Radio Properties of Low Redshift Broad Line Active Galactic Nuclei Including Extended Radio Sources

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ABSTRACT

We present a study of the extended radio emission in a sample of 8434 low redshift (z < 0.35) broad line active galactic nuclei (AGN) from the Sloan Digital Sky Survey (SDSS). To calculate the jet and lobe contributions to the total radio luminosity, we have taken the 846 radio core sources detected in our previous study of this sample and performed a systematic search in the Faint Images of the Radio Sky at Twenty-centimeters (FIRST) database for extended radio emission that is likely associated with the optical counterparts. We found 51 out of 846 radio core sources have extended emission (> 4'') from the optical AGN that is positively associated with the AGN, and we have identified an additional 12 AGN with extended radio emission but no detectable radio core emission. Among these 63 AGN, we found 6 giant radio galaxies (GRGs), with projected emission exceeding 750 kpc in length, and several other AGN with unusual radio morphologies also seen in higher redshift surveys. The optical spectra of many of the extended sources are similar to that of typical broad line radio galaxy spectra, having broad H α emission lines with boxy profiles and large M_{BH}. With extended emission taken into account, we find strong evidence for a bimodal distribution in the radio-loudness parameter $\mathcal{R} (\equiv \nu_{\rm radio} L_{\rm radio} / \nu_{\rm opt} L_{\rm opt})$, where the lower radio luminosity core-only sources appear as a population separate from the extended sources, with a dividing line at $\log(\mathcal{R}) \approx 1.75$. This dividing line ensures that these are indeed the most radio-loud AGN, which may have different or extreme physical conditions in their central engines when compared to the more numerous radio quiet AGN.

Subject headings: galaxies: active – galaxies: nuclei – galaxies: Seyfert – radio continuum: galaxies

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1. Introduction

It is not uncommon to find a particularly radio luminous active galactic nucleus (AGN) classified as a broad line radio galaxy (BLRG), a quasar, and a Fanaroff & Riley (1974) class II object (an FR II's radio emission is lobe-dominated and edge-brightened, whereas an FR I is jet-dominated and edge-darkened). Generally, an AGN's classification can depend on many factors such as when and in what part of the spectrum it was first discovered, which particular study it is being used in, and the source of the data. Moving beyond an often blurred and overlapping system of identification into one based on more quantitative parameters could allow a more continuous classification scheme that is easier to apply to the large samples that continue to become available with large area surveys, e.g., in the radio (VLA's FIRST survey), infrared (2MASS), optical (SDSS), and X-ray (ROSAT) bands. The AGN in these large samples can now be classified based on measured quantities in a statistical fashion that is inherently more continuous than the discrete nomenclature generally used (e.g., Kewley et al. 2006).

All AGN are believed to be powered by the accretion of matter onto a supermassive black hole (SMBH), and show strong emission and variability in all wavebands from the radio to X-ray regimes. Although not a fundamental physical parameter, the inclination of the BH/accretion disk system to our line of sight is an observational parameter that, according to accepted unification models, is responsible for the presence or absence of permitted broad lines (BL) (in type 1 and type 2 AGN, respectively) in optical spectra due to toroidal obscuration by gas and dust when viewed at large inclination angles (Antonucci 1993; Urry & Padovani 1995). Typically we assume that BL AGN have lower inclinations to our line of sight and we are looking down onto the BL region (BLR) clouds that lie just outside the immediate vicinity of the BH and accretion disk system.

An important fundamental parameter is black hole mass (M_{BH}), which has been determined directly through various methods including H₂O-maser observations and reverberation mapping (RM) (e.g., Moran et al. 1995; Peterson et al. 2004). RM becomes a powerful tool when applied to large spectroscopic samples in that the scaling relations derived from RM analysis allow single epoch (single spectra) M_{BH} determinations for BL AGN (e.g., Kaspi et al. 2000, 2005; Bentz et al. 2009). Another important parameter, the Eddington ratio, is the ratio of the bolometric luminosity (L_{bol}) to the Eddington luminosity ($L_{Edd} \propto$ M_{BH}). Determination of the true L_{bol} gives a measure of the accretion rate and requires a full spectral energy distribution (SED) that spans from radio to X-ray emission and beyond for most AGN. AGN that have an observed SED that spans the entire spectrum provide normalization relations so that one can use a single continuum measurement in the optical or X-ray bands to stand in as a reasonable proxy for L_{bol} (e.g., Elvis et al. 1994, 2002; McLure & Dunlop 2004).

The degree of radio-loudness is another means by which to classify AGN, and is based on the amount of radio emission in the form of core emission, jets and/or lobes that can be positively associated with the central engine and accretion phenomenon. There are two main characterizations of the radio-loudness of AGN. The first is to set a dividing line between radio-loud (RL) and radio-quiet (RQ) based on the \mathcal{R} parameter defined as the ratio of the monochromatic 5 GHz radio luminosity to the 4400 Å optical luminosity $(\nu_{5GHz}L_{5GHz}/\nu_{4400}L_{4400})$. By convention, RL AGN have $\mathcal{R} > 10$ and RQ AGN have $\mathcal{R} < 10$ 10 (Kellermann et al. 1989). The second way to characterize the degree of radio-loudness is by using the radio luminosity alone. Fanaroff & Riley (1974) originally found a transition from the FR I type radio morphology to the FR II type corresponding to a luminosity of $10^{24.5}$ Watts Hz⁻¹ at 1.4 GHz (Kawakatu et al. 2009). While this luminosity is not a RL/RQ dividing line, the distribution in the radio luminosity plane shows that most FR Is have luminosities below this dividing line and FR IIs have luminosities above. However it is well established that many FR Is are RL when following the classic \mathcal{R} convention. Therefore a lower luminosity dividing line has occasionally been used as an alternate way to classify AGN as either RL or RQ; e.g., Best et al. (2005) specify 10^{23} Watts Hz⁻¹ to be this division for FIRST data at 1.4 GHz.

A quasar radio dichotomy has been postulated because only 5% - 10% of all AGN are RL according to the $\mathcal{R} > 10$ criterion (Kellermann et al. 1989; Urry & Padovani 1995; Ivezić et al. 2002; White et al. 2007). This has led to claims that there is a bimodal distribution in the \mathcal{R} parameter for high optical luminosity, high redshift sources (Laor 2003; Ivezić et al. 2004, and references therein), where usually only the core radio emission is taken into account. While the RL AGN are usually thought to be powered by the same phenomenon of matter accreting onto a SMBH, it has been suggested that they may have a different accretion mode, e.g., advection dominated accretion flow (Narayan & McClintock 2008) versus a standard thin disk, or that their BH's are more massive or spinning faster, or some combination of both (e.g., Sikora et al. 2007, and references therein). Other models propose that powerful jets tap the spin energy of the BH (e.g., Blandford & Znajek 1977) so the accretion rate is nearly irrelevant. Either case suggests that \mathcal{R} , although not a fundamental quantity, may be linked to one. Very often the most extreme RL AGN are FR II types that have giant radio lobes that grow and extend from the host galaxy out to Mpc scales while being fed by highly collimated jets. Statistically, these AGN are associated most often with giant elliptical galaxies that tend to have optical spectra with very broad Balmer line (H α , H β) profiles with a large full widths at half maximum (FWHM), typically > 8000 km s⁻¹ (Osterbrock & Ferland 2006). In studies of high redshift, high luminosity AGN, it has generally been thought that most RL AGN have M_{BH} > 10⁸ M_{\odot} (e.g., Laor 2000; McLure & Jarvis 2004). This clearly manifests itself for most FR IIs when determining M_{BH} from single epoch measurements, since generically, M_{BH} \propto FWHM²_{H α}L^{0.5} (e.g., Bentz et al. 2009).

It has been shown in studies by Ho (2002) and Sikora et al. (2007) that there is a strong correlation between radio-loudness and Eddington ratio, where AGN with very low accretion rates (corresponding to ~ 10^{-5} L_{bol}/L_{Edd}) are almost exclusively all RL based on the \mathcal{R} parameter, and a clear trend can be seen of decreasing radio-loudness with increasing L_{bol}/L_{Edd}. Further, Sikora et al. (2007) find two separate populations of AGN in the \mathcal{R} vs L_{bol}/L_{Edd} plane, where the upper population consists of FR Is, BLRGs and RL quasars hosted by giant elliptical galaxies, and the lower population are mostly Seyfert and Low Ionization Nuclear Emission-line Region (LINER) types hosted by spiral galaxies. While these studies do show a dependence of radio-loudness on accretion rate, they do not exclude the possibility that there may be other factors that contribute to the generation of strong radio emission, such as accretion modes which are directly related to the amount of matter in the accretion disk, or the spin of the SMBH.

In Rafter, Crenshaw & Wiita (2009) (hereafter Paper I), we investigated these issues with the low-redshift sample of broad line AGN from Greene & Ho (2007), which was not selected on the basis of any radio property. We found no clear gap between RL and RQ AGN, and provided evidence for a significant radio-intermediate population in the local Universe. Using the above definition, we found that 4.7% of the AGN in a flux-limited subsample were radio loud ($\mathcal{R} > 10$). We also found evidence that the radio-loud fraction (RLF) decreases with Eddington ratio, in agreement with the above findings. Finally, we found a significant number of RL AGN with $M_{BH} < 10^8 M_{\odot}$, which indicates that RL AGN are not a product of only the most massive black holes in the Universe.

In this paper, we reexamine our sample to study the extended radio emission (> 4" from the optical AGN). We investigate the FR I/FR II luminosity break and its relation to the claimed bimodal distribution in radio loudness. We also identify a number of unusual radio morphologies for future detailed study. Finally, we compare these new results to those in Paper I, where only the core emission was taken into account when calculating L_{radio} .

2. Data Sample and Analysis

As discussed in detail in Paper I, we have taken the BL AGN sample from Greene & Ho (2007), who calculated M_{BH} and L_{bol}/L_{Edd} from the full width at half maximum of the broad H α line (FWHM_{H α}) and the luminosity of H α (L_{H α}) for 8434 BL AGN from the Sloan Digital Sky Survey (SDSS) Data Release 4 (DR4). We performed a follow up search for these objects using the 2008 April version of the Very Large Array's (VLA) 1.4 GHz Faint Images of the Radio Sky at Twenty-centimeters (FIRST) survey database (Becker et al. 1995). The FIRST survey operates at a frequency of 1.4 GHz, has an angular resolution of $\sim 5''$ and a limiting magnitude of 1 mJy. Ivezić et al. (2002) find that 90% of all SDSS/FIRST matched AGN only show radio emission at, or close to, the optical source using a 1".5 search radius. Many of these 'core' sources only appear to be compact or unresolved, meaning that detailed structure on scales < 5'' will not be resolved due to the modest angular resolution of the FIRST survey. Such unresolved cores could be arising from orientation effects, where the radio jet is closely aligned with our line of sight, or they could be fairly young radio sources whose emission has not had time to expand out to a significant distance from the host galaxy. Therefore AGN with unresolved features, whether FR I or FR II type, will appear as core-only sources in this sample.

This paper follows our earlier paper in which we used a 4'' search radius to identify radio sources associated with the optical AGN in this sample and where we showed this leads to very few false radio detections with an optical counterpart. We find that of the 8434 objects, 846 have core radio sources inside this radius (we note that this number is updated from Paper I, where we found 832 objects using the 2003 April 11 version of the FIRST catalogue). In the study of Paper I, only the core radio emission was taken into account in order to compare that work with other studies (mentioned above) at higher redshift. In this work, we have first taken these AGN with radio core emission and performed a search around a much wider, 60'' radius, to identify any extended emission (at positions > 4" from the optical AGN) that may be associated with them. The 60" search radius was chosen due to the fact that the largest known FR IIs are on the scale of a Mpc (Saripalli & Subrahmanyan 2009, and references therein), and at the sample redshift limit of z = 0.35, a 60" search radius corresponds to nearly 1 Mpc in diameter. All extended sources were visually inspected in the SDSS and FIRST images to give us confidence that the radio emission is associated. This does not mean that any clearly associated emission out past 60" was not included. but that any associated emission out past 60'' was added to the total by hand after visual inspection of the FIRST images.

In order to confirm the association of extended emission with the optical counterpart

it is first necessary to make sure that the extended emission is not associated with another optical source in the field. The majority of cases where this takes place is when there is one core source within 4" and a second radio source within 60", and where the second source is at the same position as another galaxy in the SDSS image. Therefore, any FIRST sources found in the extended search with obvious optical counterparts in the SDSS images were eliminated as possible extended source matches (e.g., SDSS J094603.94+013923.6 is a BL AGN misclassified as a star in SDSS DR7 with a resolved spiral galaxy to the north that is the likely the source of the extended radio emission).

The criteria used to confirm the association of the extended emission to the central optical source are illustrated in Figure 1, where the center of each image is the SDSS optical AGN position and the linear scale is given below it. In Figure 1, the sources a-e were all found to have core emission in Paper I. In Figure 1a (top left) we show the radio map of SDSS J170013.70+400855.6, which has a core-source with a nearby (~ 35 kpc projected distance) knot of radio emission. There is also a possible lobe to the south-west that is below the flux limit of FIRST. The association is based on the fact that the second emission region is close to the host galaxy and there is no optical source at or in the vicinity of the extended emission. The sources that had only two emission regions turned out to be the most numerous, and most were associated in this fashion. In Figure 1b we show the radio map of SDSS J122011.89+020342.2. Here the association is based on the physical connection of several emission knots in the eastern jet to the core-source, and to a somewhat distant $(\sim 275 \text{ kpc projected distance})$ faint lobe to the west. In Figure 1c we show the radio map of SDSS J132834.14-012917.6. The association is based on the alignment of the very distant lobes (both are ~ 500 kpc projected distance) with the radio core emission along with clear trails of radio emission back to the core. There are several variations of this type, such as those having small bending angles (usually less than $\sim 15^{\circ}$) between the distant lobes, as shown in Figure 1d. In Figure 1e we show the radio map of SDSS J091401.76+050750.6. The association is based on the distant southern lobe (~ 400 kpc projected distance) having a hot spot and lobe emission structure that points back to the core radio emission. This object may in fact have an additional lobe source to the north that is just outside of the image. However, this was not added to the total radio emission due to the fact that association at that distance is not guaranteed without the other criteria being met. In this case, the exclusion of this 'could-be lobe' has very little effect on the conclusions due to the fact that it is very dim and the added emission would have been only 4% of the total. After visual inspection of all possible matches, we believe that there are very few false positives (no more than 2 radio sources outside 4'' but inside 60'' that are not associated with the optical and radio core) in this search when the objects with < 4'' separation between radio core emission and optical position are selected.

We find 51 (6% of the original radio core emission sample and 0.6% of the total sample) AGN with extended emission that must be taken into account when calculating the total AGN radio luminosity. Of these 51, we find a large range in the amount of extra emission that is picked up. Some objects have a bright core and one dimmer lobe (~ 10%-50% in added radio emission), but we also find bright FR IIs that have total integrated fluxes in the 1000 mJy range (~ 100%-600% in added radio emission). In order to characterize the amount of flux added due to extended emission, we show in Figure 2 the fraction of extended flux added with respect to the initial core emission. About half of the sources lie in the 0.01 – 2 range, showing that nearly half of the sources add only a small fraction and up to twice of the core flux to the total, while the other half of the sample at least doubles the amount of flux added to the core, and the brightest source adds nearly 70 times more emission when compared to the core.

We performed a second search using the entire optical sample to find possible FR II types in which radio emission is only seen from lobes but there is weak (below the 1 mJy flux limit of FIRST) or no core radio emission. The largest group found in this search has just one single radio source that is within 60". After visual inspection, usually there is another optical source matched to the extended radio source. Even when there is no such alternative optical identification it is not possible to claim an association since there is no discernible jet to lobe connection or double lobe symmetry that would be excellent indications of association. Most of these were rejected outright. We do however find an additional 12 objects (not included in the 51 AGN discussed above) that have significant flux inside the 60'' search radius, but no core emission inside 4", that can be positively associated with the optical source. All of these were visually inspected to ensure that the radio emission was not associated with another optical source in the field and any clearly associated emission at distances > 60'' was taken into account and added by hand to the total radio flux. The criteria for establishing association for these objects is the alignment of two sources of emission out past 4'' with the optical source (having no detected radio core), as shown in Figure 1f for SDSS J091519.56+563837.8. We do note that any sources with radio lobes that have significant bending angles would not satisfy our alignment criteria, and some true associations may be excluded due to this effect.

3. Results: Properties of the Extended Sources

Table 1 lists the SDSS name of all 63 AGN with extended radio emission along with their redshifts, projected physical extent and a 'by eye' classification of the radio morphology based on FIRST images. There are 22 sources with no previous radio identification in the NASA extragalactic database (NED) from other radio surveys and they therefore have no radio catalogue source name in Table 1. The radio classification column makes use of the 'giant radio galaxy' (GRG) classification, where the total projected linear extent exceeds 750 kpc (Saripalli & Subrahmanyan 2009, and references therein), and the hybrid morphology radio sources (HYMORS) classification, where an FR II lobe is seen on one side and an FR I jet is seen on the other side of the central source (Gopal-Krishna & Wiita 2000). We also classify X-shaped radio sources (e.g., Gopal-Krishna et al. 2003), where a possible reorientation of the jets has taken place to feed two individual sets of lobes, and the double-double morphology (DDRG) where interruption of the jets can cause two distinct sets of lobes to form throughout the lifetime of the AGN, where the first and older set is at a larger distance than the second, younger pair (e.g., Schoenmakers et al. 2000). Table 2 summarizes the morphologies of the extended sources; the 'indeterminate' designation is given to sources that were unresolved in the FIRST images.

We used the usual flux-luminosity relation with the same cosmology used by Greene & Ho (2007) from Spergel et al. (2003) (H₀ = 71 km s⁻¹ Mpc⁻¹, $\Omega_{\rm m} = 0.27$, and $\Omega_{\Lambda} = 0.73$) to calculate the total radio luminosity for each source. From these new data, we update the $\mathcal R$ values of the radio detected sample following Paper I, including all associated extended emission. Since the optical sample is the same, those properties are unchanged. We also break the sample into subsamples as in Paper I. The 'detected sample' consists of all AGN with radio emission, and contains the core-only sources and the extended sources. The 63 extended sources are all RL (i.e., all have $\mathcal{R} > 10$) with the exception of one ($\mathcal{R} = 2.39$) that is a face-on spiral galaxy (SDSS J220233.84-073225.0) with a modest $L_{H\alpha} = 10^{42.01}$ ergs s^{-1} , but a very low flux radio core ($F_{int} = 2.36 \text{ mJy}$) with an even fainter 'lobe' ($F_{int} = 0.97$ mJy) offset by 10".5. We find that of the 793 remaining core-only sources, 383 are RL and 410 are RQ, based on \mathcal{R} . The 'flux limited sample' is explicitly defined in Paper I and has 5485 total objects, using an upper limit of 1 mJy for all AGN without radio detections as an optical flux cutoff. For the flux limited sample we find that 4.9% (270/5485) of the AGN are RL compared to the 4.7% (259/5485) found in Paper I when extended emission was not taken into account.

In order to determine how the extended sources differ from the rest of the sample we first compare the optical properties of the different subsets, namely the core-only sources, the extended sources and the total flux limited sample. In Figure 3 we show the FWHM distributions of the broad component of the H α line (FWHM_{H α}) for the extended, core-only, and non-radio detected sources in the flux limited sample, where all are normalized by the number in each group. The extended source distribution has an average FWHM of 5010 km s⁻¹ and the core-only sources have an average FWHM of 3550 km s⁻¹. The peak

of the distribution for the extended sources is at ~ 4500 km s⁻¹ and is shifted to higher FWHM values by about 2000 km s⁻¹ when compared to the core-only sources, that peak at ~ 2500 km s⁻¹. Both histograms have long tails that fall off at about the same rate toward higher FWHMs. A K-S test between the core-only source distribution and the extended source distribution yields a probability value of 1.2×10^{-5} and a maximum difference of 0.35, showing that it is extremely likely these two distributions are from different parent populations. A K-S test between the core-only sources and the non-radio detected sources yields a probability value of 0.077 and a maximum difference of 0.05, meaning that the two have similar enough cumulative distribution functions that they may well be from the same parent population. Visual inspection of the optical spectra shows that many of the extended AGN have characteristically wide H α profiles. This is consistent with the claim that most BLRGs have intrinsically large M_{BH} (Laor 2003; Dunlop et al. 2003; Chiaberge et al. 2005). This result is of course favored when calculating M_{BH} based on single epoch M_{BH} relations, where M_{BH} \propto FWHM², but a large M_{BH} determination is not always guaranteed since this relation also depends on the optical luminosity of the central source (M_{BH} \propto FWHM²L^{0.5}).

The next optical property we compare between the radio types is the H α luminosity (\propto L₅₁₀₀). The histogram in Figure 4 shows the normalized distributions for the extended, coreonly, and non-radio detected sources in the flux limited sample. We find that the extended source distribution is shifted to higher L_{H α} by about 0.5 dex when compared to the core-only distribution, but overall the full distributions have similar peak values and show significant overlap. More precisely, the extended sources have an average L_{H α} = 10^{42.7} ergs s⁻¹ with a standard deviation of 0.60 dex, and the core-only sources have an average L_{H α} = 10^{42.3} ergs s⁻¹ with a standard deviation of 0.68 dex. A K-S test comparing the extended sources and the core-only sources yields a probability value of 1.4 ×10⁻⁴ and a maximum difference of 0.32 indicating that these two distributions may well be from different parent populations. In the context of M_{BH} determinations, somewhat similar L_{H α} distributions but systematically higher FWHM distributions should give larger M_{BH} estimates for the extended AGN when compared to the core-only sources. This turns out not to always be the case, since our extended sample has 36 sources with M_{BH} < 10⁸ M_{\odot} and 27 sources have M_{BH} > 10⁸ M_{\odot}.

The normalized distribution of 1.4 GHz radio luminosity $(L_{1.4GHz})$ is shown in Figure 5 for the flux limited sample. The peak of the extended sources is shifted to higher luminosities by a factor of 100 when compared to the core-only sources. This is not surprising given the high luminosities of FR II lobes. Looking at the region of overlap we find that there are few sources in these normalized distributions in the $10^{24.5}$ Watts Hz^{-1} region, where the deficit of sources is at the FR I/FR II transition luminosity originally found by Fanaroff & Riley (1974); see also Kawakatu et al. (2009). This is important for the $log(\mathcal{R})$ histogram shown in Figure 6. In the top plot we show the core-only and extended source histograms normalized by the number in each group. The normalization is useful since there are many fewer extended radio sources, making this trend in the unnormalized histogram not as obvious. Here we find what looks like two separate populations, or an apparent bimodality, in that the extended sources peak at $\log(\mathcal{R}) \approx 2.5$ whereas the core-only sources peak at about $\log(\mathcal{R}) \approx 0.75$. This can be explained by the fact that most of the extended sources have much higher radio luminosities compared to the core-only sources, but not much higher H α luminosities, causing the shift of extended sources to higher $\log(\mathcal{R})$ values. This produces a bimodal distribution where the upper mode is comprised of RL objects ($\mathcal{R} > 10$) populated by only the extended sources whose distribution drops below $\log(\mathcal{R}) = 1$ only for the one RQ source mentioned above. The core-only distribution, however, goes well above and below the $\log(\mathcal{R}) = 1 \text{ RL/RQ}$ dividing line.

The bottom plot in Figure 6 shows the histogram of two different populations from the detected sample (core-only and extended sources) based on a radio luminosity dividing line. The value of the radio luminosity dividing line was found by adjusting the break luminosity value until the lower histograms best matched the original core-only versus extended source histograms shown in the upper plot (based on K-S statistics given below), and was found to be $10^{24.4}$ Watts Hz⁻¹. It is interesting that the two sets of histograms are most similar when the break radio luminosity is nearly equal to that of the FR I/FR II transition luminosity. It is clear that the AGN with $L_r < 10^{24.4}$ Watts Hz⁻¹ have a log(\mathcal{R}) distribution nearly identical to the core-only sources and the AGN with $L_r > 10^{24.4}$ Watts Hz⁻¹ have a log(\mathcal{R}) distribution nearly identical to the extended sources. A K-S test comparing the extended sources in the top plot and the FR II-like distribution in the bottom plot yield a probability value of 1.0 and a maximum difference of 0.04, showing that it is extremely unlikely that these two are from different parent populations. This is also found for the core-only and FR I-like distributions, which have a K-S probability value of 0.82 and a maximum difference of 0.03.

Therefore, in order to move away from the 'by eye' morphological classification schemes used to describe individual sources, we can in general use our extended sources as a proxy for the classic FR II objects, and the core-only sources as a proxy for the FR I sources based on a break radio luminosity that is consistent with the previous FR I/FR II dividing line. From this plot we also find that a log(\mathcal{R}) value of ≈ 1.75 is well suited to separate the FR Is from the FR IIs. The peak values of the \mathcal{R} histogram are consistent with the bimodal distributions found by the previous studies of Ivezić et al. (2004) and Cirasuolo et al. (2004) who find peaks at log(\mathcal{R}) << 1, and log(\mathcal{R}) $\approx 2-3$ using only the radio core sources out to higher redshifts, which may possess complex (extended) structure, but which would be unresolvable at the higher redshifts probed in these samples. Here we show that our two populations basically consist of the lower radio power FR Is (which could be young, unresolved or well aligned with the line-of-sight jets and/or lobes) and the higher radio power FR IIs, and that the \mathcal{R} bimodality seen here is likely a manifestation of the FR I/FR II break originally found by Fanaroff & Riley (1974).

We updated the radio luminosities of the AGN in our sample to determine the effects of the extended radio emission on our previous results in Paper I. As might be expected, the additional flux in a small fraction ($\sim 8\%$) of the radio-detected sample had little effect on the overall trends that we found between radio loudness and Eddington ratio and/or black-hole mass (see Rafter (2010) for the updated plots).

4. Conclusions

We have taken the SDSS BL AGN sample from Greene & Ho (2007) and performed a search for extended associated radio emission using the VLA's FIRST survey. We find that 846 of the objects (10%) have core emission and 63 (0.8%) have extended emission that must be taken into account when calculating the total radio luminosity and radio-loudness. We compare these results to Rafter, Crenshaw & Wiita (2009) and find that the trends in radio-loudness with other physical properties are largely unchanged, which is unsurprising as the detected sample was only modestly enlarged overall. The RLF as a function of L_{bol}/L_{Edd} and M_{BH} are essentially the same, and we still find a modest trend of decreasing RLF with increasing $\log(L_{bol}/L_{Edd})$, along with an increase of the RLF as M_{BH} increases above ~ 2×10⁸ M_{\odot} . We do note that about half of the extended RL AGN do *not* have the most massive BHs ($M_{BH} > 10^8 M_{\odot}$), indicating that even extreme radio-loudness is not based solely on M_{BH} , but must also be closely tied to other fundamental parameters such as black hole spin or accretion mode, although our data do not allow us to draw conclusions as to which, if either, of those theoretical paradigms for radio power is more likely to be correct.

With extended emission taken into account, we find evidence for a distinct population of RL AGN comprised of the extended sources that is separate from the RL and RQ core-only sources. We find that most of the extended AGN in this low redshift sample are FR IIs based on radio morphology and luminosity, using the same FR I/FR II break luminosity defined by Fanaroff & Riley (1974). We find a bimodal distribution in the \mathcal{R} parameter, but at a value above the classic RL/RQ dividing line and propose that this is a manifestation of the FR I/FR II break. In the previous high redshift studies mentioned above, where only the 'core' radio emission is used, the bimodality in \mathcal{R} may again be a manifestation of the FR I/FR II transition, although what is considered to be core emission may in fact include jets and/or lobes (or relatively young sources) whose true radio structure is unresolved due to their extreme distances. We do note that for the sources with just two components, where

one is the core source and the other is not at a large angular distance, the morphology is not easy to determine based on the resolution of the FIRST survey.

The distributions of optical luminosity for the H α emission line (Figure 4) are more similar for both the core-only and extended sources, as well as the total sample, than are the distributions of radio luminosities (Figure 5). This difference gives rise to the radio dichotomy seen when evaluating radio-loudness based on the \mathcal{R} parameter in this sample. From our sample we propose that a more interesting dividing line is at a log(\mathcal{R}) value of ~ 1.75 instead of the classical log(\mathcal{R}) = 1. This higher break value for log(\mathcal{R}) separates local broad-line AGN into two distinct populations of undetected/core-only radio sources and extended radio sources in the FIRST survey.

The claims of bimodality between RL and RQ AGN have usually been based on the somewhat arbitrary $\log(\mathcal{R}) = 1$ criteria, and were heavily debated based on sample selection and inclusion/exclusion criteria (see Section 1 and references therein). While the dichotomy between RL and RQ AGN is called into question in the studies of White et al. (2007) and Rafter, Crenshaw & Wiita (2009), the study by Sikora et al. (2007) does find evidence for this dichotomy and further, postulates physical conditions that may be responsible for its existence. In this work we can clearly reproduce a dichotomy between the core-only sources, comprised of RQ and weak/unresolved FR I type AGN, against the most powerful FR I and FR II type AGN in our sample. Such a distinction may have a more physical and theoretically compelling basis as opposed to being a distinction between RL and RQ that is influenced strongly by observational constraints. As shown in Figure 6, all the AGN in the upper population have extended emission and resolved complex morphologies whose BH/accretion disk system may have different or extreme physical properties when compared to the much more numerous undetected and core-only sources. The lower population (core-only) sources may then be made up of two types. The first type, where the radio emission originates from coronal emission on subparsec scales, as discussed in Laor & Behar (2008), could constitute the bulk of objects with $\log(\mathcal{R}) < 1$. The second type could contain either unresolved young jets which emit on a scale of a few pc and/or weak jets with intrinsically weak radio emission and low kinetic jet power. This second type of object would still fit into our lower population while having $1.75 > \log(\mathcal{R}) > 1$, thereby satisfying the classic paradigm that FR Is tend to be RL based on $\log(\mathcal{R}) > 1$. Once the threshold of $\log(\mathcal{R}) = 1.75$ is crossed in Figure 6, there is a clear transition to the most radio powerful AGN, with strong jets and bright extended emission; these are plausibly a result of some difference in accretion mode, accretion rate, or BH spin in the central engine, whereby the efficiency of jet launching is greatly enhanced.

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| SDSS Name | Radio Catalogue and Source Name | Redshift | Total Integrated Flux (mJy) | Projected Physical Size (Mpc) | Radio Classification |
|---------------------------|---------------------------------------|----------|--------------------------------|----------------------------------|---------------------------|
| (1) | (2) | (3) | (4) | (5) | (6) |
| J005550.75-101905.6 | FBQS J0055-1019 | 0.3091 | 48.58 | 0.94 | GRG/FR II |
| $J013352.65{+}011345.3$ | 87GB 013118.8+005811 | 0.3081 | 67.15 | 0.62 | FR II |
| J072406.79 + 380348.6 | | 0.2413 | 203.46 | 0.58 | FR II |
| J074906.50 + 451033.9 | B3 0745+453,GB6 J0749+4510 | 0.1921 | 117.74 | 0.12 | Core + weak jet(5%) |
| $J075244.19 {+} 455657.3$ | $B30749{+}460A, 6CB074906.2{+}460422$ | 0.0518 | 238.41 | 0.14 | FR I |
| J075643.09 + 310248.7 | | 0.2715 | 22.59 | 0.14 | Classic Triple FR II |
| J080129.57 + 462622.8 | | 0.3159 | 13.37 | 0.26 | Classic Triple FR II |
| J082133.60 + 470237.2 | 3C 197.1, *B3 0818+472A | 0.1280 | 1711.27 | 0.06 | Bright FR II |
| $J082355.36{+}244830.4$ | | 0.2339 | 2.32 | 0.06 | Faint FR II |
| $J084600.36{+}070424.6$ | 87GB 084319.4+071534 | 0.3421 | 241.53 | 0.85 | GRG/FR II |
| $J085348.18 {+} 065447.1$ | PMN J0853+0654 | 0.2232 | 769.90 | 0.08 | Core + 1 Bright lobe |
| $J085627.91{+}360315.6$ | | 0.3449 | 29.96 | 0.20 | FR II |
| $J091133.85 {+} 442250.1$ | $B3\ 0908{+}445, GB6\ J0911{+}4422$ | 0.2976 | 433.23 | 0.15 | FR I |
| $J091401.76 {+} 050750.6$ | 4C + 05.38 | 0.3014 | 328.72 | 0.46 | Large FR II lobe in SW |
| J091519.55 + 563837.8 | | 0.2631 | 19.98 | 0.56 | FR II |
| J092308.16 + 561455.3 | | 0.2493 | 143.01 | 0.23 | FR II |
| J092837.97 + 602521.0 | 8C 0924+606 | 0.2955 | 278.21 | 0.25 | FR II |
| J093200.08 + 553347.4 | 6C B092828.4+554656 | 0.2657 | 73.43 | 0.94 | GRG/FR II |
| J094144.82 + 575123.6 | GB6 J0941+5751 | 0.1585 | 90.43 | 0.11 | FR II |
| J094745.14 + 072520.5 | 3C 227, PKS 0945+07 | 0.0858 | 3117.09 | 0.40 | FR II |
| $J095456.89 {+} 092955.8$ | 4C +09.35, PKS 0952+097 | 0.2984 | 440.66 | 0.17 | FR II |
| J100726.10 + 124856.2 | 4C +13.41, PKS 1004+13 | 0.2406 | 959.14 | 0.52 | FR II |
| J100819.11 + 372903.4 | | 0.0522 | 2.27 | 0.02 | 2nd source in host galaxy |
| J103143.51 + 522535.1 | 4C + 52.22, GB6 J1031 + 5225 | 0.1662 | 904.01 | 0.13 | FR II |
| $J103458.35 {+} 055231.8$ | | 0.3002 | 28.72 | 0.15 | one lobe SW |
| J105220.30+454322.2 | | 0.2406 | 112.05 | 0.26 | FR I (asymmetric) |

 Table 1.
 The Matched SDSS and FIRST Sample

- 16 -

| SDSS Name | Radio Catalogue and Source Name | Redshift | Total Integrated Flux (mJy) | Projected Physical Size (Mpc) | Radio Classification |
|---------------------------|------------------------------------|----------|--------------------------------|----------------------------------|--|
| (1) | (2) | (3) | (4) | (5) | (6) |
| J105500.33+520200.9 | 6C B105202.4+521804 | 0.1874 | 461.07 | 0.21 | FR II |
| $J105632.01{+}430055.9$ | | 0.3177 | 19.37 | 0.22 | FR II |
| $J110845.48 {+} 020240.8$ | PKS 1106+023 | 0.1574 | 784.08 | 0.08 | Core + possible lobe |
| J111432.79 + 105034.7 | | 0.1931 | 780.25 | 0.23 | DDRG/FR II |
| J113021.40 + 005823.0 | 4C + 01.30, PKS $1127 + 012$ | 0.1323 | 566.72 | 0.16 | X-shaped (0.26Mpc) |
| J114004.35-010527.4 | [WB92] 1137-0048 | 0.3470 | 34.17 | 1.12 | GRG/HYMORS |
| J114047.90 + 462204.8 | 87GB 113808.0+463858 | 0.1149 | 91.99 | 0.06 | $\operatorname{core} + \operatorname{bent} \operatorname{jet}$ |
| J114958.70 + 411209.4 | 6C B114721.6+412848 | 0.2497 | 118.46 | 0.33 | FR I |
| $J115409.27{+}023815.0$ | 87GB 115136.0+025423 | 0.2106 | 64.12 | 0.26 | FR I |
| J115420.72 + 452329.4 | | 0.1912 | 964.77 | 0.29 | FR II |
| J120612.67 + 490226.2 | | 0.1194 | 6.30 | 0.09 | Possible core-only source \neg |
| $J122011.89{+}020342.2$ | PKS 1217+02 | 0.2404 | 482.78 | 0.57 | FR I (asymmetric and bent) $$ |
| J123807.77 + 532555.9 | 87GB123550.3+534219 | 0.3475 | 61.60 | 1.02 | GRG/FR II |
| J123915.39 + 531414.6 | 6C B123659.8+533024 | 0.2013 | 23.11 | 0.26 | FR II w/ faint core |
| $J130359.47{+}033932.1$ | 4C + 03.26 | 0.1837 | 210.85 | 0.45 | FR II |
| J131827.00 + 620036.2 | 87GB131634.0+621623,8C1316+622 | 0.3075 | 133.41 | 0.38 | FR II |
| J132404.20+433407.1 | | 0.3377 | 239.62 | 1.10 | GRG/FR II |
| J132834.14-012917.6 | | 0.1514 | 158.85 | 0.98 | GRG/FR II |
| $J133253.27 {+} 020045.6$ | 3C 287.1 | 0.2158 | 1759.16 | 0.57 | FR II |
| J133437.48+563147.9 | 87GB133243.4+564710 | 0.3428 | 164.18 | 0.24 | FR I |
| J134545.35 + 533252.3 | 87GB 134352.4+534755 | 0.1354 | 278.19 | 0.13 | FR II |
| $J134617.54 {+} 622045.4$ | 6C B134441.6+623604 | 0.1164 | 142.99 | 0.15 | FR I (bent) |
| $J141613.36 {+} 021907.8$ | | 0.1582 | 107.70 | 0.67 | DDRG/FR II |
| J144302.76 + 520137.2 | 3C 303 | 0.1412 | 2119.27 | 0.12 | FR II |
| $J151640.22{+}001501.8$ | GB6 J1516+0015, 4C +00.56 | 0.0524 | 1090.21 | 0.28 | FR II |
| J151913.35 + 362343.4 | 6C B151717.1 + 363448 | 0.2857 | 207.25 | 0.58 | HYMORS candidate |

Table 1—Continued

| SDSS Name (1) | Radio Catalogue and Source Name (2) | Redshift (3) | Total Integrated Flux (mJy) (4) | Projected Physical Size (Mpc) (5) | Radio Classification (6) |
|-----------------------|---|-----------------|---------------------------------------|---|------------------------------|
| J152942.20+350851.2 | 7C 1527+3519,6C B152745.2+35192 | 0.2873 | 109.27 | 0.08 | Bright core $+ 1$ lobe |
| J155206.58-005339.3 | | 0.2977 | 105.67 | 0.12 | FR I (partially resolved) |
| J163856.53 + 433512.5 | B3 1637+436A,6CB163723.1+434051 | 0.3390 | 133.04 | 0.45 | FR II |
| J164442.53 + 261913.2 | | 0.1442 | 110.36 | 0.06 | Unresolved core structure |
| J170013.70+400855.6 | | 0.0941 | 20.68 | 0.07 | faint lobe SW, FR II? |
| J170425.11+333145.9 | | 0.2902 | 36.07 | 0.37 | FR II |
| J171322.58+325628.0 | FBQS J171322.6+325628 | 0.1013 | 44.80 | 0.15 | faint FR I |
| J220233.84-073225.0 | | 0.0594 | 3.33 | 0.02 | RQ,2nd source in host galaxy |
| J230545.66-003608.6 | 4C -01.59, PKS 2303-008 | 0.2689 | 517.76 | 0.15 | FR II |
| J233313.16+004911.8 | PKS 2330+005 | 0.1700 | 317.86 | 0.17 | FR I |
| J235156.12-010913.3 | 4C -01.61, PKS 2349-01 | 0.1740 | 1460.41 | 0.09 | FR II ∞ |

Table 1—Continued

Note. — Col.(1): SDSS Name; Col.(2): Radio Catalogue and Source Name: taken from the NASA Extragalactic Database (NED); Col.(3): Redshift: taken from SDSS spectra; Col.(4): Total Integrated Radio Flux at 1.4 GHz (mJy); Col.(5): Projected Physical Size: these approximate values are calculated using the FIRST radio maps (Mpc); Col.(6): Radio Classification: Radio Quiet (RQ), Fanaroff & Riley class 1 & 2 (FR I, FR II respectively), Giant Radio Galaxy (GRG), HYbrid MOrphology Radio Source (HYMORS), Double-Double Radio Galaxy (DDRG), X-shaped (having radio emission that resembles an 'x' pattern, where there are two sets of symmetric emission regions at $\sim 90^{\circ}$ to each other).

 Table 2.
 Summary of Radio Morphologies

| Radio Morphology | Numbe | |
|------------------|-------|--|
| | | |
| FR I | 1 | |
| FR II | 2 | |
| FR II/GRG | | |
| DDRG | | |
| X-shaped | | |
| HYMORS | | |
| Indeterminate | 1 | |



Fig. 1.— Images of extended FIRST sources with the optical source at the center of each frame, north is up and east is to the left. The SDSS name and projected physical size is given beneath each image. **a:** The 1.2×1.2 image shows a double source with one component on the optical core and one offset from it. **b:** The 3.0×3.0 image has a strong jet and lobe to the east and a weaker lobe to the west. **c:** The 6.0×6.0 image shows a giant FR II where the lobe to the NE is aligned with the radio core and lobe to the SW. **d:** The 3.0×3.0 image shows a distant lobe to the east, a radio core, and a lobe to the west slightly misaligned. **e:** The 3.0×3.0 image shows a giant radio lobe with multiple sources to the south that all point back to the radio core. Not shown in this image is a more distant and slightly misaligned source to the north that may be an associated lobe, but with very low flux. **f:** The 3.0×3.0 image shows two lobes that are roughly aligned with the optical center, but with no detected radio core.



Fig. 2.— Histogram characterizing the amount of extended radio flux detected for the 51 extended sources with core emission. Nearly half (25) of the sources add only a fraction and up to two times the core flux. The inset shows that the largest increase in total flux due to extended emission is nearly 70 times the core flux.



Fig. 3.— FWHM_{H α} histogram: the solid line is for the extended sources, the dashed line is for the core-only sources, and the dotted line is for the non-radio detected sources in the flux limited sample. The extended source distribution is shifted to higher values by ~ 2000 km s⁻¹ compared to the core-only and flux limited samples.



Fig. 4.— $L_{H\alpha}$ histogram: the solid line is for the extended sources, the dashed line is for the core-only sources, and the dotted line is for the non-radio detected sources in the flux limited sample. The distributions have similar shapes, peak values, and show significant overlap at luminosities greater than 10^{42} ergs s⁻¹.



Fig. 5.— $L_{1.4 \text{ GHz}}$ histogram: the solid line is for the extended sources, the dashed line is for the core-only sources, and the dotted line is for the full optical sample. The sharp drop off of the dotted line at $10^{23.5}$ Watts Hz^{-1} is due to normalization and does not actually go to zero. The relative lack of sources at $10^{24.5}$ Watts Hz^{-1} is a manifestation the FR I/FR II dividing line.



Fig. 6.— $\log(\mathcal{R})$ histogram: Top, the solid line is for the extended sources and the dotted line is for the core-only sources. Bottom, for the combined sample of core-only and extended sources the dashed line is for objects with $L_{1.4GHz} < 10^{24.4}$ Watts Hz^{-1} and represents an FR I-like population and the dot-dashed line is for objects with $L_{1.4GHz} > 10^{24.4}$ Watts Hz^{-1} and represents an FR II-like population.