QSO HOSTS AND ENVIRONMENTS AT $z = 0.9-4.2$: $JHK$ IMAGES WITH ADAPTIVE OPTICS

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ABSTRACT

We have observed nine QSOs with redshifts of 0.85 to 4.16 at near-infrared wavelengths with PUEO, the Adaptive Optics (AO) Bonnette of the Canada-France-Hawaii Telescope. Exposure times ranged from 1500 to 24,000 s (mostly near 7000 s) in the $J$, $H$, and/or $K$ bands with pixels 0.035 on the sky. The FWHMs of the co-added images at the location of the quasars are typically 0.16. Including another QSO published previously, we find associated QSO structure in at least eight of 10 objects, including the QSO at $z = 4.16$. The structures seen in all cases include long, faint features that appear to be tidal tails. In four cases we have also resolved the QSO host galaxies, but we find them to be smooth and symmetric. Future point-spread function removal may expand this result. Of the nine objects (including one object previously reported) with more extended structure, five are radio-loud, and all but one of these appear to be in a dense, small group of compact galaxy companions. The radio-quiet objects do not occupy the same dense environments as seen in the near-infrared. In this small sample we do not find any apparent trends of these properties with redshift over the range $0.8 < z < 2.4$. The colors of the host galaxies and companions are consistent with young stellar populations at the QSO redshift. Our observations suggest that AO observations in the visible region will exhibit luminous signatures of the substantial star formation activity that must be occurring.

Key words: galaxies: interactions — instrumentation: adaptive optics — quasars: general

1. INTRODUCTION

QSO host galaxies are well investigated at redshifts up to $\sim 0.6$, with both ground-based and *Hubble Space Telescope* (HST) images at both visible and near-infrared (NIR) wavelengths (e.g., Hutchings & Neff 1992, 1997a; McLeod & Rieke 1995; Bahcall et al. 1997 and references therein). Much has been written on the general evidence for tidal events being the trigger for nuclear activity, the hybrid morphology of the QSO host galaxies, associated star formation, and the different environments of companion galaxies between radio-loud and radio-quiet QSOs.

At higher redshift, there have been ground-based data that resolve QSO hosts at redshifts in the range 2.0 to 2.5. These, particularly the radio-loud ones, appear to be very luminous galaxies, with very high star formation rates (SFRs), and with no counterparts in the present-day universe (see, e.g., Heckman et al. 1991; Lehnert et al. 1992; Hutchings & Neff 1997b; Hutchings et al. 1998; Aretxaga, Boyle, & Terlevich 1995; Aretxaga et al. 1998). There are also indications that QSOs of all kinds occur in small, dense groups of companion galaxies that also have high SFRs (Hutchings 1995, 1998; Campos et al. 1999). There is a clear similarity to radio galaxies at comparable redshifts; they also are very luminous and are located in dense environments (see, e.g., Röttgering 1998; Pentericci et al. 1999). The high-redshift QSOs observed so far lack the spatial detail and the statistical samples that are available for the lower redshift QSOs, which means that several key questions cannot yet be answered. Primarily, these concern the cosmic evolution of the QSO phenomenon. We do not know how the nature of QSO activity evolves with redshift: Do the sites of QSO activity evolve as different environments become favorable? Does the environment evolve at all? Or does the environment not matter? We also do not know if the trigger of nuclear activity changes with redshift (as the host galaxies age or as the interaction rate changes) or if the luminosity and visibility of QSO activity evolves. Is star formation a cause, an effect, or a parallel process in QSO events? Do radio-loud and radio-quiet QSOs evolve differently?

We have begun a program to obtain high-resolution and high signal-to-noise images of QSOs in the redshift range $1 < z < 4$. The data reported here are from NIR images obtained with PUEO, the Adaptive Optics (AO) Bonnette of the Canada-France-Hawaii Telescope (CFHT; Rigaut et al. 1998). We have previously reported similar observations for the $z = 1.1$ optically selected QSO 1055+019 (Hutchings et al. 1998). In this paper we add nine more to the sample and discuss the individual cases and the trends we see in the sample so far. As noted in Hutchings et al. (1998), our observing list is restricted to QSOs with nearby bright guide stars for the AO system. Thus, while we are investigating objects with redshifts greater than $\sim 0.8$, the sample available at any date of observation is not large, and our principal criteria have been to attempt to match radio-loud and radio-quiet objects and to cover a wide range of redshift.

2. OBSERVATIONS AND DATA

The data reported here were obtained with PUEO in 1998 January and March. Table 1 lists the objects observed, and Table 2 provides a journal of observations. All obser-
vations used a nearby guide star, as listed in the table, and corrected images at the location of the QSOs generally have FWHM $\sim 0.2$ or better. We used the KIR camera, a 1024 $\times$ 1024 pixel HgCdTe detector described at the CFHT Web site. This detector has lower noise and less image retention than the 256 pixel MONICA camera used previously (i.e., fewer reads are required to remove the effects of bright objects in the detector). Pixels are 0.035", yielding a field of 36", so that the guide star, along with the QSO and its local companions, is usually in the science image. The observations were 5 minute integrations performed in a nonrepeating dither pattern covering several arcseconds. Conditions were good for both runs. Uncorrected seeing was in the range 0.5 to 0.9 FWHM, and the transparency was good for all observations reported. All observations were made in standard $J$, $H$, and $K$ filters. Performance in the $K$ band is somewhat compromised by additional thermal background from the AO system, but unfortunately no $K'$ or $K_s$ filter was available for our observations.

NIR photometric standards (Casali & Hawarden 1992) were observed, and images were also obtained of crowded stellar fields (M91 and M15) to calibrate the variation of the point-spread function (PSF) with the distance and brightness of the guide star.

Table 2 summarizes the data. The FWHMs were measured at the QSO location (these are, of course, somewhat worse than at the guide star). In the best data, the FWHMs typically vary from 0.13 at $K$ to 0.15 at $H$ and 0.20 at $J$. There were substantial differences during and between nights, and on average, the results were better during the March run than the January run.

The data were processed using "standard" NIR techniques, but in several cases processing was done independently and differently by more than one author. We describe two approaches. First, sky frames were obtained as medians of the unshifted dither frames. In cases where the saturated guide star was in the image, they were edited out before the median was computed, because otherwise they usually leave a faint imprint. In most cases we were able to use sky frames from the entire period of observation of an object. However, during nights when the sky brightness was very variable, we used running medians of data taken closely in time. After sky subtraction, the data frames were shifted to superpose the QSOs exactly and combined with sigma clipping. (The shifts were done with linear interpolation, after checking that more elaborate shifts produced the same result.) Although flat-field images of dome lights were obtained, it was found empirically that flat-field division did little to improve the sky flatness or noise—presumably because the sky frames constitute a flat field—so they were generally not used.

The small pixels and the bright sky make it hard to see faint extended features such as tidal tails or the outer parts of galaxies. Furthermore, no very sharp morphological features were detected in any of the QSOs or their companions. Thus, to improve detection of faint features, we further smoothed the sky by editing out the QSO and companions and fitting a spline surface to the remaining sky. This was subtracted from the image to remove sky brightness variations on scales of several arcseconds or more, which improved our ability to investigate and measure faint tails and flux extensions over scales up to a few arcseconds. The

| QSO    | $m_g$ | $z$  | Radio | Comments                                               |
|--------|-------|------|-------|--------------------------------------------------------|
| 0915 $\pm$ 213 .... | 17.5  | 0.85 | RL    | Resolved host, knot, tail, compact cluster*          |
| 1055 $\pm$ 019 .... | 20.5  | 1.06 | RQ    | Resolved, faint jet or extended companion*             |
| 0804 $\pm$ 499 .... | 17.5  | 1.43 | RL    | $\sim$ Unresolved, tail                                 |
| 1337 $\pm$ 013 .... | 18.7  | 1.61 | RL    | Compact group, possible connection to nearest knot     |
| 1540 $\pm$ 180 .... | 18    | 1.66 | RL    | Resolved, tail, compact cluster                        |
| 0849 $\pm$ 120 .... | 20.5  | 1.76 | RQ    | Two possible companions, one with possible tail        |
| 1236 $\pm$ 003 .... | 19.1  | 2.18 | RQ    | $\sim$ Unresolved, possible tail, nearby companion     |
| 0552 $\pm$ 398 .... | 18    | 2.37 | RL    | Interacting (?) dense cluster                          |
| 1307 $\pm$ 297 .... | 18.6  | 3.09 | RQ    | Short exposures, unresolved, one companion             |
| 0104 $\pm$ 022 .... | 19.7  | 4.16 | RQ    | Resolved + tail? Faint companions                      |

* See Hutchings et al. 1998.

### TABLE 2

JOURNAL OF OBSERVATIONS ORDERED BY RIGHT ASCENSION

| NAME           | MONTH (1998) | EXPOSURE (s) | GUIDE STAR | OFFSET (arcsec) | FWHM (arcsec) |
|----------------|--------------|--------------|------------|-----------------|---------------|
|                |              | $J$          | $H$        | $K$             | $J$           | $H$          | $K$          |
| 0104 $\pm$ 022 | Jan          | ...          | 4800       | 24000           | 13.8          | 14           | ...          | 0.32 | 0.17         |
| 0552 $\pm$ 398 | Jan          | ...          | ...        | 9300            | 11.7          | 26           | ...          | 0.24 | ...          |
| 0804 $\pm$ 499 | Mar          | 6000         | 7200       | ...             | 14.6          | 11           | 0.23         | 0.24 | ...          |
| 0849 $\pm$ 120 | Jan          | 9600         | 7200       | ...             | 13.4          | 16           | ...          | 0.16 | 0.19         |
| 0915 $\pm$ 213 | Mar          | ...          | 7200       | 7200            | 13.2          | 12           | ...          | 0.16 | 0.16         |
| 1236 $\pm$ 003 | Jan          | 9600         | 7200       | ...             | 12.8          | 19           | ...          | 0.25 | 0.15         |
| 1307 $\pm$ 297 | Jan          | ...          | 1500       | 1800            | 8.1           | 21           | ...          | 0.15 | 0.15         |
| 1337 $\pm$ 013 | Mar          | 7200         | 7800       | ...             | 13.4          | 20           | 0.19         | 0.15 | ...          |
| 1540 $\pm$ 180 | Mar          | 6000         | 6000       | 6000            | 12.6          | 17           | 0.23         | 0.14 | 0.13         |
above process was repeated several times with slightly different edits and surface fits, and to remove spurious artifacts. *Final results are a mean of the individual results.* The features we report here are seen in all processed images even before this flattening procedure, so we have good confidence in their reality. Finally, in most cases we found that images with 4 × 4 block-averaged pixels (0.14 pixels) revealed the faint extended features more clearly.

A similar procedure was developed and used independently by one of us to deal with changing sky brightness and the faint halos around the bright guide stars. First, a median sky frame was generated from all target exposures on each QSO for each filter. After correction with this first-order flat field, the exposures were grouped and combined according to mean sky brightness, and a mask was generated that included all bright pixels. Second-order flat fields were then generated using the masks and applied for each group. Finally, the frames were registered and median-combined.

The features that we discuss are faint, difficult to display, and in some cases comparable with sky features. However, we note that they are seen independently of the different authors' processing, often appear in more than one filter, are robust to sky-smoothing processing, and have flux measures from differently processed images in agreement. Features that did not pass all these criteria were rejected.

Flux measurements were made by summing the signal in pixels that include the structures of interest and subtracting the mean nearby sky level. This was done on both the full-resolution and binned data. All galaxies and symmetric features were also measured by using the IRAF task IMEXAM. Limiting surface brightnesses vary with filter and integration time, as well as sky conditions, but our rough surface brightness limits in magnitudes per square arcsecond are 22.4 in K, 23.4 in H, and 24.4 in J.

We describe below the individual QSOs and their environments, concluding with some collective remarks on the ensemble. The tables for each object field give all mea-

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**Fig. 1.—** Location of detected objects in all fields. The field side is 36″. North is up, and east to the left. Some objects not shown were seen in a partially exposed larger field because of dither patterns. The guide star is indicated as “GS” when it is in the field. The QSO is indicated by “Q,” assumed foreground galaxies by “F,” and stars by asterisks. Photometry of most numbered galaxies is in the tables.
sures made in this way. Generally, the magnitude errors for smooth, round objects are $\pm 0.1$ mag for $J = 19.0$, $H = 18.4$, $K = 17.9$, and these increase to $\pm 0.2$ mag for objects $2.3$ mag fainter and $\pm 0.4$ mag for objects yet another $1$ mag fainter. Errors in extended features are comparable, while those for PSF-subtracted fluxes are discussed individually. In this paper we have not attempted to do careful PSF modeling and removal or deconvolution. That will be dealt with in a separate paper. We mention the results of simple PSF subtraction in a couple of cases where the QSO is sufficiently well resolved that this is not a significant issue.

We quote absolute magnitudes at the QSO redshift for objects whose size, brightness, and colors suggest that they are possible companions. These are for an assumed $H_0 = 75$ km s$^{-1}$ kpc$^{-1}$ and $q_0 = 0.5$, with no $K$-correction ($K$-corrections depend on stellar population and bandpass, but for young populations at these redshifts they are likely to be close to zero: $-1$ mag for B0 stars and zero for A0 stars). Comparison of these luminosities indicates that the possible companions (and QSO host galaxies) have rest-wavelength values in the range typical of bright galaxies. If they have active star formation, they will be more luminous at shorter rest wavelengths. The shortest rest wavelengths we are observing range from 4600 to 7000 Å for the three $J$-band observations. In the $H$ band, the range is from 4900 to 9000 Å.

Figure 1 shows the distribution of detected objects in all well-exposed fields. Measures of most of them are given in individual tables. The figure indicates which objects are assumed from their size and/or brightness to be foreground galaxies ("F") or stars (asterisks), as well as the guide stars ("GS") when they appeared in the field. We discuss the fields below in order of increasing redshift.

3. 0915—213

This is a radio-loud QSO at $z = 0.85$. It has a flat radio spectrum of medium flux (0.6 Jy at 5 GHz) and is probably compact, but there is no published radio map. Our data are in the $H$ and $K$ bands. In both, the QSO lies in a group of four faint objects occupying one quadrant of the KIR image—the rest of the field is empty with the exception of two larger, low surface brightness galaxies (and two stars) that are widely spaced. We suppose these to be foreground galaxies with low surface brightness.

The QSO is extended asymmetrically to the northeast, and lying very close (1.4) to the faintest compact companion (No. 3), to the northwest. A fainter companion (No. 1) lies farther to the north (see Fig. 2). There is an extended wisp of luminosity beyond the line to the nearby companion that turns through 90° and brightens slightly some 4° from the QSO. These are very faint features, but we regard them as real because they show up on subsets of our data and also in both colors. Table 3 shows the photometric measures of objects in the field of 0915—213.

We have not yet obtained good PSF subtraction in the central QSO, either because of real complex structure or because the PSF distortion away from the guide star is unusually large. However, preliminary results indicate that the QSO host is elliptical, with its long axis in the direction of the large extended luminosity to the northeast. The fluxes given for the QSO host are derived from the subtractions and also from the azimuthally averaged profiles, which agreed to within 30%.

![Fig. 2.—$H$-band (left) and $K$-band images of 0915—213 (lower bright object). The images have been binned 4 × 4 (to 0.14 pixels) to enhance faint features. North is up, and east is to the left; the panels are 8° × 12°. Note the extension of the QSO to the northeast and the nearby compact object to the northwest. There is probably a faint arc of flux to the northwest, seen in both bands, but more clearly in $K$.](image-url)
TABLE 3
PHOTOMETRY IN THE 0915—213 FIELD

| Object       | $K$  | $H$  | $H-K$ | $M_H$ |
|--------------|------|------|-------|-------|
| QSO .......... | 15.9 | 16.7 | 0.8   | -25.8 |
| QSO host..... | 20.3 | 20.6 | 0.3   | -21.9 |
| 1 ............ | 17.9 | 18.0 | 0.1   | Star  |
| 2 ............ | 18.7 | 19.1 | 0.4   | -23.4 |
| 3 ............ | 21.0 | 21.7 | 0.7   | -20.8 |
| 4 ............ | 19.5 | 19.5 | 0.0   | -23.0 |
| 5 ............ | 19.1 | 19.8 | 0.7   | -22.7 |
| Wisp .......... | 20.5 | 21.4 | 0.9   | -21.1 |

The host galaxy extension differs between $H$ and $K$, suggesting a color gradient. The nearby companion does not have a bright nucleus and is extended tangentially to the direction to the QSO. While signal levels are low, we see no structure within the features described, and their overall structure is very suggestive of a tidal extension of an old population of stars associated with the QSO host galaxy (see, e.g., 2141 + 175 in Hutchings et al. 1994).

4. 0804 + 499

This QSO, at $z = 1.43$, was observed in the $H$ and $J$ bands. It is a radio source that is unresolved at sub-arcsecond levels. The field is quite empty, containing only the guide star, another object comparable to the QSO, and a single faint galaxy some 20″ away in both the $H$ and $J$ bands. In the $J$ band, we also see a very faint galaxy 10″ to the south of the QSO. Thus, if there are companions, they are faint in the NIR. Table 4 gives our photometry of the objects.

The QSO does show a faint straight “jet” or tail in both $J$ and $H$, extending 3:5 to the north (see Fig. 3). The feature is almost parallel to the diffraction spikes seen in the guide star, but is at 11° to it and emerges off-center from the QSO. We thus consider it real, although it is difficult to measure accurately because of its faintness, the varying sky near the guide star, and the presence of diffraction spikes. Measures were made after surface fitting and subtraction of the sky, and also after rotation and subtraction, both in full resolution and $4 \times 4$ block-averaged images.

The jet is relatively featureless but appears to have a small opening angle. It suggests, once again, that even in this apparently empty field there has been a recent tidal event. Deep optical images may show if any companions with younger stellar populations are present. The color of the jet is comparable to that of the whole QSO, but its value is poorly determined.

Aside from the jet, the QSO image is not detectably extended and has the same profile as the stars. However, the

TABLE 4
PHOTOMETRY IN THE 0804 + 499 FIELD

| Object       | $J$   | $H$   | $J-H$ | $M_H$ |
|--------------|-------|-------|-------|-------|
| QSO .......... | 16.9  | 15.9  | 1.0   | -27.0 |
| QSO jet...... | 22.5  | 21.9  | 0.6   | -21.4 |
| Star .......... | 17.1  | 16.6  | 0.5   | ...   |
| 1 ............ | 19.2  | 18.7  | 0.5   | -24.7 |

Fig. 3.—$J$-band image of 0804 + 499 ($z = 1.43$) with full resolution and with $4 \times 4$ pixel binning to enhance visibility of faint jet. The images are 8″ × 11″.
This QSO is another one that appears to be in a group of galaxies and in interaction with one of its close neighbors. The blue color of the close companions suggests that they are both dominated by active star formation, presumably as result of the tidal events with the QSO or its nuclear radiation. The companions are projected at 10 and 20 kpc from the QSO nucleus.

| TABLE 5 |
| --- |
| PHOTOMETRY IN THE 1337–013 FIELD |
| --- |
| Object | $H$ | $J$ | $J - H$ | $M_J$ |
| QSO | 17.3 | 18.1 | 0.8 | -26.2 |
| Nearby knot | 22.3 | 22.3 | 0.0 | -21.9 |
| 1 | 22.5 | 22.4 | -0.1 | -22.0 |
| 2 | 20.4 | 21.2 | 0.8 | -23.1 |
| 3 | ... | 22.7 | ... | ... |
| 4 | ... | 22.8 | ... | ... |

This QSO is another one that appears to be in a group of galaxies and in interaction with one of its close neighbors. The blue color of the close companions suggests that they are both dominated by active star formation, presumably as result of the tidal events with the QSO or its nuclear radiation. The companions are projected at 10 and 20 kpc from the QSO nucleus.

| TABLE 6 |
| --- |
| PHOTOMETRY IN THE 1540+180 FIELD |
| --- |
| Object | $K$ | $H$ | $J$ | $J - H$ | $H - K$ | $M_J$ |
| QSO | 17.6 | 18.3 | 19.0 | 0.7 | 0.7 | -25.4 |
| QSO host | 19.2 | ... | ... | ... | ... | ... |
| 1 | 18.7 | 19.6 | 20.3 | 0.7 | 0.9 | -24.1 |
| 2 | 19.7 | 20.7 | 21.6 | 0.9 | 1.0 | -22.8 |
| 3 | 19.4 | 20.6 | 21.7 | 1.2 | 1.2 | -22.9 |
| 4 | 20.5 | 21.4 | 22.0 | 0.6 | 0.9 | -22.6 |
| 5 | 18.5 | 19.0 | 20.0 | 1.0 | 0.5 | ... |
produced by the guide star, and there are several of these in a characteristic pattern. The K-band image shows a clear northeast extension to the QSO and possible faint luminosity farther to the north. The H-band image does not show the bright arm to the northeast. However, there is a curved region of extended luminosity extending about 4'' to the north and ending in a brighter region. In the J-band image, this long curved region is only marginally detected, but the bright region at the end is present. This luminosity is in the general direction of the nearest galaxy but, to the limit of our detection, does not connect with it. We see no luminosity to the south of the QSO.

The radio structure to the north matches the NIR faint luminosity quite closely, but not exactly. The radio lobe to the north has the same length and lies mostly alongside, to the east of the NIR flux, and the edge-brightened lobe ends next to the brighter region of H and J emission. The radio structure suggests that the north lobe is the more active at the present time. The K-band extension of the QSO does not match the direction of the radio structure nearest the nucleus.

This is the only field for which we have three colors and are able to make a color-color plot to compare with stellar population models. Two-color photometry of the QSO and its companions is shown in Figure 6, compared with age tracks for stellar populations at different redshifts. Object 5 appears as a larger disk galaxy, corresponding in this plot to a slightly reddened galaxy of intermediate age at redshift ~0.3. The other nearby galaxies lie in positions on the plot that correspond to the QSO redshift. Another compact galaxy near the edge of the field is not seen in all colors because of pointing offsets, but may also be a companion. The QSO nucleus has the bluest color, but the colors of the companions indicate that they are all young, with a spread of age or dust content. The objects are compact, with diameters in our image from 2 to 5 kpc (at 5 kpc arcsec⁻¹, all are smaller than 1''). Thus, this appears to be a compact group of galaxies dominated by young stellar populations. A similar situation is seen around the $z = 2.2$ QSO 1345+580 (Hutchings 1998). The galaxies have a luminosity comparable to that of the QSO host, and they lie within a diameter of less than 100 kpc. This is therefore a very dense group that is likely to evolve by merging or breaking up over cosmic time.

The QSO has several lower redshift absorption-line systems around $z = 0.7$ and one at $z = 1.46$. The compan-
ion galaxy colors do not correspond to objects at \( z = 0.7 \), but we cannot exclude their lying at 1.46, which is close to the emission-line redshift of 1.66.

Crude PSF subtraction in the \( K \) band shows the northeast tail clearly, indicating a resolved flux comparable to the companion galaxies (see Fig. 7). The QSO is well resolved in this band, and the subtracted host galaxy flux is not significantly dependent on the PSF correction for distance from the guide star. In the \( H \) band, however, the resolution of the host galaxy is marginal and depends strongly on the PSF correction. In the \( K \)-band resolved flux, photometric \( K \)-corrections are likely to be no more than a few tenths (small
TABLE 7

PHOTOMETRY IN THE 0849 + 120 FIELD

| Object   | $H$  | $K$  | $H - K$ | $M_H$ | Comment     |
|----------|------|------|---------|-------|-------------|
| QSO      | 19.5 | 19.1 | 0.4     | -25.0 |             |
| 1        | 22.2 | 21.3 | 0.9     | -22.3 | Compact     |
| 2        | 18.8 | 18.5 | 0.3     |       | Large       |
| 3        | 22.2 | ...  | ...     |       | Large, faint|
| 4        | 22.1 | ...  | ...     | -22.4 | Compact     |
| 5        | 19.7 | 19.6 | 0.1     |       | Bright      |
| 6        | 17.5 | 17.3 | 0.3     |       | Star        |

if the populations are young), so the luminosities are typical of luminous galaxies.

The brightest companion (No. 1) has an exponential inner luminosity profile (≈1 kpc), but at larger radii the profile becomes peculiar. None of the companions has any structure at NIR wavelengths—they are smooth and sym-

TABLE 8

PHOTOMETRY IN THE 1236 — 003 FIELD

| Object          | $H$  | $K$  | $H - K$ | $M_H$ |
|-----------------|------|------|---------|-------|
| QSO             | 17.4 | 16.7 | 0.7     | -27.9 |
| 1               | 19.4 | 19.2 | 0.2     |       |
| 2               | 18.3 | 17.9 | 0.4     |       |
| 3               | 20.3 | 19.8 | 0.5     |       |
| 4               | 22.0 | 21.9 | 0.1     | -23.3 |
| QSO extension   | 21.0 | 20.0 | 1.0     | -22.3 |

metric and well-resolved, even though their colors suggest young stellar populations. They have bright, compact nuclei.

7. 0849 + 120

This QSO is faint at $m_e = 20.5$ and is radio-quiet. It lies in a field with several other objects with a wide range of

Fig. 8.—$H$- and $K$-band images of the field around QSO 0849 + 120, binned 4 × 4. In the $K$ band there is a luminous connection to the nearest companion to the northeast. The panels are 12” × 8”.

Fig. 9.—$H$-band (left) and $K$-band (right) images of QSO 1236 — 003, binned 4 × 4. There is a compact companion to the northwest (seen more clearly in $H$) and connected extended flux to the northeast (seen similarly in both $H$ and $K$). The panels are 11” × 11”.
Table 9
Photometry in the 0552 + 398 Field

| Object  | K  | M_H |
|---------|----|-----|
| QSO...... | 15.2 | -29.3 |
| 1......... | 19.1 | -25.4 |
| 2......... | 20.7 | -23.8 |
| 3......... | 20.9 | -23.6 |
| 4......... | 20.5 | -24.0 |
| 5......... | 19.3 | ...  |
| 9......... | 19.7 | -24.8 |
| 10........ | 19.7 | -24.8 |
| 13........ | 20.4 | -24.1 |
| 14........ | 20.7 | -23.8 |
| 17........ | 20.6 | -23.9 |
| 18........ | 20.4 | -24.1 |

brightness and size. Only two of these are likely to be associated with the QSO (see Fig. 8 and Table 7); the others are too bright and/or too large.

The closest companion (No. 1) lies about 5″ to the north and slightly east, and in the K-band image there may be a faint connecting luminous bridge between it and the QSO. However, this bridge is not seen in the H band, and there are comparable sky background fluctuations. The QSO itself is not measurably extended.

8. 1236 — 003

This QSO is at z = 2.18, is optically moderate at \( m_v = 19.1 \), and is radio-quiet. It has three companions, all at about 15″ separation and well separated in direction. Table 8 shows their magnitudes, which are too bright for it to be likely that they are associated galaxies. Their sizes and colors are also consistent with their being at considerably lower redshift—perhaps 0.2.

The closest companion to 1236 — 003 is seen most clearly in the H-band image, at some 4″ to the northwest. It is also (just) detected in the K-band image (see Fig. 9). There is no detectable flux connection to the QSO or tidal elongation. In both the H and K bands, the QSO images appear to have extended flux to the northeast, curving to the east. This is faint enough to be questionable, but it is suggestive that it appears identically in both H and K. While colors are subject to errors at these faint levels, the companion is blue and the extended flux is redder than the QSO, as shown in Table 8.

The structure and companion seen here are fainter than in the radio-loud objects, and the field is otherwise lacking in companions as bright as those seen in the radio-loud objects. However, the data are also suggestive of some tidal event in 1236 — 003.

9. 0552 + 398

This is a bright, radio-loud QSO at \( z = 2.36 \). It lies in a very crowded field, in which our K-band image clearly shows 20 objects besides the QSO. Of these, 10 are bright or large enough that they cannot be companions. Nine of the other 10 objects form a band some 5″ wide on either side of the QSO at least the length of the image (36″). These objects are compact and in the range of 4 to 6 mag fainter than the QSO. Table 9 shows their magnitudes and also the H-band absolute magnitudes, assuming they have standard colors \((H - K = 1)\) for a young population at this redshift. For brevity, we have omitted from the table those galaxies that are too bright to be companions. Figure 1 shows the positions of most of them—a few lie outside the boundary.
TABLE 10

| Object | $K$ |
|--------|-----|
| QSO    | 18.0|
| 1      | 21.8|
| 2      | 22.2|
| 3      | 20.6|
| 4      | 20.9|
| 5      | 21.4|
| 6      | 18.7|
| 7      | 21.7|
| 8      | 21.8|
| 9      | 20.9|

shown because of the dither. These galaxies appear more luminous than those in other fields—possibly because there are significant negative $K$-corrections at this higher redshift, as would be the case for young populations. As in all other cases, we have adopted no $K$-correction. Also, Hα is shifted into the $K$ band at this redshift, which might increase the flux if these galaxies have Balmer emission.

The nearest companion lies about 2′′ to the north, and there appears to be curved connecting luminosity to the QSO, suggesting tidal interaction (see Fig. 10). We thus have evidence that the QSO is a member of a dense group of compact galaxies of comparable luminosity to the host and each other. The FWHM of the companions is 0′′.35, and all are round with no structure and a bright nucleus.

The radio source is compact, luminous, variable, and gigahertz-peaked, and it has structure seen only with VLBI: a weak halo extended more east-west than north-south. This suggests that the source is young.

10. 1307 + 297

This is a radio-quiet QSO at redshift 3.09. Our exposures are shorter than for the other objects by a factor 3 to 4, so that our detection limits are significantly different. In addition, it has a very bright guide star that casts a high level of scattered light over much of the 36′′ field. Nevertheless, we can easily see one galaxy 11′ away in the $H$ band at $H = 20.3$ and can also detect it, but no other objects, at $K = 20.5$. The blue color and brightness indicate that it is likely to be a foreground object. The QSO is measured at $H = 19.1$ and $K = 18.1$, making its catalog value of $m_v = 18.6$ seem too bright. Or perhaps it is currently in a faint state.

Given the poorer detection threshold and the bright guide star, our observation of this radio-quiet object provides weak evidence that it is not in a dense galaxy environment. The QSO itself does not appear to be resolved in these exposures.

11. 0104 + 022

This QSO is radio-quiet, with redshift 4.16. Because of its high redshift we used a much longer exposure for this field, mainly in the $K$ band (rest-frame $U/B$). The field appears empty and has one other object of similar brightness to the QSO that is detected with limits similar to those in other fields. However, when we compare combined integrations of about 11,000 s each from two separate nights, some very faint objects and features are seen in both. Table 10 shows the measures of these objects and their positions are shown in Figure 1. Figure 11 shows the environment of the QSO.

The objects are fainter than any others measured, and some are very compact while others are larger and diffuse. The group made up of Nos. 3, 4, and 5 are all diffuse and have diameters of 2′ to our limit of detection. The compact objects are all 0′:4 to 0′:6 across. At the QSO redshift they

Fig. 11.—Deep $K$-band image around QSO 0104 + 022. The QSO is the bright object, which is extended almost east-west (the guide star lies to the south, and the lower left contains its diffraction spike). The QSO also appears to have a curved filament to the northeast. Faint objects that may be companions lie at about equal distances to the west and southwest. The image is 12′ × 11′.
have absolute $K$ magnitudes of about $-25$, without $K$-correction.

The QSO itself appears to be extended in a nearly east-west direction. This is almost perpendicular to the radius vector to the guide star and thus is not likely to be the result of PSF effects, which are radial. The extended light is stronger on the west side. In addition, there is a suggestion of a faint, smooth tail to the north and curving to the east, as seen in the figure. This is so faint that it may be an artifact, and it appears more clearly on one night's image than the other. Seeing and transparency were similar on the two nights. The shorter $H$-band exposure does not reveal any of these objects or features.

We will discuss the PSF removal of this (and other) objects more rigorously in a separate publication. Nevertheless, we have suggestive evidence from our $K$-band data that this high-redshift object has an asymmetric host galaxy, some nearby companions, and perhaps a tidal tail as well. The QSO magnitude is 18.3 in $H$ and 18.0 in $K$, giving it a very blue color.

12. DISCUSSION

At redshifts near 1, 1.6, and 2.2, our relatively small QSO sample is fairly well matched between radio-loud and radio-quiet. The small pixel size allowed long integration times, so that our images are limited by sky noise. The AO camera performance has produced images with FWHMs well under 0.2 in most bands and objects: we were careful to observe only those objects that have guide stars close and bright enough to yield optimal correction. We have only reported data obtained in good natural seeing and clear conditions. Thus, the data on all objects are very comparable.

The extended features seen in most objects are faint, so that we may be missing some fainter structure that is lost in the sky noise. This is increasingly true as we move through the $JHK$ range, so that, in all three cases in which we observed in $J$, the faintest structures are seen only in the $J$ band. It appears that there is no very small scale structure present in any of the objects, so we binned the data $4 \times 4$ (to effective pixels 0.14) to decrease sky noise and make some measurements easier.

It is notable that we find faint structures in all observed objects to redshift 2.4 and, probably, also in the $z = 4.1$ object. These structures are smooth in overall shape and brightness, which are characteristics of the tidal tails of stars from a galaxy, rather than blue and knotty, which is the characteristic structure of active star formation. However, our observations are at relatively long rest-frame wavelengths, so they are not very sensitive to star formation activity. It will be important to obtain high-resolution, shorter wavelength (i.e., $CCD$) data to check our conclusion that tidal activity is more important than star formation. In any event, the data suggest that tidal events are an even more marked cause (or effect) of QSO activity at higher redshifts than they are known to be from well-known observations of interactions at lower redshifts.

In our sample of date, there is also a notable difference in galaxy environment between radio-loud and radio-quiet QSOs, with the latter generally being located in poorer environments. The exceptions are the radio-loud, but apparently isolated, QSO 0804+499 and possibly the radio-quiet QSO 0104+022, although we detected the latter's companions only because of our much deeper exposure in this field. We caution against drawing a general conclusion on the basis of our small and incomplete sample, but we note that this environmental difference is an extension of what is seen at lower redshifts, although we are only able to detect the brightest of possible companion galaxies. We note also that Hutchings (1995), at visible wavelengths, finds excess galaxies around both radio-loud and radio-quiet QSOs. Thus, the difference may possibly be in the population age of companions. The space density of the NIR-observed companions of the radio-loud QSOs is very high—in average, the separation between galaxies in the four crowded fields observed is 35 kpc. This suggests that merging will be an important part of the activity in these groups with time. Until we can study the environments to greater depth, however, we cannot tell if these are simply small groups or may be the cores of what will evolve by accretion from the field into a major cluster at lower redshift. Here, too, deep CCD observations with high resolution are called for to take advantage of the lower sky brightness.

One possible related issue is the connection between objects in the field and foreground absorbers. The Hewitt & Burbidge (1993) catalog has references to absorbers in only one object: 1540+180. Thus, this is the only known case where we may have likely foreground confusion. (However, it may be that other QSOs have not been observed with sufficient resolution to detect foreground absorbers.) We have noted in § 6 on 1540+180 that we may be seeing absorbing objects from the $z = 1.46$ system, but not the others at $z \sim 0.7$. At this point, our main inferences about the QSO environments are not affected by known foreground absorbers.

Five of our sources are radio-loud. Two have no published radio maps (but are almost certainly compact), and two others are unresolved in the radio. The only source with comparably sized resolved radio structure is 1540+180, which has some (but not all) corresponding visible/NIR structure. In this connection, we also note that radio-loud QSO 1345+580 (Hutchings 1998) has Ly$\alpha$ emission at the places of bright radio knots in a very bent radio structure.

In the only field for which we have two colors and, hence, can estimate redshifts, we find that there are several companions that appear to lie at the QSO redshift. In other fields, we eliminate foreground objects on the basis of their large size and scale length and, in many cases, their brightness. The remaining possible companion galaxies are all much more compact—less than 1 (5 kpc) in diameter. They are mostly round and featureless except for unresolved nuclei in some. Those for which the signal-to-noise ratio is sufficient to measure luminosity profiles are neither pure disk nor power-law galaxies. The small size is consistent with reports for other high-redshift galaxies (e.g., Steidel et al. 1996). The smooth, round morphologies suggest that the older stellar populations that we are imaging have regular shapes, in contrast to the more irregular shapes seen in visible (rest UV) wavelengths, where we are seeing the clumpy nature of star-forming regions and possibly the results of dust obscuration. The small size and relatively high luminosity of these objects suggest that they represent a stage in the early formation of galaxies. The high space density in some fields also suggests that these galaxies may merge with time to form large galaxies like those we observe today. Röttgering (1998) has proposed a similar scenario for the dense environments around high-redshift radio galaxies.
REFERENCES

Aretxaga, I., Boyle, B. J., & Terlevich, R. J. 1995, MNRAS, 275, 27
Aretxaga, I., Le Mignant, D., Melnick, J., Terlevich, R. J., & Boyle, B. J. 1998, MNRAS, 298, L13
Bahcall, J. N., Kirhakos, S., Saxe, D. H., & Schneider, D. P. 1997, ApJ, 479, 642
Campos, A., Yahil, A., Windhorst, R. A., Richards, E. A., Pascarelle, S., Impey, C., & Petry, C. 1999, ApJ, 511, L1
Casali, M., & Hawarden, T. 1992, JCMT-UKIRT News., No. 4, 33
Heckman, T. M., Lehnert, M. D., van Breugel, W., & Miley, G. K. 1991, ApJ, 370, 78
Hewitt, A., & Burbidge, G. 1993, ApJS, 87, 451
Hutchings, J. B. 1995, AJ, 109, 928
———. 1998, AJ, 116, 20
Hutchings, J. B., Crampton, D., Morris, S. L., & Steinbring, E. 1998, PASP, 110, 374
Hutchings, J. B., Holtzman, J., Sparks, W. B., Morris, S. C., Hanisch, R. J., & Mo, J. 1994, ApJ, 429, L1
Hutchings, J. B., & Neff, S. G. 1992, AJ, 104, 1
———. 1997a, AJ, 113, 550
———. 1997b, AJ, 113, 1514
Lehnert, M. D., Heckman, T. M., Chambers, K. C., & Miley, G. K. 1992, ApJ, 393, 68
McLeod, K. K., & Rieke, G. H. 1995, ApJ, 454, L77
Pentericci, L., Röttgering, H. J. A., Miley, G. K., McCarthy, P., Spinrad, H., van Breugel, W. J. M., & Machetto, F. 1999, A&A, 341, 329
Rigaut, F., et al. 1998, PASP, 110, 152
Röttgering, H. 1998, in IAU Symp. 186, Galaxy Interactions at Low and High Redshift, ed. J. Barnes & D. Sanders (Dordrecht: Kluwer), 184
Steidel, C. C., Giavalisco, M., Pettini, M., Dickinson, M., & Adelberger, K. L. 1996, ApJ, 462, L17