Search for protoclusters in COSMOS 
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Background

The formation of large scale structures (LSS) in our universe and its relation to the formation and evolution of galaxies have been one of the important issues based on the so-called cold dark matter scenarios. In the local universe, the most spectacular sites of such LSSs are clusters of galaxies. It is known that the dominant populations in the clusters of galaxies are elliptical and S0 galaxies while those in the field are spiral and irregular galaxies; the morphology-density relation (Dressler 1980, ApJ, 236, 351). Actually, the origin of this relation has been in debate; i.e., nature (e.g., intrinsic, or initial condition) or nurture (e.g., extrinsic, or galaxy - galaxy merger).

To order to clarify which is more essentially important, it is absolutely necessary to probe high-redshift universe. Here, our main questions are; (1) when and how such large scale structure were grown up in the universe ? (2) when and how galaxies were formed and evolved during the course of LSS evolution ? The problem is that we know very little on these issues even now.


Although large scale structures in the early universe are found from Lyman $\alpha$ emitters surveys, the number of protoclusters that are confirmed by spectroscopic observation is only a few [ SSA22 ($z = 3.1$, Hayashino et al. 2004, AJ, 128, 2073) , SDF ($z = 4.9$, Shimasaku et al. 2004, ApJ, 605, L93) , SXDS ($z = 5.7$, Ouchi et al. 2005, ApJ, 620, L1) ]. There are some reports on the some protoclusters that do not include AGNs as a byproduct of protocluster surveys around AGNs. For example, Intema et al. (2006) found 4 - 7 protoclusters besides the protocluster around active radio galaxy TN J1338-1942. They estimated the volume density of protoclusters but they do not confirm that those protoclusters are real ones by spectroscopic observations. Kashikawa et al. (2007) also found over-density regions of both Lyman break galaxies and Lyman $\alpha$ emitters in the field that include QSO SDSS J0211-0009. Recently Kang & Im (2009, ApJ, 691, L33) found a protocluster at $z \sim 3.7$ and estimated the mass of that regions as $\sim 10^{14} M_\odot$. We cannot still discuss the statistical properties of protoclusters, because there are not enough numbers of protoclusters that are confirmed by spectroscopic observation.

Now, we have found protocluster candidates beyond $z = 3$ in the COSMOS 2 square degree field from our large sample of $U$-dropout galaxies. We propose the spectroscopic observation using FOCAS to confirm real protoclusters to investigate the statistical properties of protoclusters and the evolution of galaxies in the protoclusters beyond $z = 3$.

Proposed observation

We propose a spectroscopic observation of Lyman break galaxies in the protocluster regions found in the COSMOS 2 square degree field using FOCAS. The large area coverage of the COSMOS combined with accurate photometric redshifts and multi-waveband data provides the data needed for studying the relation between the evolution of galaxies and their environment. The COSMOS data provide accurate way for identifying the LBGs. In this data set, Mid-infrared data observed by Spitzer Space Telescope are also available. These data will be highly useful in investigating the stellar mass assembly process and star formation history of galaxies in our protoclusters. Using this data, we can study the mass assembly as a function of environment of galaxies. It is expected that the rate of mergers and the mass assembly is higher in denser environment. This can be quantified in protoclusters. In the COSMOS, we have also ACS morphology of galaxies and hence, could study the origin of the Hubble sequence. This is NOT possible with any other survey. We can estimate star formation rates (SFRs) of galaxies in protoclusters using a multiwavelength data of galaxies in the COSMOS project. We could therefore study changes in SFR as a function of environment and morphology in galaxies. It is important to find out what is the SFR and the stellar mass of galaxies associated with protoclusters compared to those in general field. We could discuss these problems using these results. The COSMOS data include narrowband data, so we could study clustering of the LBGs and LAEs simultaneously and in the same field of view.

Protocluster regions have been selected by the following procedure. First, we have selected LBGs at $3.2 < z < 3.6$ in the COSMOS field following Carilli et al. (2008, ApJ, 689, 883). The selection criteria are as follows:

- $u - B \geq 0.7(B - i) + 0.7 \lvert u - B \geq 1.4 \lvert B - i \leq 2.5$,
- the objects are classified as galaxies based on the ACS images, and
- their photometric redshifts are larger than 2.5.

As we noted above, the most of protoclusters that have been studied are biased toward quasars and radio galaxies. The proposed technique, based on the photometric redshifts, provides an unbiased sample of protoclusters and an
unbiased estimate the number density of protoclusters. In addition, by this observation, we can compare protoclusters formed around quasars and radio galaxies with those selected based on their redshifts, as measured in this proposal.

Next, using the above LBG samples, we calculate local surface density \( \sigma = \frac{11}{\pi \theta^2} \) for each galaxy, where \( \theta \) is the distance (arcmin) to the 10th nearest neighbor. We have selected 5 protocluster candidates that include galaxies whose local density is about 6 times higher than the average (Fig.1). We call them C-LBG-1 (Cluster of LBGs 1), C-LBG-2, C-LBG-3, C-LBG-4 and C-LBG-5 as figure 1. Taking into account the sensitivity of FOCAS, we have selected 3 protoclusters having at least 5 LBGs with \( V < 28.4 \) (C-LBG-1, C-LBG-2 and C-LBG-3). C-LBG-1, C-LBG-2 and C-LBG-3 have 12, 11 and 13 LBGs with \( V > 24.8 \) and 5, 5 and 3 LBGs with \( V < 24.8 \) into the field of view (FOV) of FOCAS. We calculate the number density of LBG candidates with \( V > 24.8 \) in COSMOS, and estimate numbers of them that are observed in the FOV of FOCAS. We find that predicted numbers of them that are observed in the FOV of FOCAS is fewer than 1. If our targets with \( V > 24.8 \) in a protocluster candidate are in similar redshift range, We can predict that they form a protocluster.

In summary, in this project, we measure the redshift of LBGs in protocluster candidates. We select real protoclusters from their redshift distribution and evaluate the number density of real protoclusters. Based on these results, we will investigate how overdensity regions grew up in high redshift universe and how galaxies evolved in them. We will estimate the stellar mass and the SFRs of galaxies in protoclusters, and then study the relation between these and morphology or environment of galaxies using the COSMOS data.

Figure 1

![Figure 1](image1.png)

Figure 1 (left): Spatial distribution of protocluster candidates at \( 3.2 < z < 3.6 \) in the COSMOS field. Contour lines indicate the value of local density. The lowest level of the contour is half of the average of local density over the 2 deg\(^2\) field. Intervals between contours are half of the average. The average is about \( \left( \frac{\text{number of all LBG samples}}{\text{COSMOS survey area}} \right) 0.22 \text{ arcmin}^{-2} \). Red circles show protocluster candidates. The size of the circle is same the FOV of FOCAS. (right): Spatial distribution of LBG candidates at \( 3.2 < z < 4.0 \) in the COSMOS field.

Figure 2

![Figure 2](image2.png)

Figure 2: The Subaru telescope \( V \)-band image of C-LBG-1 (at center) and images of galaxies of C-LBG-1 (around the center image). The scales of both a vertical axis and a horizontal axis is 180 arcsec on the center image and 15 arcsec on all small images. Black crosses indicate LBG candidates which have \( V \geq 24.8 \). Red crosses indicate LBG candidates which have \( V < 24.8 \). The Center of this image located at RA = 149.89433, DEC = 1.652568. The comoving distance equivalent to 180 arcsec and 15 arcsec in \( z = 3.6 \) are 6.0 Mpc and 0.5 Mpc, respectively.