THE HOST GALAXIES OF RADIO-LOUD AND RADIO-QUIET QUASARS

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Abstract
I review our knowledge of the properties of the host galaxies of radio-loud and radio-quiet quasars, both in comparison to each other and in the context of the general galaxy population. It is now clear that the hosts of radio-loud and radio-quiet quasars with \( M_V < -23.5 \) are virtually all massive elliptical galaxies. The masses of these spheroids are as expected given the relationship between black-hole and spheroid mass found for nearby quiescent galaxies, as is the growing prevalence of disc components in the hosts of progressively fainter AGN. There is also now compelling evidence that quasar hosts are practically indistinguishable from normal ellipticals, both in their basic structural parameters and in the old age of their dominant stellar populations; at low \( z \) the nuclear activity is not associated with the formation of a significant fraction of the host galaxy. While the long-held view that quasar radio power might be a simple function of host morphology is now dead and buried, I argue that host-galaxy studies may yet play a crucial role in resolving the long-standing problem of the origin of radio loudness. Specifically there is growing evidence that radio-loud objects are powered by more massive black holes accreting at lower efficiency than their radio-quiet counterparts of comparable optical output. A black-hole mass \( > 10^9 M_\odot \) appears to be a necessary (although perhaps not sufficient) condition for the production of radio jets of sufficient power to produce an FRII radio source within a massive galaxy halo.

1. Introduction
Studies of the host galaxies of low-redshift quasars are of crucial importance for defining the subset of the present-day galaxy population which is capable of producing quasar-level nuclear activity. They are also of value for constraining physical models of quasar evolution, for exploring the extent to which radio-loudness might be connected with host-galaxy properties, and as a means to estimate the masses of the central black holes which power the active nuclei.
Our view of low-redshift quasar hosts has been clarified enormously over the last five years, primarily due to the angular resolution and dynamic range offered by the Hubble Space Telescope. In this overview I have therefore chosen to concentrate on the results of recent, primarily HST-based studies of low-redshift quasars, and will only briefly mention the latest results at higher redshift which are discussed in detail elsewhere in these proceedings. I have also chosen to centre the discussion around our own, recently-completed, HST imaging study of the hosts of quasars at $z \simeq 0.2$. Preliminary results from this programme can be found in McLure et al. (1999) and final results from the completed samples are presented by Dunlop et al. (2001). Here I focus on a few of the main results from this study and discuss the extent to which other authors do or do not agree with our findings.

2. **Host galaxy luminosity, morphology and size**

After some initial confusion (e.g. Bahcall et al. 1994), recent HST-based studies have now reached agreement that the hosts of all luminous quasars ($M_V < -23.5$) are bright galaxies with $L > L^*$ (McLure et al. 1999, McLeod & McLeod 2001, Dunlop et al. 2001). However, it can be argued, (with some justification) that this much had already been established from earlier ground-based studies (e.g. Taylor et al. 1996).

In fact the major advance offered by the HST for the study of quasar hosts is that it has enabled host luminosity profiles to be measured over sufficient angular and dynamic range to allow a de Vaucouleurs $r^{1/4}$-law spheroidal component to be clearly distinguished from an exponential disc, at least for redshifts $z < 0.5$. In our own study this is the reason that we have been able to establish unambiguously that, at low $z$, the hosts of both radio-loud quasars (RLQs) and radio-quiet quasars (RQQs) are undoubtedly massive ellipticals with (except for one RQQ in our sample) negligible disc components (McLure et al. 1999, Dunlop et al. 2001). This result is illustrated in figure 1.

Figure 1 confirms that the hosts of radio-loud quasars and radio galaxies all follow essentially perfect de Vaucouleurs profiles, in good agreement with the results of other studies. The perhaps more surprising aspect of figure 1 is the extent to which our radio-quiet quasar sample is also dominated by spheroidal hosts. At first sight this might seem at odds with the results of some other recent studies, such as those of Bahcall et al. (1997) and Hamilton et al. (2001) who report that approximately one third to one half of radio-quiet quasars lie in disc-dominated hosts. However, on closer examination it becomes clear that there is no real contradiction provided one compares quasars of similar
The host galaxies of radio-loud and radio-quiet quasars

Figure 1. Histograms of the best-fit values of $\beta$, where host-galaxy surface brightness is proportional to $\exp(-r^\beta)$, shown for the radio-galaxy, radio-loud quasar and radio-quiet quasar sub-samples imaged with the HST by Dunlop et al. (2001). The dotted line at $\beta = 0.25$ indicates a perfect de Vaucouleurs law, and all of the radio-loud hosts are consistent with this within the errors. Two of the three RQQs with hosts for which $\beta > 0.4$ transpire to be the two least luminous nuclei in the sample, and should really be reclassified as Seyferts.

power. Specifically, if attention is confined to quasars with nuclear magnitudes $M_V < -23.5$ we find that 10 out of the 11 RQQs in our sample lie in ellipticals, Bahcall et al. find that 6 of their 7 similarly-luminous quasars lie in ellipticals, while an examination of the data in Hamilton et al. shows that in fact at least 17 out of the 20 comparably-luminous RQQs in their archival sample also appear to lie in spheroidal hosts.

It is thus now clear that above a given luminosity threshold we enter a regime in which AGN can only be hosted by massive spheroids, regardless of radio power. It is also clear that, within the radio-quiet population, significant disc components become more common at lower nuclear luminosities. This dependence of host-galaxy morphology on
Figure 2. The relative contribution of the spheroidal component to the total luminosity of the host galaxy plotted against absolute V-band luminosity of the nuclear component. The plot shows the results for our own HST sample (RLQs as open circles, RQQs as filled circles) along with the results from Schade et al. (2000) for a larger sample of X-ray selected AGN spanning a wider but lower range of optical luminosities (asterisks). This plot illustrates very clearly how disc-dominated host galaxies become increasingly rare with increasing nuclear power, as is expected if more luminous AGN are powered by more massive black holes which, in turn, are housed in more massive spheroids.

nuclear luminosity is nicely demonstrated by combining our own results with those of Schade et al. (2000) who have studied the host galaxies of lower-luminosity X-ray selected AGN. This I have done in figure 2 where the ratio of bulge to total host luminosity is plotted as a function of nuclear optical power. Figure 2 is at least qualitatively as expected if black-hole mass is proportional to spheroid mass (Magorrian et al. 1998, Merritt & Ferrarese 2001), and black-hole masses $> 5 \times 10^8 M_\odot$ are required to produce quasars with $M_R < -23.5$.

In concluding this discussion of host morphology I should note that there is at least some (albeit yet tentative) evidence that the hosts of some of the most luminous quasars may in fact have a significant disc contribution (Percival et al. 2001). At first sight this would appear to be at odds with the appealingly simple picture presented in figure 2, and it will certainly be interesting to see if this result survives the scrutiny of HST imaging currently underway. However, if confirmed, such a result need not contradict the universality of elliptical hosts, but rather might mean that some of the most luminous quasars arise from the merger of the elliptical host with a massive gas-rich disc galaxy, in which case the
underlying massive elliptical might (at least temporarily) appear to have acquired a significant disc component.

In our HST study we have also been able to break the well-known degeneracy between host galaxy surface-brightness and size. This point is illustrated by the fact that we have, for the first time, been able to demonstrate that the hosts of RLQs and RQQs follow a Kormendy relation (figure 3). Moreover the slope \( (2.90 \pm 0.2) \) and normalization of this relation are identical to that displayed by normal quiescent massive ellipticals. The average half-light radii of the host galaxies in our subsamples are 11 kpc for the RGs, 12 kpc for the RLQs, and 8 kpc for the RQQs \( (H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_m = 1.0) \). For comparison the average half-light radius of brightest-cluster galaxies observed by Schneider et al. (1983) is 13 kpc.

\[ \text{Figure 3.} \quad \text{The Kormendy relation followed by the hosts of all 33 powerful AGN studied by Dunlop et al. (2001) with the HST. The solid line is the least-squares fit to the data which has a slope of } 2.90 \pm 0.2, \text{ in excellent agreement with the slope of } 2.95 \text{ found by Kormendy (1977) for inactive ellipticals. For the few RQQs which have a disc component the best-fitting bulge component has been plotted.} \]

3. Host galaxy ages

It is well known from simulations that the merger of two disc galaxies can produce a remnant which displays a luminosity profile not dissimilar to a de Vaucouleurs \( r^{1/4} \)-law. This raises the possibility that the apparently spheroidal nature of the quasar hosts discussed above might be the result of a recent major merger which could also be responsible for stimulating the onset of nuclear activity. This would also be the natural prediction of suggested evolutionary schemes in which ULIRGs are
presumed to be the precursors of RQQs. Could a recent merger of two massive gas-rich discs be simultaneously responsible for the triggering of nuclear activity and the production of an apparently spheroidal host?

The answer appears to be no. One piece of evidence against such a picture comes from the fact that, as mentioned above, the Kormendy relation displayed by quasar hosts appears to be indistinguishable from that of quiescent, well-evolved massive ellipticals. However, a more direct test comes from attempts to determine the ages of the dominant stellar populations in the quasar hosts. Within our own sample we have attempted to estimate the ages of the host galaxies both from optical-infrared colours (now possible for the first time by combining our HST images with our pre-existing UKIRT data; Taylor et al. 1996) and from deep optical off-nuclear spectroscopy (Nolan et al. 2000). The results of this investigation are summarized in figure 4, which shows that the hosts of both radio-loud and radio-quiet quasars are dominated by old well-evolved stellar populations (with typically less than 1% of stellar mass involved in recent star-formation activity). There are currently no comparably-extensive studies of host-galaxy stellar populations with this result can be compared. However, Canalizo & Stockton (2000) have published results from a more detailed spectroscopic study of three objects, one of which, Mkn 1014, is also in our RQQ sample. This is in fact the only quasar host for which we have found clear spectroscopic evidence of A-star features and a significant (albeit still only \(\approx 2\%\) by mass) young stellar population. It is presumably no coincidence that this is also the only quasar in our sample which was detected by IRAS, and the only host which displays spectacular tidal-tail features comparable to those commonly found in images of ULIRGs (see Sanders, this proceedings). However, even for this apparently star-forming quasar host, Canalizo & Stockton agree that \(\approx 95\%\) of the host is dominated by an old well-evolved stellar population (although they argue that \(5 - 8\%\) of the galaxy has been involved in recent star formation).

In summary, at least for low-redshift quasars, the timescale of the primary star-formation epoch in the host appears to be completely disconnected from that of the more recent nuclear activity which has resulted in the object featuring in quasar catalogues. The production of a low-redshift quasar only seems to require the massive, well-evolved spheroid housing the massive black hole to undergo a relatively minor interaction. In contrast the production of a ULIRG seems to require a major merger between two massive galaxies at least one of which is gas rich. Present evidence suggests that the overlap between these two phenomena is rather limited at low redshift, and that the ULIRG → quasar evolutionary route can only apply to a fairly small subset
The host galaxies of radio-loud and radio-quiet quasars

Figure 4. The age distribution of the dominant stellar populations in the subsamples of host galaxies studied by Nolan et al. (2001). The ages were derived by fitting a 3-component model (comprising scattered quasar light, a young (0.1Gyr) stellar population, and an underlying stellar population of age ranging from 0.1 to 14 Gyr) simultaneously to off-nuclear optical spectra and the $R-K$ colours of the host galaxies. The dominant populations in the hosts of both radio-loud and radio-quiet AGN are predominantly old (12-14 Gyr) as is found for quiescent elliptical galaxies.

of objects (e.g. Mkn 1014). Of course at high redshift the prospect for star-formation and nuclear activity having completely disconnected timescales is much more limited, and it seems likely that the first epoch of quasar activity in a massive galaxy is closely connected with massive (possibly dust-enshrouded) star-formation activity in the host (e.g. Fabian 1999, Archibald et al. 2001).

4. Black hole masses and radio loudness

Having established that the hosts of quasars are massive spheroids one can estimate the mass of their central black holes using the relationship between spheroid luminosity and black-hole mass recently derived from dynamical studies of nearby galaxies (e.g. Magorrian et al. 1998, Merritt & Ferrarese 2001). While undoubtedly uncertain to within a factor of a few, the attractiveness of this approach is that it allows an estimate of the central black-hole mass which is independent of any of the observed properties of the active nucleus. This estimate can then be compared with, for example, an estimate based on the assumption that the nucleus is accreting at the Eddington limit.
Using one of the most recent determinations of the black-hole:spheroid mass relationship, \( M_{bh} = 0.0013 M_{\text{spheroid}} \) (Merritt & Ferrarese 2001), we find average black-hole mass estimates of \( \langle M_{bh} \rangle = 1.5 \times 10^9 M_\odot \) for the RLQs in our sample, and \( \langle M_{bh} \rangle = 0.9 \times 10^9 M_\odot \) for the RQQs. This subtle but apparently persistent difference (see below) arises directly from the fact that, although perfectly matched in optical nuclear luminosity, the hosts of our RQQs are, on average, \( \simeq 1.5 - 2 \) times less luminous than the hosts of their radio-loud counterparts.

Figure 5. A comparison between the black-hole masses of quasars as predicted from host-galaxy spheroidal luminosity by Dunlop et al. (2001), and the corresponding values determined from \( H\beta \) line-width by McLure & Dunlop (2001). The shaded area is shown to demonstrate that there is a region in which both approaches agree that \( M_{bh} > 10^9 M_\odot \), and that this region contains all except one of the RLQs (open circles), but excludes all except 2 of the RQQs (filled circles).

A comparison of the resulting predicted Eddington luminosities with the actual observed output of the quasar nuclei leads to the conclusion that most of the RLQs in our sample are emitting at \( \simeq 5 - 10\% \) of their potential Eddington limit, while the radio-quiet objects span a wider range in efficiency, from \( \simeq 10\% \) to 100\% of the Eddington limit.

The above black-hole mass estimates can also be compared with values derived, completely independently, from an analysis of the velocity width of the \( H\beta \) lines in the quasar nuclear spectra under the assumption that the broad-line region is gravitationally bound. This has been a growth industry in recent years (e.g. Wandel 1999, Laor 2000), bolstered by estimates of the size of the broad-line region from reverberation mapping of Seyfert galaxies. Recently Ross McLure and I have applied this technique to estimate the masses of the black holes which power the quasars we have imaged with the HST. The results are remarkably
The host galaxies of radio-loud and radio-quiet quasars

Figure 6. Mean absolute $V$-band magnitude versus mean redshift for the host galaxies of the RLQs (open circles) and RQQs (filled circles) in the NICMOS study of Kukula et al. (2001). Also shown is the subset of 5 RLQs and 7 RQQs from the Dunlop et al. (2001) WFPC2 study of quasars at $z \sim 0.2$ which have total (host + nuclear) luminosities in the same range as the high-redshift samples ($-24 \geq M_V \geq -25$). Error bars show the standard error on the mean. The dotted lines show the luminosity evolution of present day $L^*$, $2L^*$ and $4L^*$ elliptical galaxies, assuming a formation epoch of $z = 5$ with a single rapid burst of star formation followed by passive evolution thereafter. LH panel: assuming $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 1.0$ and $\Omega_\Lambda = 0.0$. RH panel: $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

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similar to the values described above, with the $H_\beta$ line-width yielding $\langle M_{bh} \rangle = 1 \times 10^9 M_\odot$ for the RLQs, and $\langle M_{bh} \rangle = 5 \times 10^8 M_\odot$ for the RQQs.

Such agreement (to within a factor of two - figure 5) suggests that these mass estimates should be taken seriously, and of special interest is the fact that the apparent mass offset between the black holes which power radio-loud and radio-quiet objects persists (figure 5). Indeed, given the uncertainties involved, the division in mass appears fairly clean, at least in the sense that the radio-loud objects all lie above a certain mass threshold. Black-hole mass estimation from host spheroid luminosity leads to the conclusion that 9 out of the 10 RLQs have $M_{bh} > 10^9 M_\odot$ while only 4 out of the 11 RQQs lie above this threshold. From the $H_\beta$ analysis 11 out of 13 RLQs have $M_{bh} > 10^{8.8} M_\odot$, while only 4 out of 17 RQQs lie in this regime (see McLure, these proceedings). A similar conclusion has recently been reached by Laor (2000).

There are a number of possible explanations for this apparent black-hole mass difference between radio-loud and radio-quiet objects. Interestingly Blandford (2000) argues that highly-collimated jets might only be produced by sub-Eddington accretion. Thus it may simply be the case that by selecting RLQs and RQQs of comparable optical output, we are guaranteed to find sub-Eddington accreters in the radio-loud sample, whereas the radio-quiet sample can contain at least some less massive holes emitting at close to maximum efficiency.
5. The connection to high redshift

The effective study of quasar hosts at high redshift is still in its infancy. However, already it is becoming clear that the mass offset between RQQ and RLQ hosts described above appears to grow with increasing redshift (see figure 6, plus Kukula et al. (2001), and contributions from Kukula, Ridgway, Impey and Rix in these proceedings), lending additional credence to its reality. Specifically, for the same nuclear luminosity, RQQ hosts at $z \approx 2$ appear to be a factor of 2-3 less massive than either their low-z counterparts or their $z \approx 2$ radio-loud counterparts. It is too early to say whether this is due to changes in the host population, or simply due to (on average) more efficient black-hole fueling revealing more clearly the mass threshold required for radio-loud activity. Over the next few years it will be extremely interesting to see if high-resolution infrared imaging with 8-m class telescopes can clarify our picture of high-z quasar hosts in the same way as has been achieved with the HST at low redshift.

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