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The relationship between radio luminosity and black-hole mass in optically-selected quasars

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ABSTRACT
Using a sample of more than 6000 quasars from the Sloan digital sky survey (SDSS) we compare the black-hole mass distributions of radio-loud and radio-quiet quasars. Based on the virial black-hole mass estimator the radio-loud quasars (RLQs) are found to harbour systematically more massive black holes than radio-quiet quasars (RQQs) with very high significance ($\gg 99.99\%$), with mean black-hole masses of $< \log(M_{bh}/\mathrm{M}_{\odot}) >= 8.89 \pm 0.02$ and $< \log(M_{bh}/\mathrm{M}_{\odot}) >= 8.69 \pm 0.01$ for the RLQs and RQQs respectively. Crucially, the new RLQ and RQQ samples have indistinguishable distributions on the redshift-optical luminosity plane, excluding the possibility that either parameter is responsible for the observed black-hole mass difference. Moreover, this black-hole mass difference is shown to be in good agreement with the optical luminosity difference observed between RLQ and RQQ host galaxies at low redshift (i.e. $\Delta M_{host} = 0.4 - 0.5$ magnitudes). Within the SDSS samples, black-hole mass is strongly correlated with both radio luminosity and the radio-loudness $\mathcal{R}$ parameter ($> 7\sigma$ significance), although the range in radio luminosity at a given black-hole mass is several orders of magnitude. It is therefore clear that the influence of additional physical parameters or evolution must also be invoked to explain the quasar radio-loudness dichotomy.

Key words: black hole physics - galaxies:active - galaxies:nuclei - quasars:general

1 INTRODUCTION

Ever since the discovery that only a small minority of optically-selected quasars are also luminous radio sources (e.g. $L_{5\mathrm{GHz}} > 10^{24}\mathrm{WHz}^{-1}\mathrm{sr}^{-1}$), many studies have attempted to isolate the physical mechanism underlying this so-called quasar radio-loudness dichotomy. Although previous studies found a clear bimodality in the radio luminosities of optically-selected quasars (eg. Kellermann et al. 1989; Miller, Peacock & Mead 1990), more recently the very existence of the radio-loudness dichotomy has been questioned (Lacy et al. 2001; Cirasuolo et al. 2003; although see Ivezić et al. 2002 for an alternative viewpoint). The principal reason behind this renewed interest in the radio properties of optically selected quasars is the ability to combine the large SDSS and 2dF optical quasar samples with wide-area radio surveys such as the Faint Images of the Radio Sky at Twenty-cm (FIRST) and the NRAO VLA Sky Survey (NVSS). The FIRST survey (Becker, White & Helfand 1995) in particular has identified large numbers of so-called radio-intermediate quasars which have largely filled-in the apparent gap in radio luminosities between the RLQ and RQQ populations (eg. Lacy et al. 2001). Consequently, the distribution of optically-selected quasars on the optical-radio luminosity plane is undoubtedly more continuous than was previously thought. Irrespective of this, the fundamental question of what causes luminous quasars with seemingly identical optical properties to differ in their radio luminosities by several orders of magnitude remains unanswered.

Recent progress has been made in largely eliminating two parameters which were originally suspected of influencing the radio-loudness dichotomy; host-galaxy morphology and cluster environment. Thanks largely to the Hubble Space Telescope (HST), quasar host-galaxy morphologies have now been investigated out to intermediate redshifts, $0.1 < z < 0.5$ (eg. Dunlop et al. 2003; Schade et al 2000; McLure et al. 1999; Disney et al. 1996). Drawing together the results of these studies, it is clear that the hosts of optically luminous quasars (i.e. $M_R < -24$) are bulge-dominated, spheroidal galaxies irrespective of radio luminosity (Dunlop et al. 2003; Schade et al. 2000). In the light of the discovery of the correlation between black-hole and bulge mass (Magorrian et al. 1998; Gebhardt et al. 2000; Ferrarese & Merritt 2000), this result is perhaps not surprising. However, it should also be remembered that in the optical the hosts of RLQs are consistently found to be $\simeq 0.5$ magnitudes brighter than their RQQ counterparts (eg. Dunlop et

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al. 2003), the implications of which will be discussed in Section 3. In addition, it now appears that cluster environment does not greatly influence quasar radio luminosities either. Recent studies of the cluster environments of AGN have tended to show that quasars prefer to inhabit poor clusters (e.g. Abell class 0) or groups, rather than the cores of rich clusters (Best 2004; Söchting, Clowes & Campusano 2004). Where a direct comparison of matched samples of RLQs and RQQs has been performed (eg. Wold et al. 2001; McLure & Dunlop 2001a) little difference has been found in their respective cluster environments.

Following the inconclusive nature of the results regarding the Mpc and Kpc-scale environments of RLQs and RQQs, attention has now become focussed on possible differences in the properties of their central engines. At the same time the robustness of the so-called virial black-hole mass estimator (Wandel, Peterson & Malkan 1999; Kaspi et al. 2000) has now become established, allowing estimates of AGN black-hole masses to be derived from a continuum luminosity and broad-line FWHM measurement only (i.e. $M_{bh} \propto \lambda L_{\lambda}^{0.6}\mathrm{FWHM}^2$). Consequently, many studies have exploited the virial mass estimator to investigate whether black-hole mass could be the hidden parameter controlling the radio-loudness dichotomy; with widely contrasting results. Several authors (eg. Laor 2000; McLure & Dunlop 2001b,2002; Dunlop et al. 2003) have concluded that RLQs have systematically higher black-hole masses than their RQQ counterparts, and have suggested the existence of a black-hole-mass threshold (e.g. $M_{bh} \simeq 10^8\,\mathrm{M}_{\odot}$) above which the fraction of RLQs increases significantly. This separation of the RLQ and RQQ populations in terms of black-hole mass is further supported by the principal components analysis of RLQ and RQQ spectra by Boroson (2002). Moreover, by combining the FIRST Bright Quasar Survey (FBQS, Gregg et al. 1996) and the PG quasar survey (Green, Schmidt & Liebert 1986), Lacy et al. (2001) found that, given enough dynamic range, radio luminosity and black-hole mass were strongly correlated, albeit with substantial scatter. More recently, McLure et al. (2004) found a significant correlation between black-hole mass and integrated low-frequency (151 MHz) radio luminosity from a complete sample of 41 powerful radio galaxies at $z \simeq 0.5$.

In contrast to the previously mentioned studies, several authors have concluded that no strong link exists between black-hole mass and radio luminosity in AGN (eg. Urry 2003; Oshlack et al. 2002; Woo & Urry 2002; Ho 2002). With particular relevance to optically luminous quasars, both Oshlack et al. (2002) and Woo & Urry (2002) highlight that the apparent existence of extremely radio-loud flat-spectrum quasars (FSQs), with virial black-hole mass estimates in the range $10^6\,\mathrm{M}_{\odot} < M_{bh} < 10^8\,\mathrm{M}_{\odot}$, effectively rule out a strong correlation between black-hole mass and radio-loudness (although see Jarvis & McLure 2002 for a different interpretation of the FSQ data).

In this paper we revisit the issue of whether black-hole mass and radio luminosity are related in quasars using the virial black-hole mass estimates calculated by McLure & Dunlop (2004) for objects from the SDSS quasar catalog II (Schneider et al. 2003). The aim of this paper is to determine whether RLQs and RQQs, matched in terms of redshift and optical luminosity, have distinguishable black-hole mass distributions or not. Throughout the paper we adopt the spectral index convention $f_{\nu} \propto \nu^{-\alpha}$ and the following cosmology: $H_0 = 70\mathrm{km\,s}^{-1}$, $\Omega_{\Lambda} = 0.7$, $\Omega_m = 0.3$.

2 THE SAMPLE

The sample adopted in this paper is drawn from the SDSS quasar catalog 2 (Schneider et al. 2003) which consists of 16714 quasars in the redshift interval $0.1 < z < 5.3$ with $M_i(AB) < -22$. The black-hole mass estimates are taken from McLure & Dunlop (2004) who produced virial black-hole mass estimates for more than 12000 of the SDSS quasar catalog 2 (SQC2) objects with redshifts $z \leq 2.1$, based on both the Hβ and MgII emission lines. Full details of the modelling of the SDSS quasar spectra and the calibrations of the virial mass estimator can be found in McLure & Dunlop (2004) and McLure & Jarvis (2002). The final samples of RLQs and RQQs were selected from the full SQC2 via application of the following criteria:

(i) All objects which fell outside the SDSS/FIRST overlap region were excluded to ensure consistent radio data for the final sample.

(ii) All objects with $i(AB) > 19.1$ or which did not satisfy the SDSS quasar colour selection algorithm for follow-up spectroscopy were also excluded. This criterion ensures that the final samples are not biased by the inclusion of pre-selected FIRST sources or serendipitous targets (Schneider et al. 2003).

The remaining objects were cross-correlated with the McLure & Dunlop (2004) black-hole mass estimates which cover $> 90\%$ of the SDQ2 objects with $z < 2.1$. This final list of quasars was then separated into the RLQ and RQQ samples based on the radio-loudness $\mathcal{R}$ parameter ($\mathcal{R} = f_{5GHz}/f_B$, where f_{5GHz} [1] and f_B are the observed flux densities at 5GHz and 4400Å respectively). Following the standard convention we classify every object with $\mathcal{R} \geq 10$ as radio-loud, and everything with $\mathcal{R} < 10$ as radio-quiet. An upper limit in $\mathcal{R}$ was calculated for quasars undetected by FIRST using the nominal FIRST object-detection threshold of 1mJy. To investigate the possibility that the quasar radio luminosities are underestimated, due to the FIRST survey resolving out extended flux (e.g. Blundell 2003), we cross-correlated our samples with the lower resolution NVSS survey. The results of this showed no significant differences in 1.4GHz flux densities, which suggests that the radio emission of these optically-selected quasars is fairly compact.

The final RQQ and RLQ samples produced by our selection process comprise 6099 and 436 objects respectively. We note here that adopting $\mathcal{R} \geq 10$ as our radio-loudness threshold is conservative, in the sense that 30% of the final RLQ sample have 5GHz radio luminosities less than the alternative radio-luminosity based threshold of $10^{24}\mathrm{WHz}^{-1}\mathrm{sr}^{-1}$ (Miller, Peacock & Mead 1990). The results of adopting the strict radio luminosity threshold are discussed further in Section 3.

2.1 Matched samples

In order to investigate any differences in the black-hole mass distributions of the RLQs and RQQs the samples should be free from biases which could affect the virial black-hole mass estimator. Given the role of optical luminosity in the virial mass estimator ($M_{bh} \propto \lambda L_{\lambda}^{0.6}\mathrm{FWHM}^2$), this essentially requires that the two samples are indistinguishable in terms of their optical luminosity and redshift distributions.

[1] The 5GHz flux-density is extrapolated from 1.4GHz using the mean spectral index of FBQS quasars; $\alpha = 0.5$ (White et al. 2000)

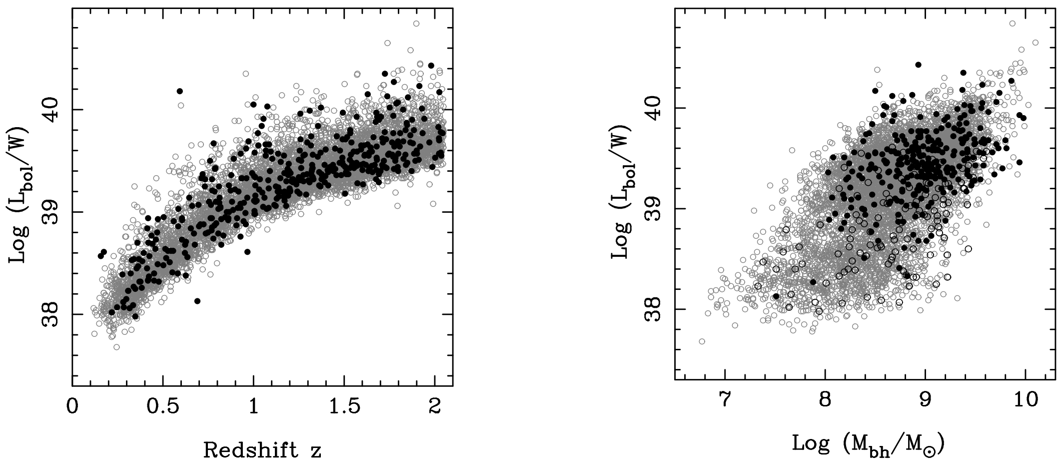

Figure 1. (a) Bolometric luminosity versus redshift for the RQQ (open grey circles) and RLQ (filled black circles) samples.(b) Bolometric luminosity versus virial black-hole mass estimate for the same samples, with those RLQs with $L_{5\rm GHz} < 10^{24}\rm WHz^{-1}sr^{-1}$ plotted as open black circles.

In Fig 1a we show the RLQ and RQQ samples on the $L_{bol} - z$ plane where, following McLure & Dunlop (2004), the quasar bolometric luminosities are estimated from either the 5100Å or 3000Å luminosities as $L_{bol} = 9.8\lambda L_{5100}$ or $L_{bol} = 5.9\lambda L_{3000}$, depending on their redshift (McLure & Dunlop 2004 demonstrated that the ratio of these two bolometric luminosity estimators is unity for $\simeq 1200$ quasars where both could be measured). The application of the one-dimensional Kolmogorov-Smirnov (KS) test finds that both the L_{bol} and redshift distributions of the RLQ and RQQ samples are indistinguishable; $p = 0.16$ and $p = 0.50$ respectively. In addition, an application of the two-dimensional KS test to the $L_{bol} - z$ distribution shown in Fig 1a confirms that the two-dimensional distributions of the RLQ and RQQ samples are also indistinguishable; $p = 0.21$. Consequently, any black-hole mass difference between the two quasar samples should not be a product of significant biases in their redshift or optical luminosity distributions.

3 BLACK-HOLE MASS DISTRIBUTIONS

The distributions of the RQQ and RLQ samples on the $L_{bol} - M_{bh}$ plane are shown in Fig 1b. The application of the two-dimensional KS test returns a probability of only $p = 1.2\times10^{-10}$ that both samples are drawn from the same parent population. The mean black-hole masses for the RQQ and RLQ samples are as follows:

$$\rm RLQ: \;\; < \log(\mathit{M_{bh}}/M_\odot) >= 8.89 \pm 0.02 \quad (8.93)$$

$$\rm RQQ: \;\; < \log(\mathit{M_{bh}}/M_\odot) >= 8.69 \pm 0.01 \quad (8.74)$$

where the quoted uncertainties are the standard errors and the values in parenthesis are the sample medians. Although the optical luminosity distributions of the RLQ and RQQ samples are indistinguishable, the mean optical luminosity of the RLQs is 0.06 dex brighter than that of the RQQs. Given that the virial mass estimator adopted here has a luminosity dependence of $\lambda L_\lambda^{0.6}$ (McLure & Dunlop 2004), this will account for 0.04 dex of the black-hole mass difference between the samples. Consequently, accounting for this slight luminosity bias, we conclude that RLQs typically harbour black holes 0.16 dex (45%) more massive than their radio-quiet counterparts. Moreover, by calculating the mean RLQ−RQQ black-hole mass difference in narrow luminosity bins (0.3 dex width) it was confirmed that the black-hole mass difference is consistent with a constant 0.16 dex off-set over the full luminosity range.

3.1 Line-width difference

The measured difference in mean black-hole mass between the RLQ and RQQ samples is predominantly due to fact that the FWHM of the low-ionization Hβ and MgII emission lines of the RLQs are $\simeq 20\%$ larger than in the RQQs of the same optical luminosity. The conclusion that RLQs exhibit broader low-ionization emission lines than RQQs is in good agreement with many previous studies (eg. Boroson & Green 1992; Corbin 1997; McLure & Dunlop 2002; Sulentic et al. 2003). However, although the velocity-width difference between RLQs and RQQs has been noted previously, because of potential selection effects, attributing this directly to a difference in black-hole mass has been problematic. For example, given that the FWHM of low-ionization emission lines in RLQs are known to be influenced by viewing angle (Wills & Browne 1986; Brotherton et al. 1996), the velocity-width difference between RLQs and RQQs could potentially be an orientation effect produced by comparing radio and optically selected samples. However, as discussed in Section 2, here both samples have been selected consistently by the SDSS $ugri$ colour algorithm, with targeted FIRST sources deliberately excluded. Combined with the excellent sample matching in terms of optical luminosity and redshift, the influence of potential orientation effects should therefore be minimized. Consequently, the simplest interpretation of these new results is that at a fixed optical luminosity RLQs do, on average, harbour more massive black-holes than RQQs, accreting at a commensurately lower fraction of their Eddington limit.

3.2 Comparison with host-galaxy results

Irrespective of the virial black-hole mass estimates presented here, it could reasonably be argued that the correlation between bulge and black-hole mass ($M_{bh} - M_{bulge}$) and the well known $K - z$ relation for powerful radio galaxies (Lilly & Longair 1984) immediately imply that RLQs should harbour black holes with masses $\gtrsim 10^8\,\rm M_\odot$. The recent Willott et al. (2003) study showed that the radio-galaxy $K - z$ relation is consistent with the passive evolution of a $\simeq 3L^\star$ elliptical formed at high redshift ($z \geq 5$). Therefore,

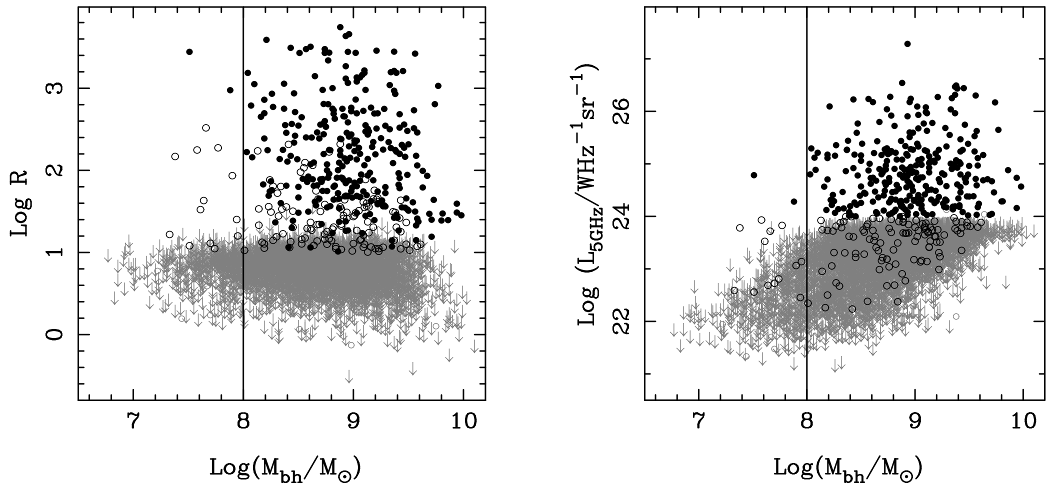

Figure 2. (a) Radio-loudness parameter $\mathcal{R}$ versus black-hole mass. (b) Absolute 5GHz radio luminosity versus black-hole mass. Symbols as Fig 1. RQQs undetected by FIRST are shown as upper limits. A black-hole mass of $10^8\,\mathrm{M}_\odot$ is highlighted by a solid vertical line in both figures.

if the predictions of orientation-based unification are correct, the host-galaxies of RLQs of comparable radio luminosity should have similar $K-$band luminosities .

Notably, using the McLure & Dunlop (2002) fit to the $M_{bh}-M_{bulge}$ relation, the mean black-hole mass of the RLQ sample corresponds to a $K-$band bulge luminosity of $3.8\pm0.5L^{\star}$ (assuming a $z=0$ colour of $R-K=2.7$; Bruzual & Charlot 2003), in good agreement with the Willott et al. $K-z$ relation. Moreover, it is also interesting to compare the RLQ black-hole mass estimates derived here with those derived via host-galaxy luminosities for a complete sample of 41 $z\simeq0.5$ radio galaxies by McLure et al. (2004). Based on HST imaging of radio galaxies spanning the same range of radio luminosities as the current RLQ sample, the mean black-hole mass was determined to be $<\log(M_{bh}/\mathrm{M}_\odot)>=8.87\pm0.04$, in excellent agreement with the mean black-hole mass of the RLQ sample derived here.

In addition to comparisons with radio galaxy studies, it is also possible to compare the black-hole mass difference between the RLQ and RQQ samples determined here with imaging studies of quasar host-galaxies. The most accurate quasar host-galaxy studies are those based on high-resolution HST imaging data (eg. Dunlop et al. 2003; Schade et al. 2000; Disney et al. 1995). Among the various HST-based host galaxy studies, the Dunlop et al. (2003) study has the advantage of featuring RLQ and RQQ samples which have well matched redshift - optical luminosity distributions. Based on the results of this $R-$band imaging study, the hosts of RLQs are typically $\simeq 0.4$ mags brighter than their RQQ counterparts. Combining this with the McLure & Dunlop (2002) fit to the $M_{bh}-M_{bulge}$ relation implies that RLQ and RQQ black-hole masses should differ by $\simeq 0.2$ dex, in good agreement with the virial-based results derived here.

4 THE CORRELATION BETWEEN BLACK-HOLE MASS AND RADIO LOUDNESS

In Fig 2 we plot both the radio-loudness $\mathcal{R}$ parameter and absolute radio luminosity versus black-hole mass for the RLQ and RQQ samples. In order to assess the significance of the apparent correlations in the presence of upper limits we have applied the generalized Kendall's τ test in the ASURV package (Isobe, Feigelson & Nelson 1986) . The Kendall's τ test detects a highly significant correlation in both cases, returning values of $\tau=0.0497$ (7.6σ) and $\tau=0.0697$ (11.4σ) for the $\mathcal{R}-M_{bh}$ and $L_{5GHz}-M_{bh}$ correlations respectively.

The detection of a significant correlation between black-hole mass and radio-loudness is in good agreement with the Lacy et al. (2001) study of the combined FBQS+PG sample. Furthermore, it can be seen from Fig 2a that the RLQs are virtually exclusively confined to $M_{bh}\geq10^8\,\mathrm{M}_\odot$, as previously found by Laor (2000), Lacy et al. (2001), Boroson (2002) and McLure & Dunlop (2002). Qualitatively, the fraction of RQQs with $M_{bh}\leq10^8\,\mathrm{M}_\odot$ is $9.2\%\pm0.4$, whereas the equivalent fraction of RLQs is only $3.7\%\pm1.0$. In fact, if the definition of radio-loud is restricted to only those quasars with $L_{5GHz}>10^{24}\mathrm{WHz}^{-1}\mathrm{sr}^{-1}$ only two objects have $M_{bh}\leq10^8\,\mathrm{M}_\odot$ ($<1\%$). This result, combined with the radio galaxy $K-z$ relation (e.g. Jarvis et al. 2001; Willott et al. 2003), strengthens the claim that regardless of the exact nature of the black-hole mass - radio luminosity relationship in luminous quasars, sample selection based on high radio luminosity is effective in isolating the largest black holes, and presumably host galaxies, at all epochs (eg. McLure 2003).

4.1 Flat-spectrum quasars

In contrast to the results found here, we note that Woo & Urry (2002) found no indication of a $\mathcal{R}-M_{bh}$ correlation in their study of a heterogeneous sample of 747 quasars in the redshift interval $0<z<2.5$. The simple reason for this apparent discrepancy is that within their sample Woo & Urry include the 39 flat-spectrum quasars (FSQs) studied by Oshlack et al. (2002). Jarvis & McLure (2002) have examined the likely effects of orientation on both the radio luminosities and black-hole mass estimates for the Oshlack et al. (2002) sample. Although estimates of the intrinsic unbeamed $\mathcal{R}$ parameters are hard to accurately determine, Jarvis & McLure concluded that the radio luminosities and black-hole mass estimates of Oshlack et al. (2002) are likely to be over/under-estimated by factors of $\simeq100$ and $\simeq4$ respectively.

Consequently, in all likelihood the Oshlack et al. FSQs are not inconsistent with the $L_{\rm 5GHz}-M_{bh}$ correlation seen in Fig 2b, with all the FSQs with *intrinsic* radio luminosities $L_{\rm 5GHz}>10^{24}\mathrm{WHz}^{-1}\mathrm{sr}^{-1}$ likely to have $M_{bh}\gtrsim10^8\,\mathrm{M}_\odot$. Notably, if the

FSQs are removed from the Woo & Urry (2002) sample, then their results are entirely consistent with those derived here.

5 CONCLUSIONS

In this paper we have compared the black-hole mass distributions of RQQs and RLQs using large samples which have indistinguishable distributions in the redshift-optical luminosity plane. The results of this comparison demonstrate that at a fixed optical luminosity RLQs harbour black-hole masses which are typically 0.16 dex (45%) more massive than their radio-quiet counterparts. In agreement with previous studies, this black-hole mass difference is shown to be largely produced by RLQs displaying broader low-ionization emission lines than comparable RQQs. Moreover, using the combined RQQ+RLQ sample we have shown that black-hole mass is strongly correlated with both absolute radio luminosity and the radio-loudness parameter $\mathcal{R}$. Furthermore, the black-hole masses of genuine RLQs are found to be virtually exclusively confined to $M_{bh} \geq 10^{8}\,\mathrm{M}_{\odot}$, in good agreement with the conclusions of previous studies (Laor 2000; Boroson 2002, McLure & Dunlop 2002).

Combining the virial black-hole mass estimates with the local $M_{bh} - M_{bulge}$ relation suggests that RLQ host galaxies are fully consistent with the radio galaxy $K - z$ relation, in agreement with AGN orientation-based unification. It is therefore clear that sample selection based on high radio luminosity is an effective method for cleanly isolating the largest black-holes, and presumably host galaxies, at all epochs. However, the new results presented here also confirm that no tight correlation exists between radio luminosity and black-hole mass, and that at a fixed black-hole mass the range in quasar radio luminosities covers several orders of magnitude. Consequently, there is clearly a large overlap between the RLQ and RQQ populations, with many RQQs being indistinguishable from RLQs in terms of black-hole mass, accretion rate, orientation, host galaxy properties and cluster environment. In conclusion, it therefore appears inescapable that the influence of additional physical parameters such as black-hole spin and/or evolutionary effects must contribute to the radio-loudness dichotomy.

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