THE RADIO LOUDNESS DICHOTOMY: ENVIRONMENT OR BLACK-HOLE MASS?

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Abstract
The results of a comprehensive study of the cluster environments and black-hole masses of an optically matched sample of radio-loud and radio-quiet quasars are presented. No evidence is found for a difference in large-scale environments, with both quasar classes found to be located in clusters of Abell class $\sim 0$. Conversely, virial black-hole mass estimates based on H$\beta$ line-widths show a clear difference in the quasar black-hole mass distributions. Our results suggest that a black-hole mass of $\sim 10^9M_\odot$ is required to produce a powerful radio-loud quasar, and that it is black-hole mass and accretion rate which hold the key to the radio-loudness dichotomy.

Cluster environments of powerful AGN at $z \simeq 0.2$

The sample for this study consists of 44 powerful AGN with redshifts in the range $0.1 < z < 0.3$. The full sample is comprised of three matched sub-samples of 10 radio galaxies (RGs), 13 radio-loud quasars (RLQs) and 21 radio-quiet quasars (RQQs), the majority of which are drawn from the HST host-galaxy study of McLure et al. (1999) and Dunlop et al. (2001), with further objects taken from the host-galaxy study of Bahcall et al. (1997). The sub-samples are matched such that the $L_{5GHz} - z$ distribution of the two radio-loud sub-samples, and the $M_V - z$ distribution of the two quasar sub-samples are statistically indistinguishable.

Counts of excess galaxies surrounding each AGN were used to calculate the spatial clustering amplitude ($B_{qq}$) in order to provide a quantitative estimate of the richness of their cluster environments (Longair & Seldner 1979). A full description of the analysis and results of this study can be found in McLure & Dunlop (2001a).
Do RLQs have richer environments than RQQs?

The spatial clustering amplitude results for the three sub-samples are shown in Fig 1. It can be seen that there is no indication that the RLQs occupy systematically richer environments than the RQQs, with their respective mean clustering amplitudes of $267 \pm 51$ and $326 \pm 94\text{Mpc}^{1.77}$ indicating that both quasar classes occupy cluster environments comparable to Abell class 0. We note here that our finding that RQQs occupy similar environments to RLQs is not in general agreement with the literature, with the majority of previous studies finding RQQs to inhabit poorer environments than RLQs. For example, both Smith, Boyle & Maddox (1995) and Ellingson, Yee & Green (1991) found that at $z < 0.3$ RQQs have environments perfectly consistent with those of field galaxies. Although the exact cause of this discrepancy is difficult to determine, it is probably due to the fact that the RQQs and RLQs in our study our well matched in terms of nuclear luminosity.

Further support for this argument is provided by the good agreement between our results and those of the recent study by Wold et al. (2000; 2001; these proceedings) which involved a similar analysis of an optically matched sample of RQQs and RLQs at redshifts in the range $0.5 < z < 0.8$. Wold et al. also conclude that there is no difference in the average cluster richness of RQQs and RLQs of similar optical luminosity, suggesting that our results persist at higher redshift. In Fig 2 we show a comparison of the clustering results for our RLQ sample, and those for a sub-sample of the Wold et al. RLQs which display the same range in radio luminosity. It is clear from Fig 2 that there is no evidence for evolution in RLQ cluster environments, at least out to $z \sim 0.8$. 

Figure 1. The $B_{qq} - z$ distribution for the three sub-samples. Also shown are approximate Abell cluster classifications according to the linear scheme proposed by Yee & López-Cruz (1999), renormalized such that $B_{qq} = 300\text{Mpc}^{1.77}$ corresponds to Abell class 0.
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Figure 2. The left-hand and middle panels show the matching between our RLQ sample (open circles) and the sub-sample of the objects studied by Wold et al. (2000) discussed in the text (filled circles). The right-hand panel shows a comparison of their respective spatial clustering amplitudes.

The lack of any significant difference in the cluster environments of optically-matched samples of RQQs and RLQs suggests that cluster environment cannot be the primary cause of the quasar radio-loudness dichotomy. In the following section we move on from studying the large-scale environments of quasars, to explore what role (if any) is played by black-hole mass in determining the radio luminosity of AGN.

The black-hole masses of quasars and Seyfert galaxies

In this study (McLure & Dunlop 2001b) the quasar sample from host-galaxy study of McLure et al. (1999) and Dunlop et al. (2001) was combined with a sample of 15 Seyfert 1 galaxies from the reverberation mapping study of Wandel, Peterson & Malkan (1999). This combined sample provided the opportunity to investigate the relation between black-hole mass ($M_{\text{bh}}$) and host-galaxy bulge mass ($M_{\text{bulge}}$) over a wide range in AGN nuclear luminosity, and was assembled with the aim of addressing two important questions. Firstly, is the ratio of $M_{\text{bh}}/M_{\text{bulge}}$ in Seyfert galaxies really a factor of twenty lower than seen in nearby galaxies and quasar hosts, as claimed by Wandel (1999), or can the apparent discrepancy be explained by a systematic over-estimate of the Seyfert bulge luminosities? Secondly, do differences in black-hole masses and gas accretion rates play a crucial role in determining the radio properties of AGN?

Host-galaxy bulge luminosities for the vast majority (39/45) of the sample were determined via full two dimensional disc/bulge decomposition of high resolution HST data, with the luminosities of the remaining objects being taken from literature disc/bulge decompositions. Consequently, our revised Seyfert bulge luminosities should be more accurate
than the \( L_{\text{bulge}}/L_{\text{tot}} \) morphology-based estimates adopted by Wandel (1999). The black-hole masses are virial estimates (Wandel, Peterson & Malkan 1999) where it is assumed that the velocities of the broad-line regions clouds (as estimated from the FWHM of the H\(_{\beta}\) emission line) are due to the gravitational potential of the central black-hole. We make the further assumption that the broad-line region has a flattened disc-like geometry, and that the H\(_{\beta}\) line-widths are therefore orientation dependent, as suggested by the results of Wills & Browne (1986). The success of this model in reproducing the observed line-width distribution is illustrated in Fig 3.

\[ \begin{align*} \text{Figure 3.} \quad & \text{The left-hand panel shows the distribution of H}_{\beta} \text{FWHM measurements for} \quad \text{the 45 objects in the combined quasar+seyfert sample. The right-hand panel shows} \\ & \text{the cumulative FWHM distributions displayed by the data (thick line) and that of the} \quad \text{disc BLR model discussed in the text (thin line). The two cumulative distributions} \\ & \text{are indistinguishable, with a KS test probability of} \quad p = 0.99 \end{align*} \]

The \( M_{\text{bh}} - M_{\text{bulge}} \) relation

The black-hole mass vs. bulge luminosity relation for the combined quasar and Seyfert galaxy sample is plotted in Fig 4. The two quantities can be seen to be well correlated, with the rank-order coefficient of \( r_s = -0.66 \) having a significance of 4.4\( \sigma \). It can be seen immediately that, with our revised bulge luminosity estimates, there is no evidence that the Seyfert galaxies follow a different relation to the more luminous quasars. The best-fitting relation (\( \chi^2 = 64.8 \) for 45 d.o.f.) is found to be:

\[ \log(M_{\text{bh}}/M_\odot) = -0.61(\pm0.08)M_R - 5.41(\pm1.75) \]  

and is shown as the solid line in the left-hand panel of Fig 4. It is noteworthy that the slope expected from a linear \( M_{\text{bh}} - M_{\text{bulge}} \) relation is \(-0.52\), which is not inconsistent with the best-fitting value of
Both panels show black-hole mass vs. host galaxy $R$-band magnitude. The quasars are shown as open (radio quiet) and filled (radio loud) circles, while the Seyfert galaxies are shown as filled squares. In the left-hand panel the solid line is the best fit to the data. The solid line in the right-hand panel is the predicted relation from Magorrian et al. (1998). The dashed line in the right-hand panel is best fit to the data forcing a constant $M_{\text{bh}}/M_{\text{bulge}}$ ratio, and corresponds to $M_{\text{bh}}/M_{\text{bulge}} = 0.0025$. Consequently, a least-squares fit of the data was undertaken with an enforced slope of $-0.52$, and is shown as the dashed line in the right-hand panel of Fig 4. This can be seen to be a reasonable representation of the data, and corresponds to a relationship of the form $M_{\text{bh}} = 0.0025 M_{\text{bulge}}$. For reference, the solid line in right-hand panel of Fig 4 shows the predicted relation from Magorrian et al. (1998), which can be seen to systematically over predict the black-hole masses by a factor of $\sim 2.5$.

The black-hole mass estimates for the 17 RQQs and 13 RLQs quasars provide an opportunity to determine the influence (if any) of black-hole mass on quasar radio luminosity. The continuum luminosity distributions of the two quasar sub-samples are indistinguishable, implying that any difference in their black-hole mass distributions are presumably linked to the difference in radio properties.

Our results suggest that a difference does exist between the RQQ and RLQ black-hole mass distributions, with the median black-hole mass of the RLQs being a factor of three larger than their radio-quiet counterparts. A natural division between the quasar sub-samples appears to occur at $M_{\text{bh}} \sim 10^{8.8} M_\odot$. Only 2/13 of the radio-loud quasars have $M_{\text{bh}} < 10^{8.8} M_\odot$, while only 4/17 of the radio-quiet have $M_{\text{bh}} > 10^{8.8} M_\odot$. This difference in black-hole mass distributions is shown to be significant at the $2.9\sigma$ ($p = 0.004$) level by a KS test. The implication from the quasar sample is therefore that (albeit with substantial overlap) for a given nu-
clear luminosity, the probability of a source being radio-loud increases
with black-hole mass, or alternately decreases with $L/L_{\text{Edd}}$. The same
conclusion was recently reached by Laor (2000) from his study of the
virial black-hole masses of PG quasars.

Conclusions

- We find no detectable difference in the average cluster environ-
  ments of optically matched RQQs and RLQs at $z \sim 0.2$, implying
  that cluster richness is not the primary cause of the radio-loudness
dichotomy.

- Our results suggest that on average, luminous quasars occupy cluster
  environments as rich as Abell class 0, although a large scatter
  is present.

- We find that the bulges of both Seyfert galaxies and quasar host
  galaxies follow the same relation between black-hole and bulge
  mass, with a best-fitting linear relation of $M_{\text{bh}} = 0.0025 M_{\text{bulge}}$.

- Our black-hole mass estimates suggest that black-hole mass is a
  key parameter in determining an AGN’s radio luminosity, and that
  a black-hole of mass $\sim 10^9 M_\odot$ is required to produce a powerful
  radio-loud quasar.

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