INFRARED EMISSION-LINE GALAXIES ASSOCIATED WITH DAMPED \textbf{Ly}α AND STRONG METAL ABSORBER REDSHIFTS\textsuperscript{1}

\textbf{F. MANNUCCI,\textsuperscript{2} D. THOMPSON,\textsuperscript{3} S. V. W. BECKWITH,\textsuperscript{3} AND G. M. WILLIGER\textsuperscript{4}}

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\begin{abstract}
Eighteen candidates for emission-line galaxies were discovered in a narrowband infrared survey that targeted the redshifts of damped \textbf{Ly}α or metal lines in the spectra of quasars. The presence of emission lines is inferred from the photometric magnitudes in narrowband and broadband interference filters, corresponding to \textbf{H}α at redshifts of 0.89 (six objects) and 2.4 (10 objects) and to [\textbf{O} \textsc{ii}] λ3727 at a redshift of 2.3 (two objects). Most of the candidates are small, resolved objects that are compatible with galaxies at the redshifts of the damped \textbf{Ly}α absorbers. Because a similar survey, targeted at the redshifts of quasars themselves, uncovered only one emission-line galaxy in a larger volume, the results imply substantial clustering of young galaxies or a formation within filaments or sheets whose locations are indicated by the redshifts of strong \textbf{Ly}α line absorption along the lines of sight to more distant quasars.

\textit{Subject headings:} cosmology: observations — early universe — galaxies: formation — infrared: galaxies
\end{abstract}

1. INTRODUCTION

The exploration of the high-redshift universe and the discovery of the most distant objects are still in their infancy. Only recently have the tools been available to detect normal galaxies at redshifts larger than one, when the first galaxies were created (Pascarelle, Windhorst, \& Odewahn 1996; Hu \& McMahon 1996; Cowie \& Hu 1998; Steidel et al. 1996). It seems likely that young galaxies will have a variety of different signatures, so that it will be necessary to use several diverse techniques to uncover all of them: searches at optical, infrared, X-ray, and radio wavelengths, for example. In particular, basing the statistical studies of the high-redshift galaxies only on objects detected in the rest-frame UV could miss many young galaxies (Franceschini et al. 1998; Guiderdoni et al. 1997), and the sampling of longer wavelength ranges is necessary.

We carried out a survey for infrared emission-line galaxies by imaging through narrowband (\( \Delta \lambda/\lambda \sim 0.01 \)) and broadband filters between 1 and 2.5 \( \mu \)m, identifying objects that appeared brighter in the narrow filters (Thompson, Mannucci, \& Beckwith 1996, hereafter TMB96). Our first survey was designed to uncover emission lines at the redshifts of quasars within each survey field, in case there is substantial clustering marked by quasars. In an area of 276 arcmin\(^2\), only one emission-line galaxy was discovered (Beckwith et al. 1998). The surface density of such objects that is implied by these results is similar to that inferred from other surveys (Cowie et al. 1994; Graham \& Dey 1996; Malkan, Teplitz, \& McLean 1996; Bechtold et al. 1997) and suggests that the infrared emission-line galaxies constitute at most a modest population of young galaxies at high redshift.

Using the same instruments, we undertook a second infrared survey for emission-line galaxies targeted at the redshifts of damped \textbf{Ly}α or metal absorption lines in the spectra of quasars. Damped \textbf{Ly}α absorbers are thought to contain as much baryonic matter as seen in all spiral galaxies today (Wolfe et al. 1986) and may therefore mark sites of ongoing star formation. Several other groups (Lowenthal et al. 1991; Macchetto et al. 1993; Wolfe et al. 1992; Möllner \& Warren 1993; Djorgovski et al. 1996; Francis, Woodgate, \& Danks 1997) carried out similar surveys at optical wavelengths, looking for \textbf{Ly}α emission-line galaxies in these regions. They discovered only a few such emission-line (non–active galactic nucleus) galaxies, but Wolfe (1993) showed that the implied volume density was significantly higher than in the general field. Metal absorption systems also indicate that star formation has taken place, and these systems are identifiable from the ground at lower redshifts than \textbf{Ly}α alone.

We selected damped \textbf{Ly}α systems or metal absorbers whose redshifts put the main optical lines \textbf{H}α, \textbf{H}β, [\textbf{O} \textsc{ii}], and [\textbf{O} \textsc{ii}] into standard narrowband filters in the \( J, H, \) and \( K \) bands. The resulting redshift ranges are \( 0.5 < z < 1.9, \) \( 2.1 < z < 2.5, \) and \( 3.1 < z < 3.8 \). Special emphasis was given to the \textbf{H}α line, which is expected to be the brightest in young star systems and the least affected by dust. This Letter describes the results of the new survey.

2. OBSERVATIONS

As described in TMB96, pairs of narrowband (NB) and broadband (BB) images were taken at the selected fields. Most of the data, 163 arcmin\(^2\) in 13 fields, were obtained at the Calar Alto 3.5 m telescope, using the NICMOS3 256\(^2\) MAGIC cameras (Herbst et al. 1993) with a scale of 0′′81 pixel\(^{-1}\). One field, 38.6 arcmin\(^2\), was observed at the same telescope with the Omega Prime camera using a 1024\(^2\), HgCdTe Hawaii array with 0′′40 pixel\(^{-1}\). Five more fields, for a total of 26.2 arcmin\(^2\), were observed with the IRAC2b camera at the 2.2 m ESO/MPI telescope at La Silla. The area-weighted average limiting flux is \( 2.4 \times 10^{-16} \) ergs \( \text{cm}^{-2} \text{ s}^{-1} \), or \( 1.6 \times 10^{-16} \) ergs \( \text{cm}^{-2} \text{ s}^{-1} \), if only the Calar Alto data are considered. The comoving volume sampled by this survey at the redshift of the absorbers is about 20,600 Mpc\(^3\), assuming that only the target line at the appropriate redshift could be detected. Considering all four principal optical lines \([\textbf{O} \textsc{ii}], \textbf{H}β, [\textbf{O} \textsc{ii}] \) and \textbf{H}α, the total sampled volume is 90,000 Mpc\(^3\) (\( H_0 = 50, q_0 = 0.5 \), assumed throughout this Letter). For comparison, the total sampled vol-
Figure 1.—Color-magnitude diagram for the Q0100+130 (PHL 957) field. The solid lines indicate the 3σ uncertainties; the dashed line shows the position of objects with an emission line with EW = 50 Å. The two candidate emission-line galaxies are marked as A and B.

The distance between objects is only 4 arcseconds. Neither A nor B is seen in the Lowenthal et al. (1991) image, while our candidate A is barely visible on the Bunker et al. (1995) narrow band image, implying faint Hα emission. Both A and B are visible in their broadband K image as well, thus supporting the reality of the detections in our survey.

From the color-magnitude diagrams of five of the 19 fields in this survey, we discovered 18 candidates for emission-line galaxies. The emission lines, if spectroscopically confirmed, would correspond to Hα at redshifts of 0.89 (six objects) and 2.4 (10 objects), or [O II] λ3727 at a redshift of 2.3 (two objects). Most of the objects are a few seconds of arc in extent, suggesting that they are galaxies at redshifts greater than a few tenths.

Table 1 lists the coordinates of the candidates, their offsets from the quasar, and their morphology as deduced from our images. The angular distances from the quasars are between 9′ and 120′, corresponding to projected distances between 70 Mpc.

### Table 1

| Object       | R.A. (2000) | Decl. (2000) | Δα (arcsec) | Δδ (arcsec) | P.A. (deg) | Size (arcsec) | Shape               |
|--------------|-------------|--------------|-------------|-------------|------------|---------------|---------------------|
| Q0100+130A   | 01 03 10.39 | 13 17 03.7   | 1.1         | 48          | 344.3      | 5.4 × 1.5     | Possibly double     |
| Q0100+130B   | 01 03 13.30 | 13 16 58.7   | 0.5         | 51          | 35.3       | 1.9 × 1.2     | Unresolved          |
| Q0201+365A   | 02 04 56.28 | 36 49 14.9   | 0.5         | 9           | 112.6      | ... (a)       | Unresolved          |
| Q0201+365B   | 02 04 56.86 | 36 50 02.2   | 0.5         | 46          | 18.9       | 1.8 × 1.8     | Resolved            |
| Q0201+365C   | 02 04 50.20 | 36 47 47.4   | 0.5         | 112         | 215.6      | 2.4 × 1.4     | Resolved            |
| Q0201+365D   | 02 05 01.75 | 36 47 47.0   | 0.5         | 117         | 141.0      | 1.4 × 1.2     | Core/asymmetric halo|
| Q1623+268A   | 16 25 48.56 | 26 47 07.9   | 0.5         | 9           | 340.9      | 1.6 × 1.0     | Resolved            |
| Q1623+268B   | 16 25 51.30 | 26 47 21.1   | 0.5         | 40          | 56.7       | 3.8 × 2.2     | Irregular, diffuse  |
| Q1623+268C   | 16 25 51.62 | 26 48 17.2   | 0.5         | 87          | 25.9       | 2.5 × 2.5     | Irregular           |
| Q1623+268D   | 16 25 43.39 | 26 45 40.9   | 0.5         | 106         | 222.8      | 2.9 × 1.8     | Faint, elongated    |
| Q1623+268E   | 16 25 56.69 | 26 46 08.1   | 0.5         | 117         | 115.6      | 1.1 × 1.1     | Faint, unresolved   |
| Q1623+268F   | 16 25 56.42 | 26 46 06.1   | 0.5         | 152         | 117.3      | 1.8 × 1.0     | Core/asymmetric halo|
| Q2038–012A   | 20 40 52.99 | −01 05 29.2  | 0.7         | 25          | 69.6       | 2.5 × 1.5     | Elongated           |
| Q2038–012B   | 20 40 47.62 | −01 07 15.8  | 0.7         | 113         | 210.0      | 1.5 × 1.5     | Diffuse             |
| Q2038–012C   | 20 40 53.61 | −01 07 32.6  | 0.7         | 119         | 163.7      | 2.2 × 1.2     | Irregular           |
| Q2038–012D   | 20 40 57.93 | −01 06 50.8  | 0.7         | 122         | 126.5      | 1.3 × 1.2     | Unresolved          |
| Q2348–011A   | 23 50 57.29 | −00 52 02.5  | 0.7         | 11          | 225.6      | ... (a)       | Unresolved          |
| Q2348–011B   | 23 50 54.64 | −00 52 58.4  | 0.7         | 68          | 315.6      | 1.6 × 1.2     | Faint, elongated    |

Note:—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

(a) Radial uncertainty in the position.

(b) Projected distance and position angle (north to east) from the QSO.

(c) Object sizes measured by the FWHM along, respectively, the major and minor axis of elliptical Gaussians fitted to the objects.

(d) Not fitted because of the presence of a nearby object.

(e) The distance between objects is only 4′ (33 kpc); they could be one galaxy.
TABLE 2

| Object              | λ(NB) (µm) | NB (mag) | BB (mag) | Rank* | S/N | Line Flux (10^-16 cgs) | Line | EW (Å) | SFR (M_☉ yr^-1) |
|---------------------|-----------|---------|----------|-------|-----|---------------------|------|--------|----------------|
| Q0100+130A ....... | 1.237     | 20.33   | 21.44    | 2     | 3.8 | 1.9 ± 0.5           | [O ii] | 2.31   | 75 ± 26       | 198 ± 50     |
| Q0100+130B ....... | 1.237     | 19.88   | 20.88    | 2     | 5.6 | 2.7 ± 0.5           | [O ii] | 2.31   | 63 ± 14       | 283 ± 50     |
| Q0201+365A* .......| 2.248     | 18.45   | 19.37    | 2     | 4.2 | 1.8 ± 0.4           | Hα   | 2.42   | 65 ± 20       | 68 ± 16      |
| Q0201+365B ....... | 2.248     | 18.55   | 19.62    | 2     | 4.3 | 1.8 ± 0.4           | Hα   | 2.42   | 88 ± 27       | 71 ± 16      |
| Q0201+365C ....... | 2.248     | 18.92   | >20.78   | 2     | 4.2 | 1.9 ± 0.4           | Hα   | 2.42   | >182          | 58—92        |
| Q0201+365D ....... | 2.248     | 18.71   | 20.12    | 1     | 4.5 | 2.0 ± 0.4           | Hα   | 2.42   | 158 ± 62      | 76 ± 16      |
| Q1623+268A ....... | 1.237     | 20.47   | 21.35    | 1     | 2.6 | 1.4 ± 0.6           | Hα   | 0.89   | 91 ± 49       | 6 ± 3        |
| Q1623+268B ....... | 1.237     | 19.96   | 20.98    | 2     | 4.5 | 2.5 ± 0.6           | Hα   | 0.89   | 115 ± 37      | 10 ± 3       |
| Q1623+268C ....... | 1.237     | 20.24   | >22.18   | 2     | 4.6 | 2.7 ± 0.3           | Hα   | 0.89   | >248          | 8—14         |
| Q1623+268D ....... | 1.237     | 20.40   | 21.29    | 3     | 2.8 | 1.5 ± 0.6           | Hα   | 0.89   | 92 ± 47       | 6 ± 3        |
| Q1623+268E ....... | 1.237     | 20.42   | >22.18   | 3     | 3.7 | 2.1 ± 0.6           | Hα   | 0.89   | >180          | 6—12         |
| Q1623+268F ....... | 1.237     | 20.50   | 21.40    | 3     | 2.6 | 1.4 ± 0.6           | Hα   | 0.89   | 94 ± 51       | 6 ± 3        |
| Q2038−012A ....... | 2.248     | 18.09   | 18.77    | 2     | 3.5 | 1.7 ± 0.4           | Hα   | 2.42   | 37 ± 10       | 68 ± 16      |
| Q2038−012B ....... | 2.248     | 19.01   | 20.73    | 2     | 3.3 | 1.7 ± 0.4           | Hα   | 2.42   | 256 ± 170     | 65 ± 16      |
| Q2038−012C ....... | 2.248     | 18.44   | 19.66    | 1     | 4.5 | 2.3 ± 0.4           | Hα   | 2.42   | 115 ± 32      | 88 ± 16      |
| Q2038−012D ....... | 2.248     | 18.90   | >20.84   | 1     | 3.9 | 2.0 ± 0.4           | Hα   | 2.42   | >194          | 60—94        |
| Q2348−011A* .......| 2.248     | 18.74   | 20.27    | 2     | 3.0 | 2.0 ± 0.6           | Hα   | 2.43   | 191 ± 95      | 78 ± 21      |
| Q2348−011B ....... | 2.248     | 18.81   | >20.79   | 3     | 3.2 | 2.2 ± 0.6           | Hα   | 2.43   | >199          | 63—107       |

* The rank degree of significance (1 is highest, 3 is lowest) was estimated by inspection to take into account systematic uncertainties, such as a very bright continuum, the proximity to the edge of the field, and the proximity of nearby objects, making accurate magnitudes difficult to derive.

* Magnitudes may be affected by nearby objects.

kpc and 1 Mpc at the distances to the absorption-line systems. Very few, if any, of these objects could therefore be identified with the absorption-line objects, whose typical extents are probably those of galaxies or protogalactic clumps, ~5—60 kpc across (Fukugita, Hogan, & Peebles 1996; Haehnelt, Steinmetz, & Rauch 1996). However, due to the coarse sampling in our images, no attempt was made yet to subtract a point-spread function from the QSO image, so objects within a few arcseconds from the QSO would not have been easily seen.

Table 2 gives the magnitude, a rank of the significance of the detection, the statistical signal-to-noise ratio (S/N) of the emission line, and the line flux for each candidate. The final four columns give the line identification, redshift, rest equivalent width, and derived star formation rate (SFR) (Mannucci & Beckwith 1995; TMB96), assuming the line is at the redshift of the absorption line. The derived SFRs attribute all of the line emission to H II regions, ignoring any contribution from an active galactic nucleus (AGN), an assumption that may be incorrect in at least some cases (Beckwith et al. 1998).

Figure 2 shows images of each candidate in the narrow and broad filters. The typical angular resolution is about 1.2”, corresponding to about ~10 kpc for redshifts between 1 and 3. Most of the objects appear resolved, even at this resolution. The field around Q1623+268 was observed by C. C. Steidel in 1996 May with the Hubble Space Telescope (HST) using the Wide Field Planetary Camera 2 (WFPC2) with the F702W filter and total integration time of 87 minutes. Two of our emission-line candidates, Q1623+268A and Q1623+268D, appear in these images, parts of which are shown in Figure 3. Both objects appear to be late-type spiral or irregular galaxies. The object sizes are 2.4” (Q1623+268A) and 3.6” (Q1623+268D), corresponding to 20 and 30 kpc for z = 0.9. If these objects are at the assumed redshifts, they are large, well-formed galaxies. The detected star formation activity with SFRs between 5 and 10 M_☉ yr^-1 would be the normal activity of late-type spiral or irregular galaxies.

4. DISCUSSION

The most striking result of this survey is the large number of candidates discovered in a small area, implying that by choosing the right redshift intervals, it is possible to detect emission-line objects rather easily. The total sky coverage in this survey was 228 arcmin^2 compared with 276 arcmin^2 in TMB96, yet 18 candidates were discovered in the second survey compared with a single emission-line galaxy in the first. Taken at face value, the new results suggest that damp Lyα and metal absorbers pinpoint the regions where galaxy formation is taking place.

Confirmation of the exact nature of these objects will require spectroscopic follow-up and perhaps additional imaging with the HST. Since not all the objects are resolved at the coarse pixel scale used, some could be stars or other nearby objects. A few objects are near the 3σ detection limit. Statistical comparison must therefore be regarded with some caution until further data are available.

Nevertheless, we believe that the main result of this survey is robust: there are more emission-line galaxies associated with damp Lyα and metal absorber redshifts than with the redshifts of quasars or at arbitrary redshifts. First, the observational method employed was identical to that of TMB96, but the resulting number of candidates is almost 20 times larger. Second, the one candidate, eK39, discovered in the first survey by TMB96 was also coarsely sampled, but it is indeed an emission-line galaxy (Beckwith et al. 1998) that is spectroscopically confirmed and easily resolved with the Keck telescope. Third, the HST images of two of our least statistically significant candidates show them to be galaxies of exactly the size expected for objects at redshifts greater than a few tenths and with the kind of morphology expected of objects in late stages of assembly.

These results may be compared with similar studies of Lyα-emitting galaxies in the neighborhood of damped Lyα.
Fig. 2.— Images of the candidates. In each panel, the BB image is on the left and the corresponding NB image on the right, with the candidate at the center. A white cross marks the QSO when present in the field. The images have been convolved with a Gaussian with an FWHM about equal to the seeing in order to make the faint objects more visible. The dimensions of each subimage are 40″. North is up, and east is left.

Fig. 3.— HST WFPC2 images of two of the candidates in the Q1623+268 field: A (left) and D (right). The dimensions of each image are 72 pixels or 72″ on each side. The images have been rotated from the original WFPC2 orientation so that north is up and east is to the left.

absorption-line systems. By the number of detected objects (Lowenthal et al. 1991; Wolfe et al. 1992; Macchetto et al. 1993; Möller & Warren 1993; Djorgovski et al. 1996) and observed fields (Smith et al. 1989; Deharveng, Bowyer, & Buat 1990; Lowenthal et al. 1995), an average comoving density of these systems of about $7 \times 10^{-4}$ Mpc$^{-3}$ is derived down to a limiting SFR of about $5 \ M_{\odot}$ yr$^{-1}$, assuming case B recombination and no dust. The infrared technique gives similar results, i.e., detections in about 1/3 of the fields and a density of $9 \times 10^{-4}$ Mpc$^{-3}$. The range of SFR implied by our observations, 6–200 $M_{\odot}$ yr$^{-1}$, is somewhat higher than that usually obtained by the optical searches, 5–20 $M_{\odot}$ yr$^{-1}$, but not dramatically so. If there is modest local extinction to the star formation regions in high-redshift galaxies, optical derived SFRs must be increased by a factor of about 3 to get the true SFR (Pettini et al. 1998), making their range almost coincident with ours.
Our results are perhaps more consistent with the limiting SFR of 30–80 $M_\odot$ yr$^{-1}$ along sight lines toward eight $z > 2$ damped Ly$\alpha$ absorbers as derived from redshifted H$\alpha$ (Bunker et al. 1998).

On the other hand, the lines could be produced by active galactic nuclei. There are several good reasons to believe that this could be the case for the one emission-line object discovered in the survey of TMB96 (Beckwith et al. 1998) and that it could be a widespread phenomenon (Francis et al. 1997). If so, the density of such objects in these regions is considerably higher than the cosmic average. The density of known quasars at these redshifts (e.g., Andreani & Cristiani 1992) implies about $(4–8) \times 10^{-7}$ quasars per field, meaning that we might be seeing far more AGNs than expected. Although the damped Ly$\alpha$ redshifts mark regions with many galaxies, the nature of each single galaxy will remain a mystery until proper follow-up observations will be able to distinguish between emission due to star formation and AGNs.

Cold dark matter (CDM) simulations of early galaxy formation produce filaments of galaxies (White 1994) with groups of high-redshift metal and damped Ly$\alpha$ absorbers spanning up to several hundred kiloparsecs (Rauch, Haehnelt, & Steinmetz 1997). If the damped Ly$\alpha$ absorbers actually trace the positions of these filaments, then the high detection rate of emission-line galaxies in this survey may support the overall structure predicted by CDM. This conclusion can be made quantitative by measuring the average overdensity of objects near damped Ly$\alpha$ and metal systems with respect to TMB96.

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