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Subaru/HSC identifications of protocluster candidates at $z \sim 6-7$: Implications for cosmic reionization

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Abstract. We report fourteen and twenty-eight protocluster candidates at $z = 5.7$ and 6.6 over 14 and 19 deg^2 areas, respectively, selected from 2,230 Lyα emitters (LAEs) photometrically identified with Subaru/Hyper Suprime-Cam (HSC) deep images. Six out of the 42 protocluster candidates include at least 1 spectroscopically confirmed LAEs at redshifts up to $z = 6.574$. By the comparisons with the cosmological Lyα radiative transfer (RT) model reproducing LAEs with the reionization effects, we find that more than a half of these protocluster candidates might be progenitors of the present-day clusters with a mass of $\gtrsim 10^{14} M_\odot$. We also investigate the correlation between LAE overdensity and Lya rest-frame equivalent width (EW), because the cosmological Lyα RT model suggests that a slope of EW-overdensity relation is steepened towards the epoch of cosmic reionization (EoR), due to the existence of the ionized bubbles around galaxy overdensities easing the escape of Lyα emission from the partly neutral intergalactic medium. The available HSC data suggest that the slope of the EW-overdensity correlation does not evolve from the post-reionization epoch $z = 5.7$ to the EoR $z = 6.6$ beyond the moderately large statistical errors.

Keywords. galaxies: high-redshift - galaxies: evolution - galaxies: formation

1. Introduction

It is important to study the physical process of cosmic reionization in astronomy today. In theoretical models, it is predicted that star-forming galaxies make ionized regions in the IGM around galaxies, called ionized bubbles. Large ionized bubbles are expected to form in galaxy high-density regions, and it is suggested that the cosmic reionization proceeds from high- to low-density regions (Overzier 2016). This process is called 'inside-out scenario'. The observation of galaxy high-density regions and identification of signatures of ionized bubbles are keys to testing the inside-out scenario of cosmic reionization. Observations of galaxy high-density regions near the epoch of cosmic reionization (EoR) are also important for a study of the early galaxy formation. In standard structure formation models, it is predicted that a large fraction of high-z galaxy high-density regions evolve into massive galaxy clusters at $z = 0$. These galaxy high-density regions are called protoclusters. A protocluster is usually defined as a structure expected to evolve into a galaxy cluster with a halo mass $M_{\rm h} > 10^{14}\,{\rm M}_{\odot}$ (Chiang *et al.* 2013; Overzier 2016). Protoclusters at the EoR would be important examples of the early galaxy cluster formation (e.g. Ishigaki *et al.* 2016). Although the importances of high-z galaxy high-density regions are well recognized, there are only a few protoclusters at $z > 6$ reported (ouchi *et al.* 2005; Utsumi *et al.* 2010; Toshikawa *et al.* 2012, 2014; Chanchaiworawit *et al.* 2017). To enlarge samples of protocluters at $z > 6$, we need large field survey of galaxy high-density regions. In this study, we conduct protocluster survey at $z = 5.7$ and 6.6 based on the samples of Lyα emitters (LAEs) obtained with Subaru/Hyper Suprime-Cam (HSC).

2. Data

HSC LAE Sample. We use LAE samples of HSC SSP data to calculate galaxy overdensity and identify protocluster candidates (see also Shibuya *et al.* 2018a). Shibuya *et al.* (2018a) select LAEs based on the HSC datasets. The color selection criteria are defined as

$$i - NB816 \geqslant 1.2 \text{ and } g > g_{3\sigma} \text{ and } [(r \leqslant r_{3\sigma} \text{ and } r - i \geqslant 1.0) \text{ or } (r > r_{3\sigma})] \tag{2.1}$$

and

$$\begin{gathered} z - NB921 \geqslant 1.0 \text{ and } g > g_{3\sigma} \text{ and } r > r_{3\sigma} \text{ and} \\ [(z \leqslant z_{3\sigma} \text{ and } i - z \geqslant 1.0) \text{ or } (z > z_{3\sigma})] \end{gathered} \tag{2.2}$$

for $z = 5.7$ and 6.6 LAEs, respectively. We find 1,077 (1,153) LAEs at $z = 5.7$ (6.6).

SC LAE Sample. In addition to the HSC LAE samples, we use photometric samples of Ouchi *et al.* (2008) (Ouchi *et al.* 2010) to select the spectroscopic targets of $z = 5.7$ (6.6) LAEs. Ouchi *et al.* (2008) and Ouchi *et al.* (2010) find 401 and 207 LAEs at $z = 5.7$ and 6.6, respectively.

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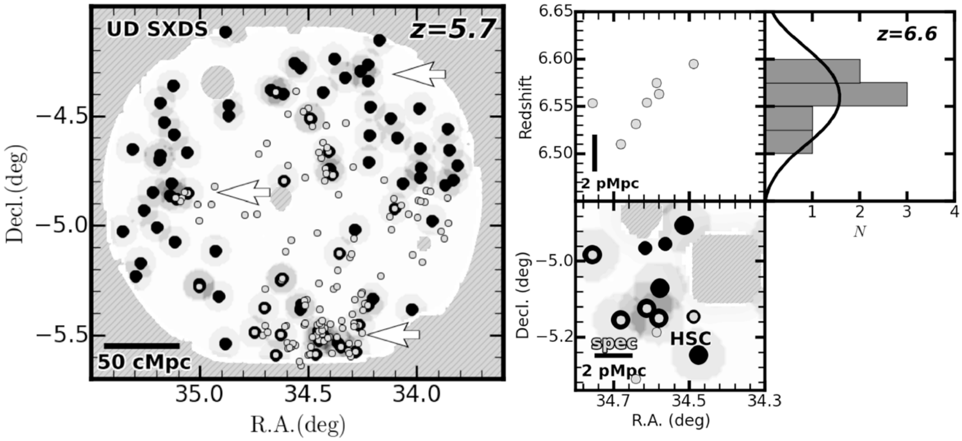

Figure 1. (Left) Example of the sky distribution of the LAEs with δ contours (gray colors) at $z = 5.7$. Black filled circles indicate HSC LAEs used for δ calculation. The gray filled circles show spec-LAEs. Masked regions and shallow regions are shown with gray regions. White quivers show the position of protocluster candidates. (Right) Example of our protocluster candidates at $z = 6.6$. The bottom panel is same as the left figure, but for the example of protocluster candidates at $z = 6.6$. The top-left panel presents the distribution of the spec-LAEs on the plane of R.A. vs. redshift directions. The top-right panel shows the redshift distribution of the spec-LAEs with the mean expected number of LAEs (black line).

Spectroscopic Sample. We carry out spectroscopic observations for our LAE samples. The details of spectroscopic observations for the HSC (SC) samples are shown in Shibuya *et al.* (2018b) (Higuchi *et al.* 2018). In addition to the spectroscopic sample of Shibuya *et al.* (2018b) and Higuchi *et al.* (2018), we refer other redshift catalogues of confirmed LAEs at $z = 5.7$ (6.6) taken from Ouchi *et al.* (2005), Ouchi *et al.* (2008) and Mallery *et al.* (2012) (Chanchaiworawit *et al.* 2017, and Guzmán *et al.* 2017). We make unified catalogs of ~ 200 spectroscopically confirmed LAEs (spec-LAEs) at $z = 5.7$ and 6.6.

3. Results and Discussions

Overdensity Measurements. We calculate LAE overdensities with the HSC LAE samples. The LAE overdensity δ is defined as $\delta = \frac{n - \overline{n}}{\overline{n}}$, where n ($\overline{n}$) is the total (average) number of LAEs found in a circle for the δ measurements. We use a circle with a radius of 0.07 deg (10 cMpc), which would be a typical size of protoclusters at $z \sim 6$ (Chiang *et al.* 2013). We show an example of the HSC LAE sky distribution and the δ map at $z = 5.7$ in Figure 1. We find some regions where δ values significantly exceed beyond those expected by random distribution. We call these regions as high-density regions (HDRs). We define a HDR as a region which has at least 4 LAEs in a radius of 0.07 deg. We identify 14 (28) $z = 5.7$ (6.6) HDRs in total.

Halo Mass Estimates. We estimate the probability of HDRs evolving into massive galaxy clusters at $z = 0$. From the theoretical model of Inoue *et al.* (2018), we derive a relation between the halo mass and δ ($M_{\rm h}$ - δ relation). We calculate the present-day halo masses of the haloes at $z = 5.7$ and 6.6, using the $M_{\rm h}$ - δ relation and extended Press-Schechter model of Hamana *et al.* (2006). We find that ∼60% of the haloes in the HDRs are expected to evolve into haloes with a mass of $> 10^{14}\,{\rm M}_{\odot}$ by $z = 0$. Because more than a half of the haloes in the HDRs are supposed to be progenitors of the present-day clusters, these HDRs can be regarded as protocluster candidates (the properties of protocluster candidates are listed in Higuchi *et al.* 2018).

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Implications for Csomic Reionization. We study the relations between Lyα rest-frame equivalent width (EW) and δ (EW-δ relation) at $z = 5.7$ and 6.6. We calculate EW values for HSC LAE samples and fit a linear function to the EW and δ to evaluate the evolution of the slope of the linear function. We find that the EW-δ relation does not evolve from $z = 5.7$ to 6.6 beyond the errors. We conduct the same analysis for the model (Inoue *et al.* 2018), and find the evolution beyond statistical errors towards the early EoR due to the existence of the ionized bubbles around galaxy high-density regions. The model suggests there is a possibility of detecting the evolution of the EW - δ relation from $z = 5.7$ to 7.3 by the upcoming HSC observations which provides larger samples of LAEs including a new sample of LAEs at $z = 7.3$ (see also Higuchi *et al.* 2018).

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Discussion

T. Goto: Do lyman break galaxies cluster around PCCs?

R. Higuchi: We have not checked lyman break galaxies around PCCs because we do not have GOLDRUSH sample at $z \sim 7$ (see Ono *et al.* 2018). I remember Pavesi *et al.* (2016) referred to our study and suggested that a dusty, starbursting galaxy at $z = 5.7$ exists around our PCCs.