Quasars and Ultraluminous Infrared Galaxies: At the Limit?

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ABSTRACT

We have detected the host galaxies of 16 nearby, radio-quiet quasars using images obtained with the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS). We confirm that these luminous quasars tend to live in luminous, early-type host galaxies, and we use the host-galaxy magnitudes to refine the luminosity/host-mass limit inferred from ground-based studies. If quasars obey the relation $M_{blackhole}/M_{spheroid} \sim 0.006$ found for massive dark objects in nonactive galaxies, then our analysis implies that they radiate at up to $\sim 20\%$ of the Eddington rate. An analogous analysis for ultraluminous infrared galaxies shows them to accrete at up to similar Eddington fractions, consistent with the hypothesis that some of them are powered by embedded quasars.

Subject headings: galaxies:photometry—galaxies:active—infrared:galaxies—accretion

1. Introduction

Although active quasars constitute only a small fraction of galaxies today, it appears that most large galaxies harbor central massive dark objects (MDOs) with $M_{MDO}/M_{spheroid} \sim 0.006$ (Kormendy & Richstone 1995; Faber et al. 1997; Magorrian et al. 1998). These MDOs are plausibly the supermassive black holes required by the current paradigm for active galactic nuclei. This result has been predicted by studies of quasar demographics that show quasar activity is more likely a short-lived phenomenon in a majority of large galaxies than a long-lived one in a small fraction of galaxies (Soltan 1982; Haehnelt & Rees 1993). This conclusion is based on the assumptions that quasars are found in massive spheroids and radiate at the Eddington rate.

Recently, quasar host-galaxy studies have added several pieces of evidence in support of this picture. First, near-infrared and HST imaging programs show that luminous quasars do in fact reside mainly in luminous, early-type hosts (McLeod & Rieke 1995b; Hutchings 1995; Taylor et al. 1996; McLeod 1997; Bahcall et al. 1997; Boyce et al. 1998; McLure et al. 1998). Second, there appears to be an upper bound to the quasar luminosity as a function of host galaxy stellar mass (McLeod & Rieke 1995a and references therein). McLeod (1997) pointed out that if the quasar nuclei at this "luminosity/host-mass limit" are emitting at a significant fraction of the Eddington limit, then the black holes must obey a relation similar to the one for normal galaxies with MDOs. This result supports the notion that present day quiescent galaxies harbor "dead quasars" in their nuclei, a conclusion that has recently been supported by McLure et al. (1998).

The nature of ultraluminous infrared galaxies (ULIRGs) has been of great interest since their discovery by Rieke & Low (1972), and particularly since IRAS found them in substantial numbers (e.g. Sanders et al. 1988). It has been widely proposed that infrared galaxies with luminosity of $\sim 10^{12}$ $L_\odot$ or greater derive their energy predominantly from heavily dust-embedded AGNs (e.g. Sanders & Mirabel 1996 and references therein). If this model is correct, virtually all the blue, ultraviolet, and soft x-ray energy from the quasar will be absorbed by the dust and degraded to the far infrared, where the huge luminosity will emerge unavoidably. Comparison with the nuclear luminosity/host-mass limit relation therefore can test the connection between ULIRGs and quasars.

The quasar luminosity/host-mass limit was determined first from our groundbased data (McLeod & Rieke 1994ab,1995ab and references therein), where relatively poor resolution precluded a detailed study of the hosts. We report here higher resolution imaging using HST's Near Infrared Camera and MultiObject Spectrometer (NICMOS). We combine the results with previous data to improve the definition of the relation. We then use data from the literature to compare this relation with its counterpart for ULIRGs.

2. NICMOS Observations and Data Reduction

To test the robustness of our luminosity/host-mass limit, we observed from our "high-luminosity sample" (McLeod & Rieke 1994b) all 10 quasars that had not been previously observed with HST. To this we added 6 luminous quasars for which ground-based attempts to resolve a host galaxy had failed. All 16 objects are in the redshift range $0.13 < z < 0.40$ with an average $z = 0.25$.

Each quasar was observed for a single orbit using the NIC2 MULTIACCUM mode in a four position dither pattern. Because this mode allows the observer to use intermediate readouts, we were able to build up an image that was both deep and linear over the entire quasar field. At the end of each orbit, we used the same dither pattern to observe a bright star near the quasar. This star provided a measurement of the point-spread function (PSF). The quasar and PSF star images were reduced using the NICRED package provided by B. McLeod. Full details will be provided in McLeod et al. 1999.

3. Determining Host-galaxy Magnitudes

We determined host-galaxy magnitudes using a 1-D analysis technique that allowed us to compare with our ground-based results and provided a graphical way to judge the goodness-of-fit of various galaxy models. First, we generated a 1-D radial intensity profile of each quasar, each PSF star, and a "combined PSF" made from a noise-weighted average of all of the PSF stars. The profiles extended to surface brightness limit of $m_H \approx 23.2 \mathrm{mag}/''^2$ and excluded light from companions. Second, we normalized each PSF to have the same central intensity as the quasar. Third, we removed the nuclear contribution by subtracting the highest fraction of the normalized PSFs for which the resulting intensity in the first Airy minimum was non-negative. On average, 72% of the light in the central peak was attributed to the nucleus, whereas the full range for the sample was 65-90%. The combined PSF gave comparable results to each quasar's own PSF. Finally, we numerically integrated the resulting profile to obtain a magnitude for the host.

Figure 1 shows the 1-D profiles for one of the hosts to illustrate the effect of subtracting different amounts of the normalized PSF. The host magnitudes derived by integrating under the three profiles shown are H=14.0, 15.0, and 15.4 (top to bottom respectively). As seen in the Figure, most of the difference is in the nuclear contribution; there is very little effect on most of the galaxy. We estimate from tests like these that our host galaxy magnitudes generally have uncertainties of ~ 0.2 mag from the PSF subtraction. Despite the order-of-magnitude difference in the spatial resolutions of the ground-based and NICMOS data, we found excellent agreement in the host magnitudes (within 0.2 mag) for 8 of the 10 quasars that we had imaged previously. For the other two, the ground-based intensities were apparently too high due to contamination from close companions.

The resulting magnitudes for all 16 quasars in our sample are plotted in Figure 2a, along with (i) WFPC2 host magnitudes from the literature for the rest of the McLeod & Rieke (1994b) sample; (ii) our own and other ground-based data for other samples previously shown in McLeod & Rieke (1995a,b); and (iii) high-quality data recently published for two additional samples. All magnitudes have been converted to rest-frame values assuming nuclear k-corrections and colors from Cristiani & Vio (1990); galaxy k-corrections and colors appropriate for early-type galaxies, computed from a galaxy spectrum provided by M. Rieke (and shown in Figure 1 of McLeod & Rieke 1995b); and $H_0 = 80 \mathrm{km/s/Mpc}$, $q_0 = 0$. The redshifts of the $M_B < -22$ quasars on the plot range from $0.06 < z < 0.8$ with an average $z \approx 0.3$ (90% have $z < 0.5$). In addition to uncertainties due to PSF subtraction, the host M_H values carry uncertainties due to the underlying galaxy energy distribution. For the galaxies observed in H, the k-corrections themselves are < 0.1 mag over this redshift range. For the galaxies observed in the visible, however, the uncertainties in the k-corrections and colors can total several tenths of a magnitude.

From the 1-D profiles, we also determined that approximately half of these radio-quiet quasars have hosts that are better described by deVaucouleurs laws than by exponentials, in agreement with the other recent results mentioned above. Full details of our 1-D analysis, including the radial

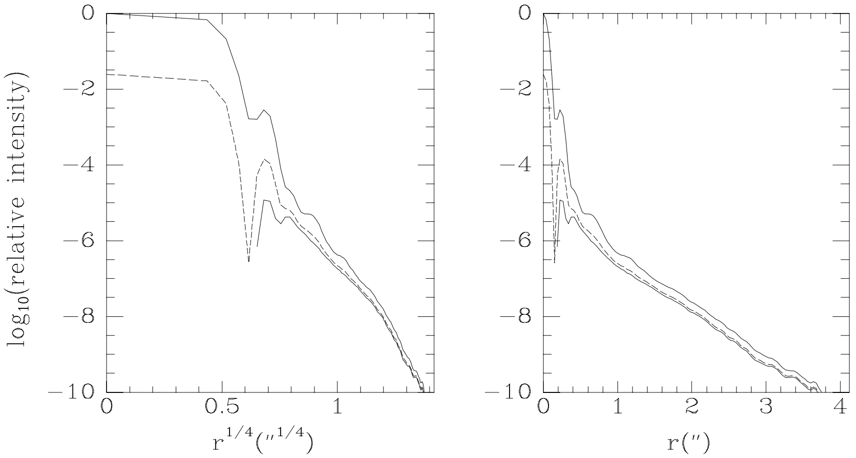

Fig. 1.— Sample radial profiles. Profiles are of PG1352+183 plotted v. $r^{1/4}$ (left) and r (right). Top solid line shows the unsubtracted profile. Dashed line shows the quasar profile after subtracting the optimal fraction of the normalized PSF (see text). Bottom solid line shows the quasar profile after subtracing 100% of the normalized PSF. The central ringing is due to the Airy pattern.

profiles, will be published along with the images and a 2-D morphological analysis in McLeod et al. 1999. However, the addition of the new data to Figure 2a allows us to take a new look at the luminosity/host-mass limit now.

4. Results

4.1. The Eddington Limit for Quasars

Figure 2a allows us to test the combined assumptions that all large galaxies contain black holes with the Magorrian et al. (1998) mass fraction and that quasars radiate near the Eddington limit.

For quasars near the luminosity/host-mass limit, the galaxy contribution to the B-band light is negligible. Thus, we can convert $\mathrm{M_B}$ to a quasar bolometric luminosity through a bolometric correction $\mathrm{BC} \equiv \nu \mathrm{L}_\nu(\mathrm{B})/\mathrm{L_{bol}}$. We adopt as a reference the rest-frame value BC=12 (Elvis et al. 1994).

To estimate black hole masses, we adopt the average value of $f \equiv M_{MDO}/M_{spheroid} \sim 0.006$ from Magorrian et al. (1998). We convert spheroid masses to galaxy absolute magnitudes assuming $V - H = 3.0$ for bulge stellar populations and a mass-to-light ratio $\Upsilon_{\mathrm{V}} = 7.2 M_\odot/L_\odot$,

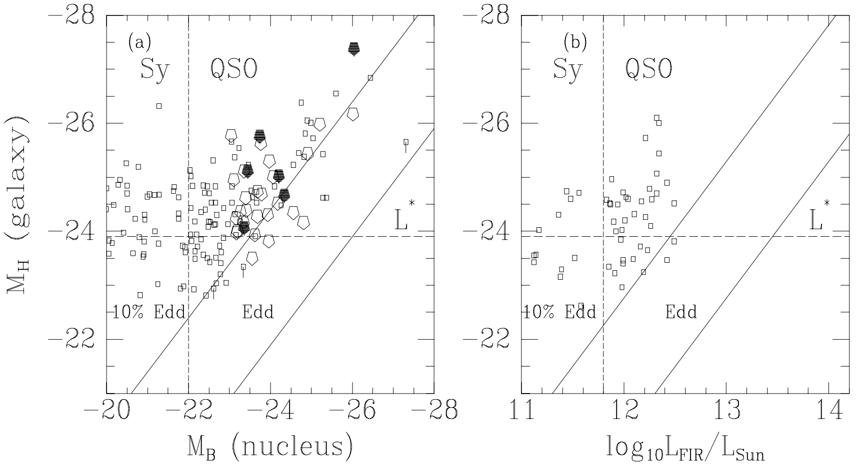

Fig. 2.— (a) Galaxy v. nuclear absolute magnitudes for QSOs. Low-redshift QSOs and Seyferts shown as boxes are taken from McLeod & Rieke 1995a and references therein, with additional new data from Ronnback et al. 1996 (R-band imaging survey; three upper limits shown) and Hooper, Impey, & Foltz 1997 (WFPC2 imaging survey). QSOs shown as open pentagons constitute the high-luminosity sample from McLeod & Rieke 1994b, with host magnitudes derived from either NICMOS images (McLeod et al. 1999) or WFPC2 images (Bahcall et al. 1997; McLure et al. 1998). Filled pentagons are the other 6 QSOs from our NICMOS imaging. Also shown are the QSO/Sy boundary (dashed vertical line), position of an L^* galaxy (dashed horizontal line), and loci of Eddington and 10% Eddington luminosities for galaxies obeying the Magorrian et al. (1998) relation. All values are rest-frame magnitudes with H_0 = 80km/s/Mpc, $\mathrm{q}_0 = 0$. (b) Galaxy v. far-infrared luminosity for the ULIRGs. The axes cover exactly the same range as in (a) for the bolometric correction given in the text.

which is an average for the 24 most luminous galaxies ($\mathrm{M_V} \leq -20$) in their sample. Thus, both our bulge and black hole masses are traceable to Magorrian et al. (1998), which should reduce systematic errors in the conversion between them.

Combining the assumptions described above, the relation between nuclear absolute B magnitude and bulge absolute H magnitude is:

$$M_B = M_H - 2.1 - 2.5[log_{10}(\epsilon) + log_{10}(\frac{\Upsilon_{\mathrm{V}}}{7.2M_\odot/L_\odot}) + log_{10}(\frac{f}{0.006}) - log_{10}(\frac{BC}{12})]$$

where $\epsilon \equiv L/L_{Edd}$. The diagonal lines in Figure 2a show the positions of $\epsilon = 0.1$ and 1.0. For our default values of Υ_{V}, f, and BC, most quasars fall within the $\epsilon \approx 0.20$ envelope.

A complementary analysis by Laor (1998) indicates that quasars like the ones in our samples do in fact follow the Magorrian et al. (1998) relation. If this is true, our results imply that the quasars are radiating at up to 20% of the Eddington rate. These results are consistent with the recent study of McLure et al. (1998) who carried out a similar analysis to ours using visible data and found most of their objects to be radiating at a few percent Eddington.

4.2. Bulge/Luminosity Relation for Ultraluminous Infrared Galaxies

The discovery that classical quasars emit up to a significant fraction ($\sim$ 20%) of their Eddington luminosities suggests that ultraluminous galaxies might emit at a similar level. This hypothesis is relatively easily tested because the integrated H-band fluxes of the ULIRGs tend to be dominated by the bulge component of the galaxy (see e.g. the imaging atlases of Smith et al. 1996 and Murphy et al. 1996; also argued by Surace & Sanders 1997). We therefore estimate the central black hole masses from the integrated absolute H magnitudes, using photometry from McAlary et al. (1979), Carico et al. (1988), Carico et al. (1990), Goldader et al. (1995), Smith et al. (1996), and Murphy et al. (1996). For the latter reference, calibrated near infrared measures are not available so we computed the bulge H magnitude from m_r and a standard color correction. In all cases, absolute magnitudes are computed as in Murphy et al. (1996). Far infrared luminosities are taken from the same references as the bulge magnitudes. The results are shown in Figure 2b, along with an Eddington limit computed exactly analogously to the limit for the quasars in Figure 2a.

While they do not span a wide enough luminosity range to define clearly a luminosity/host-mass relation, the $\sim 10^{12}$ $L_\odot$ ULIRGs radiate at a rate nearly identical to that of quasars of the same luminosity. Most fall within an envelope of $\epsilon \lesssim 0.1$, and a detailed comparison of the ϵ distributions over the whole QSO range indicates a factor of $\lesssim 2$ difference in the average Eddington fraction. This factor is likely within the uncertainties due to bolometric corrections, assumptions about measuring the bulge luminosity in ULIRGs, and other causes. It is conceivable that the two types of source have not just very similar but identical behavior relative to the Eddington limit. The close similarity supports the view that *a significant portion of the most luminous ULIRGs derive much of their luminosity from embedded AGNs.* About 30% of the ULIRGs above Seyfert luminosity fall within a factor of two of $\epsilon = 0.1$ and are candidates to be dominated by embedded AGNs.

4.3. Nature of ULIRGs

The controversy regarding the nature of ULIRGs is fed because the various indicators give contradictory results. Part of the difficulty is that many indicators can show the presence of an AGN but do not constrain its role in the energetics of the galaxy - an example is high excitation optical emission lines, seen either directly or scattered. Recently, Genzel et al. (1998) have used ISO spectroscopy to argue that the majority (70-80%) of these objects are dominated energetically by star formation, both because the high excitation infrared fine structure lines are weak and because the low excitation lines imply adequate energy generation by starbursts. Rieke (1988) concluded from the lack of hard xrays from this class of object that most of them were powered by starbursts. Although hard xrays could be blocked by very thick accretion tori in some cases (Sanders & Mirabel 1996), it is improbable that such heavy columns would lie along our line of sight for all cases. Surace et al. (1998) detect knots of star formation in HST images, but they also detect putative nuclei and argue that the star forming knots are not energetically important. Veilleux, Sanders, & Kim (1997) find evidence for energetically important AGNs in at least 20-30% of the ULIRGs from the presence of near infrared broad lines. Lonsdale, Smith, & Lonsdale (1995) find VLBI radio sources at levels consistent with the theory that an AGN dominates the luminosity in 55% of ULIRGs. On the other hand, in followup VLBI observations of one such source, Arp 220, Smith et al. (1998) show that the compact radio emission actually originates in multiple radio supernovae.

All four indicators are consistent with $\sim 75\%$ of the $\sim 10^{12}$ $L_\odot$ ULIRGs being powered predominantly by starbursts, with $\sim 25\%$ powered by AGNs. Although this general agreement is encouraging, a number of individual galaxies yield contradictory indications of their underlying energy source using differing methods.

5. Conclusions

Our study of quasar host galaxies supports the hypothesis that all galaxy spheroids contain black holes with $\sim 0.6\%$ of the stellar mass. In QSOs, the black holes accrete at up to $\sim 20\%$ of the Eddington rate. In ULIRGs, the nature of the power source remains unclear; however, if they are powered by embedded quasars then they accrete at a similar rate. The large Eddington fractions in both kinds of objects imply a small duty cycle for activity over the Hubble time. Otherwise, the accretion process would produce higher-mass black holes than we infer today.

At high redshift, quasars are very luminous but large galaxies might not yet have been assembled. Therefore, we expect that the luminosity/host-mass limit must ultimately break down. This may indicate that rather than the stellar mass, it is the depth of the large-scale potential well of the dark matter halo that is fundamentally related to the mass of the supermassive black hole.

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