The First Appearance of the Red Sequence of Galaxies in Proto-Clusters at $2 \lesssim z \lesssim 3$

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ABSTRACT
We explore the evolved galaxy population in the proto-clusters around four high-$z$ radio galaxies at $2 \lesssim z \lesssim 3$ based on wide-field near-infrared (NIR) imaging. Three of the four fields are known proto-clusters as demonstrated by over-densities of line emitting galaxies at the same redshifts as the radio galaxies found by narrow-band surveys and spectroscopic follow-up observations. We imaged the fields of three targets (PKS 1138–262, USS 0943–242 and MRC 0316–257) to a depth of $K_s \sim 22$ (Vega magnitude, 5σ) over a $4' \times 7'$ area centered on the radio galaxies with a new wide-field NIR camera, MOIRCS, on the Subaru Telescope. Another target (USS 1558–003) was observed with SOFI on the NTT to a depth of $K_s = 20.5$ (5σ) over a $5' \times 5'$ area. We apply colour cuts in $J - K_s$ and/or $JHK_s$ in order to exclusively search for galaxies located at high redshifts: $z > 2$. To the 5σ limiting magnitudes, we see a significant excess of NIR selected galaxies by a factor of two to three compared to those found in the field of GOODS-South. The spatial distribution of these NIR selected galaxies is not uniform and traces structures similar to those of emission line galaxies, although the samples of NIR selected galaxies and emitters show little overlap, from which we conclude that the former tend to be an evolved population with much higher stellar mass than the latter, young and active emitters. We focus on the NIR colour–magnitude sequence of the evolved population and find that the bright-end ($M_{\text{stars}} > 10^{11} M_\odot$) of the red sequence is well populated by $z \sim 2$ but much less so in the $z \sim 3$ proto-clusters. This may imply that the bright-end of the colour–magnitude sequence first appeared between $z = 3$ and 2, an era coinciding with the appearance of submm galaxies and the peak of the cosmic star formation rate. Our observations show that during the same epoch, massive galaxies are forming in high density environments by vigorous star formation and assembly.

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

1 INTRODUCTION
The colour–magnitude relation is a well established scaling relation seen in cluster early-type galaxies locally (e.g., Visvanathan & Sandage 1977, Bower, Lucey, & Ellis 1992), and is well recognised even in distant clusters at least out to $z \sim 1$ (e.g., Ellis et al. 1997).
Therefore, the massive-end of the relation should have been established since early times \((z \gg 1)\). Identifying the epoch of massive galaxy formation is important since it can place strong constraints on the bottom-up formation of galaxies predicted by theories of the CDM Universe (e.g., Kauffmann & Charlot 1998, De Lucia et al. 2006). By looking back further in time, we should eventually be able to witness the first appearance of the bright end of the red sequence galaxies in proto-clusters, and hence we can observationally identify the formation epoch of massive galaxies.

Despite its obvious immediate importance, however, such a study has been largely limited until very recently by the following two factors. First of all, samples of proto-clusters were very sparse not only due to the observational difficulty in finding them due to the faintness of the targets but also due to the intrinsic underdevelopment of the structures at high redshifts. Secondly, the small field of view of near-infrared (NIR) cameras has prevented us from sampling the rest-frame optical light that provides most of the information on the more evolved stellar population, for a large number of high-z galaxies. A large amount of work has been devoted to surveys for line emitters around high redshift radio galaxies using narrow-band imaging and/or spectroscopy in the optical (e.g., Kurk et al. 2004, Venemans et al. 2002, Venemans et al. 2007; Steidel et al. 2000; 2005), which in fact successfully found a number of over-dense regions at high redshifts traced by young star forming galaxies. The Lyman break technique based on the broad-band multi-colour imaging in the optical has also been used to survey some concentrations of high-z galaxies such as at \(z \sim 3\) (e.g., Steidel et al. 1998).

The advent of a new wide-field NIR camera MOIRCS (Multi-Object Infra-Red Camera and Spectrograph; Ichikawa et al. 2006) on Subaru (providing a \(4' \times 7'\) field of view) has extended our ability of searching for proto-clusters in the NIR. In this paper, we present photometric properties and spatial distribution of galaxies in the fields of four known proto-clusters around radio galaxies at \(2 \leq z \leq 3\). The candidate proto-cluster member galaxies associated to the central radio galaxies are extracted on the basis of their NIR colours. We will focus on the appearance of the massive end of the red sequence of galaxies in the proto-clusters.

The structure of the paper is the following. Our observational data-set will be described in §2, and the colour selection of proto-cluster member candidates will be explained in §3. The results on the colour-magnitude diagrams and the spatial distribution will be given in §4 and §5, respectively and a summary is given in §6. The Vega-referred magnitude system and cosmological parameters of \(H_0=70\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}\), \(\Omega_m = 0.3\), and \(\Omega_{\Lambda} = 0.7\) are used throughout the paper.

## 2 TARGETS, OBSERVATION AND DATA REDUCTION

### 2.1 Target selection

Radio galaxies are often used as markers of high density regions at high redshifts, since they are among the most massive galaxies at any redshift \((M_{\text{star}} > 10^{12}M_\odot,\) Rocca-Volmerange et al. 2004). In fact, about half of the powerful radio galaxies at intermediate redshift inhabit rich environments (Hill & Lilly 1993, Bornancini, Lambas, & De Breuck 2006). Also, given the correlation between AGN activity and bulge mass (Magorrian relation, Gebhardt et al. 2000), it is natural to imagine that massive cD galaxies sitting in deep potential wells of clusters tend to host massive powerful AGN which are therefore identified as radio galaxies at high redshifts. Narrow-band surveys of Ly\(\alpha\) emitters around high-z radio galaxies up to \(z \sim 5\) have been intensively conducted by the Leiden group (e.g., Kurk et al. 2000, Venemans et al. 2002, Venemans et al. 2007) over many years revealing a large number of emitters at the redshifts of the radio galaxies, and a large fraction of those emitters have been spectroscopically confirmed. The over-dense regions traced by the star forming galaxies are embedded in large scale structures in the early Universe and are likely to evolve into massive systems at the present day, such as clusters of galaxies. These are therefore ideal sites to study the ancestors of present-day early-type galaxies in their formation phase.

Recently, some NIR surveys have been carried out searching for “evolved” galaxy populations around radio galaxies at \(1 \leq z \leq 3\), an approach complementary to the line emitter surveys. Some over-dense regions of red galaxies were reported, which are probably associated to the radio galaxies (e.g., Best et al. 2003, Hall et al. 1998, Kodama & Bower 2003, Toft et al. 2003). Kajisawa et al. (2006) have recently conducted deep \(JHK'S\) surveys with CISCO on Subaru, and found two convincing proto-clusters at \(z \sim 2.5\) that show over-densities of NIR-selected galaxies by more than a factor of three compared to the general field \(GOODS-South\) (hereafter \(GOODS-S\)).

From the currently available sample of proto-cluster candidates, we select four targets, of which three (PKS 1138–262, USS 0943–242 and MRC 0316–257) are fields with a number of spectroscopically confirmed Ly\(\alpha\) and/or H\(\alpha\) emitters associated with the radio galaxies. Another target (USS 1558–003) is selected from the sample of Kajisawa et al. (2006) as, in earlier CISCO observations, it shows a clear over-density of NIR-selected galaxies. No line emitter survey has been conducted around this target yet. All the targets lie at \(2 \leq z \leq 3\) and are listed in Table[1]. Hereafter, they are sometimes referred to as 1138, 0943, 0316 and 1558 for short.

### 2.2 Observation and data reduction

We performed NIR imaging observations in the \(J, H\) and \(K_s\) bands of the fields of three high-z radio galaxies at \(2 \leq z \leq 3\) with MOIRCS on the Subaru Telescope on 2006 January 6–7. MOIRCS has a field of view (FoV) of \(4' \times 7'\) arcmin\(^2\) with a 0.117\(^{''}\) pixel scale covered by two 2k by 2k CCDs, which provide a co-moving area of \(6 \times 10.5\) Mpc\(^2\) at \(z \sim 2\) and 7.5 \(\times 13\) Mpc\(^2\) at \(z \sim 3\). Two corners of the MOIRCS CCDs are vignetted. After removing these, the final areal coverage used is about 25 arcmin\(^2\). Our targets and the on-source exposure times are given in Table[1]. The weather conditions were stable during the observations, and the seeing varied between 0.4\(^{''}\) and 0.7\(^{''}\) (FWHM) for most of the nights.

The fourth radio galaxy field, USS1558–003, was imaged with SOFI on the NTT in the \(J\) and \(K_s\) bands on 2006...
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Table 1. Summary of the observational data

| Name     | Redshift | Telescope/Instrument | Exp. Time (min) | PSF FWHM (arcsec) | FoV (arcmin²) | lim. mag. (5σ) |
|----------|----------|----------------------|-----------------|-------------------|---------------|----------------|
| PKS 1138−262 | 2.156    | Subaru/MOIRCS        | J H Ks          | 0.5−0.7           | 25            | J=23.3, K=22.0 |
| USS 1558−003  | 2.527    | NTT/SOFI             |                | 0.6−0.7           | 25            | J=22.5, K=20.5 |
| USS 0943−242  | 2.923    | Subaru/MOIRCS        | J H Ks          | 0.4−0.6           | 25            | J=23.5, H=22.6, K=22.0 |
| MRC 0316−257  | 3.130    | Subaru/MOIRCS        | J H Ks          | 0.6−0.7           | 25            | J=23.0, H=22.6, K=21.8 |

March 20–22 under photometric and good seeing conditions. The pixel scale of SOFI is 0.288″ and its FoV is 4.9×4.9 arcmin², close to the effective MOIRCS FoV.

The MOIRCS data were reduced using a purpose-made pipeline software package called MCSRED (MoirCS REDuction; Tanaka et al. 2007). We performed flat-fielding with the super-flat frames constructed by combining our object frames without being registered, and subtracted dark and sky background. Then the data were co-registered and combined. The SOFI data were reduced in the same manner.

For each target, the images were convolved with a Gaussian kernel to match the PSF of the image taken under the worst seeing (see Table I).

Source detection was performed in the Ks-band images using the SExtractor image analysis package (Bertin & Arnouts 1996). We adopted MAG_AUTO from SExtractor as the total Ks-band magnitude of detected objects. For colour measurements in J − Ks and H − Ks, we used aperture magnitudes MAGAPER with a 1.5″ diameter aperture, using the dual image mode with detection in the Ks-band. The UKIRT Faint Standards were used for the flux calibration. The 5σ limiting magnitudes for each field are given in Table 1. All magnitudes are corrected for Galactic extinction, which is estimated at the positions of the galaxies (near the center of each observed field) based on Schlegel, Finkbeiner, & Davis (1998).

3 COLOUR SELECTION OF PROTO-CLUSTER MEMBER CANDIDATES

3.1 A new definition of NIR-selected galaxies at 2 ≤ z ≤ 3

Our original Ks-selected catalogues contain ∼700–1000 objects per field and most of them should be foreground/background galaxies or galactic stars which are not physically associated to the proto-clusters around the targeted radio galaxies. It is therefore essential to remove those contaminations as much as possible while keeping most of the member candidates in order to examine the galaxy population in the proto-clusters.

For this purpose, we apply colour selections either by J − Ks > 2.3 or in JHKs colour–colour space. The former criterion is a single colour cut in J − Ks, devised by the FIRES team (Faint InfraRed Extragalactic Survey; Franx et al. 2003). The galaxies that satisfy this criterion were named Distant Red Galaxies (DRGs) and they have been shown to correspond to 2 < z < 3 galaxies with a high completeness rate when followed up spectroscopically (e.g., van Dokkum et al. 2003, Förster Schreiber et al. 2004, Reddy et al. 2007). In fact, such red colours of galaxies can only be reproduced either by Balmer/4000Å-break galaxies with old populations at z ≥ 2 or foreground galaxies with heavy dust extinction (Fig. 1). The latter criterion is based on cuts in the three JHKs bands, devised by some of the authors, first defined and applied in Kajisawa et al. (2006). Figure 1 illustrates the J − Ks versus H − Ks colour–colour diagrams of our two z ∼ 3 targets. As shown by three model tracks and the thick dashed line connecting the z = 3 points, most of the galaxies at 2.4 ≤ z ≤ 3.1 are expected to lie at the top left corners of these diagrams. Therefore, if we apply the colour cuts shown by the dot-dashed lines (i.e., J − Ks > 2 × (H − Ks) + 0.5 & J − Ks > 1.5), we can effectively isolate these galaxies. This criterion is met while the Balmer/4000Åbreak of galaxies falls between J-band and H-band at this redshift range. In this paper, we further classify the JHK−selected galaxies (hereafter JHKs) into red and blue populations separated at J − Ks = 2.3, and we hereafter call them r-JHK and b-JHK, respectively. The definitions of the galaxy classes are summarised in Table 2.

This two-colour-based selection in JHKs has a significant advantage over the classical DRG selection in the single J − Ks colour, since the two-colour cut can pick out not only passive or dusty galaxies but also younger or star forming galaxies at 2.5 ≤ z ≤ 3 which have relatively bluer colours in J − Ks and would have been missed by the single J − Ks > 2.3 cut. It should be also noted that this selection is robust against dust extinction, since the reddening vector (indicated by an arrow in Fig. 1) is almost parallel to the boundary line of the JHK-selection. At the same time, contamination from lower-z galaxies (z ≤ 2) due to dust extinction is expected to be minimal. In addition, cool M, L and T dwarfs are also efficiently excluded by this criterion, as they are either too blue in J − Ks or located on the right side of the boundary line of the JHK-selection (Kajisawa et al. 2006). By using this JHK-selection technique, Kajisawa et al. (2006) has identified proto-cluster candidates with evolved galaxy populations around some radio galaxies at z ∼ 2.5. It is notable that 5 out of 6 radio galaxies themselves (which we know are located at z ∼ 2.5 by spectroscopy) satisfied our JHK colour selection criteria. This means that our selection actually works for blue members with on-going star formation even though the strong emission lines from an AGN component could affect their colours (Iwamuro et al. 2003). The central radio galaxies 0943 and 0316 are labeled by stars in Fig. 1, which shows that 0943 satisfies the b-JHK criterion while 0316 does not. Furthermore, galaxies that are selected by our JHK cut show a clear statistical excess (factor 2−4) in two of the fields when they are compared to the general field of GOODS-S. This is true for the bluer JHK population (b-
histories (passive, intermediate, and active) formed at $z$ respectively. Solid, dashed and dotted curves represent the evolutionary tracks of galaxies over $0 < z < 4$ with different star formation histories (passive, intermediate, and active) formed at $z_{\text{form}} = 5$ (Kodama et al. 1999). The thick dashed line connects the model points at $z = 3$, showing that our selection technique works to pick out not only passively evolving galaxies at $2 \leq z \leq 3.2$ but also star forming galaxies at $2.4 \lesssim z \lesssim 3.1$. Red filled circles and green filled circles are r-JHK and b-JHK populations, respectively. The size of the symbols is scaled according to apparent magnitudes in $K_s$-band (where larger means brighter). Yellow filled circles with black boundaries show the galaxies that satisfy the DRG criterion but not the JHK criterion. A large star indicates the targeted radio galaxies. The arrow shows a reddening vector of Calzetti et al.’s law (Calzetti et al. 2000) of $E(B-V) = 0.2$ at $z = 3$. Importantly the vector is almost parallel to the boundary line of our JHK selection, and thus our method is robust against dust extinction. Moreover, contamination from lower-$z$ ($z \lesssim 2$) galaxies due to dust extinction is expected to be minimal. Note that the direction of reddening vector on this diagram hardly changes for $0 < z < 3$ (less than 12 per cent in the slope).

### Table 2. Definitions of various NIR selected galaxies

| category | definition |
|----------|------------|
| DRG      | $J - K_s > 2.3$ |
| JHK      | $J - K_s > 2 \times (H - K_s) + 0.5$ \& $J - K_s > 1.5$ |
| r-JHK    | JHK \& $J - K_s > 2.3$ |
| b-JHK    | JHK \& $J - K_s < 2.3$ |

JHK) as well, which further supports the effectiveness of our selection technique.

We apply the same JHK-selection for the two proto-clusters at $z \sim 3$ (0943, 0316) in this paper for which a complete $JHK_s$ data-set is available. For the remaining two targets at $2 \lesssim z \lesssim 2.5$ (1138, 1558), we apply the single colour cut of $J - K_s > 2.3$ instead.

The NIR selected galaxies are highlighted in Fig. 1 with different symbols. Red filled circles and green filled circles are r-JHK and b-JHK populations, respectively. The size of the symbols is scaled according to the $K_s$-band magnitude (bigger ones are brighter). Yellow filled circles with black boundaries show the galaxies that satisfy the DRG criterion but not the JHK criterion, and hence are possibly background objects. All other objects detected in the $K_s$ band are shown by small dots.

### 3.2 Over-density of the NIR-selected galaxies

Fig. 2 shows that there are many (> 70) galaxies which satisfy the JHK selection in each of the two $z \sim 3$ fields. To assess the over-density of the NIR selected galaxies compared to the general field, we use the public VLT/ISAAC version 1.5 data of the GOODS-S field (Vandame et al., prep; see also Giavalisco et al. 2004). The latter data are reproduced in Fig. 2 on NIR colour–magnitude and colour–colour diagrams. For a direct comparison with our proto-cluster fields, the effective areal coverage of the GOODS-S data was scaled down from 94 arcmin$^2$ to 25 arcmin$^2$ by randomly sampling galaxies from the catalog. By comparing Fig. 1 with Fig. 2 it is obvious that the JHK-selected galaxies in the two proto-cluster regions at $z \sim 3$ are a lot more numerous than in the scaled GOODS-S area.

To present this more quantitatively, we show the cumulative number counts of the NIR selected galaxies in the proto-cluster fields and in the GOODS-S field in Fig. 3 For 1138 and 1558 only DRGs are plotted, while for 0943 and 0316 JHKs (and its subsamples r-JHK and b-JHK) as well as DRGs are plotted. We find clear statistical excesses in all
classes of NIR selected galaxies in all of the four proto-cluster fields (thick curves) compared to GOODS-S (thin curves). The excess factors range from 1.5 to 4 depending on the field, galaxy class, and depth considered. In particular, the DRGs in 1138 and 1558 at $K_s < 20$, and JHKs in 0943 and 0316 at $K_s < 21$ show the largest excesses. These excess factors of the NIR-selected galaxies are consistent with those of the surface number densities of the Lyα emitters which are factor 2, 3 and 3 for 1138, 0943 and 0316, respectively (Kurk et al. 2004a; Venemans et al. 2007). To the 5σ limiting magnitudes of each target (see Table 1), the excess numbers of the NIR-selected objects are: 23 and 8 DRGs in 1138 and 1558 respectively, and 60 and 32 JHKs in 0943 and 0316 respectively. An indication for the existence of such red galaxies observed as EROs (Extremely Red Objects) was also found in Kurk et al. (2004a).

This strongly suggests that at least some of the NIR-selected galaxies are physically clustered and associated to the central radio galaxies. Because the $K_s$-bright galaxies ($K_s < 21$) are relatively massive ($M_{\text{stars}} > 2 \times 10^{10} M_\odot$) as we discuss later, these proto-clusters already seem to contain an evolved galaxy population as well as young Lyα/Hα emitters (Kurk et al. 2004a; 2004b; Venemans et al. 2007) which tend to be much less massive, typically by more than an order of magnitude (Gawiser et al. 2006; Venemans et al. 2005). It is likely that these fields will evolve into rich clusters of galaxies, today dominated by old passively evolving galaxies.

There is a caution, however, that field-to-field variation in the number density of intrinsically rare massive galaxies is not negligible. In fact, the GOODS-S field that we use for comparison could be a slightly underdense region of massive galaxies as suggested by van Dokkum et al. (2006).

They claim that the number density of massive galaxies ($>10^{11} M_\odot$) at $2 < z < 3$ in the GOODS-S field is ~60% of the average when compared to the MUSYC survey. Since we have computed over-densities using the GOODS-S field, our numbers may be over-estimated by at most a factor of two if compared with a larger (less biased) blank field. Therefore the excess factors of the NIR-selected galaxies could be reduced to 1.5~2 at the bright-end ($K_s < 19.5$--20) in such a case.

4 THE FIRST APPEARANCE OF MASSIVE RED SEQUENCE GALAXIES

We now focus on the build-up of the red sequence in the proto-clusters at its very first stage, which is the main theme of this paper. Massive elliptical galaxies are seen to dominate cluster cores up to a redshift of $z \sim 1$ with the red sequence firmly in place by that epoch (Kodama et al. 1998; Tanaka et al. 2005). What remains uncertain is whether this holds true at higher redshift and it is therefore unclear at what epoch massive, cluster galaxies assembled and from which stage they underwent mostly passive evolution.

The colour-magnitude diagram is one of the most powerful tools to investigate galaxy formation and evolution on a large magnitude limited sample. Fig. 4 shows NIR colour-magnitude diagrams of the four proto-cluster fields. Filled red circles indicate DRGs for 1138 and 1558, and r-JHKs for 0943 and 0316, respectively. Filled green circles are b-JHKs. The size of these symbols corresponds to magnitudes in $K_s$-band. DRGs that do not satisfy the JHK criterion are shown by small filled yellow circles. For reference, we also show the expected locations of the colour-magnitude rela-
Figure 3. Combined cumulative number counts of galaxies in the radio galaxies fields (thick lines) and those in a control field GOODS-S (thin lines). Error-bars are based on Poisson statistics. Data for the full effective area of 94 arcmin$^2$ are used for the counts in GOODS-S (Giavalisco et al. 2004).

The CMR as observed at the redshift of the central radio galaxies in the case of passive evolution for various formation redshifts as shown. These models are calibrated so as to reproduce the CMR of elliptical galaxies in the Coma cluster at $z \sim 0$ as a sequence of decreasing metallicity with magnitude [Kodama et al. 1998]. A constant stellar mass of $10^{11} M_\odot$ with Kennicut (1983) initial mass function is approximately shown by the dotted line in each panel (Kodama et al. 1998).

In all the proto-cluster fields, there are a number of very red galaxies that have colours consistent with those of passively evolved galaxies with high formation redshifts ($z > 3.5$) (Kodama et al. 1998). Such red galaxies are very rare in the general field of GOODS-S (Fig. 3). Considering the magnitudes of these red galaxies along the CMR, it becomes clear that the bright end of the red sequence ($M_{\text{stars}} > 10^{11} M_\odot$) is already well populated by $z \sim 2$ but much less so at $z \sim 3$ (Fig. 4). In fact, there are 12 and 4 galaxies at $z = 2$ and 2.5, respectively, but there are none or only two galaxies at $z \sim 3$ above this mass limit. Although the statistics are by all means poor at this stage, these results suggest that the bright-end of the colour–magnitude sequence first appeared between $z = 3$ and 2. To derive any general conclusion, however, observation of a larger sample of proto-clusters is needed so that we can average over individual characteristics of proto-clusters even at the same epoch.
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Figure 4. Colour–magnitude diagrams of the four proto-clusters at $2 \leq z \leq 3$. Filled circles indicate proto-cluster member candidates selected with $J - K_s > 2.3$ (PKS 1138–262, USS 1558–003) and $JHK_s$ diagram (USS 0943–242, MRC 0316–257), respectively (see Fig. 1 and Kajisawa et al. (2006) for our new JHK selection technique of passive/active galaxies at $2 \leq z \leq 3$). Colour-coding is the same as in Fig. 1 except for the upper plots where the red symbols indicate DRGs. The size of the symbols is scaled according to apparent magnitudes in $K_s$-band just for consistency with Figs. 1 and 5. Large star marks show the targeted radio galaxies. The radio galaxy 1138 is extraordinary bright as it is dominated by Hα in $K_s$-band (Nesvadba et al. 2006). Dotted error-bars show 1σ photometric errors.

Solid, dashed and dotted lines show the expected location of colour–magnitude relations at the radio galaxies’ redshifts in the case of passive evolution (Kodama et al. 1998). The iso-stellar-mass lines of $10^{11} M_\odot$ are also shown by thick dotted lines (the ones for $10^{10} M_\odot$ are located at 2.5 magnitudes fainter than those although they are not shown to keep good visibility of the plots). The dot-dashed lines indicate 5σ ($K_s$) and 2σ ($J$) detection limits.

Which galaxies in the $z \sim 3$ proto-clusters could be the progenitors of the massive red sequence galaxies seen in the $z \sim 2$ proto-clusters? Where are they on the colour-magnitude diagrams at $z \sim 3$? And how is the bright end of the CMR built up between $z = 3$ and 2, while only one Gyr is available between these two epochs? These are crucial questions to be answered to advance our understanding of the formation of massive elliptical galaxies. Interestingly, at $z \sim 3$, there are few blue galaxies that are already massive enough ($> 10^{11} M_\odot$) to turn into massive red galaxies and fill the bright-end of the CMR at $z \sim 2$ simply by stopping their on-going star formation (Fig. 4). Therefore, a signifi-
cant growth in stellar mass is required between $z = 3$ and 2 either by vigorous star formation or mass assembly by mergers or both. In any case, to make a $10^{11} \, M_\odot$ galaxy from a $10^{10} \, M_\odot$ within a Gyr, a mass growth rate of $\sim 100 \, M_\odot$ per yr is required. This would not be impossible, however. In fact, such a high rate of star formation is often seen in submm galaxies or dusty star-burst galaxies (such as ultra-luminous infrared galaxies and a subsample of DRGs) found in the $2 < z < 3$ Universe (e.g., Chapman et al. 2005; Webb et al. 2006). It is also interesting to note that the peak of the submm phase and the peak of the cosmic star formation rate just coincide with this era (e.g., Chapman et al. 2005; Bouwens et al. 2005). Also, there is a dramatic evolution in dusty star formation activity in the central radio galaxies themselves; their detection rate at submm wavelength rises from 15 per cent at $z < 2.5$ to $> 75$ per cent at $z > 2.5$ (Archibald et al. 2001; Reuland et al. 2004). Therefore, it is likely that the massive galaxies are still in the primitive phase of formation at $z \sim 3$, and they are just being built up by vigorous star formation and assembly between $z = 3$ and 2. At $z \sim 2$ they eventually show up at the bright-end of the CMR at their near-final stage of formation. It should be noted that the fact that galaxies are on the red sequence does not necessarily mean that star formation is completely switched off in these systems (Papovich et al. 2006; Kriek et al. 2006). In fact, a large fraction of DRGs at $z > 2$ tend to contain some on-going star formation at the level of a few to a few tens of solar masses per year, but they are reddened by dust extinction (Webb et al. 2006). We note however that those DRGs are found in random general fields such as GOODS rather than known proto-clusters as we targeted in this study, and it is not a priori clear if such remaining star formation is also present in the red massive galaxies in our proto-clusters or not.

Some of the r-JHKs and b-JHKs are bright enough to be targeted in spectroscopy both in the optical and in the NIR in order to confirm their physical association to the proto-clusters around the radio galaxies. This is the most important next step as it will also confirm the interesting results presented here on the first appearance of massive red sequence galaxies in the proto-clusters at $2 < z < 3$.

5 SPATIAL DISTRIBUTION OF THE PROTO-CLUSTER MEMBERS

The spatial structure of proto-clusters is another interesting subject, since it reflects the primordial density fluctuation and the early stage of structure formation. Kajisawa et al. (2006) have shown a hint of filamentary structure in the NIR-selected galaxies in two proto-clusters at $z \sim 2.5$, even within the $1.6 \times 1.6$ arcmin$^2$ field of view. With the larger FoVs of MOIRCS and SOFI, we are able to trace the proto-clusters structures to much larger extents, which will demonstrate any filaments if present with more certainty.

The distribution of galaxies in our four proto-clusters is shown in Fig. 5. Filled circles indicate the NIR selected galaxies, while open symbols show the Ly$\alpha$ and/or H$\alpha$ emitters. See the caption for details. The spatial distribution of the NIR selected galaxies is not uniform in general. For example, brighter DRGs in 1138 seem to form an elongated filament in the East-West direction, especially close to the radio galaxy. Croft et al. (2005) also found a similar elongated structure for X-ray emitting galaxies in the field of 1138. The JHKs and DRGs in 0943 are another good example, as they show a large overall elongated structure from ESE to NW. The filaments traced by the NIR-selected galaxies are roughly in the same direction as those formed by the Ly$\alpha$ and/or H$\alpha$ galaxies. These non-uniform structures strongly indicate that these proto-clusters are right at the stage of initial vigorous assembly to form the basic shapes of the clusters.

To be more quantitative, we have performed a 2D Kolmogorov-Smirnoff (K-S) test, and found that the probabilities that the DRGs ($K_s < 20.5$) in 1138 and JHKs ($K_s < 21$) in 0943 are drawn from a random distribution are only 0.05 and 0.0006, respectively. In contrast, probabilities that the NIR-selected galaxies and the emitters have the same spatial distribution are 0.24 and 0.09 for 1138 and 0943, respectively. This suggests that the DRGs and JHKs are clustered and possibly in a similar fashion as the line emitters at the redshifts of central radio galaxies. Note that we have subtracted field contamination for the NIR-selected sample using the GOODS-S.

Although the NIR-selected galaxies and the Ly$\alpha$/H$\alpha$ emitters trace similar structures, it is noteworthy that the individual galaxies rarely overlap between these two populations. This indicates that most of the emitters are not massive enough to be detected in our NIR imaging ($M_{\text{gals}} \gtrsim 10^{10} \, M_\odot$), and at the same time, even the b-JHK (with some on-going star formation) in the $z \sim 3$ proto-clusters do not show strong enough Ly$\alpha$ emission to be detected in the narrow-band emitter surveys (e.g., Ly$\alpha$) $\lesssim 6.2 \times 10^{41}$ erg s$^{-1}$ for 0943 and $6.9 \times 10^{41}$ erg s$^{-1}$ for 0316 at 5 sigma). There is also a possibility that the redshifts of some of these b-JHKs may be offset by more than $\sim 1500$ km s$^{-1}$ so that they cannot be detected in the narrow bands. In any case, these proto-clusters consist of both massive evolved populations as traced by JHKs or DRGs, and less massive, young populations as traced by Ly$\alpha$/H$\alpha$ emitters.

6 SUMMARY

We targeted proto-clusters around four radio galaxies at $2 < z < 3$ using wide-field NIR instruments. Most of these fields are known to show a large number of Ly$\alpha$ and/or H$\alpha$ emitters at the same redshifts as the radio galaxies. We see a clear excess of NIR selected galaxies (JHK-selected galaxies as well as DRG) in these fields, which confirms that they indeed contain proto-clusters with not only young emitters but also evolved galaxy populations. The spatial distribution of these NIR selected galaxies is filamentary, similar to the structures traced by the emitters. The observed difference in the number of red sequence galaxies between the $z \sim 3$ and the $z \sim 2$ fields in our sample may imply that the bright end of the red sequence first appeared between $z = 3$ and 2.
Since we are targeting the biased high density regions, one could imagine that galaxy formation and evolution take place faster here than in lower density or randomly selected regions (e.g., Cen & Ostriker 1993; Diaferio et al. 2001; Tanaka et al. 2005; Steidel et al. 2005). Stellar mass functions derived for ‘general’ fields such as GOODS-MUSIC (Fontana et al. 2006) and PDF+GOODS-S (Drory et al. 2005) show that the massive end ($>10^{11} M_\odot$) starts to deviate from the low-$z$ ($z \sim 0.5$) function significantly at $z \sim 1.5$ or so, which is slightly later than the epoch when we see the truncation of the massive-end of cluster red sequence ($z \sim 2.5$). This could be suggestive that massive galaxies in proto-clusters are assembled a bit earlier than those in the general fields. However, a quantitative statement on environmental dependence will have to wait until stellar mass functions for a range of redshift can be constructed from observations of a larger sample of proto-clusters, which can
be compared directly to the stellar mass functions of field galaxies.

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