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ENVIRONMENTAL DEPENDENCE OF STELLAR POPULATION PROPERTIES OF HIGH-REDSHIFT GALAXIES

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ABSTRACT

How galaxy evolution differs in different environments is one of the intriguing questions in the study of structure formation. While galaxy properties are clearly distinguished in different environments in the local universe, it is still an open issue what causes this environmental dependence of various galaxy properties. To address this question, in this work, we investigate the build-up of passive galaxies over a wide redshift range, from $z \sim 2$ to $z \sim 0.5$, focusing on its dependence on galaxy environment. In the UKIDSS/Ultra Deep Survey (UDS) field, we identify high-redshift galaxy cluster candidates within this redshift range. Then, using deep optical and near-infrared data from Subaru and UKIRT available in this field, we analyze and compare the stellar population properties of galaxies in the clusters and in the field. Our results show that the environmental effect on galaxy star-formation properties is a strong function of redshift as well as stellar mass — in the sense that (1) the effect becomes significant at small redshift, and (2) it is stronger for low-mass ($M_* < 10^{10} M_\odot$) galaxies. We have also found that galaxy stellar mass plays a more significant role in determining their star-formation property — i.e., whether they are forming stars actively or not — than their environment throughout the redshift range.

Key words: galaxies: environment — galaxies: clusters — galaxies: star formation — galaxies: evolution — galaxies: high-redshift

1. WHAT CONTROLS STAR FORMATION IN GALAXIES ?

In the local universe, we observe a well developed bi-modality of galaxies in terms of their optical color — *blue*- or *red*-galaxies (Strateva et al., 2001; Baldry et al., 2004) — or their star-formation (SF) or stellar population properties (Kauffmann et al., 2003). This clear bi-modality enables us to divide galaxies into sub-populations and to investigate their properties and evolution through time. One of the key questions in modern astrophysics, whose answer can be pursued through the investigation of these sub-populations of galaxies, is what governs the star-formation properties of galaxies or how star formation in galaxies has been quenched to produce passive or quiescent galaxies, as well as how these quiescent galaxies have evolved throughout the history of the universe to reach their current status. At $z \sim 0$, studies have shown that the star formation — or related properties, such as color or morphology — of galaxies exhibits a clear stellar-mass dependence (e.g., Kauffmann et al., 2003). In the local universe, the SF properties of galaxies also seem to depend on the environment in which they reside (e.g., Lewis et al., 2002). However, when this environmental dependence has developed or what mechanisms or processes have contributed to this dependence are still open questions. Until now, there has been an interesting disagreement on how this environment-dependent trend changes as we go to high redshift. (e.g., Cooper et al., 2006; Elbaz et al., 2007; Grützbauch et al., 2011; Scoville et al., 2013). To understand how galaxy star-formation histories have evolved in different environments, we investigate and compare the star-formation properties of high-redshift ($0.5 \lesssim z \lesssim 2$) galaxies in different environments and with different stellar masses.

2. PHOTOMETRIC REDSHIFTS AND STELLAR POPULATION PROPERTIES OF GALAXIES

We use J, H, and Ks data from the UKIRT in the UKIDSS (Lawrence et al., 2007) Ultra Deep Survey (UDS) (Almaini et al. in prep.). We also combine B, V, R, i', and z' data from Subaru (Furusawa et al., 2008) and *Spitzer*/IRAC data from the SpUDS Spitzer Legacy Survey (PI:Dunlop). After excluding stellar and AGN sources, we have around 47,000 galaxies in ~ 0.77 degree^2 area with stellar mass of log $(\mathrm{M}_*/M_\odot) \geq 9.1$, within a redshift range of $0.45 \leq z \leq 2.1$. We estimate the photometric redshifts of our sample galaxies using the EAZY photometric redshift code (Brammer et al., 2008) by fitting multi-band photometry. Then, the stellar population properties including stellar masses and

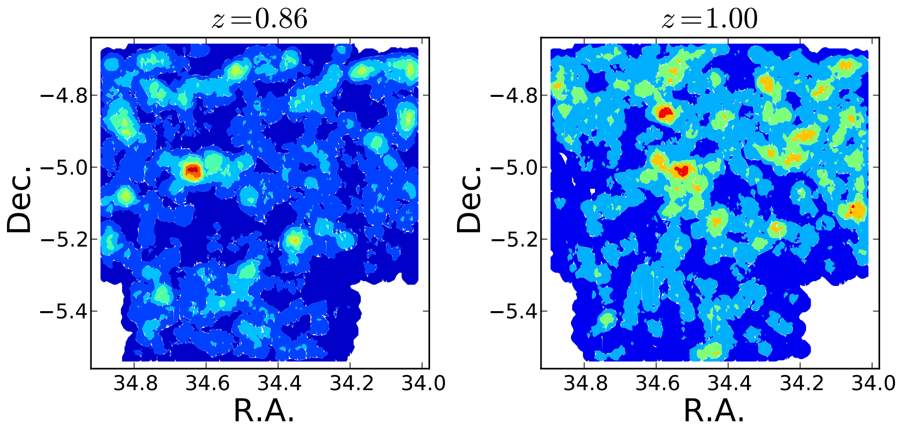

Figure 1. The density maps in redshift bins $z = 0.86$ (**Left**) and $z = 1.00$ (**Right**). Galaxy number counts are measured within the radius of $r \leq 500h^{-1}$ kpc at each grid point, which is at the distance of $12''$ from each other as explained in the text. The red colored regions show where the overdensities of galaxies exist.

star-formation rates (SFRs) of these galaxies are estimated through Spectral Energy Distribution (SED) fitting with Bruzual & Charlot (2003) spectral templates with delayed star-formation histories. We employ similar assumptions and parameter ranges as in Lee et al. (2010, 2014a).

3. HIGH-REDSHIFT GALAXY CLUSTERS

We find the candidates of (proto-)clusters of galaxies in the redshift range $0.5 < z < 2$ following the method used in Kang & Im (2009). First, we divide the data into redshift bins with a width of 0.02. Then at each redshift bin, after dividing the UDS survey region into grids whose width is $12''$, we measure, at each grid point, the number of galaxies inside a circle with a radius of $r \leq 500h^{-1}$ kpc and within $\Delta z = \pm 0.028 \times (1 + z)$. Figure 1 shows typical density maps constructed in this manner. Next, we find the *over-dense* grid points whose galaxy number counts exceed 4-σ with a Gaussian fit. Finally, we search the structures where the overdense grid points are connected with each other and are also found in three or more successive redshift bins (in the overlapped sky region). By applying these rather conservative criteria, we identified 46 (proto-)cluster candidates in the UDS region. The number of member galaxies (within 1 Mpc radius), ranges from 30 to 90. Out of 46 galaxy clusters, 13 clusters are also found by Finoguenov et al. (2010), who provide the halo mass (M_{200}) for these clusters. The halo masses of these 13 clusters are $\sim 10^{14}$ $M_\odot$.

4. EVOLUTION OF THE QUIESCENT GALAXY FRACTION

After identifying high-z galaxy clusters, we analyse various properties, including their color, star-formation properties, and morphology, of the cluster member galaxies and compare them with the properties of field galaxies in the same UDS field. One of the most interesting results of this analysis is the evolution of the passive galaxy fraction (defined as the fraction of galaxies whose specific SFR (sSFR) is lower than 10^{-10} $\mathrm{yr}^{-1}\mathrm{s}$) from $z \sim 2$ down to $z \sim 0.5$. The investigation of the evolution of this passive galaxy fraction reveals several interesting aspects regarding the cessation of the star-formation (SF) activity of galaxies. (1) The fraction of passive galaxies rapidly increases at high redshift ($z > 1.5$), in a similar manner in both in clusters and the field, while this increase becomes slower at lower redshift. (2) The difference in the passive fraction between clusters and the field becomes more evident at low redshift. (3) The passive fraction shows a clear dependence on the stellar mass limit, in the sense that the passive fraction is higher when we apply a higher stellar mass limit in analysis. The details of this analysis will be presented in Lee et al. (2014, in prep.).

5. WANING OF STAR FORMATION DEPENDING ON ENVIRONMENT AND MASS

In this work, we have found that the stellar mass of galaxies plays a significant role in determining their star-formation properties and the fraction of passive galaxies. Why the SF activities or SFHs of galaxies are affected by their stellar mass is still an open question. We have also found that the increase of the difference in the passive fraction between clusters and the field below $z \lesssim 1.5$ is more significant for less massive ($< 10^{10}$ $M_\odot$) galaxies. Further investigation of this can elucidate the process or mechanism for SF quenching in cluster environments, as well as its dependence of galaxy mass.

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