Early Stage of Galaxy Formation

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\textbf{ABSTRACT}

We discuss on the early stage of galaxy formation based on recent deep surveys for very high-redshift galaxies, mostly beyond redshift of 6. These galaxies are observed to be strong Lyman\textalpha emitters, indicating bursts of massive star formation in them. The fraction of such star-forming system appears to increase with increasing redshift. On the other hand, the star formation rate density derived from Lyman\textalpha emitters tends to decrease with increasing redshift. It is thus suggested that the major epoch of initial starbursts may occur around \( z \sim 6 – 7 \). In order to understand the early stage of galaxy formation, new surveys for galaxies beyond redshift of 7 will be important in near future.

\textbf{Key words:} galaxies: formation — galaxies: evolution

\section{1 INTRODUCTION}

The formation and evolution of galaxies have been intensively studied from both observational and theoretical points of view for these two decades. The progress in this research field can be attributed to several deep optical survey programs. For example, the galaxy evolution from \( z = 1 \) to the present day has been studied based on CFRS (= Canada-France Redshift Survey; Lilly et al. 1995), SDSS (= Sloan Digital Sky Survey; York et al. 2000), 2dF (= 2 Degree Field Survey: Colless et al. 2001), and so on. These surveys are also useful in exploring the nature of large scale structures. On the other hand, the galaxy evolution from \( z \sim 6 \) to \( z \sim 1 \) has been studied based on deep high-resolution imaging surveys with the Hubble Space Telescope such as HDF (= Hubble Deep Fields: Williams et al. 1996, 2000), GEMS (= Galaxy Evolution from Morphology and SEDs: Rix et al. 2004), GOODS (= Great Observatories Origins Deep Survey: Giavalisco et al. 2004a), HUDF (= Hubble Ultra Deep Field: Beckwith et al. 2005; Thompson et al. 2005) and COSMOS (= Cosmic Evolution Survey: Scoville et al. 2004, 2006; see also Taniguchi et al. 2005b). These huge high-quality data sets are highly useful in investigating the evolution of galaxies from \( z \sim 6 \) to the present day. Furthermore, 8-10m class ground-based telescopes also contribute to the understanding of galaxy evolution thanks to their great spectroscopic capability for large samples of very faint galaxies (e.g., Cowie et al. 1996; Steidel et al. 1996, 1999; Cohen et al. 1999 [Caltech Faint Galaxy Fields]; Abraham et al. 2004 [GDDS = Gemini Deep Deep Survey]; Vogt et al. 2005 [DEEP Groth Strip Survey]; Wirth et al. 2004 [The Team Keck Treasury Redshift Survey]; Le Fèvre et al. 2005 [VIMOS VLT Deep Survey]).

These important investigations have made great contributions to the understanding of dynamical, chemical, and luminosity evolution of galaxies in various galaxy environs from high redshift to the present day. For example, the cosmic star-formation history over a period of 10 billion years in the universe has been investigated systematically (e.g., Madau et al. 1996; Steidel et al. 1999; Giavalisco et al. 2004; Dickinson et al. 2004). It is now also accepted that the nature of galaxy evolution is understood as less massive galaxies tend to have longer star formation timescale (i.e., the down sizing: e.g., Cowie et al. 1996; Heavens et al. 2004; Kodama et al. 2004; Treu et al. 2005). It is also interesting to note that low-redshift galaxies are classified into two distinct families at a stellar mass of \( 3 \times 10^{10} M_\odot \) (Kauffmann et al. 2003), suggesting that the galaxy evolution is related to the surface mass density. Moreover, most optical surveys have been coordinated with surveys at other wavelengths, e.g., from mid- through far-infrared to submm, and X-ray. These multiwavelength surveys have explored the dark side of galaxy evolution (e.g., Hughes et al. 1998; Barger et al. 1998; Chapman et al. 2003; Elbaz et al. 1999), and the co-evolution between the galactic spheroidal system and the central supermassive black hole (e.g., Barger et al. 2001). One of remaining important issues related to galaxies is the formation of galaxies. Since the epoch of first stars (i.e., Population III objects) may be at \( z \sim 10 – 30 \) (e.g., Loeb & Barkana 2001), probing very high-redshift universe is absolutely necessary to understand the physical process of galaxy formation. Since the great success of the Hubble Deep Field project (Williams et al. 1996), a large number of high-redshift galaxies have been discovered so far to date (e.g., Taniguchi et al. 2003; Spinrad 2004). In particular, deep optical imaging surveys with a narrowband (NB) fil-
ter have been very successful in finding star-forming galaxies at \( z \approx 5 - 6 \) (Rhoads et al. 2000; Malhotra & Rhoads 2004; Hu et al. 2002, 2004; Ajiki et al. 2003; Ouchi et al. 2003, 2005; Shimasaku et al. 2004; Santos et al. 2004; see for reviews, Taniguchi et al. 2003; Spinrad 2004). Their star formation properties and the luminosity function have been intensively studied for these several years. Large samples of Lyman break galaxies at \( z \approx 6 \) are also investigated in detail (Giavalisco et al. 2004b; Dickinson et al. 2004; Stanway et al. 2004; Bouwens et al. 2004; Shimasaku et al. 2005). In this review, we give a summary of observations of galaxies beyond \( z = 6 \) to investigate the early stage of galaxy formation.

2 GALAXIES BEYOND REDSHIFT OF 6

Galaxies beyond \( z = 6 \) can be found by the following two methods; (1) searches for Ly\( \alpha \) emission (e.g., Hu et al. 2002; Taniguchi et al. 2005a and references therein), and (2) broad-band color selections such as \( I \)-band dropouts (e.g., Giavalisco et al. 2004b; Dickinson et al. 2004; Stanway et al. 2005; Bouwens et al. 2005a). Galaxies found by the first method are referred as Lyman emitters (LAEs) while those found by the second one are as Lyman break galaxies (LBGs). However, both LAEs and LBGs at \( z > 6 \) could be the same population of forming galaxies even though their selection methods are different. Indeed, some of LBGs selected as \( I \) dropouts show strong Ly\( \alpha \) emission line (e.g., Nagao et al. 2004, 2005b; Stanway et al. 2004). In this section, we discuss the nature of galaxies at \( z > 6 \) whose redshifts are confirmed by optical spectroscopy.

We give a list of 18 galaxies at \( z > 6 \) compiled from the literature by the end of July, 2005. Among the 18 objects, 13 objects have been found with the narrowband imaging technique. Although survey redshift ranges are limited because of strong OH airglow emission lines, the narrowband method appears to be very efficient to select LAEs; note that a NB filter centered at \( \lambda \approx 816 \) nm is used to find LAEs at \( z \approx 5.7 \) while that centered at \( \lambda \approx 921 \) nm is used to find LAEs at \( z \approx 6.6 \) (e.g., Taniguchi et al. 2003).

One interesting case is 0226–04 LAE found by Cuby et al. (2003). Although this object was selected as a NB-excess object, its excess emission was found to be redshifted UV continuum. Their optical spectroscopy identified this object as a LAE at \( z = 6.17 \). Another interesting case is SEXSI-SER found by Stern et al. (2005). This object, a LAE at \( z = 6.545 \), is a serendipitously identified during the course of their follow-up observations of optical counterpart of X-ray sources. Such serendipitous identifications of high-\( z \) galaxies are also reported in Dey et al. (1998) and Dawson et al. (2002).

The broadband color selection method brought us four objects at \( z > 6 \). All these objects show a strong Ly\( \alpha \) emission line. Among them, the three objects found by Nagao et al. (2004, 2005b) were identified as red \( i' - z' \) objects and thus suspected to be LBGs at \( z \approx 6 \). However, their follow up spectroscopy identified them as strong LAEs at \( z = 6.33, 6.04, \) and 6.03. This means that most of their \( i' \) fluxes come not from their UV continuum but from Ly\( \alpha \) emission.

The star formation rate (SFR) of the galaxies at \( z > 6 \) given in Table 1 is several \( M_\odot \) yr\(^{-1} \) on average (e.g., Taniguchi et al. 2005a). The star formation rate density (SFRD) at \( z \approx 6.6 \) inferred from nine LAEs studied by Taniguchi et al. (2005a) is estimated to be \( \sim 6 \times 10^{-4} M_\odot \) yr\(^{-1} \) Mpc\(^{-3} \). This is smaller by two orders of magnitude than those derived from LBGs at \( z \approx 6 \) (e.g., Giavalisco et al. 2004b; Dickinson et al. 2004; Stanway et al. 2004; Bouwens et al. 2004). Even if we correct for extinction for Ly\( \alpha \) emission (i.e., a factor of a few) and an integrate with a certain Ly\( \alpha \) luminosity function (i.e., a factor of a few), the SFRD derived from the \( z \approx 6.6 \) sample is still smaller by one order of magnitude than that derived from the \( z \approx 6 \) LBG samples. The intergalactic medium (IGM) cannot be re-ionized by the LAEs found to date; note that LBGs found at \( z \approx 6 \) also cannot reionize the IGM.

It is worth noting that the star formation rate density derived from LAEs tends to decrease with increasing redshift (e.g., Taniguchi et al. 2005; Yamada et al. 2005). This suggests that the major epoch of initial starbursts may occur around \( z \approx 6 - 7 \).

3 GALAXIES BEYOND REDSHIFT OF \( \sim 7 \)

In this section, we summarize recent results on searches for objects beyond \( z \approx 7 \). The Lyman break and Ly\( \alpha \) emission are redshifted to 730 nm and 973 nm, respectively for an object at \( z = 7 \). In particular, it becomes difficult to use the Ly\( \alpha \) emission as a probe of such very high-\( z \) galaxies because the sensitivity of CCD cameras is poor. Even if we use the Lyman break and continuum depression at wavelengths shorter than 121.6 nm, such galaxies can be detected only in \( z' \) band in the optical. Therefore, near and mid infrared data become much more important for investigations of such very high-\( z \) galaxies. Another observational difficulty should come from that such very high-\( z \) galaxies are inevitably faint. Therefore, we need new techniques to investigate galaxies beyond \( z \approx 7 \) in principle.

One promising method is searches for gravitationally amplified objects. Gravitational lensing caused by a relatively nearby massive cluster of galaxies is very useful in searching for faint, very high-\( z \) galaxies (e.g., Ellis et al. 2001; Hu et al. 2002; Santos et al. 2004). For example, nine LAEs at \( z \approx 6.6 \) are found in a field including Abell 370 while no detection of such galaxies in HDF (Cowie 2004).

The most probable galaxy at \( z \approx 7 \) is a triple-imaged galaxy found in a field of Abell 2218 (\( z_{\text{cluster}} = 0.1775 \)) (Kneib et al. 2004). This source is also detected at 3.6 and 4.5 \( \mu \)m using the Spitzer Space Telescope (Egami et al. 2005), indicating its photometric redshift of \( z_{\text{phot}} \approx 6.6 - 6.8 \). Its age is estimated to be 50 – 450 Myr with the star formation rate of 0.1 – 5 \( M_\odot \) yr\(^{-1} \). The estimated mass is \( \sim 10^{9} M_\odot \), being smaller than those of typical LBGs at \( z \approx 3 \). The finding such a small-mass (or, subgalactic) system is indeed attributed to the large amplification factor of the lensing (\( \sim 25 \))

Other probable very high-\( z \) galaxies have been found in the UDF. Bouwens et al. (2004b) found 5 probable objects at \( z \approx 7 - 8 \) among the \( 5\sigma \) dropouts in the UDF (see also Yan & Windhorst 2004). Then, Bouwens et al. (2005) also found 3 probable objects at \( z \approx 10 \) among the eight \( J \) dropouts in UDF. All of them are too faint (e.g., \( J \approx 27 \) for \( 5\sigma \) dropouts and \( H \approx 27 \) for \( J \) dropouts) to be observed.
spectroscopically. The star formation rate density (SFRD) at $z \sim 7 - 8$ and $z \sim 10$ is $\sim 10^{-2.5}$ and $\sim 10^{-3} M_\odot y^{-1} Mpc^{-3}$ in the WMAP cosmology, respectively. These data suggest the continuous decline of SFRD from $z \sim 3$ to $z \sim 10$; i.e., SFRD($z \sim 10$)/SFRD($z \sim 3$) $\sim 0.2$ (Bouwens et al. 2005). Any challenges with ground-based telescopes have been giving null results on searches for galaxies beyond $z \sim 7$. As noted above, most such very high-$z$ objects could be too faint. Since strong OH airglow emission lines make it difficult to carry out deep imaging surveys at wavelengths longer than 700 nm. In the case of the Subaru Deep Field (Kashikawa et al. 2004), although a few tens galaxies at $z \sim 6 - 6.6$ have been found (Shioya et al. 2005a; Shimasaki et al. 2005; Taniguchi et al. 2005), no object has been found at $z > 6.7$ (Shioya et al. 2005b). This is mainly due to the shallow survey depth at $z'$ band; i.e., $z'_\text{lim} \sim 26$.

In the near infrared (NIR) window, any ground-based observations share the same problem because of strong airglow emission lines and strong thermal background in NIR. Therefore, NIR broad-band imaging surveys may have difficulty in finding very high-$z$ galaxies at $z > 7$. One remaining technique is again the narrowband imaging survey. Recently, Willis & Courbin (2004) made such a narrowband deep survey using a NB filter centered at $\lambda = 1.187$ $\mu$m using the VLT/ISAAC facility; i.e., the corresponding Ly\alpha redshift is $z \sim 9$. Although their survey depth was down to $\sim 3 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$, they found no LAE.

Another search for galaxies at $z > 7$ was also made by Pélo et al. (2004) as their follow-up observations of gravitationally amplified objects in a field of Abell 1835. Although they found a possible signature of Ly\alpha emission at $\lambda = 1.337$ $\mu$m, indicating the redshift of $z \sim 10$, later investigators did not confirm this finding (Weatherley et al. 2004; Bremer et al. 2004; see also Lehnert et al. 2004). This also suggests the technical difficulty in ground-based observations of such very high-$z$ galaxies. However, their challenges and discussion given in the above papers will be useful for our future investigations (see also Cen, Haiman, & Mesinger 2005).

### Table 1. A list of galaxies beyond $z=6$

| No. | Name       | $z$  | Method$^1$ | Ref.$^2$ |
|-----|------------|-----|------------|----------|
| 1   | SDF J132522.3+273520 | 6.597 | NB | 1          |
| 2   | SDF J132432.4+271647 | 6.580 | NB | 1          |
| 3   | SDF J132418.3+271455 | 6.578 | NB | 1          |
| 4   | SDF J132518.8+273043 | 6.578 | NB | 1, 2      |
| 5   | HCM-6A     | 6.56  | NB | 3          |
| 6   | SDF J132408.3+271544 | 6.554 | NB | 1          |
| 7   | SDF J132522.7+271647 | 6.542 | NB | 1          |
| 8   | SDF J132415.7+273058 | 6.541 | NB | 1, 2      |
| 9   | SDF J132353.0+271631 | 6.540 | NB | 1          |
| 10  | SDF J132353.5+271631 | 6.540 | NB | 1          |
| 11  | LALA142442.2+353400 | 6.535 | NB | 5          |
| 12  | KCS 1106   | 6.518 | Grism | 6        |
| 13  | SDF J132418.4+273345 | 6.506 | NB | 1          |
| 14  | SDF J132440.6+273607 | 6.330 | CS | 7          |
| 15  | GOODS-N i'-drop No. 6 | 6.24 (?) | CS | 8          |
| 16  | 0226-04LAE | 6.17  | NB | 9          |
| 17  | SDF J132442.5+272423 | 6.04  | CS | 10         |
| 18  | SDF J132426.5+271600 | 6.03  | CS | 10         |

$^1$Method: NB = narrowband search, SER = serendipitious discovery, Grism = Grism imaging spectroscopy, & CS = broadband color selection. $^2$References: 1. Taniguchi et al. 2005, 2. Kodaira et al. 2003, 3. Hu et al. 2002, 4. Stern et al. 2005, 5. Rhoads et al. 2004, 6, Kurk et al. 2004, 7. Nagao et al. 2004, 8. Stanway et al. 2004, 9. Cuby et al. 2003, and 10. Nagao et al. 2005b.

### 4 FUTURE SEARCHES FOR OBJECTS BEYOND REDSHIFT OF 7 AND POPULATION III OBJECTS

One of the most important issues remained unsettled is how galaxies were assembled in their early phase and what were first objects (i.e., Population III objects) after the dark age. These problems are also related to the understanding physical processes of the cosmic reionization (e.g., Loeb & Barkana 2001). Recently, Nagao et al. (2005a) tried to detect intense He II $\lambda 1640$ emission line in one of the brightest LAEs found in the SDF (SDF J132440.6+273607: Nagao et al. 2004). If the photoionization would be dominated by Population III stars in this LAE, they could detect He II, but failed. However, since a number of apparently bright LAEs beyond $z = 6$ will be found in near future, this kind of challenges will be very important to understand the nature of star formation properties in such very high-$z$ young galaxies.

In future observations of very high-$z$ galaxies, HST will have advantage with respect to any ground-based telescopes because of low noise in the NIR window. However, in order to proceed investigations of very high-$z$ galaxies, a new, wide-field NIR camera and spectrograph for HST is necessary. If a very wide-field NIR camera is available on 8m class telescopes on the ground, deep (mostly narrowband) imaging surveys will be able to find some very high-$z$ galaxies from a statistical point of view.
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