Publications of the Korean Astronomical Society
32: 287 ∼ 291, 2017 March

pISSN 1225-1534
eISSN 2287-6936
https://doi.org/10.5303/PKAS.2017.32.1.287

PANORAMIC MID-INFRARED VIEWS OF DISTANT CLUSTERS OF GALAXIES WITH AKARI

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(Received June 9, 2015; Revised October 16, 2016; Accepted October 16, 2016)

ABSTRACT

We present the results of our mid-infrared (MIR) observations of distant clusters of galaxies with AKARI. The wide-field of view of IRC/AKARI ($10' \times 10'$) is ideally suited for studying dust-obscured star-formation (SF) activity of galaxies along the cosmic web in the distant universe. We performed a deep and wide-field 15 μm (rest-frame ≈ 8 μm) imaging observation of the RXJ1716+6708 cluster ($z = 0.81$) with IRC. We find that 15 μm-detected cluster member galaxies (with total infrared luminosities of $L_{\rm IR} \gtrsim 10^{11} L_\odot$) are most preferentially located in the cluster outskirt regions, whilst such IR-luminous galaxies avoid the cluster centre. Our Hα follow-up study of this field confirmed that a significant fraction of 15 μm-detected cluster galaxies are heavily obscured by dust (with $A_{\rm H\alpha}$>3 mag in extreme cases). The environment of such dusty star-burst galaxies coincides with the place where we see a sharp "break" of the colour-density relation, suggesting an important link between dust-obscured SF activity and environmental quenching. We also report the discovery of a new cluster candidate around a radio galaxy at $z = 1.52$ (4C 65.22), where we obtained one of the deepest IRC imaging datasets with all the nine filters at 2–24 μm. This field will provide us with the final, excellent laboratory for studying the dust-enshrouded SF activity in galaxies along the cosmic web at the critical epoch of cluster galaxy evolution with AKARI.

Key words: galaxies — galaxy clusters — galaxy evolution

1. INTRODUCTION

In the local universe, it is well established that galaxy properties are strong functions of environment (e.g. Dressler 1980). Cluster galaxies are predominantly red and dead—this indicates that the formation and evolution of galaxies are strongly linked to the formation of large-scale structures of the universe. The important question to be answered here is: *when, where, and how is the dramatic change of those present-day cluster galaxies happened?*

Infrared (IR) observations often bring a new insight into our understanding of the formation and evolution of galaxies. Recent observations with IR space telescopes have revealed that IR-luminous galaxies dominate the star-forming (SF) activity in the distant universe (e.g. Le Floc'h et al. 2005; Goto et al. 2010). This is true for cluster galaxies as well: mid-infrared (MIR) studies by *ISO* unveiled the presence of a large number of dusty star-forming (SF) population in cluster environments out to $z \sim 0.5$ (Duc et al. 2002; Biviano et al., 2004; Coia et al. 2005), and *Spitzer* extended these works towards $z \sim 1$ (e.g. Geach et al. 2006; Marcillac et al. 2007; Bai et al. 2007; Dressler et al. 2009; Koyama et al. 2013). It is demonstrated that IR activity of cluster galaxies is higher in the distant universe—which is sometimes refered to as "IR Butcher-Oemler effect" (e.g. Saintonge et al. 2008; Haines et al. 2011, c.f. Butcher & Oemler 1984).

However, these MIR studies on distant clusters of galaxies presented so far are mostly focusing on the cluster *central* part due mainly to the limited field of views (FoVs) of the IR instruments. However, some wide-field studies of distant clusters in optical wavelength suggest that the dramatic change of galaxy evolution takes place in the cluster *surrounding* environments (e.g. Kodama et al. 2001; Koyama et al. 2008). With this respect, the Infra-Red Camera (IRC; Onaka et al. 2007) on-board AKARI (Murakami et al. 2007) has wide FoV ($\sim 10' \times 10'$), and allows us to study MIR properties of galaxies in a wide range in environment from cluster core to its surrounding environment. In this paper, we review the results from our "panoramic" MIR observations of distant ($z \gtrsim 1$) clusters of galaxies performed with AKARI, and discuss the implication on the process of environmental effects acting on galaxies during the course of cluster assembly.

2. PANORAMIC MIR VIEW OF A z=0.8 CLUSTER

This section presents the results of our MIR observation of a rich galaxy cluster at $z = 0.81$ (RX J1716+6708) with AKARI. This cluster is X-ray selected (Henry et al. 1997), and spectroscopically confirmed by Gioia et al. (1999). In Koyama et al. (2007), we obtained wide-field $VRi'z'$ data with Suprime-Cam on Subaru Telescope, and identified prominent large-scale structures extending over $\sim$20 Mpc around the cluster. Because the cluster is located near the North Ecliptic Pole (i.e. excellent visibility from AKARI), we performed deep IRC 15 μm (L15) imaging observation of this cluster field.

As shown in Fig. 1, by spending three FoVs of IRC (F1–F3; total coverage of $\sim$200 arcmin^2), our observation covers the whole structure identified by Koyama et al. (2007). In Fig. 1, we show the spatial distribution of 15μm-detected galaxies throughout our field of view (black symbols). It is shown that MIR-detected galaxies (cross-identified with cluster member galaxies) are distributed along the structure, whilst the MIR-detected galaxies avoid the cluster central region (see a zoom-up view in the right-hand panel of Fig. 1). Our result suggests that galaxies residing in the cluster core are already quiescent at $z \sim 0.8$, and that those galaxies were formed at even earlier epoch (Koyama et al. 2008).

Next we investigate the optical colours of MIR-detected galaxies on the colour–magnitude diagram. In Fig. 2 (left), we show the colour–mangnitude diagrams for each environment—our sample is divided into three environmental bins based on the local galaxy density (measured with fifth nearest neighbour method; $\Sigma_{5\mathrm{th}}$). In this plot, we also show the Hα emitters selected by our narrow-band imaging survey with Subaru Telescope (open squares). The Hα emitters are mostly blue galaxies, while the 15μm-detected galaxies tend to show redder colours. Interestingly, such red SF galaxies are most preferentially seen in the "medium-density" environment, where we see an abrupt change in the galaxy colours (see Koyama et al. 2008 for details), while most of the red-sequence galaxies in "high-density" region (i.e. cluster core) are completely quiescent, suggesting a different nature of red galaxies in different environments (see review for "red star-forming" galaxies by Koyama et al. 2011).

In Fig. 2 (right), we compare the star formation rates (SFR) derived from Hα and mid-infrared (rest-frame 8μm) luminosities for galaxies detected both at Hα and MIR. It is shown that the extinction at Hα ($A_{\mathrm{H}\alpha}$) is $\sim$1 mag for moderately star forming galaxies—this is consistent with local spirals. However, in some extremely dusty cases, this extinction level exceeds $\sim$3 mag (equivalently $\mathrm{SFR_{IR}/SFR_{H\alpha}} \gtrsim 15$). Such very dusty population show optically red colours: their colours are consistent with those expected for "non-star-forming" population. Importantly, we find that those extremely dusty population (probably in the transitional phase under environmental effects) are most commonly seen in the cluster surrounding groups or filaments. This result strongly suggests an important role of the cluster surrounding environment as the key for shaping the environmentally-driven galaxy evolution (or environmental quenching). Our data thus suggest that dust-enshrouded activity of galaxies (dusty starbursts and/or AGNs) are triggered in the cluster in-fall regions, and that there exists a strong link between those dusty galaxies and environmental effects.

3. A NEWLY DISCOVERED RICH CLUSTER AT z=1.5

It is very exciting to explore MIR views of clusters at higher redsfhits, but it is of course very challenging at the same time, simply because galaxies get fainter at higher redshifts. With the CLEVL collaboration (PI: H. M. Lee), we made an extensive imaging campaign of a radio galaxy, 4C 65.22 ($z = 1.52$), located near the NEP. We obtained deep IR imaging data of this 4C 65.22 field using all nine-band filters (2,3,4,7,9,11,15,18,24μm) with IRC/AKARI. However, unfortunately, the lack of deep (ground-based) optical/NIR imaging data prevented us from doing any further detailed study of this interesting field.

Recently, we successfully completed deep $Br'z'JHK_s$ imaging observations of this field with Subaru Telescope, and discovered a strong over-density of galaxies around the radio galaxy (see Fig. 3; Koyama et al. 2014). With a help of NB1657 photometry (corresponding to the Hα

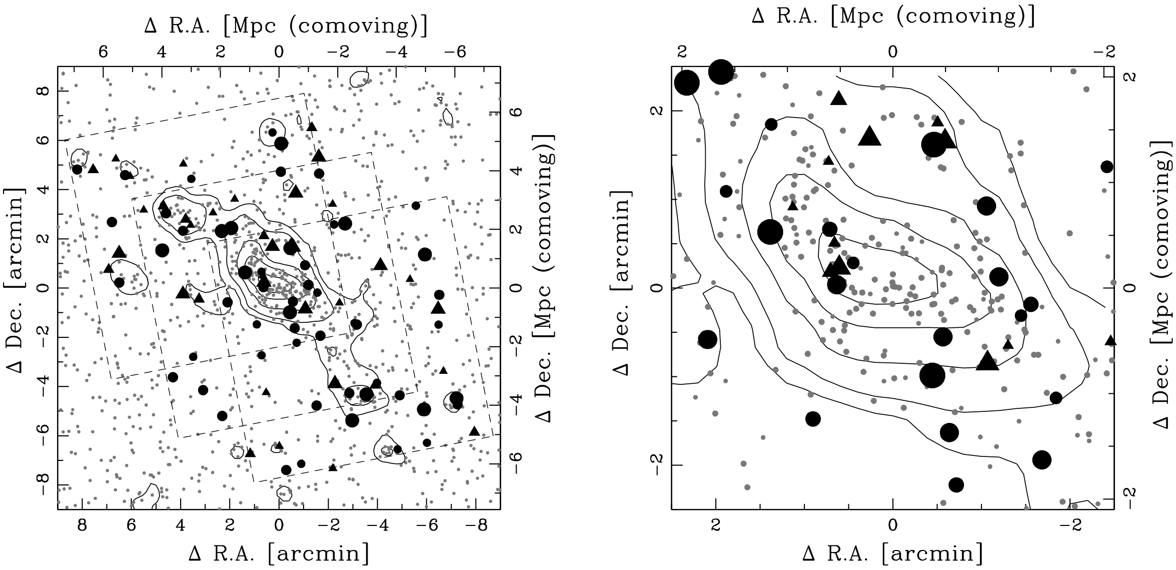

Figure 1. (Left): Spatial distribution of the 15 μm-detected cluster members (black symbols) on top of the photo-z selected cluster members (small dots) around the RXJ1716+6708 cluster at $z = 0.81$. Circles and triangles show isolated and blended sources on the MIR image. The size of the MIR galaxies indicate the MIR luminosity (i.e. larger symbols indicate higher IR luminosity). The dashed-line squares show the three FoVs of our IRC/AKARI observation (Koyama et al. 2008). (Right): A close-up view of the central $5' \times 5'$ region. Note that the cluster central region is deeper than outer fields, and in this plot we also show fainter 15 μm-detected galaxies (down to ~ 3.5 - σ level).

emission from $z = 1.52$ galaxies), it is highly likely that the structure is physically associated to the central radio galaxy. Our data suggest that red quiescent galaxies are strongly clustered within $r \lesssim 200$ kpc from the density peak (black filled circles in Fig. 3), whilst Hα emitting SF galaxies are located in the outskirt of the cluster core (black squares in Fig. 3), consistent with the results obtained for the $z = 0.8$ cluster as presented in Section 2.

Our AKARI data ($10' \times 10'$) entirely cover the large-scale structure presented in Fig. 3, and therefore this field can be an ideal laboratory for studying the IR nature of galaxies in dense environments at the peak epoch of galaxy formation. For instance, the 18μm (L18) data capture the rest-frame $\sim$8μm, allowing us to directly extend our $z = 0.8$ study based on the AKARI 15μm observation (Section 2) towards $z \sim 1.5$. Our preliminary analyses suggest that it is very hard to individually detect $z \sim 1.5$ galaxies in most cases, but we do find some individual MIR detection from Hα-emitting cluster members. Those MIR-detected galaxies are estimated to have ULIRG-class IR luminosities in spite of their moderate Hα luminosities, suggesting that we are witnessing a "bursty" phase of the present-day cluster galaxies in the forming large-scale structure at $z = 1.5$.

4. SUMMARY & FUTURE

In this work, we presented the results of our MIR observations of distant clusters of galaxies with AKARI. For the $z = 0.81$ cluster (RXJ1716+6708), we find that IR-luminous galaxies are located in the outskirts of the cluster core, whilst they are avoiding the cluster central region. By comparing the AKARI MIR data with our Subaru Hα data, we find that some of the MIR-detected cluster galaxies are heavily obscured by dust (with $A_{\mathrm{H}\alpha} > 3$ mag in extreme cases). The environment of such dusty star-burst galaxies coincides with the place where we see a sharp "break" of the colour-density relation (i.e. transition environment), suggesting an important link between dust-obscured SF activity and environmental quenching.

We also reported our recent discovery of a new cluster candidate around a radio galaxy at $z = 1.52$ (4C 65.22), where we also obtained deep IRC/AKARI imaging datasets. This field will be an ideal laboratory for studying the MIR views of galaxy clusters at the critical epoch of galaxy formation. We would promise to present the results from these datasets in the next (i.e. fourth) AKARI conference.

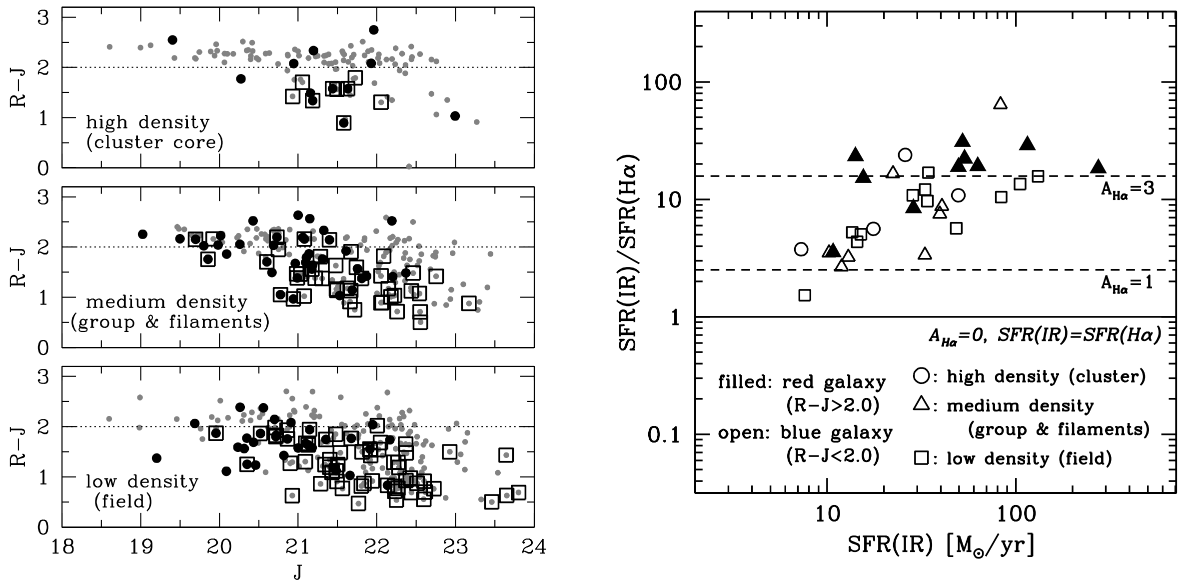

Figure 2. (Left): The colour–magnitude diagrams for $z \sim 0.8$ galaxies in three environmental bins (according to their local number density). Filed circles show 15μm-detected galaxies, and the open squares are Hα emitters selected by our narrow-band survey (Koyama et al. 2010). The red-sequence galaxies in the highest-density environment are mostly passive, whilst a large number of red galaxies in group-scale environments show signatures of SF activity (Hα or MIR detection). (Right): The $\mathrm{SFR_{IR}/SFR_{H\alpha}}$ ratio plotted against IR-derived SFR for those detected both at Hα and 15μm (Koyama et al. 2010). The meanings of the symbols are indicated in the plot. This plot demonstrates that heavily dust-obscured systems are most frequently seen in the medium-density environments such as in-falling groups or filaments, and that these dusty galaxies tend to show red colours in the rest-frame optical bands.

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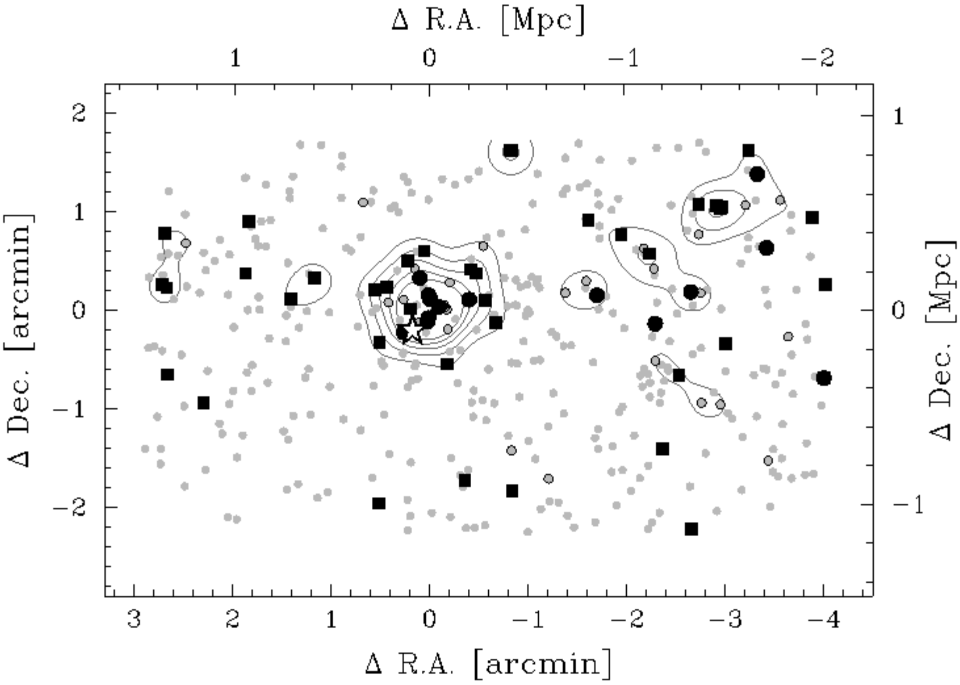

Figure 3. The newly discovered cluster candidate around a radio galaxy 4C65.22 at $z = 1.52$ (shown with the open star symbol), where we also obtained deep AKARI datasets. Here we plot photo-z selected $z \sim 1.5$ galaxies (open circles) and Hα emitters (filled squares). The black filled circles indicate red-sequence galaxies among the photo-z selected member galaxies. The grey dots present all sources detected on the Subaru NB1657 image (see Koyama et al. 2014).

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