New High-Redshift Galaxies at $z = 5.8$–$6.5$ in the Subaru Deep Field

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Abstract

In order to search for high-redshift galaxies around $z \sim 6$ in the Subaru Deep Field, we have investigated $NB816$-dropout galaxies where $NB816$ is the narrow-band filter centered at $815$ nm with FWHM of $12.5$ nm for Suprime-Cam on the Subaru Telescope. Since the $NB816$ imaging is so deep, we can detect $10$ well-defined $NB816$-dropout galaxies that are identified as objects at $z = 5.8$–$6.5$. We discuss their observational properties.

Key words: galaxies: evolution — galaxies: formation

1. Introduction

Surveys for high-redshift galaxies provide observational bases to explore the formation and evolution of galaxies. A number of such surveys have been made during this decade. Indeed, the optical broad-band color-selection technique has been utilized to find large samples of high-$z$ galaxies at $z \sim 3$–$7$, i.e., Lyman-break galaxies (LBGs) (e.g., Lanzetta et al. 1996; Madau et al. 1996; Steidel et al. 1996; Ouchi et al. 2004; Giavalisco et al. 2000; Stanway et al. 2004; Bouwens et al. 2004). Deep optical surveys with a narrow-band filter have also been conducted to search for strong Lyman $\alpha$ emitters (LAEs) at high redshift. Since the early success of narrow-band filter surveys (e.g., Hu et al. 1996; Cowie, Hu 1998), a large number of high-$z$ LAEs have been found (e.g., Rhoads, Malhotra 2001; Hu et al. 2002, 2004; Kodaira et al. 2003; Taniguchi et al. 2005; see for reviews, Taniguchi et al. 2003b; Spinrad 2004). Although such deep, narrow-band imaging data are basically used to find strong emission-line objects, they can also be used as one of the photometric data points. For example, Cuby et al. (2003) made their optical imaging survey for LAEs at $z \sim 6.6$ by using both broad-band data ($B, V, R,$ and $I$) and narrow-band data taken with their $NB920$ filter. They found a LAE at $z=6.17$ from a sample of $NB920$-excess objects. In this case, the $NB920$ data were used to sample the continuum above the Lyman break. Since the high-$z$ LAEs are usually used to find not only strong LAEs, but also “dropout” high-$z$ galaxies.

Recently, Shioya et al. (2005) proposed a new method, the intermediate-band dropout method, to search for high-$z$ galaxies (see also Fujita 2003). In this method, an intermediate-band filter at $\lambda > 7000 \text{ Å}$ is used together with typical $i'$ and $z'$ filters. We focus on dropouts using the intermediate-band filter, while Cuby et al. (2003) selected a $z=6.17$ Lyman-break galaxy using a narrow-band filter. The merit of the new method is to distinguish either very late-type stars, such as L and T dwarfs, or dusty galaxies at intermediate redshift from real high-$z$ LBGs. The reason for this is that such interlopers do not show strong narrow-band depression, although they have very red colors that are indicative of LBGs. In the survey method, we may use a narrow-band filter at $\lambda > 7000 \text{ Å}$ (Hu et al. 2004). We also note that Y. Kakazu (private communication) proposed the $NB816$-depressed method to separate high-redshift quasars and galaxies from L and T dwarfs based on the same principle. In order to find high-$z$ galaxies around $z \sim 6$, we used the data archive of the Subaru Deep Field (Kashikawa et al. 2004). Since in the SDF, deep imaging data with the narrow-band filter $NB816$ are available, they are very useful to demonstrate that the narrow-band dropout technique is powerful in finding high-$z$ galaxies.

2. The Narrow-Band Dropout Method

Our new method is basically to find narrow-band-dropout objects from a deep imaging survey data set. In order to describe our method practically, we consider the case of $NB816$ dropouts where $NB816$ is a narrow-band filter centered at $\lambda_c \sim 815$ nm with a $FWHM = 12$ nm (e.g., Taniguchi et al. 2003b, and references therein; Hu et al. 2004).

In this case, we need deep imaging data taken with filters of $i'$, $z'$, and $NB816$. In figure 1, we show the transmission curve of the three filters taken from the data for Suprime-Cam filters$^1$ (Miyazaki et al. 2002).

We also show spectral energy distributions (SEDs) of a LBG (starburst) at $z \sim 5.9$, an L dwarf star in our Galaxy, and a dusty galaxy at $z \sim 1.1$. The SED of a LBG is produced by GALAXEV (Bruzual, Charlot 2003). The SEDs of local galaxies are well reproduced by models whose star-formation rate declines exponentially (the $t$ model): i.e., $SFR(t) \propto \exp(-t/\tau)$, where $t$ is the age of galaxy and $\tau$ is the time scale of star formation. We set $\tau = 1$ Gyr and $t = 1$ Gyr to derive $^1$ (http://www.subarutelescope.org/Observing/Instruments/SCam/sensitivity.html).
the SED of a starburst (SB) galaxy. To make an SED of an SB with emission lines, we calculate emission-line fluxes using the formula $L(H\beta)$ (erg s$^{-1}$) $= 4.76 \times 10^{-13} N_{H\beta}$, where $N_{H\beta}$ is the ionizing photon production rate (Leitherer, Heckman 1995), and the table of relative luminosity to H$\beta$ luminosity in PEGASE (Fioc, Rocca-Volmerange 1997). The SED of an LBG is the SB model with $A_V = 0$, and that of a dusty galaxy is the SB model with $A_V = 10$ mag adopting the reddening curve of Calzetti et al. (2000). It is shown that the LBG at $z = 6$ is selected as a NB816 dropout. However, the L dwarf is not selected as a NB816 dropout, even though it shows a very red $i' - z'$ color. In this way, we can select LBGs at $z > 5.8$ as NB816 dropouts.

In figure 2, we show the diagram between $i' - z'$ and NB816 $- z'$ for galaxies found in the Subaru Deep Field (Kashikawa et al. 2004). The selection procedure is given in the next section. Galactic stars (Gunn, Stryker 1983) and L and T dwarfs$^2$ (Kirkpatrick 2003) are also shown. An evolutionary path of a LBG is shown by the blue curve; its SED is generated by using GALAXEV (Bruzual, Charlot 2003).

When we select LBG candidates at $z \sim 6$, we adopt a color criterion of $i' - z' > 1.3 - 1.5$ (e.g., Nagao et al. 2004; Stanway et al. 2004; Giavalisco et al. 2004). However, this criterion is not enough to select such LBGs unambiguously because L and T dwarfs also have such very red colors. In addition, some dusty galaxies at intermediate redshift may also have very red colors (e.g., a part of extremely red objects; see Hu, Ridgway 1994).

Here, we would like to stress that LBGs at $z > 5.8$ are efficiently selected if we also use another criterion of NB816 $- z' > 1.5 - 2$; i.e., NB816-depressed objects. The most important merit of this method is that LBG candidates are selected more unambiguously because this new criterion can separate LBGs from interlopers (i.e., L, T dwarfs and dusty galaxies at lower redshift). Hu et al. (2004) noted that LAEs at $z \simeq 5.7$ are well separated from L and T dwarfs if a proper criterion on the NB816 $- z'$ color is adopted.$^2$

$^2$ ⟨http://spider.ipac.caltech.edu/staff/davy/ARCHIVE⟩.
3. Application to the Subaru Deep Field Data

In order to demonstrate how the new NB dropout method works well, we applied it to the Subaru Deep Field data (Kashikawa et al. 2004). Photometric catalogs (Version 1) have been made public. In the following analysis, we use a 2′ aperture magnitude and the error in 2′ aperture magnitudes from the catalog. We also calculated errors of colors using the errors in the 2′ aperture magnitude.

As shown in figure 2, being independent of the strength of the Lyman α emission, galaxies at z > 5.73 can be identified as NB816-dropout objects. Assuming that there are no elliptical-like red galaxies at z ~ 2, we estimated a reddest NB816 − z′ color of ≈ 1.3, corresponding to the color of elliptical galaxies at z ~ 1. Therefore, we adopted the following selection criteria for NB816-dropout galaxies:

\[ NB816 − z′ > 1.5 \]  

(1)

and

\[ z′ < 26.07 \ (5\sigma) \]  

(2)

In order to reduce any contaminations from foreground hydrogen that are free from absorption by the intergalactic neutral hydrogen, we also adopted the following criteria:

\[ B > 28.45 \ (3\sigma), \]  

(3)

\[ V > 27.74 \ (3\sigma), \]  

(4)

and

\[ R_c > 27.80 \ (3\sigma). \]  

(5)

By using the above three criteria, we first obtained a sample of 42 NB816-dropout objects. From 42 NB816-dropout objects, we selected the objects with NB816 − z′ > 1.5 above the 3σ error as more reliable NB816-dropout objects. The number of more reliable NB816-dropout objects was 15.

Next, we separated high-z galaxies from Galactic low-temperature stars (L and T dwarfs). It is known that most L and T dwarfs satisfy the following relation:

\[ (i′ − z′) − (NB816 − z′) \approx 0.8, \]  

(6)

as shown in figure 2. Taking account of the scatter of the colors of L and T dwarfs, we could separate LBG candidates from them by using the following criterion:

\[ (i′ − z′) − (NB816 − z′) < 0.5. \]  

(7)

In order to securely select a reliable sample of NB816-dropout galaxies, we picked up objects that satisfied condition (7) above the 3σ error conditions from 15 more reliable NB816-dropout objects. Finally, we obtained a sample of 10 NB816-dropout galaxies. Their photometric properties are summarized in table 1. In this table, we present the 3σ error of colors.

We note that galaxies with a faint continuum and strong-emission lines in z′ (e.g., strong [OIII] emission-line objects in her NB816-depressed sample (private communication). Since there is an NB921 observation for SDF, we could separate such objects from genuine NB816 dropouts using z′ − NB921 colors. If strong-emission lines lie in both z′ and NB921, those galaxies would be observed as NB921-excess objects. If strong-emission lines do not lie in NB921, but in z′, NB921-band of those galaxies must be very faint. All our NB816-dropout sample were detected (> 3σ) in NB921-band, and their z′ − NB921 colors were nearly flat, which ranged from −0.39 to 0.02. Therefore, they were considered to be galaxies at redshift between 5.73 and 6.50. One object, ID 35247, is considered to be a LAE since its z′ − NB921 color is 1.49. In fact, this object was identified as SDF J132408.3 + 271543 in Taniguchi et al. (2005) and confirmed as a LAE at z = 6.554.

Now, we consider the UV luminosity function of star-forming galaxies at z ~ 6. In addition to the UV luminosity functions of star-forming galaxies at z ~ 3–5 (e.g., Steidel et al. 1999; Ouchi et al. 2004), those of star-forming galaxies at z ~ 6 were also recently obtained by red i′ − z′ color (i′-dropout galaxies, e.g., Bouwens et al. 2004) or by using the (i′ − zR) versus zB – zR diagram (Shimasaku et al. 2005). Hu et al. (2004) also obtained the UV luminosity function of Lyman α emitters (LAEs) at z ~ 5.7.
Since the observed $z'$ magnitude of a galaxy depends on not only the UV luminosity, but also the redshift of the galaxy and the strength of the Ly$\alpha$ emission line, we compared our results with the prediction evaluated under some assumptions. If the UV luminosity function of galaxies at $z \sim 6$ is the same as that at $z \sim 4.0$ or 4.7 (Ouchi et al. 2004), we can evaluate the number of star-forming galaxies at $z \sim 5.8$–6.6. We show the expected galaxy number evaluated using the SB model SED without emission lines in figure 3. We also show the expected number of galaxies for the UV luminosity function of LBGs at $z \sim 6$ (Bouwens et al. 2004) and that of LAEs at $z \sim 5.7$ (Hu et al. 2004). Since the strong Ly$\alpha$ emission line modifies the $z'$ magnitude for galaxies at redshift higher than $\sim 5.75$, we used our SB model with emission lines for the UV luminosity function of LAEs. The rest-frame equivalent width of Ly$\alpha$ emission is about 70 Å in our SB model with emission lines. Taking account of the completeness for the SDF sample as a function of $z'$ magnitude (Kashikawa et al. 2004), we expect that the number of galaxies brighter than $z' = 26.0$ ranges from 42 to 200 (figure 3).

The selection criteria of our final sample were so severe that the number of our final sample (10) may have given a lower limit. On the other hand, the number of our first sample (42) may have given an upper limit, since it may have included contaminations. Figure 3 suggests that the number of LBGs at $z \sim 6$ is smaller than that at $z \sim 4$–5. This trend is consistent with that derived from the observation of the Hubble Ultra Deep Field (Bunker et al. 2004) and the Hubble Ultra Deep parallel fields (UDF PFs: Bouwens et al. 2004). Although the reason why the number of our sample is smaller than the prediction using the UV luminosity function at $z \sim 6$ is still not clear, we note that the number density of bright LBGs at $z \sim 6$ in the SDF is 60% of the value obtained in the UDF PFs by Bouwens et al. (2004) (Shimasaku et al. 2005).

4. Remarks

In section 3, we have demonstrated that the NB816-dropout method is capable of selecting reliable candidates of LBGs at $z > 5.8$. Although we adopted the NB816-dropout method there, our method is also useful when we use other narrow-band filters.

For example, NB921 is useful to find galaxies at $z > 6.7$, while NB711 is useful for galaxies at $z > 4.9$. It is also noted that a rest-frame H$\alpha$ filter (NB656) and a rest-frame [O iii] filter can be used to search for galaxies at $z > 4.4$ and at $z > 3.1$, respectively. Since there are a number of deep-survey data in which some of narrow-band filters are used, it is recommended that the narrow-band dropout method be applied to them, providing new samples of LBGs/LAEs at high redshift.

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