Proto-Clusters with Evolved Populations around Radio Galaxies at $z \sim 2.5$

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ABSTRACT

We report a discovery of proto-cluster candidates around high redshift radio galaxies at $z \sim 2.5$ on the basis of clear statistical excess of colour-selected galaxies around them seen in the deep near-infrared imaging data obtained with CISCO on Subaru Telescope. We have observed six targets, all at similar redshifts at $z \sim 2.5$, and our data reach to $J = 23.5$, $H = 22.6$ and $K = 21.8$ (5σ) and cover a $1.6' \times 1.6'$ field centered on each radio galaxy. We apply colour cuts in $J H K_s$ in order to exclusively search for galaxies located at high redshifts, $z > 2$. Over the magnitude range of $19.5 < K < 21.5$ we see a significant excess of red galaxies with $J-K > 2.3$ by a factor of two around the combined radio galaxies fields compared to those found in the general field of GOODS South. The excess of galaxies around the radio galaxies fields becomes more than factor of three around $19.5 < K < 20.5$ when the two-colours cuts are applied with $JHK$s. Such overdensity of the colour-selected galaxies suggest that those fields tend to host high density regions at high redshifts, although there seems to be the variety of the density of the colour-selected galaxies in each field. In particular, two radio galaxies fields out of the six observed fields show very strong density excess and these are likely to be proto-clusters associated to the radio galaxies which would evolve into rich clusters of galaxies dominated by old passively evolving galaxies.

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

1 INTRODUCTION

From many previous studies based on fundamental planes and colour-magnitude (CM) relations in clusters up to $z \sim 1.3$, it appears that major star formation in the brightest cluster galaxies was virtually completed by $z \sim 2$ (e.g., Bower, Lucey, & Ellis 1992, Ellis et al. 1997, Kodama et al. 1998, Stanford, Eisenhardt, & Dickinson 1998, van Dokkum et al. 1998, Blakeslee et al. 2003). Therefore, one expects to find proto-clusters dominated by already passively evolving galaxies even beyond $z \sim 2$. Searching for such ancestors of present-day rich clusters of galaxies is not an easy task, however, since it requires a large volume to survey in order to find such rare objects. Radio galaxies can be viewed as good markers of such high density regions at high redshifts, since they are among the most massive galaxies at any redshift ($M_{\text{star}} > 10^{11} M_\odot$, Rocca-Volmerange et al. 2004). In fact, about half of powerful radio galaxies at intermediate redshift inhabit rich environments (Hill & Lilly 1997, Bornancini, Lambas, & De Breuck 2006). The hypothesis that radio galaxies point us towards proto-clusters at high redshift has been further supported by the recent finding of a correlation between AGN activity and bulge mass (Magorrian relation, Gebhardt et al. 2000). Given this relation, it is natural to imagine that massive cD galaxies sitting in deep potential well of clusters tend to host massive powerful AGN and hence they are viewed as radio galaxies at high redshift.

Narrow-band surveys of Lyα emitters around high-$z$ radio galaxies have been intensively conducted by the Leiden group (e.g., Kurk et al. 2000, Venemans et al. 2002) over many years who discovered a large number of emitters at the same redshifts of the radio galaxies, and a large fraction of those emitters have been spectroscopically confirmed (e.g., Kurk et al. 2000, Venemans et al. 2002). These overdense regions of star forming galaxies are embedded in large scale structures at high redshifts and are likely to evolve...
into massive systems at the present day, such as clusters of galaxies.

Alternative approach is to find evolved populations at longer wavelength. This is complementary to the emitter surveys. Best et al. (2003) found an excess of red galaxies with $R - K > 4$ around radio-loud AGNs at $z \sim 1.6$. Hall et al. (1998) and Kodama & Bower (2003) also found statistical overdensities of red galaxies around radio-loud AGNs at $1 \leq z \leq 1.5$ in near-infrared surveys. Wold et al. (2003) also report overdensities of red galaxies in optical–NIR colours around 13 QSO’s at $2 \leq z \leq 3$. These studies indicate that there is also an excess of evolved population around the high-$z$ radio galaxies, as expected if they are embedded in proto-clusters.

We take the second approach and extend the previous analyses to higher redshift based on the near-infrared (NIR) imaging. And in this Letter, we report a discovery of the overdensity of NIR-selected galaxies in the fields of six radio galaxies at $z \sim 2.5$.

The Vega-referred magnitude system is used throughout the paper.

## 2 OBSERVATION AND DATA REDUCTION

We performed the $JHK$-bands imaging observations of the fields of the five radio galaxies and one radio-loud QSO (4C +04.81) at $z \sim 2.5$ with CISCO (Motohara et al. 2002) on the Subaru Telescope on 2005 March 21-22 and September 19-20. CISCO has the field of view of about $1.8 \times 1.8$ arcmin$^2$ with 0.105" pixel scale. The target information and exposure time are given in Table 1. The weather conditions were stable during the observations, and seeing sizes were between 0.3" and 0.7" (FWHM).

The data were reduced using the IRAF software package as described in Kajisawa & Yamada (2007). We performed flat-fielding with the superflat frames for the CISCO data (Motohara et al. 2002), and subtracted the dark and sky background. Then the data were co-registered and combined. We also reduced the archival CISCO data for 4C -00.62 (5600 sec in J-band and 1040 sec in K-band) and 4C +23.56 (5600 sec in J-band, 1600 sec in H-band and 1200 sec in K-band) and combined together. These are included in Table 1. Our final multi-band combined images have the slightly smaller field of view of about $1.6 \times 1.6$ arcmin$^2$, which corresponds to $\sim 0.77b_{70}$Mpc on a side at $z \sim 2.5$ (We assume a cosmology of $\Omega = 0.3$, $\Lambda = 0.7$). For each target, the images were convolved with a Gaussian kernel to match the PSFs to the worst one. The final PSF for each target is also given in Table 1.

Source detection was performed in the K-band images using the SExtractor image analysis package (Bertin & Arnouts 1996). We adopted MAG_AUTO from the SExtractor as the total K-band magnitude of detected objects. For the colour measurements, we used the MAG_AUTO with the Kron factor of $k = 2$, which corresponds to the 20% smaller aperture size than that used in total magnitude with default value $k = 2.5$. Kron radius of each object was determined in the K-band images and the same radii were used for all $J$, $H$, and $K$-bands.

The UKIRT Faint Standards were used for the flux calibration. For the data obtained in the March run, we had to shift the $H$-band zero-point by 0.13 mag in order to reproduce the stellar tracks in $JHK$ (Kidger & Martin-Luis 2003) using the observed stellar objects in our combined images.

The 5σ limiting magnitude at 1.2 arcsec diameter is about $J = 23.5$, $H = 22.6$ and $K = 21.8$, respectively. All the magnitudes are corrected for the Galactic extinction, which is estimated at the positions of the radio galaxies (near the center of each observed field) based on Schlegel, Finkbeiner, & Davis (1998).

## 3 COLOUR SELECTION OF HIGH-Z GALAXIES

Figure 1 shows $J - K$ vs $K$ colour-magnitude diagrams of the six observed radio galaxies fields. Type of symbols differentiate the galaxies selected with different colour cuts on the $J - K$ vs $H - K$ diagram (Figure 2, see below). The square in each diagram indicates the targeted radio galaxy (radio-loud QSO) at $z \sim 2.5$. Some of the fields contain a bunch of very red galaxies ($J - K \gtrsim 2.3$), in particular 4C -00.62 and 4C +23.56 show sequences of red galaxies which are likely to be progenitors of the colour-magnitude relation of early-type galaxies commonly seen in lower redshift clusters at $z \lesssim 1$. Therefore these two fields are most plausible high-$z$ cluster candidates. For reference, we also plotted an expected C-M relation at $z = 2.5$ using the GALAXEV population synthesis spectral library (Bruzual & Charlot 2003). We assumed a single burst with a duration of 0.1Gyr and the formation redshift of $z_{\text{form}} = 5$. The observed red galaxies tend to be relatively bluer than the model prediction. In contrast, the MRC 0406-244 field contain few red galaxies, which may indicate the variety of the number densities of red companions around radio-loud AGNs at $z \sim 2.5$.

In order to efficiently pick up plausible proto-cluster members associated to the central radio galaxies at $z \sim 2.5$, we make use of our multi-colour photometric data at NIR. We apply three different colour cuts as shown in Figure 2, a combined colour-colour diagram in $J - K$ vs. $H - K$ for all the six fields.

First is a simple and single colour cut of

$$J - K > 2.3$$

as shown in the horizontal dotted line. This colour-cut is the same as is used for the selection of the Distant Red Galaxies at $z \gtrsim 2$, and many of thus selected galaxies are spectroscopically confirmed. (e.g., van Dokkum et al. 2003, F¨orster Schreiber et al. 2004, Reddy et al. 2005). In fact, such red colours of galaxies can only be reproduced either by...
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Figure 1. Colour-magnitude diagrams of the six observed radio galaxies fields. Type of the symbols differentiate the adopted colour selections as indicated in Figure 2 (see also text). Dashed lines show the $2\sigma$ limit at $J$-band. For objects with $J$-band fluxes lower than the limit, the lower limits of $J-K$ color are plotted by symbols with arrows. A square in each panel indicates the targeted radio galaxy. Solid lines represent the expected C-M relation at $z = 2.5$ calculated from a GALAXEV single burst model with a duration of 0.1Gyr with $z_{\text{form}} = 5$. The metallicity of the model is adjusted so that the model coincide with the C-M relation of Coma cluster (Bower, Lucey, & Ellis 1992) at $z = 0.02$.

Balmer/4000Å-break galaxies with old populations at $z \gtrsim 2$ or the foreground galaxies with heavy dust extinction.

Second colour cut uses two colours as:

$$J - K > 2 \times (H - K) + 0.5 \& J - K > 1.5$$  \hspace{1cm} (2)

which are shown by thick solid lines in the figure. Here we overplot the model colour tracks with various star formation histories using the GALAXEV library. As shown, the top left corner of the diagram separated by Equation (2) should be exclusively populated by galaxies located at $2 \lesssim z \lesssim 3$. This criterion is met while the Balmer/4000Å-break of galaxies falls between $J$-band and $H$-band, while most of the foreground and background galaxies would not meet such criterion. Therefore, by applying such colour-cut in $JHK$, we can effectively achieve strong contrast of plausible proto-cluster members at $z \sim 2.5$ against numerous foreground/background contamination. This two-colour-based selection also has a significant advantage over the first one based on the single $J-K$ colour, since the two-colours cut can include younger galaxies or star forming galaxies.
Figure 2. Combined $J - K$ vs. $H - K$ colour-colour diagram of all the six radio galaxies fields. The horizontal dotted line and the thick solid lines show the boundaries of our single colour selection of $J - K > 2.3$ and the two-colours selection with $JHK$, respectively. Different symbols (solid circle, open circle, triangle, cross) correspond to our different colour selections as shown in the legend (see also text). The size of the symbols for the colour-selected galaxies is scaled according to apparent magnitudes in $K$-band (the bigger, the brighter). The six open squares indicate the targeted radio galaxies at $z \sim 2.5$. The long arrow at the left side of the figure shows a reddening vector of Calzetti et al. (2000)'s law of $E(B-V) = 0.3$ at $z = 2.5$. Dashed, dotted and dotted-dash curves represent the GALAXEV models of evolutionary sequences over $0 < z < 4$ of galaxies with $z_{\text{form}} = 5$ for various star formation histories. Pentagons show the points of $z = 2.5$ in the model sequences and shaded squares show those of $z = 1, 2, 3, 4$.

at $z \sim 2.5$ which have relatively blue colours in $J - K$ and would have been missed by the single $J - K > 2.3$ cut. It should be also noted that this selection is robust against dust extinction, since the reddening vector (the long arrow in Figure 2) is almost parallel to the boundary line of the $JHK$-selection. We also confirmed with the Knapp et al. (2001)'s star catalogue that most of cool M, L and T dwarfs should be excluded by this criterion, since they are either too blue in $J - K$ or located on the right side of the boundary line of the $JHK$-selection.

Different types of the symbols correspond to different colour selections. Filled circles show the galaxies which satisfy the both criteria simultaneously. Open circles represent the objects which meet only the second criterion, and open triangle indicate those which meet only the first one (i.e., DRGs which do not satisfy the second colour-cut hence are likely to be background red objects). All the others are shown by crosses.

It is notable that all the five radio galaxies at $z \sim 2.5$ (squares in Figure 2) satisfy the two-colours cut (the remaining square outside of the top left corner is the radio-loud QSO 4C +04.81). This supports that our colour selec-
Table 2. Number densities of the colour-selected galaxies with $K < 21.8$ (arcmin$^{-2}$)

<table>
<thead>
<tr>
<th>Field</th>
<th>$J-K&gt;2.3$</th>
<th>JHK-selected</th>
<th>JHK-selected &amp; $J-K&gt;2.3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4C $-00.62$</td>
<td>2.28 ± 0.93</td>
<td>6.08 ± 1.52</td>
<td>1.52 ± 0.76</td>
</tr>
<tr>
<td>4C $-00.54$</td>
<td>2.78 ± 1.05</td>
<td>2.38 ± 0.97</td>
<td>1.19 ± 0.69</td>
</tr>
<tr>
<td>4C $+23.56$</td>
<td>5.53 ± 1.48</td>
<td>6.72 ± 1.63</td>
<td>3.95 ± 1.25</td>
</tr>
<tr>
<td>MRC 2104–242</td>
<td>1.15 ± 0.66</td>
<td>2.30 ± 0.94</td>
<td>0.38 ± 0.38</td>
</tr>
<tr>
<td>4C $+04.81$</td>
<td>2.31 ± 0.95</td>
<td>1.16 ± 0.67</td>
<td>1.16 ± 0.67</td>
</tr>
<tr>
<td>MRC 0406–244</td>
<td>0.38 ± 0.38</td>
<td>0.38 ± 0.38</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>-0062 &amp; +23.56</td>
<td>3.87 ± 0.87</td>
<td>6.97 ± 1.16</td>
<td>2.71 ± 0.72</td>
</tr>
<tr>
<td>the other 4 fields</td>
<td>1.68 ± 0.39</td>
<td>1.68 ± 0.39</td>
<td>0.65 ± 0.25</td>
</tr>
<tr>
<td>all 6 fields</td>
<td>2.39 ± 0.39</td>
<td>3.39 ± 0.46</td>
<td>1.32 ± 0.29</td>
</tr>
<tr>
<td>GOODS–S</td>
<td>1.66 ± 0.97</td>
<td>1.75 ± 1.03</td>
<td>0.66 ± 0.60</td>
</tr>
</tbody>
</table>

The cumulative number density of the galaxies with $J-K > 2.3$ in all the six radio galaxies fields significantly exceeds that in the GOODS-S at $K > 19.5$. The former density is twice higher than the latter over the magnitude range of $19.5 < K < 21.5$.

The middle panel of Figure 3 shows the cases for galaxies selected by the two-colours cut in JHK (open circles). The galaxies shown by the filled circles have been further selected as having red colours of $J-K > 2.3$ in addition to the two-colours cut. We see a significant excess in densities of the JHK-selected galaxies around the radio galaxies. In fact, the overdensity is more than factor of three compared to that of the GOODS-S at $19.5 < K < 20.5$. Red subsample with $J-K > 2.3$ also shows similar overdensity of about factor three over the range of $19.5 < K < 22$.

In the right panel of Figure 3 we show the same plots as in the middle panel but for only the two highly plausible proto-cluster candidates, namely 4C $-00.62$ and 4C $+23.56$ fields. The overdensity of galaxies selected by the two-colours cut is now more than factor of five compared to the general field. The excess is even higher for the red subsample with $J-K > 2.3$. Such strong excess of NIR-selected (approximately stellar mass-selected) galaxies indicates that these fields are likely to be proto-clusters with evolved populations associated to the central radio galaxies at $z \sim 2.5$, which would evolve into rich clusters of galaxies today dominated by old passively evolving galaxies. In fact, these two fields mainly cause the significant excess seen in all the six fields, while the average density of the other four fields is consistent with that of the general field within the uncertainty (see Table 2).

In Figure 3A we show the spatial distribution of the colour-selected galaxies in the two proto-cluster candidates around the $z \sim 2.5$ radio galaxies. Despite of poor statistics, it is suggestive that those colour-selected member candidates are distributed non-uniformly around the central radio galaxies. Such non-uniform distribution of galaxies in proto-clusters has also been reported recently by Croft et al. (2004) who found a filamentary structure in the spatial distribution of spectroscopically confirmed Lyα emitters associated to a radio galaxy at $z = 2.16$. The mass-selected members of proto-clusters may similarly trace such filamentary structures at least over the scale of $\sim 0.8h_{70}^{-1}$Mpc at this observed epoch.

4 OVERDENSITIES OF HIGH-$z$ GALAXIES

In order to quantify the overdensities of the colour-selected galaxies around the high-$z$ radio galaxies, we use GOODS-South survey (Giavalisco et al. 2004) as a comparison field for which the public VLT/ISAAC ver1.5 data are available.

The JHK-bands data of the GOODS-S has similar depths and similar PSF to those of our CISCO data, and are suitable for our purpose. The area used in the analysis is 94 arcmin$^2$, which is significantly larger than that of our radio galaxies fields. We performed the source detection and photometry exactly in the same manner as for the CISCO images.

In Figure 3B we compare the cumulative $K$-band number densities of the colour-selected galaxies in the radio galaxies fields and in the GOODS-S field. In the left panel, we plot the number counts of all the $K$-selected objects and the galaxies with $J-K > 2.3$. Note that the excess of all the $K$-selected objects at the bright end ($K \lesssim 19$) is due to stars in the radio galaxies fields, especially in the case of 4C $+23.56$ field which contain numerous stellar objects (Figure 1). The number counts of galaxies that are not selected by any color cut ("the others" in Figure 2) in the radio galaxies fields and GOODS-S are consistent, if we exclude these star excess in the radio galaxies fields by the selection such as $J-K > 1.0$ or $K > 19$. The excess of all the $K$-selected objects at $K > 19$ is caused by the overdensity of the color-selected galaxies as seen below.
**Figure 3.** Combined cumulative number counts of galaxies in the radio galaxies fields (solid lines) and those in a control field GOODS-South (dashed lines). **Left:** For all the $K$-selected objects (squares) and for red galaxies with $J-K > 2.3$ (triangles). **Middle:** For galaxies selected by two-colours cut (open circles) and for galaxies which satisfy the two criteria simultaneously (solid circles). **Right:** Same as the middle panel but only for the two most probable proto-clusters of 4C$-00.62$ and 4C$+23.56$. Errorbars on the radio galaxies fields are Poissonian (i.e., square roots of the observed numbers), and errorbars on the GOODS-S data indicate the field-to-field variance scaled to the same area as the radio galaxies fields (six, six and two times $1.6 \times 1.6$ arcmin$^2$ for the left, middle and the right panel, respectively).

**Figure 4.** Spatial distribution of the two most probable proto-clusters, 4C$-00.62$ and 4C$+23.56$. Symbols are the same as Figure 2.

### 5 SUMMARY

We searched for proto-clusters around the radio galaxies at $z \sim 2.5$ based on the deep $JHK$-bands imaging taken with Subaru telescope. In order to largely subtract foreground/background contamination and have high contrast of proto-cluster member candidates associated to the radio galaxies, we applied several colour selections; (1) a widely used single colour cut of $J-K > 2.3$ and (2) our new two-colours cut with $JHK$-bands. In both cases, we see a clear excess in the number densities of colour-selected galaxies in the observed radio galaxies fields compared to the general field GOODS-South. The overdensity in the six combined radio galaxies fields is about factor of two for the galaxies with $J-K > 2.3$ and is factor of three for those selected by the two-colours cut, although the variety of the overdensity in each field is also seen. In particular, two radio galaxies fields, namely 4C$-00.62$ and 4C$+23.56$, show the highest overdensities of the colour-selected galaxies of more than factor of five. Therefore, we are likely to be witnessing the assembly and formation of proto-clusters with many evolved galaxies at $z \sim 2.5$ associated to the radio galaxies.

### ACKNOWLEDGEMENTS

We thank Dr. Kentaro Aoki who supported our CISCO observations. We thank Drs. Carlos de Breuk, Joël Vernet, Nick Seymour, Margrethe Wold and Alvio Renzini for discussion on the target selection and the results. This work was financially supported in part by a Grant-in-Aid for the Scientific Research (No. 15740126) by the Japanese Ministry of Edu-
Proto-Clusters at $z \sim 2.5$.

This study is based on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan. This study is also in part based on data collected at Very Large Telescope at the ESO Paranal Observatory under Program ID: LP168.A-0485. Data reduction/analysis was carried out on “sb” computer system operated by the Astronomical Data Analysis Center (ADAC) and Subaru Telescope of the National Astronomical Observatory of Japan.

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