radio flux and optical luminosity, and is not selected against any particular (radio and optical) morphology, which makes it well suited for investigating the FR I/II dichotomy. The minimum, mean, and maximum redshift of our sample are 0.027, 0.165, and 0.299, respectively. At $z = 0.3$, the resolution of FIRST survey ($5''$) corresponds to a physical scale of 22 kpc.

Finally, we cross-match all the galaxies in the NYU-VAGC with the DR7 of MPA/JHU-VAGC, which provides continuum-subtracted measurements of emission line strengths (Kauffmann et al. 2003a), star formation rates (Brinchmann et al. 2004), and stellar mass (Salim et al. 2007), among other physical properties. These auxiliary measurements are used in Section 5 when we compare these properties among RGs and between RL and RQ galaxies.

### 3. QUANTIFICATION OF RADIO SOURCE MORPHOLOGY

One of our main goals is to study various properties of RGs and determine if their distribution is bimodal or is continuous. Our first task is therefore to define an objective measure (or measures) that allows us to trace the galaxy population smoothly from FR type-I-like sources to type-II-like ones (as opposed to a sharp and perhaps arbitrary type I versus type II division). With the aid of such a measure, we hope to reduce the subjectiveness inherited in the traditional ways of classification, thus increasing the repeatability of our results by other researchers.

Let us denote the angular separation between the HSB spots on either sides of the galaxy as $S$, and the total linear size of the radio source as $T$. We follow FR and define $r_\ell \equiv S/T$ as our primary measure of the morphology of the radio sources. We primarily use data from FIRST to measure both $S$ and $T$, except for very large, diffuse sources which become invisible at FIRST resolution, or components of a multi-source RG, we use the fitted parameters from FIRST to determine whether a source is extended. A point source needs to satisfy the following conditions: (1) the integrated flux-to-peak flux ratio $f_{\text{int}}/f_{\text{peak}} < 1.2$ and (2) the deconvolved major axis $<5''$ (e.g., Becker et al. 1995; Kimball & Ivezić 2008).

For every extended RG (containing in most cases at least two FIRST sources) whose lobes/jets are aligned to within $\sim 30''$ (i.e., not strongly bent as in wide/narrow angle tail objects), we measure $T$ and $S$ as follows.

1. $T$. (1) In most of the cases, there are two or more FIRST sources associated with an RG; we use the length of the line that passes through the FIRST source locations and intersects with the outermost FIRST source ellipses as $T$ (Figure 1). (2) In the cases where we need to use NVSS for the total size measurement, we use the length of the line that passes through the NVSS/FIRST source locations and intersects with the NVSS source ellipses. If the size of the major axis for an NVSS source in either of the above cases is given as a upper limit, we remove the RG from our sample.

2. $S$. We use the peak flux of the FIRST sources to determine the position of the HSB spots; the separation between such spots on the two sides of the RG is $S$ (e.g., Figure 1). In some cases where one of the lobes is not well detected and modeled by FIRST, we use the FIRST images directly. For about 1/3 of the sources, the HSB spot coincides with the center of the galaxy (Figure 2), which is likely due to (unresolved) jets; if the spot is extended and accounts for at least 10% of the total flux, we use the size of the spot as a measure of $S$. Otherwise we use the separation between the other high SB spots on the two sides of the galaxy as $S$.

From visual inspection, 1244 RGs appear to be extended (with apparent lobes and/or jets). We have measured $S$ and $T$ by hand for these objects using the Aladin sky atlas tool (Bonnarel et al. 2000). Based on repeated measurements for about 50 sources, we find our procedure is highly repeatable and the resulting sizes usually agree to within 5%, except for very complex sources. To reduce resolution dependence on our classification scheme, and to remove compact sources (e.g., O’Dea 1998), we further select a subset of 1040 sources that have angular size $T > 30''$

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8 http://www.mpa-garching.mpg.de/SDSS/DR7/
Figure 1. Illustration of the way we measure the total size $T$ and the separation $S$ between the highest surface brightness (HSB) spots, for class $a$ (i.e., sources with two HSB spots on either side of the galaxy). The contrast of these FIRST images is chosen to show various components clearly, with overlays based on the FIRST source catalog. The small red squares are at the locations of the sources, while the red ellipses represent the best-fit Gaussian models and enclose 95% of the flux. The cross shows the location of the host galaxy. In both panels north is up, east is to the left. Left: a galaxy at $(\alpha, \delta) = (174.3390, 61.3337)$ with $z = 0.111$. The image is $4' \times 4'$. A line that connects the two HSB spots (at the edges of the source) and the host galaxy is drawn; $T$ is the separation between the two intersections of the line and the two outermost FIRST ellipses. $S$ is the separation between the HSB spots; in this case, they fall almost along that same line. These two lines are shown in orange in the figure, offset from each other for clarity. This source has $r_s = 0.93$. Right: a galaxy at $(\alpha, \delta) = (161.5181, 38.4678)$ with $z = 0.127$. The image is $1.2' \times 1.2'$. $T$ is the separation between the intersections of the line that passes most of the centers of the components (i.e., the squares) and the outermost FIRST ellipses (determined in a $\chi^2$-by-eye fashion). $S$ is the separation between the two HSB spots, which are the two components closest to the host galaxy. This source has $r_s = 0.26$.

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

Figure 2. Similar to Figure 1, but for class $b$, in which the HSB spot is coincident with the galaxy. Left: a galaxy at $(\alpha, \delta) = (112.7111, 44.9336)$ with $z = 0.072$. The image is $1/2' \times 1/2'$. $T$ is determined in the same way as the examples shown in Figure 1, as indicated by the orange line. In this case, we use the major axis of the central FIRST ellipse as $S$. This source has $r_s = 0.55$. Right: a galaxy at $(\alpha, \delta) = (208.6374, 28.2434)$, $z = 0.065$, with $r_s = 0.25$. The image is $2/4' \times 2/4'$. (A color version of this figure is available in the online journal.)

and physical size $T_P > 40$ kpc for the analysis presented below. Again, our RGs also satisfy $M_r^{0.1} < -21.27$, $0.02 < z < 0.3$, and $f_{1.4} \geq 3$ mJy.

Motivated by the above considerations, and based on the ratio $r_s$, flux, and location of the HSB spot(s) (extended or point-like; coincident with the host galaxy or not), we group the RGs into five classes: ($a$) there are two HSB spots on opposite sides of the RG; ($b$) there is a single extended HSB spot coincident with the galaxy, with flux $\geq 0.1 f_{\text{tot}}$, where $f_{\text{tot}}$ is the total flux from all the components of the RG; ($c$) the HSB spot coincides with the galaxy, is extended, and its flux is $< 0.1 f_{\text{tot}}$; ($d$) the HSB spot coincides with the galaxy, is unresolved, and its flux is $\geq 0.3 f_{\text{tot}}$; and ($e$) the HSB spot coincides with the galaxy, is unresolved, and its flux is $< 0.3 f_{\text{tot}}$. For class $b$, $S$ is the size of the HSB spot; for all other classes, $S$ is the separation between the other high SB spots on both sides of the galaxy.

This classification scheme is devised primarily for the ease of measuring $r_s$. We do not mean to suggest there are five distinct
fundamental difference between classes

We will focus exclusively on these two classes in what follows, a region where the jet is highly dissipative, and thus the lobes without much impediment, suggesting either a strong strength and nature of the jet as well as the density of the environment, which depends on the degree of interaction between the jet and the environment, which depends on the radio flux threshold and consisted of sources at much higher redshifts than our RGs). Nevertheless, one might be tempted to make a correspondence between the two distributions in Figure 3 with the two FR types.

Others have built upon the FR scheme and used more sophisticated criteria to classify the RGs, such as the presence of jets or “hot spots” toward the edge of the lobes (e.g., OL89; Leahy 1993; Gendre & Wall 2008). In the analyses presented below, we will seek the best way to distinguish various populations of RGs; in doing so we will find ourselves defining several subsets of class \(a\) (\(a_{0.9}\), \(a_{<0.8}\), \(d_{maj}\), and \(a_{0.9,em}\); see Table 2). We will show that, if one sticks with a simple FR-like classification scheme, a division at \(r_s \approx 0.8\) (between what we call the \(a_{<0.8}\) and \(a_{0.9}\) subsets) best separates objects of different physical properties (for radio data at FIRST resolution; Section 5). A scheme that works even better is based both on features of the radio morphology \((r_s)\) and the nuclear optical emission properties; we will refer to these as the \(a_{0.9,em}\) \((r_s > 0.8\) and \(L_{O_III} > 10^8 L_{\odot}\); Section 6.1) and \(d_{maj}\) (the rest of class \(a\) subsets). We will argue in Section 6.1 that the \(a_{0.9,em}\), \(d_{maj}\), and \(b\) classes represent three populations of extended RGs, which roughly correspond to the CD, FD, and TJ types of OL89, respectively. The correspondence between these and the FR types will be discussed in Section 6.1.

4. BIMODALITY IN THE RADIO–OPTICAL LUMINOSITY PLANE?

We start by analyzing the distribution of RGs in the radio power–optical magnitude plane (\(P–M\) plane for short). Owen and collaborators suggested that the transition from one FR type to the other is quite abrupt on this plane (Section 1; OL89; Owen & White 1991; Owen 1993; Ledlow & Owen...
Figure 4. Distribution in the radio power–optical magnitude plane for objects in the class a (left panels) and class b (right panels). From top to bottom, the panels show the distribution in bins of decreasing $r_s$. At the lower left corner of each panel, we show the $r_s$ range, followed by the number of sources in that range. The black points (upper left panel) are class a objects with $r_s \geq 0.9$, and are repeated in all other panels for comparison. There is a systematic shift of the locus of the RGs toward lower radio power, as $r_s$ decreases, for class a. However, there are class a objects with lower value of $r_s$ in the region occupied by the highest-$r_s$ RGs. This trend is weaker for class b. In each panel, (green) crosses denote sources with Seyfert-like emission line ratios, while squares denote those with LINER-like line ratios (see Section 5.4 and Table 3).

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

If this were true, and if their FR classification was solely based on morphological measures such as $r_s$, we would expect RGs of different values of $r_s$ to occupy distinct regions in the plane.

In Figure 4, we show the distribution of objects in classes a (left panels) and b (right panels). We have assumed a typical radio spectral index of $\alpha = -0.8$ (with the convention that $f \propto \nu^\alpha$) to convert fluxes to power. From top to bottom, we show the distribution for RGs in bins of decreasing $r_s$. Let us first focus on class a. The black points (upper left panel) are RGs with $r_s \geq 0.9$, and are shown in all other panels for comparison. As we will see below, many of these high-$r_s$ objects are distinct from the rest of the population in their host properties and environment. There is a gradual shift of the locus of the RGs toward lower radio power, as $r_s$ decreases. Even so, the region occupied by these high-$r_s$ RGs is still populated by some RGs with (much) lower value of $r_s$ (e.g., $r_s \sim 0.5$). Thus, no particular region on this plane is inhabited solely by a type of object defined by some specific range of $r_s$.

For class b (right panels), the trend of decreasing mean radio power with decreasing $r_s$ is very weak, but they tend to be lower in luminosity than the $r_s \geq 0.9$ class a objects.

These results appear to be in contradiction with those obtained by Owen and co-workers. If we were to assign an $r_s$ value that serves as the FR I/II divide (say $r_s = 0.9$), we would not obtain any clean-cut separation for the RGs. Additional classification criteria, such as special features in the radio source morphology (e.g., hot spots at the edge of the lobes), or/and optical properties of the nuclei, may be required to define two (or maybe more) distinct populations in the $P$–$M$ plane (see Section 6.3).

As an independent check, we show in Figure 5 the distribution of FR I (blue/triangle) and II (red/circle) RGs in the $P$–$M$ plane, using about 100 RGs at $z < 0.3$ from the CONFIG sample (Gendre et al. 2010). This is a radio flux-limited sample that was constructed by combining data from both NVSS and FIRST. The morphological classification was carried out by these authors and was based on FIRST and deeper VLA A-array observations. We cross-match the $z < 0.3$ RGs from this sample with the NYU-VAGC DR7 sample to obtain the absolute $r$-band magnitude. Although FR IIs are on average more powerful than FR Is, substantial overlap between the two types is readily seen. This overlap still persists using a volume-limited subsample that consists of 34 FR Is and 28 FR IIs (selected with $z < 0.16$ and $M_r \leq -21.77$). In addition, Best (2009) and Wing & Blanton (2010) also noted a substantial overlap between the two FR types in the $P$–$M$ plane. These results support our notion that in a flux-limited sample, there is no sharp division among RGs in the $P$–$M$ plane when the classification is made solely based on $r_s$. Possible causes of the discrepancy between our results and those of Owen et al. are discussed in Section 6.3.
5. HOST GALAXY PROPERTIES OF EXTENDED RADIO SOURCES

We now examine the distribution of various physical properties of the galaxies as a function of $r_e$ for classes $a$ and $b$. These include the global properties of the host galaxy, derived quantities of the stellar populations, emission line properties, and properties related to the radio source and environments.

In this section, we focus on the observational results, and leave the interpretation to Section 6. We discuss the properties of classes $a$ (Section 5.1) and $b$ (Section 5.2) separately. We investigate the environments of the RGs in Section 5.3. A comparison with RQ galaxies whose global properties are matched to the RGs is made in Section 5.4.

5.1. Class $a$

Throughout this paper, we are concerned mainly with the mean behavior of samples, and thus in this section we will examine the medians of various quantities, and their trend with $r_e$.

In Figure 6, we show the median value and its uncertainty for some global properties of the host galaxies as a function of $r_e$, for classes $a$ (red) and $b$ (blue). The small data points represent individual RGs, also color coded according to their classes. The left panels, from top to bottom, show the absolute $r^{0.1}$-band magnitude $M_r^{0.1}$, rest-frame color $(g-r)^{0.1}$, stellar velocity dispersion $\sigma$, Sersic index $n$, and concentration $c$. The panels on the right show the effective radius $r_{eff}$, dynamical mass $M_{dyn}$, total mass density $\rho$, axis ratio $b/a$ for the de Vaucouleurs profile fit to the SB profile, and redshift. Here, $c \equiv r_{90}/r_{50}$ is the ratio of the radii that enclose 90% and 50% of the Petrosian fluxes, $M_{dyn} \equiv 5r_{eff}\sigma^2/G$ is a crude estimate of the total mass, and $\rho \equiv M_{dyn}/(4\pi r_{eff}^3/3)$ represents the (central) mass density. We follow Graham et al. (2005) to estimate $r_{eff}$ from $n$, $r_{50}$, and $r_{90}$. The $r$-band measurements are used for all these photometric quantities. Using the SMBH $M_{BH}$-$\sigma$ relation (e.g., from Tremaine et al. 2002), we can estimate the SMBH mass $M_{BH}$; for our sample the range of $M_{BH}$ is $2 \times 10^7$–$13 \times 10^8 M_\odot$, with a median of $2.5 \times 10^8 M_\odot$.

We have also examined another measure of the galactic structure, the stellar mass surface density, $\mu \equiv M_{star}/\pi r_{eff}^2$, where $M_{star}$ is the stellar mass (described below), and found that the trend with $r_e$ is similar to that of $\rho$.

We focus on class $a$ in this section. The color, Sersic index, and concentration, and the SB profile (not shown) of the RGs are consistent with those of RQ early-type galaxies. The numbers of RGs in the seven $r_e$ bins are (from lowest to highest): 118, 106, 102, 105, 101, 90, and 49. The median redshift is almost constant for different $r_e$ bins (panel j). Trends or changes with $r_e$ are in most cases gradual and mild, with the exception of the highest-$r_e$ bin. Although the distributions of the properties are quite broad (cf. the small points in Figure 6), one can identify two populations, roughly separated at $r_e \approx 0.8$: sources with higher $r_e$ (hereafter the $a_{0.9}$ subset) are less luminous and massive (and thus likely harboring smaller SMBH), are smaller, and have slightly higher density. For the rest (hereafter the $a_{0.8}$ subset), trends with $r_e$ are either weak (e.g., $r_{eff}$, $n$, $\sigma$) or absent. However, it is important to bear in mind that there is significant overlap in physical properties of RQs grouped by the $r_e$ value. Some of the $a_{0.9}$ objects are as massive ($\sigma$, $M_{dyn}$) and large ($r_{eff}$) as the $a_{0.8}$ ones (see Section 6.1), and, conversely, some of the latter population share the characteristic properties of the former.

Four derived properties of the stellar populations (left panels), as well as emission line measurements (right panels), are shown in Figure 7. All these quantities are taken from the MPA/JHU-VAGC. The stellar mass $M_{star}$ is derived from broadband $ugriz$ photometry (see Salim et al. 2007 for details). The specific star formation rate (sSFR) is derived using the method presented in Brinchmann et al. (2004). The $H_\alpha$ and $D_{4000}$ indices are measures of the stellar age and star formation history (e.g., Kauffmann et al. 2003b). As in Figure 6, the $a_{0.9}$ and $a_{0.8}$ subsets show quite different behavior. While the $a_{0.8}$ RGs have roughly the same median stellar masses, sSFR, and stellar ages, and do not have strong emission lines, the majority of the $a_{0.9}$ objects are quite active, but less massive, and have higher sSFR and younger stellar age. For example, Kauffmann et al. (2003a) suggested the use of $[O\,\text{III}]\lambda 5007$ luminosity as an indicator of AGN activity; 26% of the $a_{0.9}$ RGs can be regarded as strong AGNs (e.g., log $L_{5007} > 7$). We do not apply any dust-extinction correction to the line luminosities, as (1) dust content is expected to be low in the early-type galaxies of our sample, and (2) any such correction (e.g., that based on the Balmer line ratios) is itself uncertain.

In each panel of Figure 6, we show as crosses the RGs whose spectra show signatures of Seyfert-type activity, and as squares those with LINER-like spectra. We follow Kauffmann et al. (2003a) to classify the spectra according to the $[O\,\text{III}]\lambda 5007/H_\beta$ and $[N\,\text{II}]\lambda 6583/H_\alpha$ line ratios on the BPT diagram (Baldwin et al. 1981; Veilleux & Osterbrock 1987). The class $a$ sources with higher values of $r_e$ contain larger fractions of active nuclei. For example, $6/21 \approx 29\%$ of the $r_e \geq 0.9$ sources have a

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10 The uncertainty of the median is taken as $\sigma/\sqrt{2N}$, where $\sigma$ is the standard deviation, and $N$ is the number of RGs (e.g., Lupton 1993).
Figure 6. Median values of several physical properties of the host galaxies as a function of $r_s$, for classes a (red) and b (blue). The error bars show the uncertainty of the median values. Small points are individual RGs. Panels (a)–(j) show the absolute $r_{0.1}$-band magnitude, rest-frame $(g-r)^{0.1}$ color, velocity dispersion, Sersic index, concentration, effective radius, dynamical mass, mass density within $r_{\text{eff}}$, the axis ratio from the de Vaucouleurs profile, and redshift, respectively. Trends or changes with $r_s$ are in most cases gradual.

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

Figure 7. Median values of several derived properties of the host galaxy stellar populations, as well as emission line measurements, as a function of $r_s$, for classes a (red) and b (blue). Panels (a)–(h) show the stellar mass, specific star formation rate, Hδ index, 4000 Å break strength $D_{4000}$, [O III] λ5007 line luminosity (no extinction correction applied), [O III] equivalent width (EW), Hα line luminosity, and Hα EW, respectively. The error bars show the uncertainty of the median values. Small points are individual RGs.

(A color version of this figure is available in the online journal.)
Seyfert-like spectrum, and 2/21 $\approx$ 10% can be classified as LINERs. In Table 3, we record the fraction of RGs with Seyfert- and LINER-like nuclei as a function of $r_s$. Note that the $r_s$ binning in the table is the same as that in Figures 6–8, chosen such that each bin contains roughly equal number of RGs (except for the highest-$r_s$ values), and is thus different from that shown in Figure 4. While the fraction of class a RGs with LINER-like spectra is roughly the same for all $r_s$ bins (at about few percent), the fraction of Seyfert-like spectrum is a strong function of $r_s$. About 20% of the objects in the $a_{0.9}$ subset have strong emission lines that are characteristic of active nuclei.

As an indicator of the accretion rate onto the SMBH, we show in Figure 8 (panel g) the [O iii] line Eddington ratio, which is the [O iii] $\lambda$5007 luminosity divided by the Eddington luminosity $L_{\text{Edd}}$ (which is estimated using the $M_{\text{BH}}$-$\sigma$ relation). The median accretion rate is quite close to zero for most of the $r_s$ bins, but is higher for the $a_{0.9}$ systems. In panel (f), we show the analogous radio Eddington ratio ($P_{1.4}/L_{\text{Edd}}$) at 1.4 GHz, which exhibits the same trend as $L_{\text{Oiii}}/L_{\text{Edd}}$. Note that we do not integrate over the radio spectrum (e.g., from 0.1 to 10 GHz) to obtain the total radio power; but as we are mainly interested in the trend with $r_s$, this should not be a problem under the assumption that the spectral shape is not a function of $r_s$. Assuming a mean spectral index of $\alpha = -0.8$ for all RGs and integrating over the frequency range $\nu = 0.1$–10 GHz, we would need to scale the 1.4 GHz Eddington ratio by a factor of 74 to obtain the radio Eddington ratio.

The other panels in Figure 8 are related to the environments and other radio properties of the RGs. As a simple, statistical measure of the number of neighbors, for each RG we count the number of luminous galaxies ($M^* - 3.5 \leq L^*_r \leq M^* + 1.5$) within 1 Mpc and 0.5 Mpc in the SDSS photometric catalog, assuming they are at the redshift of the RG, and subtract the expected number of galaxies (from the global galaxy counts) in the same apparent magnitude range. These neighbor counts are denoted as $\Sigma_{1}$ and $\Sigma_{0.5}$, respectively, and are shown in panels (a) and (b). These two scales are chosen to reflect the scales of the host group/cluster and of any possible local structure within the group/cluster. On average, class a RGs live in dense environments (i.e., in excess with respect to the global background). The median number of neighbors decreases with increasing $r_s$.

Panel (c) shows the mean 1.4 GHz radio power as a function of $r_s$. Here, objects in the $a_{0.9}$ subset have the highest luminosity, while $a_{0.8}$ RGs have very similar median radio power. Panel (d) shows the distribution of physical sizes of the RGs. Not surprisingly, the RGs with highest $r_s$ are also largest (median size exceeding 300 kpc), since it is mainly the lobes that contribute to the low-frequency radio fluxes.

Panel (e) is another measure of the radio source morphology: the central-to-total flux ratio $r_f$. We estimate the central flux by summing fluxes from all components within 0.15$T$ from the center. For class a, the $r_f$ ratio is on average small ($< 0.1$). Note that this must be partially a selection effect, for if a strong source is present at the center, it will likely be the HSB spot and the RG would be put in other classes (b–e).

Finally, panel (h) shows the logarithm of the radio-to-optical luminosity ratio (calculated simply as log $P_{1.4}/L^*_r$), which is also almost constant at $r_s \lesssim 0.8$, and rises sharply at highest-$r_s$ bin; this enhancement for $a_{0.9}$ is due to the combined effect of it having the lowest median optical luminosity and highest median radio power among the class a objects.

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11 Although there are 24 RGs with $r_s \geq 0.9$ (Figure 4), only 21 have spectra of good enough quality for line measurements.
Table 3
Fraction of AGN-like Spectrum

| $r_s$ Range | $N^a$ | Class $a$ | Seyfert$^b$ | LINER$^b$ | $r_s$ Range | $N^a$ | Class $b$ | Seyfert$^b$ | LINER$^b$ |
|-------------|------|-----------|--------------|-----------|-------------|------|-----------|--------------|-----------|
| 0.85–1.00   | 46   | 0.196 (0.015) | 0.043 (0.049) | 0.50–1.00 | 37 | 0 (0.005) | 0 (0.012) |
| 0.75–0.85   | 85   | 0.082 (0.004) | 0.024 (0.021) | 0.30–0.50 | 41 | 0.024 (0.005) | 0 (0.021) |
| 0.68–0.75   | 91   | 0.033 (0.002) | 0.022 (0.028) | 0.20–0.30 | 58 | 0 (0.002) | 0.017 (0.046) |
| 0.61–0.68   | 95   | 0.053 (0.008) | 0.011 (0.019) | 0.12–0.20 | 67 | 0 (0.003) | 0 (0.030) |
| 0.53–0.61   | 88   | 0 (0.001) | 0.011 (0.017) | 0.00–0.12 | 53 | 0 (0.008) | 0.008 (0.040) |
| 0.42–0.53   | 93   | 0 (0.003) | 0.022 (0.019) | ... | ... | ... | ... |
| 0.00–0.42   | 94   | 0.011 (0.004) | 0.021 (0.030) | ... | ... | ... | ... |

Notes.
$^a$ Number of all RGs with good velocity dispersion and spectral line measurements.
$^b$ The numbers in parentheses are for radio-quiet (RQ) galaxies whose properties are matched to the radio-loud (RL) galaxies in the $r_s$ bin. See Section 5.4 for more details in the matching between RL and RQ galaxies.

Table 4
Basic Properties of Radio Galaxies

| SDSS ID | VAGC ID$^a$ | Class | R.A. (J2000) | Decl. (J2000) | $z$ | $\log P_{14}$ (W Hz$^{-1}$) | $M^{0.1}_{\text{e}}$ | $\sigma$ (km s$^{-1}$) | $r_{\text{eff}}$ (kpc) | $r_p$ (kpc) | $L_{\text{o}m}$ ($10^9 L_{\odot}$) | $\Sigma_{0.5}$ |
|----------|-------------|-------|-------------|-------------|-----|-----------------|-----------------|----------------|----------------|-------------|----------------|----------------|
| 587731186743967908 | 1659866 | b | 7.247278 | 0.333494 | 0.222 | 24.44 | −23.063 | 331 | 11.5 | 111 | 0.48 | ... |
| 588015510345163463 | 1699168 | b | 5.794018 | 0.976323 | 0.227 | 24.68 | −23.039 | 266 | 9.2 | 120 | 0.24 | ... |
| 58801509086645367 | 2179614 | b | 0.877957 | 0.467584 | 0.192 | 24.60 | −22.824 | 342 | 6.9 | 259 | 0.16 | ... |
| 587724232634980800 | 354077 | a | 7.205604 | 14.979081 | 0.0977 | 24.96 | −21.627 | 177 | 6.8 | 368 | 0.56 | ... |
| 587722273009378666 | 303272 | e | 0.447139 | −9.289778 | 0.1726 | 24.42 | −23.206 | 262 | 13.1 | 377 | 0.85 | ... |
| 587731185132503151 | 1652016 | a | 5.281742 | −0.925413 | 0.1082 | 24.52 | −22.985 | 268 | 9.5 | 117 | 0.69 | ... |
| 587731186207031493 | 1657598 | b | 7.184482 | −0.096430 | 0.2166 | 24.44 | −22.865 | 253 | 9.8 | 133 | 0.26 | ... |
| 58801508736254946 | 2171995 | b | 8.546325 | −0.242890 | 0.2486 | 24.53 | −22.994 | 306 | 8.8 | 234 | 0.13 | ... |
| 588015081973434140 | 2167815 | b | 3.928198 | −0.812972 | 0.1543 | 24.88 | −22.486 | 209 | 10.2 | 131 | 0.35 | ... |
| 58772225690783827 | 327303 | a | 1.531292 | −10.509092 | 0.2171 | 24.83 | −22.806 | 311 | 8.3 | 169 | 0.58 | ... |

Notes.
The full table is also available and kept up-to-date at http://member.ipmu.jp/yen-ting.lin/AGN/index.html
$^a$ NYU VAGC DR6 object ID.
(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

All the results from Figures 6–8 indicate that there appear to be two populations of RGs among class $a$: galaxies in the $a_{0.9}$ subset have lowest stellar mass, but have the highest star formation rate, AGN activity, and radio power, and live in relatively poorer environments, while the $a_{-0.8}$ RGs, especially those with $r_s \approx 0.4–0.8$, share very similar properties, such as the luminosity, size, dynamical mass, density, indices of recent star formation history (e.g., $D_{4000}$ and H$\delta$ indices), and neighbor counts within 0.5 and 1 Mpc. We should emphasize that the division in $r_s$ of the two populations is not sharp; we choose to distinguish the two subsets at $r_s = 0.8$ mainly for simplicity.

Can we identify these two populations with the two FR types? The general properties of these two populations do conform roughly to the characteristics of the two FR types found in the literature (Section 1). Before making a direct correspondence (see Section 6.1), however, it is important to investigate where the class $b$ objects fit in the context of the FR I/II dichotomy.

5.2. Class $b$

The $r_s$ binning in Figures 6–8 for the class $b$ (blue points) is the same as that shown in Figure 4 (right panels); the numbers of RGs in the five bins are (from lowest to highest): 57, 78, 68, 44, and 42. The median redshift slightly increases with $r_s$ (Figure 6, panel j; see Appendix A.1).

Broadly speaking, the class $b$ RGs are typical early-type galaxies in their optical properties (based on, e.g., the color, concentration, and Sersic index). One gets an impression from Figures 6–8 that there is not much variation with $r_s$ for galaxies in class $b$. For example, $r_{\text{eff}}$, $M_{\text{dyn}}$, $\rho$, $\mu$, and 1.4 GHz Eddington ratio all have median values that do not vary much with $r_s$. The most notable systematic variations are that the $(g–r)^{0.1}$ color becomes redder as $r_s$ increases, a positive correlation between $r_f$ and $r_s$, and a negative correlation between the total size of the radio source and $r_s$.

There is considerable overlap in the distributions of various physical properties between the $a_{-0.8}$ and class $b$ RGs. However, the class $b$ objects have slightly higher median $\sigma$, $c$, $\rho$, $\mu$, smaller $r_{\text{eff}}$, lower emission line strength, neighbor counts, radio power and Eddington ratio, and radio-to-optical luminosity ratio. That is, they are more compact and are more quiescent in terms of their nuclear and radio activity. Of the 597 class $a$ objects for which classification of spectral properties using the BPT diagram is possible, 37 (=6.2%) are Seyferts or LINERs. For class $b$, the fraction is only 4/256 = 1.6%.

In Table 4, we list the basic properties of the RGs in our sample.

5.3. Environments of Extended Radio Galaxies

From Figure 8, we see that the $a_{-0.8}$ subset has the highest neighbor counts (median $\Sigma_{0.5} \approx 9.9 \pm 0.6$), while those of class $b$ and $a_{0.9}$ are close ($\Sigma_{0.5} \approx 7.4 \pm 0.6$ and 6.7 ± 1.1, respectively). For reference, for the most luminous galaxies ($M_r^{0.1} \approx −22.77$ to $−24.27$, irrespective of radio properties), $\Sigma_{0.5} \approx 10.8 \pm 1.0$. 

To better understand the environments of these RGs, we further examine their association with galaxy clusters, and calculate their clustering properties. First, we cross-match our RG sample with the clusters found by the maxBCG algorithm (Koester et al. 2007). 704 (= 75%) of our class a and b RGs lie in the footprint and the redshift range (z = 0.1–0.3) of the maxBCG survey. We focus on clusters more massive than ≈ 10^{14} M_\odot, above which the cluster catalog is about ~80% complete. The cluster mass and the virial radius are estimated using the weak lensing-calibrated mass-observable scaling relation from Reyes et al. (2008). Only 13%, 24%, and 14% of the RGs in the a_0.9, a_0.8, and b subgroups are associated (i.e., within one virial radius) with these optically selected clusters.\(^{12}\) However, > 80% of those RGs that are in clusters lie within 20% of the virial radius from the cluster center, consistent with previous findings that RGs are centrally concentrated in clusters (e.g., Ledlow & Owen 1995; Lin & Mohr 2007).

The RGs are mainly hosted in dark matter halos more massive than ~2 × 10^{13} M_\odot (Mandelbaum et al. 2009), so the small fraction of RGs associated with maxBCG clusters suggests that the majority of our RGs must be associated with clusters or groups of mass ≈ (2–10) × 10^{13} M_\odot, a range in which the maxBCG catalog is highly incomplete (Koester et al. 2007). We then resort to the clustering properties of the RGs, which provides some insight into the relative mass scales of halos that host these subsets of RGs. We calculate the cross-correlation functions between the RG subgroups and the general galaxy population, constructed as a volume-limited sample of 73,202 galaxies from the NYU-VAGC DR6 (z ≤ 0.16, M^* \approx -21.77). We select the RGs to satisfy the same redshift and magnitude cuts as well as a lower limit in radio power log P_14 \geq 23.31, which results in 41, 211, and 123 objects for a_0.9, a_0.8, and b subgroups, respectively. The redshift space cross-correlation functions are shown in Figure 9, for a_0.9 (black triangles), a_0.8 (red circles), and class b (blue squares). Although all three subgroups have similar clustering strengths at scales ≥ 200h^{-1} kpc, there is a slight hint of lower clustering amplitude for the a_0.9 objects; if this is confirmed with larger RG samples, this implies the host halos of the a_0.9 subset are on average less massive than the hosts of the other subgroups.

Combining these results, we see that the distributions of host halo mass for the a_0.8 and class b sub-samples are similar at group mass scale, but that of the former must have a higher tail toward clusters (≥ 10^{14} M_\odot). For RGs in groups, the a_0.8 objects must be more centrally concentrated than the class b.

5.4. Radio Loud versus Radio Quiet

So far we have made comparisons among different subsets of RGs. It is important to place them in the context of general diffuse galaxy populations. Furthermore, some of the correlations between the physical properties and r_s may be due to other fundamental correlations of the early-type galaxies that have no physical connection to the radio source. For example, given that optical luminosity and effective radius are tightly correlated in elliptical galaxies (e.g., Shen et al. 2003), an anti-correlation between M_r and r_s would imply a similar anti-correlation between r_eff and r_s (Figure 6). To take out such an effect, for every RG we find up to 10 RG galaxies that have very similar redshift and absolute magnitudes in the 8\,0.1, r\,0.1, and i\,0.1 bands. For all RGs in a given r_s bin, we calculate the average value of the physical property in question from all the matched RG galaxies and subtract that value off from the mean obtained for the RGs (or take the ratio of the two, depending on the nature of the properties). Note that some AGNs (Seyferts and LINERs) may be included in the RG sample, as we do not distinguish truly quiescent galaxies from those that can be regarded as AGNs based on the optical emission line diagnostics.

Figures 10 and 11 show the results as a function of r_s. The comparisons presented in these two figures are between each class and its RG counterparts, not between the two classes. For most of the properties shown in Figure 10 (environments and global galaxy properties), RL galaxies have higher mean values than do the RG ones (e.g., more neighbors, higher mass and velocity dispersion, larger effective radius). The only exception is the central mass density/stellar surface density, for which the a_0.8 subset appears to be less dense than its RG counterparts, mainly due to their larger scale lengths. Figure 11 shows comparisons for some derived quantities of the stellar population and the line measurements. The a_0.8 and class b RGs on average have slightly higher stellar mass, and older stellar age (ΔH\odot = H_\odot - H_\odot < 0), than their respective RG counterparts. Among the class a objects, galaxies in the a_0.9 subset are closest to their RG matches in terms of neighbor counts, r_eff, M_{dyn}, and μ, but show dramatically stronger emission lines and

\(^{12}\) The class a and b RGs only account for < 10% of our full RG sample. The narrow-angle tail objects, whose morphology is believed to be due to the relative motion of the galaxies and the intracluster medium, together with the compact sources (which account for the majority of the sources), are excluded in the current sample. The fraction of all RGs that are cluster members is therefore higher than we have estimated here.

Figure 9. Redshift space RL–RQ cross-correlation functions for the a_0.9 (black triangles), a_0.8 (red circles), and b (blue squares) subgroups. These are calculated using galaxies that form a volume-limited sample (z ≤ 0.16, M^* \approx -21.77; for RGs an additional criterion is log P \geq 23.31). At scales larger than ≈200 h^{-1} kpc, both a_0.8 and class b have similar clustering strength, suggesting that they are hosted by halos of similar mass. The a_0.9 subset might be the result of higher mass, although a larger sample is needed to test this possibility. Some a_0.9 RGs have similar optical properties and likely also similar environment as the other two subsets (see Section 6.1).

(A color version of this figure is available in the online journal.)
Figure 10. Differences between RL and RQ galaxies. Red and blue points denote classes $a$ and $b$, respectively. For every RG, we find up to 10 RQ galaxies that have very similar $M^{0.1}_g$, $M^{0.1}_r$, and $M^{0.1}_i$ magnitudes and redshift; after calculating the mean value of a given physical quantity from all RGs in a given $r_s$ bin, we then take the ratio (or the difference if the quantity is logarithmic) between the mean value of the RGs and that obtained from all the RQ galaxies that are matched to the RGs in question. The left panels, from top to bottom, show the ratio in neighbor counts within 1 Mpc and 0.5 Mpc, the velocity dispersion, Sersic index, and concentration. The right panels, from top to bottom, show the ratio/difference in effective radius, log dynamical mass, log mass density, contribution of the de Vaucouleurs profile to the SB profile (normalized to unity), and the axis ratio. The error bars denote the uncertainties in the mean value.

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

Figure 11. Differences between RL and RQ galaxies. Red and blue points denote classes $a$ and $b$, respectively. The left panels (from top to bottom) show the differences (RL minus RQ) in stellar mass, specific star formation rate, H$\delta$ index, and 4000 Å break strength. The right panels (from top to bottom) show the line ratios (RL divided by RQ) for [O III] and H$\alpha$. See caption of Figure 10 for details of the RL–RQ matching. The error bars denote the uncertainties in the mean value.

(A color version of this figure is available in the online journal.)
sSFR. In contrast, emission lines are weaker for class b RGs than their RQ counterparts. Class b objects also live in environments that are closer to their RQ counterparts than those of class a, and their sizes ($r_{\text{eff}}$) are also more similar.

Let us examine the spectral properties of the RGs in more detail. In Table 3, in parentheses, we list the fraction of the matched RG galaxies that show Seyfert- and LINER-like spectrum. This is useful for evaluating whether the active nucleus fraction is elevated in a given $r_s$ bin. For example, for class a with $r_s > 0.85$, 19.6% of RGs have Seyfert nuclei, while only 1.5% of the matched RG galaxies exhibit the same level of activity. In the same $r_s$ bin, 4.3% (4.9%) of the RL (RQ) galaxies have LINER nuclei. The LINER fraction for class a is roughly independent of $r_s$, and is fully consistent with what is found in the RQ populations, but the Seyfert activity is enhanced by about a factor of 10 in RGs with $r_s > 0.6$ (see also Ivezic et al. 2002).

There is some suggestion that the nuclei of class b galaxies are actually more quiescent than the matched RQ galaxies. For example, there are 2659 RQ galaxies matched to the class b subsample, out of which 84 are LINERs. We thus expect to find about eight LINERs in the 256 class b RGs, but only detect three, which is inconsistent with the Poisson expectation at 99% level (Gehrels 1986).

The differences in the optical spectral features are further illustrated in Figure 12, which shows stacked SDSS spectra of various subsamples of RGs. To make a fair comparison among the three subsets ($a_{0.9}$, $a_{0.8}$, $b$), as well as between RQ and RL galaxies, we select galaxies in three SMBH mass (stellar velocity dispersion) bins, and limit the ranges of dynamical mass and stellar mass surface density to be within 50% of the $a_{0.9}$ locus. These properties are chosen to select RGs of similar central engine, fuel supply, and structure. There are (19, 46, 23) RGs in the lowest mass bin for the $a_{0.9}$, $a_{0.8}$, and $b$ subsets, respectively. In the intermediate and high mass bins, the numbers of RGs are (11, 99, 63) and (11, 71, 40). In the figure, the three columns correspond to the three mass bins (in increasing mass order from left to right); three pairs of panels are shown in each column (from top to bottom: $a_{0.9}$, $a_{0.8}$, $b$). The pair consists of the mean spectra of an RQ subsample and the RQ galaxies of similar $M_{\text{BH}}$, $M_{\text{dyn}}$, and $\mu$ (upper panel) and the differences between the RL and RQ spectra (lower panel). For each $M_{\text{BH}}$ bin, the RQ galaxy mean spectrum is an average over 80 randomly selected galaxies, which are chosen irrespective of their spectral properties, and thus may contain some AGNs (Seyferts and LINERs).

A few points are worth noting from the RL−RQ spectral difference panels. (1) Only $a_{0.9}$ RGs have statistically significantly stronger emission lines than their RQ counterparts. (2) The emission line (particularly [O iii] $\lambda$5007 and H\textalpha) strength decreases as $M_{\text{BH}}$ increases for $a_{0.9}$ objects. (3) In the lowest mass bin, $a_{0.8}$ and class b RGs are redder than their RQ counterparts (based on the difference spectrum); this is not seen in the other bins. In addition, the H\textalpha line is much weaker than that in the RQ galaxies. (4) In each mass bin, $a_{0.8}$ and class b have, to first order, similar difference spectra, indicating their spectra are close to each other.

6. DISCUSSION

In this section, we build upon the observational results presented in the previous two sections to investigate some intriguing questions related to the physical nature of RGs: What is the correspondence between the FR types and the classes $a$ and $b$? Do class $a$ or $a_{0.8}$ objects represent evolutionary sequences? What is the physical origin of various morphologies?

6.1. Three Types of RGs?

Forty-six out of eighty-five $a_{0.9}$ objects have no detectable [O iii] $\lambda$5007 emission line (i.e., the signal-to-noise ratio of the line is less than three). How do they differ from those objects with emission lines? About 75% of $a_{0.9}$ RGs with [O iii] line luminosity $> 10^6 L_{\odot}$ (roughly corresponding to [O iii] Eddington ratio of $> 10^{-7}$) show clear hot spots at the edge of the lobes (giving the impression of a bullet shot into a tenuous medium), while about 2/3 of the $a_{0.9}$ objects without emission lines have HSB spots that show less contrast with the lobes, or have lobes that are not well aligned. It is plausible that the mechanism that creates the emission lines is physically related to the process responsible for the generation of hot spots.

The distributions of many physical properties for the $a_{0.9}$ RGs with and without emission lines are often offset from each other (albeit with substantial overlap). It is the $a_{0.9}$ RGs with emission lines (hereafter $a_{0.9,em}$ objects; Table 2) that make this
subset stand out from the rest of RGs. On the other hand, the \(a_{0.9}\) objects without emission lines share very similar properties with the \(a_{0.8}\) subset; the median values of most physical properties are within 1σ of each other. We may regard them as the same population as the \(a_{0.8}\) subsample, and refer to the combined population, which accounts for the majority of class \(a\) objects, as \(a_{\text{maj}}\) (see Table 2).

We emphasize that the \(a_{0.9,\text{em}}\) objects are still massive galaxies (\(M_r \lesssim M^\ast\)), and that the distinction of this population from the rest of RGs is far less dramatic than the red–blue galaxy bimodality of the general galaxy population (e.g., Baldry et al. 2004).

Since our proposed classification scheme combines both radio morphology and nuclear emission line strength, while previous ones usually rely on one or the other of these criteria (see Section 1), a perfect correspondence between the two is not expected. We also emphasize that our scheme is more quantitative, objective, and reproducible, than are either the FR or OL89 classifications.

Broadly speaking, we can identify the \(a_{0.9,\text{em}}\) objects with HE RGs, and the rest in our sample with LE RGs, with the caveat that some of the \(a_{\text{maj}}\) objects do have strong emission lines (cf. Table 3). Regarding the classification scheme of OL89, the \(a_{0.9,\text{em}}\) subset corresponds to the CD type (mainly because of the high occurrence of hot spots of the former), the \(a_{\text{maj}}\) subset is consistent with the FD type, and class \(b\) coincides with the TJ type. Although the average optical properties of class \(b\) and \(a_{<0.8}\) (or \(a_{\text{maj}}\)) RGs are similar, we regard them as distinct populations, mainly based on the differences in their environment, radio, and nuclear activity.

By definition, the \(a_{0.9,\text{em}}\) objects have \(r_s > 0.8\), and are thus associated with FR IIs according to the original FR definition. A direct correspondence between the FR types and our \(a_{\text{maj}}\) and \(b\) subsets is not possible, however, given that the \(r_s\) distributions for both class \(b\) and \(a_{\text{maj}}\) objects are quite broad (e.g., Figures 6-8). If we have to adopt a dichotomy classification scheme, as advocated by FR and followed by many others, then we may call the class \(b\) plus \(a_{<0.8}\) objects type I, and the \(a_{0.9}\) objects type II.

To summarize, based on the properties of the host galaxies and radio morphology, the radio emission, we suggest there are three groups of RGs in our sample: \(a_{0.9,\text{em}}\), \(a_{\text{maj}}\), and class \(b\). There is no single physical property that can be used to cleanly separate one group from the others. For example, the \(r_s\) distribution of the \(a_{\text{maj}}\) group is quite broad (cf. Figure 3), almost encompassing that of the \(a_{0.9,\text{em}}\) objects at the high-\(r_s\) end. A simple morphological measure such as \(r_s\) is thus only of limited use for classifying extended RGs.

In addition to \(r_s\), we have also explored the use of radio power \(P_{1.4}\) in the classification scheme. Although the ~5% of the RGs with the highest radio power are reasonably separated from the rest in plots like Figures 6-8 (with abscissa replaced with \(P_{1.4}\)), suggesting that selecting via \(P_{1.4}\) can in principle produce a subsample similar to \(a_{0.9}\), we decide to stick with the morphological parameter \(r_s\), as understanding the origin of differences in the radio morphology is one of the main objectives of this paper (see Section 6.4).

We conclude by estimating the abundances of the three morphological groups, using the same volume-limited sample as in Section 5.3 (\(z \lesssim 0.16\) and \(M_B^0 \lesssim -21.77\); for RGs an additional requirement is \(\log P_{1.4} \geq 33.31\)). The abundances relative to all galaxies are \((a_{0.9,\text{em}}, a_{\text{maj}}, b) = (0.034\%, 0.41\%, 0.20\%)\). Among the RGs (irrespective of morphology/extendedness), the fraction of these types are 0.9%, 11.1%, and 5.5%, respectively (see also Table 2).

6.2. Evolutionary Sequences?

The small dependence of the majority of physical properties we have examined on \(r_s\) for the class \(b\) objects prompts the question: are they the same RGs viewed at different stages of evolution? One could imagine that a young RG starts with large \(r_s\) and \(P_{1.4}\) (and smallest total size \(T_p\)) as the jets/lobes advance, \(r_s\) and \(P_{1.4}\) both decrease, while \(T_p\) grows. Such a trend seems to be present in Figure 8. It is important to realize that, however, many such evolutionary sequences (of different combinations of the host galaxy, central engine, environments, etc.) are probably simultaneously present in our sample, and therefore the median behavior of the class (as seen in Figures 6-8) may not reflect any one sequence. To single out an evolutionary sequence, one should therefore only consider RGs of very similar properties (at least those properties that will not change over radio lobe time scales), such as mass, structure, and neighbor counts. We test this idea in Figure 13. The cyan open points are a subset of galaxies in class \(b\) selected to have \(M_{B}^{0.1}, M_{\text{dyn}}, \mu_{\text{em}}, \Sigma_{\text{em}}\),

![Figure 13](image-url)
and $\Sigma_{0.5}$ similar to the median value of the $r_i = 0.2$–0.3 bin. If they can be regarded as an evolutionary sequence parameterized by decreasing $r_i$, we would expect $r_f$ to decrease while $T_p$ increases, which is in rough agreement with the observed trends (of the open points), although we caution that the trends may be somewhat driven by the few objects at larger $r_i$.\footnote{Another caveat is that the surface brightness of the class $b$ objects may decrease rapidly outwards, producing correlations between $r_i$, $T_p$, and $r_f$ similar to that due to an evolutionary sequence for sources close to the detection limit. We thank Philip Best for pointing this out. A larger sample, with careful selection criteria, would be needed to assess the contamination due to this effect.}

Even though their size becomes bigger, their radio power stays about the same, probably due to the fast dissipation of energy in the jets; the outer regions do not contribute much to the luminosity.

We saw in Section 5.2 that there is significant overlap in the distributions of various properties for class $b$ and $a_{<0.8}$ RGs. It is possible that some of the $a_{<0.8}$ RGs represent the later phases of evolution of class $b$ objects. In Figure 13, we show as magenta open squares the $a_{<0.8}$ objects with the same ranges of $M_{\nu}$, $M_{\text{dyn}}$, $\mu$, and $\Sigma_{0.5}$ as the class $b$ objects (cyan points). The most notable trend with $r_i$ is $T_p$. If these subsets of the two classes were related, $r_i$ needs to increase as the sources age. However, the higher typical radio power of the $a_{<0.8}$ objects makes such an evolutionary scenario implausible.

6.3. The P–M Plane Revisited

In Section 4, we noted that RGs in our sample are not separated into two groups in the $P$–$M$ plane via a simple division in $r_i$. With the correspondence between our three subsets and the three morphological groups identified by Owen and co-workers (Section 6.1), could we better reconcile their results with ours?

In Figure 14, the small green dots show all the extended RGs in our sample, and triangles are the $a_{0.9}$ subset. The color bar in this figure represents the $\Sigma_{0.5}$ $P$–$M_{\nu}$ line Eddington ratio (OER). There is a better, although still not complete, separation in the $P$–$M$ plane of the $a_{0.9, \text{em}}$ RGs with relatively higher level of nuclear activity (e.g., OER $> 10^{-5}$), roughly corresponding to $L_{\text{OIII}} > 10^7 L_\odot$ from the rest of the population.

The significant overlaps among the different classes of RGs in the parameters we have surveyed (e.g., $P_{1.4}$, $M_{\nu}^{0.1}$, mass, structure, environment; Figures 6–8) imply that no simple combination of non-radio observables can be used to determine/predict the morphology of the RGs (which may suggest there are many physical processes that determine the radio morphology). It is also possible that the overlap in properties is due to a mixture of RGs at different stages in their evolution, as we argued above.

We suspect the discrepancy between our finding and that of Owen et al.—who stated that the FR I and II RGs could be separated “cleanly” on the $P$–$M$ plane—is due to sample construction. Substantial overlap between the two types is apparent using either our sample or the subsample from Gendre et al. (2010), see Figure 5), both are radio flux limited (see also Best 2009; Wing & Blanton 2010). However, sample selection was quite heterogeneous in some of the earlier works (OL89; Owen & White 1991; Owen 1993), where the main criterion for inclusion was to sample the $P$–$M$ plane as much as possible. In this sense, FR II objects are overrepresented. With samples assembled under better defined criteria (e.g., limited by flux and redshift, restricted to central parts of clusters), some overlap between the two types were seen in Ledlow & Owen (1996).

\footnote{The results are qualitatively the same if we use the $P_{1.4}^{0.7}/\mu$ ratio instead.}

6.4. Origin of Different Morphologies?

The existence of objects whose two lobes exhibit clearly different FR morphologies from each other (“HYMORS” objects; Gopal-Krishna & Wiita 2000) argues that the immediate surroundings of the host galaxies must play some role in shaping the morphology. In addition, analytic models of radio sources suggest that a key quantity in determining the large-scale morphology is the jet power-to-ambient density ratio ($L_j/\rho_a$) of the host galaxies (e.g., Kaiser & Best 2007; Kawakatu et al. 2009 and references therein). Here, $\rho_a$ is measured at the core radius of the host galaxy. Jets from hosts with low values of $L_j/\rho_a$ are more prone to the development of turbulence and become subsonic, resulting in plume-like morphology beyond the deceleration point, while jets from systems with high $L_j/\rho_a$ ratio are strong enough to remain supersonic, leading to the hot spots at the edge of the lobes. Since the jet mechanical power is not directly observable, we assume it is proportional to $P_{1.4}^{0.7}$ (e.g., Cavagnolo et al. 2010 and references therein). We also assume $\rho$ can be regarded as a faithful proxy for the local interstellar medium density in the host galaxies. The median mechanical power-to-total mass density ratio ($\propto P_{1.4}^{0.7}/\rho$) for $a_{0.9, \text{em}}$, $a_{\text{maj}}$, and $b$ is roughly 3.2:2:1, a trend in qualitative agreement with the models. In fact, the median values of $\rho$ for the three subsamples vary only by about 35%, and it is mainly the difference in the radio power that drives the $P_{1.4}^{0.7}/\rho$ ratio.\footnote{The results are qualitatively the same if we use the $P_{1.4}^{0.7}/\mu$ ratio instead.}

We suspect that the accretion rate onto the SMBH is more important than the structure of the galaxy in determining the different radio morphologies (see also Baum et al. 1995; Ho 2008; for discussions on the modes of accretion, see, e.g., Best et al. 2005a; Hardcastle et al. 2007; Kauffmann et al. 2008). At high accretion rates, the primary accretion flow is...
likely a geometrically thin, optically thick disk, which may launch jets that are very well collimated over hundreds of kpc scale. As the accretion rate decreases, the thin disk moves away from the SMBH, and the inner region is occupied by a radiatively inefficient accretion flow (RIAF; see Esin et al. 1997; Narayan 2005), with diminished emission line luminosity. Such an accretion flow is known to create outflows (e.g., Narayan & Yi 1995; Blandford & Begelman 1999), and it is likely that jets so created will not be well collimated (e.g., beyond hundreds of kpc), or are collimated initially, but suffer entrainment and deceleration very early on due to their lower intrinsic power.

If this picture is correct, we may understand the three subsets as follows. First, \(a_{0.9, em}\) objects have the highest SMBH accretion rates (e.g., \(OER > 10^{-6}\)), are powered by classical thin accretion disks with strong, well-collimated jets that can produce strong hot spots, and are usually associated with lower mass galaxies living in less dense environments (with respect to the other subsamples considered here). The \(a_{maj}\) RGs are massive, found in dense environments, and their central engines are likely fed by lower accretion rates (e.g., \(OER < 10^{-6}\)), probably in an RIAF. Finally, those galaxies with low accretion rates and with relatively low \(L_j / \rho_a\) ratio will likely show jet-dominated morphology, making them class b RGs.

To some degree the accretion rate correlates with \(r_s\); variations in the SMBH spin, magnetic fields, the structure of the galaxy, and the density of the intergalactic/intracluster medium, however, may all cause spreads in \(r_s\) at a given accretion rate. It is possible that uncertainties in \(M_{\bullet}\) (inferred from the \(M_{\bullet}-\sigma\) relation) also smear the correlation. About 12% (9%) of the \(a_{0.8}\) (class b) RGs have \(OER \gtrsim 10^{-8}\); while these high accretion rate class b objects may represent earlier phases in evolution of CDs, the active class a RGs with \(r_s < 0.8\) may be manifestations of the variations in \(r_s\) at a given accretion rate mentioned above.

The difference in the accretion rate (and in turn the jet-launching mechanisms) may also explain the spectral properties of the host galaxies (see Figures 7 and 12). For jets created by a thin disk, the “zone of influence” within the host galaxy is quite small (e.g., the jets may only punch two small “holes” in the galaxy), and thus any feedback due to the jets cannot suppress efficiently the star formation activity that may be linked to the onset of the AGN activity. On the other hand, if the jets launched by an RIAF are not well collimated, they may influence a much larger volume of the host galaxy and thus terminate star formation more easily. The most efficient feedback mode (for the host galaxy itself) may be a combination of an RIAF and a dense interstellar medium (or immediate surrounding of the host galaxy), which slows down the jets quickly and creates the class b morphology.

7. CONCLUSION

Extended RGs have been classified based on their radio morphology or nuclear emission line activity. In this paper, we have proposed a hybrid classification scheme that combines both features, and presented a comprehensive study of the host galaxy properties of RGs. Our main objectives are to detect and define distinct populations of RGs, to understand the traditional FR type I/II dichotomy in the context of our new scheme, and to unravel the origin of different radio morphologies. Our RG sample consists of 1040 objects selected with 1.4 GHz radio flux density \(f_{1.4} \geq 3\) mJy, \(\nu^{0.1}\)-band absolute magnitude \(M^{0.1}_r \leq -21.27\) (i.e., more luminous than \(M^{*}\), the characteristic magnitude of the galaxy luminosity function), radio angular diameter \(T > 30^\prime\), physical size \(T_p > 40\) kpc, and at \(0.02 \leq z \leq 0.3\). All of the RGs in our sample appear to be massive early-type galaxies.

We use the \([O\,III] \lambda 5007\) line luminosity as an indicator of the nuclear emission strength, and use a parameter \(r_s \equiv S / T\) as a continuous parameterization of the RG radio morphology. Here, \(T\) is the total size of the radio sources, and \(S\) is the separation between the HSB spots on either sides of the galaxies. Roughly 60% of our objects show HSB spots on both sides of the host galaxy; we refer to these as class a RGs. About 30% of the sources appear to have prominent jets, with HSB spot coincident with the host galaxy. We call this population class b (see Figures 1 and 2; Table 1).

Our main results are as follows.

1. The distribution of \(r_s\) is bimodal (Figure 3), although we argue that the two peaks do not correspond to the two FR types (Sections 3 and 5).

2. Among the class a objects, a small population with high values of \(r_s \gtrsim 0.8\) and high \([O\,III] \lambda 5007\) line luminosity (\(L_{[O\,III]} > 10^{20} L_\odot\)) seems to be distinguished from the rest, in the sense that on average they are hosted by lower mass galaxies, live in relatively sparse environments, and have higher accretion rates onto the central SMBH, as manifested by the \([O\,III] \lambda 5007\) line Eddington ratio (Section 5.1; Figures 6–8). We refer to these RGs as the \(a_{0.9, em}\) subset, and the rest, the majority of class a, as the \(a_{maj}\) subset (Table 2). The distribution of \(r_s\) for the \(a_{maj}\) objects is quite broad, encompassing the range occupied by the \(a_{0.9, em}\) RGs at the high-\(r_s\) end. A simple morphological measure such as \(r_s\) is thus only of limited use for classifying extended RGs.

3. The average properties of \(a_{maj}\) and class b RGs, such as the optical luminosity, stellar mass, 4000 Å break strength, and velocity dispersion, differ by 20% or less from one another. However, because of the differences in the environments (e.g., characterized by the neighbor counts within 0.5 Mpc; Figure 8, panel b) and the (nuclear) emission line properties (Figure 8, panels g and h; Table 3), we regard them as distinct populations (Sections 5.2 and 5.4).

4. Among the three subsamples (\(a_{0.9, em}, a_{maj}, b\)), galaxies in class b have the lowest Eddington ratio and radio power, and their nuclear and/or star formation activity even appears to be suppressed relative to the RG galaxies that have similar luminosities and mass (Section 5.4; Table 3).

5. Different researchers usually have adopted somewhat different definitions for the FR I/II types. As our proposed classification scheme is based on both radio morphology and nuclear emission line strength, and the original FR scheme is purely morphology based, there is no one-to-one correspondence between the two. Nevertheless, given the similarities of class b and class a objects with \(r_s \lesssim 0.8\), and the large difference between these subsamples and the class a RGs with \(r_s > 0.8\) (Section 5.1), we can broadly identify the FR I type with the former and FR II with the latter sources (see the discussion in Section 6.1). However, there is considerable overlap in the distributions of physical properties for the three subsamples, and the transition from one FR type to the other is far from sharp (Sections 4 and 6.3). In particular, our findings do not support the previous claim that the two FR types occupy distinct regions in the radio luminosity–optical magnitude plane.

6. Although on average the \(a_{0.9, em}\) objects are less massive than the other RG subsamples, they are still hosted by massive galaxies \((M_r^{0.1} \lesssim M^{*})\). The distinction of this
subset from the other RGs is far less dramatic than the blue–red bimodality of the general galaxy population.

7. To single out $r_{90, em}$ from the rest of the population in a statistically complete, low-redshift RG sample for which optical emission line measurements are not available, a possible approach is to select sources with $r_S$ ranked in the top 10% of the distribution.

8. Some of the objects in class $b$ may form an evolutionary sequence, that is, they can be regarded as RGs seen at different stages of evolution, as evidenced by an anti-correlation between size and $r_S$ (Section 6.2; Figure 13). A larger sample is needed to evaluate the effect of systematic uncertainties in the sample selection, however.

9. Many different mechanisms must be at work for the generation of radio jets, but we suggest that the accretion rate onto the SMBH is the main driver for the different radio morphologies, with host galaxy structure and/or density of the surrounding environment playing a secondary role. This is primarily motivated by the stark differences in the nuclear emission properties of the RG subsets. At high accretion rates (e.g., $[O\,\text{III}]$ λ5007 line Eddington ratio $> 10^{-6}$), the accretion mode is likely dominated by a geometrically thin, optically thick disk which could generate powerful, well-collimated jets that create strong hot spots at the edge of the lobes (i.e., the “classical double” morphology). At lower accretion rates, an RIAF takes over; the outflows/jets from such accretion flows may not be as well collimated beyond the galactic nucleus scale, resulting in the “fat double” morphology (i.e., without obvious hot spots at the edge of the lobes). At slightly lower accretion rates (e.g., $[O\,\text{III}]$ Eddington ratio $\lesssim 10^{-7}$) and for galaxies with sufficiently high galactic density, a jet-dominated morphology is created (Section 6.4).

10. Based on the spectral properties of the galaxies, we suggest that outflows/jets from an RIAF may be more efficient in suppressing processes that cause star formation and/or nuclear activity than the jets from thin accretion disks. The latter could affect the large-scale surroundings of the RGs, however (Section 6.4, Figure 8).

The advent of wide-field, uniform radio and optical surveys such as NVSS, FIRST, and SDSS makes it possible to produce the large RG sample used here, and the classification scheme we propose. Although it is not clear if our scheme is more physically motivated than the existing ones (e.g., those of FR and OL89), our classification should be among the most objective and quantitative, and easily reproducible by other researchers.

In this study, we have only concerned ourselves with the extended sources with relatively “straight” lobes, that is, we have excluded wide-angle tail and NAT objects. We have also left out the compact/point-like sources and radio quasars in the analysis. In a future publication, we will compare the host properties of RGs of these other morphologies, which may provide further insights into the generation of the radio emission in galactic nuclei.

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This research has made use of the NED database, the data products from the NVSS and FIRST surveys, and the Aladin sky atlas. The extensive support from the CDS helpdesk is much appreciated.

**APPENDIX**

**APPENDIX A.1**

**RESOLUTION OF FIRST IMAGES**

Part of the SDSS Stripe 82 has been observed with the VLA in the A configuration (1.5 FWHM) at 1.4 GHz, reaching rms $\sim 0.07$ mJy beam$^{-1}$. Fifteen RGs in our sample lie in the region covered by this deep survey$^{17}$ (PI: G. Richards; Hodge et al. 2010, in preparation). Their redshifts range from 0.04 to 0.25, which is representative of our sample (Figure 6, panel j). We compare the $S$ and $T$ measurements from these data with those from FIRST (hereafter with the subscripts $V$ and $F$, respectively). Among the 15 objects, 5 are in class $b$. For the 10 class a RGs, the ratio $S_V/S_F$ has a mean of 0.95 and a scatter of 0.15. We also find that the total size measurements are very close, which suggests that the $r_S$ value derived from FIRST is robust against resolution issues.

For four of the class a RGs, the HSB coincides with prominent jets in the host galaxy in the deep VLA images, and are classified as class $b$ or $c$, depending on the central-to-total flux ratio (Section 3). We note, however, that some of the flux from the lobes is resolved out in these A-array maps, and therefore ideally one should combine both the high- and low-resolution data to measure the proportion of flux that is in the jet component which only shows up in high-resolution maps. These objects tend to have $r_J$ values higher than the majority of the class a RGs, based on FIRST data; that is, FIRST does detect the central component. Because of the poorer angular resolution of FIRST, the jets are not as prominent as in the A-array maps.

For the current analysis, we acknowledge the possibility that some of our objects which we have put into class a may in fact belong to class $b$ if measured with better data. Using the distribution of (FIRST-based) $r_S$ and $r_J$ of the above four class

$^{17}$ http://www.physics.drexel.edu/~gtr/vla/stripe82/
$a$ RGs, we estimate that 13% of class $a$ objects may be subject to this misclassification.

Although the redshift distribution for class $a$ is quite consistent across the $r_s$ bins, class $b$ RGs with higher $r_s$ are on average at slightly higher redshift (Figure 6, panel j). Given the inherent sensitivity of the classification on the resolution, this is perhaps not surprising. For the five class $b$ objects with deeper, higher-resolution VLA data, two have $r_s \approx 0.5$ based on FIRST, and have redshift of 0.224 and 0.252, respectively. At three times finer resolution than FIRST, these RGs remain jet dominated (i.e., class $b$), although their $r_s$ decreases. Given that the properties of class $b$ objects do not vary much with respect to $r_s$, we conclude that our results for class $b$ should be robust (except for the possible addition of class $a$ RGs with better measurements).

**APPENDIX A.2**

**MEASUREMENT OF TOTAL SIZE**

We have the option of using either NVSS or FIRST data to measure the total size $T$ of the radio sources, and have chosen to use the latter as the default (except for the 41 cases where the FIRST-based sizes are much less than those from NVSS, presumably due to the insensitivity of FIRST to diffuse emission; see Section 3). We have repeated our analysis with NVSS-based $T$ measurements. If the fitted size of the major axis of radio sources from NVSS is only an upper limit, we exclude the sources from the sample; in addition, a minimal size of $T = 50''$ (rather than $T = 30''$ as adopted in Section 3) is imposed, and therefore the sample size (797 RGs) with NVSS-based measurement is smaller.

Variations of physical properties as a function of $r_s$, analogous to Figures 6–8, are shown in Figures 15 and 16, for both FIRST-based and NVSS-based results. The main difference is in the total size $T_p$ of the sources (Figure 16, lower left panel): those derived from NVSS are larger than the ones based on FIRST, as expected. Since $S$ is still measured using FIRST data and thus remains unchanged, the NVSS-based $r_s$ values are systematically lower than the FIRST-based ones; any trends with $r_s$ seen in Figures 6–8 would therefore appear “stretched” horizontally and shifted toward low $r_s$ a bit.

Using NVSS-based $T$ measurements, we still find that class $a$ objects with the highest $r_s$ stand out from the rest of the sample, although the division is now at $r_s \approx 0.7$. The subtle difference in properties between class $b$ and class $a$ RGs with $r_s < 0.7$ also remains.

A possible concern of using either NVSS or FIRST to measure $T$ is the relatively high SB limits of these surveys. One could imagine that an FD source with HSB spots far from the edge of the lobes would appear as high-$r_s$ objects if observed with insufficient depth. We have checked against the NASA/IPAC Extragalactic Database (NED) to look for archival radio images for our $a_{0.9}$ objects. Only eight RGs ($\sim 10\%$) have been imaged with decent data from the literature, and all of them would still have high $r_s$ in those deeper maps. Even if such a bias due to the depth of the surveys exists, we suspect the difference in morphology between a bona fide hot spot at the edge of a lobe and an HSB region within a lobe for lower-$r_s$ RGs would be obvious enough in FIRST images so that a visual inspection would be able to pick up such cases.

We noted in Section 6.1 that the combination of the presence of hot spots at the edge of the lobes and the high accretion rate as indicated by the presence of emission lines seems to be a pretty robust indicator for the type of RGs corresponding to FR II, or the CDs. Since $r_s$ is unfortunately somewhat resolution dependent, and emission line properties in the optical are not always easily available, perhaps a more objective approach to
Figure 16. Similar to Figure 8, but showing median results with $T$ derived from NVSS (magenta and cyan triangles) and those with $T$ from FIRST (red and blue points). For class $b$ RGs (blue and cyan points), we plot the results with negative values of $r_s$ to avoid cluttering the figure. (A color version of this figure is available in the online journal.)

single out CDs from the rest of the population in a statistically complete, low-redshift RG sample (so that our results are fully applicable) is to select sources with $r_s$ ranked in the top 10% of the distribution.

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