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Quasar Hosts and the Black Hole-Spheroid Connection

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Abstract

I review our current understanding of the structures and ages of the host galaxies of quasars, and the masses of their central black holes. At low redshift, due largely to the impact of the *Hubble Space Telescope*, there is now compelling evidence that the hosts of quasars with $M_V < -24$ mag are virtually all massive ellipticals, with basic properties indistinguishable from those displayed by their quiescent counterparts. The masses of these spheroids are as expected given the relationship between black hole and spheroid mass now established for nearby galaxies, as is the growing prevalence of significant disk components in the hosts of progressively fainter active nuclei. In fact, from spectroscopic measurements of the velocity of the broad-line region in quasars, it has now proved possible to obtain an independent dynamical estimate of the masses of the black holes that power quasars. I summarize recent results from this work, which can be used to demonstrate that the black hole-spheroid mass ratio in quasars is the same as that found for quiescent galaxies, namely $M_\bullet = 0.0012 M_{\rm sph}$. These results offer the exciting prospect of using observations of quasars and their hosts to extend the study of the black hole-spheroid mass ratio out to very high redshifts ($z > 2$). Moreover, there is now good evidence that certain ultraviolet quasar emission lines can provide robust estimates of black hole masses from the observed optical spectra of quasars out to $z > 2$, and perhaps even at $z > 4$. By combining such information with deep, high-resolution infrared imaging of high-redshift quasar hosts on 8-m class telescopes, there is now a real prospect of clarifying the evolution of the black hole spheroid connection over cosmological time scales.

1.1 Introduction

With the discovery that all spheroids (i.e., elliptical galaxies and disk galaxy bulges) appear to house a massive black hole of proportionate mass (Magorrian et al. 1998; Gebhardt et al. 2000a; Merritt & Ferrarese 2001), the nature and evolution of quasar host galaxies has grown from a subject explored primarily by AGN researchers, into an area of interest for all astronomers concerned with the formation and evolution of galaxies and of compact objects.

Indeed, black hole and spheroid formation/growth are now recognized as potentially intimately related processes (Silk & Rees 1998; Fabian 1999; Granato et al. 2001; Archibald et al. 2002), with the evolution of quasar host galaxies as a function of redshift now seen as a key measurement in observational cosmology (e.g., Kauffmann & Haehnelt 2000). In this review I have chosen to focus on what can be learned about the nature of the black hole spheroid connection from observations of quasars and their hosts. I have therefore deliberately avoided detailed discussion of many other topics of interest related to quasar host galaxy research, such as the triggering of quasar activity, the origin of radio loudness, and the nature of possible links between quasars and ultraluminous infrared galaxies (ULIRGs).

This Chapter is divided into three sections as follows. First I summarize what has been learned about the host galaxies of low-redshift quasars from deep imaging/spectroscopy over the last decade. Second I discuss the latest dynamical estimates of the masses of the black holes that power quasars. Third I consider the immediate future prospects for extending these two prongs of measurement to higher redshift, to explore the nature of the black hole spheroid connection as a function of cosmological time.

Unless otherwise stated, an Einstein-de Sitter Universe with $H_0 = 50\,\mathrm{km\,s^{-1}Mpc^{-1}}$ has been assumed for the calculation of physical quantities.

1.2 The Host Galaxies of Low-redshift Quasars

Many imaging studies and several spectroscopic studies of "nearby" ($z < 0.3$) quasar host galaxies have been attempted over the last quarter of a century, but it is only in the last decade that a clear picture of the nature of quasar hosts has emerged from this work. This progress can be attributed first to the advent of deep near-infrared imaging (Dunlop et al. 1993; McLeod & Rieke 1994; Taylor et al. 1996), and second to the high angular resolution provided by the refurbished *Hubble Space Telescope (HST)* (e.g., Disney et al. 1995; Bahcall et al. 1997; Hooper, Impey, & Foltz 1997; McLure et al. 1999).

Some workers have chosen to focus on some of the morphological peculiarities and evidence of "action" revealed by this deep imaging, such as tidal tails, and nearby companions (perhaps responsible for triggering the nuclear activity). However, the clearest results, and most meaningful insights have emerged from studies that have focused on determining the properties of the mass-dominant stellar populations in quasar hosts, and exploring how these compare with those of quiescent galaxies.

Figure 1.1 provides an example of how clearly the basic structure of low-redshift quasar host galaxies can be discerned with an exposure of ~ 1 hour on the *HST*. This image (taken from Dunlop et al. 2003) demonstrates not only that the host galaxy is well resolved, but also the extent to which the vast majority of the optical light from the host can generally be attributed to a simple, symmetric, "normal" galaxy (in this case an elliptical, with an $r^{1/4}$ de Vaucouleurs luminosity profile, and a half-light radius of 7.5 kpc).

For simplicity I have chosen to center the following summary of what has been learned from such images around the main results from our own, recently completed, *HST* imaging study of the hosts of radio-loud quasars (RLQs), radio-quiet quasars (RQQs) and radio galaxies (RGs) at $z \simeq 0.2$ (Dunlop et al. 2003). However, wherever appropriate, I have also endeavored to discuss (and if possible explain) the extent to which other authors do or do not agree with our findings.

1.2.1 Host Galaxy Luminosity, Morphology, and Size

After some initial confusion (e.g., Bahcall, Kirhakos, & Schneider 1994), recent *HST*-based studies have now reached agreement that the hosts of all luminous quasars ($M_V < -23.5$ mag) are bright galaxies with $L > L^{\star}$ (McLure et al. 1999; McLeod & McLeod 2001; Dunlop et al. 2003). This result is illustrated by Figure 1.2 (left panel), taken from Dunlop

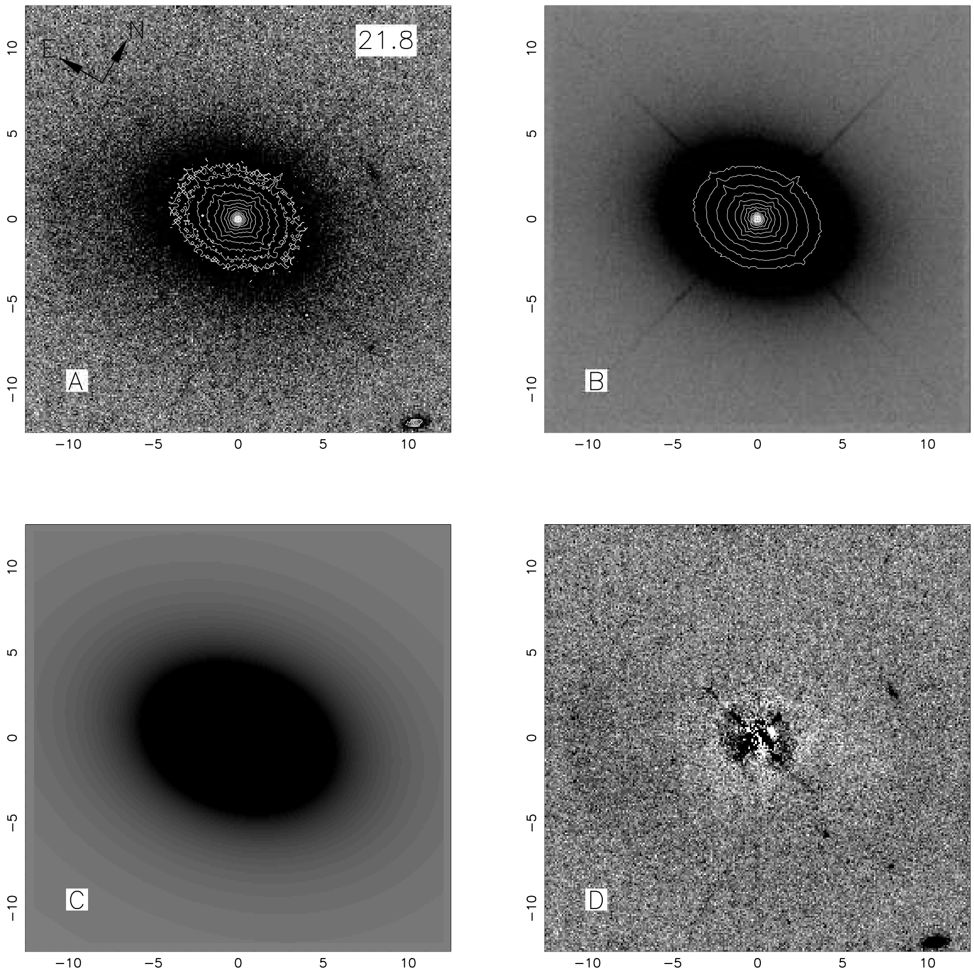

Fig. 1.1. An example of deep *HST* imaging of the host galaxy of a low-redshift quasar. A greyscale/contour representation of an *R*-band image of the $z = 0.1$ RQQ 0204+292 obtained with the WFPC2 is shown in the upper-left panel (the image is $25'' \times 25''$ in size). The upper-right panel shows the best-fitting model of this image (after convolution with the *HST* point-spread function), which comprises a de Vaucouleurs law elliptical galaxy (of half-light radius $r_{1/2} = 7.5\,\mathrm{kpc}$) along with an unresolved nuclear component. The lower-left image shows the best-fitting host galaxy as it would appear if the nucleus were inactive, while the lower-right panel is the residual image that results from subtraction of the complete model from the image. Further details of the modeling procedure used can be found in McLure, Dunlop, & Kukula (2000) and Dunlop et al. (2003).

et al. (2003). However, it can be argued, with 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

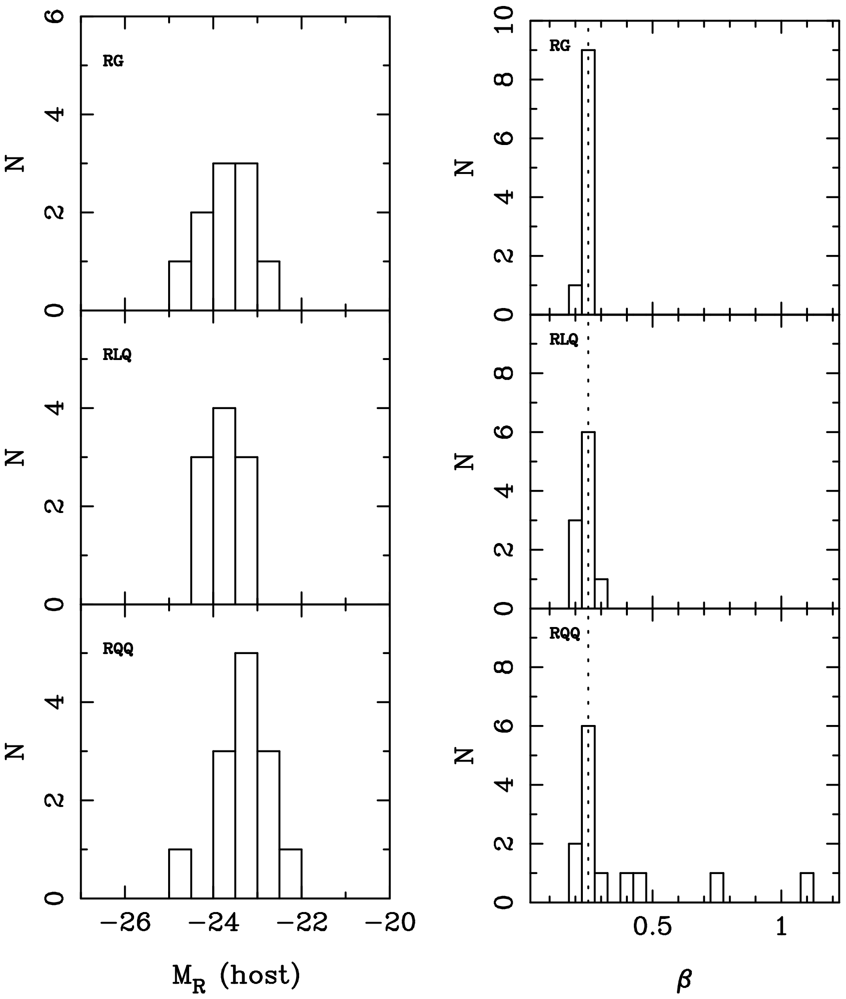

Fig. 1.2. *Left:* Histograms of host galaxy integrated *R*-band absolute magnitudes for the RG, RLQ, and RQQ subsamples imaged with the *HST* by Dunlop et al. (2003). For comparison, the integrated *R*-band absolute magnitude of an $L^{\star}$ galaxy is $M_R = -22.2$ mag. *Right:* Histograms of the best-fit values of β, where host galaxy surface brightness is proportional to $\exp(-r^{\beta})$, for the same three subsamples. The dotted line at $\beta = 0.25$ indicates a perfect de Vaucouleurs law, and all of the radio-loud hosts and all but three of the radio-quiet hosts are consistent with this to 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 be reclassified as Seyferts.

to allow a de Vaucouleurs $r^{1/4}$-law spheroidal component to be clearly distinguished from an exponential disk, 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 RLQs *and* RQQs are undoubtedly massive ellipticals with (except for one RQQ in our sample) negligible disk components (McLure et al. 1999; Dunlop et al. 2003). This result is illustrated in the right panel of Figure 1.2. This figure confirms that the hosts of RQQs and RGs all follow essentially perfect de Vaucouleurs profiles, in good agreement with the results of other studies. Perhaps the more surprising aspect is the extent to which the RQQ 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, Casertano, & Turnshek (2002), who report that approximately one-third to one-half of RQQ lie in disk-dominated hosts. However, on closer examination, it becomes clear that there is no real contradiction provided one compares quasars of similar power. Specifically, if attention is confined to quasars with nuclear magnitudes $M_V < -23.5$ mag we find that 10 out of the 11 RQQs in our sample lie in ellipticals, 6 out of 7 similarly luminous quasars in the sample of Bahcall et al. lie in ellipticals, and at least 17 out of the 20 comparably luminous RQQs in Hamilton et al.'s 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 AGNs can only be hosted by massive spheroids, regardless of radio power (a result confirmed by the recent *HST* study of the most luminous low-redshift quasars by Floyd et al. 2004). It is also clear that, within the radio-quiet population, significant disk components become more common at lower nuclear luminosities. This dependence of host galaxy morphology on nuclear luminosity is nicely demonstrated by combining our own results with those of Schade, Boyle, & Letawsky (2000) who have studied the host galaxies of lower-luminosity X-ray selected AGNs. This is shown in Figure 1.3 where the ratio of bulge to total host luminosity is plotted as a function of nuclear optical power. Figure 1.3 is at least qualitatively as expected if black hole mass is proportional to spheroid mass, and black hole masses $> 2 \times 10^8 M_\odot$ are required to produce quasars with $M_R < -23.5$ mag.

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 Kormendy's (1977) relation (i.e., the photometric projection of the fundamental plane; Fig. 1.4). Moreover the slope (2.90 ± 0.2) and normalization of this relation are identical to that displayed by normal quiescent massive ellipticals.

1.2.2 Host Galaxy Ages

It is well known from simulations that the merger of two disk galaxies can produce a remnant that 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 that 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 disks be simultaneously responsible for the triggering of nuclear activity and the production of an apparently spheroidal host?

The answer, at least at low redshift, appears to be no. First, as mentioned above, the Kormendy relation displayed by quasar hosts appears to be indistinguishable from that of quiescent, well-evolved massive ellipticals. Moreover, as discussed by Genzel et al. (2001) and Dunlop et al. (2003), ULIRGs generally lie in a different region of the fundamental plane to quasar hosts, with the former apparently destined to evolve into lower or intermediate-mass spheroidal galaxies.

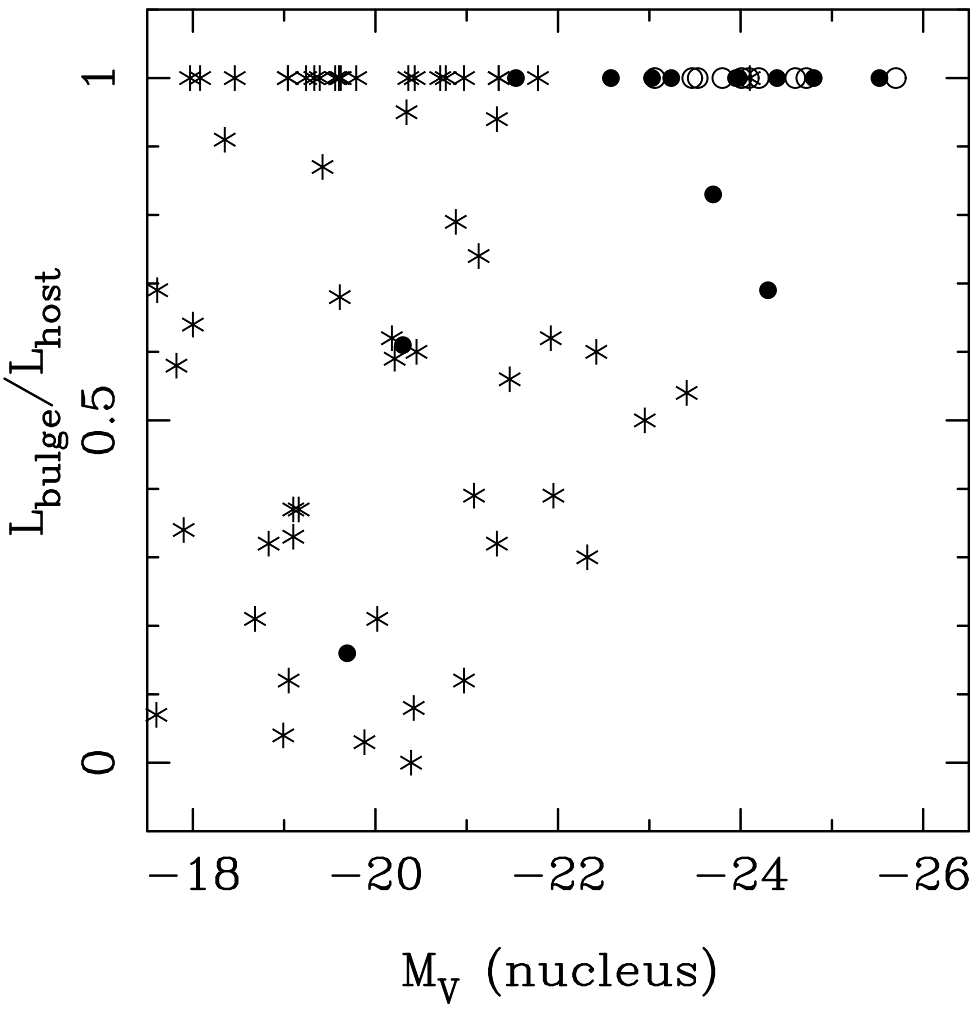

Fig. 1.3. The relative contribution of the spheroidal component to the total luminosity of the host galaxy plotted against the absolute V-band magnitude of the nuclear component. The plot shows the results from Dunlop et al. (2003) (RLQs as open circles, RQQs as filled circles) along with the results from Schade et al. (2000) for a larger sample of X-ray selected AGNs spanning a wider but lower range of optical luminosities (asterisks). This plot illustrates very clearly how disk-dominated host galaxies become increasingly rare with increasing nuclear power, as is expected if more luminous AGNs are powered by more massive black holes, which, in turn, are housed in more massive spheroids.

Secondly, direct attempts to determine the ages of the dominant stellar populations in the quasar hosts provide little evidence of recent, widespread star formation activity. Within the Dunlop et al. sample we have attempted to estimate the ages of the host galaxies both from optical-infrared colors and from deep optical off-nuclear spectroscopy (Nolan et al. 2001). The results of this investigation are 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

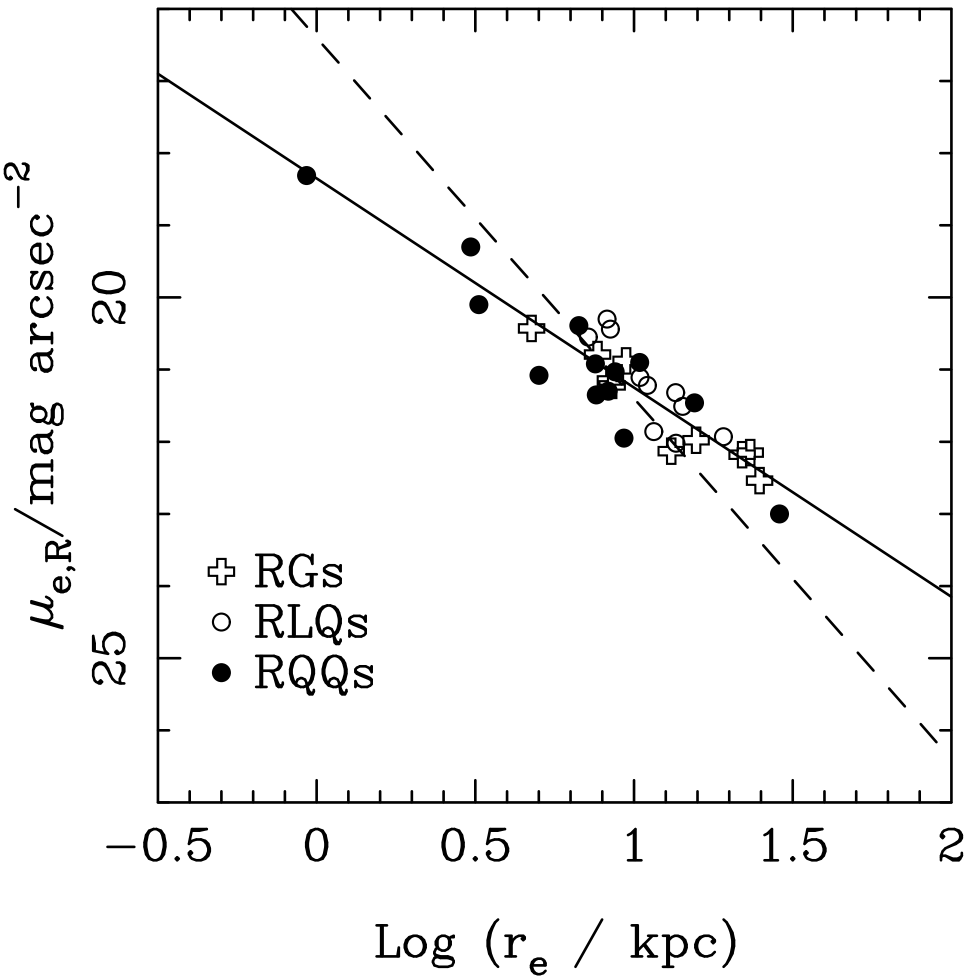

Fig. 1.4. The Kormendy (1977) relation followed by the hosts of all 33 powerful AGNs studied by Dunlop et al. (2003) with the *HST*. The solid line is the least-squares fit to the data that has a slope of 2.90 ± 0.2, in excellent agreement with the slope of 2.95 found by Kormendy for inactive ellipticals. For the few RQQs that have a disk component the best-fitting bulge component has been plotted. The dashed line has a slope of 5, indicative of the "pseudo Kormendy relation" expected if the scale lengths of the host galaxies had not been properly constrained (see Dunlop et al. 2003). (Adapted from Dunlop et al. 2003.)

mass involved in recent star formation activity). There are currently no comparably extensive studies of host galaxy stellar populations with which this result can be compared. However, Canalizo & Stockton (2000) have published results from a more detailed spectroscopic study of three objects, one of which, Mrk 1014, is also in the Dunlop et al. RQQ sample. This is in fact the only quasar host in the Dunlop et al. sample for which Nolan et al. (2001) found clear spectroscopic evidence of A-star features and a significant (albeit still only $\simeq 2\%$ by mass) young stellar population. It is presumably no coincidence that this is also the only quasar in the Dunlop et al. sample that was detected by *IRAS*, and the only host that displays spectacular tidal tail features comparable to those commonly found in images of ULIRGs. However, even for this apparently star-forming quasar host, Canalizo & Stockton agree that $\simeq 95\%$ 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).

Finally, despite claims to the contrary, recent measurements of molecular gas in AGN host galaxies reported by Scoville et al. (2003) are completely consistent with this picture. Scoville et al. detected substantial molecular gas masses in the hosts of lower luminosity quasars with known substantial disk components, and failed to detect molecular gas in the hosts of the three most luminous quasars in their sample.

In summary, the available evidence indicates that the hosts of quasars with $M_V < -23.5$ mag are virtually all massive elliptical galaxies. Moreover, quasar hosts appear to be "normal" ellipticals in the sense that their basic structural properties, and the ages of their dominant stellar populations are, at least to first order, indistinguishable from those of their quiescent counterparts. Both the universality of elliptical hosts for the most luminous low-redshift quasars and the growing prevalence of significant disk components in the hosts of progressively fainter active nuclei can be viewed as a natural reflection of the proportionality of black hole and spheroid mass now established for nearby quiescent galaxies. In the next section I describe the results of recent attempts to obtain dynamical estimates of the masses of the black holes that power quasars. Such studies allow a direct test of whether or not the constant of proportionality between black hole and spheroid mass is the same in the active and inactive galaxy populations.

1.3 The Black Hole-Spheroid Mass Ratio in Low-redshift Quasars

If one assumes that quasars emit at the Eddington limit, it is straightforward to obtain a very rough estimate of the masses of their central black holes. However, a potentially much more reliable estimate of black hole mass can be obtained via an analysis of the velocity widths of the Hβ lines in quasar nuclear spectra. 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 (BLR) from reverberation mapping of low-redshift, broad-line AGNs.

1.3.1 The Virial Black Hole Mass Estimator

The underlying assumption behind the virial black hole mass estimator is that the motion of the broad-line emitting material in AGNs is virialized. Under this assumption the width of the broad lines can be used to trace the Keplerian velocity of the broad-line gas, and thereby allow an estimate of the central black hole mass via the formula $M_\bullet = G^{-1} R_{\rm BLR} V_{\rm BLR}^2$, where $R_{\rm BLR}$ is the BLR radius and $V_{\rm BLR}$ is the Keplerian velocity of the BLR gas. Currently, the most direct measurements of the central black hole masses of powerful AGNs are for 17 Seyferts and 17 PG quasars for which reverberation mapping has provided a direct measurement of $R_{\rm BLR}$ (Wandel, Peterson & Malkan 1999; Kaspi et al. 2000).

An important outcome from these studies is the discovery of a correlation between $R_{\rm BLR}$ and the monochromatic AGN continuum luminosity at 5100 Å (e.g., $R_{\rm BLR} \propto \lambda L_{5100}^{0.7}$; Kaspi et al. 2000). By combining this luminosity-based $R_{\rm BLR}$ estimate with a measure of the BLR velocity based on the FWHM of the Hβ emission line, it is now possible to produce a virial black hole mass estimate from a single spectrum covering Hβ. This technique has recently been widely employed to investigate how the masses of quasar black holes relate to the

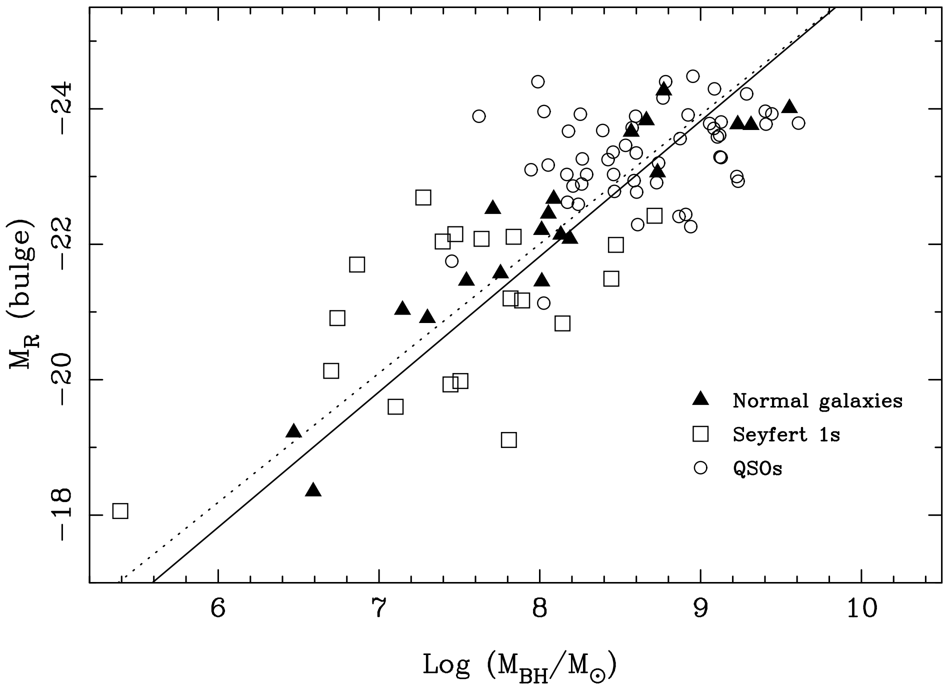

Fig. 1.5. Absolute *R*-band bulge magnitude versus black hole mass plotted for 72 AGNs and 18 inactive elliptical galaxies. The black hole masses for the 72 AGNs are derived from their Hβ line widths using a disklike BLR model (see McLure & Dunlop 2002). The black hole masses of the inactive galaxies (triangles) are dynamical estimates as compiled by Kormendy & Gebhardt (2001). Also shown is the formal best fit (solid line) and the best-fitting linear relation between spheroid and black hole mass (dotted line).

properties of the surrounding host galaxies (e.g., Laor 2001; McLure & Dunlop 2001,2002) and the radio luminosity of the central engine (Lacy et al. 2001; Dunlop et al. 2003).

Of most direct relevance to the topic of interest in this review is the result shown in Figure 1.5. This shows how the relationship between host galaxy luminosity and black hole mass derived for quasars and Seyferts compares with that derived for normal galaxies (McLure & Dunlop 2002).

Under the assumption that $M_\bullet \propto M_{\rm sph}$ the best-fitting constant of proportionality derived from the fit to the quasar and Seyfert data points in Figure 1.5 is 0.0012. This is essentially identical to the value (0.0013) for nearby inactive galaxies derived by Kormendy & Gebhardt (2001), and to the value (0.0012) derived by Merritt & Ferrarese (2001). While the virtually exact agreement between these numbers may be fortuitous, the similarity of the mass relationships derived for the active and inactive samples can be fairly viewed as providing confirmation both that the $M_\bullet - M_{\rm sph}$ relation is the same in active and inactive galaxies, and that the assumption of gravitational equilibrium made in applying the Hβ virial mass estimator is valid (see also Gebhardt et al. 2000b).

1.3.2 Eddington Ratios

Having confirmed the constant of proportionality between host spheroid and black hole mass for quasars one can then re-address the issue of how the actual nuclear luminosities of quasars compare with their predicted Eddington-limited values (as inferred from the luminosities of their host galaxies).

This is illustrated in Figure 1.6, in which host galaxy absolute V-band magnitude is plotted against quasar nuclear absolute magnitude for an expanded sample of quasars assembled from five recent studies [see figure caption and Floyd et al. (2004) for details]. Also shown in this plot are the predicted relations for black holes emitting at 100%, 10% and 1% of the Eddington limit.

This plot provides (perhaps surprisingly good) evidence that, at any given host luminosity, the most luminous quasar nuclei are emitting at the predicted Eddington limit (as calculated on the basis of a black hole mass inferred from host luminosity using the relation shown in Fig. 1.5). It also shows that the majority of low-redshift quasars studied to date are emitting at between 10% and 100% of the Eddington limit, and that their host galaxies range in luminosity from $L^{\star}$ to 10 $L^{\star}$.

In concluding this section, I note that on the basis of this plot it would be predicted that the most luminous quasars found in the high-redshift Universe, with $M_V < -27$ mag, can only be produced by the black holes at the centers of the most massive ($10L^{\star}$) ellipticals, or their progenitors.

1.4 Cosmological Evolution of the Black Hole-Spheroid Mass Ratio

The two main results presented in the last two sections can be summarized as follows. First, it is clear that the host galaxies of low-redshift quasars are normal massive ellipticals. Second, it appears that by combining deep host galaxy imaging with the spectroscopic Hβ virial black hole mass estimator, low-redshift quasars can be used to provide an unbiased estimate of the black hole-spheroid mass ratio in the present-day inactive elliptical galaxy population.

These two results provide confidence that, through the study of quasars at higher redshifts, we can establish the cosmological evolution of the black hole-spheroid mass ratio in the general elliptical galaxy population. This is important for two reasons. First, from a purely practical point of view, we are forced to study quasars to explore the redshift evolution of this mass relationship. This is simply because a virial mass estimator based on bright, observable, emission lines offers the only realistic method by which to measure black hole masses in high-redshift objects. Second, it can certainly be argued that, to all intents and purposes, the high-redshift elliptical galaxy population *is* the high-redshift quasar population. Whereas only 1 in $10^4 - 10^5$ present-day ellipticals is active, Figure 1.6 coupled with a comparison of the present-day elliptical and high-redshift quasar luminosity functions leads to the conclusion that at least 10% of the progenitors of present-day massive ellipticals were active quasars at $z \simeq 2.5$.

So, to explore the cosmological evolution of the black hole-spheroid mass ratio in massive galaxies, we require a version of the Hβ virial mass estimator that can be applied to high-redshift quasars, coupled with a means to estimate the masses of high-redshift quasar hosts. Below I consider the current status of these two observational challenges, starting with the problem of black hole mass estimation at high redshift.

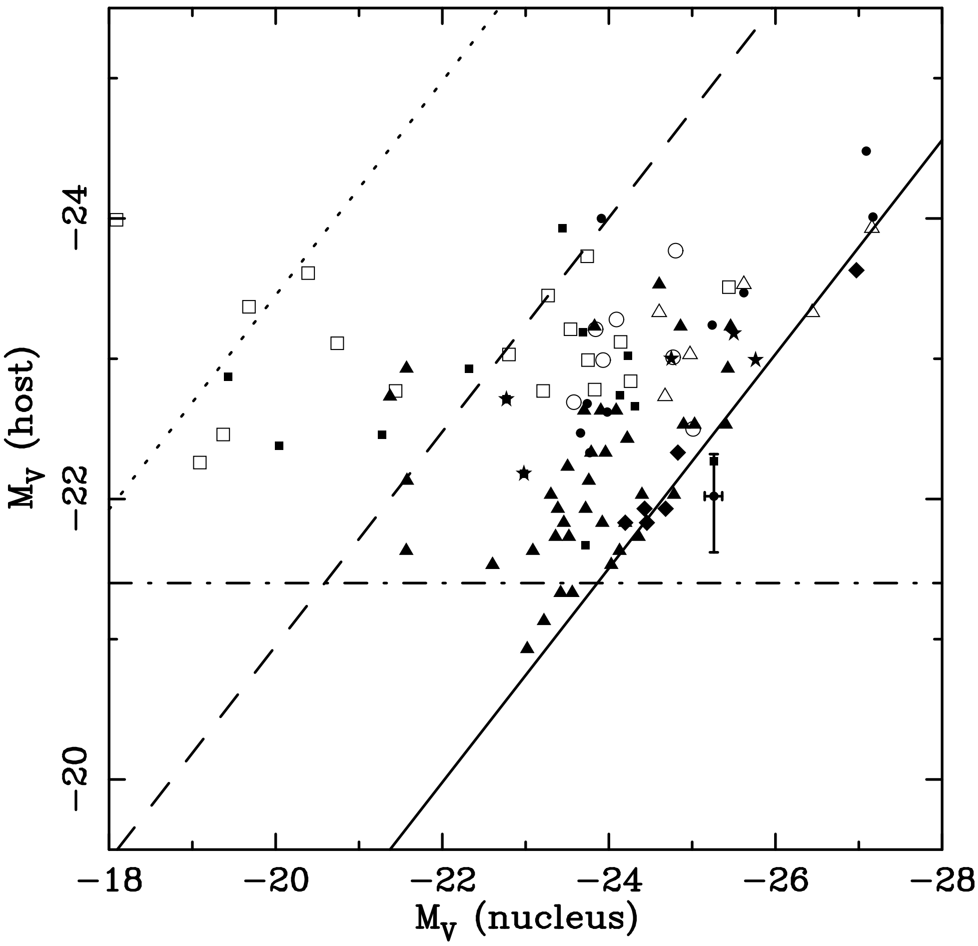

Fig. 1.6. Host absolute magnitude plotted versus nuclear absolute magnitude for the quasars studied by Floyd et al. (2004; circles), Dunlop et al. (2003; squares), McLeod & Rieke (1994; triangles), McLeod & McLeod (2001; diamonds), and also for five objects reimaged with *HST* by Percival et al. (2001; stars). The solid line illustrates the predicted limiting relation on the assumption of Eddington-limited accretion, with the dashed and dotted lines denoting 10% and 1% of the Eddington limit, respectively. The one object in this combined sample that appears to be more luminous than the Eddington limit is the luminous quasar 1252+020. However, as indicated by the large error bars, this is also the object for which Floyd et al. (2004) have least confidence in the robustness with which host and nuclear luminosity have been separated (see Floyd et al. 2004 for further details). (Adapted from Floyd et al. 2004).

1.4.1 Black Hole Mass Measurement in High-redshift Quasars

The well-studied Hβ emission line is observable from the ground out to $z \simeq 3$. However, because it is redshifted into the near-infrared at a redshift of $z \sim 1$, it is observationally expensive to use Hβ to estimate the black hole masses of $z > 1$ quasars. Consequently, a concerted effort has recently been invested to establish whether or not any of the ultraviolet

(UV) emission lines, so prominent in the observed optical spectra of high-redshift quasars, can be exploited and trusted to yield a comparably accurate and unbiased estimate of black hole mass.

Two studies have recently been published that provide evidence that this can indeed be achieved. First, Vestergaard (2002) has proposed and calibrated a UV black hole mass estimator based on the FWHM of the C IV emission line (λ = 1549Å) and the continuum luminosity at 1350Å. Second, McLure & Jarvis (2002) have proposed and confirmed the robustness of a UV black hole mass estimator based on the FWHM of the Mg II emission line (λ = 2799Å) and the continuum luminosity at 3000Å.

In terms of accessible redshift range, these two proposed mass estimators are reasonably complementary, and in the near future it will be interesting to see how well they can be bootstrapped together to explore the black hole-spheroid mass ratio over a broad baseline in redshift. However, at present it is probably fair to say that while the C IV-based estimator in principle allows black hole mass estimation from optical spectroscopy out to $z \simeq 5$, the Mg II-based estimator appears to be more robust and is better understood.

The main reason for adopting Mg II as the UV tracer of BLR velocity is that, like Hβ, Mg II is a low-ionization line. Furthermore, due to the similarity of their ionization potentials, it is reasonable to expect that the Mg II and Hβ emission lines are produced by gas at virtually the same radius from the central ionizing source. Although care has to be taken in dealing with Fe II contamination in the vicinity of the Mg II line, this presumption has now been directly tested and confirmed by McLure & Jarvis (2002) through a comparison of Mg II FWHM and Hβ FWHM for a sample of 22 objects with reverberation mapping results for which it also proved possible to obtain Mg II FWHM measurements.

Building on this result, McLure & Jarvis (2002) have produced a calibrated, reliable, Mg II virial black hole mass estimator that can be applied over the redshift range $0.3 < z < 2.5$ from straightforward optical spectroscopy. In terms of a useful formula the final calibration of this UV black hole mass estimator is given by McLure & Jarvis as:

$$\frac{M_\bullet}{M_\odot} = 3.37 \left(\frac{\lambda L_{3000}}{10^{37}\,\mathrm{W}}\right)^{0.47} \left(\frac{\mathrm{FWHM(Mg\ II)}}{\mathrm{km\,s^{-1}}}\right)^{2}$$

The robustness of this new black hole mass estimator is illustrated in Figure 1.7. The left-hand panel shows a comparison of the results derived from the established optical (Hβ) black hole mass estimator plotted against the results from this new UV (Mg II) black hole mass estimator for a combined sample of 150 objects [see McLure & Jarvis (2002) for sample details]. Also shown is the BCES bisector fit to the data, which has the form

$$\log M_\bullet(\mathrm{H}\beta) = 1.00(\pm 0.08) \log M_\bullet(\mathrm{Mg\ II}) + 0.06(\pm 0.67),$$

perfectly consistent with a linear relation. The right-hand panel shows a histogram of $\log M_\bullet(\mathrm{Mg\ II}) - \log M_\bullet(\mathrm{H}\beta)$ for this quasar sample. The solid line shows the best-fitting Gaussian, which has $\sigma = 0.41$. These results lead McLure & Jarvis to conclude that, compared to the traditional optical black hole mass estimator, the new UV estimator provides results which are unbiased and of equal accuracy.

In concluding this subsection I note that an exciting demonstration of how, through near-infrared spectroscopy, this estimator can be applied to estimate the black hole masses of the most distant known quasars at $z > 6$ has recently been provided by Willott, McLure, & Jarvis (2003).

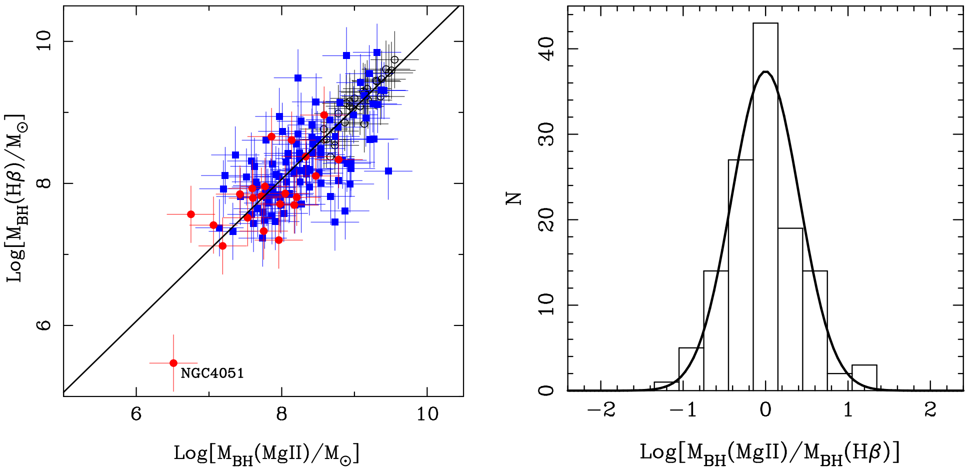

Fig. 1.7. *Left:* The optical (Hβ) versus UV (Mg II) virial black hole estimators for 150 objects from the combined RM (filled circles), LBQS (filled squares), and MQS (open circles) samples described by McLure & Jarvis (2002). The solid line is the BCES bisector fit to the 128 objects from the MQS and LBQS samples and has a slope of 1.00 ± 0.08. The outlying narrow-lined Seyfert NGC 4051 has been highlighted. *Right:* Histogram of $\log M_\bullet(\text{Mg II}) - \log M_\bullet(\text{H}\beta)$ for the 128 objects from the LBQS and MQS samples. Also shown is the best-fitting Gaussian, which has $\sigma = 0.41$. (Adapted from McLure & Jarvis 2002.)

1.4.2 Host Galaxy Mass Measurement at High Redshift

The price to be paid for having a bright quasar nucleus from which to make emission-line based black hole mass estimates at high redshift is, of course, that the measurement of the mass of the host galaxy becomes a challenge. The combination of generally unfavorable K corrections and strong surface brightness dimming means that the effective study of quasar hosts beyond $z \simeq 1$ is much harder than the study of low-redshift hosts discussed above.

It is thus natural and sensible to consider whether there is any alternative to host galaxy imaging that might be utilized to estimate host galaxy mass at high redshift. This is the motivation behind the recent suggestion by Shields et al. (2003) that the FWHM of the [O III] emission line in high-redshift quasars provides a measure of the velocity dispersion of the stars in the central regions of the host galaxy. If true, then the black hole-spheroid mass ratio in high-redshift quasars could be estimated simply from high-quality optical and near-infrared spectroscopy.

Unfortunately, this claim seems to be optimistic. While there is reasonable evidence that [O III] FWHM can be used as a proxy for central stellar velocity dispersion in low-luminosity, low-redshift AGNs (Nelson 2000), there are many reasons why this is unlikely to be the case in more luminous objects, especially at high-redshift (Boroson 2003). Moreover, as demonstrated in Figure 1.8, there is little evidence of a statistically useful correlation between the proposed [O III] estimator of spheroid mass and spheroid luminosity for the quasars and AGNs considered earlier in Figure 1.5. Unfortunately, therefore, to obtain

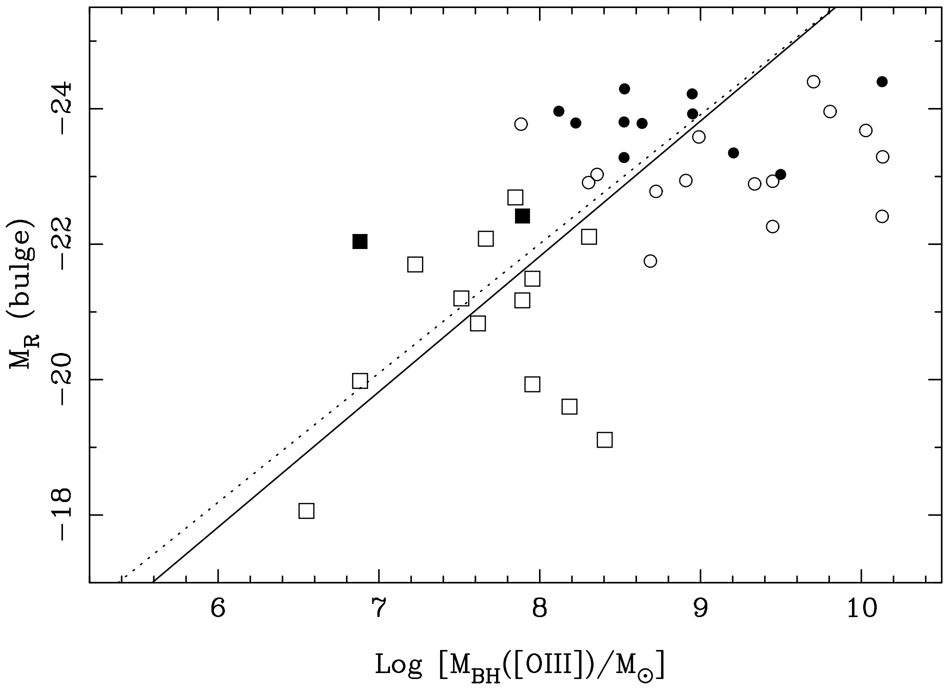

Fig. 1.8. Host spheroid absolute magnitude plotted against the [O III]-based mass estimator proposed by Shields et al. (2003) for the subset of quasars and Seyferts shown in Figure 1.5 for which a reliable FWHM for [O III] could be measured. Comparison of this “relationship” with the tight correlation shown in Figure 1.5 provides little confidence that [O III] can be used as a reliable estimator of stellar velocity dispersion in the hosts of high-redshift quasars. Removal of the radio-loud objects (black data points) does not improve the significance of the correlation.

meaningful estimates of host galaxy masses for high-redshift quasars there currently appears to be no alternative but to attempt to measure host galaxy luminosities.

What, then, are the prospects for determining the masses of high-redshift quasar host galaxies from deep imaging data? Obviously high angular resolution and a sound knowledge of the detailed form of the point-spread function remain a necessity. Also, to minimize the uncertainty in galaxy mass estimation introduced by the evolution of the host stellar population, it is desirable to undertake observations of high-redshift quasar hosts at near-infrared wavelengths.

The advent of the NICMOS camera on *HST* allowed its unique ability to provide images with robust and repeatable point-spread functions to be extended into the near-infrared. Although NICMOS is only effective out to the H band at 1.6 μm, this was sufficient to allow Kukula et al. (2001) to extend the restframe V-band study of the hosts of moderate luminosity quasars from the $z = 0.2$ regime probed by Dunlop et al. (2003) out to $z \simeq 2$.

Kukula et al. (2001) defined two new quasar samples at $z \simeq 1$ and 2, confined to the luminosity range $-24 > M_V > -25$ mag, and by observing these with NICMOS through the J and H band, respectively, obtained line-free images of the quasar hosts at both redshifts in the restframe V band.

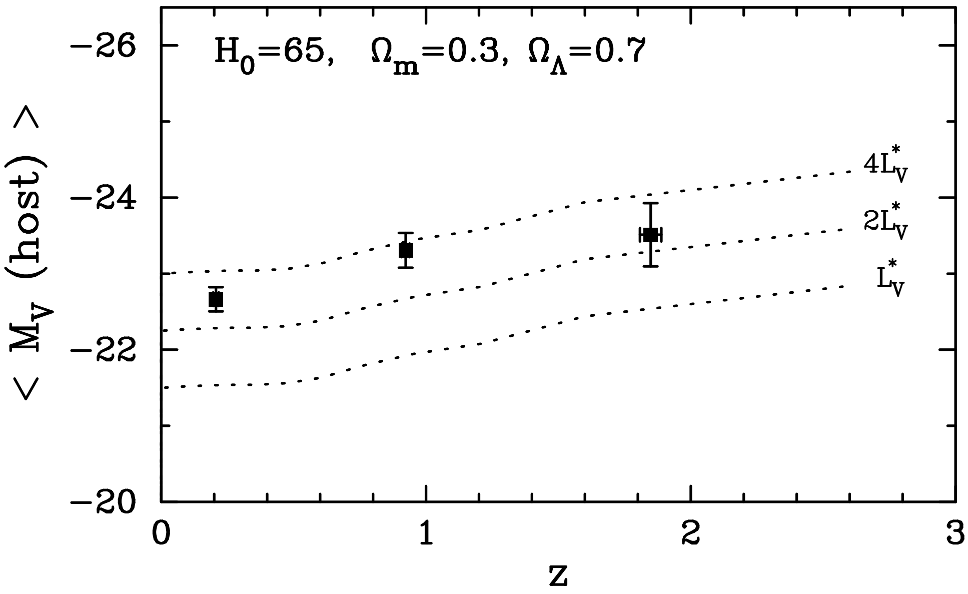

Fig. 1.9. Mean absolute magnitude versus redshift for the quasar host galaxies from the *HST* imaging programs of McLure et al. (1999), Kukula et al. (2001) and Dunlop et al. (2003). The dotted lines show the passive evolutionary tracks for present-day $L^\star$, $2L^\star$, and $4L^\star$ galaxies assuming that they formed in a single starburst event at $z \approx 5$. At all redshifts the average mass of the quasar host galaxies is consistent with that of a present-day $3L^\star$ elliptical, under the assumption of passive evolution.

At $z \simeq 1$ Kukula et al. found it was still possible, on the basis of the NICMOS data, to estimate the scale lengths of the host galaxies with sufficient accuracy to demonstrate that they were at least consistent with the (passively evolved) Kormendy relation derived by Dunlop et al. at $z \simeq 0.2$ (see Fig. 1.4). Therefore, just as at low redshift, the host galaxies of quasars at $z \simeq 1$ appear to be large, luminous systems. However, while for three of the $z \simeq 1$ quasars Kukula et al. found strong evidence that the hosts follow a de Vaucouleurs surface brightness profile, in the majority of cases the data did not allow an unambiguous fit.

By $z \simeq 2$, despite deliberately deeper imaging, the increased size of the H-band point-spread function, coupled presumably with the impact of additional surface brightness dimming, meant that Kukula et al. were unable to determine unambiguous morphologies for any host galaxy, and only highly uncertain scale lengths in most cases. However, extended starlight was still detected in every object and it proved possible to still obtain meaningful measurements of host luminosity.

The most robust result from this study that can be extracted at all redshifts is the average luminosity of the quasar host galaxies in the restframe V band. This is plotted against redshift in Figure 1.9, which shows that, under the assumption of passive evolution, the hosts of comparably luminous quasars are basically unchanged in mass out to $z \simeq 2$.

Although Figure 1.9 represents an interesting first attempt to determine the mass evolution of quasar hosts, this result cannot yet be regarded as anything like as secure as the results on low-redshift quasar hosts presented in § 1.2. First, the samples are small. Second, at present the mass estimates remain vulnerable to the validity of assuming passive evolution. Third, while the complete quasar host sample appears, on average, to have the same stellar mass from $z \simeq 0.2$ to $z \simeq 2$, there is evidence within the data that the RQQ hosts are less massive at high redshift by a factor of $2-3$. This is consistent with, although less extreme than, the decrease in radio-quiet host galaxy mass with increasing redshift reported by Ridgway et al. (2001) from an analysis of NICMOS data. Recently, Lacy et al. (2002) have also found evidence for a slight decline in host galaxy mass by $z \simeq 1$, using ground-based near-infrared imaging coupled with active/adaptive optics.

1.5 Future Prospects

To obtain improved estimates of the masses of high-redshift quasar hosts will require color information (to test the assumption of passive evolution; Kukula et al. 2004) and the extension of high-resolution imaging observations into the K-band with the largest available telescopes. This work is already underway (e.g., Hutchings 2003) and over the next few years, with careful study design (e.g., selection of quasars within a few arcseconds of an appropriate star for reliable PSF determination) and the necessary major investment of telescope time, it is not unreasonable to expect that the Gemini telescopes and the VLT can revolutionize the effective study of high-redshift quasar hosts in much the same way as *HST* has revolutionized the study of low-redshift hosts.

In the very near future the new UV viral black hole mass estimators described above will be applied to the extensive databases of quasar optical spectra now being released by, for example, the Sloan Digital Sky Survey.

Therefore, within the next 2 years or so, it is not unreasonable to anticipate the construction of the first robust measurements of the redshift dependence of black hole-spheroid mass ratio within the bright quasar population out to $z \simeq 5$. Such measurements promise to provide fundamental new insights into our understanding of the relationship between black hole and galaxy formation.

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