STAR FORMATION IN LOW RADIO LUMINOSITY ACTIVE GALACTIC NUCLEI FROM THE SLOAN DIGITAL SKY SURVEY

W. H. de Vries, J. A. Hodge, and R. H. Becker
University of California, 1 Shields Avenue, Davis, CA 95616, USA; and Lawrence Livermore National Laboratory, L-413, Livermore, CA 94550, USA; devries1@llnl.gov

R. L. White
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA

AND

D. J. Helfand
Columbia Astrophysics Laboratory, Columbia University, 550 West 120th Street, New York, NY 10027, USA

Received 2006 December 11; accepted 2007 April 14

ABSTRACT

We investigate faint radio emission from low- to high-luminosity active galactic nuclei (AGNs) selected from the Sloan Digital Sky Survey. Their radio properties are inferred by co-adding large ensembles of radio image cut-outs from the FIRST survey, as almost all of the sources are individually undetected. We correlate the median radio flux densities against a range of other sample properties, including median values for redshift, [O III] luminosity, emission-line ratios, and the strength of the 4000 Å break. We detect a strong trend for sources that are actively undergoing star formation to have excess radio emission beyond the \( \sim 10^{28} \text{ergs s}^{-1} \text{Hz}^{-1} \) level found for sources without any discernible star formation. Furthermore, this additional radio emission correlates well with the strength of the 4000 Å break in the optical spectrum, and may be used to assess the age of the star-forming component. We examine two subsamples, one containing the systems with emission-line ratios most like star-forming systems, and one with the sources that have characteristic AGN ratios. This division also separates the mechanism responsible for the radio emission (star formation vs. AGNs). For both cases we find a strong, almost identical correlation between [O III] and radio luminosity, with the AGN sample extending toward lower, and the star formation sample toward higher luminosities. A clearer separation between the two subsamples is seen as function of the central velocity dispersion \( \sigma \) of the host galaxy. For systems at similar redshifts and values of \( \sigma \), the star formation subsample is brighter than the AGN in the radio by an order of magnitude. This underlines the notion that the radio emission in star-forming systems can dominate the emission associated with the AGN.

Key words: galaxies: active — galaxies: starburst — radio continuum: galaxies

1. INTRODUCTION

The formation of the bulge component of galaxies and their central black holes is now understood to be tightly linked (e.g., Richstone et al. 1998; Kauffmann & Haehnelt 2000; Heckman et al. 2004). There are several observational lines of evidence for this theoretical claim. For instance, the central velocity dispersion of bulges is found not just to correlate with the mass of the bulge, but also with the inferred mass of the central black hole (e.g., Ferrarese & Merritt 2000; Gebhardt et al. 2000). Since the correlation between the mass of the central black hole and the bulge exists over a large range of bulge masses, it is thought that, above some lower mass limit, all bulges harbor massive central black holes. Locally, accurate black hole mass measurements have been made for our own Galaxy (e.g., Schödel et al. 2003; Ghez et al. 2005) and the Andromeda galaxy (e.g., Bender et al. 2005). Our own Galactic black hole is rather dormant based on its relatively low X-ray emission (e.g., Baganoff et al. 2003; Xu et al. 2006), but in general these massive black holes are considered a key component of active galactic nuclei (AGNs), in which accretion onto the black hole itself can produce large amounts of energy efficiently (e.g., Lynden-Bell 1969; Pringle 1981).

It is of interest, then, to study AGN properties over a large range of luminosities, ranging from the AGN-emission-dominated quasars to galaxies for which the presence of a weak AGN can be inferred through unusual optical emission line ratios. Kauffmann et al. (2003a, hereafter K03a) and Kauffmann et al. (2003b) studied the properties of the host galaxies of AGNs, using large, well-defined samples from the Sloan Digital Sky Survey (SDSS, e.g., York et al. 2000; Stoughton et al. 2002). The sheer size of these samples (a few tens of thousands of galaxies) allows for very accurate measurements of sample averages and their trends as a function of optical continuum and emission-line (mainly [O III]) luminosities. One of the conclusions from K03a is that the main difference between low- and high-luminosity AGNs is the significant presence of a young stellar population in the latter.

In this paper we concentrate on the radio emission properties of a large sample of AGNs, similarly selected from the SDSS survey (Data Release 4, Adelman-McCarthy et al. 2006). We use the latest AGN compilation of Kauffmann et al.\(^1\) who used the BPT (Baldwin et al. 1981) diagram of emission-line ratios to select for AGN activity. The current version of this catalog contains 80,156 candidate objects which are also covered by the VLA\(^2\) FIRST radio survey (Becker et al. 1995). In addition, we selected 14,165 quasars from the DR4 release for which we have FIRST images and [O III] line coverage (limiting the quasar redshifts to \(< 0.8 \)). These quasars will form the high-luminosity portion of our sample.

We focus our attention on the radio emission of the AGNs for several reasons. First, almost all AGNs are thought to produce...
radio flux at some level; even the Galactic black hole, currently in a "quiescent" phase, emits in the radio. Some AGNs are extremely luminous in the radio (compared to their optical output)—the so-called radio-loud objects, although we are not considering these specifically, as our average AGN is radio-quiet by a wide margin. Second, radio emission is unaffected by intrinsic absorption within each source. It therefore provides a more or less accurate measure of AGN radio output, with the sole caveat being relativistic beaming effects. Since none of our sources are classified as blazars for which beaming effects can be large, we assume this to play a minor role. Finally, the ready availability of a large-area, high-resolution radio survey in FIRST provides radio information on the large numbers of AGNs in its 9033 deg$^2$ coverage.

There is, however, one apparent problem: almost none of the sources in the SDSS sample are detected by the FIRST survey, with its flux density threshold at 1.4 GHz of 1.0 mJy (5 $\sigma$). Out of 80,154 AGNs, only 5875 (7.3%) are detected directly by the FIRST survey. The relevant numbers for the quasars are only slightly better: 1493 out of 14,165 (10.5%). Clearly by limiting the sample to the brightest sources, one is ignoring the bulk ($\sim$90%) of the population. Fortunately, we can stack radio images and detect the mean and median peak flux densities of ensembles of undetected sources. This method is discussed in depth by White et al. (2007, hereafter Paper I); we summarize the method in § 2. Given our large sample size, we are able to not just detect the (median) ensemble flux density values, but also discern small trends in those values. For our typical stack sample size of 5000 sources, we attain an rms noise of 2.6 $\mu$Jy, and are therefore very sensitive to small changes in the sample median values as we vary other parameters such as the redshift distribution and the [O iii] luminosity distribution. We only have a single sample, so the way we investigate the varying dependencies is by regrouping the stacks according to the quantity of interest. For instance, if we order the sample by redshift and generate 15 adjacent bins (5343 sources per bin), the resulting radio stacks will be different from the 15 bins sorted by [O iii] luminosity; each plot in this paper contains the exact same data, but arranged differently.

The typical median radio flux densities for these sources is found to be on the order of 50 to 100 $\mu$Jy, well below the FIRST threshold, but clearly within the capabilities of the VLA. Indeed, various very deep, small-scale radio surveys exist (e.g., Hopkins et al. 1998; Richards et al. 1999; de Vries et al. 2002). At these low flux densities, star formation could account for a large fraction of the radio emission in our objects, since flux density levels of 50 $\mu$Jy are well within range of star-forming galaxies (without AGNs) at similar redshifts (see, e.g., Windhorst et al. 1999; Fomalont et al. 2002). We cannot, therefore, assign all of the radio emission to the AGNs, as some fraction of the emission may be due to star formation.

The paper is organized as follows. In § 2 we summarize the stacking method as presented in Paper I. The next section describes the properties of the complete sample of 80,156 sources. We then use emission-line ratios, as well as the strength of the 4000 Å break, to isolate two subsamples of 26,715 sources each (§ 3). The first subsample has properties most consistent with the presence of an AGN (the “pure” AGN sample); the second has star formation characteristics while still meeting the AGN selection criterion of K03a. Section 4 details the differences and similarities of these subsamples, which are discussed in further in § 5.

2. FIRST IMAGE STACKING TECHNIQUE

Paper I demonstrates that it is possible to measure the mean and median radio flux density values of distributions of sources, even though individual sources fall far below the detection threshold of the FIRST survey. Provided that the sample is large enough, one can attain rms noise values in the radio sky well below the canonical FIRST value of 0.15 mJy. Actual snapshot stacking experiments of blank pieces of sky$^5$ conform to the expected $1/\sqrt{N}$ behavior in the pixel statistics, down to better than 1 $\mu$Jy. Based on these numbers, it is clear that one can detect stacked point-source mean flux densities of a few tens of $\mu$Jy with high fidelity (see Table 1).

As outlined in Paper I, we prefer to use the median value of the distributions over the mean. The latter quantity is rather easily affected by outliers with large flux densities (the ones which are actually above the FIRST detection threshold). Simply removing the sources above the threshold from the sample to arrive at the mean of the undetected sources is not robust, as a small change in the cut-off flux density (e.g., from 1.0 to 0.9 mJy) results in a significant change in the mean flux value.

The second concern addressed in Paper I is the calibration of the stacking procedure for effects introduced by the radio data analysis in general and the CLEAN algorithm in particular. Analysis of both stacked artificial sources, and actual subthreshold sources detected in full-synthesis, deeper radio imaging shows that one does not recover fully the flux that went into the stack. These results are illustrated in Figure 2 of Paper I; the correction for this “snapshot bias” for subthreshold sources is given by $S_{p corr} = 1.40 S_{p}$, where $S_{p}$ is the median peak flux density value. All of our stacked peak flux density measurements have been corrected by this factor.

2.1. Stacking Luminosity Images

Since most of our subsequent discussion deals with radio luminosities, and not radio flux densities, we have to consider whether there are any distribution peculiarities that might affect these quantities. We do not know the flux density distribution of subthreshold sources, nor the nature of the sources that make up this population. Below flux densities of a few millijanskys, the

| $z_{median}$ | SFR ($M_{\odot}$ yr$^{-1}$) | $\log (\bar{L}_{radio})$ (ergs s$^{-1}$ Hz$^{-1}$) | $F_{peak}$ ($\mu$Jy$^{-1}$) | $D_{p}(4000)$ |
|-------------|-----------------|-----------------|-----------------|-----------------|
| 0.0784....... | 0.15 | 27.6±0.02 | 61.7±3.6 | 1.814 |
| 0.0845....... | 0.47 | 27.90±0.02 | 80.4±3.6 | 1.754 |
| 0.0819....... | 0.79 | 27.96±0.02 | 91.0±3.8 | 1.728 |
| 0.0832....... | 1.12 | 28.06±0.01 | 101.8±3.9 | 1.704 |
| 0.0842....... | 1.47 | 28.14±0.01 | 114.2±3.4 | 1.697 |
| 0.0865....... | 1.85 | 28.24±0.01 | 128.0±3.2 | 1.683 |
| 0.0908....... | 2.26 | 28.26±0.01 | 127.1±3.8 | 1.671 |
| 0.0946....... | 2.72 | 28.36±0.01 | 139.3±3.6 | 1.653 |
| 0.0994....... | 3.26 | 28.41±0.01 | 143.9±3.5 | 1.639 |
| 0.1045....... | 3.90 | 28.54±0.01 | 172.9±3.6 | 1.625 |
| 0.1081....... | 4.68 | 28.62±0.01 | 190.7±3.8 | 1.612 |
| 0.1151....... | 5.65 | 28.71±0.01 | 193.5±3.6 | 1.595 |
| 0.1193....... | 6.97 | 28.80±0.01 | 224.6±3.4 | 1.584 |
| 0.1292....... | 9.08 | 28.92±0.01 | 242.9±3.5 | 1.565 |
| 0.1481....... | 14.1 | 29.15±0.01 | 316.8±3.9 | 1.527 |

Notes.—Both the radio luminosities and flux densities have been corrected for the snapshot bias (see text). The star formation rate is taken from Brinchmann et al. (2004).

$^5$ No pieces of the sky are truly blank, but will consist of faint, unresolved background objects. Our stacking technique is not sensitive enough to pick up this signal: we measured a background signal consistent with 0 $\mu$Jy to within the 0.9 $\mu$Jy rms noise (for 80,154 empty patches).
composition of the radio source population changes from AGN-dominated to star formation–dominated (e.g., Windhorst et al. 1999).

There are two ways of calculating the median radio luminosity. One is simply to stack the cut-outs (with pixels in units of janskys), and use the median peak flux density and median redshift (of the sources that were used in the stack) to calculate the median radio luminosity. The tacit assumption here is that those two median values actually describe the same “median object.” The alternative approach is to convert each snapshot into a luminosity image using the redshift of the individual source, and then stack these images instead. Each pixel in a snapshot image is converted from flux density to luminosity using the following cosmological parameters: \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_\Lambda = 0.7, \) and \( \Omega_M = 0.3. \)

It turns out that the results are not exactly the same. Table 2 (cols. [4] and [5]) lists the radio luminosities derived using both methods for the sample sorted in \( D_n(4000) \) strength, showing typical differences of less than 25%. For the sake of consistency, we use the luminosity-stacked values instead of the flux density-stacked ones for the remainder of the paper.

3. STAR FORMATION VERSUS AGN ACTIVITY

Our data sample was initially selected based on source locations in the BPT plot (K03a; see also Kewley et al. 2006). The ratios of the narrow lines of [N \( ii \)] and [O \( iii \)] over the permitted Balmer lines H\( \alpha \) and H\( \beta \), respectively, serve as an excellent proxy for the amount of star formation in an object (e.g., Osterbrock 1989). Our galaxies with AGNs cover a large range in the BPT plot, and are thus affected by star formation to varying degrees; the objects found close to the sample cut-off arc, toward the left of the distribution (see Fig. 1), have optical spectra dominated by emission-line ratios commonly associated with ongoing star formation. It should also be noted that Kauffmann et al. used a more liberal cut for their AGN classification than, for instance, Kewley et al. (2001), resulting in a fraction of the sources being more H\( \alpha \) region–like than AGN-like. These sources are classified as “composite” in the related Brinchmann et al. (2004) paper.

We use the 4000 \( \AA \) break strength index \( D_n(4000) \) as defined by Kauffmann et al. (2003b). This index can be parameterized as the age since the last (instantaneous) episode of star formation (see Fig. 2 of Kauffmann et al. 2003b), in the sense that smaller break strengths correspond to more recent star formation. The ranges of the \( D_n(4000) \) under consideration for our sources roughly correspond to ages since star formation between \( 10^8 \) and \( 10^{10} \) yr. The short end of this range is comparable to typical galaxy merger

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**TABLE 2**

| \( D_n(4000) \) | \( z_{\text{median}} \) | \( z_{\text{mean}} \) | \( \log (L_{\text{radio,flux}}) \) (ergs s\(^{-1}\) Hz\(^{-1}\)) | \( \log (L_{\text{radio,lum}}) \) (ergs s\(^{-1}\) Hz\(^{-1}\)) | \( \log (L_{\Omega = 0}/L_{\odot}) \) | \( \log (L_{\Omega = 0}/L_{\odot}) \) |
|---------------|----------------|----------------|--------------------------------|--------------------------------|----------------|----------------|
| 2.044......... | 0.0724 | 0.0818 | 28.15 | 28.05 | 6.08 | 6.50 |
| 1.942......... | 0.0826 | 0.0927 | 28.21 | 28.10 | 6.12 | 6.54 |
| 1.885......... | 0.0873 | 0.0963 | 28.20 | 28.05 | 6.18 | 6.57 |
| 1.836......... | 0.0928 | 0.0994 | 28.26 | 28.10 | 6.28 | 6.64 |
| 1.791......... | 0.0951 | 0.1009 | 28.24 | 28.06 | 6.30 | 6.71 |
| 1.747......... | 0.0960 | 0.1027 | 28.30 | 28.14 | 6.39 | 6.79 |
| 1.705......... | 0.0972 | 0.1034 | 28.36 | 28.21 | 6.53 | 6.91 |
| 1.665......... | 0.1008 | 0.1063 | 28.42 | 28.28 | 6.65 | 7.01 |
| 1.624......... | 0.1014 | 0.1077 | 28.48 | 28.35 | 6.79 | 7.17 |
| 1.584......... | 0.1031 | 0.1079 | 28.56 | 28.44 | 6.92 | 7.30 |
| 1.541......... | 0.1053 | 0.1095 | 28.66 | 28.55 | 7.04 | 7.39 |
| 1.496......... | 0.1069 | 0.1106 | 28.73 | 28.62 | 7.17 | 7.53 |
| 1.446......... | 0.1114 | 0.1147 | 28.86 | 28.79 | 7.34 | 7.69 |
| 1.384......... | 0.1143 | 0.1178 | 28.99 | 28.94 | 7.54 | 7.86 |
| 1.276......... | 0.1201 | 0.1244 | 29.21 | 29.19 | 7.85 | 8.11 |

Notes.—The \( \log (L_{\text{radio,flux}}) \) and \( \log (L_{\text{radio,lum}}) \) are luminosities based on flux stacking and luminosity stacking, respectively. The bolometric luminosity of the Sun \( (L_{\odot}) \) is \( 3.826 \times 10^{33} \) ergs s\(^{-1}\).
timescales (e.g., Springel et al. 2005), whereas \(10^{10}\) yr at \(z \sim 0.2\) is close to the age of the universe and therefore represents the initial burst of star formation. Since we are not going to distinguish between starbursts of different metallicities, we are approximating the relation between age and \(D_n(4000)\) by a straight line over the \(D_n(4000)\) range 1.3–2.0 (the relevant range for our sample): \(\log(\text{age}) = 6.21 + 1.87D_n(4000)\), with age given in years.

The results for median radio luminosity as function of the strength of the 4000 Å break are plotted in Figure 2. It is clear that the brightest radio emission is associated with the smallest breaks (i.e., the most recent episodes of star formation). The approximate time since the last epoch of star formation is given across the top of the plot. Above a \(D_n(4000)\) index of about 1.8, there is no change in radio luminosity, which levels off at about \(10^{28}\) ergs s\(^{-1}\) Hz\(^{-1}\). This might reflect the absence of any contribution to the radio emission from star formation. The color coding indicates the [O \text{III}] luminosity, which is also seen to decline steeply as \(D_n(4000)\) increases.

3.1. Line Emission Diagnostics

As a double check on the level of star formation, we can see where the \(D_n(4000)\)-sorted data points from Figure 2 land on the BPT plot. In other words, do the sources with the low \(D_n(4000)\) values have emission-line ratios that reflect a higher incidence of star formation? The results are plotted in Figure 1 as a gray-scale sequence of squares, running from light gray to black for the small-to-large valued \(D_n(4000)\) systems. It is clear that these two quantities do correlate rather well for our objects, and trace out a sequence of decreasing star formation versus increasing 4000 Å break strength. The gray squares in the top right corner have emission-line ratios completely consistent with pure AGN emission, whereas the squares to the left are significantly affected by star formation.

The combination of Figures 1 and 2 leads us to suggest that for the “pure” AGN cases as indicated by large 4000 Å breaks, the radio luminosity is strictly due to the AGNs with average luminosities near \(10^{28}\) ergs s\(^{-1}\) Hz\(^{-1}\). The additional radio luminosity we see for other sources can be attributed completely to ongoing star formation. This star-forming component can be an order of magnitude more luminous than the radio component due to the AGNs.

Brinchmann et al. (2004) use the strength of the 4000 Å break to calculate the inferred star formation rate (their sample not only encompasses our AGN sample, but also non-AGNs which land to the left of the distribution in Fig. 1). They corrected for the limited angular extent of the SDSS fiber which typically does not contain all of the light of the galaxy. We use these corrected values to sort our sample in ascending order of star formation rate. The median stacked radio luminosities for 15 bins of ~5000 sources each are calculated and plotted against median star-formation rate in Figure 3. The strong correlation again underlines the importance of the star formation component to the overall radio luminosity, even for systems containing AGNs. The \(10^{28}\) ergs s\(^{-1}\) Hz\(^{-1}\) “ground-state” radio luminosity from Figure 2 corresponds, based on this plot, to a star formation rate of \(\sim 1\ M_\odot\) yr\(^{-1}\), or less, whereas the largest radio luminosities from Figure 2 have rates exceeding \(10\ M_\odot\) yr\(^{-1}\).

The non-AGN portion of the Brinchmann et al. sample, once sorted by star formation rate, exhibit a very tight correlation with median radio luminosity (Fig. 3). The least-squares fit is given by \(\log(L_{R,\text{non-AGN}}) = (1.37 + 0.02) \log(\text{SFR}) + (27.67 \pm 0.01)\). This slope of 1.37 is almost identical to that of Bell (2003), who finds a slope of 1.30 for radio luminosities less than \(6.4 \times 10^{28}\) ergs s\(^{-1}\) Hz\(^{-1}\). The Bell results, however, show a different normalization, suggesting they underestimate the amount of star formation for a given radio luminosity by a factor of 2.
Even more remarkable than the tight correlation between estimated star formation rate and mean radio luminosity over 2 orders of magnitude is that the AGN contribution to the radio luminosity can be represented by a constant $\left(4.5 \times 10^{27}\right)$ ergs s$^{-1}$ Hz$^{-1}$) which, once added to the star formation estimate (black line), gives us the red line. This single constant implies that the AGN output (in the radio) is more or less independent of the star formation level of the host galaxy. It is also a better measure of this AGN “ground state” than the $10^{28}$ value derived from Figure 2.

In summary, since the star formation rates are based on the $D_4(4000)$ values, we use the latter to isolate two subsamples: one that presumably has no, or very little, ongoing star-formation (labeled I in Figs. 1 and 2), and one that contains the systems with the most ongoing star formation (labeled II). Each one of these subsamples contain 26,715 sources.

4. A CLOSER LOOK AT THE “PURE” AGN SUBSAMPLE

We designate the five rightmost data points in Figures 1 and 2 as representing the most AGN-like sources. Their emission-line ratios are the least star formation–like, and their median [O iii] and [O ii] luminosities are among the lowest in our sample (see Table 2).

Figure 4 shows the distribution densities in redshift versus velocity dispersion space for the large 4000 Å break, low star formation sources (red contours), compared to the sources with the smallest 4000 Å break and the highest levels of star formation (blue contours). The redshift distribution for each subset is comparable, whereas there is a clear offset in velocity dispersion. This is most likely due to the way the subsets have been selected. For a given burst of star formation with some upper limit to its optical luminosity, it will appear more prominent [with a consequently lower value of the $D_4(4000)$ index] in smaller galaxies than in large systems. Since the mass and size of the galaxy spheroid scales with its central velocity dispersion (e.g., Gebhardt et al. 2000; Ferrarese & Merritt 2000), we will be biased toward finding more star formation among the lower $\sigma$ systems.

4.1. Radio Luminosity and Redshift Dependence

Luminosity, as in all flux-limited samples, is closely correlated with redshift, resulting in an apparent correlation that is dominated by the lack of bright sources locally, and faint sources at higher redshifts (due to the detection limit). This is illustrated in Figure 5. Both subsamples I and II were sorted in redshift, and divided up into 13 bins of 2025 sources each. The “pure” AGN–like bins are plotted as pentagons, and the sources most affected by star formation as stars. In addition, we plotted seven bins of 2025 quasars each, depicted as green squares.

It is immediately clear that the median radio luminosities of the quasars are directly comparable to the narrow-line AGN values. There is no a priori reason for the quasar radio luminosity medians not to be much brighter than the galaxies, but their values are comparable at the same redshift. The quasar radio luminosities are slightly less than the star formation values, and slightly more than the AGN subsample values (at the same redshift). On the other hand, quasars are consistently brighter in [O iii] luminosity than the narrow-line AGNs at similar redshifts (see Fig. 6).

The fact that the median radio luminosity is the same would suggest that we are observing an isotropic emission component, and not orientation/obscuration–dependent quantities like emission lines and the presence of broad permitted lines. The median radio luminosity therefore underlines the validity of the standard AGN unification model (e.g., Barthel 1989; Antonucci 1993).

Another result based on Figure 5 is that the star formation–dominated galaxies are brighter in the radio than the pure AGN galaxies, albeit that the difference becomes smaller at redshifts beyond 0.1 (where both samples I and II merge into the low end
of the quasar trend). The more or less constant offset of a factor \(\sim 3\) (0.5 in logarithm) between the two subsamples (below \(z \sim 0.1\)) suggests that the average radio luminosity due to the AGN accounts for at most 25% of the total radio emission during an ongoing phase of star formation.

4.2. \([\text{O}\text{ III}]\) Luminosity as AGN Activity Indicator

The \([\text{O}\text{ III}]\) emission-line luminosity offers another way of gauging the AGN output. K03a estimate that perhaps as little as 7% of the \([\text{O}\text{ III}]\) line emission can be attributed to star formation in their AGN composite spectrum. This means that, even though both the radio and \([\text{O}\text{ III}]\) luminosities depend on redshift, their correlation should be relatively free of redshift bias (by dropping out of the ratio).

For this purpose, we first order the sample in \([\text{O}\text{ III}]\) luminosity, and then stack the cutouts to calculate the median radio luminosity. The \([\text{O}\text{ III}]\) luminosities have been corrected for extinction using the \(H\alpha/H\beta\) extinction-line ratio, under the assumption that the \([\text{O}\text{ III}]\) emission is isospatial (see K03a). The \([\text{O}\text{ III}]\) sorting and stacking also helps in minimizing the redshift differences among the bins. Ideally, one would like to have similar source redshift distributions for each \([\text{O}\text{ III}]\) luminosity bin, which would in effect isolate one from the other.

The results are presented in Figure 6. We see a strong correlation between \([\text{O}\text{ III}]\) and radio luminosity. For comparison, we also included seven bins of low-redshift quasars. The spectral coverage of the SDSS is such that the \([\text{O}\text{ III}]\) emission line is included in the spectrum up to redshifts of \(\sim 0.8\). This results in a sample of 14,165 DR4 quasars that have \(z < 0.8\) and are covered by the FIRST survey. We split the sample into seven equal-sized bins, sorted in \([\text{O}\text{ III}]\) luminosity. Since we are looking at presumably unobscured quasars, we do not correct the \([\text{O}\text{ III}]\) luminosities for intrinsic extinction.

The two solid lines are least-squares fits to the quasars and the star formation subsample. The first 10 data points of the AGN subsample (pentagons) are more or less consistent with the quasar relation, although we do note that there are excursions along the quasar fit. This may have to do with the extinction correction being less than ideal for the AGN subsample. The star formation subsample does not exhibit similar behavior. The fits are

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L_{r,\text{AGN}} = (0.87 \pm 0.02)L_{\text{[O III]}} + (2.5 \pm 0.8), \quad L_{r,\text{SF}} = (0.70 \pm 0.03)L_{\text{[O III]}} + (9.1 \pm 1.2),
\]

with all the luminosities in units of \(\log (\text{ergs s}^{-1})\). It should be noted that the origin of the radio emission is different for the two subsamples. For the AGN-dominated sample the radio emission is largely due to the AGNs (although the star formation component dominates at the highest luminosities; see Fig. 3), whereas the AGN component is only a small contributor for the star-formation subsample. As such, it is clear that the differences in the \([\text{O}\text{ III}]\)–radio luminosity relations cannot be explained by a simple translation along either the \([\text{O}\text{ III}]\) or the radio luminosity axes. From Figure 5 we already know that the star-forming subsample is brighter in the radio than either the AGN or quasar samples (at the same redshifts). Therefore, the correct conclusions from Figure 6 are as follows: the star-forming subsample is brighter in both \([\text{O}\text{ III}]\) and radio luminosity than the AGN subsample at the same redshift, and they have a different slope. Also, the AGN subsample has a slope similar to that of the quasar sample, which is what one would expect if the AGNs are unobscured quasars.

4.3. Velocity Dispersion

The central velocity dispersions of galaxies have been found to correlate tightly with the inferred masses of their central black holes (e.g., Ferrarese & Merritt 2000; Gebhardt et al. 2000). The latter quantity also scales with the mass of the stellar bulge. There is some evidence that the most massive bulge systems are more likely to be radio-loud compared to less massive systems (e.g., Laor 2000; Lacy et al. 2001), but in our cases we derive median radio luminosities well below what one would consider radio-loud objects. As such, our analysis pertains more to ordinary systems covering a range of AGN indicators (see § 3).

The results are shown in Figure 7. It is clear that there is a trend for the most massive systems (highest values of \(\sigma\)) to have the highest radio luminosities. This should not come as a surprise, based on the correlations between black hole mass and bulge mass. As seen in § 4.1, the median radio luminosity is apparently not very much affected by orientation effects (since the radio luminosities are comparable for quasars and AGNs to within a factor of 2 at the same redshift), and provides a rather clean measure of the AGN output (at least for the “pure” AGN subsample). This trend would presumably scale nicely with the mass of the central black hole, giving rise to the tight correlation between median radio luminosity and velocity dispersion (see Fig. 7, \cite[5]{we know that the main sample of galaxies has to have some extinction toward the AGN (they would otherwise appear as type 1 Seyfert objects), so correcting for the [O III] luminosity (mainly due to the AGN) makes sense. But since the quasars are type 1 objects, we assume that the corrections for the quasars are considerably smaller than the typical factor of ~10 corrections in the median [O III] luminosity for the galaxies.}.

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Fig. 6.—Correlation of median values for radio luminosity and \([\text{O}\text{ III}]\) luminosity. The color indicates the median redshift for a particular bin. The seven squares are broad-line AGNs/quasars. The units on the top and right side are converted from the measured values by the following constants: \(\log (1.4 \times 10^{30}) \text{ Hz} \) and \(\log (3.826 \times 10^{33}) \text{ ergs s}^{-1}\) for the \(x\)-axis (observing frequency) and \(y\)-axis (bolometric luminosity Sun), respectively. Note that for all these points the radio luminosity is at least 3 orders of magnitude lower than typical radio-loud objects. Symbols are the same as in Fig. 5.
The AGN-dominated sample does not allow for a straight line (in log-log) fit, which may indicate other dependencies beyond a simple velocity dispersion/galaxy mass scaling.

One thing we need to check, however, is the effect the small range in redshift may have on radio luminosity. Based on their tight correlation in Figure 5, a small change in median redshift may account for most of the trend we see in Figure 7. To this end, we calculated the median redshift of the sources used for each velocity dispersion bin, and applied the redshift–radio luminosity fits from Figure 5 to infer the radio luminosity that way. These values are overplotted as the smaller black symbols (so each $\sigma$ bin has two radio luminosities associated with it). Now, if the large and small symbols closely track each other, then the correlation between velocity dispersion and radio luminosity is spurious due the sample being flux-limited. However, since this is not the case, the radio luminosity–velocity dispersion correlation is real.

Note that the offset in radio luminosity between the star formation–dominated and “pure” AGN subsamples is even larger than in Figure 5, at about an order of magnitude compared to a factor of about 3 (for $z < 0.1$). Clearly for some objects at similar redshifts and similar mass (velocity dispersion), star formation can account for 90% of the total radio luminosity. This would also suggest that the correlation for the star formation subsample is driven by the bulge mass–$\sigma$ relation [higher $\sigma$ equals a more massive galaxy, which translates into a higher absolute amount of star formation for a given $D_{25} (4000)$ value]. The radio luminosity for the “pure” AGN subsample (Fig. 7, pentagons), on the other hand, scales with the mass of the central black hole, which itself scales with the bulge mass (which is directly related to the velocity dispersion).

5. DISCUSSION AND SUMMARY

We note the correlations of the median values of the $[\text{O} \text{III}]$ and radio luminosities in § 4.2 and Figure 6, in particular the similar ratios for the AGN, star formation, and quasar subsamples. Given that the mechanisms responsible for the radio emission are thought to be different between the AGN and star formation subsamples, this comes as a surprise. Our work is not the first that touches on this subject. For instance, Wills et al. (2004) worked on $[\text{O} \text{III}]$ radio source population. This can be put into more perspective by comparing our sample to the one of Best et al. (2005). Their paper is also based on FIRST and SDSS data. Actually, their data set is wholly contained within ours.

In Figure 8 we replot the data from Figure 6 onto the data from Wills et al. (2004) on local low-luminosity AGNs.

6 We converted their 5 GHz radio flux densities to 1.4 GHz values using a constant spectral radio index of $-0.5$. 

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**Figure 7.** Median radio luminosity as a function of central velocity dispersion $\sigma$ of the host galaxy, for the AGN-dominated (1, pentagons) and star formation–dominated (II, stars) subsamples. The spread in median redshift is indicated by the color coding. The close correlation between the median values of the velocity dispersion and the radio luminosity is apparent, especially for the star formation sample. The small symbols indicate where the colored dots would lie if we use its median redshift and the redshift–radio luminosity correlation of Fig. 5. Note that the offsets are along the $\gamma$-axis. Low-$\sigma$ galaxies are underluminous in the radio compared to the average redshift trend, and the most massive galaxies are over-luminous in the radio (this holds true for both subsamples).

**Figure 8.** Comparison of the correlation between $[\text{O} \text{III}]$ and radio luminosities (see Fig. 6; note that the axes are switched) to values from the literature. The sample of Best et al. (2005) contains SDSS objects with a radio flux of $< 5$ mJy and is represented by the small open squares (color coded with redshift). The offsets in radio luminosity between our median values and theirs can exceed 3 orders of magnitude. It should be noted that our sample of 80,156 includes the Best et al. sample, underlining the severe bias one introduces by selecting the brightest radio sources. The solid line is the fit from Wills et al. (2004) on local low-luminosity AGNs.
(open squares) that are both in our sample and have detected [O III] emission (the bottom right panel of Fig. 9 in Best et al. includes a set of [O III] nondetections). Our median [O III] values cover the exact same range as the Best et al. sample; the main difference is the radio luminosity. Since our data represent median values, it implies that a full 50% of the sources are located to the left of our data points. The fact that the Best et al. data can be up to more than 3 orders of magnitude brighter (in the radio) illustrates the severe radio selection bias of their sample. It also makes it clear than an order of magnitude larger than high-index objects).

We furthermore find that the AGN contribution to the overall median radio luminosity is roughly constant in these galaxies at the $5 \times 10^{23}$ ergs s$^{-1}$ Hz$^{-1}$ level. The other component is very tightly correlated to the star formation rate (as derived from the optical spectrum). This also implies that if one is considering a system without an AGN, its star formation rate can be accurately assessed using the radio luminosity of the system. There is no indication that this correlation cannot be extended to star formation rates below 0.1 $M_\odot$ yr$^{-1}$.

It is clear that by studying (median) statistical properties of carefully selected and representative samples, one can infer subtle trends that otherwise are either too small to detect, or are masked by source intrinsic variations. Our median radio luminosity measurements are at least a few orders of magnitude below typical studies (see Fig. 8), and provide a much less biased view of the radio properties of galaxies. Methods such as that used in this paper hold great potential when applied to future, large-scale multiwavelength surveys.

We would like to thank the anonymous referee for helpful comments. The work by W. D. V. and R. H. B. was partly performed under the auspices of the US Department of Energy, National Nuclear Security Administration, by the University of California, Lawrence Livermore National Laboratory under contract W-7405-Eng-48. J. A. H. acknowledges support of a GAANN Fellowship from the US Department of Education. The authors also acknowledge support from the National Radio Astronomy Observatory, the National Science Foundations (grant AST 00-98355), and the Space Telescope Science Institute.

5.1. Summary

Combining a large number of objects across a range of AGN activity from the SDSS with the FIRST radio survey allows us to correlate various sample statistics with radio emission at levels that are too low for individual sources to be detected. We are able to measure median radio emission down to a few tens of microjanskys, well below the FIRST detection threshold.

We find the following quantities to correlate strongly with the median radio luminosity:

1. $D_{4000}$ index/star formation rate. This index traces the amount of star formation in a given galaxy by measuring the amount of blue light relative to the red. Low values of the $D_{4000}$ index correspond to more active star formation, and are found to have the highest median radio luminosities (more than an order of magnitude larger than high-index objects).

2. [O III] luminosity. Higher levels of [O III] luminosity correspond to higher median radio luminosities. This is true over at least 3 orders of magnitude. The [O III]–radio luminosity correlation for the “pure-AGN” subsample is consistent with the same relation for quasars, but extended toward lower luminosities. The highest levels of [O III] and median radio emission are seen among the “pure star formation” subsample, with levels comparable to the quasar ones.

3. Central velocity dispersion $\sigma$. Generally, higher values of $\sigma$ (i.e., larger galaxies) correspond to larger median radio luminosities. However, there are clear differences between the AGN- and star formation–dominated subsamples. For a given median radio luminosity, star-forming systems have a much smaller $\sigma$ than AGN-dominated systems. Conversely, for a given galaxy size and $\sigma$, star formation–dominated systems can be an order of magnitude more luminous in the radio than the AGN-dominated systems.

### Table 3

| $z_{\text{median}}$ | log ($L_{\text{radio}}$) (ergs s$^{-1}$ Hz$^{-1}$) | SFR ($M_\odot$ yr$^{-1}$) |
|---------------------|----------------------------------|-----------------|
| 0.075               | 27.60                            | 0.45            |
| 0.095               | 28.10                            | 1.07            |
| 0.100               | 28.34                            | 1.61            |
| 0.101               | 28.46                            | 1.97            |
| 0.106               | 28.57                            | 2.37            |
| 0.108               | 28.72                            | 3.06            |
| 0.112               | 28.78                            | 3.38            |
| 0.115               | 28.91                            | 4.49            |
| 0.119               | 28.99                            | 5.40            |
| 0.123               | 29.08                            | 6.64            |
| 0.128               | 29.23                            | 9.38            |
| 0.134               | 29.34                            | 12.1            |
| 0.149               | 29.65                            | 24.7            |

Note.—For reference, an $L_{\text{radio}}$ galaxy corresponds to log ($L_{\text{radio}}$) $=28.81$ and a star formation rate of $3.57 M_\odot$ yr$^{-1}$.

7 That is not to say that our sample is without biases: galaxies in our sample have to have measurable emission-line ratios.
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