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Luminous Quasars and Their Hosts: Accretion at the Limit?

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Abstract

We present the results of our recent Hubble Space Telescope imaging study, in which we have successfully deconvolved host and nuclear flux for the some of the most luminous quasars in the Universe. Host morphologies have been recovered for each of our 17-strong sample. From these fits, we have estimated Black Hole masses through extrapolation of the Black Hole - Spheroid mass relation and begun to address the complicated issue of fuelling vs black hole mass in determining quasar luminosity: We find that the order-of-magnitude increase in luminosity is due to increased black hole size, and to increased fuelling efficiency, in roughly equal measure. The brightest objects are found to radiate at or near the Eddington limit.

1.1 Introduction

As the most powerful class of AGN, quasars provide a striking example of the complex interelationship between galaxies and the supermassive black holes in their centres. Thanks largely to the Hubble Space Telescope (HST), the last five years have seen huge advances in our understanding of the host galaxies of the nearest ($z < 0.3$) quasars.

Most quasar host studies have hitherto concentrated on quasars of relatively low luminosity, because it is much easier to disentangle the contributions of host and active nucleus. However, the quasar population includes objects as bright as $M_V \sim -30$, and the majority of currently known high-z quasars belong to the high end of the luminosity function (largely due to the degeneracy inherent in any flux-limited sample). The aim of the current study is to break this degeneracy between quasar luminosity and redshift by studying a sample of quasars at a single redshift, but spanning an appreciable fraction of the quasar luminosity range (fig. 1.1). The lowest redshift at which this can be done is $z \sim 0.4$.

Not only will this allow us to explore the relation between quasar luminosity and the properties of their host galaxies, but the most luminous objects in this programme will also provide a low redshift baseline against which to compare the hosts of luminous high-z quasars in future studies.

1.2 Observational Strategy

Imaging of quasars must be carefully choreographed. We require extremely high dynamic range in order to accurately characterise both the low-surface-brightness features of the host, and the critical, highly luminous core region. HST's stable pointing accuracy

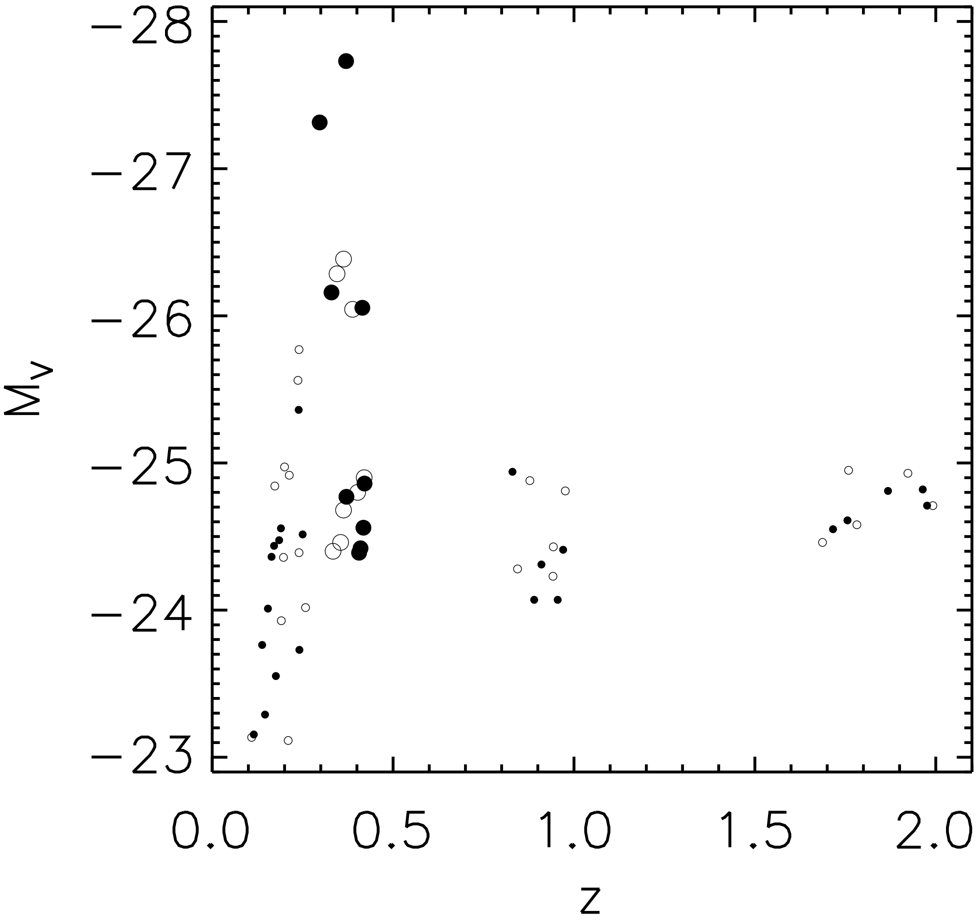

Fig. 1.1. Absolute magnitude versus redshift for quasars observed to date in our HST host-galaxy imaging programmes. Filled circles represent radio-quiet quasars (RQQs) and open circles radio-loud quasars (RLQs). Our earlier work (small symbols) concentrated mainly on quasars of relatively low luminosity (typically $M_V > -25$) in three redshift regimes ($z \simeq 0.2, 1$ & 2), allowing us to probe the evolution of the host galaxies over a large fraction of cosmic history (Mclure et al. 1999; Kukula et al. 2001; Dunlop et al. 2002). The current study (large symbols) is designed to explore an orthogonal direction in the $M_V - z$ plane, by sampling a large range of quasar luminosities at a single redshift, $z \simeq 0.4$. This is the lowest redshift at which very luminous quasars (those with $M_V < -27$) can be found, comparable to the most luminous quasars in the high-redshift universe.

allows us to take several deep integrations, and splice shorter ones directly into the core where saturation has occurred.

A thorough knowledge of the PSF is essential, and across an immense dynamic range. To this end, we combine the sub-pixel centred models of TINYTIM (Krist, 1999) with extremely deep stellar PSF's to accurately model all of the scattered flux in the wings. (see Floyd et al. (2002) for full details).

We minimise the nuclear to host ratio, through careful filter selection. We observe in the V-band in the quasar's restframe (longwards of the 4000Å break), and avoid any strong emission lines from the circumnuclear region (H$\alpha\lambda$6563; [OIII]λ5007). By excluding such emission from the images, we obtain a cleaner picture of the distribution of starlight in the hosts.

1.3 Image Analysis & Modelling

We then fit using the model of Sersic (1968):

$$\mu(r) = \mu_0 \exp\left\{ -\left(\frac{r}{r_0}\right)^{\beta} \right\} \tag{1.1}$$

where $\mu(r)$ describes an azimuthally-symmetric distribution, which can be projected onto a generalised elliptical coordinate system to allow for different eccentricities and orientations of the host galaxy. Additional flux is added to the central pixel to model the unresolved nuclear component.

We therefore have a 6-dimensional model:

- L_n = nuclear luminosity
- $\mu_{1/2}$ = host surface brightness
- $R_{1/2}$ = host half-light radius
- Θ = position angle
- $\xi = \frac{a}{b}$ = axial ratio
- β− parameterising host profile shape

The model is convolved with the PSF and compared to the real quasar image. We choose weighting on an individual pixel basis, assigning each pixel an error based on its Poisson noise. We use the downhill simplex method as a robust technique for χ^2 minimisation.

1.4 Results

We began by fixing the morphology *a priori* to either a bulge ($\beta = \frac{1}{4}$) or a disc ($\beta = 1$). The best fit bulge and disc models are then compared, and the full 6-dimensional model is run.

Overall, the morphologies of the hosts in the current sample agree well with the results of Dunlop et al. (2002). We find a clear preference for elliptical hosts in all cases bar three (three out of the five least luminous RQQs - in each case deconvolved nuclear luminosity is close to the dividing line with Seyfert nuclei). For the majority of objects the morphological preference was confirmed by the variable-β model. The hosts are also found to follow a Kormendy relation similar to that displayed by nearby quiescent ellipticals (fig. **??**).

1.5 Black Hole Mass

It has become increasingly clear from studies of inactive galaxies that black hole and galaxy formation and growth are intimately linked processes (Magorrian et al. 1998, Gebhardt et al. 2000, Merritt & Ferrarese 2001). We use luminosities from our galaxy models to estimate host masses, (assuming mass-to-light ratio of an early-type galaxy). We then use the Magorrian Relation to estimate Black Hole mass. From the black hole mass we can then calculate the theoretical Eddington luminosity of each object, and compare this with the actual luminosity of the quasar nucleus obtained from our model fit. The results of

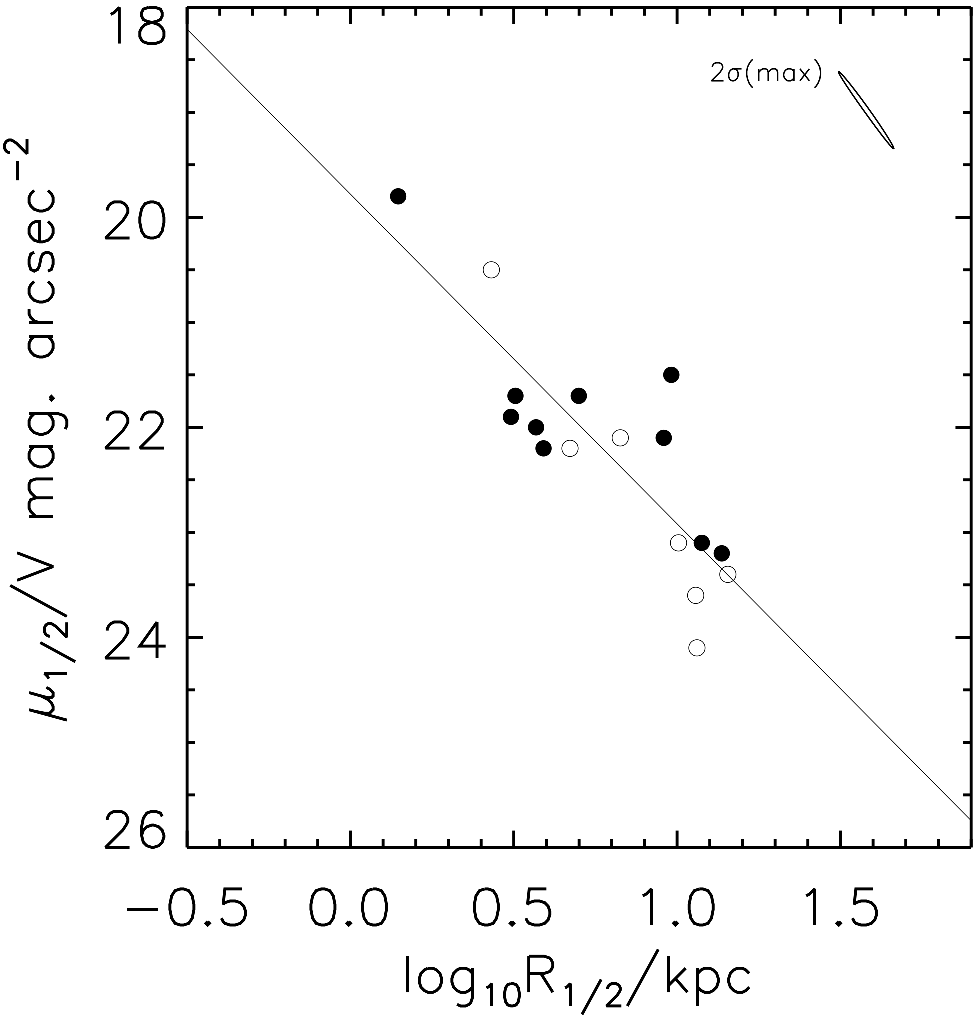

Fig. 1.2. The half-light radius ($R_{1/2}$) vs surface brightness ($\mu_{1/2}$) at the half-light radius for our sample. Filled circles represent RQQ hosts, open circles RLQ hosts. The solid line shows the best fit Kormendy relation to the sample and has the form $\mu_{1/2} = 19.8 + 3.14 log_{10} R_{1/2}$. The narrow ellipse in the top right corner of the plot shows the 2σ error contours for the least robust model fit in the current sample.

this work can be compared directly with those from other recent host-galaxy studies (fig. **??**). We find that all objects are radiating at or below the Eddington limit.

Several ground based studies have resulted in points that appear to the right of the Eddington limit (e.g. Percival et al. 2001), but we believe that this is due largely to poor seeing preventing accurate disentanglement of host and nuclear flux. We obtained HST archive images of 3 objects from the sample of Percival et al. (2001), and analysed them as for our sample (Floyd et al. 2002). We also included the 2 cases for which Percival et al. unambiguously uncover an Elliptical host. These objects are included in fig. **??**, marked by stars. This

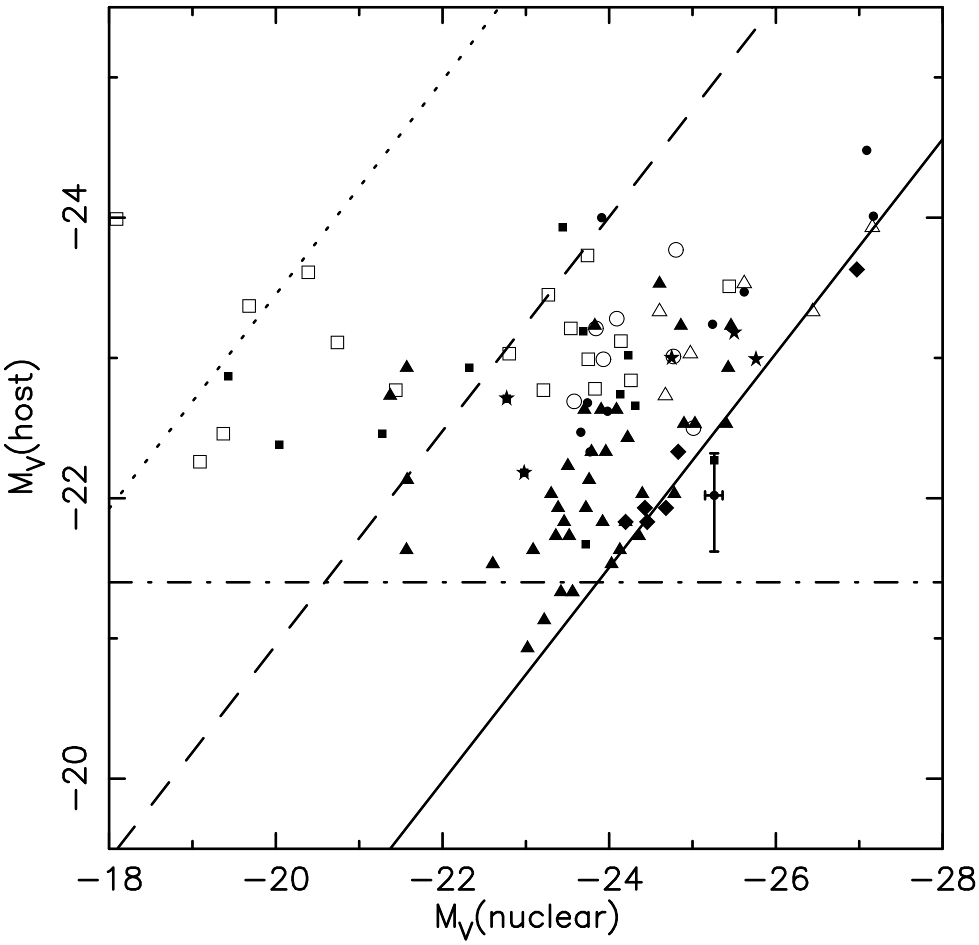

Fig. 1.3. Host vs Nuclear magnitudes for quasars from this work (circles), along with those from Dunlop et al. (2002) - squares; McLeod & Rieke (1994) - triangles; McLeod & McLeod (2001) - diamonds; and also 5 objects from Percival et al. (2001) - stars. The solid line illustrates the Eddington limited accretion rate, with the dashed and dotted lines denoting the 10% and 1% levels respectively. The one object from our sample that appears to be accreting at somewhat higher than the Eddington limit is the luminous quasar 1252+020, and is the one object for which we do not believe that we have successfully disentangled host and nuclear flux (see Floyd et al. (2002) for more details).

substitution of ground based data results in a remarkable agreement with Eddington limited accretion.

1.6 Conclusions

- Quasar hosts are large, luminous ellipticals ($L > L^{\star}$), consistent with radio galaxies; we are well into the exponential tail of the galaxy luminosity function.
- The factor of 10 increase observed in quasar nuclear luminosity appears to be due to a combination of increasing fuelling efficiency and increasing black hole mass.

- The Eddington limit seems to impose the maximum luminosity for an AGN in a given host. An Elliptical like M87, with $M_V \approx -25$, would therefore be capable of hosting an AGN as luminous as $M_V \approx -29$.
- Observations to yield direct measurements of black hole mass (e.g. Hβ linewidths) form a natural next step. These will allow more accurate determination of black hole mass and accretion efficiency.

1.7 The Future

It is clear now that both engine size and fuelling efficiency are key factors in determining a quasars optical luminosity. However, their contributions are still unclear. We now need tests of the Spheroid - Black Hole Mass relation for the high end of the galaxy luminosity function. More direct measures of Black Hole Mass (e.g. from BLR line widths) will assist. The 2D modelling technique also offers us an automated morphological tool for the study of inactive galaxies, as well as a wide range of active ones.

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