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$z \sim 6$ *i*-DROPOUT GALAXIES IN THE SUBARU/XMM-NEWTON DEEP FIELD*

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ABSTRACT

We conducted an extremely wide field survey of $z \sim 6$ Lyman break galaxies (LBGs) to precisely derive their bright end surface density overcoming the bias due to cosmic variance. We selected out LBG candidates in the Subaru/*XMM-Newton* Deep Survey Field (SXDS) over the total of ~1.0 deg^2 sky area down to $z'_{AB} = 26.0$ ($\gtrsim 3\sigma$, 2.″0 aperture) using $i' - z' > 1.5$ color cut. This sample alone is likely to be contaminated by M/L/T dwarfs, low-z elliptical galaxies, and $z \sim 6$ quasars. To eliminate these interlopers, we estimated their numbers using an exponential disk star count model, catalogs of old ellipticals in the SXDS and other field, and a $z \sim 6$ quasar luminosity function. The finally derived surface density of $z \sim 6$ LBGs was 165 mag^{-1} deg^{-2} down to $z'_{AB} = 26.0$ and shows good agreement with previous results from the narrower field survey of *HST* GOODS.

Key words : cosmology: observations — early universe — galaxies: evolution — galaxies: formation

I. INTRODUCTION

Probing the statistical properties of star-forming galaxies way back to higher redshifts is essential to understand the galaxy/structure formation and evolution and cosmic star formation history. One of the most powerful approaches is the dropout technique already having demonstrated its remarkable effectiveness to detect $z \sim 3$–6 Lyman break galaxies (LBGs) (e.g., Steidel et al. 1996, 1999; Dickinson et al. 2004; Stanway et al. 2004). Especially, recently emerging *i*-dropout for $z \sim 6$ LBG detection is extremely important since the reionization epoch was considered ended around this redshift (Fan et al. 2001,2002; Becker et al. 2001). To date, several sets of *i*-dropout studies have probed $z \sim 6$ LBG surface and luminosity densities over the very compact areas but down to the exceptional depth in the Great Observatories Origins Deep Survey (GOODS) and Hubble Ultra Deep Field (UDF) using *Hubble Space Telescope (HST)* powered by Advanced Camera for Surveys (ACS) (Bouwens et al. 2003, 2004; Dickinson et al. 2004; Stanway et al. 2004). Combination of both deep optical and near infrared images were used as a standard manner to isolate low-z interlopers and ground-based follow-ups by large aperture telescopes successfully have confirmed its validity. However, these survey results might be biased due to the cosmic variance and small area coverage. To derive more reliable $z \sim 6$ LBG density taking the field-to-field variation into account, a survey over far much wider fields with outstanding depth is required. Motivated with this, we for the first time conducted a large area *i*-dropout survey using extraordinarily wide (~1.0 deg^2) and deep ($z' \lesssim 26.1$–26.4) data of the Subaru/*XMM-Newton* Deep Survey (SXDS; Sekiguchi 2004). Our survey covers ~10 and 1,000 times wider area than GOODS and UDF suited for robust determination of the bright end of LBG number density overcoming its cosmic fluctuation. However, infrared images wide and deep enough to discriminate interlopers are not yet available at this moment, we instead estimated their numbers using a star count model, catalogs of elliptical galaxies, and a quasar luminosity function. In the present paper, we report the preliminary results of our survey. Throughout the paper, we adapt an $(\Omega_M, \Omega_\Lambda, h) = (0.3, 0.7, 0.7)$ cosmology and AB magnitude system unless otherwise specified.

II. CANDIDATE SELECTION

(a) Survey Field

Our survey area, the SXDS field, is centered at RA = $02^h18^m00^s$, Dec = $-05°00'00''$ (J2000). Deep optical $BVRi'z'$ images were taken by Subaru Prime Focus Camera (SuprimeCam; Miyazaki et al. 2002, $34' \times 27'$ field of view) onboard the 8.2-m Subaru Telescope during 2002–2003 as one of the Subaru Observatory Projects. The entire SXDS field image is ~ 1.3 deg^2 wide and consists of five ~ 0.25 deg^2 component images taken by five SuprimeCam pointings (See Figure 3). We utilized the SXDS version 1.0 data that are the latest images and catalogs available. The depth and

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seeing of these five pointing images are slightly different but approximately uniform: $B \leq 27.9$–28.1, $V \leq 27.0$–27.2, $R \leq 27.3$–27.5, $i' \leq 27.1$–27.3, $z' \leq 26.1$–26.4 (3σ, $2.''0$ aperture), and $0.''81$–$0.''85$, respectively.

(b) Photometry and Candidate Selection

The object detection and photometry were made using SExtractor (Bertin & Arnouts 1996). The parameter MAG_AUTO was used for the total magnitude of each band, and $2.''0$ aperture magnitudes were used for $i' - z'$ colors. In each component image, strong and weak stellar halos were masked and excluded from our analysis. Also, we cut out the low S/N CCD edge region to avoid spurious detection. This procedures reduced the total survey area down to ~ 0.97 deg^2. The Galactic extinction was corrected for each band with $A_V = 0.068$ estimated at the center of SXDS field. For i' and z' aperture magnitudes fainter than 2σ, we replaced them by their 2σ limiting magnitudes as $i' - z'$ color limit. Then, we selected out the objects satisfying the following criteria as $z \sim 6$ LBG candidates:

- S/N < 2 in B and V
- $i' - z' > 1.5$
- $z' \leq 26.0$

The first criterion was required since null detections in B and V are expected due to the strong absorption at the blueward wavelength of Lyα line. Also, this can help reduce the number of contaminating dwarf stars. We did not impose similar R-band cut considering the possible detections of weak Lyβ and Lyγ fluxes. The second i-dropout criterion was used for the secure detection of the sharp Lyman break feature. The cutting value $i' - z' = 1.5$ was determined using SED models to avoid the contamination by $z \sim 1$–2 old ellipticals as shown in Figure 1. The z'-band 3σ limiting magnitude cut was so-determined since its value varies among five pointing images of SXDS field ($z' \sim 26.1$–26.4). Finally, we selected out 210 i-dropouts in total over ~ 0.97 deg^2 as shown in Figure 2. Spatial distribution of these objects is shown in Figure 3. The dense and sparse regions of i-dropouts are clearly seen implying this might be a possible primitive structure at $z \sim 6$.

III. CONTAMINATION ESTIMATES

The i-dropouts we have selected out include not only $z \sim 6$ LBGs but also some interlopers such as cool dwarf stars, $z \sim 1$–2 old ellipticals (i.e., Extremely Red Objects: EROs), and $z \sim 6$ quasars. We estimated the number of these contaminants to investigate how serious their influences are and make necessary corrections for the precise number counting of $z \sim 6$ LBGs.

(a) M/L/T Dwarfs

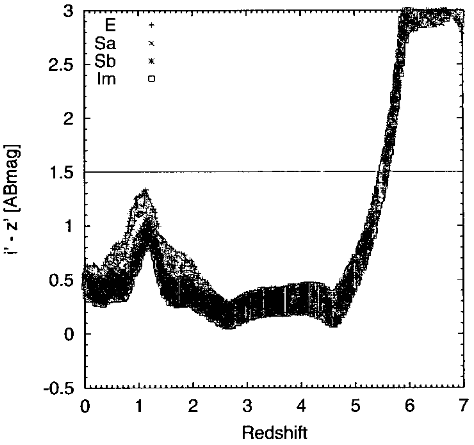

Fig. 1.— Color-redshift plot of galaxies with evolving stellar population calculated for SuprimeCam i' and z' filters using Bruzual & Charlot (1993) SEDs and the Lyα absorption model by Madau (1995).

According to a vast amount of accumulated data from Sloan Digital Sky Survey (SDSS), ultracool late-type dwarf stars have very red colors and satisfy $i' - z' > 1.5$ when their spectral types become later than M7 (Hawley et al. 2002). Unfortunately, near infrared images wide and deep enough to isolate these dwarfs are not yet available for the entire SXDS field. Instead, we modified a star count model constructed and improved by Nakajima et al. (2000) so that it can calculate the number of M/L/T dwarfs as a function of z'-band magnitude at the Galactic coordinate (l, b) of the SXDS. This is an exponential disk model composed of thin and thick disk components and constructed using nearby-star K-band Luminosity Function $\Phi(M_K)$ derived by Reid & Gizis (1997) :

$$\Phi(M_K, R, z) = \Phi(M_K)\exp\left(\frac{R_0 - R}{H}\right) \times \left[(1-\beta)\exp\left(-\frac{|z|}{h_1}\right) + \beta\exp\left(-\frac{|z|}{h_2}\right)\right]$$

where (R, z) is the Galactic position in cylindrical coordinates, $R_0 = 8$ kpc is the Galactocentric distance, $H = 3.5$ kpc is the Galactic scale length, and h_1, h_2, β are the scale heights of thin and thick disk stars, and the thick disk normalization factor, respectively. Preliminary L/T dwarf star count model based on the SDSS data (Knapp et al. 2004) for $i' - z' > 2.2$ has been presented elsewhere (Nakajima et al. 2004). The luminosity function of dwarfs later than L4 are based on this preliminary model. For the dwarfs later than L4, thick disk scale heights of 100, 200, and 300 pc are considered and no thick disk contribution is assumed. This difference in the scale height varies the predicted number of L and T dwarfs by the factors of $\sim$2–4 at $z' \sim 23.0$–24.5 and $\sim$6–10 at $z' \sim 24.5$–26.0. The detailed discussion is given in Nakajima et al. (2004). The volume limited sample of Cruz et al. (2003) constructed from Two Micron All Sky Survey (2MASS) provides more complete data for earlier dwarfs and we

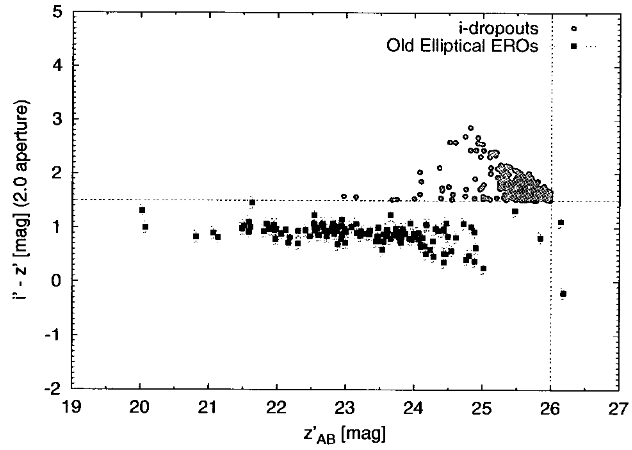

Fig. 2.— Color-magnitude plot of all objects detected in SXDS. Filled circles and squares are i-dropouts and z ~1–4 EROs (See also Fig. 4). No $i' - z' > 1.5$ EROs were found.

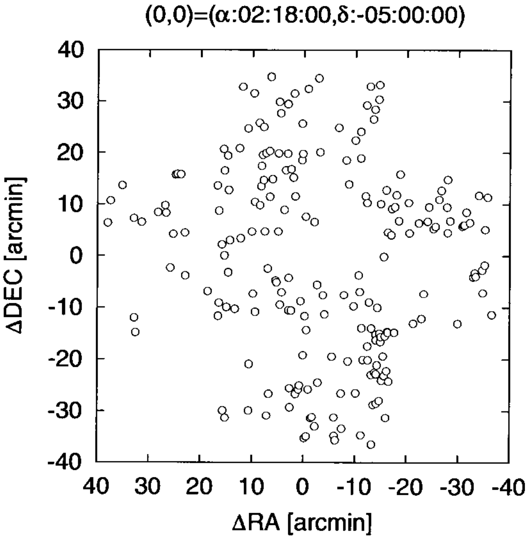

Fig. 3.— Spatial distribution of i-dropouts in the SXDS field. Dense and sparse regions are clearly seen. The image was taken by five SuprimeCam pointings.

converted $\Phi(M_K)$ into $\Phi(z')$ for M7–L4 dwarfs. Thin and thick disk scale heights $(h_1, h_2) = (300, 910)$ pc with $\beta = 0.059$ are assumed. The luminosity functions derived from the SDSS and 2MASS agree reasonably well at around L4. We used this composite luminosity function to estimate the surface number density of dwarfs with M7 and later, which are contaminants to color selected LBGs. The result is shown in Figure 5.

(b) $z \sim$ 1–2 Old Elliptical EROs

Another possible contaminant is $z \sim$ 1–2 old elliptical EROs when their 4000Å Balmer break is redshifted beyond the i'-band. As shown in Figure 1, we expect no contamination by lower-z EROs for our color selection. However, we also used a catalog of z ~1–2 old ellipticals in the SXDS with known photometric redshifts constructed by Miyazaki et al. (2003) to inspect if any fraction of our i-dropout sample consists of actual EROs. These EROs were detected with K_s-band and selected by the criteria: $R - K_s \geq 3.35, K_s \leq 22.1$ (5σ, 2.″0 aperture). To calculate their $i' - z'$ color with 2.″0 aperture used for our photometry, we made source matching between our catalog and Miyazaki et al.'s. Figure 2 and 4 show z' magnitude and redshift dependence of $i' - z'$ color of these EROs, respectively. We found no $i' - z' > 1.5$ EROs at $z \sim$ 1–2 down to $z' \leq 24.0$ where the sample is complete in K_s. However, most of i-dropouts are located at $z' > 24.0$ and the catalog lacks such a faint ERO sample. Hence, we also used a catalog of 17 faint (z' ~24.7–29.5) EROs in the UDF constructed by Yan et al. (2004) to roughly estimate the possibility of contamination by faint EROs. 15 out of 17 EROs also satisfy the same criterion, $R - K_s \geq 3.35$ as Miyazaki et al.'s. We found no faint EROs satisfying $i_{775} - z_{850} > 1.5$. Note that this is rough investigation since the ACS i_{775} and z_{850} filters are different from ours and instead of aperture magnitudes, total magnitudes provided in the catalog were used to calculate colors. Eventually, we assumed contamination by low-z EROs can be ignored for our survey.

(c) $z \sim$ 6 Quasars

It is known from the SDSS that $z \sim$ 6 quasars are also detected as i-dropouts (Fan et al. 2001). To estimate their number, we made use of a double power-law quasar luminosity function used in Yan et al. (2004),

$$\Phi(M) = \frac{\Phi_*}{10^{0.4(\beta_1+1)(M-M_*)} + 10^{0.4(\beta_2+1)(M-M_*)}}$$

with $\Phi_* = 1.53 \times 10^{-8}$ Mpc^{-3}, $M_* = -23.9$, and $\beta_1 = -2.58$. To deal with the uncertainty of faint end slope, we also followed Yan et al. (2004) taking three possible values $\beta_2 = -1.58, 2.00, 2.58$. This varies predicted quasar number by a factor of only 1.2–1.8 in the magnitude range of our sample $z' = 22.5$–26.0.

IV. RESULTS AND DISCUSSION

Finally, we derived surface density of $z \sim$ 6 LBGs subtracting the interlopers from the total number of i-dropouts as shown in Figure 5. The contamination by M dwarfs was largest. Correcting for the contamination by these interlopers, we could obtain the meaningful number of $z \sim$ 6 LBGs only at $z \geq 24.5$. In Figure 6, we compared our result with several previous works. Since the SXDS field is extremely wide, we could determine the reliable surface density of $z \sim$ 6 LBGs at the bright end overcoming the effects of cosmic variance. It is also interesting that at brighter magnitude

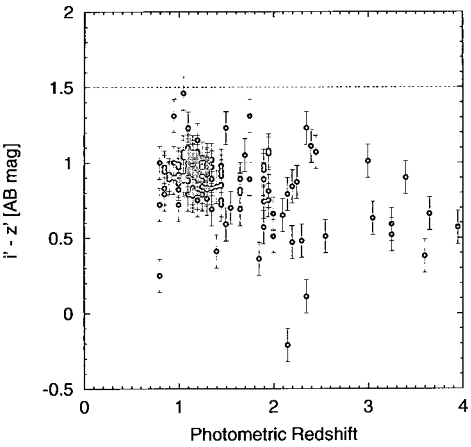

Fig. 4.— Redshift dependence of $i' - z'$ color of EROs in the SXDS. No EROs satisfy i-dropout criterion.

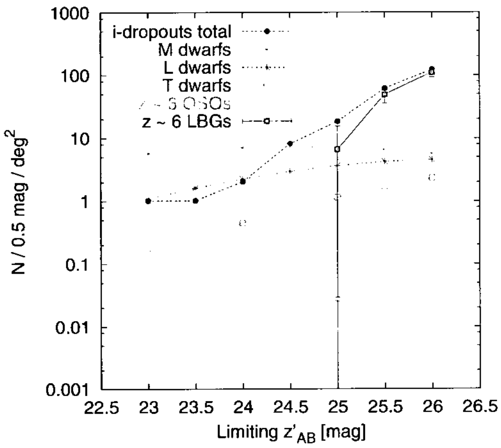

Fig. 5.— Surface densities of i-dropout members in the SXDS. Error bars for dwarf counts are omitted for clarity.

$z' \sim$ 24.5–25.5, our number counts have good agreement with those from the GOODS derived by Bouwens et al. (2004) and Dickinson et al. (2004) even though our survey field is ~10 times wider than theirs. This implies the GOODS field covered a relatively unbiased sky area that contains a typical distribution of $z \sim 6$ LBGs. At fainter magnitude $z' \sim 26.0$, our number count is slightly smaller possibly because it is close to our detection limit. We are now deriving luminosity densities correcting for the incompleteness due to our sensitivity to fainter and higher redshift galaxies. This will allow the more detail discussion precisely constraining the bright end of a $z \sim 6$ LBG luminosity function. We also plan to make follow-up spectroscopy of our sample for the confirmation of $z \sim 6$ LBGs.

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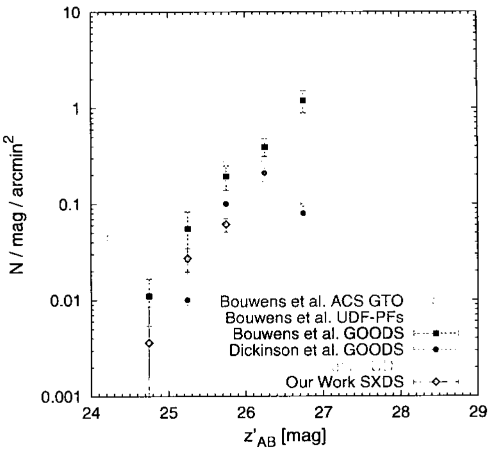

Fig. 6.— $z \sim 6$ LBG surface densities derived by us and others. Our and GOODS results agree at the bright end.

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