Resolving the Rise and Fall of Star Formation in Galaxies
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Star-formation Property of High Redshift Galaxies in Clusters: Perceptive View from Observation and Simulation

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Abstract. The evolution of star formation properties of galaxies depends on the environment where galaxies reside, and generally star formation of galaxies in dense environment decreases more quickly. Interestingly, the star formation property of high-redshift galaxies clusters vary largely even though they are at similar redshift. We have found that the large-scale environment surrounding each galaxy cluster can contribute to make this cluster-by-cluster variation. This correlation is found in the results from observational data as well as in the simulations of galaxy formation. We suggest the 'Web-feeding model' to explain this trend. Star-forming galaxies falling into the galaxy cluster from surrounding large-scale structure make the quiescent galaxy fraction of the cluster lower than relatively isolated clusters.

Keywords. star formation, galaxy cluster, high redshift, large scale structure

1. Introduction

Galaxies are building blocks of the Universe, and understanding the evolution of galaxies is an interesting and important subject in modern astronomy. Among various properties of galaxies, the evolution of star formation activity of galaxies is one of the matters of substance, because it is the main channel of galaxy growth (modulo merging).

For this reason, there have been many observational efforts to understand the star formation properties of galaxies. While there are many issues which are still in controversy, one major uncontroversial finding is that the Universe experienced a decrease of an order of magnitude in the star formation rate density within it from $z \sim 2$ to now (e.g., Madau & Dickinson 2014). Also, many observational results have shown that average star formation rate (SFR) of $z \sim$ 1-2 galaxies is much higher than local.

Here, we briefly summarize our current understanding about the evolution of star formation activity of galaxies and present the results from our recent study on the environmental dependence of star formation properties of galaxies.

2. Star formation activity of high redshift galaxies

2.1. *Evolution and quenching of Star formation*

As stated above, the average SFR has been changed throughout the history of the Universe. Especially, it has decreased significant during the last 10 billion year from $z \sim 2$ to $z \sim 0$. There have been many mechanism or causes which can cut down or stop the star formation activity of galaxies. These can be categorized into two: (1) internal or nature or mass-quenching and (2) external or nurture or environmental quenching.

The suggested candidates for internal quenching includes shock heating of gas, stellar and AGN feedback and morphological transformation (such as bulge formation). These effects show somehow the dependence on stellar mass of galaxies, which is the reason this is called as 'mass-quenching'.

Environmental quenching is associated with processes occur mainly in dense environment such as galaxy clusters. These include ram pressure stripping (Gunn & Gott 1972) and strangulation (or starvation; Larson *et al.* 1980).

2.2. *Environmental Effects: Evolution of Environmental Dependence*

While average SFRs galaxies have been known to decrease since $z \sim 2$, this decrease is more significant in dense environment (e.g., Scoville *et al.* 2013). The evolution of relative importance of 'mass-quenching' and 'environmental quenching' has been studied by many authors (e.g., Peng *et al.* 2010; Lee *et al.* 2015).

This is the subject for which many researches are still being done, but most results from these studies suggest the relative importance of environmental quenching increases with decreasing redshift with crossing redshift occurs at $z \sim 1.4$-1.5, and environmental effects are manifested more significantly for low mass galaxies (e.g., Lee *et al.* 2015).

3. Galaxy Clusters in Different Large-scale Enivronment

One of interesting findings in Lee *et al.* (2015) was that the star formation property (measured by the quiescent galaxy fraction) shows a large variation among clusters residing at similar redshfit. The reason for this cluster-by-cluster variation among high redshift galaxy clusters was investigated in our subsequent works as summarized below.

3.1. *QF-Environment correlation in UDS and COSMOS*

We studied properties of galaxy clusters at $z \sim 0.65$-0.8 in the UDS, using the data from the multi-object spectroscopy (MOS) obtained by the Inamori-Magellan Areal Camera Spectrograph (IMACS) on the Magellan telescope (Lee *et al.* 2019). In this study, we found that the quiescent galaxy fraction of galaxy clusters shows a dependence on the large-scale environment where each galaxy cluster resides, in a sense that galaxy clusters located in more dense large-scale environment have on average lower quiescent galaxy fraction.

We parametrized the large-scale environment of galaxy clusters using 'FoF fraction', which is defined as the ratio of dense surface area within the 10 Mpc radius vicinity of each galaxy cluster. The galaxy clusters in the UDS show a anti-correlation between the quiescent galaxy fraction and the FoF fraction: galaxy clusters with large FoF fraction have low quiescent galaxy fraction. We have also found a similar trend between the quiescent galaxy fraction and cluster's large scale environment in the study done in the COSMOS field (Ko, E. et al. in preparation).

3.2. *Web Feeding Model*

To explain this correlation, we suggested the 'Web-feeding model' (Lee *et al.* 2019). The assumption of the web-feeding model is that new material, such as galaxies and gas, keeps infalling into the central galaxy clusters from surrounding overdense structures. This infalling material makes the quiescent galaxy fractions to be maintained low, comapred to relatively isolated clusters.

These aussmptions have been checked using Illustris TNG300 simulation and found to be true: (1) if there are filamentary structures connected to the galaxy clusters, galaxies are falling into clusters from the connected filametary structure, and (2) these infalling galaxies have lower level of quiescent galaxy fraction than cluster galaxies (Ko, E. et al. in preparation).

3.3. *Web Feeding and QF-FoF correlation in Galaxy Formation Models*

The correlation between the quiescent galaxy fraction of galaxies and the large-scale environment (e.g. FoF fraction) is also found in the galaxy formation models. For this, we analysed about 300 groups and clusters at $z \sim 0.9$ from the Horizon Run 5 (HR5) galaxy formation simulation (Lee *et al.* 2021).

These clusters from the HR5 simulation also shows a large range of quiescent galaxy fraction, similarly with the galaxy clusters found in the UDS and COSMOS. From the analysis of these mock groups and clusters, we have found that there are several factors which can affect the quiescent galaxy fraction of these groups and clusters. Among these factors, the large-scale environment of clusters, parametrized as FoF fraction, is found to affect and has correlation with the quiescent galaxy fraction of galaxy clusters, assuring our observational finding (Lee, S.-K. et al. in preparation).

4. Conclusion

In this proceeding, we present a brief summary of our interesting findings about the star formation properties of high redshift galaxy clusters. These findings are done utilizing observational survey data, follow-up spectroscopic data, as well as the up-to-date simulations of galaxy formation.

Our findings can be summarized as follows.

(1) The quiescent galaxy fraction of high redshift galaxy clusters increases with decreasing redshift.
(2) There is a cluster-by-cluster in the quiescent galaxy fraction among galaxy clusters even though they reside at similar redshift.
(3) The quiescent galaxy fraction shows a dependence on the large-scale environment surrounding each galaxy cluster.
(4) To explain this correlation, we suggest the 'Web-feeding model', in which infalling fresh star-forming galaxies from surrounding environment can keep the quiescent galaxy fraction of galaxy cluster to be lower compare to isolated clusters.

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