

CLUSTERING AROUND THE RADIO GALAXY MRC 0316–257 AT $z = 3.14$

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ABSTRACT

We report the spectroscopic identification of galaxies in the neighborhood of the radio galaxy MRC 0316–257, at a redshift $z \sim 3.14$. Candidate cluster galaxies were selected from deep V and I images combined with narrowband imaging at the wavelength of redshifted Ly α . Follow-up multislit spectroscopy has allowed confirmation of the redshift of the radio galaxy, $z = 3.1420 \pm 0.0020$, and identification of two associated galaxies at redshifts $z = 3.1378 \pm 0.0028$ and $z = 3.1351 \pm 0.0028$. The first is $0.3 h_{50}^{-1}$ Mpc from the radio galaxy, is resolved with an intrinsic size of $11.6 \pm 1.1 h_{50}^{-1}$ kpc, and shows Ly α in emission with rest $W_{\text{Ly}\alpha} = 55 \pm 14$ Å. In addition, its extremely blue $V - I$ color might indicate a protogalaxy forming a first generation of stars in a low-dust medium. The second galaxy is $1.3 h_{50}^{-1}$ Mpc from the radio galaxy, is marginally resolved, and, in addition to Ly α in emission, shows C IV in emission with a broad component that indicates the contribution from an active galactic nucleus. The comoving density of galaxies with $V < 23.8$ and Ly α flux greater than 10^{-16} ergs cm^{-2} s^{-1} in the vicinity of MRC 0316–257 is $\sim 2.5 \times 10^{-3} h_{50}^3 \text{ Mpc}^{-3}$, significantly higher than the expected background density of field galaxies with similar properties, and may indicate a rich cluster or protocluster environment. These observations indicate that the environment of high-redshift radio galaxies may provide significant numbers of galaxies with which to study the early stages of cluster formation and galaxy evolution.

Subject headings: cosmology: observations — galaxies: clusters: general — galaxies: evolution — galaxies: formation — large-scale structure of universe

1. INTRODUCTION

The evolution of clusters of galaxies has important implications for our knowledge of the fundamental cosmological parameters. As they are the most massive gravitationally bound systems in the universe, the evolution of clusters is highly sensitive to the physics of cosmic structure formation and the values of the fundamental cosmological parameters. Moreover, clusters are valuable laboratories for study of the evolution of many galaxies at a common redshift.

Although a number of galaxies with luminosities $\sim L^*$ are now observed out to redshifts ~ 3 – 4 (Steidel et al. 1996; Fontana et al. 1996), very few candidate clusters of galaxies have been spectroscopically confirmed at redshifts near or above unity (Giavalisco, Steidel, & Szalay 1994; Le Fèvre et al. 1994b; Dickinson 1995; Pascarelle et al. 1996; Francis et al. 1996). At these very high redshifts, the prevalence of clusters, protoclusters, or other large-scale structures in the galaxy distribution is as yet unknown, and the evolution of large-scale structures may well be at a critical stage (Peebles, Daly, & Juszkwicz 1989; Evrard & Charlot 1994; Frenk et al. 1996) at which observations can directly constrain cosmological models.

At intermediate redshifts, powerful radio galaxies are frequently located in rich clusters (Yee & Green 1984; Hill & Lilly 1991; Dickinson 1994); therefore, a possible search strategy is to look for clusters around known powerful radio

galaxies. As part of a program to identify clusters and study their properties at redshifts greater than $z \sim 0.8$, we report here the discovery of galaxies within $\sim 1 h_{50}^{-1}$ Mpc and 1000 km s^{-1} from the 1 Jy radio galaxy MRC 0316–257 (McCarthy et al. 1990), at $z = 3.14$.

$H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$ are used throughout this Letter.

2. OBSERVATIONS

We have observed a 9.2×8.5 field around MRC 0316–257 with the Multiobject Imaging Spectrograph at the Canada-France-Hawaii Telescope (Le Fèvre et al. 1994a). Deep broadband V and I images, as well as narrowband images in a filter with central wavelength 5007 Å and bandwidth 96 Å , containing the Ly α line redshifted to $z \sim 3.14$, were obtained the night of 1995 December 20. Several images were obtained for each filter, after small telescope offsets were performed, to improve the flat-fielding accuracy. Total integration times were 2700, 1200, and 5100 s in the V , I , and 5007 Å filters, respectively. Standard image processing was performed the next day, and the V and 5007 Å images were blinked visually to provide a list of cluster candidates for subsequent multislit spectroscopy during the nights 1995 December 21–24. The narrowband 5007 Å images can be expected to identify galaxies with Ly α in a redshift range $z = 3.081$ – 3.160 , foreground galaxies with [O II] $\lambda 3727$ in emission with $z = 0.330$ – 0.356 , or the rarer occurrence of galaxies with [O III] $\lambda 5007$ at $z \sim 0$.

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The narrowband image is compared to the V -band image of the MRC 0316–257 field in Figure 1 (Plate L1). Two galaxies exhibit strong excess emission in the narrowband filter and were subsequently observed spectroscopically, together with more marginal candidates. Multislit masks were prepared, with the highest priority given to the cluster candidates as defined above, and other slits were placed on galaxies brighter than $V \sim 23.8$ when no other candidate was available. The observations of ~ 30 galaxies per mask were performed with the O300 grism, with 300 lines mm^{-1} and peak transmission at $\sim 5900 \text{ \AA}$, and slits $1''.75$ wide, providing a spectral range of $4500\text{--}9000 \text{ \AA}$ and a resolution of 20 \AA . Three masks have received cumulative exposure times of 19,800, 8700, and 8700 s. Data reduction of the spectra in the first mask, obtained the night of 1995 December 21, was performed the following afternoon and confirmed that these candidate galaxies had emission lines at $\sim 5030 \text{ \AA}$. These galaxies were subsequently reobserved in the following multislit mask, for a total exposure time of 28,500 s.

Final data reduction was performed with the MULTIREDD package, implemented under IRAF, and redshifts were measured and assigned classes as described in Le Fèvre et al. (1995). The two galaxies common to two different masks were treated separately by averaging the flat-fielded and sky-corrected two-dimensional spectra obtained from each mask. The 3σ detection limit in the shortest integration spectra is $\sim 1.5 \times 10^{-18} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$ around 5000 \AA , and our spectra would have allowed us to identify any emission line with a flux greater than $3 \times 10^{-17} \text{ ergs cm}^{-2} \text{ s}^{-1}$. A total of 51 galaxies have secure redshift measurements in the range $0 \leq z \leq 1.3$; two stars were identified, and we failed to measure redshifts for 45 galaxies.

3. RESULTS

McCarthy et al. (1990) noted that $\text{Ly}\alpha$ was the only feature in support of their redshift for MRC 0316–257, while Eales & Rawlings (1993) identified $[\text{O III}] \lambda 5007$ from IR spectroscopy. Our spectra confirm $\text{Ly}\alpha$ in emission, as well as $\text{C IV } \lambda 1549$, $\text{He II } \lambda 1640$, and $\text{C III] } \lambda 1909$ (Fig. 1). The redshift of the radio galaxy MRC 0316–257 is therefore $z = 3.1420 \pm 0.0020$. The V image shows another galaxy of roughly equal magnitude $2''.7$ away while, in the 5007 \AA image, the eastern galaxy disappears almost completely.

In addition to the radio galaxy, we have spectroscopically identified two galaxies with a redshift similar to the radio galaxy. The first, “galaxy A,” is $44''$ away from the radio galaxy. Its spectrum shows a strong line at 5030.3 \AA and faint features with marginal signal-to-noise ratio at the same redshift (Fig. 2). A cross-correlation of the spectrum of galaxy A, after subtraction of the 5030 \AA emission line, with a template spectrum with line widths taken from Yee et al. (1996), yields a marginal correlation at $z = 3.14$ with a correlation coefficient $R = 2.8$ (R as defined in Tonry & Davis 1979). The observed equivalent width of the emission line is $230 \pm 60 \text{ \AA}$, which, if it were $[\text{O II}] \lambda 3727$ at $z = 0.350$, would indicate a rest-frame $W_{\text{O II}} = 170 \pm 44 \text{ \AA}$, greater than any equivalent width for galaxies in the Canada-France Redshift Survey (CFRS), or 3 times greater than for any galaxy at $z \leq 0.4$ in CFRS (Hammer et al. 1996). Moreover, all galaxies in CFRS with rest $W_{\text{O II}} > 30 \text{ \AA}$ have rest $W_{\text{O III}} > 5 \text{ \AA}$ and $W_{\text{H}\alpha} > 40 \text{ \AA}$, which would have been easily identified in our spectra at

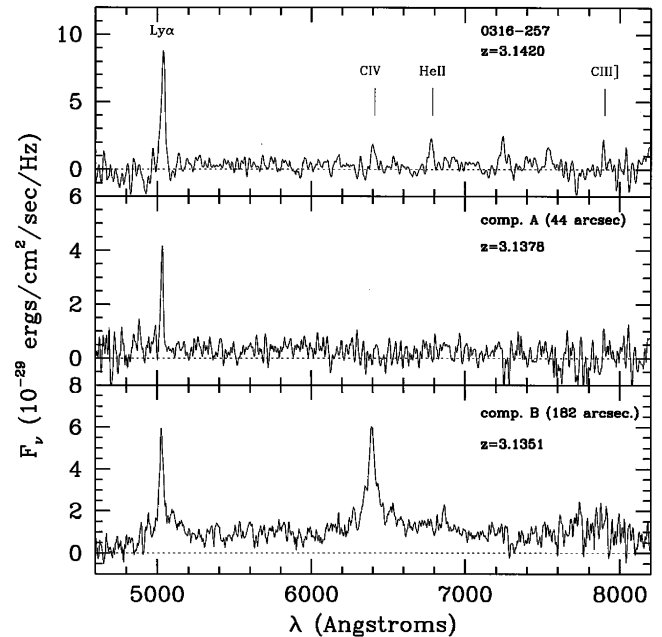


FIG. 2.—CFHT spectra: the radio galaxy MRC 0316–257 (top), galaxy A (middle), and galaxy B (bottom).

$z = 0.349$. The identification of the line at 5030 \AA with $\text{Ly}\alpha$ at $z = 3.1378 \pm 0.0028$ therefore seems secure.

The second galaxy, “galaxy B,” is located $182''$ from MRC 0316–257. Its spectrum shows $\text{Ly}\alpha$ and $\text{C IV } \lambda 1549$ and, therefore, yields a secure redshift $z = 3.1351 \pm 0.0028$. Both $\text{C IV } \lambda 1549$ and, to a lesser extent, $\text{Ly}\alpha$ exhibit a broad component, which indicates the presence of an active galactic nucleus (AGN).

Close examination of the images indicates that both MRC 0316–257 and galaxy A are resolved under $\text{FWHM} = 1''.5$ seeing while galaxy B is only marginally resolved. After deconvolution from the observed point-spread function, the half-light radii of MRC 0316–257 and galaxy A are 8.9 ± 2.0 and $11.6 \pm 1.1 h^{-1} \text{ kpc}$, respectively. The fact that galaxy B is quite compact supports the contribution of an AGN. The V , I , and $\text{Ly}\alpha$ images of galaxy A are strikingly different: the peaks of continuum V and line emission are offset by $0''.6$ with the peak of $\text{Ly}\alpha$ emission extending toward the southwest, where little or no continuum light is detected in the V and I bands, and little or no emission is observed in I at the peak of $\text{Ly}\alpha$ emission, while several blobs of emission appear $3''$ to the northwest in the I band.

4. DISCUSSION

In Figure 3, we plot the $V - I$ versus $V - 5007 \text{ \AA}$ color-color diagram. Besides MRC 0316–257 and the two associated galaxies identified in spectroscopy, two galaxies have significant excess emission in the 5007 \AA filter ($V - 5007 \text{ \AA} > -1.2$). One of these has a redshift $z = 0.335$, and the excess emission in the 5007 \AA filter comes from $[\text{O II}] \lambda 3727$. The other, “galaxy C,” has not been observed spectroscopically. Therefore, in our imaging field of view of 78.2 arcmin^2 , we have three confirmed galaxies at $z \sim 3.14$, above our detection thresholds of $W_{\text{Ly}\alpha} > 12 \text{ \AA}$ and $V < 23.8$, and a fourth galaxy, galaxy C, which remains a good but unconfirmed candidate galaxy at $z \sim 3.14$. Table 1 summarizes the properties of these objects.

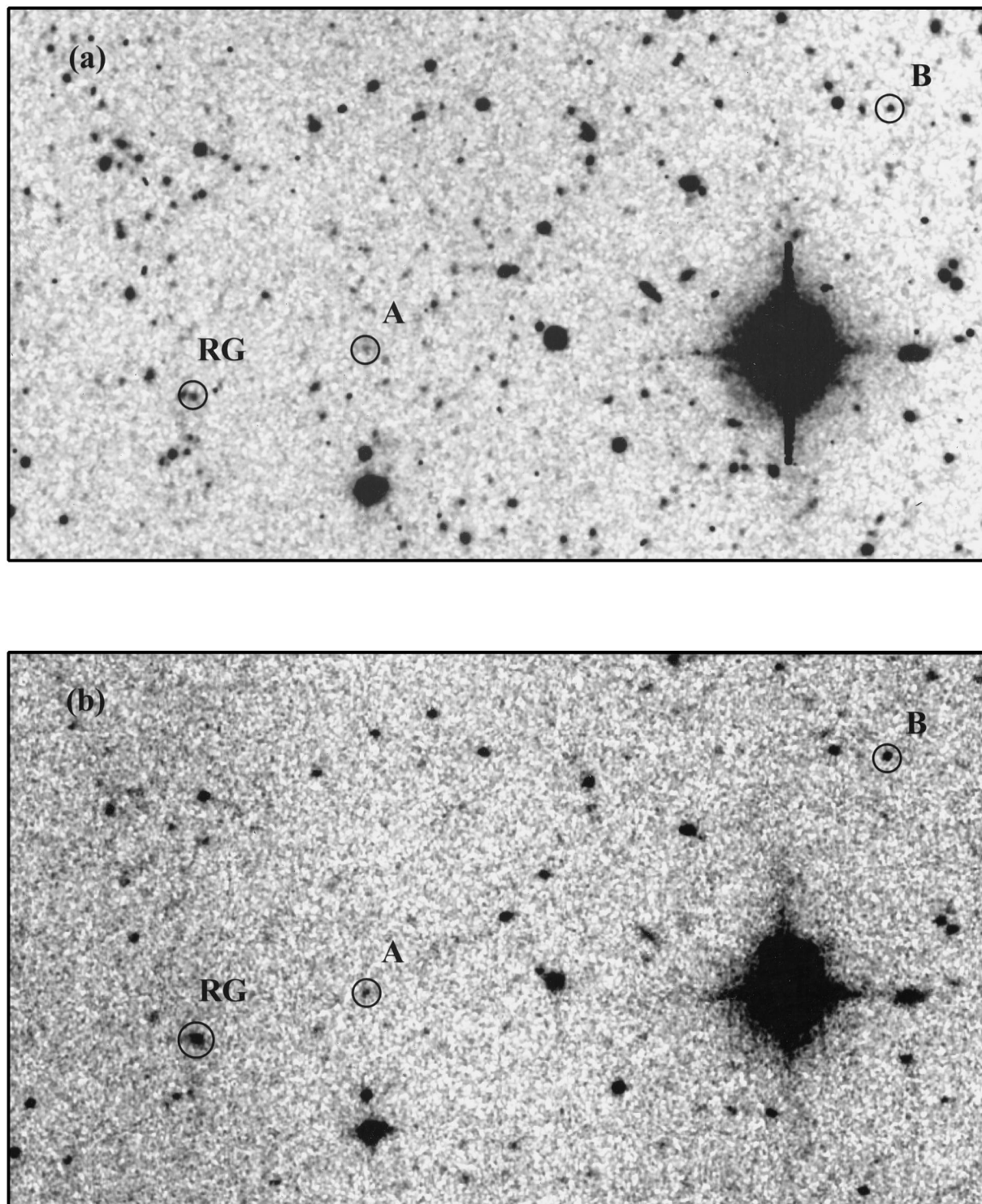


FIG. 1.—*V*-band (*top*) and 5007 Å (*bottom*) images of a $4' \times 2'.15$ field around the radio galaxy MRC 0316–257 (“RG”). North is at the top, East is to the left. Galaxies A and B clearly exhibit excess emission in the 5007 Å filter, which contains Ly α redshifted to $z \sim 3.14$.

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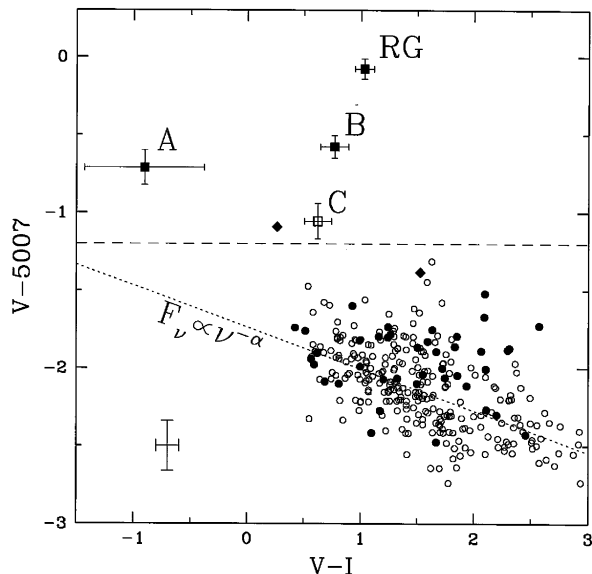


FIG. 3.— $V - I$ vs. $V - 5007 \text{ \AA}$ diagram. Filled symbols indicate spectroscopically observed galaxies: squares for $z \sim 3.14$ galaxies, diamonds for the galaxies with $z \sim 0.35$, and circles for other galaxies with measured redshifts. Open symbols indicate galaxies not observed spectroscopically: a square for a galaxy with $V - 5007 \text{ \AA} > -1.2$, a good candidate $z \sim 3.14$ galaxy, and circles for other galaxies. Note that $V - I$ for galaxy A is $V - I = -0.7$ after correction for the $\text{Ly}\alpha$ line contamination in the filter bandpass, still extremely blue.

Any estimate of the space density of $z \approx 3.14$ galaxies from our observations is necessarily quite uncertain because of the small number of objects that we detected. The maximum redshift probed is set by the range over which our narrowband filter would detect the $\text{Ly}\alpha$ emission line, i.e., $3.081 < z < 3.160$. Under this assumption, the resulting comoving cosmological volume surveyed is therefore $13,900 h_{50}^{-3} \text{ Mpc}^3$, assuming $q_0 = 0.5$ (for $q_0 = 0$, the effective volumes are 7.4 times larger, and the densities correspondingly smaller). However, the three galaxies that we have confirmed spectroscopically are confined to a much smaller redshift range, close to that of the radio galaxy: $3.1351 < z < 3.1420$. This corresponds to a rest-frame velocity difference $\Delta v = 500 \text{ km s}^{-1}$, quite in line with expectations for galaxy clusters, “walls” of large-scale structure, or both. It is therefore likely that the effective “cluster” volume is much smaller than the value given above. Assuming $\Delta z = 0.0069$, the corresponding comoving volume would then be $1210 h_{50}^{-3} \text{ Mpc}^3$. We therefore may

bracket the range of possible space densities by assuming $3/13,900 < n (\text{Mpc}^{-3}) < 4/1210$, or $2.2 \times 10^{-4} < n (h_{50}^3 \text{ Mpc}^{-3}) < 3.3 \times 10^{-3}$, with a “best guess” value of $3/1210 \approx 2.5 \times 10^{-3} h_{50}^3 \text{ Mpc}^{-3}$.

The population of $3.0 < z < 3.5$ field galaxies identified by Steidel et al. (1996) has a comoving space density of $3.6 \times 10^{-4} h_{50}^3 \text{ Mpc}^{-3}$ for $q_0 = 0.5$. At face value, this implies that our “best guess” space density represents an overdensity of ~ 7 times compared to the field population at similar redshift. However, it is difficult to make a direct comparison between our “cluster” space density and the “field” value, since our galaxies were selected on the basis of strong $\text{Ly}\alpha$ flux and have brighter continuum magnitudes ($V < 23.8$) than the Steidel et al. objects (which have $R < 25.5$). Therefore the estimate given above for the cluster overdensity is almost certainly a substantial underestimate. Even our derived lower limit of $n > 2.2 \times 10^{-4} h_{50}^3 \text{ Mpc}^{-3}$ for the field of 0316–257 is substantially higher than the corresponding space density of field galaxies that share the same continuum magnitudes and $\text{Ly}\alpha$ properties.

The rest-frame $\text{Ly}\alpha$ equivalent widths are 500 ± 150 , 55 ± 14 , and $110 \pm 18 \text{ \AA}$ for the radio galaxy and galaxies A and B, respectively. While the radio galaxy and galaxy B have resolved $\text{Ly}\alpha$, with $\text{FWHM} = 30 \pm 3$ and $22 \pm 4 \text{ \AA}$, respectively, and C IV is resolved for galaxy B, with $\text{FWHM}(\text{C IV}) = 38 \pm 8 \text{ \AA}$ after deconvolution by the instrumental response, $\text{Ly}\alpha$ is unresolved at our resolution for galaxy A. This may indicate that $\text{Ly}\alpha$ in galaxy A is produced mainly by stellar photoionization. Even after correcting for the contribution of the $\text{Ly}\alpha$ line to the V band, galaxy A is extremely blue, with $V - I < -0.5$. This is very unusual for faint galaxies, and indeed galaxy A is by far the bluest object in our field of view, as can be seen from Figure 3. Galaxy A is bluer than most or all of the $z \sim 3$ objects reported by Steidel et al. (1996). It is also interesting that its $\text{Ly}\alpha$ emission is significantly stronger than that in most of the Steidel et al. Lyman break galaxies. The blue color and strong $\text{Ly}\alpha$ emission may indicate an object dominated by OB stars in a strong starburst with very little dust. The complex morphology of galaxy A is quite different from the morphology of galaxies identified on the basis of the 912 \AA discontinuity (Steidel et al. 1996; Giavalisco, Steidel, & Macchetto 1996), with complex spatial distribution of continuum and line emission, as described in § 3. While the evidence for old stars will have to be searched for at a redder wavelength, this galaxy may well be forming its first stars and fit the definition of a protogalaxy.

TABLE 1
PROPERTIES OF THE GALAXIES AT $z \approx 3.14$

Object	α_{1950}	δ_{1950}	$f_{\text{Ly}\alpha}$ ($10^{-16} \text{ ergs}^{-1} \text{ cm}^{-2}$)	V (mag)	I (mag)	$M_B^{a,b}$ (mag)	FWHM^a (kpc)
0316–257	03 16 02.66 ^c	–25 46 03.70 ^c	3.3 ± 0.1	23.24 ± 0.04	22.53 ± 0.06	–23.27	8.9 ± 2.0
A	03 15 59.62	–25 45 52	1 ± 0.1	23.84 ± 0.04	24.97 ± 0.30	–22.67	11.6 ± 1.1
B	03 15 50.32	–25 44 53	2.3 ± 0.2	23.21 ± 0.03	22.67 ± 0.09	–23.30	2.3 ^d
C ^e	03 15 51.92	–25 42 38	0.5 ^f	23.87 ± 0.06	23.48 ± 0.10	–22.64	6.3 ± 0.9

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

^a Assuming $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$.

^b The K -correction has been estimated from Bruzual 1983.

^c From McCarthy et al. 1990.

^d Unresolved.

^e Candidate $z = 3.14$ galaxy on the basis of narrowband imaging only.

^f Estimated from narrowband imaging.

5. CONCLUSION

We have spectroscopically identified two galaxies at the same redshift as the radio galaxy MRC 0316–257, at $z \sim 3.14$. These galaxies exhibit Ly α in emission with $W(\text{Ly}\alpha) > 50 \text{ \AA}$. One galaxy is resolved, with size $11 h^{-1} \text{ Mpc}$, and has unresolved Ly α and extremely blue $V - I$ color, which might indicate that the main photoionizing process is coming from a first generation of young stars in a low-dust medium. The other is unresolved and has broad Ly α and C IV emission lines, indicating the presence of an AGN.

These observations of galaxies around MRC 0316–257 provide tentative evidence for a region of high galaxy density, possibly indicating clustering of galaxies at $z = 3.14$, and

indicate that the search for galaxies around very high redshift radio galaxies is indeed possible from Ly α imaging techniques. However, the total number of galaxies identified with an observed Ly α luminosity greater than $10^{-16} \text{ ergs cm}^{-2} \text{ s}^{-1}$ is small, indicating the limits of this technique, in agreement with previous searches. Lyman break techniques, as successfully applied by Steidel et al. (1996), will be required to identify additional galaxies at the same redshift and confirm the existence of a cluster or protocluster of galaxies.

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