SPICA Distant Cluster Survey: Unveiling the Dust-Obscured Star Formation Triggered by Young Cluster Environments

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ABSTRACT

We present the results of our star-forming galaxy survey of distant clusters of galaxies using Subaru (Hα) and *AKARI* (MIR). By comparing the Hα and MIR data, we revealed that dust-obscured star-forming galaxies are most preferentially located in the cluster outskirts at $z \sim 1$. We propose to extend this Hα- and IR-based environmental study to higher redshifts, but a problem so far is that the existing MIR–FIR surveys always suffer from their limited depths. We can overcome this problems with the wide-field mid-infrared (MIR) camera on-board *SPICA* (5′FoV), which will allow us an efficient, and extremely deep MIR survey of distant clusters. In particular, the expected high sensitivity of *SPICA* at 20–40 μm regime promotes us to extend IR galaxy survey out to z = 2–4 (i.e. the "peak epoch" of galaxy evolution) based on their rest-frame 8 μm feature. We provide a quick overview of our recent progress with the MAHALO-Subaru collaboration, and then discuss how significantly *SPICA* can improve our understanding of the environmental effects on galaxy evolution in the early universe.

1. INTRODUCTION

Galaxy clusters in the distant universe are ideal laboratories for studying environmental effects on galaxy formation and evolution in the early universe. In the local universe, galaxy clusters are dominated by red early-type galaxies (e.g. Dressler 1980; Goto et al. 2003). These red cluster population form a tight colour–magnitude sequence, indicating that the majority of their stellar components are formed in the very early universe at $z \gg 1$ with relatively short time scales (e.g. Bower et al. 1992; Kodama et al. 1998). It is therefore crucial to study young (star-bursting) cluster galaxies in order to fully understand the physical drivers of the evolution of cluster galaxies.

Recent observations have shown that star formation (SF) activity in galaxies (as traced through cosmic star formation rate density) has its peak at $z \sim$1–3 (e.g. Hopkins & Beacom 2006). In this peak epoch of galaxy formation, it is suggested that the contribution of LIRG or ULIRG-class population is much higher than in the local universe. In such luminous systems, a large fraction of SF activity are obscured by dust (e.g. Le Floc'h et al. 2005; Goto et al. 2010). This is of course true for distant *cluster* galaxies as well. Deep MIR–FIR studies of distant clusters are thus essential to unveil the real (dust-obscured) SF activity taking place within young cluster galaxies.

With an advent of *AKARI*, *Spitzer* and *Herschel* space telescopes, recent IR studies of distant clusters have unveiled dust-obscured SF activity (down to LIRG-class population) in distant cluster environments out to $z \sim 1$ (e.g. Geach et al. 2006; Koyama et al. 2008). These IR studies of distant galaxy clusters showed that SF activity is enhanced in the cluster in-fall regions (see Section 2). The number of known (proto-)clusters ($z > 1.5$) have been increased, and Hα or [O II] emission-line surveys of these high-z clusters have unveiled highly star-forming cluster members in the high-z cluster core regions, suggesting a dramatic change of the nature of cluster galaxies at the peak epoch of galaxy formation (Hayashi et al. 2010; Tadaki et al. 2012; Koyama et al. 2013a). One of the important goals of the *SPICA* mission is to completely unveil the dust-obscured SF activity within these young forming galaxy clusters with extremely deep MIR–FIR observations (see Section 3).

2. DUST-ENSHROUDED STAR FORMING GALAXIES AROUND DISTANT CLUSTERS AT Z ~ 1

We here present a highlight of our Hα and MIR study of a distant galaxy cluster at z = 0.81 (RXJ1716+6708) with Subaru and *AKARI*. In the left-hand panel of Figure 1, we show the spatial distribution of narrow-band-selected Hα emitters and MIR galaxies (Koyama et al. 2010). It can be seen that both of these population avoid the cluster central part, suggesting that SF activity of galaxies in the core of this cluster was completely terminated before $z \sim 0.8$. On the other hand, a large fraction of galaxies are still actively forming stars in the cluster outskirt regions. We measured their star formation rates independently from Hα and MIR (rest-frame 8 μm) luminosities, and find that the extinction at Hα is

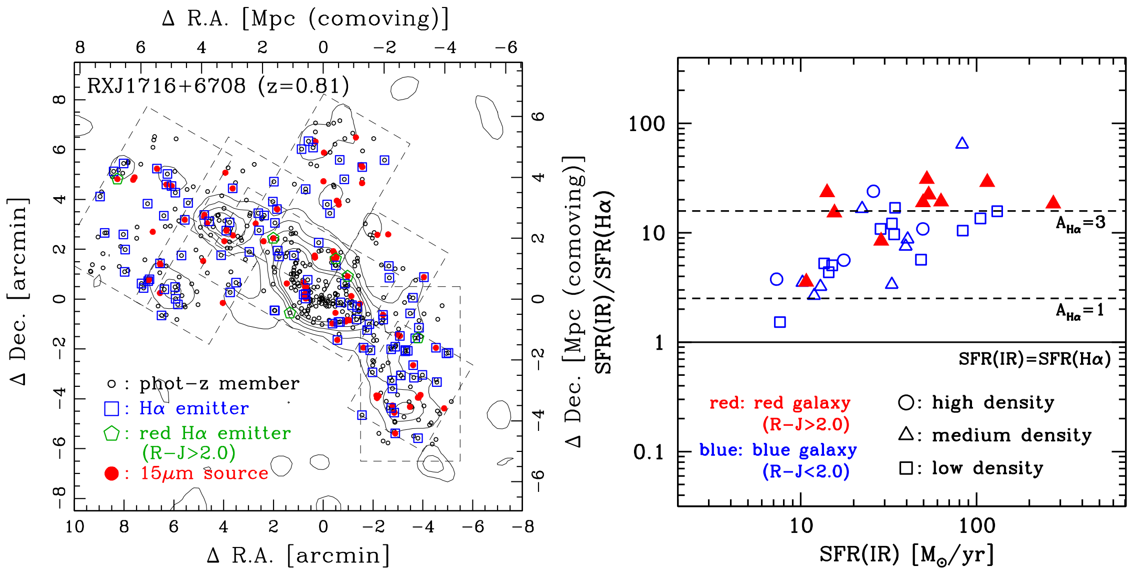

Figure 1. *Left:* A 2-D map of galaxies around the RXJ1716 cluster at $z = 0.81$. The meanings of the symbols are indicated in the plot. The dashed-line boxes show our MOIRCS FoVs (the survey area of Hα emitters). Note that the Hα survey area is fully covered by our *AKARI* 15 μm observation. *Right:* The SFR(IR)/SFR(Hα) ratio plotted against SFR(IR). This plot demonstrates that the Hα emission lines are heavily obscured by dust for very luminous sources, and these dusty sources are most prevalent in the medium-density group/filaments.

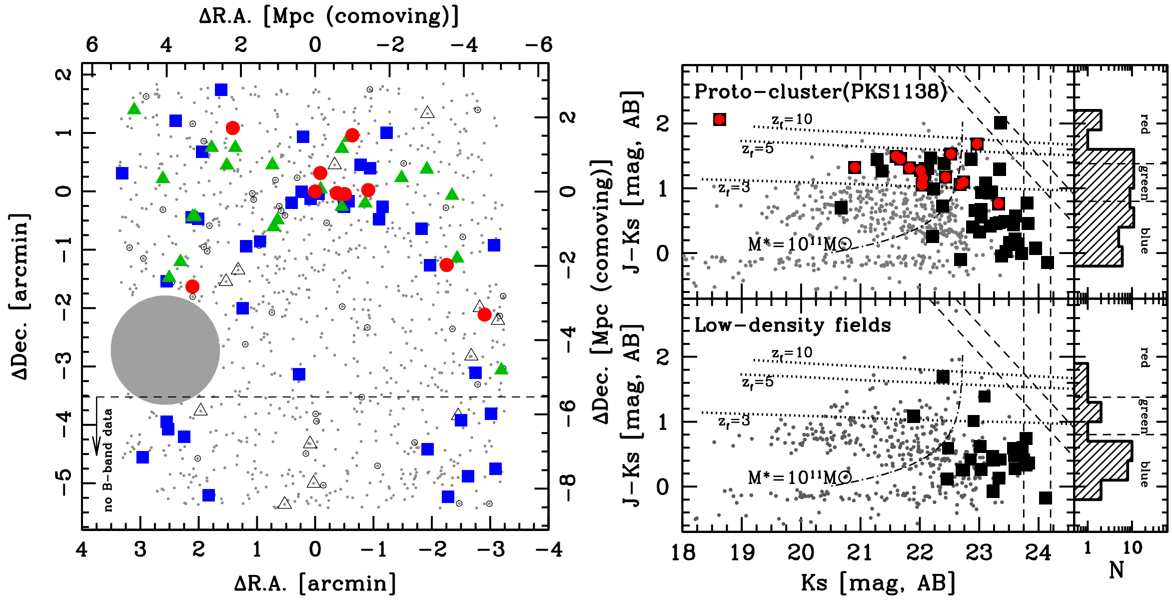

Figure 2. *Left:* The spatial distribution of Hα emitters at $z = 2.16$ around the PKS 1138 proto-cluster field. The filled circles, triangles, and squares show red ($J - K_s > 1.4$), green ($0.8 < J - K_s < 1.4$), and blue ($J - K_s < 0.8$) emitters, respectively. The open circles and triangles denote DRGs and K_s-undetected emitters, respectively. *Right:* A color–magnitude diagram ($J - K_s$ versus K_s) for Hα emitters at $z \sim 2$ in cluster (top) and field environments (bottom). The filled circles show the 24 μm-detected galaxies. It is clear that there is a strong excess of massive/red SF galaxies ($M_* > 10^{11}$ M$_\odot$) in the cluster environment, while these massive population are very rare in general field environments at the same redshift.

$A_{\mathrm{H}\alpha}$~1 mag for moderately star forming galaxies, which is consistent with local spirals. However, in some extremely dusty galaxies, this value exceeds ~3 mag. Such very dusty galaxies show "red" rest-frame optical colors (as red as passively evolving galaxies). Importantly, we find that these dusty galaxies (probably in the transitional phase under the influence of some environmental effects) are most commonly seen in the cluster surrounding groups or filaments (see right-hand panel of Figure 1), which coincide with the environment where galaxy color transition also takes place (e.g. Kodama et al. 2001; Koyama et al. 2008). This result strongly supports an idea that the cluster surrounding environments hold the key for understanding the physics of environment-driven galaxy evolution. In these ways, with a combination of wide-field Hα and MIR study, we find an evidence that the dust-obscured, enhanced SF activities of galaxies are indeed triggered in the cluster in-fall regions, suggesting a strong link between these hidden activity and environmental effects.

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3. MASSIVE STARTBURST GALAXIES DISCOVERED IN PROTO-CLUSTERS AT $Z > 2$

To extend our SF galaxy survey to higher-redshift clusters, we have been conducting the “MAHALO-Subaru” project (*MApping H-Alpha and Lines of Oxygen with Subaru*). The aim of this project is to construct a large, uniformly selected sample of SF galaxies in the distant universe ($0.4 < z < 2.6$), using a lot of narrow-band filters on Subaru. An important advantage of this project is that we observe wide range in environments from general fields (Tadaki et al. 2011) to rich (proto-)clusters (Kodama et al. 2004; Hayashi et al. 2011, 2012; Tanaka et al. 2011; Koyama et al. 2011), allowing us to study environmental effects in the very early universe.

In the left-hand panel of Figure 2, we show the spatial distribution of Hα emitting galaxies in the PKS 1138 proto-cluster at $z = 2.16$. By examining the properties of Hα emitters along the filamentary structure, we find that galaxies in the proto-cluster environments tend to have redder colours, higher stellar masses, and higher SFRs compared to galaxies in more underdense regions (see the right-hand panel of Figure 2). We note that these “red” SF galaxies have $M_* > 10^{11}\,M_\odot$, suggesting that they already formed a large part of stellar mass contents before $z \sim 2$. Furthermore, we find that many of these red emitters are detected in the 24 μm data taken with *Spitzer*, indicating that they are still vigorously star-forming objects (SFR $> 100\,M_\odot$/yr). However, the current IR instruments can detect only extremely luminous sources at $z > 1$ (ULIRG or HyLIRG class population).

The important role of *SPICA* is therefore to fully unveil the dust-obscured SF activity taking place in the forming proto-clusters. In particular, the wide field of view of MIR camera of *SPICA* will allow us to make a panoramic mapping of dusty galaxies over the proto-cluster fields down to faint objects such as LIRG class at $z \sim 2$ or ULIRG class at $z \sim 4$, based on the rest-frame 8 μm feature. It will also be possible to quantify the obscured active galactic nuclei (AGNs) based on the rest-frame MIR colors. Recent studies suggest that the SF main sequence (the SFR–M_* relation) is independent of environment since $z \sim 2$ as far as the SFRs are derived from Hα luminosity alone (Koyama et al. 2013b), but the *SPICA* will be able to determine if it is really true when we consider the activity completely hidden by dust.

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