THE UBIQUITOUS RADIO CONTINUUM EMISSION FROM THE MOST MASSIVE EARLY-TYPE GALAXIES

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ABSTRACT

We have measured the radio continuum emission of 396 early-type galaxies brighter than $K = 9$, using 1.4 GHz imagery from the NRAO Very Large Array Sky Survey, Green Bank 300 ft Telescope, and 64 m Parkes Radio Telescope. For $M_K < -24$ early-type galaxies, the distribution of radio powers at fixed absolute magnitude spans four orders of magnitude and the median radio power is proportional to $K$-band luminosity to the power $2.78 \pm 0.16$. The measured flux densities of $M_K < -25.5$ early-type galaxies are greater than zero in all cases. It is thus highly likely that the most massive galaxies always host an active galactic nucleus or have recently undergone star formation.

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

Online-only material: color figure, machine-readable table

1. INTRODUCTION

The most massive early-type galaxies reside within dark matter halos with masses of $10^{13} M_\odot$ or more (e.g., Brown et al. 2008). One may expect the gas within these dark matter halos to radiatively cool, gravitationally collapse, and form stars (e.g., White & Rees 1978). In contrast to this expectation, stellar population synthesis modeling reveals that the bulk of the stars in very massive galaxies formed $\sim 10$ Gyr ago, with relatively little star formation since (e.g., Tinsley 1968; Trager et al. 2000). While some early-type galaxies harbor cold gas, the most massive galaxies are typically bathed in plasma with temperatures on the order of millions of kelvin (e.g., Canizares et al. 1987). What is heating the plasma and regulating star formation in very massive galaxies has yet to be robustly identified.

In the recent literature, a popular mechanism for heating the plasma is the injection of energy from an active galactic nucleus (AGN) feedback (e.g., Tabor & Binney 1993; Croton et al. 2006). While a quasar could heat the gas within its host galaxy (e.g., Hopkins et al. 2006), powerful quasars are so rare that they probably cannot be responsible for the lack of star formation in nearby massive galaxies. For nearby galaxies, it is more plausible that low luminosity AGNs (with a high duty cycle) are heating the plasma. Bubbles in the distribution of X-ray-emitting gas surrounding nearby radio galaxies correspond to the locations of radio lobes (e.g., Fabian et al. 2003; McNamara et al. 2000). The dissipation of shocks and sound waves resulting from the production of these bubbles and jets may inject sufficient energy into the plasma to offset radiative cooling (Fabian et al. 2003).

Radio observations provide insights into the plausibility and nature of AGN feedback. We may expect to observe radio emission from all massive galaxies, resulting from star formation and/or AGNs. Radio emission is associated with the cavities in the X-ray-emitting plasma produced by AGNs and radio emission results from recent star formation (Condon 1992). However, in isolation, the presence of radio emission from massive galaxies is not proof of AGN regulation of star formation. For example, AGNs with low power jets (e.g., Baldi & Capetti 2009) may have little impact on the surrounding plasma. If there are massive galaxies without radio emission, this may indicate that brief bursts of AGN activity are sufficient to truncate star formation (e.g., Hopkins et al. 2006). Alternatively, a mechanism other than AGN feedback may be heating the plasma surrounding galaxies (e.g., Birnboim & Dekel 2003).

Previous studies show that ~30% of the most massive galaxies are radio continuum sources (e.g., Fabbiano et al. 1989; Sadler et al. 1989; Wrobel & Heeschen 1991; Best et al. 2005; Shabala et al. 2008). These studies matched optical and radio source catalogs, which limits the sample to radio sources that meet conservative signal-to-noise criteria, so catalogs are not swamped by noise. (Even when conservative criteria are applied, the tail of the noise distribution may produce spurious sources.) Recent studies have generally utilized large redshift surveys that exclude the nearest galaxies, and thus miss radio sources fainter than $10^{25}$ WHz$^{-1}$. Consequently, the faint radio emission from nearby early-type galaxies has not been completely characterized by the prior literature.

In this Letter, we present a study of the 1.4 GHz radio emission from $K < 9$ early-type galaxies. The choice of 1.4 GHz is pragmatic, as it allows us to utilize existing NRAO Very Large Array (VLA) Sky Survey (NVSS; Condon et al. 1998) and single-dish imagery. We assume the radio emission is the consequence of either recent star formation or an AGN. If this assumption holds, our conclusions do not depend on which emission process is dominant in these galaxies (i.e., synchrotron, free–free). Rather than match our early-type galaxies to radio source catalogs alone, we also measure flux densities from radio images. We can thus include significant (albeit noisy) information on the radio flux densities of early-type galaxies that would have otherwise been excluded from our study. This allows us to characterize the very faint radio emission from the most massive early-type galaxies.

2. THE SAMPLE

Our parent sample is the Two Micron All Sky Survey (2MASS) Extended Source Catalog (Jarrett et al. 2000), from which we select objects with apparent magnitude $K < 9$ (dust
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Table 1

| Name  | J2000 Coordinates | 2MASS $m_K$ | RC3 T Type | $S_{1.4}$ (mJy) | $d_L$ (Mpc) | $M_K$ | $P_{1.4}\times$ (W Hz$^{-1}$) |
|-------|-------------------|------------|------------|-----------------|-------------|-------|------------------|
| NGC 16| 00:09:04.300+27:43:46.03 | 8.76 | −3.0 | −1.0 ± 0.5 | 42 | 24.34 | \ldots |
| NGC 50| 00:14:44.555−07:20:42.38 | 8.66 | −3.0 | 22 ± 1 | 75 | 25.72 | $1.5 \times 10^{22}$ |
| NGC 57| 00:15:30.873+17:19:42.22 | 8.65 | −5.0 | 0.9 ± 0.5 | 74 | 25.70 | $<1.2 \times 10^{21}$ |
| NGC 80| 00:21:10.865+22:21:26.11 | 8.90 | −2.5 | 0.9 ± 0.5 | 78 | 25.56 | $<1.3 \times 10^{21}$ |
| NGC 128| 00:29:15.070+02:51:50.57 | 8.51 | −2.0 | 1.5 ± 0.5 | 58 | 25.30 | $6.0 \times 10^{20}$ |
| NGC 205| 00:42:20.075+41:41:07.08 | 5.56 | −5.0 | 0.1 ± 0.5 | 0.8 | 18.84 | $<6.9 \times 10^{16}$ |
| NGC 221| 00:42:41.825+40:51:54.61 | 5.05 | −6.0 | 0.7 ± 0.5 | 0.8 | 19.50 | $<1.3 \times 10^{17}$ |
| NGC 315| 00:57:48.916+30:21:08.33 | 7.93 | −4.0 | $(1.8 \pm 0.1) \times 10^{3}$ | 68 | 26.23 | $1.0 \times 10^{24}$ |
| NGC 383| 01:07:24.939+32:24:45.82 | 8.46 | −3.0 | $(4.8 \pm 0.2) \times 10^{3}$ | 70 | 25.76 | $2.8 \times 10^{24}$ |
| NGC 410| 01:10:58.872+33:09:07.30 | 8.36 | −4.0 | 5.8 ± 0.5 | 73 | 25.94 | $3.6 \times 10^{21}$ |
| NGC 439| 01:13:47.251+31:44:50.09 | 8.68 | −3.3 | 21 ± 1 | 79 | 25.79 | $1.6 \times 10^{22}$ |
| NGC 474| 01:20:06.696+03:24:54.97 | 8.54 | −2.0 | 0.3 ± 0.5 | 32 | 23.97 | $<1.5 \times 10^{20}$ |
| NGC 499| 01:23:11.459+33:27:36.30 | 8.71 | −2.5 | 0.7 ± 0.5 | 60 | 25.18 | $6.9 \times 10^{20}$ |
| NGC 507| 01:23:39.950+33:15:22.22 | 8.28 | −2.0 | 62 ± 2 | 67 | 25.87 | $3.4 \times 10^{22}$ |
| NGC 524| 01:24:47.707+09:32:19.65 | 7.13 | −1.0 | 3.1 ± 0.4 | 24 | 24.77 | $2.1 \times 10^{20}$ |
| NGC 533| 01:25:31.432+01:45:33.57 | 8.43 | −5.0 | 29 ± 1 | 76 | 25.97 | $2.0 \times 10^{22}$ |
| NGC 547| 01:26:00.577−01:20:42.43 | 8.48 | −5.0 | $(5.9 \pm 0.5) \times 10^{3}$ | 76 | 25.92 | $4.0 \times 10^{24}$ |
| NGC 584| 01:31:20.755−06:52:05.02 | 7.29 | −5.0 | 0.6 ± 0.5 | 20 | 24.23 | $<7.3 \times 10^{19}$ |
| NGC 596| 01:32:51.906−07:01:53.54 | 7.96 | −4.0 | 0.1 ± 0.5 | 22 | 23.73 | $<5.7 \times 10^{19}$ |
| NGC 636| 01:39:06.529−07:30:45.37 | 8.43 | −5.0 | −0.3 ± 0.5 | 30 | 23.94 | $6.4 \times 10^{19}$ |

Note. *When the flux density is within 2σ of zero, a 2σ upper limit for the radio power is provided. 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.*

Corrected; Schlegel et al. 1998), declination $\delta > −40^\circ$, and galactic latitude of $|b| > 15^\circ$. Of the 1107 objects selected with these criteria, 979 have morphologies available from the Third Reference Catalog of Bright Galaxies (de Vaucouleurs et al. 1991), while virtually all of the remaining objects are Galactic.

Our principal sample is the 400 galaxies that are classified as elliptical or lenticular galaxies in the RC3 (with T-type classifications of $−1$ or less). Many of these galaxies have redshifts in the RC3 catalog, while the remainder have redshifts provided by Falco et al. (1999), Huchra et al. (1999), Wegner et al. (2003), Jones et al. (2009), and the NASA Extragalactic Database. For 170 galaxies we have redshift-dependent distances from Extragalactic Distance Database (Tully et al. 2009), while for the remaining galaxies we use a Hubble constant of $73$ km s$^{-1}$ Mpc$^{-1}$ (Spergel et al. 2007). The luminosity distances of the galaxies span from 0.7 to 10$^3$ Mpc.

Our principal radio imaging is the 1.4 GHz NVSS (Condon et al. 1998), which has an angular resolution of 45$''$ and an rms noise of $\approx 0.45$ mJy. As the NVSS can underestimate the flux densities of powerful and extended radio sources, we also measure flux densities using lower resolution (≈12$''$) imaging from the 300 ft Green Bank and the 64 m Parkes radio telescopes (Condon & Broderick 1985, 1986; Barnes et al. 2001; M. Calabretta 2011, in preparation).

We employed the following method to measure flux densities for each galaxy. At the 2MASS position of each galaxy, we measured a flux density per beam directly from the NVSS images. For those galaxies with a flux density per beam greater than 2 mJy, we searched for the nearest counterpart in the NVSS catalog within 2$''$ and used the NVSS catalog deconvolved flux density. To account for powerful extended sources, we measured the flux density per beam using Green Bank 300 ft and Parkes single-dish data, and utilized this flux density measurement if it was greater than 0.6 Jy. If the flux density per beam measured with single-dish imagery was greater than 5 Jy, we utilized the integrated flux density rather than the flux density per beam.

Our flux density measurements are imperfect, but our principal conclusions remain unchanged unless gross systematic errors are present. To verify that our data were free of such errors, we visually inspected the radio imagery and compared our flux densities with those from the literature. Visual inspection also revealed that few galaxies in our sample are extended Fanaroff & Riley (1974) class II radio sources. The flux densities of four galaxies neighboring bright radio sources could not be reliably measured, and excluding these galaxies reduced our final sample to 396 early-type galaxies. The properties of the sample galaxies are summarized in Table 1.

3. THE RADIO FLUX DENSITY AND LUMINOSITY DISTRIBUTIONS

The 1.4 GHz flux densities of the 396 $K < 9$ early-type galaxies are plotted as a function of $K$-band absolute magnitude in Figure 1. For the lowest mass galaxies, with $M_K \sim −22.5$, only a small fraction have counterparts in the NVSS catalogs and most galaxies have flux densities consistent with zero plus a random measurement error. In contrast, all 59 of the $M_K < −25.5$ early-type galaxies (corresponding to stellar masses of $\geq 2.5 \times 10^{11} M_\odot$) have measured flux densities greater than zero and just two of the 61 $−25.0 < M_K < −25.5$ early-type galaxies have measured flux densities below zero. As random errors will result in measured flux densities scattered above and below the true flux densities, it is highly likely that all $M_K < −25.5$ early-type galaxies in our sample are radio continuum sources, with flux densities of $\gtrsim 1$ mJy.

In Figure 2, we present the radio power of early-type galaxies as a function of $K$-band absolute magnitude. As noted by others (e.g., Fabbiano et al. 1989; Sadler et al. 1989), the radio powers of early-type galaxies are a strong function of absolute magnitude. Although our $K = 9$ mag limit excludes some extremely powerful radio sources (e.g., Cygnus A), the radio power of $M_K < −24$ galaxies at fixed $K$-band magnitude (or
stellar mass) still spans four orders of magnitude. The most massive galaxies can have 1.4 GHz powers as large as that of M 87 ($\approx 7 \times 10^{24}$ W Hz$^{-1}$) or less than the Milky Way ($\approx 4 \times 10^{21}$ W Hz$^{-1}$).

To model the distribution of radio powers, $P_{1.4}$, we have utilized a log-normal probability density function where

$$
\rho(P_{1.4}; \mu, \sigma) = \frac{1}{P_{1.4}\sigma\sqrt{2\pi}} \exp \left[ -\frac{(\ln P_{1.4} - \mu)^2}{2\sigma^2} \right],
$$

(1)

$$
\mu = \ln \left[ \alpha \left( \frac{L_K}{10^{11}L_\odot} \right)^\beta \right],
$$

(2)

$$
\sigma = \gamma \mu,
$$

(3)

where $L_K$ is the $K$-band luminosity and $\alpha$, $\beta$, and $\gamma$ are free parameters. This parameterization is empirical (i.e., lacks physical motivation) but, as discussed below, provides a good description of the observed distribution of radio powers as a function of $L_K$. If the radio emission from early-type galaxies was a function of $L_K$ and time only, then this parameterization would directly measure the radio duty cycle of early-type galaxies. However, the radio emission from early-type galaxies is a function of environment (host halo mass and location within a halo; e.g., Best et al. 2007; Wake et al. 2008; Mandelbaum et al. 2009), so this parameterization constrains rather than measures the duty cycle. The integral of the probability density function provides an estimate of the fraction of galaxies with luminosity $L_K$ that have radio powers above (or below) a particular threshold, and this can be compared with estimates from the prior literature (e.g., Best et al. 2005). The radio luminosity function can be derived by convolving the probability density function with the $K$-band luminosity function of early-type galaxies.

We used our model of the distribution of radio powers and an empirical model of the NVSS flux density measurement errors to determine the likelihood of a particular galaxy (with known luminosity distance and $M_K$) having a particular measured flux density. Our model of the NVSS flux density measurement errors is the distribution of flux densities measured in each pixel of the NVSS, so we account for the non-Gaussian error distribution and source confusion. We then used the maximum likelihood method to determine the best-fit values and uncertainties for our model of the radio powers of early-type galaxies. All galaxies were used when fitting the model, irrespective of their measured flux densities. However, $M_K > -23$ galaxies provide limited constraints on the model parameters, so our conclusions principally apply to $M_K < -23$ early-type galaxies. Our best-fit values for the log-normal distribution parameters $\alpha$, $\beta$, and $\gamma$ are $(1.16 \pm 0.20) \times 10^{20}$ W Hz$^{-1}$, $2.78 \pm 0.17$, and $(6.62 \pm 0.29) \times 10^{-3}$, respectively.

To verify our model, we have used it to generate 500 realizations of the anticipated observed properties of our sample, and four of these “mock catalogs” are plotted in Figure 3. Two-dimensional Kolmogorov–Smirnov tests (Peacock 1983) run on the mocks and the original sample show that the our model is consistent with the observed distribution of radio powers. We also used the mocks to test the assumption that the measured minimum flux density is an underestimate of the true minimum flux density for $M_K < -25.5$ early-type galaxies (due to random errors broadening the measured flux density distribution). For 96% of the mock catalogs, the measured minimum 1.4 GHz flux density is less than the true minimum 1.4 GHz flux density for $M_K < -25.5$ early-type galaxies. It is thus highly likely that all $M_K < -25.5$ early-type galaxies are radio continuum sources.

The median 1.4 GHz radio power of early-type galaxies is proportional to $K$-band luminosity to the power of $2.78 \pm 0.17$. For comparison, Fabbiano et al. (1989) and Sadler et al. (1989) find 5 GHz radio power is proportional to $B$-band luminosity to
the distribution of radio powers.

and mock catalogs, but these are not significant departures from our model of approximates what is seen in Figure 2. Apparent features are seen in the real absolute magnitude for four mock catalogs. The distribution of radio powers the power of $2^\frac{1}{2}$ Figure 3.

The most powerful radio sources in our sample are clearly early-type galaxies and their measured flux densities are greater than zero. To verify the presence of weak radio sources in massive galaxies, we have stacked NVSS images of the 16 $M_K < -25.5$ early-type galaxies without counterparts in the NVSS catalogs. For comparison, we have also stacked images of the 119 $M_K > -24$ early-type galaxies without counterparts in the NVSS catalogs. As we show in Figure 4, a 0.9 mJy source is present in the stack of massive galaxies, while radio emission is only marginally detected in the stack of lower mass galaxies. This is not unexpected, as the median radio power of early-type galaxies is an extremely strong function $K$-band absolute magnitude. The radio continuum emission from $M_K < -25.5$ early-type galaxies indicates that they are rarely (perhaps never) truly passive, as the vast majority harbor an AGN or have recently ($\lesssim 100$ Myr) undergone star formation.

While others have explored the correlations between radio power and environment (e.g., dark matter halo mass) in detail, two galaxies in our sample illustrate that any correlation between environment and radio power is likely to have considerable scatter. Coma cluster galaxies NGC 4874 and NGC 4889 (the brightest cluster galaxy) both have $M_K \simeq -26.2$ and RC3 T Types of $-4$, but their 1.4 GHz flux densities are 206 mJy and 1 mJy, respectively. This large difference in radio flux density for two otherwise similar galaxies suggests that the radio powers of early-type galaxies may vary by roughly two orders of magnitude over long periods of time.

4. WEAK RADIO SOURCES IN EARLY-TYPE GALAXIES

We have previously concluded that all $M_K < -25.5$ early-type galaxies are probably radio sources, as their measured flux densities are greater than zero. To verify the presence of weak radio sources in massive galaxies, we have stacked NVSS images of the 16 $M_K < -25.5$ early-type galaxies without counterparts in the NVSS catalogs. For comparison, we have also stacked images of the 119 $M_K > -24$ early-type galaxies without counterparts in the NVSS catalogs. As we show in Figure 4, a 0.9 mJy source is present in the stack of massive galaxies, while radio emission is only marginally detected in the stack of lower mass galaxies. This is not unexpected, as the median radio power of early-type galaxies is an extremely strong function $K$-band absolute magnitude. The radio continuum emission from $M_K < -25.5$ early-type galaxies indicates that they are rarely (perhaps never) truly passive, as the vast majority harbor an AGN or have recently ($\lesssim 100$ Myr) undergone star formation.

The most powerful radio sources in our sample are clearly AGNs, but the weakest radio sources could result from star formation. Star formation is known to produce $10^{31}$ W Hz$^{-1}$ of radio emission in some early-type galaxies (Wrobel & Heeschen 1988), which would result from just $\sim 1 M_\odot$ yr$^{-1}$ of star formation (Bell 2003). However, there are weak arguments for AGNs being responsible for the broad distribution of observed radio powers for $M_K < -25.5$ early-type galaxies. The radio emission in the stacked images is compact, as one may expect from low-luminosity AGNs, although the NVSS beam is 45$''$ wide. Slee et al. (1994) found parsec-sized radio cores in 70% of early-type galaxies, even when the total radio power was only $10^{22}$ W Hz$^{-1}$. If radio emission is being produced by
multiple mechanisms, one may expect an obvious superposition of multiple distributions. This should be the case for X-ray emission from early-type galaxies (e.g., Fabbiano et al. 1989), but we do not see this in the radio in Figure 2. However, these are not definitive arguments for the presence of radio AGNs in all massive galaxies and further observations are required. Inconsistencies between star formation rates derived from observations at radio and other wavelengths (e.g., mid-IR) may identify the weakest AGNs in early-type galaxies. Alternatively, AGNs may be identified using source sizes and brightness temperatures determined with high-frequency and high-resolution radio imaging.

5. SUMMARY

We have measured the 1.4 GHz radio continuum emission from $K < 9$ early-type galaxies, utilizing archival imagery from the NVSS, Green Bank 300 ft Telescope, and 64 m Parkes Radio Telescope. The distribution of radio powers at fixed absolute magnitude spans four orders of magnitude for $M_K < -24$ early-type galaxies, and the median radio power is proportional to $K$-band luminosity to the power $2.78 \pm 0.16$. Our analysis is not restricted to galaxies with high signal-to-noise radio detections, and the distribution of noisy flux density measurements provides important constraints on the radio emission from early-type galaxies. Relatively few low-mass early-type galaxies are detected with high signal to noise, and the flux density measurements for the remaining objects are scattered around zero. In contrast, most $M_K < -25.5$ early-type galaxies have robust detections, and the remaining galaxies consistently have flux density measurements greater than zero. As random measurement errors will broaden the measured distribution of flux densities, it is highly likely that all massive galaxies are radio continuum sources. If this is the case, all $M_K < 25.5$ early-type galaxies harbor an AGN or have recently undergone star formation.

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