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PANORAMIC VIEWS OF GALAXY CLUSTER EVOLUTION: GALAXY ECOLOGY

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ABSTRACT

Taking the great advantage of Subaru's wide field coverage both in the optical and in the near infrared, we have been providing panoramic views of distant clusters and their surrounding environments over the wide redshift range of $0.4 < z < 3$. From our unique data sets, a consistent picture has been emerging that the star forming activity is once enhanced and then truncated in galaxy groups in the outskirts of clusters during the course of cluster assembly at $z < 1$. Such activity is shifted into cluster cores as we go further back in time to $z \sim 1.5$. At $z = 2 - 2.5$, we begin to enter the epoch when massive galaxies are actually forming in the cluster core. And by $z \sim 3$, we eventually go beyond the major epoch of massive galaxy formation. It is likely that the environmental dependence of star forming activity is at least partly due to the external environmental effects such as galaxy-galaxy interaction in medium density regions at $z < 1$, while the intrinsic effect of galaxy formation bias overtakes the external effect at higher redshifts, resulting in a large star formation activity in the cluster center.

key words: galaxies: clusters: general; galaxies: formation; galaxies: evolution; galaxies: high-redshift

1. "NATURE" OR "NURTURE" IN SHAPING GALAXIES ACROSS ENVIRONMENTS

It is well known that properties of galaxies such as morphology and spectral type depend strongly on environment in the sense that E/S0 galaxies with old stellar populations preferentially reside in dense environment, while spiral galaxies with active star formation are located in lower density environment. This indicates that galaxy formation and subsequent evolution is closely related to the surrounding environments.

There seem to be two types of effects behind it: (1) Intrinsic ("nature") effect called "biased galaxy formation" where higher density regions collapse earlier and galaxy formation is more accelerated, whereas lower density regions collapse later and galaxy formation is delayed (Cen & Ostriker, 1993). (2) External ("nurture") environmental effects such as galaxy-galaxy interactions and ram-pressure gas stripping which influence galaxy types and star forming activity as they assemble to higher density regions (Moore et al., 1996; Abadi et al., 1999). Although identifying the origin of environmental variation is of fundamental importance, the relative importance of these two types of effects has remained elusive. To break this situation, we should both (1) go to higher redshifts to see the intrinsic effect as the galaxy formation bias would become stronger in the past, and (2) go further out from the cluster core so that we can cover the infall region to witness any external effects in action directly.

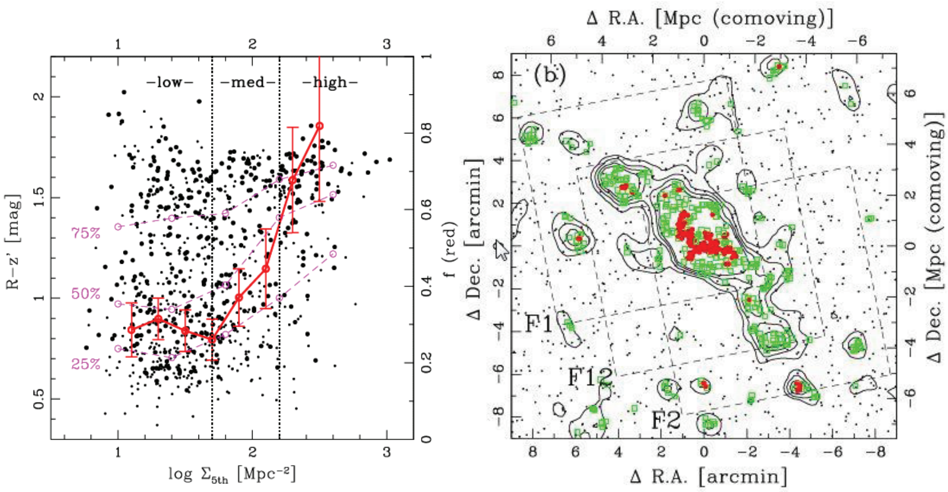

Fig 1.— Colors of galaxies are plotted against local density of galaxies (left panel; Koyama et al., 2008) for RXJ1716 cluster at $z = 0.81$. We see a sharp color transition in the medium density regions at $\Sigma_{5\mathrm{th}} \sim 100$ Mpc^{-1}. The galaxies in such transition environments (outskirts/groups) are shown by open squares in the 2-D map of the cluster (right panel; Koyama et al., 2008). They avoid the cluster central region. See Koyama et al. (2008) for details.

2. SPATIAL PROPAGATION AND TRUNCATION OF STAR FORMING ACTIVITIES IN CLUSTERS

With these motivations, we have been conducting a panoramic study of distant clusters and their surrounding regions with Subaru (PISCES and HzRG projects; Kodama et al., 2005 and Kodama et al., 2007) by utilizing its unique wide-field instruments both in the optical (Suprime-Cam) and in the near-infrared (MOIRCS). We have mapped out large scale structures (LSS) in and around ∼10 X-ray clusters at $0.39 < z < 1.62$ initially based on phot-z and many of the structures have been spectroscopically confirmed later on (e.g. Tanaka et al., 2006). These LSS's over the wide redshift range serve as unique and ideal sites for environmental studies, as they practically cover all possible environments at every epoch from the richest cluster cores to low densiy regions comparable to general fields. In this project, we have found for the first time that the colour distribution of galaxies changes sharply to red in medium density regions (or groups or cluster outskirts) rather than in dense cluster cores for all clusters at $z \lesssim 0.8$ (Figure 1; Tanaka et al., 2005). This indicates the importance of such environments for the external effects.

We have also performed narrow-band surveys of [O$_{\rm II}$] (RXJ1716 and XCS2215) and Hα emitters (RXJ1716), with Suprime-Cam and MOIRCS, respectively. We reached down to a dust-uncorrected SFR of 1.5, and 3 M$_\odot$/yr, respectively. From these unique data, we find that Hα emitter candidates in RXJ1716 avoid the cluster center (<200 kpc) and are preferentially located in the cluster outskirt, suggesting the star formation activity has been already finished in the cluster core but is probably enhanced in the medium density regions (left panel of Figure 2; Koyama et al., 2010). This interesting result is also reproduced by another unique data set of this cluster, i.e., AKARI 15 μm imaging which captures strong PAH features from the cluster and is sensitive to dusty star formation. AKARI sources also avoid the cluster core and many are located in the surrounding region or in groups (Koyama et al., 2008). In contrast, [O$_{\rm II}$] emitter candidates in XCS2215 are seen

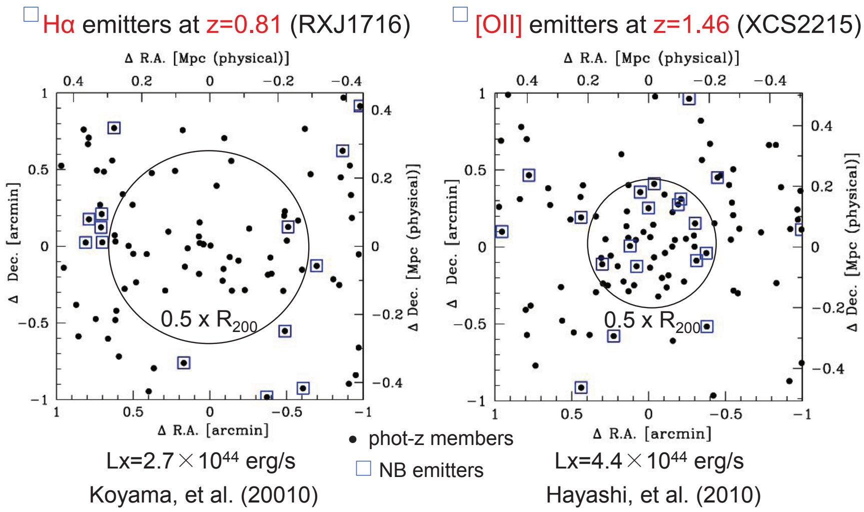

Fig 2.— Spatial distribution of star forming galaxies in two cluster cores at different redshifts. Hα in RXJ1716 at $z = 0.81$ (left panel; Koyama et al., 2010) and [O$_{\rm II}$] in XCS2215 at $z = 1.46$ (right panel; Hayashi et al., 2010) are shown.

all the way up to the cluster centre, suggesting high star forming activity even in the cluster core (right panel of Figuer 2; Hayashi et al., 2010). This may indicate an inside-out propagation of star formation activity in clusters between these two epochs (Figure 3).

Such impressive difference in the spatial distribution between these two clusters may indicate that the galaxy formation bias is getting more effective and visible in high density regions at $z \sim 1.5$. We may be entering the epoch when such bias starts to reverse the well-known lower-z relationship of decreasing star formation activity with increasing density. It seems that the star formation activity is once very high in the cluster core at $z \sim 1.5$, but is truncated from the center and propagated to outer regions with time (Figure 3).

At a certain point, one may eventually reach to the epoch when the galaxies are forming rapidly in the biased cluster core, while galaxies are only slowly forming or not yet formed in lower density regions.

3. "MAHALO-SUBARU" PROJECT

These results are all intriguing and informative, but we do not know whether these trends reflect the universal evolutionary effects in general clusters or just the intrinsic scatter in characteristics among different clusters. We should definitely increase the sample of clusters at $z \sim 1.5$ to discuss the universality/variation. We should also go further back in time and explore more distant clusters at $z > 1.5$.

We have been awarded an extended Subaru intensive program called "MAHALO-Subaru" (MApping Hα and Lines of Oxygen with Subaru). We will target 8 known clusters/proto-clusters at $z > 1.5$ and a blank field to cover the whole range of environment. This project will map out star forming activities, sketch its spatial propagation with time and probe how the cluster galaxies are formed and transformed as they assemble to clusters.

4. THE FIRST APPEARANCE OF CLUSTER RED-SEQUENCE IN PROTO-CLUSTERS

At higher redshifts ($z > 2$), we have also been conducting wide-field near-infrared imaging of seven proto-clusters around radio galaxies (RG) with MOIRCS (Kodama et al., 2007). Figure 4 shows the colour-magnitude diagrams of the K_s-selected galaxies in two proto-clusters at $z = 2.16$ and 2.92. We select cluster member candidates associated to the RGs on the ba-

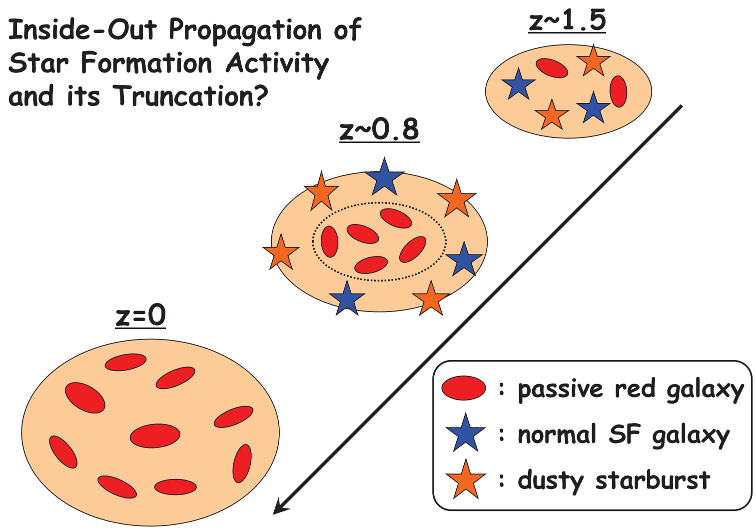

Fig 3.— A schematic diagram showing the inside-out propagation/truncation of star formation activity in clusters with time.

sis of their $J-K_s$ or JHK_s colours. The red galaxies with $K_s < 20$ in PKS1138 show clear excesses (factor ~ 4) compared to a general field. However, as one goes further back in time to $z \sim 3$ (USS0943), the stellar masses of the red sequence galaxies show a sharp cut-off at the massive-end beyond 10^{11} $M_{\odot}$. This implies that we may be entering the epoch when the massive galaxies are eventually in their formation phase at $z > 2$. Two physical processes, i.e. star formation and mass assembly, must be playing roles here, but we do not know the relative importance of these processes in growing massive galaxies. If star formation is dominant, we should be able to identify starbursting galaxies in these systems. In which environment and at which galaxy mass do we see such intense star formation? And how does it propagate with time in space and in mass? These are the fundamental questions to be answered based on a large sample of proto-clusters explored by the MAHALO-Subaru project.

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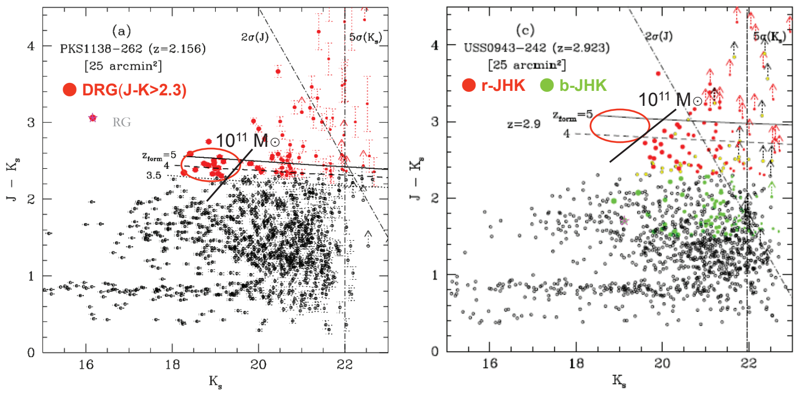

Fig 4.— The first appearance of massive galaxies on the red sequence in proto-clusters between $2 \lesssim z \lesssim 3$. PKS1138 at $z = 2.16$ (left) and USS0943 at $z = 2.92$ (right) are shown. Massive red galaxies ($> 10^{11}$ M$_\odot$) have been well developed in PKS1138 but there are no such galaxies in USS0943, suggesting that massive galaxies grow rapidly between the two epochs in cluster cores. See Kodama et al. (2007) for details.

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