Mapping dusty star formation in and around a cluster at $z = 0.81$ by wide-field imaging with AKARI

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ABSTRACT

We present environmental dependence of dusty star-forming activity in and around the cluster RXJ1716.4+6708 at $z = 0.81$ based on wide-field and multiwavelength observations with the Prime Focus Camera on the Subaru Telescope (Suprime-Cam) and the Infrared Camera onboard the AKARI satellite. Our optical data show that the optical colour distribution of galaxies starts to dramatically change from blue to red at the medium-density environment such as cluster outskirts, groups and filaments. By combining with the AKARI infrared data, we find that 15-μm-detected galaxies tend to have optical colours between the red sequence and the blue cloud with a tail into the red sequence, consistent with being dusty star-forming galaxies.

The spatial distribution of the 15-μm-detected galaxies over ∼200 arcmin$^2$ around the cluster reveals that few 15-μm galaxies are detected in the cluster central region. This is probably due to the low star-forming activity in the cluster core. However, interestingly, the fraction of 15-μm-detected galaxies in the medium-density environments is as high as in the low-density field, despite the fact that the optical colours start to change in the medium-density environments. Furthermore, we find that 15-μm-detected galaxies which have optically red colours (candidates for dusty red galaxies) and galaxies with high specific star formation rates are also concentrated in the medium-density environment. These results imply that the star-forming activity in galaxies in groups and filaments is enhanced due to some environmental effects specific to the medium-density environment (e.g. galaxy–galaxy interaction), and such a phenomenon is probably directly connected to the truncation of star-forming activity in galaxies seen as the dramatic change in optical colours in such environment.

Key words: galaxies: clusters: individual: RXJ1716.4+6708 – galaxies: evolution – galaxies: starburst – large-scale structure of Universe.

1 INTRODUCTION

1.1 Galaxy properties as a function of environment

Galaxies live in various environments. Recent redshift surveys have shown filamentary-large-scale structures in the local Universe. In the distant Universe, at least up to $z \lesssim 1$, similar filamentary nature of large-scale structures is found around clusters through wide-field observations of distant clusters (e.g. Kodama et al. 2005). There are also some hints that the large-scale structure is present at much higher redshifts up to $z \sim 6$ (Shimasaku et al. 2003; Ouchi et al. 2005).

Environment must have played an important role in the history of galaxy evolution since galaxy properties are strongly dependent on environment. This is first noted by Dressler (1980), who showed that early-type galaxies dominate in high-density regions while late-type galaxies tend to live in low-density regions. This trend is called ‘morphology–density relation’. After the Dressler’s work, this interesting trend was confirmed and extended by many authors (e.g. Postman & Geller 1984; Dressler et al. 1997; Goto et al. 2005).

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2003c; Postman et al. 2005). However, it is still unclear what is the key physical process to produce the morphology–density relation or other environmental dependence of galaxy properties.

The morphology–density relation can be understood, at least partly, as a result of morphological transformation of a substantial number of galaxies when they entered high-density environments. Many mechanisms to suppress the star-forming activity and to contribute to the morphological transformation have been proposed (see the review by Boselli & Gavazzi 2006). For example, ram-pressure stripping due to the interaction with hot plasma gas filled in the cluster core (e.g. Gunn & Gott 1972) is expected to be effective in rich cluster cores. High-speed encounters between galaxies, which are often called ‘galaxy harassment’, should occur in very high density environments (e.g. Moore et al. 1996). In addition, mergers or galaxy–galaxy interactions should also contribute to the galaxy transformation (e.g. Toomre & Toomre 1972). Interactions with the cluster potential may also cause a tidal force when galaxies pass the central region of clusters (e.g. Byrd & Valtonen 1990). Another mechanism that can be effective is the so-called ‘strangulation’ (e.g. Larson, Tinsley & Caldwell 1980), which leads to a slow decline in star formation rate (SFR) after a galaxy falls into a more massive (i.e. group or cluster) halo. Identification of the key processes behind the galaxy transformation is one of the major remaining issues in galaxy evolution.

It is well known that the fraction of blue star-forming galaxies in clusters increases towards higher redshifts (Butcher-Oemler effect; Butcher & Oemler 1984). Therefore, the transition from blue active galaxies to red passive galaxies should be more commonly seen in distant clusters. We can expect to see directly such truncation in action through observations of distant clusters (see also Goto et al. 2003a). However, importantly, it is reported that most of the actions take place in the outskirts of clusters rather than in the cluster core. In fact, some recent studies focus on the galaxy properties in the surrounding regions of clusters and try to identify the environment where the truncation of star formation occurs in accreted galaxies (e.g. Abraham et al. 1996; Balogh et al. 1999; Pimbblet et al. 2002). In such environment, it is reported that passive spirals (i.e. spiral morphology but no star formation) tend to be found (e.g. Goto et al. 2003b). Kodama et al. (2001) performed a wide-field imaging of the CL0039 cluster at $z = 0.41$ and discovered that the colour distribution changes dramatically at the intermediate-density environment which corresponds to groups/filaments. A very similar result was reported by Tanaka et al. (2005) for the surrounding regions of higher redshift clusters, CL0916 at $z = 0.55$ and RXJ0152 at $z = 0.83$. They suggest that the intermediate-density environment such as groups or filaments around clusters is the very sites where the truncation of galaxies is taking place. These pioneer works are really telling us the need for wide-field observation of distant clusters in order to study the physical mechanisms that are responsible for the truncation of galaxies from active to passive phase during the course of hierarchical assembly of galaxies to clusters.

1.2 Dusty star-forming galaxies in the local and distant Universe

It is well known that red galaxies tend to have little star-forming activity (passive galaxies), while blue galaxies have ongoing star-forming activity (star-forming galaxies) at a given redshift. However, the classification of passive or star-forming galaxies based only on their optical colours is sometimes highly uncertain. In fact, Haines, Gargiulo & Merluzzi (2008) showed that ~30 per cent of field red-sequence galaxies selected from optical colour–magnitude diagrams have ongoing star formation activity with EW(Hα) > 2 Å, using their local galaxy samples from Sloan Digital Sky Survey (SDSS; York et al. 2000). Davoody et al. (2006) also showed in their SDSS and Spitzer Wide-Area Infrared Extragalactic (SPIRE) survey (Lonsdale et al. 2003) that ~18 per cent of their samples have red optical colours and infrared (IR) excess at the same time, which include both active galactic nuclei (AGN) and ongoing dusty star-forming galaxies. Similar results are shown for cluster red sequence. For example, Wolf, Gray & Meisenheimer (2005) studied the Abell 901/902 cluster at $z = 0.17$, and showed that ~22 per cent of red-sequence galaxies are dusty red galaxies from the fitting results of spectral energy distribution (SED) using the Classifying Objects by Medium-Band Observations in 17 filters (COMBO17; Wolf, Meisenheimer Röser 2001).

Instead of using optical colours, optical emission lines [e.g. [OⅡ]$(\lambda = 3727$ Å) and Hα $(\lambda = 6563$ Å)] are often and widely used to measure SFRs (Kennicutt 1998). However, these lines, especially [OⅡ] lines in the rest-frame ultraviolet, are attenuated by interstellar dust in the galaxies. Also, [OⅡ] strength is affected by AGN contribution, if any, and dependent on metallicity as well. Although Hα line is a much better indicator than [OⅡ] in this respect (and is in fact one of the best indicators of SFRs among emission lines), it is redshifted to near-infrared (NIR) regime at $z \gtrsim 0.5$, where large format wide-field camera or spectrograph has become available only recently. Given these difficulties in optical and NIR observations, IR luminosity of a galaxy that can be sensitively obtained by space telescopes, serves as an ideal measure of SFR, and it is also well calibrated with local starburst galaxies (Kennicutt 1998). Since the total IR luminosity of a galaxy can be estimated through single broad-band imaging at mid-infrared (MIR) (e.g. Takeuchi et al. 2005), it is critically important to observe clusters in MIR bands as well as in the optical/NIR in order to reveal the hidden star formation activity and hence trace its true star formation history. This is especially true at high redshifts, because the luminous infrared galaxies (LIRGs) which have $10^{11} \leq L_{IR}(8–1000$ μm) $\leq 10^{12} L_{⊙}$ and ultraluminous infrared galaxies (ULIRGs) which have $L_{IR}(8–1000$ μm) $\geq 10^{12} L_{⊙}$ are more commonly seen in the distant Universe than in the local Universe (e.g. Sanders & Mirabel 1996; Le Floc’h et al. 2005).

1.3 Infrared observation of galaxy clusters

Taking these situations into account, wide-field MIR study of galaxy clusters covering entire structure around the cluster is required to investigate the ‘true’ environmental dependence of star formation activities of galaxies. However, until recently, IR studies of galaxy clusters have been conducted mainly with the Infrared Space Observatory satellite (ISO; Kessler et al. 1996), which have been limited to very inner regions of clusters (see the review by Metcalfe, Fadda & Biviano 2005). Even though, some of these studies showed the importance of large amount of hidden star formation activity in the cluster environment (e.g. Duc et al. 2002). The recent advent of the Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004) has enabled us to investigate wider fields of distant clusters up to $z \sim 0.8$. Geach et al. (2006) observed very wide field (25 × 25 arcmin$^2$) around CL0024 ($z = 0.39$) and MS0451 ($z = 0.55$) clusters by mosaicing MIPS images. Marcillac et al. (2007) and Bai et al. (2007) observed RXJ0152 and MS1054 (both at $z = 0.83$), respectively, but their field coverage is limited only to cluster central regions. Bai et al. (2007) actually imply that for rich clusters at $z \sim 0.8$ even wider field IR studies are needed.
In the local Universe, it is well established that star formation activity depends strongly on environment in the sense that it systematically declines towards higher density regions (e.g. Gómez et al. 2003). Recently, however, surprising results are reported where such a relationship between star formation activity and local galaxy density becomes inverted at \( z \sim 1 \) (Cooper et al. 2008; Elbaz et al. 2007), i.e. SFR increases towards higher density environment at \( z \sim 1 \). This is naively expected that one approaches to the formation epoch of cluster galaxies which is probably systematically skewed to higher redshifts compared to the formation epoch of field galaxies. Therefore, looking back the environmental dependence of star formation activity in galaxies as a function of redshift is a basic but vital step towards understanding the environmentally dependent galaxy formation and evolution.

In this paper, we conduct for the first time a panoramic MIR study of a \( z \sim 0.8 \) cluster, over a very large area including surrounding groups, filaments and outer fields. Throughout this paper, we use \( \Omega_m = 0.3 \), \( \Omega_{\Lambda} = 0.7 \) and \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \). Magnitudes are all given in the AB system, unless otherwise stated.

2 DATA

2.1 RXJ1716 cluster

The RXJ1716.4+6708 cluster at \( z = 0.81 \) that we study in this paper was first discovered in the ROSAT North Ecliptic Pole Survey (NEP; Henry et al. 1997). Optical spectroscopy was performed by Gioia et al. (1999) and 37 cluster members were identified. Using these spectroscopic samples, Gioia et al. (1999) determined the velocity dispersion of this cluster to be \( \sigma = 1522^{+215}_{-150} \text{ km s}^{-1} \). This value is relatively large for its rest-frame X-ray luminosity of \( L_{\text{bol}} = 13.86 \pm 1.04 \times 10^{44} \text{ erg s}^{-1} \) and the temperature \( kT = 6.8^{+1.0}_{-0.6} \text{ keV} \) which are based on Chandra data (Ettori et al. 2004, see also Gioia et al. 1999; Vikhlinin et al. 2002; Tozzi et al. 2003). Therefore, it is suggested that this cluster is not totally virialized yet. In fact, the brightest cluster galaxy (BCG) of this cluster is located on the north-western edge of the structure (Clowes et al. 1998), which may be linked to the fact that the structure of this cluster is still being formed. The weak-lensing mass of this cluster is estimated to be \( 2.6 \pm 0.9 \times 10^{14} M_{\odot} \) (Clowes et al. 1998). This is consistent with the estimated mass based on the X-ray data in Ettori et al. (2004); \( M_{\text{X}} = 4.35 \pm 0.83 \times 10^{14} M_{\odot} \). As the X-ray properties of this cluster suggest this cluster is relatively rich for a cluster at this redshift.

It has been known that this cluster has a small subcluster or group to the north-east (NE) of the main cluster, and the morphology of the X-ray image of this cluster elongates towards the subcluster (e.g. Jeltema et al. 2005). Koyama et al. (2007) performed wide-field optical imaging of this cluster and discovered prominent large-scale structures penetrating the cluster core and the second group of this cluster towards the south-west (SW) of the cluster core based on the photometric redshift technique (see Section 2.2).

2.2 Optical data

We have been conducting the Panoramic Imaging and Spectroscopy of Cluster Evolution with Subaru project (PISCES project; Kodama et al. 2005). Taking advantage of the wide-field coverage of the Prime Focus Camera on the Subaru Telescope (Suprime-Cam; Miyazaki et al. 2002), we have investigated various environments around the X-ray detected distant clusters at \( 0.4 \lesssim z \lesssim 1.3 \) (e.g. Kodama et al. 2005; Nakata et al. 2005; Tanaka et al. 2005, 2006; Koyama et al. 2007; Tanaka et al. 2007a,b). As a part of this project, Koyama et al. (2007) conducted a deep and wide-field optical study of the RXJ1716 cluster with the Suprime-Cam. We observed this cluster in \( VR' \) \( \prime \) bands which neatly bracket the 4000 Å break feature of \( z \sim 0.8 \) galaxies. Catalogues were created with \( z' \lesssim 24.9 \) galaxies, which correspond to 5\( \sigma \) detection limits of our \( z' \)-band image. We select the cluster members by photometric redshift technique (phot-\( z \)) using the code of Kodama, Bell & Bower (1999), and showed the prominent large-scale structures around the cluster (see figs 3 and 4 of Koyama et al. 2007). Galaxies with \( 0.76 \lesssim z_{\text{phot}} \lesssim 0.83 \) were used to map out the large-scale structures and this member selection is used in this paper. See Koyama et al. (2007) for the summary of our optical data, data reduction and the combined colour image of this cluster.

2.3 Infrared data

We obtained deep and wide-field IR imaging data for the RXJ1716 cluster with the Infrared Camera (IRC; Onaka et al. 2007) onboard the AKARI satellite (Murakami et al. 2007). Due to the good visibility of NEP directions from AKARI, we could get very deep data for the RXJ1716 cluster which is located near the NEP (see Section 2.1). The observations were executed from November 26 to December 8 in 2006, on an open-use program CLNEP (PI: T. Kodama) and a mission program CLEVL (PI: H. M. Lee). We observed this cluster in the N3 (3.3 \( \mu \)m), S7 (7.0 \( \mu \)m) and L15 (15.0 \( \mu \)m) filters, using the Astronomical Observation Templates (AOT) for deep observation (IRC05) with an AOT filter combination parameter of ‘b’ (see AKARI IRC Data User Manual, Lorente et al. 2007). We should note that the L15 filter neatly captures the polycyclic aromatic hydrocarbon (PAH; Puget & Leger 1989) emissions from star-forming galaxies at \( z \sim 0.8 \) (Fig. 1).

We set the three field of views (FoVs) (F1, F12 and F2) to cover the large-scale structures around the RXJ1716 cluster photometrically discovered by Koyama et al. (2007) (see Figs 2 and 7b). The number of the pointed observations and corresponding integration time for each field are summarized in Table 1. Note that 10 and 30 frames with effective exposure times 44.4 and 16.4 s were included

![Figure 1](https://academic.oup.com/mnras/article-abstract/391/4/1758/1747186/2.3.png)
The three AKARI FoVs (F1, F12 and F2) on the \( z' \)-band image (left-hand panel) and final co-added \( L15 \)-band image (right-hand panel). North is up and east is to the left in both the figures. The size of each panel is \( \sim 18 \times 18 \) arcmin\(^2\).

**Figure 2.**

### Table 1.

Summary of the AKARI (IR) observation. The number of pointings and corresponding exposure time for each filter and each field is shown.

| Filter | \( F1 \) | \( F12 \) | \( F2 \) |
|--------|--------|--------|--------|
| \( N3 \) | 14 (104 min) | 2 (15 min) | 3 (22 min) |
| \( S7 \) | 14 (115 min) | 3 (25 min) | 3 (25 min) |
| \( L15 \) | 3 (25 min) | 15 (123 min) | 4 (33 min) |

in a single-pointed observation for \( N3 \) and \( S7/L15 \), respectively. Therefore, typically, one-pointed observation corresponds to 7.4 and 8.2 min exposure observation for \( N3 \) and \( S7/L15 \), respectively. IRC has a wide FoV (about \( 10 \times 10 \) arcmin\(^2\)), and our observed fields F1, F12 and F2 covered about 200 arcmin\(^2\) in total (see Figs 2 and 7b). We stress here that our study is the first attempt to cover such a wide field around the \( z \geq 0.8 \) cluster in MIR bands. We can study the cluster core to outskirt regions at once and this is critically important to discuss the environmental dependence of the IR properties of galaxies in and around high-\( z \) clusters.

The data were reduced with the IRC imaging pipeline (version 20071017, Onaka et al. 2007) in a standard manner (see Lorente et al. 2007). We ran the pipeline for each of the pointed observational data, and we made the reduced image for each of the pointed observations at first. In this process, we subtracted the median filtered sky with \( 20 \times 20 \) kernel for individual frame before co-adding the frames. Note that the pipeline often fails to align \( L15 \) frames because of the small number of firmly detected sources. Therefore, we used ‘coaddLusingS’ option in the pipeline, which uses the alignment of the \( S7 \) frames to align the \( L15 \) frames (see also Lorente et al. 2007; Wada et al. 2007). After that, we matched the position of all the images generated from each pointed observational data using the IRAF tasks ‘GEOMAP’ and ‘GEOTRAN’, and we co-added all the images together. The final 15-\( \mu \)m image is shown in the right-hand panel of Fig. 2.

Since the exposure times are not uniform over the observed field, limiting flux depends on the position. However, as we observed with 14 pointings for \( F1 \) field in \( N3 \) and \( S7 \) band and with 15 pointings for \( F12 \) field in \( L15 \) band (see Table 1), the depths of the data depend mainly on whether a position is covered by these deep observations or not. We thus divide each image into ‘deep’ and ‘shallow’ regions, and estimate the sky noise limits of both regions by a simple aperture photometry of randomly distributed apertures in all the images. Note that we do not use areas near very bright sources. The aperture diameters were set to 8, 10 and 11 arcsec for \( N3 \), \( S7 \) and \( L15 \), respectively. These correspond to twice the size of full width at half-maximum (FWHM) of the point spread function of each image. We also used these diameters for source extraction (see below). The 5\( \sigma \) limiting fluxes of deep and shallow regions for each band are summarized in Table 2. Sources were extracted using SExtractor (Bertin & Arnouts 1996). Using the same size of apertures (i.e. twice the size of FWHM of each image), we measured FLUX\(_{\text{APER}} \) of sources in each image. We made the 3 \( \mu \)m catalogue with FLUX\(_{\text{APER}} \geq 7.0 \) \( \mu \)Jy in \( N3 \) band, the 7 \( \mu \)m catalogue with FLUX\(_{\text{APER}} \geq 21.9 \) \( \mu \)Jy in \( S7 \) band and the 15-\( \mu \)m catalogue with FLUX\(_{\text{APER}} \geq 66.5 \) \( \mu \)Jy in \( L15 \) band. These 5\( \sigma \) detection criteria for the deep regions approximately correspond to \( \sim 3.5\sigma \) detection for the shallow regions (Table 2). Also, we use FLUX\(_{\text{AUTO}} \) and MAG\(_{\text{AUTO}} \) as the total fluxes and the total magnitudes of the sources as shown in Wada et al. (2007). We note that all the scientific quantities such as total IR luminosities and SFRs are measurements based on these total fluxes (see also Section 3.2).

### 3 ANALYSIS

#### 3.1 Cross-identification between optical and IR sources

We need to cross-match between the AKARI IR sources and the Subaru optical sources. We should be very careful when we identify the sources in a crowded region like a galaxy cluster. We have cross-identified the 15-\( \mu \)m sources in the optical (\( z' \)-band) image and created ‘15-\( \mu \)m member’ catalogues in the following way.

First, we search for any optical counterpart(s) using a 8 arcsec radius from each 15-\( \mu \)m source. This radius is sufficiently larger than the FWHM of the point spread function (PSF) in the 15-\( \mu \)m image (\( \sim 5.5 \) arcsec). The relative positional accuracy between the \( z' \)-band image and the \( L15 \) image is also sufficiently smaller (\( \lesssim 1 \) arcsec) than this search radius. We find that 149 of 15-\( \mu \)m sources in a single-pointed observation for \( N3 \) and \( S7/L15 \), respectively, that are not detected in the Subaru optical catalogues. The number of pointings and corresponding exposure time for each filter and each field is shown.

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| Filter | \( F1 \) | \( F12 \) | \( F2 \) |
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**Table 2.** 5\( \sigma \) limiting fluxes of \( N3 \), \( S7 \) and \( L15 \) images. Deep regions approximately correspond to \( F1 \) field of \( N3/S7 \) images and \( F12 \) field of \( L15 \) image. Shallow regions are defined as the rest of the deep regions (see the text).

| Filter | Deep (5\( \sigma \)) (\( \mu \)Jy) | Shallow (5\( \sigma \)) (\( \mu \)Jy) |
|--------|----------------|----------------|
| \( N3 \) | 7.0 | 11.9 |
| \( S7 \) | 21.9 | 33.0 |
| \( L15 \) | 66.5 | 96.5 |
sources have at least one phot-z member galaxy [i.e. with $0.76 \leq z_{\text{phot}} \leq 0.83$ as used in Koyama et al. (2007) to trace the large-scale structure] within this radius. Secondly, we carefully examine all of them by eye. We basically select the nearest object as the optical counterpart of each 15-μm source. If the optical counterpart is confirmed to be an isolated phot-z member galaxy, we put it in the ‘resolved 15-μm member catalogue’ (see an example in Fig. 3a).

On the other hand, due to the large FWHM of the PSF of the 15-μm image compared to the optical image, some 15-μm sources are not resolved in the source extraction process although they show multiple peaks or extended shape in the 15-μm image. We find that the number of such extended sources is not negligible. Therefore, in such a case, we carefully look at the shape of the 15-μm image by eye and judge if the 15-μm multipeak or extended source is associated with any phot-z members. If we find any phot-z members associated with the 15-μm source, we put it into the second catalogue, named ‘unresolved 15-μm member catalogue’ (see the examples in Figs 3b and c).

Most of the ‘resolved’ 15-μm members have optical counterparts within 2 arcsec radius (median value is 0.7 arcsec), while counterparts of ‘unresolved’ 15-μm members are found at relatively larger distance (median value is 2.5 arcsec). We note that in the latter catalogue, there are some 15-μm sources which have more than one optical counterparts (Figs 3b and c). For such sources, there is a possibility that the 15-μm flux of them is measured as a sum of the fluxes from more than one objects. Therefore, we cannot know its separated individual 15-μm fluxes correctly and we can only know an upper limit. The cross-identification itself is more difficult for unresolved 15-μm members due to the complexity of the shape of the 15-μm sources. Given these problems, we have to treat them carefully in the following sections, and in fact we do not include these ‘unresolved’ 15-μm members in the following analyses whenever the 15-μm fluxes are required. We count these sources only if the detection at 15 μm is concerned. However, we have confirmed that the inclusion of such ‘unresolved’ sources or not does not affect our results (see also Section 4.4).

For the total of 436 sources detected at 15 μm in our AKARI field, we find that 91 of 15-μm sources are associated with phot-z members. In this sample, 54 sources are turned out to be resolved 15-μm members. The remaining 37 sources are unresolved cases and we have 65 unresolved 15-μm members. This is because about a half of these 37 sources are associated with more than one phot-z members. Therefore, we have 54 resolved and 65 unresolved 15-μm members in total as the numbers of optical counterparts. For the resolved 15-μm members, we search for a counterpart in N3 and S7 images in the same way as the cross-identification between L15 sources and optical sources described above (i.e. after searching for N3/S7 counterparts using 8 arcsec radius from each 15-μm member, checking them by eye). In the resolved 15-μm members, 18 sources are identified in both N3 and S7 bands, and 24 sources are identified only in N3 band. The rest of them are not well distinguished as a single object in either N3 or S7 bands. Our main interest is in the 15-μm-detected cluster members because these sources are the candidates for dusty star-forming galaxies. Therefore, we use 15-μm-detected cluster members in the following sections regardless of the identification in N3 or S7 images.

Note that photometric redshift is not always the precise criterion to select the cluster member galaxies. There remains a possibility that some foreground/background contaminations are included in our 15-μm member catalogues. Unfortunately, we cannot estimate the probability that a galaxy out of the 0.76 $\leq z_{\text{phot}} \leq 0.83$ range falls into this redshift range by our phot-z estimation because we do not have spectroscopic information of normal galaxies in our RXJ1716 field. However, we do know some spectroscopic redshifts for the X-ray sources in our RXJ1716 field from Kim et al. (2007). We find that only 1 out of 27 such sources is misidentified as our phot-z member. Therefore, the foreground/background contamination in our phot-z samples is expected to be very small, although firm conclusion waits for a similar check using normal galaxies, which cannot be done at the moment because of unavailability of their redshifts. Marcillac et al. (2007), who studied the RXJ0152 cluster at $z = 0.83$, estimated that the fraction of 151 spectroscopically confirmed non-members that fall into the 0.76 $\leq z_{\text{phot}} \leq 0.83$ range is only $\sim 7$ per cent. They used the photometric redshifts estimated in Tanaka et al. (2005) (i.e. phot-z code in Kodama et al. 1999, using the Subaru VRI′z′ data), which is the same as that used in this study. Marcillac et al. (2007) also showed that the photometric redshifts worked well for their spectroscopically confirmed MIR member galaxies ($|\Delta z| = |z_{\text{phot}} - z_{\text{spec}}| \sim 0.01$). Therefore, the photometric redshift selection would not do any critical harm on the statistical properties of our 15-μm members, either. We should, however, confirm the physical association of these sources to the cluster through spectroscopic follow-up observations in our future work.

3.2 Derivation of star formation rates for the 15-μm members

The AKARI’s L15 band corresponds to $\sim 7$–9 μm in the rest frame of the RXJ1716 cluster at $z = 0.81$. This wavelength range neatly includes 7.7 and 8.6 μm broad-line emission features of PAHs (Fig. 1). It is well known that MIR broad-band luminosity correlates with total IR luminosity ($L_{IR}$) and hence SFR through a good correlation between $L_{IR}$ and SFR (Kennicutt 1998). It is particularly true in this case, since the PAH emissions originate from photo dissociation regions associated to star-forming regions and the intensity of PAH features themselves are in good correlation with SFR (e.g. Chary & Elbaz 2001).

To derive $L_{IR}$ of each galaxy, we use the template SEDs of starburst galaxies from Lagache et al. (2004). We calculate the conversion factor of our 15-μm (rest frame $\sim 8$ μm) luminosity to the total (8–1000 μm) luminosity using their five template SEDs (i.e. templates for 10$^0$, 10$^{10}$, 10$^{11}$, 10$^{12}$ and 10$^{13}$ L$_{\odot}$ starburst galaxies). The derived correlation between $uLV$ (8 μm) (AKARI L15-band flux) and $L_{IR}$ (8–1000 μm) is shown in Fig. 4. Using this correlation, we estimate the total IR luminosity from the measured total 15-μm flux (i.e. FLUX/AUTO value from SExtractor) of each 15-μm

![Figure 3](https://academic.oup.com/mnras/article-abstract/391/4/1758/1747186/1758-1770)
in clusters is only $\sim 1$ per cent from optical spectroscopic surveys (e.g. Dressler et al. 1999 for their 10 clusters at $0.37 < z < 0.56$). However, an excess of X-ray detected AGN is also reported in some clusters (e.g. Martini et al. 2002). In our 15-μm member galaxies, we identified three X-ray point sources using the Chandra X-ray point source catalogue constructed by Kim et al. (2007). Although we admit that we cannot detect all AGN in X-ray, these three sources are strong candidates for AGN and we consider that at least a part of their 15-μm fluxes is emitted from AGN. Another possible technique to distinguish AGN from starburst galaxies is to use rest-frame NIR colours, based on the different NIR SED properties of these two populations (e.g. Webb et al. 2006). Rest-frame NIR SEDs for starburst galaxies are relatively flat, while AGN produce power-law SEDs which increases towards longer wavelength. In our data set, the slope of the NIR SEDs calculated using the fluxes in N3 (rest-frame 1.8 μm) and S7 (rest-frame 3.9 μm) would be useful. We therefore investigated the N3 – S7 colour of each resolved 15-μm member galaxy to see if there is any possible candidate of AGN. In our 54 resolved 15-μm members with $f$(15μm) ≥ 67 μJy, 18 galaxies are identified in both N3 and S7 bands, 24 are identified only in N3 band, and the remaining 12 are identified in neither N3 nor S7 bands (see also Section 3.1). Out of the 18 galaxies detected in both bands, only two have NIR colour that is redder than N3 – S7 = 0.0, which could be considered as AGN candidates. However, we note that these two sources are not detected in X-ray.

In these ways, we have identified five AGN candidates in total from our 15-μm member galaxies. However, we do not exclude these objects from our sample because we cannot know if all the MIR emissions from these sources are from AGN. It is still possible that starburst is also in place in the AGN host galaxies. We stress here that the effect of including these AGN candidates for our conclusion is negligible (see more detailed discussion in Section 4.4). We should note, however, that we do not have any information of NIR SEDs for the objects that are not detected in either N3 or S7 bands. There remains some possibility that some of these objects could be associated with AGN, but we cannot exclude them under present conditions. In any case, future spectroscopic follow-up observations of the 15-μm members are necessary to discuss the AGN contamination further.

4 RESULTS

4.1 15-μm members on the colour–magnitude diagram

In this section, we present optical properties of the 15-μm-detected galaxies in the RXJ1716 cluster, mainly focusing on optical colours of these galaxies. In Fig. 6(a), we show a colour–magnitude diagram in $R - z'$ versus $z'$ for the entire field covered by the AKARI observations. All the cluster member galaxies selected on the basis of photometric redshifts are shown. The 15-μm cluster members are represented by open symbols. The ‘resolved’ and ‘unresolved’ 15-μm members are indicated by open circles and triangles, respectively. Most of the 15-μm members are optically bright galaxies with $z' < 22.5$ mainly because of the limited depth of the MIR observations.

The 15-μm members are distributed in slightly bluer side of the red sequence, which is often called a ‘green valley’ region. We show in Fig. 6(b) the histograms of $R - z'$ colour distribution for all the phot-$z'$ selected cluster member galaxies with $z' < 22.5$ (open histogram) and for only the 15-μm member galaxies with $z' < 22.5$ (hatched histogram). A clear bimodality is seen in the open histogram, while the hatched histogram shows a unimodal
distribution that fills the gap between the two peaks of red and blue galaxies. This trend is quantified by calculating the fraction of MIR detected galaxies as a function of $R - z'$ colou using the $z' < 22.5$ galaxies (a locus in Fig. 6b). A similar colour distribution was reported in Geach et al. (2006) for two $z \sim 0.5$ clusters based on Spitzer MIPS observations. The medium colours of the MIR detected galaxies bridging the ‘green valley’ would be due to dust reddening of blue star-forming galaxies. We also find that this trend can be seen even if we limit the sample for relatively bright ($z' < 21.5$) or faint ($21.5 < z' < 22.5$) galaxies. We should note, however, that this trend might be produced partly due to the small systematic difference in luminosity of galaxies between those in the green valley (brighter) and those in the blue cloud (fainter).

It is interesting to note that some red-sequence galaxies are detected at 15 μm. It can be interpreted that they are forming stars but are highly reddened by dust. Recently, it is reported that the fraction of such MIR detected star-forming galaxies on the red sequence in the total star-forming galaxies increases towards distant clusters (Saintonge, Tran & Holden 2008). We hereafter call these optically red 15-μm members ‘dusty red galaxies’, and discuss them further in Section 4.4.

4.2 Optical colour transition in the outskirts of the cluster

In this section, we define galaxy environment on the basis of local projected number density of galaxies. We use a nearest neighbour density, which is widely used by many authors (e.g. Tanaka et al. 2005). The number density at each galaxy’s position is calculated using the neighbouring galaxies located within the circle of the radius that is equal to the distance from the galaxy to the 5th-nearest galaxy (hereafter, $\Sigma_{5g}$). In this calculation, all the optically selected phot-z members are used.

Fig. 7(a) shows the $R - z'$ colours of individual member galaxies as a function of the above defined local density ($\Sigma_{5g}$). The colour distribution changes dramatically at $\log \Sigma_{5g} \sim 2.0$ as the median (50 per cent) colour locus suggests. It can also clearly be seen in the fraction of red galaxies that starts to increase sharply at $\log \Sigma_{5g} \geq 1.7$. We divide the galaxies into three environmental bins, namely, low-density ($\log \Sigma_{5g} < 1.65$), medium-density ($1.65 \leq \log \Sigma_{5g} < 2.15$) and high-density ($\log \Sigma_{5g} \geq 2.15$) regions. The medium-density region is defined to a relatively narrow range of local density where the optical colour distribution starts to change. These definitions of the environments may seem a little arbitrary, but our results do not change if we slightly change the definitions of the environments. In Fig. 7(b), we show the spatial distribution of the member galaxies in each environment with different symbols. The high-density region corresponds approximately to the cluster core region. The medium-density environment traces outskirts of the cluster core, groups and filaments. The low-density environment corresponds to the remaining fields outside the groups and filaments. We note that the median value of $\log \Sigma_3$ for all the galaxies with $0.76 \leq \Sigma_{(phot)} \leq 0.83$ in our entire Suprime-Cam field ($34 \times 27$ arcmin$^2$) is $\sim 1.3$. Excluding the cluster region would only lower this value by a negligible amount. Therefore, we can reasonably consider that our low-density region corresponds to a general field at the $z \sim 0.8$ Universe at least in terms of the local density of galaxies.

The above finding that the colour distribution dramatically changes in the ‘medium-density’ environment is consistent with the previous works. Kodama et al. (2001) showed similar results for the $z \sim 0.4$ cluster, and Tanaka et al. (2005) also found similar trends for $z = 0.55$ and 0.83 clusters, both based on the panoramic imaging with Suprime-Cam on the Subaru Telescope. The current result for another cluster (RXJ1716) lends further support to the scenario that galaxies start to be truncated in groups or outskirts of clusters before they entered a very high density environment such as cluster cores. This scenario requires some mechanism that works efficiently in relatively low-density environment and truncates star formation activity.

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Figure 6. Panel (a): the colour–magnitude diagram in $R - z'$ versus $z'$ for all the member galaxies in the field covered by AKARI FoVs. Open circles and triangles represent the resolved and the unresolved 15-μm members, respectively. The three sizes of the symbols (large, middle and small) indicate 15-μm flux with $f(15 \mu m) \geq 100 \mu Jy$, $f(15 \mu m) \geq 100 \mu Jy$ and $f(15 \mu m) \geq 67 \mu Jy$, respectively. The solid line shows the best-fitted colour–magnitude relation defined in Koyama et al. (2007), and the two long dashed lines indicate ± 0.2 mag from the best-fitting colour–magnitude relation. The vertical and slanted short dashed lines show the limiting magnitudes in $z'$ and $R$ band, respectively. Panel (b): $R - z'$ colour distribution of all the member galaxies (open histogram) and the 15-μm members (hatched histogram). Histograms are constructed using only the optically bright $z' < 22.5$ galaxies in the field covered by AKARI FoVs. The solid-line locus indicates the fraction of the 15-μm members in each colour bin (see the label and the tick marks on the right-hand side). Error bars indicate the Poisson errors. The open histogram shows two peaks which correspond to red/blue bimodal populations, while the hatched histogram shows a single broad peak located between the two peaks of the open histogram.
Star formation around a z \sim 0.8 cluster

Figure 7. Panel (a): $R - z'$ colours of phot-z member galaxies (0.76 \leq z_{phot} \leq 0.83) as a function of local projected number densities of member galaxies within the area covered by our AKARI observations. The vertical dotted lines at log \Sigma_{5th} = 1.65 and log \Sigma_{5th} = 2.15 define the ‘low’-, ‘medium’- and ‘high’-density environments as indicated. Three dashed lines represent the loci of the 25th, 50th and 75th percentile colours. The solid line shows the fraction of red galaxies in each environmental bin. Error bars represent the Poisson errors. Panel (b): spatial distribution of the phot-z selected galaxies in high/medium/low-density environments. The contours show the local 2D number density of galaxies at 2, 3, 4, 5 \sigma above the peak of the density distribution. We apply Gaussian smoothing (\sigma = 0.2 \text{ Mpc in physical}) on each galaxy and combine the tails of Gaussian wings to measure the local density at a given point. A bin size of 0.1 Mpc (physical) is used to draw isodensity contours. The three large dashed-line squares show the three FoVs of our AKARI pointing observations. The medium-density environment corresponds to the outskirts of the cluster core, subclumps and filaments.

Figure 8. Panel (a): spatial distribution of the 15-\mu m members around the cluster for the entire field covered by our AKARI observation. Small dots show all the phot-z member galaxies. Open circles and triangles indicate the resolved and the unresolved 15-\mu m members, respectively. The sizes of the open circles and triangles indicate 15-\mu m fluxes as in the previous figure (Fig. 6). Panel (b): close-up view of the central 5 \times 5 arcmin$^2$ region of the left-hand panel. The meanings of the symbols are the same as in the left-hand panel, but contour levels are changed to 3, 5, 10, 15, 20 \sigma above the peak of the density distribution. In this plot, 15-\mu m members are shown down to 3.5\sigma level as thin-line tiny open symbols. Note that few 15-\mu m members are detected in the very central region (i.e. \lesssim 1 arcmin from the cluster centre).

4.3 Low star formation rate in the cluster core

We show in Fig. 8(a) the spatial distribution of 15-\mu m member galaxies on top of the distribution of phot-z member galaxies over the 18 \times 18 arcmin$^2$ area centred on the RXJ1716 cluster. This area corresponds to \sim 15 \times 15 Mpc in comoving scale at z = 0.81. The open circles and triangles indicate the positions of the resolved and the unresolved 15-\mu m members, respectively. The 15-\mu m fluxes of the 15-\mu m members are indicated by three different sizes of the symbols (brighter objects are shown in larger symbols).

A close-up map of the central 5 \times 5 arcmin$^2$ region is shown in Fig. 8(b). It is worth noting that a 5 \times 5 arcmin$^2$ field corresponds to the FoV of a single pointing with Spitzer MIPS, and our total spatial coverage with AKARI is \sim 8 times wider than that. Our data are deepest at this cluster central region because this region is covered by all the F1, F2 and F12 fields. Therefore, we here plot the 15-\mu m members all the way to the faintest end at 15 \mu m.
(\(\geq 3.5\sigma\) detection). However, we rarely see 15-\(\mu\)m members in the very central region of the cluster (i.e. \(\lesssim 1\) arcmin from the centre), although the number density of the phot-z cluster members is the highest in this very central region. In contrast, the outer regions just outside this zone of avoidance of the 15-\(\mu\)m members, many 15-\(\mu\)m members are detected. In particular, they are distributed preferentially at the region \(\sim 1\) arcmin NE and SW away from the centre. These regions are located right on the large-scale NE–SW filament penetrating the cluster core and hosting two distinct groups (see Fig. 8a).

To show it more quantitatively, we plot the cumulative radial profiles of the member galaxies as a function of distance from the cluster centre out to 4 arcmin in Fig. 9. Fig. 9 clearly shows that the 15-\(\mu\)m members are less concentrated in the \(\lesssim 1\) arcmin region of the cluster than the general cluster member galaxies. From the slope of the curve for the 15-\(\mu\)m members, we see that many 15-\(\mu\)m members are located in the radius range of \(\sim 1.5–2.0\) arcmin from the centre, which in fact corresponds to the region just around the cluster centre (see also Fig. 8b). A Kolmogorov–Smirnov test on these two subsamples shows that the probability that these two are from the same parent is only \(\sim 3.5\) per cent. A more detailed analysis of the distribution of the 15-\(\mu\)m member galaxies will be carried out in Section 4.4.

### 4.4 Enhancement of dusty star formation activity in the cluster outskirts

For each environment (i.e. low, medium and high density), we calculate the fraction of the 15-\(\mu\)m members in all the member galaxies with \(z' \leq 22.5\), including both resolved and unresolved 15-\(\mu\)m members. We show in Fig. 10 the fractions of the 15-\(\mu\)m members with \(f(15\mu m) \geq 67\mu Jy\) for red, blue and red+blue cluster member galaxies as a function of the environment. The boundary between red and blue is set as

\[ (R - z') = 2.51 - 0.049 \times z', \]

which is defined as 0.2 mag bluer than the best-fitted CMR shown in Koyama et al. (2007) (see also Fig. 6a). We only used the galaxies with \(z' \leq 22.5\) because the number of 15-\(\mu\)m members with \(z' \geq 22.5\) is very small due to the depth of the 15-\(\mu\)m image (see Fig. 6a).

We show in Fig. 10 that the 15-\(\mu\)m fraction for all galaxies decreases dramatically in the high-density environment compared with low- and medium-density environments. This represents the very low star-forming activity in the cluster core. On the other hand, we find that the 15-\(\mu\)m fraction is still high in the medium-density environment compared with the low-density fields, although we showed in Section 4.2 that the galaxy colours start to sharply change in the medium-density environments. Although the statistics is not very good, the fraction seems to be higher in the medium-density environment than in the low- and high-density environments. Such a trend is likely to be strong for the red galaxies. This may indicate that in the medium-density environments dusty red galaxies are preferentially produced and/or the star-forming activity is once enhanced for some galaxies (see below).

In this calculation, we included all the 15-\(\mu\)m members down to the limit of \(f(15\mu m) = 67\mu Jy\) (i.e. 5.0\(\sigma\) in the deep region and 3.5 \(\sigma\) in the shallow region), but we found that this trend does not change if we limit the sample to relatively brighter 15-\(\mu\)m members [e.g. \(f(15\mu m) \geq 100\mu Jy\) which corresponds to 7.5\(\sigma\) in the deep region and 5.2 \(\sigma\) in the shallow region]. Also, as noted above, we included both resolved and unresolved 15-\(\mu\)m cluster members in this calculation. If we use only the resolved 15-\(\mu\)m cluster members, the significance of the high fraction of optically red 15-\(\mu\)m members in the medium-density environment becomes even higher.

We now focus on the optically red 15-\(\mu\)m members (i.e. dusty red galaxies) that we have noted in Section 4.1. We find 19 such galaxies in the entire field, and they are detected at significantly larger fraction in the medium-density environment compared to the low- and high-density environments (more than \(\sim 2\) times larger). Detection in 15 \(\mu\)m of the optically red galaxies should mean that these galaxies still have ongoing star formation activity, although their
The spatial distribution of the optically red 15-μm cluster members (open circles and triangles) on all optically red cluster members. The size of the open symbols indicates the 15-μm flux as in the previous figures (e.g. Fig. 8). The large and small filled dots represent the \( z' \leq 22.5 \) and \( z' > 22.5 \) optically red cluster members, respectively. We can see that the distribution of optically red 15-μm members is aligned in the direction of the filament, and matches well with the distribution of the galaxies in the medium-density environment (groups/filaments).

\( R - z' \) colours are as red as passively evolving galaxies. As described in Section 4.1, these galaxies are strong candidates for star-forming galaxies heavily attenuated by dust. Our results therefore suggest that the dusty star formation activity is induced by some mechanisms which are effective in the medium-density environment. We plot the spatial distribution of these optically red 15-μm cluster member galaxies in Fig. 11 on top of all the optically red phot-z members. It is quite notable that almost all dusty red galaxies are distributed exclusively along the filament including groups traced by the optical members, and in fact, this distribution is very similar to that of the member galaxies in the medium-density environment (see Fig. 7b). Although there are a few dusty red galaxies in the low- and high-density environments as well (Fig. 10), almost all of them are located immediately outside of the filaments.

To study the properties of the 15-μm members in the medium-density environment further, we investigate the \( z' - L_{15} \) colours for the 15-μm members. The \( z' \)-band magnitudes approximate the stellar mass of galaxies (\( \sim 5000 \) Å in the rest frame for \( z \sim 0.8 \) galaxies) and the 15-μm magnitude approximates the SFR. Therefore, \( z' - L_{15} \) colour approximately corresponds to specific star formation rate (SSFR) which is defined as SFR per unit stellar mass of galaxies. Since SSFR has a unit of inverse of time, it can be regarded as a time-scale of star formation activity (i.e. galaxies which have high SSFR are considered to have short star formation time-scales).

In Fig. 12, we plot the \( z' - L_{15} \) colours for the resolved 15-μm members as functions of local density and \( z' \)-band magnitude. We note that 9 out of 54 galaxies plotted in Fig. 12 have large colour indices of \( z' - L_{15} > 3.7 \). We can consider these galaxies are forming stars vigorously and efficiently for their stellar masses. This boundary roughly corresponds to \( 1/\text{SSFR} \sim 0.25 \) Gyr for \( z' = 22 \) mag galaxies. This calculation is based on the stellar mass of a galaxy calculated from the \( z' \)-band magnitude using the disc galaxy model in Kodama et al. (1999) and the SFR calculated from the 15-μm mag. We hereafter call these galaxies 'high SSFR galaxies'. Interestingly, many of the high SSFR galaxies also tend to live in the medium-density environment (see Fig. 12a). We note that 7 out of 23 (\( \sim 30 \) per cent) 15-μm members satisfy the high SSFR criterion in the medium-density environment, while only 2 out of 29 (\( \sim 7 \) per cent) galaxies in the low-density environments are high SSFR galaxies, and there is no such galaxy in the high-density environments. In Fig. 12(b), we can see that the \( z' \)-band magnitudes of such high SSFR galaxies tend to be fainter than \( z' \sim 21.5 \). We show the spatial distribution of such high SSFR galaxies in Fig. 13 with large open stars. The high SSFR galaxies also tend to be seen in or just around the filament, although their distribution may...
be slightly more extended than that of the dusty red star-forming galaxies (i.e. open circles and triangles in Fig. 13).

We note that in Section 3.2 we found five possible AGN candidates, at which three have X-ray detections and the other two have red N3 – S7 colours. We find none of these five sources satisfy the high SSFR criterion of $z' - L15 > 3.7$. We find two optically red sources in these five AGN candidates (one in the low-density environment and the other in the medium-density environment). Therefore, we find that these AGN candidates do not strongly affect our results on the high SSFR galaxies and the dusty red galaxies. We stress here that even if these galaxies are really associated with pure AGN and if we exclude these galaxies from our sample, our conclusion is not changed.

It is found that both the ‘dusty red galaxies’ and the ‘high SSFR galaxies’ prefer to live in the medium-density environment. Since this environment is the one where colour distribution of galaxies starts to change drastically from blue to red (see Section 4.2), it is reasonable to think that these galaxies are related to such a colour transition of galaxies, and they may be at the transient phase from blue active galaxies to red passive galaxies during the course of hierarchical assembly to higher density regions.

5 DISCUSSION

In this section, we discuss our results in broader context of environmental dependence of galaxy evolution in clusters by comparing with previous works in the literature. Since our study is the first attempt to investigate around a $z \sim 1$ cluster with such a wide-field coverage in MIR observation, we cannot directly compare our results with others for the region far out from the cluster centre. As for the cluster central regions, two $z \sim 0.8$ clusters (RXJ1052 and MS1054, both at $z = 0.83$) are studied recently with Spitzer MIPS by Marcillac et al. (2007) and Bai et al. (2007). Marcillac et al. (2007) found that MIR cluster members are distributed outside the two main clumps traced by X-ray emissions in the RXJ1052 cluster. Similarly, Bai et al. (2007) showed that there are few IR galaxies in the high-density regions of the cluster. For the RXJ1716 cluster, we find in Section 4.3 that the 15-μm member galaxies are distributed avoiding the central part of the cluster, which is qualitatively consistent with the results of Marcillac et al. (2007) and Bai et al. (2007). The absence of luminous IR galaxies in the cluster centre is also reported for some lower-$z$ clusters, including local Coma and Virgo clusters by ISO (see review by Metcalfe et al. 2005). Therefore, we have confirmed the low star formation activity in the high-density environment such as cluster centres with the MIR observations to $z \sim 0.8$. It is natural to think that the red optical colours of the galaxies in cluster centres are primarily due to the lack of star formation activity and not due to the reddening by dust.

We found that MIR bright cluster members are detected relatively far out from the cluster centre, especially in group/filament environment. Very recently, Fadda et al. (2008) conducted a very wide field MIR observation with Spitzer MIPS which covers two filaments around the Abell 1763 cluster ($z = 0.23$), and found that the fraction of starburst galaxies is more than twice larger in the filaments than in the inner region or outer fields of the clusters. The enhancement of star-forming activity in filaments is also suggested in nearby clusters in the optical studies (e.g. Porter & Raychaudhury 2007; Porter et al. 2008). Our result for the cluster at $z = 0.81$ is qualitatively consistent with these studies in the sense that star-forming activity is enhanced in the intermediate-density environment between low-density general field and the high-density cluster core. From the field study at $z \sim 1$, it is reported that the environment of LIRGs/ULIRGs is denser than that of field galaxies (e.g. Marcillac et al. 2008). Elbaz et al. (2007) studied a structure at $z \sim 1$ in the Great Observatories Origins Deep Survey North field (GOODS-North) with Spitzer MIPS, and showed that galaxies with strong star formation are preferentially seen in group centres. They suggested that, at $z \sim 1$, SFR of individual galaxies increases with increasing density up to a certain critical density and it decreases again at higher density (see also Cooper et al. 2008). For distant clusters, Poggianti et al. (2008) recently suggest a possible peak in the SFR–density relation based on the [O ii] line study of ESO Distant Cluster Survey (EDisCS) clusters at $z = 0.4$–0.8. These studies are also qualitatively consistent with our results, although the structures investigated in Elbaz et al. (2007) would be much poorer systems than the RXJ1716 cluster, judging from their weak X-ray detection.

We now focus on the optically red star-forming galaxies (i.e. ‘dusty red galaxies’). Dusty red star-forming galaxies in clusters were studied in some previous works. For example, Coia et al. (2005) studied the CL0024+1654 cluster at $z \sim 0.39$ with ISO, and found that about half of the MIR sources in the cluster reside on the red sequence. These dusty galaxies are not concentrated in high-density regions. Based on the COMBO17 data for the A901/902 clusters at $z \sim 0.17$, Wolf et al. (2005) also showed that more than one-third of the red-sequence galaxies have dusty red SEDs. They also found that these dusty red galaxies prefer medium-density outskirts of the clusters and they are rare in low- or high-density environments. Since the redshifts of these clusters are lower than that of RXJ1716 ($z = 0.81$), we cannot conclude that these are the same populations as our dusty red galaxies. However, judging from their optically red colours while having signs of ongoing star formation activity, we expect that our dusty red galaxies are similar counterparts of the dusty populations seen in the two low-$z$ clusters studied by Coia et al. (2005) and Wolf et al. (2005). As we showed in Fig. 11, our dusty red galaxies are preferentially located in the medium-density environment. It is interesting to note that these optically red star-forming galaxies are common in the outskirts of

Figure 13. The distribution of the high SSFR galaxies (open stars). Small dots indicate all the phot-$z$ member galaxies. The high SSFR galaxies are also distributed preferentially in the medium-density environment (i.e. groups/filaments). Open circles and triangles represent the ‘dusty red galaxies’, same as in Fig. 11.
Figure 14. Examples of the optical counterparts for 15-μm members (upper panels) and their 15-μm image (lower panels). Circles show the positions of 15-μm members and their radius are set to 8 arcsec in all the panels. Small squares represent the positions of phot-z selected member galaxies and the size of the squares is 4 × 4 arcsec². Panel (a) is a candidate for an infalling group. Panels (b) and (c) are the prominent cases of the interacting systems with 15-μm emissions.

clusters at all redshifts through 0.1 ⩽ z ⩽ 0.8, although the number of cluster sample is very limited.

Finally, we discuss the physical mechanisms that can play major roles in galaxy truncation of star-forming activity. Marcillac et al. (2007) found that MIR members in the RXJ0152 cluster seem to be mostly associated with the infalling late-type galaxies classified by Blakeslee et al. (2006). They suggest that a burst of star formation can occur during the galaxy infall process. Since we do not have spectroscopic data for our 15-μm cluster members, we cannot be sure at this stage that our 15-μm members are physically associated to the infalling galaxies, but it is likely that at least some of our 15-μm cluster members in the RXJ1716 cluster are indeed the galaxies that are infalling along the filament to the main body of the cluster by gravity. In fact, we have some good candidates of infalling groups far away from the cluster centre located at around (6.0, 0.0), (0.0, 6.0) and (−2.0, 2.0) arcmin in Fig. 8(a) as the iso-density contours clearly show. We show in Fig. 14(a) an example of the candidates of an infalling group located at (−0.5, 1.5) arcmin in Fig. 8(b) which is ⃍1 Mpc away from the cluster centre. We need spectroscopic confirmation of the physical association of these systems to the cluster.

We have revealed that the 15-μm members are found far out from the cluster core especially in the medium-density environment such as groups or filaments where the optical colour distribution strongly changes. Our results suggest that many galaxies which entered medium-density environment from the low-density field experience starburst, and these galaxies are observed as dusty star-forming galaxies and/or high SSFR galaxies around the RXJ1716 cluster. Moreover, it would be natural to consider that the burst of star formation is linked to the colour and morphological changes of galaxies and truncation of star-forming activity. The most likely physical mechanism at work in these medium-density regions which also involves starburst would be galaxy–galaxy interaction or mergers (e.g. Hopkins et al. 2008; Martig & Bournaud 2008). We have two good examples of 15-μm members which show prominent interacting features (Figs 14b and c). The strong MIR emissions from these systems must be produced in the process of the galaxy interaction. These findings may suggest a link between the dusty star-forming activity of galaxies and galaxy–galaxy interaction. However, it is difficult to firmly conclude that the majority of our 15-μm galaxies are activated via galaxy–galaxy interactions or mergers. The seeing size of our ground-based optical image is ⃍0.7 arcsec and it is not sufficient to determine the morphology for all of our 15-μm galaxies and to find any interacting signatures. We should also admit that spectroscopic confirmation of membership of the phot-z members especially for the 15-μm members is crucial to draw any firm conclusions. Since our study reaches far out from the cluster core, it would have more contaminations than other studies limited in the cluster cores. The surface number density of the contaminant galaxies with z ⩽ 22.5 mag is estimated to be ⃍0.93 arcmin⁻², using the galaxies in the control fields defined in our Suprime-Cam field (see fig. 3 of Koyama et al. 2007). A rough estimate shows that, among all the phot-z members with z ⩽ 22.5 mag, ⃍10 and ⃍25 per cent galaxies can be contaminant galaxies in the cluster region (i.e. high-density region) and the group region (i.e. medium-density region), respectively (see fig. 4 of Koyama et al. 2007 for the definitions of the cluster and the groups). Furthermore, we should keep in mind that the properties and/or fraction of the MIR galaxies may be different from cluster to cluster, as suggested in Geach et al. (2006), even if we investigate clusters nearly at the same redshifts. Wide-field MIR observations on a larger sample of distant clusters are clearly required to obtain more general picture of the environmental effects on galaxy evolution.

6 SUMMARY AND CONCLUSIONS

We have performed a wide-field and multiband optical and IR study of the distant galaxy cluster RXJ1716.6+6708 (RXJ1716) at z = 0.81. A unique wide-field coverage both in optical and IR has enabled us to classify galaxies into three environmental bins, namely, high-density regions (cluster core), medium-density regions (cluster outskirts, groups, filament) and low-density regions (field), and has thus allowed us to investigate galaxy properties as a function of environment along the structures in and around the distant cluster.

We find many of the 15-μm cluster members show intermediate optical colours between the red sequence and the blue cloud. This may indicate that these 15-μm cluster members are actively star-forming galaxies but attenuated by dust hence showing intermediate optical colours, although relatively fewer detection at 15 μm of blue galaxies may be partly because they tend to be optically faint.

We quantified the environment around the cluster using the local projected number density of cluster member galaxies, and confirmed that the optical colour distribution starts to dramatically change at the ‘medium’-density environment that corresponds to groups and/or filaments. We showed that the 15-μm members are very rare in the high-density cluster centre. This is probably due to the low star-forming activity in such regions. However, interestingly, the fraction of the 15-μm-detected cluster members in the medium-density environment is as high as in the low-density fields, despite the fact that optical colours of galaxies start to dramatically change from blue to red in the medium-density environment. Although the statistic is not very good, the fraction is slightly higher in the medium-density environments even compared with the low-density fields.

We also find that dusty red galaxies (optimally red 15-μm cluster members) and the galaxies with high specific SFRs (red in z – 15-μm colour) are both concentrated in the medium-density environment. These results may suggest that the star formation activity in galaxies is once enhanced by some physical processes which are effective in group/filament environment (e.g. galaxy–galaxy interaction).
interaction), before their star-forming activity is eventually truncated and they move on to the red sequence.

We stress that all these new findings are based on the widest field MIR observation of a \( z \sim 0.8 \) cluster so far. There is no other study that covers such a wide field around clusters in MIR at \( z \gtrsim 0.8 \). Since our study is a case study for just one cluster at \( z = 0.81 \), we are desperately in need for a larger sample of distant clusters viewed in the IR regime and at the same time covering a wide FoV so that we can witness the galaxy truncation in action in the infall regions of distant clusters along the filaments. This is essential in order to confirm this interesting trend and to obtain a general view of galaxy evolution.

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