Near-IR Properties of Quasar Host Galaxies

Kim K. McLeod

Smithsonian Astrophysical Observatory, 60 Garden St., Cambridge, MA 02140, USA

Abstract. We have obtained deep, near-IR images of nearly 100 host galaxies of
nearby quasars and Seyferts. We find the near-IR light to be a good tracer of lu-
minosous mass in these galaxies. For the most luminous quasars there is a correlation
between the maximum allowed B-band nuclear luminosity and the host galaxy mass, a
“luminosity/host-mass limit”. Comparing our images with images from HST, we find
that the hosts of these very luminous quasars are likely early type galaxies, even for
radio-quiet objects whose lower-luminosity counterparts traditionally live in spirals. We
speculate that the luminosity/host-mass limit represents a physical limit on the size of
black hole that can exist in a given galaxy spheroid mass. We discuss the promises of
NICMOS for detecting the hosts of luminous quasars.

1 Introduction

Although most of the attention given to AGN is concentrated on the “N,” there
are compelling reasons to understand the “G.” The central engine and the host
galaxy must influence each other, and the exact connections hold crucial clues
for understanding the quasar phenomenon. Moreover, it is plausible that nuclear
activity has played a role in the evolution of a significant fraction of all galaxies;
Seyferts account for $\gtrsim 10\%$ of galaxies today (Maiolino & Rieke 1995; Ho 1996),
and AGN were even more important in the past. Therefore, to understand the
evolution of galaxies, we must understand the host galaxies of AGN.

By now it is well established that the redshift range $2 \lesssim z \lesssim 3$ represents
a critical period in the evolution of both “normal” galaxies and quasars. It is
likely that galaxies at that epoch were starting to turn their gas into stellar
disks. The mass in neutral hydrogen gas in damped Lyman–$\alpha$ absorbers at
that redshift is comparable to the mass in disk stars today and shows strong
evolution since that time (Lanzetta et al. 1995; Storrie-Lombardi et al. 1996).
Furthermore, a photometric-redshift analysis of the Hubble Deep Field shows
that the luminosity density from star-forming galaxies peaks near that same
redshift (Sawicki et al. 1996). The AGN luminosity function shows a similarly
strong evolution; if described in terms of luminosity evolution (but see Wisotzki
et al. in these proceedings), the “characteristic” luminosity of quasars increases
as $\sim (1 + z)^{3.4}$ to $z \sim 2$ and flattens between $2 < z < 3$ (Boyle 1993). Thus
quasars were an energetically important component of galaxies at a critical period
in their evolution and could have influenced their growth. Understanding the
relationships between AGN and their hosts thus holds clues to the processes of
galaxy formation and evolution.

HST and near-IR imaging together have become especially powerful tools for
studying quasar hosts. The spatial resolution of HST has allowed us, for the first
time, to determine morphological types for hosts of luminous quasars (McLeod and Rieke 1995b; Bahcall et al. and Disney et al. in these proceedings). Near-IR imaging has done a good job of showing the host galaxy starlight with less contamination from the nucleus than at visible wavelengths (McLeod & Rieke 1994ab,1995ab; Dunlop et al. 1993; Kotilainen & Ward 1994). As shown in Fig. 1, the host galaxy starlight peak coincides with the near-IR minimum in the nuclear energy distribution. Furthermore, the near-IR light highlights the old, red, mass-tracing stars in the population while suffering less from extinction and emission-line contamination than the visible images.

**Fig. 1.** Energy distributions of a typical quasar (from J. McDowell) and galaxy (from M. Rieke) for $H_0 = 80$. The H-band gives good contrast of starlight to nuclear light and is a good tracer of luminous mass in the host galaxy.

## 2 The IR Images

We have exploited this wavelength range by obtaining deep near-IR images for nearly 100 AGN using a 256x256 NICMOS array camera on the Steward Observatory 2.3m telescope. We chose two samples of AGN that allowed us to investigate host galaxy properties over 10 B magnitudes in nuclear luminosity. For low-luminosity AGN we used the CfA Seyfert sample, which is selected on the basis of the nuclear spectrum and which has roughly equal numbers of Sy1’s and Sy2’s. For high-luminosity AGN, we chose the lowest redshift ($z < 0.3$) quasars from the PG sample, to ensure a sample selected on the basis of nuclear properties and close enough so that the host galaxies would be resolved. The quasars were imaged in the H-band (1.65$\mu$m) and we were able to measure the isophotes down to a 1$\sigma$ level of $H \approx 23$mag arcsec$^{-2}$, which corresponds approximately to $B \approx 26.7$mag arcsec$^{-2}$ for typical galaxy colors.
The results have been presented in McLeod and Rieke (1994ab,1995ab). We describe in these papers the relationships between host galaxy luminosities (and masses) and nuclear properties; the existence of substantial obscuration coplanar with the disks of host spirals of Seyferts; and the search for signs of disturbances that could aid the flow of fuel towards the centers of the galaxies. The reader is encouraged to consult these papers for details; here we will concentrate on one of the most intriguing results.

3 The Luminosity/Host-Mass Limit: Observations

We find the near-IR light to be a good tracer of luminous mass in these galaxies. In Fig. 2 we plot host near-IR luminosity against nuclear luminosity, for the objects in our samples and from other near-IR studies in the literature. As shown in this figure, Seyferts are found in galaxies with a range of H-band luminosity, and hence luminous mass, from $\sim 0.1$ to $\sim 5L^*$. Their morphological types range from S0 to Sc. The lowest-luminosity quasars live in similar kinds of galaxies spanning the same range of H-band luminosity centered around $L^*$.

![Fig. 2. Host v. nuclear luminosity for Seyferts and quasars with $z < 0.3$ for $H_0 = 80$ (McLeod & Rieke 1995a and references therein). For quasars brighter than $M_B \lesssim -23$, there is a minimum host galaxy luminosity that increases with nuclear power. The dotted lines show the positions of $L^*$ and $2L^*$ galaxies. Filled squares are objects for which the host galaxy luminosities are upper limits or weak detections–we will obtain NICMOS images for these and other high-luminosity objects. The diagonal line shows the luminosity/host-mass limit.](image-url)
We have found, however, that for the highest-luminosity quasars, there is a minimum host $H$-band luminosity that increases with nuclear power, shown as a diagonal line in Fig. 2. This is reminiscent of a similar trend previously noted in the visible (Yee 1992). The relationship has the functional form $M_H(\text{galaxy}) \approx M_B(\text{nucleus})$ with an onset approximately one magnitude brighter than the traditional (arbitrary) quasar/Seyfert boundary. Because $H$-band light probes the galaxy mass by highlighting the old, red, mass-tracing stars of the stellar population, this “luminosity/host-mass limit” reflects a relation between fundamental physical parameters that govern the process of hosting a quasar: galaxies with more mass can sustain more activity.

WFPC2 images have been published for $\sim 30$ luminous, nearby quasars including many of our highest-luminosity objects (e.g. Hutchings et al. 1994; Disney et al. 1995; Bahcall et al. 1996ab). Of these, only a few ($\sim 3$) appear to be spiral hosts like those of Seyferts. The rest are plausibly smooth, early-type galaxies or ellipticals in the making (mergers), despite being radio quiet objects that are traditionally assumed to be spirals (McLeod & Rieke 1995b; see also Taylor et al. 1996).

**4 The Luminosity/Host-Mass Limit: Wild Speculation**

Intriguingly, the transition from spiral hosts to spheroid-dominated hosts appears to occur approximately at the nuclear luminosity where the luminosity/host-mass limit becomes apparent. A simple explanation is that the objects along the diagonal line in Fig. 2 are early-type galaxies that have a maximum allowed black hole mass for their galaxy mass and that the black hole is accreting at the Eddington rate. In this case and for typical galaxy mass-to-light ratios, the diagonal line then represents a line of constant fraction of black hole mass to stellar spheroid mass, with value $f_{BH} \equiv M_{BH}/M_{stars} \approx 0.0015$.

This suggestion is especially exciting because central compact objects (presumably dead quasars) discovered in nearby spheroids show a similar relation with $f_{BH} \approx 0.002$ (Kormendy & Richstone 1995), and an HST study of bulges and ellipticals indicates that compact objects following approximately this same relation are likely required to produce the cores seen in the starlight (Faber et al. 1996). Thus, the luminosity/host-mass limit possibly results from general physical processes that govern the formation and evolution of the spheroid components of galaxies.

**5 The Luminosity/Host-Mass Limit: Wilder Speculation**

If the luminosities of most powerful quasars really do trace the potentials of the most massive spheroids, then we might be able to use the evolution of the quasar luminosity function to trace the history of spheroid formation in the universe. The observed evolution of the quasar luminosity function can be nicely reconciled with the model of galaxy evolution recently summarized by Fukugita
et al. (1996), in which spheroid components of very massive galaxies formed at $z > 3$, followed by less massive objects at later epochs (see also Sawicki et al. 1996). We speculate that the $z \sim 5$ quasars formed as parts of the most massive spheroids, the peak in the quasar population at $z \sim 2$ occurred when massive disks were being added, and less powerful AGN formed later in less massive galaxies. Thus, central black holes themselves form as the spheroids are being assembled, and the changing AGN population reflects the changing population of galaxies. The luminosity functions would then require nearly every large galaxy to go through an AGN phase that lasts a modest portion of the galaxy’s lifetime (e.g. Weedman 1986).

6 Future Work: All Hail NICMOS!

Before we can exploit the luminosity/host-mass limit we must answer several questions. We are already at work on the theoretical basis for such a limit, and we are beginning a groundbased imaging and spectroscopy program to determine whether the limit applies to AGN in smaller spheroids (Seyferts in bulges).

Importantly, we need to know whether the limit is strictly correct especially at high nuclear luminosities where our statistics are poor. We have been granted Cycle 7 HST time to address this question with NICMOS. NICMOS will combine the advantages of near-IR imaging with the superior spatial resolution of HST. We will look to find exceptions to the luminosity/host-mass limit by imaging objects whose hosts have been thus far elusive from the ground. We will also extend our sample to slightly higher redshifts to allow a look at higher luminosity objects. As shown in Fig. 3, NICMOS will be very good at detecting the extended emission from smooth hosts that are difficult to see with WFPC2.

Eventually, we need to probe nucleus–host relationships at high redshifts where galaxies are being assembled. The NICMOS GTO program (Weymann et al.) will provide near-IR images of radio-quiet quasar hosts at $z \approx 1$. We will probe further by obtaining near-IR images using adaptive optics on the soon-to-be-upgraded MMT. Preliminary adaptive optics results (John Hutchings, this conference) suggest that this method holds great promise for host studies at high redshift. By measuring morphologies and near-IR luminosities of the distant quasar hosts from the images and then applying models of stellar and dynamical evolution, we will predict what those galaxies look like today.

Acknowledgements: Thanks to the conference organizers for conference organizing, thanks to Avi Loeb for very fruitful discussions, thanks to Dr. Yamada for pointing out the Kormendy ratio, and thanks to B. Wilkes for financial support.

References

Bahcall, J. N., Kirhakos, S., & Schneider, D. P. 1996a, ApJ, 457, 557
Bahcall, J. N., et al. 1996b, preprint
Boyle, B. J. 1993, in “The Environment and Evolution of Galaxies” p. 433 (Kluwer; eds. J. M. Shull & H. A. Thronson, Jr.)
Fig. 3. Simulated 2800s images of $z = 0.4$ quasars with NIC2 (left) and WFC2 (right).
The hosts at top are $L^*$ spirals, the ones at bottom are $L^*$ ellipticals. In both cases, the nucleus has been removed and the linear greyscale stretch runs from -1 to 10 times the 1σ noise. The frame is 19.2'' on a side (the size of one NIC2 frame).

Disney, M. J. et al. 1995, Nature, 376, 150
Dunlop, J. S., Taylor, G. L., Hughes, D. H., & Robson, E. I. 1993, MNRAS, 264, 455
Faber, S. M. et al. 1996, AJ, preprint
Fukugita, M., Hogan, C. J., & Peebles, P. J. E. 1996, Nature, 381, 489
Ho, L. 1996 preprint
Hutchings, J. B. et al. 1994, ApJL, 429, L1
Kormendy, J. & Richstone, D. O. 1995, ARAA, 33, 581
Kotilainen, J. K. & Ward, M. J. 1994, MNRAS, 266, 953
Lanzetta, K. M., Wolfe, A. M., & Turnshek D. A. 1995, ApJ, 440, 435
Maiolino, R., & Rieke, G. H. 1995, ApJ, 454, 9
McLeod, K. K., & Rieke, G. H. 1994a, ApJ, 420, 58
McLeod, K. K., & Rieke, G. H. 1994b, ApJ, 431, 137
McLeod, K. K., & Rieke, G. H. 1995a, ApJ, 441, 96
McLeod, K. K., & Rieke, G. H. 1995b, ApJL, 454, L77
Sawicki, M. J., Lin, H., & Yee H. C. K. 1996, AJ, preprint
Storrie-Lombardi, L. J., McMahon, R. G., & Irwin M. J. 1996, MNRAS preprint
Taylor, G. L., Dunlop, J. S., Hughes, D. H., & Robson, E. I. 1996, MNRAS preprint
Weedman, D. W. 1986, “Quasar Astronomy” (Cambridge University Press)
Yee, H. C. K. 1992, in “Relationships Between Active Galactic Nuclei and Starburst Galaxies” ASP Conference Series, Vol. 31, A. V. Filippenko (ed.), 417–422