The duty cycle of local radio galaxies

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ABSTRACT

We use a volume- and flux-limited sample of local \((0.03 \leq z \leq 0.1)\) radio galaxies with optical counterparts to address the question of how long a typical galaxy spends in radio active and quiescent states. The length of the active phase has a strong dependence on the stellar mass of the host galaxy. Radio sources in the most massive hosts are also retriggered more frequently. The time spent in the active phase has the same dependence on stellar mass as does the gas cooling rate, suggesting the onset of the quiescent phase is due to fuel depletion. We find radio and emission-line active galactic nuclei (AGN) activity to be independent, consistent with these corresponding to different accretion states.

Key words: galaxies: active – intergalactic medium – galaxies: jets – galaxies: luminosity function, mass function.

1 INTRODUCTION

Recent theoretical and observational evidence suggests that the growth of galaxies and supermassive black holes at their centres are closely related phenomena (Magorrian et al. 1998; Gebhardt et al. 2000; Haring & Rix 2004). As accretion on to these black holes is believed to power active galactic nuclei (AGN) jets, such AGN activity is thus intricately linked to the process of galaxy formation and evolution. The notion of AGN feedback through radio sources, where the AGN jets heat up and expel the surrounding gas, has received particular attention in recent times for a number of reasons. Jet heating of the intracluster gas (ICM) decreases the rate of accretion on to the central black hole, until it is shut off completely. Once the gas has had sufficient time to cool, the accretion can restart. Although one can envisage a stable configuration in which the accretion rate and gas heating are balanced, outward transport of central gas by the jet (e.g. Basson & Alexander 2003) implies that AGN heating must be sporadic in order to keep some gas available for fuelling (Kawata & Gibson 2005). Even if all the fuel is carried away from the central regions, the AGN jet can restart once this gas is replenished, for example via an interaction with another galaxy (Bahcall et al. 1997). Such an interaction will eventually lead to an increase in the accretion rate and hence a relaunching of the radio jets. This inherent intermittency of the feedback process is confirmed by observations of rising radio bubbles (Churazov et al. 2001) and multiple radio lobe pairs in the same source (Giovannini et al. 1998; Giovannini, Taylor & Arbizzani 1999; Venturi, Dallacasa & Stefanachi 2004). The intermittency also provides a natural way of keeping the black hole and spheroid growth in step. Furthermore, AGN heating has also been invoked to explain the lack of star formation in the most massive galaxies (the so-called cosmic downsizing; e.g. Croton et al. 2006), and suppression of cooling flows in the cores of massive clusters (Fabian et al. 2003; Forman et al. 2005).

The questions of how long an average radio source spends in an active state, and the length of time between outbursts, are thus crucial to quantifying the importance of AGN feedback. A number of methods have been employed in attempts to quantify these. The oldest and best known of these invokes spectral ageing and lobe expansion speed arguments (Alexander & Leahy 1987), yielding on times of a few \(10^7\) yr. Simulations suggest the jets will be disrupted after times of the order of \(10^8\) yr (Tucker & David 1997; Omma & Binney 2004); while energy injection rates required to quench cooling flows point to time-scales of the order of few \(10^7\) to few \(10^8\) yr (Owen & Eilek 1998; McNamara et al. 2005; Nulsen et al. 2005). Observations of revived radio relic sources (Ensslin & Gopal-Krishna 2001) constrain the time between outbursts to around \(10^9\) yr. The local radio-loud fraction of a few per cent (e.g. Best et al. 2005b) also suggests the radio sources spend an order of magnitude longer in their quiescent state than in the active state.

Radio source evolution depends strongly on both the environment of the radio source, and jet characteristics (Kaiser & Alexander 1997; Kaiser, Dennett-Thorpe & Alexander 1997; Alexander 2000; Kaiser & Cotter 2002). Recently, Best et al. (2005b) have found a strong dependence of the local \((0.03 \leq z \leq 0.1)\) radio-loud AGN fraction on the stellar mass of the host galaxy. In other words, it appears that the radio jets get retriggered more frequently in massive hosts. Best et al. (2005a,b) also investigated the relationship between radio and emission-line AGN activity by splitting their radio–optical sample into AGN and star-forming galaxies according to the diagnostics appropriate for each case, and found that these are different phenomena. This finding is confirmed by studies of radio and emission-line AGN activity in the brightest group and cluster galaxies (Best et al. 2007). In this work we investigate these...
intriguing results in more detail by employing a flux- and volume-limited sample of radio sources with host properties.

Much like Best et al. (2005a), we combine optical information available from the Sloan Digital Sky Survey (SDSS) Data Release 2 (York et al. 2000) with two radio surveys, NRAO VLA Sky Survey (NVSS; Condon et al. 1998) and Faint Images of the Radio Sky at Twenty Centimetres (FIRST; Becker, White & Helfand 1995) to construct a local \((0.03 \leq z \leq 0.1)\) radio–optical sample. Unlike previous works, which are only flux limited, however, our sample is both volume and flux limited at both the radio and optical (\(r\)-band) wavelengths. We also use a combination of the FIRST and NVSS 1.4-GHz fluxes, ensuring sensitivity to both compact and diffuse structures.

As the main focus of this work is on radio AGN activity, we split our sample into AGN and star-forming galaxies according to the radio diagnostic, and construct the bivariate radio–optical luminosity function by further dividing the AGN subsample in stellar mass. Radio source models are then used to fit individual source sizes and luminosities (as derived from the FIRST and NVSS catalogues) and derive the typical length of the active phase as a function of stellar mass. Observed bivariate luminosity functions then set the time a radio source spends in a quiescent state.

The paper is structured as follows. In Section 2 we describe our volume- and flux-limited sample. Separation into AGN and star-forming galaxies, as well as the resultant radio and bivariate luminosity functions, are discussed in Section 3. Section 4 outlines our radio source model, and the results are presented in Section 5. We conclude with a discussion of our findings in the context of AGN fuelling mechanisms in Section 7.

Throughout the paper we assume the cosmological parameters \(\Omega_M = 0.3, \Omega_{\Lambda} = 0.7\) and \(H_0 = 70\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}\).
Table 1. FIRST/SDSS and NVSS/SDSS catalogue matching summary. For FIRST/SDSS we adopt 3 arcsec as the separation distance with the best compromise between maximum completeness and minimum contamination. For NVSS/SDSS the corresponding value is 15 arcsec.

| Separation (arcsec) | Real matches | Completeness (per cent) | False matches | Contamination (per cent) |
|---------------------|-------------|-------------------------|---------------|--------------------------|
| FIRST/SDSS          |             |                         |               |                          |
| 1.5                 | 2243        | 87.7                    | 0             | 0                        |
| 3                   | 2391        | 93.4                    | 2             | 0                        |
| 5                   | 2448        | 95.7                    | 13            | 0.5                      |
| 10                  | 2553        | 99.8                    | 77            | 3.0                      |
| 20                  | 2814        | 100                     | 289           | 11.3                     |
| 30                  | 3221        | 100                     | 651           | 25.4                     |
| 40                  | 3745        | 100                     | 1186          | 46.3                     |
| NVSS/SDSS           |             |                         |               |                          |
| 5                   | 1205        | 43.5                    | 15            | 1.2                      |
| 10                  | 2001        | 72.2                    | 62            | 3.1                      |
| 12                  | 2200        | 79.4                    | 81            | 3.7                      |
| 15                  | 2393        | 86.3                    | 119           | 5.0                      |
| 20                  | 2656        | 95.8                    | 202           | 7.6                      |
| 40                  | 3600        | 100                     | 880           | 24.4                     |
| 60                  | 4799        | 100                     | 2027          | 42.2                     |

Table 2. Flux criteria.

| Use FIRST flux                                                                 | Use NVSS flux                                                                 |
|-------------------------------------------------------------------------------|-------------------------------------------------------------------------------|
| F1 Source is compact in FIRST (possibly extended in NVSS) and there are other compact sources in the NVSS envelope or a source with no obvious connection to the central FIRST/SDSS source of interest | N1 Source is compact in FIRST (possibly extended in NVSS) with no other obvious unrelated sources in the NVSS envelope |
| F2 No catalogued source in NVSS because either the NVSS field is empty or the flux detected by NVSS is too low to be officially identified as a source | N2 Source is extended in NVSS or unresolved and will need integrating |
| F3 Source is confused in NVSS but potentially included in FIRST and will need integrating | N3 Source is extended in NVSS within the FIRST envelope with no other unrelated sources in either field and NVSS flux is complete |
| F4 Calculated integrated flux is higher in FIRST and/or assumed to be more accurate | N4 Source not detected in FIRST because emission is too diffuse and/or extended |

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3 THE LOCAL RADIO LUMINOSITY FUNCTION

3.1 Observed luminosity function

We construct the radio luminosity function (RLF) for our radio flux- and volume-limited sample. In our cosmology, sources with $L_{1.4\text{ GHz}} < 8 \times 10^{22}\text{ W Hz}^{-1}$ are too weak to be detected throughout the observed volume, and are only seen because of their low redshifts. For these sources we apply the usual $V/V_{\text{max}}$ correction (Condon 1989). The resultant RLF is given in Table 3 and also plotted in Fig. 1, along with relevant previous works.

The sample is split into star-forming galaxies and AGNs. Traditionally, this is done using the emission-line properties of the objects as given by their location in the [O III] 5007/H$\beta$–[N II] 6583/H$\alpha$ plane (Baldwin, Phillips & Terlevich 1981; Sadler et al. 2002; Kauffmann et al. 2003b). However, Best et al. (2005a) found that the radio and emission-line AGN activity are independent phenomena, and argued that the 4000-Å break, $D_n(4000)$, represents the best way of separating the radio AGN from their star-forming counterparts. This break is a consequence of accumulation of a large number of spectral lines in a narrow region in wavelength, and depeps significantly from unity for older, metal rich galaxies (Kauffmann et al. 2003b). Using derived star formation rates, Best et al. (2005a; their fig. 9) calculated the contribution of stellar emission to the 1.4-GHz flux.
luminosity and compared this with measured values to derive a demarcation in the $D_{2}(4000)$–$L_{1.4\,\text{GHz}}/M_*$ plane separating the objects into radio AGN and star-forming galaxies. Since in this work we are primarily concerned with the radio AGN activity, we adopt this demarcation. Stellar mass $M_*$ for each object was evaluated by using the Petrosian $z$-band magnitude, and assuming that all stars are of solar type. Corrections for dust obscuration were made by comparing $z$- and $K$-band fluxes. Nikolic (2005) found $z - K = 2.5$ for our sample, and thus the stellar masses derived from $z$-band luminosities are underestimated by a factor of 3.2. Proceeding in this way, we find 653 radio-loud AGN and 538 star-forming galaxies. The resultant RLFs are given in Table 3 and plotted in Fig. 2.

The total luminosity function is in good agreement with previous studies at high luminosities, $L_{1.4\,\text{GHz}} > 10^{23}$ W Hz$^{-1}$. At luminosities below this value, however, our luminosity function is systematically lower than those of other authors. It is due to the fact that we are using a volume-limited sample, and have introduced a cut-off of $-20.45$ in $r$-band magnitude. The radio–optical correlation at low ($L_{1.4\,\text{GHz}} < 10^{23}$ W Hz$^{-1}$) luminosities means that in discarding objects with lower $r$-band magnitudes we are also excluding some radio sources. In Fig. 3 we illustrate this effect by binning our sample in radio luminosity, and plotting distributions of $r$-band magnitudes in each bin. There are relatively few objects with $M_r > -21.8$ at higher radio luminosities; however, when $L_{1.4\,\text{GHz}} < 10^{23}$ W Hz$^{-1}$ there is a significant contribution from galaxies with $M_r > -21.8$, suggesting that there is also an appreciable number of low-luminosity radio sources with $M_r > -20.45$ that we have discarded due to our optical completeness limit. Not surprisingly, the difference between our luminosity function and those for flux-limited samples becomes apparent at around $10^{22.5}$ W Hz$^{-1}$.

It is worth noting that the 4000-Å break is not the only way to separate star-forming galaxies from radio AGNs in our sample. Another possible method is to use the concentration index, defined as the ratio of Petrosian $50–90$ per cent light radii, $C = R_{50}/R_{90}$. Low values of $C (\sim 0.33)$ correspond to early-type galaxies, which are more likely to harbour powerful radio sources, while late-type (star-forming) galaxies are those with $C > 0.375$. We have carried out the subsequent analysis using both the $D_e(4000)$ and concentration index diagnostics to split up our sample, and found very similar results. Therefore, only the 4000-Å break demarcation findings are presented here.

### 3.2 Bivariate luminosity function

We construct a bivariate luminosity function by binning all objects in stellar mass and plotting the RLF for each bin. Fractions plotted represent the number of AGNs in a certain stellar mass range brighter than a given radio luminosity, divided by the total number of objects in that stellar mass bin. Again, corrections using the $V/V_{\text{max}}$ method (Condon 1989) were applied. As $r$ and $z$ spectroscopic bands largely track the same population of old bulge stars, we expect completeness in $r$-band to imply that our sample is also complete in $z$-band, and hence in stellar mass. The bivariate luminosity function is shown in Fig. 4.

The most striking feature of the bivariate luminosity function is the strong mass dependence of the radio-loud fraction (equal to the cumulative fraction in the lowest radio luminosity bin). This result was also found by Best et al. (2005b), with the radio-loud fraction $f_{\text{RL}} \propto M_*^{1.8}$. A vital question is whether this implies that in the
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4 RADIO SOURCE MODEL

4.1 Source evolution

We model radio-loud AGN as an evolutionary phase in the lifetime of every galaxy. The source is radio-loud when the synchrotron jet is ‘on’; and once it switches off or the source luminosity falls below the detection threshold, the source becomes radio-quiet. We assume the black hole mass is already in place when the jet switches on, consistent with results of various semianalytic models (e.g. Kauffmann & Haehnelt 2000; Bower et al. 2006; Croton et al. 2006) and observed black hole accretion rates in quasars (Hopkins, Narayan & Hernquist 2006; Yu & Tremaine 2003), and hence jet injection is represented by a top hat function, with the durations of on and off phases denoted as $t_{on}$ and $t_{off}$.

To account for the initial rise in the source radio power, we assume the source initially evolves in a flat atmosphere (such as a galaxy core), followed by two power-law profiles of the form $\rho(r) \propto r^{-\gamma}$ corresponding to expansion within a galaxy, followed by a steeper cluster atmosphere (see Fig. 5). We adopt the models of Alexander (2000) for the initial evolution within the core, and Kaiser & Alexander (1997) and Kaiser et al. (1997) for evolution in a power-law profile. As the radio source ages, it will suffer adiabatic, synchrotron and inverse Compton losses. Once energy supply from the jet ceases, we assume the radio luminosity quickly drops to a value below our detection threshold. In practice, the cocoon will enter a ‘coasting’ phase (Kaiser & Cotter 2002); however the radio luminosity declines rapidly in this phase, rendering our approach sufficiently accurate.

These models describe the evolution of powerful (Fanaroff–Riley type II; FR II) radio sources. Although our sample consists of both these objects and the less powerful FR IIs, our approach is justified in the following sections by the relative paucity of resolved sources with FR I morphologies.

Figure 2. Local RLF at 1.4 GHz for (a) AGN and (b) star-forming galaxies as classified by a demarcation in the $D_{40000} - L_{1.4 \text{GHz}}/M_\ast$ plane (Best et al. 2005a). There is good agreement between our work and other studies for $L_{1.4 \text{GHz}} > 10^{23} \text{W Hz}^{-1}$. However, the luminosity functions diverge at luminosities below this value. This is especially evident in the case of the star-forming galaxies, and is due to our cut-off in $r$-band optical magnitude and the $M_\ast - L_{1.4 \text{GHz}}$ correlation (see Fig. 3).

Figure 3. Cuts through the bivariate radio–optical luminosity function. At high ($L_{1.4 \text{GHz}} > 10^{23} \text{W Hz}^{-1}$) radio luminosities only very few objects have low enough $r$-band absolute magnitudes to be affected by our optical completeness limit. However, objects with optical magnitudes at or below our completeness cut-off of $M_r = -20.45$ become important for $L_{1.4 \text{GHz}} < 10^{23} \text{W Hz}^{-1}$. These missing sources account for the differences between our flux- and volume-limited luminosity function, and those derived from samples that are only flux limited.

Figure 4. Bivariate luminosity function, with objects binned by stellar mass as calculated from the $z$-band magnitude (see text). Cumulative fraction of AGNs within a given $M_\ast$ range brighter than the specified radio luminosity [fraction $(L) = N_{L_{1.4 \text{GHz}} > L}/N_{\text{total}}$] is shown.

more massive hosts the radio sources are on for longer, or whether they are simply triggered more frequently (with the duration of a typical active phase being the same for all masses). We address this question in subsequent sections by employing detailed radio source modelling.
Figure 5. Radio source and environmental parameters. The collimated jet expands into the ICM described by a core and double power law, and eventually terminates in a hotspot, inflating a cocoon of synchrotron-emitting radio plasma. Because the jet is supersonic, a bow shock forms ahead of the cocoon, and a contact discontinuity separates the entrained gas from the radio plasma (see Kaiser & Alexander 1997).

For an active jet, source size and radio luminosity are functions of core density $\rho_{\text{core}}$, core radius $r_{\text{core}}$, transition radius $r_{\text{trans}}$ between the galaxy and cluster power laws, density exponents $\beta_{\text{galaxy}}$ and $\beta_{\text{cluster}}$, jet opening angle $\theta$ (related to the axial ratio $R_T$ of the source) and jet power $Q_{\text{jet}}$. In adopting values for these parameters we are guided by observations of nearby X-ray luminous elliptical galaxies and relaxed clusters. In the inner regions (Allen et al. 2006), power-law exponents $\beta \sim 0.8-1.2$ and core radius $r_{\text{core}} \sim 1$ kpc provide a good fit to $r \sim 10$ kpc. Density profiles of nearby relaxed galaxy clusters (Vikhlinin et al. 2006) are well fitted by a double power law, with inner regions having $\beta_{\text{galaxy}} \sim 0.8-1.1$, and $\beta_{\text{cluster}} \sim 1.8-2.6$. Transition between the two power laws occurs at $r_{\text{trans}} \sim 50-200$ kpc. As Fig. 6 illustrates, radio source tracks in the power–size (P–D) plane are rather flat and hence not very sensitive to the exact value of $\beta_{\text{galaxy}}$ for $0.8 \leq \beta_{\text{galaxy}} \leq 1.2$ until the late phases (1 to a few $\times 10^8$ yr) of their lifetimes, when the sources begin to suffer appreciably from inverse Compton losses (Kaiser et al. 1997) and/or enter the steeper part of the atmosphere. At that point, the losses will typically be the dominant factor in determining the radio power of the source. This allows us to fix $\beta_{\text{galaxy}} = 1.0$, $\beta_{\text{cluster}} = 1.9$ and $r_{\text{trans}} = 50$ kpc in our models. Conservation of mass then sets the electron density within the core to be $n_{\text{core}} \sim 0.1$ to few $\times 0.1$ cm$^{-3}$, and we adopt $n_{\text{core}} = 0.2$ cm$^{-3}$ from the Allen et al. (2006) sample. Following observations of Cygnus A (Begelman & Cioffi 1989) we also set $R_T = 2.0$, corresponding to a jet opening angle of 31° (Kaiser & Alexander 1997).

4.2 Dependence of predicted RLF on model parameters

Given durations of jet ‘on’ and ‘off’ time-scales, we can now predict the RLF for a population of such sources observed at random stages in their evolution. Fig. 7 explores the dependence of the RLF on input parameters. We adopt the same base quantities as above, in addition taking the scatter in jet power (as expected from the observed $M_{\text{BH}}-M_*$ (Magorrian et al. 1998; H"aring & Rix 2004) and $Q_{\text{jet}}-M_{\text{BH}}$ (Allen et al. 2006) relations) to be 0.8 dex. The jet is 10$^1\sim 10^2$ kpc; short-dashed curve is for 1 kpc in our models. Contraction between the galaxy and cluster power laws, density exponents $\beta_{\text{galaxy}}$, and transition radius $r_{\text{trans}}$. Long-dashed curve is for $\beta_{\text{galaxy}} = 0.8$, $r_{\text{trans}} = 50$ kpc; dotted curve is for $\beta_{\text{galaxy}} = 1.0$, $r_{\text{trans}} = 50$ kpc; short-dashed curve is for $\beta_{\text{galaxy}} = 1.2$, $r_{\text{trans}} = 50$ kpc; and solid curve for $\beta_{\text{galaxy}} = 1.0$, $r_{\text{trans}} = 20$ kpc. Also shown are the time markers of 10$^7$, 10$^8$, 10$^9$ and 3 $\times$ 10$^9$ yr. The source luminosity does not evolve substantially until it begins to suffer significant inverse Compton losses, which happens around the same time as the source enters the steeper part of the atmosphere.

Figure 6. Example radio luminosity–size tracks for sources evolving in different atmospheres. In all cases the adopted parameters are $\rho_{\text{core}} = 3.7 \times 10^{-22}$ kg m$^{-3}$ (corresponding to $n_{\text{core}} = 0.2$ cm$^{-3}$), $r_{\text{core}} = 1$ kpc, $\beta_{\text{cluster}} = 1.9$, $R_T = 2$ and $Q_{\text{jet}} = 3 \times 10^{35}$ W. Evolution for $t_{\text{on}} = 5 \times 10^8$ yr is shown. Varied parameters are the inner density exponent, $\beta_{\text{galaxy}}$, and transition radius $r_{\text{trans}}$. Long-dashed curve is for $\beta_{\text{galaxy}} = 0.8$, $r_{\text{trans}} = 50$ kpc; dotted curve is for $\beta_{\text{galaxy}} = 1.0$, $r_{\text{trans}} = 50$ kpc; short-dashed curve is for $\beta_{\text{galaxy}} = 1.2$, $r_{\text{trans}} = 50$ kpc; and solid curve for $\beta_{\text{galaxy}} = 1.0$, $r_{\text{trans}} = 20$ kpc. Also shown are the time markers of 10$^7$, 10$^8$, 10$^9$ and 3 $\times$ 10$^9$ yr. The source luminosity does not evolve substantially until it begins to suffer significant inverse Compton losses, which happens around the same time as the source enters the steeper part of the atmosphere.

To explore the sensitivity of our predicted cumulative RLFs on model parameters, each of these parameters is varied in turn (with the others fixed). The relative unimportance of the exact density profile of the atmosphere into which the source is expanding, as discussed above, is the reason very similar RLFs are predicted for various $r_{\text{trans}}$ and $\beta_{\text{cluster}}$ values in Figs 7(a) and (b). Significantly, this implies that very similar RLFs are also predicted for sources of very different ages, so long as the duty cycle (i.e. $t_{\text{on}}/t_{\text{off}}$) remains the same, and sources are not old enough for inverse Compton losses to dominate. This is shown in Fig. 7(c), where we vary the jet on time, while keeping $t_{\text{on}}/t_{\text{off}}$ constant. The duty cycle is the main factor determining the number of radio-quiet sources, since the fraction of sources old enough to drop below the luminosity detection threshold is expected to be relatively small. This is illustrated in Fig. 7(d), where duration of the active phase is kept constant, while the length of the quiescent phase is varied.

The flatness of the tracks for ages less than a few Myr for a range of power-law exponents in Fig. 6 also implies that the RLF is also not very sensitive to changes in the density profile within the galaxy. This is seen in Fig. 7(e). The ‘characteristic’ luminosity of a source before it suffers significant inverse Compton losses is largely determined by mean jet power (Fig. 7f), core radius (Fig. 7g) and density (Fig. 7h), and axial ratio (Fig. 7i) of the source, in the sense that higher values of $Q_{\text{jet}}$, $r_{\text{core}}$, $\rho_{\text{core}}$ and lower value of $R_T$ result in higher characteristic luminosities. Finally, effects of scatter in jet power are shown in Fig. 7(j). As expected, larger scatter in jet power results in less sources at the break (or ‘characteristic’) luminosity, and hence a broader distribution of sources across the radio luminosity bins. The crucial feature of these plots is that they clearly show that changes in most of the parameters only result in redistributing the radio-loud sources.
fraction is \( t_{\text{off}} / t_{\text{on}} \), i.e. the duty cycle. Hence observed radio-loud fractions place tight constraints on relative durations of the radio active and quiescent phases in our sample.

Our sample is complete to \( L_{1.4} = 8 \times 10^{22} \text{ W Hz}^{-1} \), rather than the \( 10^{23} \text{ W Hz}^{-1} \) plotted in Fig. 7. Therefore, only sources with luminosities brighter than this value can be used to constrain the models. Inspection of Fig. 7 shows that the discussion above is still applicable, although jet and environmental parameters affect the total radio-loud fraction to a larger degree for this higher \( L_{1.4} \) value.

5 DURATION OF RADIO ACTIVE AND QUIESCENT PHASES

5.1 Source sizes

It is clear from Section 4.2 that observed RLFs can be used to constrain the duty cycles (i.e. relative lengths of the radio active and quiescent phases); however, it is difficult to place constraints on actual values of \( t_{\text{on}} \) and \( t_{\text{off}} \). Instead, only tentative upper or lower limits can be placed on these. The former would correspond to a case where the best fit to the observed RLF is for a population of
sources that do not suffer significant inverse Compton losses; and the latter to a case when they do.

A much better constraint on these time-scales is obtained by considering source sizes. For a constant jet power, dynamical models of Kaiser & Alexander (1997), Kaiser et al. (1997) and Alexander (2000) predict source sizes as well as radio luminosities as a function of time (see Fig. 6). Sources are observed at various stages in their lifetimes, and it is the oldest sources that give an estimate of either the duration of the active phase, or the age of the source when its radio luminosity falls below our detection threshold. The discussion of Section 4.1 suggests the latter case will only occur for very weak jets, and even then this is unlikely.

Contour maps of the 1191 radio-loud sources in the present sample allow source sizes to be determined. Sizes of sources with prominent lobes (FR II s) were determined manually. Defining source size for low-luminosity FR I s is not easy, since the source surface brightness decreases smoothly with distance from the nucleus. For the purposes of a comparative analysis within the presented sample, however, it is sufficient to adopt catalogued NVSS and FIRST major and minor axes FWHM.

Strictly speaking, the radio source model employed in this work only describes the evolution of FR II sources. However, two points justify its applicability to the whole radio source population in our sample. Fig. 12 shows that there are relatively few bona fide FR Is. The largest sources are invariably FR II s, and at smaller sizes the sample is dominated by sources that are only just resolved (and hence are those sources for which morphologies cannot be reliably determined). As all radio sources undergo an initial phase of supersonic expansion, we expect the FR II model to provide an accurate description of this subpopulation. Once the supersonic jets are disrupted, observed distributions of source sizes (Kaiser & Best 2007) and theoretical considerations (Alexander 2000) suggest source luminosities quickly drop below the detection threshold. We performed the analysis outlined below on both the full radio source sample, and with FR Is excluded, and obtained identical results. This justifies our application of the radio source model to FR I sources, and in what follows we present the results for the whole population.

5.2 Orientation effects

No spectral information is available for the catalogued radio sources. This means various orientation effects must be considered when interpreting source properties such as size and luminosity. The observed quantities will only correspond to actual source parameters for sources that are observed face-on. Any other orientation (i.e. beaming) conspires to decrease the apparent source size, and increase its luminosity. In other words, the source must be moved right and down in the P–D plane from the observed position.

Consider a source subtending angle $\phi$ to the line of sight. If the source has size $D$, its projected size will be $D_{\text{app}} = D \sin \phi$. The apparent luminosity is related to intrinsic luminosity via (Blandford & Königl 1979) $L_{\text{app}} = L_{\text{core}} \delta_0^{3/4}$, where $\delta_0 = [(1 - \beta_D^2)^{1/2} (1 - \beta_D \cos \phi)]^{-1}$ is the Doppler factor for $\beta_D = v_{\text{source}}/c$ and $\alpha$ is the spectral index of the source.

Observations of powerful radio galaxies (Hardcastle et al. 1998) suggest $v_{\text{source}} \sim 0.8 c$, and adopting $\alpha = 0.8$ we have

$$L_{\text{app}} \approx (1 - 0.8 \cos \phi)^{-3.8} \left(\frac{D_{\text{app}}}{D}\right) = \sin \phi. \quad (1)$$

![Figure 8. Probability of detecting a source with flux below the catalogue threshold, $S < S_{\text{min}}$. The non-relativistic extended component of the flux is not affected by beaming.](image)

The solid angle subtended by $\phi$ is $\Delta \Omega = 2\pi (1 - \cos \phi)$. In accordance with AGN unification models there should be no preferred direction for the beaming, and hence this solid angle is directly related to the probability of the major axis of the radio source being directed within $\phi$ of the line of sight. A convolution of this probability with the expression for $L_{\text{app}}$ in Equation (1) then gives the probability of a source with luminosity $L$ (or flux $S$) below the flux threshold (3.4 mJy for the present sample) being detected due to the beaming. Fig. 8 plots this probability as a function of intrinsic source flux.

Most radio sources contain a core component as well as more extended emission such as lobes. Since only the relativistic core component will be beamed, the level of sample contamination by low-luminosity sources is sensitive to the adopted core-to-total flux ratio, with core-dominated sources prone to substantial beaming. In general this effect is difficult to quantify. However, the presented sample is volume limited. This means that the objects were selected according to their optical properties, which are unaffected by orientation. Moreover, the correlation between optical and radio luminosities at the low-luminosity end of the sample (Section 3.1 and Fig. 3) suggests there are very few sources with uncharacteristically high radio luminosities. Thus the radio luminosities of objects in the sample are unlikely to be greatly affected by beaming.

The apparent source sizes will not be affected by the beaming by anywhere near the same amount as the luminosities. For $\Delta \Omega/4\pi = 0.01$ equation (1) gives $D_{\text{app}}/D = 7$, while $L_{\text{app}}/L_{\text{total}} = 1/200$. For an appreciable solid angle of $\Delta \Omega/4\pi = 0.3$ this value drops to $D_{\text{app}}/D = 1.4$, while $L_{\text{app}}/L_{\text{total}} = 1/25$. Hence any orientation-related corrections are likely to affect the derived radio luminosities to a much greater extend than source sizes. As a zeroth-order approximation, the source will move (almost vertically) down in the P–D plane. This introduces larger errors in the derived jet powers than source ages.

6 DERIVED SOURCE PROPERTIES

6.1 Jet powers

For a given atmosphere and cocoon axial ratio, a source with specified radio luminosity and size can only be described by a single evolutionary track. Hence, adopting the density profiles of Section 4.2 and once again taking $R_f = 2$, the position of a source in
the P–D plane uniquely defines its age and jet power. Proceeding in this fashion, we derived jet powers and ages for every source classified as a radio-loud AGN. The corresponding jet powers are plotted as a function of stellar mass in Fig. 9. Although the scatter is large, the more massive hosts contain less sources with lower (log \( Q_{\text{jet}} \) < 35.5 W) jet powers.

This point is illustrated in Fig. 10, where we plot the jet power fractile ranges for various stellar mass bins. In the bulk of the sample (0.3–0.8 fractile ranges) all mass bins follow a similar trend, with the more massive hosts consistently hosting more powerful radio sources.

The mean jet power (Table 4) increases with stellar mass as \( \bar{Q}_{\text{jet}} \propto M_{\odot}^{0.6 \pm 0.2} \). Benson et al. (2007) analysed a sample of \(~9000\) SDSS galaxies and found that almost all stellar mass is located in the spheroid component for the stellar masses considered in the present sample. Hence \( \bar{Q}_{\text{jet}} \propto M_{\text{bulge}}^{0.6 \pm 0.2} \) or \( \bar{Q}_{\text{jet}} \propto M_{\text{BH}}^{0.5 \pm 0.5} \) using the 0.3 dex scatter in the \( M_{\text{BH}}–M_{\text{bulge}} \) relation (Haring & Rix 2004). This is significantly less steep than the \( Q_{\text{jet}} \propto M_{\odot}^2 \) expected from Bondi accretion, suggesting there exists some factor limiting the accretion/outflow process. The more massive galaxies also show a larger fraction of high \( Q_{\text{jet}} \) values (i.e. a larger scatter at the high-\( Q_{\text{jet}} \) end; see Table 4). Since it is the number of powerful sources that determines the shape of the RLF at the bright, low number counts end, these values for the scatter in jet power are adopted when fitting the observed bivariate luminosity function below.

**Table 4.** Jet powers and time-scales determined from observed RLFs and source distribution in the P–D plane. Jet powers and median source ages are determined from observed source sizes using parameters of Section 4.2.

| \( M_\ast (M_\odot) \) | \( \bar{Q}_{\text{jet}} \) (W) | \( \sigma_{\log Q_{\text{jet}}} \) (W) | \( t_{\text{on,median}} \) (yr) | \( t_{\text{off,median}} \) (yr) | \( t_{\text{off}} \) (yr) |
|-----------------|----------------|----------------|----------------|----------------|----------------|
| \( > 11.76 \)   | 35.6           | 1.0            | \( 5 \times 10^6 \) | 2              | \( 2 \times 10^7 \) |
| 11.56–11.76     | 35.5           | 0.7            | \( 4 \times 10^6 \) | 6              | \( 5 \times 10^7 \) |
| 11.36–11.56     | 35.5           | 0.7            | \( 3 \times 10^6 \) | 6              | \( 10^8 \) |
| 11.16–11.36     | 35.5           | 0.7            | \( 10^6 \)       | 6              | \( 10^8 \) |
| 10.96–11.16     | 35.5           | 0.7            | –               | –              | –               |

**6.2 Independence of optical and radio AGN activity**

Best et al. (2005b) considered the relation between emission-line and radio AGN activity in their sample in two ways. First, they looked at the distribution of \([\text{O}\text{III}]\) luminosities as a function of radio luminosity, and found there to be no correlation between the two quantities for their (mostly low \( L_{1.4\text{GHz}} \) ) sample (their fig. 5). Secondly, Best et al. compared the radio-loud AGN fractions as a function of stellar mass in emission-line and optically inactive AGN, finding no significant difference between the two (their fig. 7). These findings suggest that whether or not a given object is classified as an emission-line AGN or a normal galaxy has no bearing on how likely it is to host a radio AGN. An identical analysis of our sample confirmed these results.

Using radio source models, we extend this analysis to investigating the radio jet power dependence on \([\text{O}\text{III}]\) line luminosity, as shown in Fig. 11.

The \([\text{O}\text{III}]\) luminosity probes the narrow-line region, and is thus indicative of the AGN bolometric luminosity. No correlation

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**Figure 9.** Distribution of jet power as a function of bulge mass. These are derived by combining observed source sizes and luminosities with the radio source model. Radio source and environmental parameters of Section 4.1 are used for the modelling.

**Figure 10.** Fractile distribution of jet power for the top four stellar mass bins. Lowest mass bins are not shown due to large numbers of unresolved sources in these affecting the statistics significantly. Massive galaxies host more powerful jets.

**Figure 11.** Distribution of jet power with \([\text{O}\text{III}]\) line luminosity for the radio AGN subsample. The Rawlings & Saunders (1991) relation is shown by a dashed line.
between $Q_{\text{bol}}$ and $L_{\text{bol}}$ is observed in the largely low radio luminosity sample presented here. By contrast, using spectral ages to estimate jet powers, Rawlings & Saunders (1991) found a tight relation between narrow-line optical luminosity and jet power in powerful radio sources; this is shown in Fig. 11 by a dashed line. The fact that no such correlation exists for low-luminosity radio sources confirms the claim of Best et al. that radio and optical AGN activity are distinct phenomena in these objects. An intriguing possibility is that these correspond to different accretion states. In this picture, powerful radio jets would be fuelled when the accretion disc is in a radiatively inefficient, low-luminosity state; while optical AGNs are detected when the disc is radiatively efficient and correspondingly the jet power is low (Narayan, Mahadevan & Quataert 1998; Meier 2001).

### 6.3 Active time-scales

The distribution of sources in the P–D plane can also be used to place constraints on radio source ages. Fig. 12 shows the observed for each $M_*$ bin. Also plotted are P–D tracks for $\log Q_{\text{jet}} = \log Q_{\text{jet}} \pm 1$ using the parameters of Section 4.2 and the derived distribution of jet powers given in Table 4. Curves corresponding to source ages of $10^5$ and $3 \times 10^8$ yr are given for guidance; these are the dotted, almost vertical lines. Finally, limits on the maximum detectable size of a source with given luminosity and redshift are plotted as straight coloured lines in log–log space. Very dim extended sources, such as radio relics, would fall below these limits. As discussed in Section 2.2, these are largely missed by the pairing process employed in constructing the present catalogue. However, since in this work the emphasis is on the currently active radio sources, this selection effect does not alter the analysis. More importantly, Fig. 12 shows that there are no resolved sources (i.e. those sources whose positions are well defined in the P–D plane) close to the NVSS detection threshold (green line). Thus it is unlikely that a significant number of large radio sources is missed.

Inspection of Fig. 12 shows that although large (and hence old) sources are found in all mass bins, the median source size is smaller in lower mass bins. Fig. 13 quantifies this statement by using the derived source ages and once again plotting the fractile ranges. Unresolved sources pose a problem for this approach, since only upper limits on their sizes are available. We assume that all unresolved sources have very small sizes and are thus younger than the smallest resolved sources. While crude, this assumption is sufficiently accurate for the highest stellar mass bins, where the unresolved number counts are low, and there are many sources larger than the upper unresolved limit. However, no meaningful information can be extracted for $\log M_*/M_\odot \lesssim 11.16$.

Much like jet powers, the derived source ages appear to depend strongly on stellar mass, with the most massive galaxies hosting older sources. Using the median $t_{\text{on}}$ values (Table 4) we find $t_{\text{on}} \propto M_*^{1.1}$.  

### 6.4 Quiescent time-scales

Duration of the quiescent phase $t_{\text{off}}$ is found from the bivariate luminosity function. Fig. 14 plots the best fits to the observed RLF for each stellar mass bin. Parameters of Sections 4.2 and 5.1, and jet powers given in Table 4, are adopted. The only adjustable parameters are the jet on and off times.

As discussed in Section 4.2, it is difficult to constrain the active phase duration from the RLF alone. However, the RLFs are very sensitive to the ratio $t_{\text{on}}/t_{\text{off}}$. Therefore, combining $t_{\text{on}}$ estimates from observed source sizes with constraints on the duty cycle from the luminosity functions yields $t_{\text{off}}$ values for each $M_*$ bin. These are given in Table 4, where $t_{\text{on}}$ is calculated from the median values of Table 4 by assuming that a typical radio source with a given stellar mass will be active for $2t_{\text{on,median}}$, i.e. it is observed halfway through its evolution.

### 7 DISCUSSION

#### 7.1 Robustness of time-scale estimates

It is important to consider how reliable the time-scales derived in the preceding section are. The ratio $t_{\text{off}}/t_{\text{on}}$ is largely set by the radio-loud fraction in each bin (see Section 4.2), and hence uncertainties in this quantity are comparable with Poisson errors in the corresponding luminosity function. These are clearly negligible in comparison with variability in parameters such as the density profile, jet power and cocoon axial ratio, all of which are important for individual source age determination.

The dynamical model of Kaiser & Alexander (1997) relates the size of a source expanding in a power-law atmosphere with exponent $\beta$ to its age $t$ and various cocoon and ICM parameters via

$$D \propto R_T^{5(5-\beta)} \left( \frac{Q_{\text{jet}}}{\rho_{\text{core}} \rho_{\text{f}}} \right)^{1.5(5-\beta)}.$$

Here, the cocoon axial ratio $R_T$ is inversely proportional to jet opening angle $\theta$. For the majority of our sample we do not expect $\theta$ to vary by more than a factor of 2, and as $t \propto R_T^{-1/3}$ we do not expect the axial ratio to affect our source age determinations by more than about a factor of 2 also.

Neglecting relativistic electron energy loss processes (adiabatic and radiative), Kaiser et al. (1997) model gives

$$L_{\text{radio}} \propto \left( \frac{\rho_{\text{core}} \rho_{\text{f}}}{\rho_{\text{f}}} \right)^{12} C_{\text{jet}}^{12} \rho_{\text{f}}^{12} D^{16-4(p+1)-5\beta}/12,$$

where $p = 2.14$ is the power-law exponent of the electron energy distribution. Rearranging yields

$$L_{\text{radio}} \propto Q_{\text{jet}}^{1.5(5-\beta)} \rho_{\text{f}}^{-5(5-\beta)}.$$

where $x = [66 + 6p - 3(p + 5\beta)/12(5 - \beta)]$ and $y = [(9 + 4p) + \beta (p + 5 - \beta)]/12[5 - \beta]$. In deriving individual source jet powers in Section 5.1 we had to assume a density profile. However, from equation (2) it is clear that source size does not depend on $Q_{\text{jet}}$ or the density profile individually, but instead the combination $q = Q_{\text{jet}}/\rho_{\text{f}}$. By knowing both the source radio luminosity and size, and using equations (2) and (4) we arrive at $q \propto q^{1/\beta}$ for $x < 2$. Taking $\beta = 1.5$ gives $x = 1.1$ and $y = 0.6$, yielding $t \propto q^{-0.5}$. Hence even an uncertainty of an order of magnitude in $q$ will alter the derived time-scale by only a factor of a few. We can thus conclude that our $t_{\text{on}}$ estimates are likely to be correct to within a factor of 2 or so. As the uncertainty associated with the ratio $t_{\text{off}}/t_{\text{on}}$ is much less than this, duration of the quiescent time-scale is also expected to be similarly accurate.

#### 7.2 Mass dependence

Best et al. (2005b) found a strong dependence of the radio-loud fraction on black hole and host galaxy mass, $f_{\text{RL}} \propto M_{\text{BH}}^{1.4\pm0.1}$. We find a similar result for our volume-limited sample (Fig. 4), with $f_{\text{RL}} \propto M_{\star}^{1.4\pm0.3}$. For a fixed spheroid-to-total light ratio (Section 6.1), using the $M_{\text{BH}}-M_\star$ relation (Häring & Rix 2004) gives $f_{\text{RL}} \propto M_{\text{BH}}^{1.8\pm0.5}$.
Best et al. (2005b) point out that this relation is similar to the $M_{\text{cool}} \propto M_{\text{BH}}^{0.5}$ gas cooling rate dependence on black hole mass derived from the X-ray–optical correlation in luminous elliptical galaxies, and suggest that AGN radio activity might be fuelled by the cooling of hot gas within the host galaxy.

The derived AGN ‘on’ time-scales in Table 4 clearly increase with stellar mass. If the AGN is fuelled by cool gas accretion, and the duration of the active phase is limited by fuel availability, one would expect for constant radiative and accretion efficiency $t_{\text{on}} \propto \dot{M}_{\text{cool}}/Q_{\text{jet}}$, which on using the scaling relations of Section 6.1 gives $t_{\text{on}} \propto M_{*}^{1.1 \pm 0.5}$. This is consistent with $t_{\text{on}} \propto M_{*}^{1.1}$ derived in Section 6.3, and suggests that the duration of the active phase may indeed be determined by the availability of fuel to ‘feed’ the jets. The quiescent phase duration (Table 4) also shows a strong dependence on $M_{*}$, with sources hosted by the most massive galaxies spending a shorter amount of time in the ‘off’ phase, consistent with higher cooling rates in those objects. In the absence of a heating source one would expect $t_{\text{off}} \propto M_{\text{cool}}^{1} \propto M_{*}^{1.7 \pm 0.3}$. However, in practice
Figure 13. Fractile distribution of radio source ages for the top four stellar mass bins. Lowest mass bins are not shown due to large numbers of unresolved sources in these affecting the statistics significantly.

Figure 14. Predicted cumulative RLFs as a function of stellar mass. The curves represent various jet on times; solid = $10^7$ yr, long-dashed = $2.5 \times 10^7$ yr, short-dashed = $8 \times 10^7$ yr, dotted = $2 \times 10^8$ yr, dot–dashed = $6.3 \times 10^8$ yr. Parameters used for fitting are the same as those from which source ages and jet powers were determined. The observed luminosity functions are only plotted for $L_{1.4} > 8 \times 10^{22}$ W Hz$^{-1}$ as the sample is incomplete below this luminosity. No plot is shown for $\log M_{*/M_\odot} < 11.16$ due to large uncertainties in derived jet powers.

8 CONCLUSIONS

We constructed a flux- and volume-limited ($0.03 \leq z \leq 0.1$) sample of radio sources with optical identifications by cross correlating the SDSS optical survey with 1.4-GHz NVSS and FIRST surveys. Source sizes and luminosities together with radio source models allowed us to derive jet powers and ages of individual sources, and hence the jet ‘on’ time as a function of stellar mass. The bivariate luminosity function was then used to constrain the time a typical radio source spends in an inactive state. Radio and emission-line AGN activity are found to be independent phenomena. We also find that both the radio source lifetime and duration of the quiescent phase have a strong mass dependence, with massive hosts harbouring longer-lived sources that are triggered more frequently. Gas cooling rate shows a similar mass dependence, suggesting that fuel depletion is the reason the jets switch off.

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