NEAR-INFRARED OBSERVATIONS OF THE ENVIRONMENTS OF RADIO-QUIET QSOs AT z ≳ 1

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ABSTRACT

We present the results of an infrared survey of QSO fields at z = 0.95, 0.995, and 1.5. Each z < 1 field was imaged to typical continuum limits of J = 20.5, K = 19 (5 σ) and line fluxes of 1.3 × 10⁻¹⁶ ergs cm⁻² s⁻¹ (1 σ) in a 1% interference filter. Sixteen fields were chosen with z ~ 0.95 targets, 14 with z ~ 0.995, and six with z ~ 1.5. A total area of 0.05 deg² was surveyed, and two emission-line objects were found. We present the infrared and optical photometry of these objects. Optical spectroscopy has confirmed the redshift of one object (at z = 0.989) and is consistent with the other object having a similar redshift. We discuss the density of such objects across a range of redshifts from this survey and others in the literature. We also present number-magnitude counts for galaxies in the fields of radio-quiet QSOs, supporting the interpretation that they exist in lower density environments than their radio-loud counterparts. The J-band number counts are among the first to be published in the J = 16–20 range.

Subject headings: galaxies: Seyfert — infrared: galaxies — quasars: general — radio continuum: galaxies

1. INTRODUCTION

Current estimates of the global star formation rate show a steep rise in activity out to a redshift of 1 (Lilly et al. 1996). Half of the stars in the current universe may have formed since z = 1. High-redshift star-forming galaxies are also seen to be highly biased tracers of the mass distribution of the universe (Steidel et al. 1998). As a result of these two observations, significant effort has been devoted in recent years to the search for galaxy clusters at redshifts beyond z = 1 (Dickinson 1997; Donahue et al. 1998, etc.) Narrow-band searches for the Hz emission line have successfully identified star-forming galaxies at z > 2 (Malkan, Teplitz, & McLean 1995, 1996; Teplitz, Malkan, & McLean 1998b, hereafter TMM98; and Mannucci et al. 1998, hereafter MTBW98), and searches for [O II] and [O III] have been used at z ~ 0.9 (MTBM98) and z > 3 (Teplitz, Malkan, & McLean 1999). In this paper we apply this imaging infrared technique to the search for z ~ 1 galaxies.

It takes patience to find the relatively rare galaxies at z = 1 simply by covering large areas of random field. Instead, we have chosen the popular tactic of looking for galaxies where they are most likely to be: near other galaxies or QSOs. In particular, we search fields containing radio-loud or radio-quiet quasars and fields containing absorption-line systems in QSO lines of sight. All of these objects have previously been associated with the presence of groups of galaxies.

Yee & Green (1987) and later Ellingson, Yee, & Green (1991) have examined galaxy clusters as the environment of quasars, although their searches extend only out to z = 0.7. They find significantly more bright QSOs in clusters at higher redshifts, indicating that quasars may be good markers of galaxy clusters. Similarly, large numbers of excess galaxies were found in radio-loud QSO fields at 1 < z < 2 by Hall & Green (1998); see also Hall, Green, & Cohen 1998. At z ~ 2, Aragón-Salamanca et al. (1996) find an excess of K-band–selected galaxies in the environments of QSOs. Also at z > 2, Hutchings (1995) finds excess R-band–selected galaxies in the fields of both radio-loud and radio-quiet QSOs. In similar searches, high-redshift radio galaxies are also seen as markers of other clustered galaxies (Dickinson 1997).

Absorption-line systems have also been studied in detail for their galaxy content. Galaxies have been identified as responsible for Mg II and C IV absorption out to z ~ 1 (e.g., Steidel et al. 1997). Aragón-Salamanca et al. (1994) have demonstrated excess K-selected galaxies in fields containing C IV absorbers. Possible damped Lyα absorption (DLA) systems have been identified past z = 3 (Djorgovski 1996; Moller & Warren 1998). The presence of galaxies as the absorbers make such systems good markers for other galaxies. However, the small impact parameters will often make the absorbers themselves hard to see except with very high resolution.

We have chosen to search for Hz as an indicator of star formation in normal galaxies, It is strong in nearby spirals, with equivalent widths of 50 Å or more in the actively star-forming galaxies (Kennicutt 1983). There are several methods of identifying ongoing star formation, and determining the star formation rate (SFR) with various degrees of accuracy. Emission may either be observed from the UV continuum of young stars, from the ionized gas in H II regions, or reradiated in the far-IR by dust. Hz emission, at 6563 Å, can be observed from nebular emission in the star-forming H II regions. This emission line has the advantage of relatively long wavelength, making it less susceptible to extinction than the UV continuum. There is a concern that the emission actually observed is a combination of lines, but the [N II] 6584 Å line is found to be weak in most cases, at most 10%–30% of Hz (Kennicutt & Kent 1983).
Kennicutt (1983) calculates the SFR based on Hα luminosity to be:

\[
SFR(\text{total}) = \frac{L(\text{H} \alpha)}{1.12 \times 10^{41} \text{ ergs s}^{-1} M_\odot \text{ yr}^{-1}}
\]  

(1)

for an initial mass function that is effectively that of Salpeter, with \( \psi(m) \propto m^{-2.5} \) and an upper mass cutoff of 100 \( M_\odot \).

Similar estimates can be made from observations of the O II emission line (Kennicutt 1992; but see Hammer et al. 1997).

The Hα emission line has also been used to measure the SFR in high-redshift galaxies selected by other methods. For example, Glazebrook et al. (1998) have spectrally measured Hα in 13 \( z \approx 1 \) galaxies selected from the Canada-France Redshift Survey (see Lilly et al. 1996). They find that \( z \approx 1 \) galaxies may have SFRs 3 times higher than would be inferred from rest frame UV observations.

2. OBSERVATIONS

All IR observations in the \( z \approx 1 \) survey were taken with the Shane 3 m telescope at Lick Observatory on Mount Hamilton, with the UCLA Two Channel Near-IR Camera, colloquially known as "Gemini" for its twin detectors (McLean 1994). Use of this instrument for deep IR imaging has been discussed by McLean & Teplitz (1996, hereafter McLean 1994). Use of this instrument for deep IR imaging has been discussed by McLean & Teplitz (1996, hereafter MT96) and Larson & McLean (1997). The observations of the six \( z \approx 1.5 \) fields were taken at the 10 m Keck I telescope using the Near IR Camera (NIRC) (Matthews & Soifer 1994). For a discussion of filter transmission in the NIRC instrument see TMM98.

The UCLA Two Channel Near-IR Camera (see also McLean et al. 1993, 1994) has two independent infrared arrays, one 256 \times 256 pixel NICMOS 3 HgCdTe device and one 256 \times 256 pixel Santa Barbara Research Corporation InSb detector. The camera is a low-noise, high-throughput system. To optimize performance, the instrument employs a variety of readout modes, including correlated double sampling, Fowler sampling (see Fowler & Gatley 1990), a multiple reads per pixel mode, and subarray readouts. Typical deep integrations, like those we employ in this project, utilize Fowler sampling, with 8–32 multiple reads. The plate scale for the detectors is \( 0.070 \) and \( \sim 0.68 \) pixel\(^{-1}\) for the short- and long-wavelength channels. These scales correspond to a field of view of \( \sim 3' \times 3' \). We chose a dichroic beam splitter which directs light longward of 2 \( \mu m \) to the SBRC array. Our typical exposure times were three 30 s each in the \( J \) band, 18 co-adds of 8 s in \( K' \), and a single 240 s exposure in the narrow band.

Each channel has a filter wheel containing 25.4 mm diameter transmission and blocking filters. In addition to the standard \( J, H \), and \( K' \) filters, this project utilized two narrowband interference filters. The filters were purchased from Barr Associates in Westford, Massachusetts. One was "off the shelf," while the other was custom made for this project. Table 1 summarizes the properties of each filter, as described below. The first narrowband filter is the standard filter at 1.28 \( \mu m \), usually used to measure the Paschen \( \beta \) (P\( \beta \)) transition. It is 141 \( \AA \) wide, which corresponds to \( \Delta \lambda / \lambda = 1.1\% \). Standard star observations show that the ratio of P\( \beta \) filter transmission to standard \( J \) filter transmission is 1:22 \( \pm 1 \). The wavelength of the P\( \beta \) filter corresponds to the redshifted wavelength of H\( \alpha \) at \( z = 0.95 \).

The second narrowband filter was custom designed for this project. The filter is centered on 1.3095 \( \mu m \) to probe a redshift range higher than that of the P\( \beta \) filter. The choice was constrained by the atmospheric absorption at the red end of the \( J \) passband. At \( z = 0.995 \), H\( \alpha \) redshifts into this filter. The filter was produced using a new oxide manufacturing process, in order to maximize throughput and cryogenic performance. The filter transmission is fairly flat around the peak of 78\%, centered on 1.3095 \( \mu m \), with a width of 0.0130 \( \mu m \), as verified in a cryogenic test. The transmission was confirmed by standard star observations which show that the ratio of transmitted flux compared with the \( J \) filter is 1:19 \( \pm 1 \).

Targets were selected from a search of NASA/IPAC Extragalactic Database (NED), in fields containing QSOs (either radio loud or radio quiet) or absorption-line systems (either DLA or metal line absorbers). Objects below \( -30^\circ \) were not considered as Keck targets, nor those south of \( -5^\circ \) as Lick targets. Subject to these constraints, we then selected fields at redshifts within \( \pm 0.3\% \) of the central redshift of the filters.

The data were reduced following the procedures outlined by TMM98 and MT96 which will only be summarized here. We obtained images in a sequence of "dithered" exposures, offsetting the telescope between exposures in a \( 3 \times 3 \) grid. Typically spaced by 10–20 pixels. The individual frames were divided by a twilight flat or dome flat (as available). Then a running median sky frame (created from the nine exposures taken closest in time to each image) was subtracted. When no such flat was available, the running median was divided into each image and sky subtraction was left to aperture photometry. Objects were identified using the SExtractor (Bertin & Arnouts 1996) software. Photometry was performed using apertures of 2.5 times the seeing disk. The same aperture was applied to broad- and narrowband exposures. Similarly, the same photometric aperture was applied to both \( J \) and \( K' \) frames. Photometric errors were estimated from aperture photometry performed on random positions in the frame. Errors in the narrowband-minus-broadband color were estimated from a Monte Carlo simulation of the ratio of numbers with large Gaussian errors in order to define the confidence intervals. (See TMM98 for details).

Follow-up optical imaging and spectroscopy was obtained with the Low Resolution Imaging Spectrometer (LRIS), which has a 2048 \( \times 2048 \) pixel CCD detector, with a field of view of \( 5' \times 7' \) (Oke et al. 1995). Spectra were taken with the 300 lines mm\(^{-1}\) grating, giving a dispersion of 2.48 \( \text{Å} \) pixel\(^{-1}\) and spectral resolution (FWHM) of 4.5 pixels. These data were reduced with standard IRAF procedures.

3. RESULTS

There were 43 known targets meeting our criteria. Of these possible fields, we imaged 30 during the 11 clear nights

| Filter | Central \( \lambda \) (\( \mu m \)) | \( \Delta \lambda \) (\( \mu m \)) | Transmission (\%) |
|--------|----------------|----------------|--------------|
| \( J \) | 1.2 | 0.285 | 70 |
| \( P\beta \) | 1.28 | 0.01408 | 65 |
| 1.3095 | 1.3095 | 0.0130 | 78 |
| \( H \) | 1.65 | 0.3 | \( \geq 70^* \) |
| \( K' \) | 2.1 | 0.35 | \( \geq 70^* \) |

* Manufacturer specification.
available for this project (see Table 2). Table 3 lists QSO photometry for each field and estimated optical magnitudes from the NED. In each field, we obtained simultaneous $J$ and $K$ imaging at integration times designed to detect $\sim L^*$ galaxies at the appropriate redshifts. Fields observed at high signal-to-noise ratios or that seemed otherwise promising were planned for narrowband follow-up. Table 4 lists narrowband observations and inferred limiting SFRs. Six fields observed with $z = 1.5$ "signposts" are also listed in Table 5.

### 3.1. Discussion of Individual Fields

In each field, the errors in the broad-narrow colors were calculated as discussed above. Objects with narrowband excesses lying at above the $99\%$ confidence interval are considered possible detections. Two apparent Hz emitters were detected in this survey. They are listed in Table 6, along with their inferred SFR and broadband photometry.

Our detection limits were typically $J = 20.5\ (5\ \sigma)$ and SFR $= 12\ M_\odot/\text{yr}^{-1}\ (2\ \sigma)$. This depth should be sufficient to pick up vigorously star-forming galaxies at $z = 1$. The GISSEL96 (see Bruzual & Charlot 1993) models predict that an evolved $L^*$ galaxy at $z = 1$ will have $J = 20.5$. Adding a strong ongoing episode of star formation encompassing $10\%$ of the galaxy's mass over $1\ \text{Gyr}$ would lead to an SFR $\geq 10\ M_\odot/\text{yr}^{-1}$.

The survey has covered approximately 190 arcmin$^2$ (in the highest signal-to-noise ratio [SNR] regions). This is sufficient to constrain the size of a moderately high redshift galaxy population with SFRs at the sensitivities we have achieved.

#### Table 3

| Field | Date    | $J$ | $K$ | $z_{em}$ |
|-------|---------|-----|-----|----------|
| 0107−025 | 1995 Aug 4 | 20.87 | 18.53 |
| 0122−003 | 1995 Aug 5 | 20.76 | 18.60 |
| 0246+009 | 1996 Oct 19 | 20.41 | 19.20 |
| 2145+067 | 1995 Aug 4 | 20.85 | 18.41 |
| 2350−0132 | 1995 Aug 5 | 20.65 | 18.67 |
| 2354+0048 | 1995 Aug 5 | 20.90 | 18.43 |

* Optical magnitudes were taken from the NED catalog. Typically they correspond to $B$ or $V$.

3.2. 0107−025

This field was of particular interest because there are two known QSOs within one UCLA Camera field of view with emission redshifts that place Hz in the P$\beta$ filter (see Fig. 1). However, no new line-emitting objects were detected. The two QSOs are clearly detected in the narrow band. Figure 2 compares the number of galaxies in this field to the average $J$ number counts for all the broadband fields. Since little $J$-band field data are available at these magnitudes (see § 5), we use our averaged number counts. There is a possible excess in several bins at $J > 19$, about $1\ \sigma$ above the average per bin.

3.3. 2145+067

Figure 3 shows the broadband image of this field. No statistical excess of galaxies has been detected (see Fig. 4). A drawback to its consideration as a target is the bright star in the southern region of the field. As a result, we decided against it in the first set of narrowband observations in 1995 August. However, we did select it as a target the following year and observed it in 1996 October.

One object in this field shows an apparent $\sim 3\ \sigma$ excess in the narrowband filter (see Fig. 5). Its $\Delta m = 1.2$ yields an inferred SFR $\geq 53\ M_\odot/\text{yr}^{-1}$, assuming the line is Hz at $z = 0.995$. The inferred equivalent width would be $132\ \text{Å}$ or $2\%\ \text{EW}/\lambda$ (EW is the equivalent width). The object lies 45" from the QSO. It has an FWHM of 4'2, compared with a
seeing disk of 2'2. Our photometry shows the galaxy to have $I = 22.5$, $J = 19.2$, and $K' = 18.6$. Optical CCD imaging of this field as a follow-up of Hubble Space Telescope QSO fields (Kirhakos et al. 1994) did not detect this object, down to a limit of $g \approx 22$, consistent with our $I$-band detection. These colors are generally consistent with a $z \approx 1$ galaxy, where the 4000/3646 Å break lies in the $I$ band. Assuming passive evolution, this galaxy would be somewhat brighter than $L_*$ today.

The line-emitting galaxy in this field is located 14' west of a bright star. This initially suggested that the detection could actually be a ghost. To test this, an image was taken through the same filter of a bright star in a relatively uncrowded field. Two ghosts were identified to the southeast of the star, as a distinctive "double." No ghost image was detected at the position of the possible Hα emitter. Also, the strong detection of the object in both the $J$ and $P\beta$ filters makes the risk of a ghost less likely.

We subsequently detected this object with LRIS imaging and spectroscopy, demonstrating that it is real and not a ghost. We do not find any emission lines to confirm the object's redshift. In a future paper, we will present an analysis of cross-correlation of this spectrum with galaxy spectra at various redshifts (see also Cohen et al. 1998).

### 3.4. LBQS 2350−0132

A single, strong Hα-emitting object is detected in this field (see Figs. 6 and 7). It shows Hα emission with an EW of 1.3%, or $\text{SFR} \geq 26.0 \, M_\odot \, \text{yr}^{-1}$. The line flux is $5.1 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$, and the EW is 86 Å in the rest frame. The object is clearly extended with FWHM = 3'0 compared with a seeing disk of 1'5. It lies 47' from the QSO (400 kpc at $z = 0.993$).

The $J - K' = 1.3$ color of this object is blue for an evolved elliptical at this redshift, but could be consistent with a starburst. Its $K'$ continuum magnitude is roughly consistent with an L* galaxy at this redshift, suggesting that this is a secondary starburst, not the initial formation of the galaxy. Photometry with LRIS shows the galaxy to have $I = 21.9$, still fairly blue for galaxies at that redshift. This same field was observed by Kirhakos et al. (1994). They do not detect this object down to a limit of $g \approx 22$, again consistent with our photometry.

The number counts for this field do not show any excess of faint galaxies (see Fig. 8). Similarly, the reddest objects in the frame are not clustered near the line emitter, nor near each other. A single very red object ($J - K' = 2.8$) lies ~45" north of the detection, although it falls in a lower SNR region of the image.

We have obtained LRIS imaging and spectroscopy of this field. The redshift inferred for the narrowband detection is confirmed to be $z = 0.989 \pm 0.001$ by the presence of the $[O \, II]$ emission line in the optical spectrum (see Fig. 9). The redshift difference between the QSO and the galaxy (along the line of sight) corresponds to 4.2 Mpc at $z = 0.99$, which is large, suggesting no physical connection with the sign-

### Table 4
Narrowband Observations of $z \approx 1$ Targets

| Field   | Filter | Date       | Integration Time (s) | 1σ SFR ($M_\odot \, \text{yr}^{-1}$) |
|---------|--------|------------|----------------------|-------------------------------------|
| 0107−025 | Pβ     | 1996 Oct 20| 14400                | 6                                   |
| 0122−003 | Pβ     | 1996 Oct 21| 14580                | 6                                   |
| 0500+019 | 1.3095 | 1996 Oct 20| 10620                | 8                                   |
| 1244+324 | 1.3095 | 1995 May 22| 11520                | 10                                  |
| 1331+170 | Pβ     | 1996 May 6 | 14580                | 6                                   |
| 1608+4636| Pβ     | 1995 May 5, 6| 14580| 6                                   |
| 1634+706 | 1.3095 | 1995 Aug 6 | 11340                | 8                                   |
| 1700+4744| 1.3095 | 1995 Aug 7 | 12960                | 4                                   |
| 2145+067 | 1.3095 | 1996 Oct 20, 21| 11340| 10                                  |
| 2350−0132| 1.3095 | 1995 Aug 9 | 13500                | 6                                   |
| 2354+0048| 1.3095 | 1995 Aug 5 | 12960                | 4                                   |
| 2358+0038| Pβ     | 1995 Aug 8 | 13860                | 6                                   |

### Table 5
Observations of $z = 1.5$ Targets

| Field       | Date       | H-Band Filter Integration Time (s) | Narrowband Filter Integration Time (s) | H 5σ |
|-------------|------------|-----------------------------------|---------------------------------------|------|
| 87GB 1554+3526 | 1994 Jan 30 | 600                               | 2000                                 | 21.0 |
| LBQS 2236−0023 | 1994 Jul 18, 19 | 1020                               | 3240                                 | 21.5 |
| CSO 190       | 1999 Jan 28 | 1680                              | 4320                                 | 21.9 |
| Q1038+311*     | 1999 Jan 28 | 1620                              | 2640                                 | 21.3 |
| Q1147+339      | 1999 Jan 28 | 840                               | 2400                                 | 20.6 |
| Q1316+3111*    | 1999 Jan 28 | 1080                              | 2400                                 | 21.0 |

* Because of observing constraints, these objects were chosen as signposts, even though they lie more than 1% from the center of the narrowband filter (both at $z = 1.45$).
post. The [O II] line is unresolved at the resolution of the spectrum, which constrains the intrinsic width to be no greater than 300 km s$^{-1}$. The line flux is $1.9 \times 10^{-16}$ ergs cm$^{-2}$ s$^{-1}$. The equivalent width of the [O II] line is 80 Å in the rest frame, or 93% of the EW of the Hz + N II complex. Kennicutt (1992) finds that most low-redshift star-forming galaxies have $\text{EW}([\text{O II}]):\text{EW}(\text{Hz})$ ratios of 0.40, although there is considerable scatter for objects with $\text{EW}(\text{Hz}) > 40$ Å, such as this one. Kennicutt also comments that Seyfert 2 galaxies are found to have high $\text{EW}([\text{O II}]):\text{EW}(\text{Hz})$ ratios while Seyfert 1 galaxies have low ratios. Thus, it is possible that this candidate object contains a Seyfert 2 nucleus, although the line ratio does not preclude a purely stellar origin. The angular extent of the continuum image argues against a broad-line object (Seyfert 1). Even a narrow-line active galactic nucleus (Seyfert 2) would be expected to produce some detectable Mg II emission, which should have fallen in a good region of our spectrum but is not seen. The 3 $\sigma$ limit at the wavelength of redshifted Mg II is $6 \times 10^{-18}$ ergs cm$^{-2}$ s$^{-1}$.

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4. EMISSION-LINE GALAXIES AT $z \sim 1$

We have detected one definite and one probable H$\alpha$-emitting galaxy at $z \geq 0.95$. This corresponds to a surface density of 0.01 galaxies arcmin$^{-2}$. For comparison at $z = 3$...

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\begin{table}[h]
\centering
\caption{Narrowband Detections at $z \sim 1$}
\begin{tabular}{llllll}
\hline
Field & $z$ & $\Delta$m & $I$ & $J$ & $K$ & SFR \\
\hline
2145+067 & \ldots & \ldots & 0.995 & 12 & 22.5 & 19.2 & 18.6 & 52.8 \\
2350−0132 & \ldots & \ldots & 0.990 & 0.9 & 21.9 & 20.2 & 19.1 & 26.0 \\
\hline
\end{tabular}
\end{table}

* Magnitude is uncertain because of overlap with PSF of bright star.
in large ($\Delta z > 0.4$) redshift windows, field galaxies are detected, with SFR $\sim 8 \, M_\odot \, \text{yr}^{-1}$, at $0.4$–$0.8 \, \text{arcmin}^{-2}$ (Steidel et al. 1996).

As a volume density, our two detections yield $4.7^{+6}_{-3} \times 10^{-4}$ galaxies Mpc$^{-3}$ (comoving). This density is similar to that for field H$\alpha$-emitting galaxies at this redshift, as determined by the NICMOS parallel grism survey (McCarthy et al. 1999). Table 7 lists results of various H$\alpha$.
surveys for star-forming galaxies for different redshifts. Comparing the results, we find broad agreement in the densities of Hα emitters, with a higher density in absorption-line fields, as already noted by TMM98 and MTBW98. We also find good agreement in the average star formation rates at different redshifts. This constant detected average SFR may be the result of the bias imposed by a flux-limited survey (for example TMM98 found fainter, less vigorously...
star-forming objects by going deeper. However, the consistency in the average SFR of galaxies brighter than the flux limit may be indicative of the constant global star formation rate observed at $z > 1$. Lyman break galaxy searches (Steidel et al. 1998) and observations in the submillimeter (cf. Smail et al. 1998) have suggested that the global SFR does not change much between redshifts of 1 and 5.

5. NUMBER-MAGNITUDE COUNTS

Our typical broadband detection limits are $J = 20.5$ and $K' = 19.0$, corresponding to an evolved $L_*$ galaxy at $z \sim 1$. In Figures 10 and 11 we plot the number-magnitude counts in $J$ and $K'$. For comparison, the number counts from the literature are also plotted. In both the $J$ and $K'$ bands we find no statistical excess of galaxies averaged over the total survey area in QSO fields. It has been suspected for some time that radio-quiet QSOs (RQQs) at most redshifts do not lie in high-density environments, unlike radio-loud QSOs (RLQs). Most of the quasars in our sample are RQQs, and so it is perhaps not surprising that our number counts agree with the field. Table 8 lists the number-magnitude counts per square degree per magnitude for the $J$ band.

Our $J$-band number counts are among the first wide-field number counts for any environment at deep $J$ magnitudes. The DENIS Survey (Mamon et al. 1998) has provided $J$-band number counts down to $J = 15$. Deep $J$-band counts will soon be available from the NICMOS parallel survey (cf. Teplitz et al. 1998a; Yan et al. 1998), and counts at $J$ fainter than 20 have been measured by Bershady, Lowenthal, & Koo (1998). It is of particular interest to have number counts in different IR wavebands, in order to provide good field comparisons for the study of cluster environments at different wavelengths (cf. Stanford, Eisenhardt, & Dickinson 1997).

### Table 7

| Redshift | Density (Comoving) | $3\sigma$ Flux Limit | $<\text{SFR}>$ | Number of Galaxies | Reference | Notes on Field Selection |
|----------|--------------------|-----------------------|---------------|-------------------|-----------|-------------------------|
| 0.7–1.9  | 2                  | 0.6                   | 50            | 30                | Random*   |                        |
| 0.95–1.0 | 4.7                | 1.3                   | 35            | 2                 | QSO emission redshift |            |
| 1.5      | <40                | :50                   | ...           | 0                 | QSO emission redshift |            |
| 2.0–2.7  | <70                | 10                    | ...           | 0                 | DLA*      |                        |
| 2.2–2.5  | 22.5               | 1.9                   | ~40           | 2                 | Radio galaxies |            |
| 2.28–2.29| <120               | 0.9                   | ...           | 0                 | QSO emission redshift |            |
| 2.3–2.4  | 9                  | 4.8                   | 70            | 18                | QSO absorption-line redshift |            |
| 2.3–2.5  | 60                 | 1.0                   | 50            | 5                 | QSO absorption-line redshift |            |

* See Beckwith et al. 1998 for a discussion.  
* Long-slit spectroscopy.  
* We have counted the density of objects from that survey with line fluxes greater than $1 \times 10^{-16}$ ergs cm$^{-2}$ s$^{-1}$.  
* Long-slit spectroscopy.

### References

- (1) McCarthy et al. 1999; (2) this work; (3) Bunker et al. 1999; (4) van der Werf et al. 1997; (5) Thompson 1996; (6) Pahre & Djorgovski 1995; (7) MTBW98; (8) TMM98.
Our result that RQQs lie in low-density environments is supported by the conclusion reached by Croom & Shanks (1998) for RQQs at $z < 1.5$. They find no significant clustering signal for galaxies down to $L^*$.

On the other hand, Jaeger, Fricke, & Heidt (1999) find a significant excess of galaxies close to RQQs at $z > 1$ in $R$-band observations. We can also consider the radial distribution of galaxies in reference to the QSO for our fields in the $J$ band (see Fig. 12). This analysis is more sensitive to small-scale clustering, which has no impact on the average number counts over the entire area. There is a marginally significant excess of galaxies within $\sim 15''$ of the QSO ($\sim 120$ kpc at $z = 1$). We note, however, that there are a total of only 66 galaxies in the three innermost bins, compared with a field expectation of 47 galaxies, or an average excess of one galaxy per two fields. The field expectation is the same, whether it is determined from the average number counts over the entire survey area or from repeating the radial binning around random points in the fields. Such a small possible excess is only present at the $\sim 2\sigma$ level. In addition, even accepting such an excess, it argues for RQQ environments being poor groups of galaxies, not rich clusters. However, the radial extent is generally consistent with the results of TMM98, which found no roll-off in the radial distribution of H$\alpha$ emitters within one NIRC field ($38'' \times 38''$).

The potentially excess galaxies detected in the broad band, if they are physically associated with the quasar signposts (within 2% of redshift), have a density which is higher than that of strong H$\alpha$ emitters. This effect would not be unexpected, if one assumes that there is a large population of less actively star-forming galaxies by a redshift of 1. The galaxies around these quasars might be seen to be actively star forming at a much earlier epoch. For example, Hu, Cowie, & McMahon (1998) and Djorgovski et al. (1997) find high densities of Ly$\alpha$ emitters around $z > 4$ QSOs. This could imply that by $z \sim 1$, little active star formation is to be found in poor groups. By contrast, richer groups around QSOs at $z \sim 1.5$ are seen to have a higher density of H$\alpha$ emitters (Hall 1998). Indeed, by $z \sim 0.4$, active star formation is more often observed in rich clusters (see Oemler 1992).

6. FUTURE PROSPECTS

This project has demonstrated that future narrowband imaging surveys can succeed in probing the $z \geq 1$ universe, if sufficiently long integration times are combined with new large-format infrared arrays. At that point it will be reasonable to make blind searches of the field, which will reveal if the targeted searches described here have benefited much from galaxy clustering around quasars and their absorbers.

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