Subaru/ MOIRCS Near-Infrared Imaging in the Proto-Cluster Region at z = 3.1

Yuka Katsuno UCHIMOTO,1,2,3 Ryuji SUZUKI,2,3 Chihiro TOKOKU,2,3 Takashi ICHIKAWA,3 Masahiro KONISHI,2,3 Tomohiro YOSHIKAWA,2,3 Koji OMATA,2 Tetsuo NISHIMURA,2 Toru YAMADA,2,3 Ichí TANAKA,2,3 Masaru KAJISAWA,4 Masayuki AKIYAMA,2,3 Yūichi MATSUDA,5 Ryosuke YAMAUCHI,6 and Tomoki HAYASHINO6

1Institute of Astronomy, The University of Tokyo, 2-21-1 Osawa, Mitaka, Tokyo 181-0015
uchimoto@ioa.s.u-tokyo.ac.jp
2Subaru Telescope, National Astronomical Observatory of Japan, 650 North A’ohoku Place, Hilo, HI 96720, USA
3Astronomical Institute, Tohoku University, Aramaki, Aoba, Sendai 980-8578
4National Astronomical Observatory, 2-21-1 Osawa, Mitaka, Tokyo 181-8588
5Department of Astronomy, Kyoto University, Kitashirakawa-Oiwake-cho, Sakyo-ku, Kyoto 606-8502
6Research Center for Neutrino Science, Graduate School of Science, Tohoku University, Aramaki, Aoba-ku, Sendai, Miyagi 980-8578

(Received 2007 December 7; accepted 2008 February 24)

Abstract

We present the results of deep near-infrared imaging observations of the z = 3.1 proto-cluster region in the SSA 22a field taken by MOIRCS mounted on the Subaru Telescope. We observed a 21.7 arcmin2 field to depths of J = 24.5, H = 24.3, and K = 23.9 (5σ). We examined the distribution of the K-selected galaxies at z ~ 3 by using a simple color cut for distant red galaxies (DRGs) as well as a photometric-redshift selection technique. The marginal density excess of DRGs and the photo-z selected objects were found around the two most luminous Lyα blobs (LABs). We investigated the correlation between the K-selected objects and the LABs, and found that several galaxies with stellar mass, \( M_\ast = 10^9 \text{–} 10^{11} M_\odot \), exist in the vicinity of LABs, especially around the two most luminous ones. We also found that 7 of the 8 LABs in the field have plausible K-band counterparts, and the sum of the stellar mass possibly associated with LABs correlates with their luminosity and surface brightness, which implies that the origin of Lyα emission may be closely correlated with their previous star-formation phenomena.

Key words: galaxies: clusters: general — galaxies: evolution — galaxies: formation — galaxies: high-redshift — infrared: galaxies

1. Introduction

The formation history of galaxies has been extensively studied in terms of the evolution of their stellar mass (Papovich et al. 2001; Kajisawa & Yamada 2006; Verma et al. 2007; Caputi et al. 2006; Fontana et al. 2006; Arnouts et al. 2007). However, it is still poorly constrained how galaxies developed their stellar systems in the early universe at z > 2. While the observed stellar-mass density of the galaxies shows significant and rapid growth along the time at z > 1, at least 10% of the present-day stellar mass is observed at z ~ 3 (Caputi et al. 2006; Fontana et al. 2006; Arnouts et al. 2007), which also seems to be true for massive galaxies with \( M_\ast > 10^{11} M_\odot \) (Caputi et al. 2006).

Where and how were they formed? The biased galaxy formation models in a universe dominated by cold dark matter suggest that galaxy formation preferentially occurs in regions with relatively high density at a larger scale (Kauffmann et al. 1999; Cen & Ostriker 2000; Benson et al. 2001; Bower et al. 2006). Recent results based on optical wide-field imaging reveal that high-redshift star-forming galaxies indeed show very strong clustering, largely biased to the expected underlying mass distribution (e.g., Steidel et al. 1998; Adelberger et al. 1998; Ouchi et al. 2001, 2005), which is also true for near-infrared (NIR)-selected massive galaxies (Daddi et al. 2003; Grazian et al. 2006; Quadri et al. 2007a; Foucaud et al. 2007; Ichikawa et al. 2007).

At z = 2–3, individual large-scale high-density regions of the galaxies have also been discovered (Steidel et al. 1998; Francis et al. 2001; Hayashino et al. 2004). Many of these fields are, however, identified as an excess in the number density of rest-frame UV bright galaxies, such as Lyα emitters (LAEs), Lyman Break Galaxies (LBGs), or their analogues. The question is how much of the stellar mass has already formed and assembled in such high-density region of star-forming galaxies at z ≥ 2. In other words, we would like to see whether the structure traced by the star-formation activity is correlated (or anti-correlated) with the structure traced by the stellar mass.

In this paper, we present the results of J-, H-, and Ks-band imaging of the z = 3.1 proto-cluster region in and around the SSA 22 field (Steidel et al. 1998, 2000; Hayashino et al. 2004) using the Multi-Object InfraRed Camera and Spectrograph (MOIRCS) (Ichikawa et al. 2006; Suzuki et al. 2007) equipped with the 8.2 m Subaru Telescope. The wide field of view of MOIRCS allowed us to observe such
proto-cluster regions efficiently.

The proto-cluster was first discovered by Steidel et al. (1998) as an excess of LBGs. Later, wider-field and deeper narrow-band observations revealed that the overdense region of LBGs is a part of a large-scale high-density structure of LAEs, which is extended over ~60 Mpc in a comoving scale (Hayashino et al. 2004; Matsuda et al. 2004). Matsuda et al. (2005) confirmed that the structure has a three-dimensional filamentary appearance. Matsuda et al. (2004) also identified 35 Lyman α Blobs (LABs, extended, bright Lyα-emitting clouds) along this structure. The large nebulae typically have Lyα luminosity > 10^{43}–10^{44} erg s^{-1} and a physical extent of 30–150 kpc. The most luminous and extended LABs are the two giant nebulae first discovered by Steidel et al. (2000) (hereafter referred as LAB 1 and LAB 2, following Matsuda et al. 2004). Rather than studying the differences in their distribution from only the UV-selected galaxies, observing the star-forming regions in NIR, the rest-frame optical wavelengths put more weight in their stellar mass content, allowing us to study the mass and population of the stars associated with them. The nature of dusty star-forming objects in such high-density structure can also be examined by the NIR data.

The field observed with MOIRCS (hereafter referred as SSA 22-M 1) corresponds to the southern part of SSA 22a (Steidel et al. 2000), and is located within the field observed by Matsuda et al. (2004). In SSA 22-M 1, there are 8 LABs (Matsuda et al. 2004), 16 LAEs (Hayashino et al. 2004), and 17 LBGs (Steidel et al. 1998, 2003b), of which 11 are located at z = 3.1. The sample selection for LAEs is overlapped with that for LABs. While LAEs are selected by the aperture photometry of the detected sources (Hayashino et al. 2004), LABs are selected by their isophotal area on the narrow-band image reduced with the optimum sky subtraction (Matsuda et al. 2004). Some LABs are associated with LAEs if they have enough compact high-surface brightness cores. On the other hand, Hayashino et al. (2004) excluded the LAEs detected in LAB 1 and LAB 2 from their sample, since they are clearly unisolated parts of diffuse Lyα nebulae. Two of the 16 LAEs in SSA 22-M 1 are identified with LABs (LAB 16 and LAB 31, referred by Matsuda et al. 2004).

We describe the observation and the data analysis method in section 2. The number density and the sky distribution of distant red galaxies (DRGs, Franx et al. 2003), the result of photometric redshift analysis of the K-selected sources, and the photometric properties of LABs, LBGs, and LAEs, are shown in section 3. In section 4 we discuss our results in terms of the mass assembly history in the proto-cluster. We use the cosmological parameter values Ω_m = 0.3, Ω_Λ = 0.7, and H_0 = 70 km s^{-1} Mpc^{-1} throughout this paper. All of the magnitude values are in the AB system (Oke & Gunn 1983; Fukugita et al. 1996), unless explicitly noted.

2. Observation and Data Analysis

\[ J, H, K_s \] -band images of the field centered at (α, δ)_{J2000} = (22^h17^m33^s9, +00°12'14") were obtained using MOIRCS mounted on the Subaru Telescope on 2005 June 15, 16, and August 14, and 2006 July 23 (UT). MOIRCS uses two 2048 × 2048 HAW AII-2 arrays with the pixel scale 0.′117 pixel^{-1} and the field of view 4′ × 7′.

The images were reduced in a standard manner with the MCSRED software packages (I. Tanaka et al. 2007, in preparation). For \( K_s \)-band flat-fielding, we used on/off sets of domeflat images to avoid thermal emission seen at the edge of the frames due to the foreground telescope structure. The median-sky for each frame was subtracted before the frames were stacked. If notable diffuse residual patterns remained after the median-sky subtraction, we further subtracted them by using the IRAF imsurfit command. We also subtracted fringe patterns in each frame, if they appeared, using templates made from the images taken in the same run.

The total exposure times of the final images were 3240 s, 3600 s, 2235 s for \( J, H, K_s \) respectively. The effective area of the image is 21.7 arcmin^2. The stellar image sizes are 0.′51, 0.′47, 0.′44 for \( J, H, K_s \) respectively. The limiting magnitudes are \( J = 24.5, H = 24.3, \) and \( K_s = 23.9 \) with 5σ in a 1′ diameter aperture. We calibrated our NIR data to the UKIRT photometric system (Tokunaga et al. 2002). We converted the Vega system to the AB system using \( J = J_{Vega} + 0.95, H = H_{Vega} + 1.39, K = K_{Vega} + 1.85 \). A summary of the observations is given in table 1.

| Filter | Integration  | FWHM | Limiting magnitude |
|--------|--------------|------|-------------------|
| J      | 3240         | 0.51 | 24.5              |
| H      | 3600         | 0.47 | 24.3              |
| \( K_s \) | 2235         | 0.44 | 23.9              |

* The 5σ limit for a point source in a 1′ diameter aperture.

The field observed with MOIRCS (hereafter referred as SSA 22-M 1) corresponds to the southern part of SSA 22a (Steidel et al. 2000), and is located within the field observed by Matsuda et al. (2004). In SSA 22-M 1, there are 8 LABs (Matsuda et al. 2004), 16 LAEs (Hayashino et al. 2004), and 17 LBGs (Steidel et al. 1998, 2003b), of which 11 are located at z = 3.1. The sample selection for LAEs is overlapped with that for LABs. While LAEs are selected by the aperture photometry of the detected sources (Hayashino et al. 2004), LABs are selected by their isophotal area on the narrow-band image reduced with the optimum sky subtraction (Matsuda et al. 2004). Some LABs are associated with LAEs if they have enough compact high-surface brightness cores. On the other hand, Hayashino et al. (2004) excluded the LAEs detected in LAB 1 and LAB 2 from their sample, since they are clearly unisolated parts of diffuse Lyα nebulae. Two of the 16 LAEs in SSA 22-M 1 are identified with LABs (LAB 16 and LAB 31, referred by Matsuda et al. 2004).

We describe the observation and the data analysis method in section 2. The number density and the sky distribution of distant red galaxies (DRGs, Franx et al. 2003), the result of photometric redshift analysis of the K-selected sources, and the photometric properties of LABs, LBGs, and LAEs, are shown in section 3. In section 4 we discuss our results in terms of the mass assembly history in the proto-cluster. We use the cosmological parameter values Ω_m = 0.3, Ω_Λ = 0.7, and H_0 = 70 km s^{-1} Mpc^{-1} throughout this paper. All of the magnitude values are in the AB system (Oke & Gunn 1983; Fukugita et al. 1996), unless explicitly noted.
3. Results

In this section, we present the observed properties of the $K$-selected objects in SSA 22-M 1. Since we are studying galaxies at $z = 3.1$, we need to apply some photometric selections to suppress any contamination of foreground/background objects. While full photometric redshift analysis is useful, it may suffer from misidentification, especially for $K$-band faint objects because the optical data used here may not be deep enough for them to achieve high photometric accuracy. A simple color-cut method, such as selecting DRGs with $(J - K)_{Vega} > 2.3$ (Franx et al. 2003), works complementarily, so that we can more completely pick-up objects possibly located at $z = 3.1$, if they exist. We therefore first consider the distribution of DRGs, and then that of the photometric redshift (photo-$z$) selected sources to compare with the UV-selected objects in the field.

3.1. Selection and Number Density of DRGs

We first focus on the distribution of DRGs in our field. DRGs are supposed to be evolved, relatively massive galaxies ($M_* \sim 10^{10}-10^{11} M_\odot$) at $2 \lesssim z \lesssim 4$ (Franx et al. 2003; Förster Schreiber et al. 2004; Reddy et al. 2005; Ichikawa et al. 2007) or dusty galaxies at $z \geq 1$ (Webb et al. 2006; Conselice et al. 2007; Quadri et al. 2007b; Lane et al. 2007). In an analysis of deep multicolor data obtained at GOODS-N, Kajisawa et al. (2006) found that 83% of the DRGs with $22 < K < 23.5$ have the photometric redshift $z > 2$, while more than a half of the DRGs with $K < 22$ have $z < 2$. Thus, the faint DRGs are supposed to be dominated by galaxies at high redshift. Since Marchesini et al. (2007) suggested that the global stellar mass at $2 \lesssim z \lesssim 3.5$ appears to be dominated by DRGs, the number of DRGs might be a good indicator of massive galaxies at $z \gtrsim 2$. In fact, Labbé et al. (2005) showed that DRGs dominate the high-mass end of the mass function at high redshift.

We used the same criteria as in Kajisawa et al. (2006), which corresponds to $(J - K)_{AB} > 1.4$ in our photometric system. The red $J - K$ color of DRGs is due to the Balmer or 4000 Å break of galaxies at $z \gtrsim 2$, or due to dust extinction (Franx et al. 2003; Reddy et al. 2005; Förster Schreiber et al. 2004). The color $(J - K)_{AB} > 1.4$ corresponds to that of a galaxy at $z = 3.1$ with a stellar population age older than 200 Myr, if no extinction and the solar metallicity are assumed (Bruzual & Charlot 2003). Förster Schreiber et al. (2004) reported that the median age and stellar mass for DRGs with $K < 25.6$ in HDF-S are 1.7 Gyr and $M_* = 0.8 \times 10^{11} M_\odot$. The $K$-band selected DRGs are supposed to be relatively more massive, more evolved objects than ultra-violet (UV)-selected galaxies, like LBGs at the same epoch.

In figure 1, we show a $K$ versus $J - K$ color–magnitude diagram of the $K$-selected objects. The objects with $J - K \lesssim 0$ are likely to be galactic stars. The color of the sequence coincides with that seen in the other field (Kajisawa et al. 2006), which suggests that our photometric calibration is robust. The $2\sigma$ limiting magnitude in the $J$-band is indicated by the solid line in figure 1. The $J$-band image is deep enough to select DRGs down to $K = 24.1$. The distribution of the photometric redshifts for DRGs is shown in figure 2. The detailed photo-$z$ analysis is described in subsection 3.2. We found that 62% of DRGs are classified as $2 < z_{phot} < 4$. The cumulative number of DRGs in our observed field is 28, and the surface density is $1.29 \pm 0.12$ arcmin$^{-2}$ at $K < 23.5$ (or $K_{Vega} < 21.5$), which is comparable with that in GOODS-N by Kajisawa et al. (2006), $1.36 \pm 0.26$ arcmin$^{-2}$ to the same depth. Figure 3 compares the differential number counts for DRGs in our observed field with those in GOODS-N. Our sample is dominated by DRGs with $22 < K < 23.5$, which implies that most of them should be at high redshift. The completeness fraction and the 95% limit, $K = 23.5$, are also marked. We do not see any notable excess in the number counts in SSA 22-M 1 over the magnitude range.

We note that there are nine hyper-extremely red objects (HEROs: Totani et al. 2001) with $(J - K)_{AB} > 2.1$ in SSA 22-M 1 at $K < 23.5$. The surface density of HEROs is $0.41 \pm 0.14$ arcmin$^{-2}$, which is consistent with those in SDF, HDF-S, and GOODS-N within the error (Maihara et al. 2001; Saracco et al. 2004; Kajisawa et al. 2006).

The sky distribution of DRGs is shown in figure 4a, and LABs (Matsuda et al. 2004), LAEs (Hayashino et al. 2004), and LBGs (Steidel et al. 2003b) are plotted in figure 4c. We then investigated the spatial correlation between DRGs and other UV-selected objects in the field. Figure 5a shows the mean surface number density of DRGs as a function of the distances from LABs, LAEs, and LBGs. First, we note that the distribution of the DRGs is weakly correlated with the sample of LABs as well as LBGs. Since the
LBGs are associated with 7 of 8 LABs, it is not surprising that similar correlations with DRGs are seen for these two populations. We also plotted the profile from the two distinctive giant LABs, namely LAB 1 and LAB 2, and found that the DRG density shows a notable excess within 1.0 (1.9 Mpc at $z = 3.1$ in comoving scale) around them. In fact, the correlation between DRGs, and LABs is found to be dominated by the two objects; if we remove them from the sample, the correlation seen in figure 5a diminishes significantly.

As mentioned in the beginning of this section, the redshift range of the DRG criteria is broad, and there may be a chance projection of interlopers at intermediate redshift. We made a simple test to see if the density excess of DRGs around LAB 1 and LAB 2 is significant by evaluating the probability of finding similar excess around the eight randomly placed objects. We found a similar profile in 592 among the 10000 trials, which gives a probability of $\approx 6\%$ in the random distribution of LAB to the observed distributions, DRGs. Thus the association of LAB 1/LAB 2 with DRGs is marginally significant ($\approx 2\sigma$). We take a closer look for $K$-selected objects near the eight LABs in the field in subsection 3.3.

We also find that there is no significant positive correlation between DRGs and LAEs, while a hint of anti-correlation is seen at $\sim 6''$ separation. It should be noted that there is such anti-correlation among the massive DRGs and less-massive LAEs.

### 3.2. Photometric Redshift of the $K$-Selected Sources

Using the $U_rBVri'z'JHK$ photometric data, we estimated the photometric redshift of all the $K$-selected sources using the HyperZ code (Bolzonella et al. 2000). The photometric redshift method performs the SED fitting with the redshift, spectral type, age, and dust extinction as free parameters. The best-fit SED with its redshift is determined from the minimum $\chi^2$ value. The template spectrum that we used were derived from GALAXEV, which is the library of evolutionary stellar population synthesis models by Bruzual and Charlot (2003).

At $z \sim 3$, the uncertainty of the photo-$z$ is typically $\Delta z \sim 0.5$ (Kajisawa & Yamada 2005; Reddy et al. 2005; Cirasuolo et al. 2007; Ichikawa et al. 2007). Figure 6 shows the resulting photometric redshifts versus spectroscopic redshifts obtained by previous studies (Songaila et al. 1994; Cowie et al. 1996; Steidel et al. 1999, 2003b; Abraham et al. 2004; Swinbank et al. 2004; Doherty et al. 2005). The relative errors, $(z_{\text{phot}} - z_{\text{sp}})/(1 + z_{\text{sp}})$, in the redshift estimation are also shown in the bottom panel of the figure. The mean of the relative errors for LBGs at $z \sim 3$ is $-0.04$ and the standard deviation is 0.08 (also see table 3 in subsection 3.3). We therefore picked up objects with $2.6 < z_{\text{phot}} < 3.6$ as candidate galaxies at $z = 3.1$. We found 29 objects, of which 9 are classified as DRGs and 6 are classified as LBGs.

Figure 4b shows a sky plot of the $K$-selected sources, similar to figure 4a, but for those with $2.6 < z_{\text{phot}} < 3.6$ and $K < 23.5$. Four LBGs associated with LABs do not appear since they are fainter than the limit in the $K$-band. A cross correlation with LABs, LAEs, and LBGs for this sample is also shown in figure 5b. We find that the association between these $K$-selected sources at $z = 3.1 \pm 0.5$ and LABs, especially LAB 1 and LAB 2, seems to be significant. In contrast to DRGs, LABs excluding the two giant blobs show the association with photo-$z$ selected objects.

### 3.3. NIR Properties of the LABs

In this section, we consider the NIR counterparts of the individual LABs. We find that 88% of the LABs have plausible $K_s$-band candidates. $K_s$-band images in a $25''$-side box for 8 LABs are shown in figure 7 and figure 8. The gray broad (green) lines indicate the NB497-band detection isophoto contours (Matsuda et al. 2004), and $R$-band sources are indicated with black sharp (red) contours in the figures.
Fig. 4. (a) Sky distribution of DRGs and LABs. DRGs are indicated with filled circles (red). LABs are indicated with large open circles (blue). Dotted squares indicate the observed regions with MOIRCS. The dotted large circle at the east side is the region excluded from the analysis due to a bright star. (b) Sky distribution of $z_{\text{phot}} = 2.6 - 3.6$ objects with $K < 23.5$ and LABs. The objects are indicated with filled circles (red). (c) Sky distribution of LABs, LAEs, and LBGs. LAEs (square, green) from Hayashino et al. (2004) and LABs (large open circle, blue) from Matsuda et al. (2004) are shown. LBGs at $z = 3.1$ from Steidel et al. (2003b) are indicated with triangles (magenta).
LBGs in the field (Shapley et al. 2001; Steidel et al. 2003b) are also marked. Of 11 LBGs at $z = 3.1$, 8 are associated with LABs. Of these, SSA 22a-C 11 (Steidel et al. 2003b, associated with LAB 1), M 14 (LAB 2), M 4 (LAB 7), C 12 (LAB 20), D 3 (LAB 30), and C 4 (LAB 31) are detected in the $K_s$-band, while C 6 (LAB 7) and C 15 (LAB 8) are not.

The photometric properties of $K$-selected objects around LABs are summarized in table 2, and the evaluated photometric redshift and physical properties of the candidates of $z = 3.1$ galaxies are presented in table 3. The stellar age, dust extinction, absolute magnitude, and stellar mass were derived from an SED fitting with GALAXEV (Bruzual & Charlot 2003) extinction law, and a solar metallicity. The characteristic time scale was set at $t = 0, 1, 9$ Gyr. The star-formation timescale, the color excess, and the age were varied as free parameters, and the best-fit SED was determined from the minimum reduced $\chi^2$ value. The mass-to-light ratio $(M/L)_V$ and the total absolute magnitude $(M_V)$ derived from GALAXEV were used to calculate the stellar mass. The errors of the stellar mass indicate a confidence level of 68%.

For LAB 1, there are five $K$-selected sources within the Ly$\alpha$ nebula. LAB 1-#1 and #2 are likely to be foreground objects, since their photometric redshifts are $z_{\text{phot}} < 1$. Steidel et al. (2000) have already reported that there is a $K_s$-band counterpart candidate with extremely red $R - K$ color near the center of the Ly$\alpha$ nebula (LAB 1-#3 in figure 7). We find that LAB 1-#3 is classified as a DRG and LAB 1-#3 and #4 have $2.6 < z_{\text{phot}} < 3.6$. While their spectroscopic redshifts are still unknown, it is very likely that #4 associates the LAB, since it is located right at the hole of Ly$\alpha$ nebulae (the right panel in figure 7); it may be an object that absorbs the Ly$\alpha$ emission at the redshift (Matsuda et al. 2007); #3 and #4 were also detected in Spitzer IRAC images in 3.6–8.0 $\mu$m (Geach et al. 2007; T. Webb et al. 2007, in preparation). The $K_s$-band counterpart of SSA 22a-C 11 at $z = 3.109$ was also detected (#5).

For LAB 2, four $K$-selected sources were found. LAB 2-#1 is classified as a DRG, and it can be the counterpart of SSA 22a-M 14 ($z = 3.091$), although it is located at 0.9 north from the $R$-band position, as mentioned in Ohyama et al. (2003). Probably, we see a mature or dusty part of the object in the $K_s$-band image. LAB 2-#2 is likely to be foreground objects, since the photometric redshift is $z_{\text{phot}} < 1$. LAB 2-#4 is also classified as a DRG with extremely red color, $R - K = 4.32$.

In LAB 7, Steidel et al. (2003b) and Shapley et al. (2001) sampled two LBGs, SSA 22a-M 4 ($z = 3.093$) and C 6 ($z = 3.092$), whereas they are separated as three objects in $BVRi'$-band images of Hayashino et al. (2004). Ly$\alpha$ emission entirely covers the three objects. From the coordinates we may identify the north component of this lump as LBG SSA 22a-M 4, which was detected in our $K_s$-band image. On the other hand, two other components were not detected either in the $J$ or $K_s$-band image.

LAB 8 is located at 15" north of LAB 1, and may form one large object (Matsuda et al. 2004). There is a LBG SSA 22a-C 15 ($z = 3.094$), which is not detected in either the $J$ or $K_s$-band.

LAB 16 is not associated with a LBG. We found a
Fig. 7. $K_s$-band (left panels) and narrowband (right panels, NB497: 4977 Å, FWHM 77 Å) images around LAB 1 and LAB 2 at $z = 3.1$ (Matsuda et al. 2004). The size of each panel is 25″, which corresponds to $\sim 190$ kpc at $z = 3.1$. Each image is centered on an LAB from Matsuda et al. (2004). The gray broad (green) and black sharp (red) contours are the isophotal levels of NB497 and $R$-band images, respectively.

Fig. 8. $K_s$-band images around LABs at $z = 3.1$ (Matsuda et al. 2004). The size of each panel is 25″, which corresponds to $\sim 190$ kpc at $z = 3.1$. Each image is centered on an LAB from Matsuda et al. (2004). The gray broad (green) and black sharp (red) contours are the isophotal levels of NB497 and $R$-band images, respectively.
### Table 2. NIR photometric properties of $K$-selected objects in LABs.

| LAB No. | Object ID | RA       | Dec      | $K$     | $J - K$ | $R - K$ |
|---------|-----------|----------|----------|---------|---------|---------|
| LAB 1  | C 11 (#5) | 22:17:25.7 | 0:12:34.6 | 23.18 ± 0.22 | 1.23 ± 0.58 | 1.31 ± 0.27 |
| #1     | 22:17:26.1 | 0:12:46.7 | 22.23 ± 0.10 | 1.08 ± 0.28 | 4.08 ± 0.42 |
| #2     | 22:17:25.8 | 0:12:43.8 | 22.75 ± 0.15 | 0.33 ± 0.29 | 1.34 ± 0.19 |
| #3     | 22:17:26.0 | 0:12:36.4 | 23.07 ± 0.20 | 1.48 ± 0.65 | 2.77 ± 0.31 |
| #4     | 22:17:26.1 | 0:12:32.3 | 22.38 ± 0.11 | 1.31 ± 0.39 | 2.20 ± 0.16 |
| LAB 2  | M 14 † (#1) | 22:17:39.1 | 0:13:30.6 | 23.30 ± 0.25 | 1.60 ± 0.82 | 2.60 ± 0.37 |
| #2     | 22:17:39.1 | 0:13:26.4 | 22.26 ± 0.10 | 0.55 ± 0.29 | 1.13 ± 0.15 |
| #3     | 22:17:38.9 | 0:13:24.0 | 19.98 ± 0.01 | 0.50 ± 0.03 | 1.85 ± 0.02 |
| #4     | 22:17:39.3 | 0:13:22.1 | 26.23 ± 0.14 | 1.95 ± 0.65 | 4.32 ± 0.65 |
| LAB 7  | M 4 C 6 | 22:17:41.0 | 0:11:27.8 | 23.78 ± 0.38 | 0.23 ± 0.54 | 0.90 ± 0.45 |
| LAB 8  | C 15 | —         | —         | —         | —         | —         |
| LAB 16 | C 12 | 22:17:24.9 | 0:11:17.5 | 23.29 ± 0.25 | 0.91 ± 0.47 | 1.78 ± 0.29 |
| LAB 20 | C 12 | 22:17:35.3 | 0:12:47.4 | 24.12 ± 0.50 | 0.70 ± 0.78 | 0.49 ± 0.48 |
| LAB 30 | D 3 | 22:17:32.5 | 0:11:32.9 | 22.88 ± 0.17 | 0.73 ± 0.37 | 1.08 ± 0.20 |
| LAB 31 | C 4 | 22:17:39.0 | 0:11:26.1 | 23.39 ± 0.27 | 1.14 ± 0.65 | 1.29 ± 0.34 |

* ID of LBGs refers to Steidel et al. (2003a).
† The associated NIR object of M 14 is located at 0.9 apart from the peak of the rest-frame UV source.

### Table 3. Photometric redshift and stellar mass of NIR counterparts.

| LAB No. | Object ID | $z_{spec}$ † | $z_{phot}$ | Age ‡ | $E(B - V)$ ‡ | $M_V$ ‡ | Stellar mass ‡ |
|---------|-----------|--------------|-----------|-------|---------------|---------|---------------|
| LAB 1  | C 11 | 3.109 | 2.83 | 1.80 | 0.08 | −22.32 | 2.5 $^{+2.4}_{-1.5}$ |
| #3     | — | 2.85 | 1.80 | 0.20 | −22.59 | 7.2 $^{+4.3}_{-2.5}$ |
| #4     | — | 2.61 | 1.61 | 0.18 | −23.19 | 10.9 $^{+4.8}_{-5.0}$ |
| LAB 2  | M 14 † | 3.091 | 3.19 | 1.80 | 0.22 | −22.64 | 8.1 $^{+4.9}_{-6.9}$ |
| #4     | — | 2.61 | 0.20 | 0.40 | −23.05 | 10.5 $^{+3.2}_{-6.3}$ |
| LAB 7  | M 4 | 3.093 | 2.70 | 0.57 | 0.06 | −21.75 | 0.7 $^{+2.8}_{-0.7}$ |
| LAB 16 | — | 2.70 | 0.06 | 0.20 | −22.50 | 1.6 $^{+3.6}_{-1.2}$ |
| LAB 20 | C 12 | 3.118 | 2.85 | 0.57 | 0.00 | −21.43 | 0.4 $^{+1.1}_{-0.3}$ |
| LAB 30 | D 3 | 3.086 | 3.31 | 1.61 | 0.08 | −22.74 | 3.4 $^{+1.1}_{-2.1}$ |
| LAB 31 | C 4 | 3.076 | 3.19 | 1.80 | 0.00 | −22.04 | 2.0 $^{+1.3}_{-1.4}$ |

* ID of LBGs refers to Steidel et al. (2003a).
† The redshift of LBGs refers to Steidel et al. (2003a).
‡ The redshifts are assumed to be $z = 3.1$ when the SEDs are calculated.
§ The associated NIR object of M 14 is located at 0.9 apart from the peak of the rest-frame UV source.
Fig. 9. (a) Lyα luminosity vs. the stellar mass of the NIR-counterpart candidates. (b) Surface brightness of Lyα vs. the stellar mass of the NIR-counterpart candidates (see text). The redshift of NIR objects is assumed to be $z = 3.1$. LBG counterparts associated with LABs are indicated with open triangles (red) and $K$-selected objects expected to be associated with LAB, but with no LBGs, are indicated with open circles (green). Since LAB 1 and LAB 2 include several NIR counterparts, the total stellar masses in each LAB are indicated with blue crosses.

counterpart candidate in the $K_s$-band, whose $R - K$ color is slightly redder than those of typical LBGs at $z = 3.1$. The photometric redshift of the object is $z_{\text{phot}} = 2.7$.

LAB 20, 30, and 31 are associated with the LBGs SSA 22a-C 12 ($z = 3.118$), D3 ($z = 3.086$), and C4 ($z = 3.076$), respectively. The $K_s$-band counterparts were detected for all of them. Of the 16 LAEs, only two were detected in the $K_s$-band, and they are both associated with the LABs (LAB 16 and LAB 31, see above). From the upper limit of their $K$-band flux, for the rest 14 LAEs, we estimate that their stellar masses are lower than $\sim 2 \times 10^9 M_\odot$, assuming the spectrum of very young (10$^6$-yr old) objects.

4. Discussion

We here discuss whether massive and/or mature galaxies have already formed in the cluster or proto-cluster, which was characterized by the overdensity of star-forming galaxies.

There is evidence that at least some relatively massive young galaxies ($10^{10-11} M_\odot$) have been formed in the proto-cluster. Figure 5b shows that the $K$-selected photo-$z$ sample exhibits an excess within a radius of 0.1–0.7 from the LABs. This indeed suggests that LABs are related to the formation of massive galaxies (Matsuda et al. 2006). We also found that the DRG density shows a notable excess around LAB 1 and LAB 2. How unique are LAB 1 and LAB 2 among the 35 LABs in the same structure? They are the largest and most luminous in Lyα emission. Moreover, Matsuda et al. (2005) suggested that LAB 1 and LAB 2 are located at the intersection of the filamentary structure of LAEs. Our results support the picture that LAB 1 and LAB 2 sit near the center of the proto-cluster, where the growth of the galaxy structure occurs most preferentially, and we are witnessing a stage where a significant amount of the stars is being formed in such regions.

We also investigated the stellar mass of the $K$-selected objects, which are expected to be associated with LABs, by assuming they are located at $z = 3.1$ as described in subsection 3.2. The result is also tabulated in table 3. Although the uncertainty of the stellar mass derived from the SED fitting is large, it is shown that the stellar mass of the LAB counterparts ranges from $4 \times 10^9 M_\odot$ to $1 \times 10^{11} M_\odot$.

Figure 9a shows the relation between the Lyα luminosity and the integrated stellar mass of the $K$-selected objects that are associated with each LAB, i.e., the objects in table 3. The
surface brightness of \Lya vs. the stellar mass is also shown in figure 9b. These figures suggest that the more massive galaxies are seen in the brighter LABs, which have a higher surface brightness in \Lya. This result implies that the origin of the \Lya emission of LABs may be related to their previous star-formation history.

Since the local or intermediate-redshift clusters are dominated by the passively-evolving old galaxies, it is worth constraining how many such passive galaxies formed at the higher redshift exist, if any, in the proto-cluster. In figure 1, we have plotted the expected color–magnitude relation for the model galaxies with $M_V = -17$ to $M_V = -22$ at $z = 0$ of the Coma metallicity-sequence model (Kodama & Arimoto 1997). It is clearly seen that few objects have color and magnitude for such passive galaxies formed at $z > 4$. This result seems to be consistent with that in Kodama et al. (2007), who reported that the bright end of the red sequence in proto-clusters around radio galaxies appeared at $z \approx 2$, whereas it was not seen at $z = 3$.

Steidel et al. (2000) reported that the volume density of LBGs at $z \approx 3.1$ in the SSA 22a/b fields, with the comoving volume of $2.7 \times 10^3 \text{Mpc}^3$ in total, was 6-times higher than the average. They also evaluated the overdensity of LAEs, which are typically 2 mag fainter than the LBGs in the UV continuum to $R = 25.5$ in the SSA 22a field, and found a similar value. Hayashino et al. (2004) revisited the issue by using the deeper and wider-area data of LAEs. They confirmed an overdensity of $\sim 6$ around SSA22a in $10^3 \text{Mpc}^3$, and found an overdensity of $\sim 3$, even at the $\sim 10^5 \text{Mpc}^3$ volume.

We tried to constrain the overdensity of such a population of galaxies in the proto-cluster from the observed surface number density of DRGs in SSA 22-M 1. To obtain the number density of DRGs in a general field at $z \sim 3$, we adopted a luminosity function with $\phi^* = 6.14 \times 10^{-4} \text{Mpc}^{-3} \text{mag}^{-1}$. $M^* = -22.63$, and $\alpha = -0.46$ for DRGs at $2.7 < z < 3.3$ (Marchesini et al. 2007). Our limiting $K$-band magnitude corresponds to $M_V = -20.8$, and the expected number density of DRGs above the luminosity is $5.9 \times 10^{-4} \text{Mpc}^{-3}$. The volume of the proto-cluster sampled in SSA 22-M 1 ($6.13 \times 3.5 \approx 11 \text{Mpc} \times 7 \text{Mpc}$ in comoving scale) is $1.4 \times 10^3 \text{Mpc}^3$, if we assume a redshift range of $z = 3.08-3.10$, which is similar to those studied for the excess density of LBGs or LAEs. Consequently, the expected average number of DRGs in the volume of SSA 22-M 1 with $\Delta z = 0.02$ was obtained to be $\approx 0.8$.

We found at least three DRGs in the vicinity of the two most luminous LABs (table 2). As a result of the number density of DRGs, it is shown that approximately 5 DRGs at the redshift provide a similar overdensity as that seen for LBGs or LAEs ($\approx 6$-times the average). Although the discussion is limited by the large uncertainty due to the small number of the objects, an overdensity similar to those of LBGs/LAEs is allowed if the number of the foreground/background DRGs in the field is less than $\sim 80\%$ of that in GOODS-N (29.5 DRGs are expected).

5. Summary

We have presented the results of our deep near-infrared imaging observations of the $z = 3.1$ proto-cluster in the SSA 22a field taken by MOIRCS mounted on the Subaru telescope. We observed a $21.7 \text{arcmin}^2$ field to depths of $J = 24.5$, $H = 24.3$, and $K = 23.9$ with $5\sigma$. Our observed field covers the area where the surface number density of the LAEs is highest.

We investigated whether massive and/or mature galaxies have already formed in the proto-cluster that is characterized by the overdensity of star-forming galaxies. We examined the distribution of $K$-selected galaxies by using a simple color cut for DRGs as well as photo-$z$ selection. The surface number density of DRGs with $(J - K)_{AB} > 1.4$ in the field was $1.3 \text{arcmin}^{-2}$ at $K < 23.4$. While it was not likely that the density values of DRGs have similar excess, as seen for LBGs at the volume, we found significant evidence that more than a few galaxies with stellar mass $M_* = 10^9-10^{11} \text{M}_\odot$ exist in the vicinity of, or might be associated with, the LABs.

We also investigated all of the $K_s$-band counterparts, which have consistent photometric redshifts not only for the LABs, but also for other objects at $z = 3.1$ in the field. We found that $88\%$ of the LABs have plausible $K_s$-band candidates. The sum of the stellar mass of the galaxies possibly associated with LABs correlated with the luminosity and surface brightness of the LABs, which implied that the origin of \Lya emission must be closely related with the massive galaxy formation phenomena. The most luminous LABs, LAB 1, and LAB 2 had $K$-selected counterparts with $M_* \sim 10^{11} \text{M}_\odot$. In addition, the marginal density excess of DRGs and the photo-$z$ selected objects was found around the most luminous LABs, LAB 1, and LAB 2.

Our results suggest that LABs are related to the formation of massive galaxies, and that a certain amount of evolved galaxies with $M_* \sim 10^{11} \text{M}_\odot$ are being formed in the central part of the high-density region of star-forming galaxies at $z = 3.1$. We are witnessing a stage when a significant amount of the stars are being formed in the central part of the growing large-scale proto-cluster at $z = 3.1$.

We thank the staff of the Subaru Telescope for their assistance with the development and observation of MOIRCS. This study is based on data collected at the Subaru telescope, which is operated by the National Astronomical Observatory of Japan. This research is supported in part by the Grant-in-Aid for Scientific Research 11554005 and 14340059 of the Ministry of Education, Culture, Sports, Science and Technology. The Image Reduction and Analysis Facility (IRAF) used in this paper is distributed by the National Optical Astronomy Observatories, U.S.A., which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
NIR Imaging in the $z = 3.1$ Proto-Cluster Region

References

Abraham, R. G., et al. 2004, AJ, 127, 2455
Adelberger, K. L., Steidel, C. C., Giavalisco, M., Dickinson, M., Pettini, M., & Kellogg, M. 1998, ApJ, 505, 18
Arnouts, S., et al. 2007, A&A, 476, 137
Benson, A. J., Frenk, C. S., Baugh, C. M., Cole, S., & Lacey, C. G. 2001, MNRAS, 327, 1041
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Bolzonella, M., Miralles, J.-M., & Pelló, R. 2000, A&A, 363, 476
Bower, R. G., Benson, A. J., Malbon, R., Helly, J. C., Frenk, C. S., Baugh, C. M., Cole, S., & Lacey, C. G. 2006, MNRAS, 370, 645
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Cirasuolo, M., et al. 2007, MNRAS, 380, 585
Conselice, C. J., et al. 2007, ApJ, 660, L55
Daddi, E., et al. 2003, ApJ, 616, 40
Ellis, R. S., & McCarthy, P. J. 2005, MNRAS, 361, 525
Förster Schreiber, N. M., et al. 2004, ApJ, 616, 40
Fontana, A., et al. 2006, A&A, 459, 745
Franx, M., et al. 2003, ApJ, 587, L79
Fukugita, M., Ichikawa, T., Gunn, J. E., Doi, M., Shimasaku, K., & Schneider, D. P. 1996, AJ, 111, 1748
Geach, J. E., Smail, I., Chapman, S. C., Alexander, D. M., Blain, A. W., Stott, J. P., & Ivison, R. J. 2007, ApJ, 655, L9
Grazian, A., et al. 2006, A&A, 453, 507
Matsumoto, T., & Arimoto, N. 1997, A&A, 320, 41
Kajisawa, M., & Yamada, T. 2005, ApJ, 618, 91
Kajisawa, M., & Yamada, T. 2006, ApJ, 650, 12
Kauflmann, G., Colberg, J. M., Diaferio, A., & White, S. D. M. 1999, MNRAS, 307, 529
Kodama, T., & Arimoto, N. 1997, A&A, 320, 41
Kodama, T., Tanaka, I., Kajisawa, M., Kurk, J., Venemans, B., De Breuck, C., Vernet, J., & Lidman, C. 2007, MNRAS, 377, 1717
Labbé, I., et al. 2005, ApJ, 624, L81
Lane, K. P., et al. 2007, MNRAS, 379, L25
Maihara, T., et al. 2001, PASJ, 53, 25
Marchesini, D., et al. 2007, ApJ, 656, 42
Matsuda, Y., et al. 2004, AJ, 128, 569
Matsuda, Y., et al. 2005, ApJ, 634, L125
Matsuda, Y., Iono, D., Ohta, K., Yamada, T., Kawabe, R., Hayashino, T., Peck, A. B., & Petitpas, G. R. 2007, ApJ, 667, 667
Matsuda, Y., Yamada, T., Hayashino, T., Yamauchi, R., & Nakamura, Y. 2006, ApJ, 640, L123
Ohyama, Y., et al. 2003, ApJ, 591, L9
Oke, J. B., & Gunn, J. E. 1983, ApJ, 266, 713
Ouchi, M., et al. 2001, ApJ, 558, L83
Ouchi, M., et al. 2005, ApJ, 635, L117
Papovich, C., Dickinson, M., & Ferguson, H. C. 2001, ApJ, 559, 620
Quadri, R., et al. 2007a, ApJ, 654, 138
Quadri, R., et al. 2007b, AJ, 134, 1103
Reddy, N. A., Erb, D. K., Steidel, C. C., Shapley, A. E., Adelberger, K. L., & Pettini, M. 2005, ApJ, 633, 748
Saracco, P., et al. 2004, A&A, 420, 125
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Shapley, A. E., Steidel, C. C., Adelberger, K. L., Dickinson, M., Giavalisco, M., & Pettini, M. 2001, ApJ, 562, 95
Songaila, A., Cowie, L. L., Hu, E. M., & Gardner, J. P. 1994, ApJS, 94, 461
Steidel, C. C., Adelberger, K. L., Dickinson, M., Giavalisco, M., Pettini, M., & Kellogg, M. 1998, ApJ, 492, 428
Steidel, C. C., Adelberger, K. L., Giavalisco, M., Dickinson, M., & Pettini, M. 1999, ApJ, 519, 1
Steidel, C. C., Adelberger, K. L., Shapley, A. E., Pettini, M., Dickinson, M., & Giavalisco, M. 2000, ApJ, 532, 170
Steidel, C. C., Adelberger, K. L., Shapley, A. E., Pettini, M., Dickinson, M., & Giavalisco, M. 2003a, ApJ, 592, 728
Steidel, C. C., Adelberger, K. L., Shapley, A. E., Pettini, M., Dickinson, M., & Giavalisco, M. 2003b, ApJ, 592, 728
Suzuki, R., et al. 2007, PASJ submitted
Swinbank, A. M., Smail, I., Chapman, S. C., Blain, A. W., Ivison, R. J., & Keel, W. C. 2004, ApJ, 617, 64
Tokunaga, A. T., Simons, D. A., & Vacca, W. D. 2002, PSAP, 114, 180
Totani, T., Yoshii, Y., Iwamuro, F., Maihara, T., & Motohara, K. 2001, ApJ, 558, L87
Verma, A., Lehner, M. D., Förster Schreiber, N. M., Bremer, M. N., & Douglas, L. 2007, MNRAS, 377, 1024
Webb, T. M. A., et al. 2006, ApJ, 636, L17

Downloaded from https://academic.oup.com/pasj/article-abstract/60/4/683/1396631 by guest on 26 July 2018