PoS PROCEEDINGS OF SCIENCE

PISCES: Galaxy Properties as Functions of Environment and time

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We discuss the environmental dependence of the galaxy evolution based on deep panoramic imaging of two distant clusters, CL0016+1609 at $z = 0.55$ and RXJ0152.7$-$1257 at $z = 0.83$, taken with Suprime-Cam on Subaru as part of the *PISCES* project. By combining with the *SDSS* data as a local counterpart for comparison, we construct a large sample of galaxies that spans wide ranges in environment, time, and stellar mass (or luminosity). Based on local and global densities of galaxies, we classify three environments: field, group, and cluster. Then we focus on the color-magnitude relation of galaxies. In particular, we quantify how the color-magnitude relation is built-up as a function of time, environment, and mass. In the field environment, there is no clear color-magnitude relation at $z = 0.83$, while a clear relation is seen at lower redshifts, especially at the bright end. In groups, a relation is visible only at the bright end ($M_V < -20$) at $z = 0.83$. The relation is found to extend down to our magnitude limit in groups at lower redshifts. Clusters have a clear relation down to the magnitude limit at all redshifts considered here. We confirm the 'down-sizing' in the star formation recently reported both at low and high redshifts, where massive galaxies complete their star formation earliest and the truncation of star formation is propagated to smaller objects as time progresses. Our results suggest that 'down-sizing' is yet at its earlier stage in lower density regions, while it is more proceeded in high density regions. All in all, it is likely that the formation and evolution of galaxies are the earliest in massive systems and in high density regions, and it proceeds to less massive systems and to lower density regions.

Baryons in Dark Matter Halos
5-9 October 2004
Novigrad, Croatia

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1. Introduction and Sample Construction

Intensive studies of galaxy properties, such as morphology and star formation rate, have significantly improved our understanding of galaxies in the Universe. It is, however, still unclear how galaxies evolve over the Hubble time. This is due, at least in part, to the complex nature of galaxy properties – galaxy properties depend not only on time, but also on environment and mass (luminosity). Furthermore, these three axes are related to each other. It is therefore important to view galaxy properties along the three axes simultaneously. Here we aim to study galaxy star formation as functions of environment, time, and mass. We base our analyses on panoramic imaging data of two high-z clusters, CL0016+1609 at $z = 0.55$ (CL0016 for short) and RXJ0152.7$-$1257 at $z = 0.83$ (RXJ0153 for short), and the SDSS data-set. The sample spans wide ranges in environment, time, and stellar mass, and gives us an unique opportunity to perform a comprehensive study of galaxy star formation along the three axis.

The two high-z clusters were observed as part of the on-going project called PISCES (*Panoramic Imaging and Spectroscopy of Cluster Evolution with Subaru*) [1]. The cluster CL0016 was observed in $BVRi'z'$ and RXJ0153 in $VRi'z'$ under photometric conditions and good seeing ($\sim 0''.6$). Our imaging is deep – we can reach as deep as $\sim M_V^* + 4$ at each redshift. Since the clusters lie at high redshifts, galaxies at the cluster redshifts are heavily contaminated by fore-/background galaxies. To eliminate the contamination, we apply photometric redshift technique [2] and additional statistical field subtraction. By comparing the photometric redshifts with spectroscopic redshifts, we confirmed that our photometric redshifts are fairly good, especially for red galaxies ($\Delta z \lesssim 0.05$).

2. Color-Magnitude Diagrams

Thanks to the wide-field imaging capability of the Suprime-Cam on Subaru [3], we obtain a wide variety of environments: sparse fields, poor groups, and rich clusters. Based on local and global density, we classify three environments, namely, field, group, and cluster. Details of the environment definition are described in [4].

We present in Figure 1 the color-magnitude diagrams of our sample. Many interesting trends are found in the figure, but the main point is that we observe the build-up of the color-magnitude relation. In the field environment, we do not see any clear relation at $z = 0.83$. But, at $z = 0.55$ and $z = 0$, a clear relation is found, especially at the bright end. In groups, a relation is seen only at the bright end at $z = 0.83$. We cannot identify any clear relation at the faint end. At lower redshifts, a clear relation is observed down to our magnitude limit. In contrast to these environments, cluster galaxies show a clear relation down to the magnitude limit at any redshifts considered here. These trends have two interesting implications. One is that the color-magnitude relation first appears at the bright end and the faint end is filled up later on. The other is that an evolutionary stage of the color-magnitude build-up is different in different environments. The relation is first built in clusters, and those of group and field galaxies are built later. We further quantify the observed build-up in the next section.

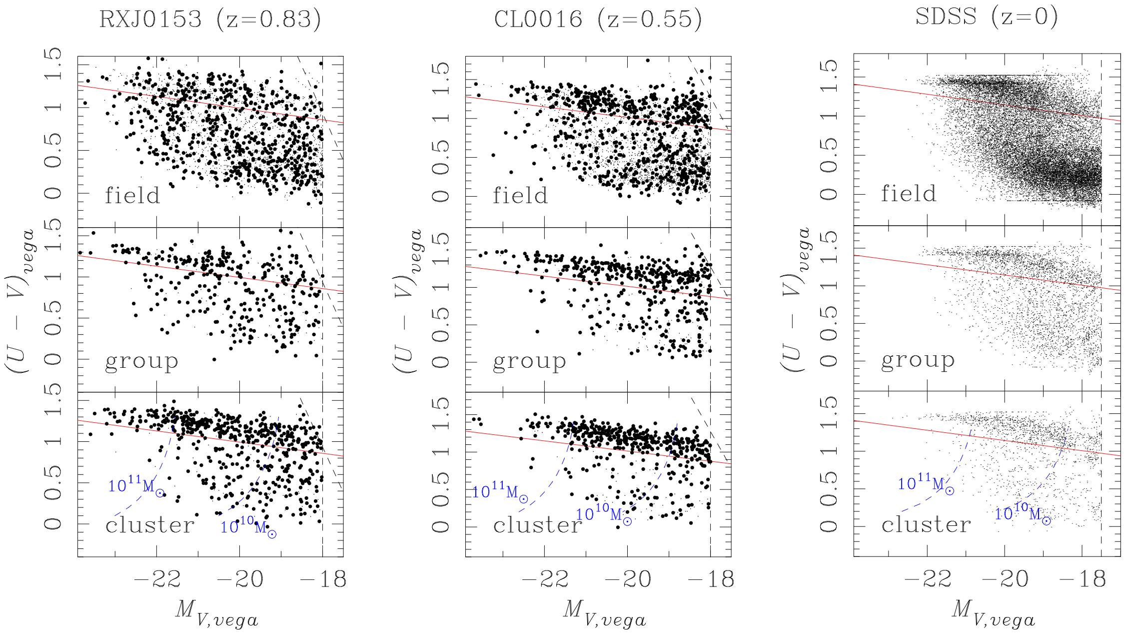

Figure 1: The rest-frame color-magnitude diagrams ($U-V$ vs. M_V) in RXJ0153 (*left*), CL0016 (*middle*), and SDSS (*right*). The solid line represents the color-magnitude relation shifted blueward by 0.15 magnitude. This solid line separates red and blue galaxies used in the following analysis. The vertical dashed line is the 5σ magnitude limit, and the slanted dashed line shows the 5σ limiting color. In the cluster plot, the curved dashed lines show loci of stellar masses of 10^{10} and 10^{11} $M_\odot$.

3. Discussion

We plot in Figure 2 the fraction of red galaxies as a function of environment, stellar mass, and time. Red/Blue galaxies are defined in Fig. 1. The general trend is that the red fraction is the lowest in the field environment and higher in groups and clusters. But, in any environments and at any redshifts, the red fraction is higher for more massive galaxies.

Due to relatively large errors, the red fraction of cluster galaxies is consistent with the idea that the red fraction does not change with redshift, except for the least massive galaxies. Group galaxies seem to show an increase in the red fraction for all the stellar mass ranges. Galaxies in the field environment also show an increase. However, the increase is larger for more massive galaxies, and the least massive galaxies seem to show little evolution (though CL0016 is rather exceptional).

This clearly demonstrates that the build-up of the color-magnitude relation is at the most advanced stage in clusters, and that of group and field galaxies are at an less advanced stage. We suggest that strong evolution has occurred since $z\sim 1$ in the 'down-sizing' way [5, 6, 7]. The bright end of the color-magnitude relation is formed first as massive galaxies stop their star formation, and the build-up proceeds to the faint end as less massive galaxies stop their star formation. This down-sizing is now found to depend on environment as well. The evolution of massive cluster galaxies is almost completed by $z=0.83$, and the evolution of the least massive galaxies is seen. In lower density environments, the evolution of massive galaxies becomes stronger, while that of less massive galaxies becomes weaker. The main population that shows strong evolution is shifted to higher mass galaxies in lower density environments.

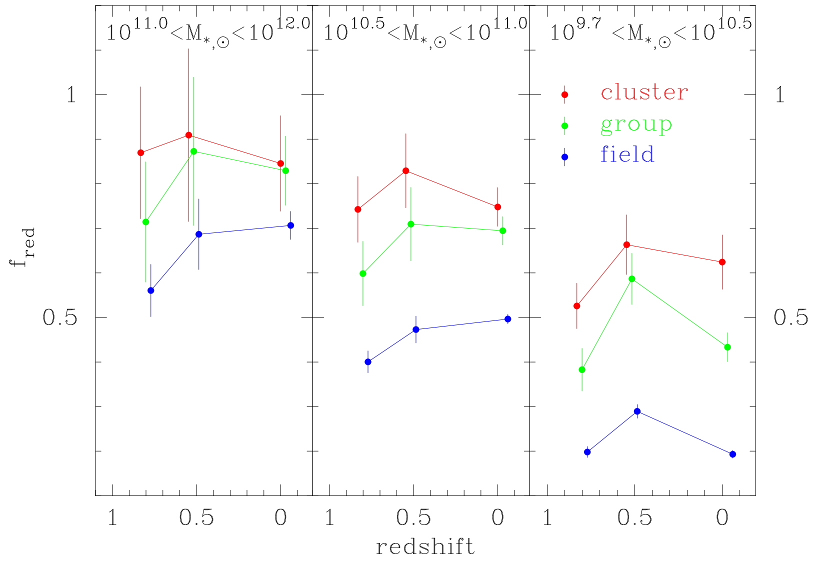

Figure 2: Fraction of red galaxies plotted against redshift for the three stellar mass bins. The meanings of the lines are shown in the figure. The error bars show the Poisson errors.

This down-sizing is likely to be related to initial conditions of galaxy formation (*a priori* effects). Galaxies are formed earlier in higher density peaks of the initial density fluctuation of the Universe. Thus galaxies in clusters are naturally at an advanced stage of galaxy evolution compared with those in lower-density environments. This may explain the environmental dependence of the build-up of the color-magnitude relation. We consider that this down-sizing effect is not solely caused by *a priori* effects, but also environmental (*posteriori*) effects should contribute significantly. Effects that suppress star formation activities are strong in high-density environments and they should accelerate the build-up of the color-magnitude relation. All in all, it is likely galaxy evolution proceeds from massive systems to less massive systems, and from high density environments to low density environments.

References

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