論文の内容の要旨

論文題目　Physical Properties of Galaxies at $z \sim 6-7$ and Their Implications for Cosmic Reionization

(赤方偏移 6—7 にある銀河の物理的性質とそれらの宇宙再電離への示唆)

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In the past 20 years, thanks to novel color selection techniques with deep images taken by state-of-the-art instruments on large ground-based telescopes and space telescopes, our knowledge on the formation history of cosmic structures has been quite developed, and we are now looking back to redshifts $z \sim 6-7$, corresponding to times when the age of the Universe was only 750 Myr – 1 Gyr, and beyond. Numerous galaxies at $z \sim 6-7$ have been found by two color selection methods, one probes redshited Lyman break, and the other does redshifted Lyα line; galaxies selected by the methods are called Lyman-break galaxies, or dropout galaxies, and Lyα emitters (LAEs), respectively. Studying the stellar populations of the galaxy populations is essential to understand their physical nature. However, most of the dropout galaxies found so far at $z \sim 6-7$ are not spectroscopically confirmed and their photometric redshifts have large uncertainties. On the other hand, uncertainties of the photometric redshifts of LAEs are relatively smaller, since they are selected by using narrowband imaging data. This galaxy population may be representative of galaxies at $z \sim 6-7$, because the Lyα method can pick up galaxies with strong Lyα regardless of their UV continuum brightness, and the ratio of dropout galaxies with strong Lyα emission to the total number of dropout galaxies, the Lyα fraction, is larger at higher redshifts (e.g., Stark et al. 2011). Although investigating the stellar populations of typical LAEs at $z \sim 6-7$ will give us a key to comprehend an early phase of galaxy evolution, only a few studies reported on it based on a very small sample, and most of them are biased toward galaxies bright in the rest-frame optical. Also important is inclusion of possible effects from nebular emission on the observed galaxy spectral energy distributions (SEDs). Since LAEs show a strong Lyα emission, they are likely to be also emitting other nebular lines and continuum. However, all of the previous studies do not include or even consider the effect of nebular emission.

Recently, the largest available sample of $z = 5.7$ and 6.6 LAEs have been constructed by Ouchi et al. (2008) and Ouchi et al. (2010), respectively, in the Subaru/*XMM-Newton* Deep Survey (SXDS) field from deep optical broadband and narrowband data. About 65% of the SXDS field is also covered by deep infrared images of JHK and *Spitzer*/IRAC 4 bands. The overlapped field is suit for multiwavelength study of LAEs at $z \sim 6-7$. In this thesis, we investigate the stellar populations of LAEs at $z = 5.7$ and 6.6 in a 0.65 deg^2 sky of the SXDS field, using deep images taken with Subaru/Suprime-Cam, UKIRT/WFCAM, and *Spitzer*/IRAC. We produce stacked multiband images at each redshift from 165 ($z = 5.7$) and 91 ($z = 6.6$) IRAC-undetected objects, to derive typical SEDs of $z \sim 6-7$ LAEs for the first time. The stacked LAEs have as blue UV continua as the *HST*/WFC3 z-dropout galaxies of similar $M_{\rm UV}$, with a spectral slope $\beta \sim -3$, but at the same time they have red UV-to-optical colors with detection in the 3.6μm band. Using SED fitting we find that the stacked LAEs have low stellar masses of $\sim (3-10) \times 10^7 M_\odot$, very young ages of $\lesssim 10$ Myr, negligible dust extinction, and strong nebular emission from the ionized interstellar medium, although the $z = 6.6$ object is fitted similarly well with high-mass models without nebular emission; inclusion of nebular emission reproduces the red UV-to-optical colors while keeping the UV colors sufficiently blue. We infer that typical LAEs at $z \sim 6-7$ are building blocks of galaxies seen at lower redshifts. From the minimum contribution of nebular emission required to fit the observed SEDs, we place an upper limit on the escape fraction of ionizing photons to be $f_{\rm esc}^{\rm ion} \sim 0.6$ at $z = 5.7$ and ~ 0.9 at $z = 6.6$.

Studying the properties of high-redshift galaxies is also useful for understanding the process of cosmic reionization. Several studies on the evolution of the Gunn-Peterson optical depth suggested that the cosmic reionization may have ended at $z \sim 6-7$ (e.g., Fan et al. 2006b; Becker et al. 2007), although they can only detect a subtle increase of the neutral fraction of the IGM. The redshift evolution in the Lyα luminosity function is also used to infer the epoch of the cosmic reionization, and several authors reported a decrease of the Lyα luminosity function from $z = 5.7$ to 6.6 (e.g., Ouchi et al. 2010; Kashikawa et al. 2011). However, the effect of cosmic variance is quite large and the IGM neutral fraction at $z = 6.6$ has still not yet determined well (Ouchi et al. 2010). Measuring the Lyα fraction provides complementary information to understand the reionization process (e.g., Stark et al. 2010). Since LBGs are selected over a broader range of redshifts, their number density is less sensitive to cosmic variance. Furthermore, the Lyα fraction method requires deep spectroscopic observations for dropout galaxies, whose UV continuum has been detected; thus, the denominator and the numerator of the Lyα fraction are derived based on exactly the same sample, being different from the Lyα luminosity function method. In this sense, the Lyα fraction method is more robust one for probing a possible decrease in the neutral fraction of the IGM. Stark et al. (2011) reported that the Lyα fraction increases with redshift from $z \sim 4$ to 6, and this trend is likely explained by the evolution in the amount of dust extinction in dropout galaxies. It is interesting to see if this trend continues toward higher redshift ($z \gtrsim 6$) or not, since this epoch may correspond to the end of the cosmic reionization, which expects to cause a decrease in the Lyα fraction.

Recently, Ouchi et al. (2009b) have built a sample of z-dropout galaxies in the Subaru Deep Field (SDF) and the Great Observatories Origins Deep Survey (GOODS) norther field. These objects are appropriate for follow-up spectroscopic observations because of their apparent brightnesses. In this thesis, we present the results of our ultra-deep Keck/DEIMOS spectroscopy of z-dropout galaxies in the SDF and GOODS-N. For 3 out of 11 objects, we detect an emission line at $\sim 1\mu$m with a signal-to-noise ratio of ~ 10. The lines show asymmetric profiles with high weighted skewness values, consistent with being Lyα, yielding redshifts of $z = 7.213$, 6.965, and 6.844. Specifically, we confirm the $z = 7.213$ object in two independent DEIMOS runs with different spectroscopic configurations. The $z = 6.965$ object is a known Lyα emitter, IOK-1, for which our improved spectrum at a higher resolution yields a robust skewness measurement. The three z-dropouts have Lyα fluxes of 3×10^{-17} erg s^{-1} cm^{-2} and rest-frame equivalent widths $\mathrm{EW}_0^{\mathrm{Ly}\alpha} = 33-43$Å. Based on the largest spectroscopic sample of 43 z-dropouts that is the combination of our and previous data, we find that the fraction of Lyα-emitting galaxies ($\mathrm{EW}_0^{\mathrm{Ly}\alpha} > 25$Å) is low at $z \sim 7$; 17 ± 10% and 24 ± 12% for bright ($M_{\rm UV} \simeq -21$) and faint ($M_{\rm UV} \simeq -19.5$) galaxies, respectively. The fractions of Lyα-emitting galaxies drop from $z \sim 6$ to 7 and the amplitude of the drop is larger for faint galaxies than for bright galaxies. These two pieces of evidence would indicate that the neutral hydrogen fraction of the IGM increases from $z \sim 6$ to 7, and that the reionization proceeds from high- to low-density environments, as suggested by an inside-out reionization model.