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James D. Lowenthal
Johns Hopkins University, jlowenth@smith.edu

Timothy M. Heckman
Johns Hopkins University

Matthew D. Lehnert
Lawrence Livermore National Laboratory

J. H. Elias
National Optical Astronomy Observatory

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IMAGING THE HOST GALAXIES OF HIGH-REDSHIFT RADIO-QUIET QSOs[1]

JAMES D. LOWENTHAL[2,3,4] AND TIMOTHY M. HECKMAN
Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, and Space Telescope Science Institute

MATTHEW D. LEHNERT[3]
Institute for Geophysics and Planetary Physics, LLNL, L-413, POB 808, Livermore, CA 94550

AND

J. H. ELIAS
Cerro Tololo Inter-American Observatory/National Optical Astronomical Observatories, P.O. Box 26732, Tucson, AZ 85726-6732

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ABSTRACT

We present new deep K-band and optical images of four radio-quiet QSOs at $z \approx 1$ and six radio-quiet QSOs at $z \approx 2.5$, as well as optical images only of six more at $z \approx 2.5$. We have examined the images carefully for evidence of extended "fuzz" from any putative QSO host galaxy. None of the $z \approx 2.5$ QSOs shows any extended emission, and only two of the $z \approx 1$ QSOs show marginal evidence for extended emission. Our 3 σ detection limits in the K images, $m_K \simeq 21$ for an isolated source, would correspond approximately to an unevolved L* elliptical galaxy at $z = 2.5$ or to 2–3 mag fainter than an L* elliptical at $z = 1$, although our limits on host galaxy light are weaker than this due to the difficulty of separating galaxy light from QSO light. We simulate simple models of disk and elliptical host galaxies, and find that the marginal emission around the two $z \approx 1$ QSOs can be explained by disks or bulges that are $\sim$1–2 mag brighter than an unevolved L* galaxy in one case and $\sim$1.5–2.5 mag brighter than L* in the other. For two other $z \approx 1$ QSOs, we have only upper limits ($L \approx$ L*). The hosts of the high-redshift sample must be no brighter than about 3 mag above an unevolved L* galaxy, and are at least 1 magnitude fainter than the hosts of radio-loud QSOs at the same redshift.

If the easily detected K-band light surrounding a previous sample of otherwise similar but radio-loud QSOs is starlight, then it must evolve on timescales of $\gtrsim 10^8$ yr (e.g., Chambers & Charlot 1990); therefore our non-detection of host galaxy fuzz around radio-quiet QSOs supports the view that high-redshift radio-quiet and radio-loud QSOs inhabit different host objects, rather than being single types of objects that turn their radio emission on and off over short timescales. This is consistent with the general trend at low redshifts that radio-loud QSOs are found in giant elliptical galaxies while radio-quiet QSOs are found in less luminous disk galaxies. It also suggests that the processes responsible for the spectacular properties of radio-loud AGNs at high redshifts might not be generally relevant to the (far more numerous) radio-quiet population.

Subject headings: galaxies: spiral — infrared: galaxies — quasars: general

1. INTRODUCTION

The AGN (active galactic nucleus) phenomenon, whose heyday was at redshifts $z \gtrsim 2$, may be closely linked to the processes governing galaxy formation. It is possible that most normal galaxies hosted an AGN at some early or intermediate stage of their lifetimes, while an alternative view is that AGNs formed independently first, somehow assembling galaxies around them later. Understanding the link between AGNs and galaxies at high redshift therefore can lead to a clearer view of the fundamentals of galaxy formation and evolution, as well as providing insight into the processes responsible for the strong cosmic evolution of the AGN population.

Additional clues to understanding the AGN-galaxy link can come from studying the differences between radio-loud and radio-quiet QSOs. At low redshift ($z \lesssim 0.5$), there appears to be a general trend that radio-loud QSOs are found preferentially in luminous elliptical galaxies, typically 1–2 mag brighter than L* (the characteristic luminosity in the galaxy luminosity function), while radio-quiet QSOs tend to live in spiral or disk galaxies with luminosities closer to L* (Smith et al. 1986; Hutchings, Janson, & Neff 1989; Véron-Cetty & Woltjer 1990; McLeod & Rieke 1994; however, see also Dunlop et al. 1993). Furthermore, studies of the large-scale environments of the two kinds of objects suggest that radio-loud QSOs inhabit denser environments, and that these environments appear to evolve more rapidly with cosmic lookback time, than in the case of their radio-quiet counterparts (Ellingson, Yee, & Green 1991 and references therein; Smith & Heckman 1990).

Extending these studies to higher redshifts is difficult mainly because of the rapid cosmological dimming of the host galaxies [surface brightness goes as $(1 + z)^4$] contrasted with the bright core of the central QSO. By $z = 2.5$, at the peak of the QSO epoch and probably an active era for galactic evolution, a nonevolved L* elliptical galaxy would appear at $K \sim 21.5$ or $I \sim 24.5$. Nevertheless, Heckman et al. (1991b) and Lehnert et al. (1992) were able to detect the extended continuum and Lyα "fuzz" around many of the radio-loud QSOs at $z = 2$–3 in their sample, and several other cases of extended structure

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[2] Current address: UCO/Lick Observatory, University of California, Santa Cruz, CA 95064. E-mail: james@lick.ucsc.edu.

[3] Visiting astronomer, Kitt Peak National Observatory and Cerro Tololo Inter-American Observatory.

[4] Hubble Fellow.

around radio-loud QSOs have recently appeared in the literature (e.g., Hu et al. 1991). The spatially resolved continuum emission observed in the optical and near-IR (rest-frame UV and optical) by Lehnert et al. was several times brighter than the most luminous galaxies seen locally, but corresponded well with the luminosities of typical high-redshift radio galaxies; indeed they fall along the previously known K-z diagram (the "K-Hubble diagram") for radio galaxies.

QSOs with radio/optical luminosity ratios as large as those studied by Lehnert et al. constitute about 0.1% of the total population of QSOs. In this paper we extend the studies of radio-loud QSO host galaxies mentioned above to a sample of otherwise similar high-redshift radio-quiet QSOs, as well as an additional sample at $z \sim 1$. Our fundamental goal was to elucidate the similarities and differences between the two types of AGNs, and to understand the generality of the earlier results.

2. OBSERVATIONS

2.1. *The Samples*

We observed two samples of QSOs, one at $z \sim 2.5$ (the "high-redshift" sample) and one at $z \sim 1.0$ (the "low-redshift" sample). The high-redshift sample was chosen to be essentially identical in QSO redshift and apparent magnitude to the radio-loud sample of Lehnert et al. (1992) but radio quiet. In addition to observing the usual constraints imposed by our allotted observing time and location, we chose optically selected QSOs from the catalogs of Hewitt & Burbidge (1987) and Veron-Cetty & Veron (1991) and from Boyle, Shanks, & Peterson et al. (1988) and Schneider, Schmidt, & Gunn (1991) with $18.5 < V < 21.5$ and redshifts either in the range $1.90 < z < 2.05$ or in the range $2.65 < z < 3.00$. The magnitude selection corresponds at $z \sim 2.5$ to luminosities of QSOs centered around absolute magnitude $M_B = -25.5$ for $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0.1$, which are used throughout this paper. Since the comoving density of the QSO population reached its peak in the redshift range $z \gtrsim 2$, and since $M_B \simeq -25.5$ is near the "knee" in the QSO luminosity function (e.g., Boyle et al. 1988), the QSOs we observed are typical of the population that is responsible for the bulk of radiant energy ever produced by QSOs over the history of the universe. The specific redshift ranges selected place Hα and [O III] λ5007 out of the bandpass of the K filter we used, so that we were measuring only continuum and not line emission.

The low-redshift sample was selected from among optically selected, radio-quiet QSOs in the Hewitt & Burbidge catalog with $19 < B < 21$ and $0.89 < z < 1.16$, where the magnitude range was chosen as a compromise between QSO/host galaxy contrast and QSO visibility on the Palomar Observatory Sky Survey plates (which were used to measure positions of the QSOs and nearby reference stars). The redshift range was chosen to be intermediate between the earlier low- and high-redshift studies and, again, to avoid placing strong emission lines in the observing bandpass.

2.2. *Infrared and Optical Imaging*

We conducted our observations during four runs: an optical and a near-IR run at the Kitt Peak National Observatory's (KPNO) 4 m telescope on 1992 May 8 and 13–15 (UT), respectively, for the high-redshift sample, and a near-IR and optical run at the Cerro Tololo Inter-American Observatory's (CTIO) 4 m telescope on 1992 November 15–16 and 29 (UT), respectively, for the low-redshift sample. The observations are summarized in Tables 1 and 2.

For the KPNO optical imaging, we used KPNO's T1KA Textronix 1024 × 1024 charge coupled device (CCD) at prime focus, yielding 0."47 pixels and a field of view 8'.0 on a side. The detector read noise was measured to be 4.6 e^- rms, and the gain was set to 1.7 e^-/count. The weather was mostly clear but not photometric; the seeing ranged from 1."5 to 2."3, less than ideal for the intended project. We obtained three or four broad-band images of each of 12 QSOs from our high-redshift sample, using either a Harris B or V filter, whichever excluded redshifted Lyα emission from the QSO. The telescope was shifted by 10" between exposures to allow for bad pixels and cosmic rays and to improve flat fields constructed from the data frames. Integration times were typically 360 s per frame, which allowed some of the brighter stars in each frame to saturate the digital/analog converter, although we took care

TABLE 1

SUMMARY OF OBSERVATIONS: HIGH-REDSHIFT SAMPLE[a]

QSO	z_{em}	Date (UT)	Filter	Integration Time (minutes)	Seeing[b]
QNB 1:26	1.917	1992 May 8	B	33	1."6
F855:102.............	2.050	1992 May 8	B	18	1.7
		1992 May 13–15	K	108	1.1
F855:148.............	2.016	1992 May 8	B	18	1.4
QNY 2:21	2.003	1992 May 8	B	18	1.3
		1992 May 13–15	K	108	0.8
QNY 2:07	1.948	1992 May 8	B	18	1.4
QNY 4:52	2.714	1992 May 8	V	18	1.6
F861:085.............	2.874	1992 May 8	V	18	1.9
F861:074.............	2.039	1992 May 8	B	12	1.7
		1992 May 13–15	K	108	1.1
QNZ 4:43	1.916	1992 May 8	B	18	1.6
Q1613.7+1715	2.729	1992 May 8	V	18	1.4
		1992 May 13–15	K	108	0.8
Q1630+3902	1.926	1992 May 8	B	18	1.6
		1992 May 13–15	K	144	1.1
PC 1640+4711......	2.764	1992 May 8	V	12	1.6
		1992 May 13–15	K	108	1.0

[a] All data obtained at KPNO 4 m telescope under nonphotometric conditions.
[b] FWHM in arcseconds, as measured in final combined image.