HST NICMOS Imaging of $z \sim 2 - 3$
radio-quiet quasars

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Abstract

We will present the results of a NICMOS H-band imaging survey of a small sample of $z \sim 2 - 3$ radio-quiet quasars. We have resolved extension in at least 4 of 5 objects and find evidence for a wide range in the morphologies and magnitudes of these hosts. The host galaxy luminosities range from sub-$L_*$ to about $4 L_*$, with most of the hosts having luminosities about $L_*$. These host galaxies have magnitudes and sizes consistent with those of the Ly break galaxies at similar redshifts and at similar rest wavelengths, but are about a magnitude fainter than the comparable 6C radio galaxies. One residual host component is not centered on the quasar nucleus, and several have close companions (within $\sim 10$ kpc), indications that these systems are possibly in some phase of a merger process.

1 Introduction

Radio-quiet quasars (RQQ) represent more than half the known AGN at high redshift ($z \sim 1$), yet information on the galaxies that host these active nuclei is currently extremely limited. At lower redshift, the luminous RQQ are found primarily in giant ellipticals with luminosities of several times a $L_*$ galaxy at $z = 0$ (e.g. McLure et al. 1999). In addition, the luminosity of the host seems to correlate roughly with that of the nucleus (McLeod & Rieke 1995; McLure et al. 1999, McLeod, Rieke, & Storrie-Lombardi 1999). Similarly, almost every

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nearby bulge-dominated galaxy contains a supermassive black hole candidate whose mass is roughly proportional to the mass of its bulge (Magorrian et al. 1998; van der Marel 1999), implying a strong link between the formation and evolution of galaxies and those of the quasars and their hosts. Semi-analytic hierarchical clustering models of galaxy formation have been applied by Kauffmann & Haehnelt (1999) to this question, and they have made some specific predictions about the evolution of the nuclear magnitude–host relation for radio-quiet quasars. To test such theories we have made HST NICMOS observations of radio-quiet quasar hosts near the epoch of the peak quasar density (z ~2 – 3). We have chosen a sample of quasars whose nuclei are faint enough to provide a good comparison sample to those of the well-studied low-z quasars. Throughout this paper we use $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_0 = 1$.

2 Sample and Observations

We selected 5 quasars from the faint quasar survey of Zitelli et al. (1992) with 21.6$<$B$<$22.0 at $z \sim 2$–3. The exact redshift range was constrained to avoid emission lines falling in the NICMOS H filter passbands; this resulted in a sample of 3 objects at $z \sim 1.8$ and 2 objects at $z \sim 2.7$. Their nuclear $M_B$ are in the range $-22$ to $-24$, making them comparable (and somewhat fainter) in absolute magnitude to many low-z quasar samples (e.g. Bahcall et al. 1997, McClure et al. 1999, McLeod et al. 1999) The observations were made using the NIC2 aperture of HST’s NICMOS camera, which has a field size of $19''2 \times 19''2$, at a scale of $0''075$ pixel$^{-1}$. To achieve emission-line-free imaging, the $z \sim 1.8$ objects were imaged in the F165M filter, resulting in a restframe wavelength of $\sim V$, and the $z \sim 2.7$ objects in the F160W filter, corresponding to restframe $\sim B$. We chose a nearby star for each of the 5 quasars, and observed this star in the same visit as the quasar using the identical dither pattern in order to characterize the point spread function (PSF). The dither pattern included half-pixel offsets to improve resolution by adequately sampling the HST PSF at these wavelengths.

We observed each of the 5 quasars (and its corresponding PSF star) with two visits separated by several months, resulting in observations of each field at significantly different position angles on the sky relative to the PSF pattern. This allows an independent check on the reality of any residual emission seen. The final FWHMs achieved were $0''14 - 0''16$. Observing times per frame were on the order of 1500 s per quasar. Total exposures for the quasars were on the order of 6000 s per visit. However, due to variable SAA CR persistence problems, sky noise levels in the final images differ.
3 Data Reduction and Analysis

We recalibrated the raw NICMOS data using a modified version of the standard pipeline process. We have combined each of the two visits to each object separately, by using a simple method that determines the locations of the bad pixels in the initial frames and creates bad pixel masks using CRREJ, resamples the corrected frames to double the linear dimensions, and combines these using standard rejection.

We achieved the cleanest subtraction with a PSF star observed during the same visit as the quasar. We have made a simple, direct PSF subtraction through an iterative method that varies the centering and scaling of the PSF versus the quasar, subtracts the two images, and measures the chi-square of the residuals. Finding an unambiguous relative centering is simple; determining the best scaling is more subjective. Here, we require flatness of the residual across some central region (generally within a radius of \( \sim 0'15 \)). This will still likely result in an oversubtraction, depending on how peaked the real host galaxy is within this inner radius. In these images, the PSF residuals seem to dominate within a radius of \( \sim 0'1 \). Within this region, we do not expect to recover morphological information; we can however find real excess flux.

4 Results

We have clearly resolved excess flux around 4 out of the 5 quasars relative to the PSF stars, and also relative to a star with an apparent magnitude similar to those of the quasars found within the field of MZZ 9592. This field star provides a good check that our results are not the product of some difference in the way we have observed and reduced the PSF stars versus the quasars. We have thus also treated this star as if it were a quasar and applied the same PSF subtraction techniques to it; we find no significant flux in the residual. In Figure 1, we show the results of these analyses for both visits of MZZ 9592, separately. We have rotated the results of the second visit to match the orientation of the first visit. In Figure 2, we give the PSF-subtracted combined results for 4 of the quasars, Gaussian-smoothed. This shows the range from the brightest to faintest of the residual host galaxies.

To provide the simplest basis for cross-comparison between samples, we have first calculated simple aperture magnitudes. We have used an aperture of 2" (corresponding to \( \sim 16 \text{ kpc} \)) to include most of the flux expected from a host galaxy, while excluding most nearby discrete companions. To estimate errors, we have also calculated the host magnitudes for the two visits separately. In most cases the differences were \( \lesssim 0.3 \text{ mag} \).
Table 1
MZZ quasar nuclear and host properties

| Name      | Redshift | B  | λ0   | $M_B$  | $M_{host}$ (Uncorrected) | Host Luminosity |
|-----------|----------|----|------|--------|--------------------------|-----------------|
| MZZ4935   | 1.876    | 21.9 | 5737 Å | -22.1 | -19.8 (V)               | $\lesssim 0.4 L^V_*$ |
| MZZ11408  | 1.735    | 22.0 | 6033 Å | -22.3 | -21.7 (V)               | 0.9 $L^V_*$ |
| MZZ1558   | 1.829    | 21.6 | 5832 Å | -24.2 | -21.5 (V)               | 0.8 $L^V_*$ |
| MZZ9592   | 2.710    | 21.9 | 4312 Å | -24.2 | -22.4 (B)               | 3.6 $L^B_*$ |
| MZZ9744   | 2.735    | 21.9 | 4284 Å | -23.8 | -21.6 (B)               | 1.7 $L^B_*$ |

We give in Table 1 the results of our magnitude analysis; we find the detected hosts vary from $\sim L_*$ to 4 $L_*$, using $L^V_*$ and $L^B_*$ at $z = 0$ from the field galaxy luminosity function of Loveday et al. (1992). The faintest residual host (around MZZ 4935) we may barely detect at a flux $\sim 0.4 L_*$. These fluxes will generally need a correction for flux lost from the PSF subtraction process which will vary depending on how compact the intrinsic, underlying host is. In the next section we discuss simple models to estimate the amount of this correction.

The morphologies of these hosts are quite compact, generally less than $\sim 0.5''$ ($\sim 4$ kpc) effective radius. We also find in 2 cases galaxies close to the quasar in projection ($\lesssim 10$ kpc), and in MZZ 9592 an off-center host residual.
Figure 1. MZZ 9592, PSF subtractions and tests. A. Visit one, PSF-subtracted, using the observed bright PSF star from the same visit. The same image with a different scaling is shown in the lower left inset, demonstrating that the residual host is not centered on the nucleus. The upper right inset shows the unsubtracted quasar. B. Visit two, PSF-subtracted, rotated to match the orientation of visit one. Extra sky noise comes from unremoved low-level CR residuals. C. Visit one, PSF-subtracted with the star that falls within the field, demonstrating that the residual is not an artifact of the mismatch between the observational strategies applied to the quasar fields and the bright PSF stars. D. The field star minus the PSF star: no residual flux.
Figure 2. PSF-subtracted MZZ quasar hosts, Gaussian-smoothed with a kernel of 0.06. Each panel is 5.7 square (or roughly 45 kpc), N up, E left. A. MZZ 9592, $z \sim 2.7$, with an inset of the central region (unsmoothed). There is an off-center residual host component. B. MZZ 9744, $z \sim 1.8$ C. MZZ 1558, $z \sim 2.7$ D. MZZ 4935, $z \sim 1.8$, host not detected. Note the apparent close ($\sim$ 10 kpc) companion galaxies in panels B and C.
4.1 Comparison to Lyman break galaxies and radio galaxies

To compare the results of our study with studies of Lyman break galaxies and radio galaxies at similar redshifts, we have made some simple simulations of the effect the presence of the quasar nucleus and the PSF-subtraction process have on the derived magnitudes and morphologies. We have used for the first set of these simulations HST NICMOS observations of a number of spectroscopically identified \( z \sim 2 - 3 \) Lyman break galaxies from the HDF North (Dickinson et al. 1999), which were observed in the F160W filter to a much greater depth than our observations. For the observed galaxies that were at the same redshift as our quasars, we first resampled these imaging data to match our final pixel scale, added “quasar nuclei” of varying magnitudes at the center of the galaxy by scaling and adding the MZZ9592 field star, then added Poissonian noise to the appropriate level. We then used one of the observed PSF stars to run the same automatic PSF-subtraction process that we used on the quasars.

We have found that the subtraction process in most cases on these Lyman break galaxies resulted in a loss of flux of \( \sim 0.3 \) magnitude, giving us an indication of the amount to correct our derived hosts. Even after such a correction, most of our quasar hosts have relatively moderate total magnitudes of \( \sim L_\star \), and these magnitudes and compact sizes are basically consistent with the magnitudes and compactness of star-forming galaxies at similar epochs (Dickinson et al. 1999).

To enable a comparison with previous ground-based infrared imaging work on radio-loud galaxies, we adjust our fluxes to match those of Eales et al. 1997, who studied 6C radio galaxies up to \( z \sim 3 \). Extrapolating our H band fluxes to the K band gives K band magnitudes of 22.0, 20.3, and 20.5 for the \( z \sim 1.8 \) quasar hosts, and 20.1 and 20.8 for the \( z \sim 2.7 \) quasar hosts (after correction to the larger aperture used by Eales et al.). They found that \( z \sim 2 \) 6C galaxies have a median \( K \) magnitude of \( \sim 18.5 \), while our 3 quasar hosts are at least a magnitude fainter than this, even allowing for a half magnitude correction to our fluxes lost in the subtraction process. Our \( z \sim 2.7 \) quasar hosts are also a magnitude fainter at K than the 6C objects.

5 Discussion

As the quasars in our sample have nuclear magnitudes that are comparable to those of the well-studied samples of low redshift quasars, we can make a direct comparison, and find that these \( z \sim 2 - 3 \) RQQ hosts are of similar or fainter \( M_V \) as those of the sample of Bahcall et al. (1997) and McLure et al. (1997), for example. However, if the host galaxies of luminous radio-quiet quasars evolve
passively into giant ellipticals today, then at high redshift they should have had similar host magnitudes to the radio galaxies, rather than the moderately faint hosts we have found. Our results are consistent with other recent results on some brighter, lensed quasars; Rix et al. 1999 find that their sample of lensed $z \sim 2$ radio-quiet quasars (de-magnified $M_B \sim 24 - 28$) also had hosts with comparably faint magnitudes. Though inconsistent with passive evolution, our finding L$_*$ hosts at $z \sim 2 - 3$ agrees fairly well with the bottom-up hierarchical galaxy formation models of Kauffmann & Haehnelt (1999); they predict median host luminosities that are somewhat below present day L$_*$ for quasars at $z = 2$ (and even fainter at $z = 3$), for quasars with the nuclear magnitudes of our sample. These hosts might therefore still be undergoing major mergers which would allow them to evolve into the present day gEs associated with low-z quasars; it is unclear in this interpretation, however, why the radio galaxies do not undergo similar mergers and evolution. Conversely, these high-z quasar hosts could be L$_*$ galaxies that will not significantly evolve in luminosity.

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