WIDE AND DEEP SURVEY OF LBGS AT $Z \sim 5$

Ikuru Iwata
Subaru Mitaka Office / Okayama Astrophysical Observatory,
National Astronomical Observatory of Japan
iwata@oao.nao.ac.jp

Kouji Ohta, Masataka Ando
Dpt. of Astronomy, Kyoto University
ohta@kusastro.kyoto-u.ac.jp, andoh@kusastro.kyoto-u.ac.jp

Naoyuki Tamura
Dpt. of Physics, University of Durham
naoyuki.tamura@durham.ac.uk

Masayuki Akiyama and Kentaro Aoki
Subaru Telescope, National Astronomical Observatory of Japan
akiyama@subaru.naoj.org, kaoki@subaru.naoj.org

Abstract We report the results obtained so far from our systematic survey of Lyman break galaxies (LBGs) at $z \sim 5$. We found more than 600 LBG candidates down to $I(\mathrm{AB}) = 26.5$. UV luminosity function of LBGs shows little change from $z \sim 3$ to $z \sim 5$ at brighter part, and the number density of faint LBGs decrease at $z \sim 5$. Follow-up optical spectroscopy and K-band imaging of sample LBGs clarified that they have experienced intense star formation until $z = 5$. We describe some implications for the evolution of LBGs.

Keywords: Lyman break galaxies, galaxy formation

Introduction

Lyman break galaxies (LBGs) are powerful probes of high-z star formation activity. Since the pioneering works by Steidel and co-workers, various kind of studies such as UV or optical luminosity function, stellar populations, metallicity, properties in multi-wavelengths (X-ray, infrared and sub-mm) have been made for LBGs at $z \sim 3$. Using deep data taken with 8–10 m class telescopes and HST/ACS explorations for higher redshift have been made (see contributions by Schaerer, Bouwens, Bremer et al. in this volume) and samples of LBGs at $z > 4$ are emerging. However, most of such deep surveys only covers a quite narrow area of the sky, and the numbers of sample galaxies are limited. Such pencil-beam style surveys would suffer significant effects of cosmic variance in deriving statistical properties of high-z populations. Also only small numbers of bright objects in surveyed area are expected, although they are suitable for detailed studies (e.g., high resolution spectroscopy and infrared imaging). The Prime-focus camera of 8.2m Subaru telescope (Suprime-Cam) has a large field of view ($34' \times 27'$), and it provides a unique opportunity of executing deep and wide surveys. We are executing a survey of LBGs at $z \sim 5$ with V, I_c and z' filters. The objects at $z \sim 5$ are the highest redshift galaxies which can be detected by applying normal two-color selection method of the Lyman break technique with well-established optical filters. There are two survey fields. One is a field centered on the Hubble Deep Field - North (12h36m, +62°12′). Our field of view includes the entire region of the northern part of the Great Observatory Origins Deep Survey (GOODS). Another one is the J0053+1234 field, one of the Caltech Faint Galaxy Redshift Survey fields. In both fields there are many galaxies at $z < 4$ with spectroscopic identifications, which enable us to define reliable color criteria for selecting Lyman break galaxies with less contamination from low-redshift galaxies. In this contribution we concentrate on the data for the HDF-N region. For the J0053+1234 field observations were completed and data analysis is in progress.

1. Imaging Data

Imaging observations for the HDF-N field with Subaru / Suprime-Cam started in February 2001. The limiting magnitudes achieved are $V = 28.2$, $I_c = 26.9$, $z' = 26.6$ (AB mag, $1.''2\phi$, 5σ). I_c and z'-band data are ~ 0.5 mag deeper than the data used in Iwata et al. (2003; hereafter I03). The survey area where these deepest limiting magnitudes were achieved is about 600 arcmin^2 (after masking haloes and saturating area around bright sources, the effective survey area is 546 arcmin^2). We selected candidates of LBGs at $z \sim 5$ by applying color selection criteria $V - I_c > 7(I_c - z') + 0.15$ and $V - I_c > 1.55$. The number of candidates brighter than $I_c < 26.5$ is 668.

2. UV Luminosity Function and Luminosity Density

We derived the rest-frame UV luminosity function (UVLF) with considerations for survey incompleteness, contamination by low-redshift galaxies and galactic stars and spurious sources, in a same manner as that described in I03. Briefly, we used artificial images to derive survey completeness as a function of magnitude and redshift, and a bootstrap-like method with photometric errors for estimating fraction of contamination. Fraction of interlopers is estimated to be ~ 25% in the bright part and ~ 6% in the faint end. Completeness in the faintest magnitude range would be $\sim 50\%$.

In figure 1(a) we show UVLF of LBGs at $z \sim 5$ we obtained and that for LBGs at $z \sim 3$ derived by Adelberger and Steidel (2000). The UVLFs at these two epochs (separated by $\sim$1 Gyr for cosmic time) are similar, especially in the bright part. In the faint end of the observed magnitude range, there is a significant drop of number density for LBGs at $z \sim 5$ from $z \sim 3$. Consequently the faint end slope of UVLFs for $z \sim 5$ is -1.4, somewhat shallower than that for $z \sim 3$ (-1.6). This shape of UVLF is consistent with our previous results derived with shallower data (I03), and the decrease of faint galaxies' number density becomes more clear thanks to 0.5mag deeper sampling.

In figure 1(b) we compare our UVLF with those for galaxies at $z = 4$–5 obtained by other deep surveys. Gabasch et al. (2004) derived UVLF of galaxies at $4 < z < 5$ based on photometric redshift catalog of the FORS deep field. Although sample selection method is different from ours, most of sample galaxies would be UV-luminous star-forming galaxies with less dust extinction and they would be similar to LBGs. The UVLF by Gabasch et al. matches well with ours, although their number of sample is smaller than ours. On the other hand, the UVLF of LBGs at $z \sim 5$ derived by Subaru Deep Field (SDF; Ouchi et al. 2004) is significantly different from ours in bright part. e.g., the number density of galaxies with $M_{\rm UV} = -22$ ($\sim 2.5L_*$) in our sample is about 5 times larger than that in Ouchi et al. (2004). Both our data and SDF data are based on deep and wide imaging ($> 500'$) and the cosmic variance might not be responsible for such a large difference. We tested changing color selection criteria with 0.1–0.2 mag in $V - I_c$ and found that the changes in the UVLF were within error bars. Thus the difference in color selection criteria seems to be not the main cause of this difference. We also note that results of a spectroscopic observation indicated that our color selection criteria were valid (see section 3). We will explore this issue by using data of additional fields.

By integrating UVLF we can derive a UV luminosity density at $z \sim 5$. For galaxies $M_{\rm UV} < -20$ (i.e., in observed magnitude range) we derived 4.9×10^{25} erg^{-1} Hz^{-1} Mpc^{-3}, and using a Schechter function fitted with observed data the total UV luminosity density integrated down to zero luminosity was derived to be 1.4×10^{26} erg^{-1} Hz^{-1} Mpc^{-3}. If we assume dust extinction of $E(B - V) = 0.15$ is common, the extinction-corrected luminosity density of LBGs at $z \sim 5$ is 60% smaller than that of LBGs at $z \sim 3$. In figure 2 we show observed estimates at various redshifts by several authors and predictions by a numerical simulation (Nagamine et al. 2004) and semi-analytic models (Somerville et al. 2001). Both the numerical simulation and the semi-analytic model which show a better match with observed data include starburst induced by collisions of galaxies, while a model with only a quiescent star formation

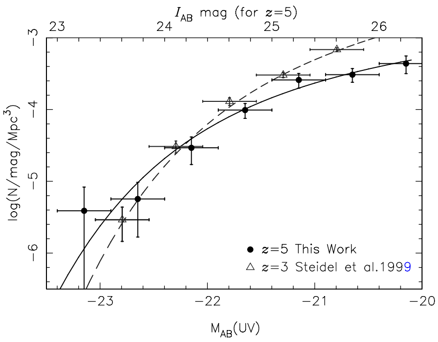

Figure 1a. UV Luminosity function (UVLF) of LBGs at $z \sim 5$ (solid line). For comparison we show a UVLF of LBGs at $z \sim 3$ derived by Adelberger and Steidel (2000) (dashed line).

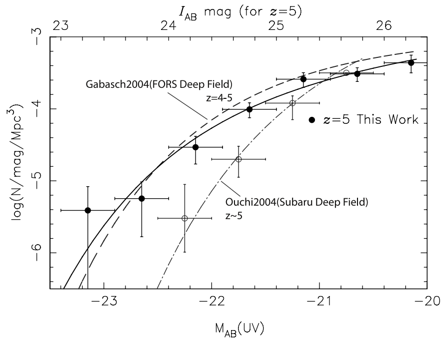

Figure 1b. Same as figure 1(a), but our UVLF is compared with UVLFs at $z = 4$–5 by other groups. Dashed line: FORS Deep Field, Gabasch et al.(2004). Dot-dashed line: Subaru Deep Field, Ouchi et al.(2004).

proportional to cold gas mass in galaxies predicts significantly smaller amount of star formation density at high redshift.

3. Optical Spectroscopy

In 2003 we initiated optical spectroscopic observations of our LBG candidates. Using Subaru / FOCAS 17 candidates with $I_c < 25.0$ have been observed, and 7 objects among them have been identified to be genuinely star-forming galaxies at $4.5 < z < 5.2$ (one object is AGN at z=5.19). For other sources S/N of spectra was poor and we could not determine their redshifts (Ando et al. 2004). We inspected properties of rest-frame UV spectra of spectroscopically identified galaxies. All of 7 objects have Lyman α lines or weak Lyman α emission lines; equivalent widths (EWs) smaller than 10 Å. This trend seems to be quite different from LBGs at $z \sim 3$; Shapley (2003) used their large spectroscopic sample of LBGs at $z \sim 3$ and found that 3/4 of them have Ly α EWs larger than 10 Å. In figure 3 we show a comparison of composite spectra of LBGs at $z \sim 5$ and $z \sim 3$. The difference in the shape of Ly α is obvious. We also found that low-ionization interstellar lines such as SiII, CII in LBGs at $z \sim 5$ are stronger than composite spectra of LBGs at $z \sim 3$. Presence of such strong interstellar lines is also found for sub-population of LBGs at $z \sim 3$ with Ly α EWs smaller than 10Å(Shapley et al. 2003).

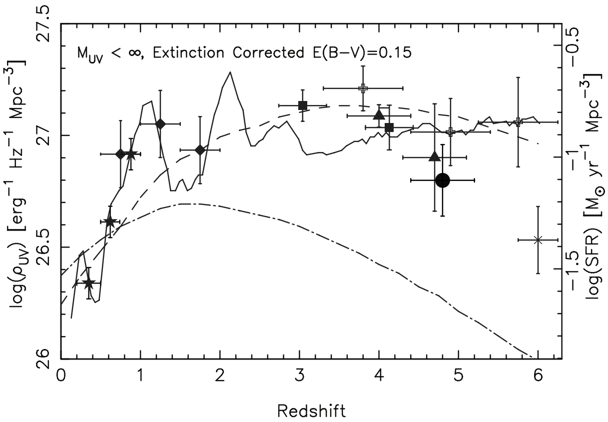

Figure 2. UV luminosity densities along redshift (so-called Madau-Lilly plot), drawn by compiling various studies. Observed values are integrated to zero luminosity using UVLFs fitted with Schechter function form, and corrected for dust extinction by assuming attenuation of $E(B-V) = 0.15$ and an extinction law proposed by Calzetti et al. (2000). Our estimates for $z \sim 5$ is indicated by a filled circle. Other data points are based on: stars: Lilly et al.(1996), diamonds: Connoly et al. (1997), squares: Steidel et al. (1999), triangles: Ouchi et al. (2004), crosses: Giavalisco et al. (2004), asterisk: Bouwens et al. (2004). Solid line is a prediction based on the cosmological numerical simulation by Nagamine et al.(2004). Other two lines are estimations based on semi-analytic modeling of galaxy evolution by Somerville et al.(2001); dashed line: collisional starburst is included in a recipe of star formation. dot-dashed line: only quiescent star formation proportional to cold gas mass is considered.

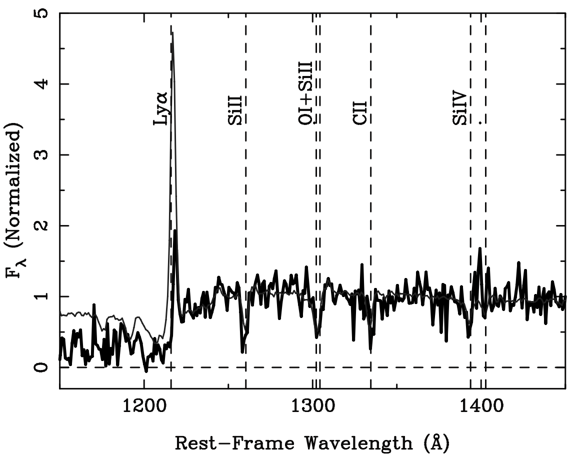

Figure 3. A composite spectrum of 7 LBGs at $z \sim 5$ (black solid line) compared with that for > 800 LBGs at $z \sim 3$ by Shapley et al.(2003) (gray line).

4. Implications for Evolution of LBGs

Recently we made a deep K-band imaging for a part of our LBG sample, mostly spectroscopically confirmed objects. Five among 6 observed objects were detected, and their UV-to-optical colors were similar to those of LBGs at $z \sim 3$, suggesting that they have already formed significant amount of stellar population by $z \sim 5$.

Although our follow-up observations of LBGs such as optical spectroscopy and K-band imaging are still in the early phase, we found that massively star-forming galaxies already exist at $z \sim 5$. Weakness of Ly α and prominent interstellar absorption lines in rest-frame UV spectra of LBGs at $z \sim 5$ might indicate that they are fairly abundant in dust and more chemically enriched than average LBGs at $z \sim 3$. This might be surprising, because $z = 5$ is about 1 Gyr earlier than $z = 3$. Our current spectroscopic sample galaxies are bright in UV continuum ($> L_*$). Lehnert and Bremer (2003) reported that they identified 6 LBGs at $z \sim 5$ with strong Ly α emission lines. Their UV luminosity is about 1.0–1.5 mag fainter than our sample. Thus the difference in UV spectra might be due to the UV luminosity; luminous objects are fairly dusty and chemically enriched than fainter ones. One possible scenario to explain this correlation would be a evolutionary sequence of LBGs; UV-luminous LBGs, probably abundant in gas (and possibly hosted by massive dark matter haloes), start to form stars earlier and become fairly chemically enriched by $z \sim 5$. The correlation between UV luminosity and Ly α emission has also been pointed out at $z \sim 3$ (Fynbo et al. 2003). At $z \sim 5$ such trend might be more evident. By increasing the number of sample and expanding the luminosity range of sample galaxies this hypothesis would be more clearly investigated.

References

Adelberger K. L., Steidel C. C., ApJ 544, 218

Ando M., Ohta K., Iwata I., Watanabe C., Tamura N., Akiyama M., Aoki K. 2004, ApJ 610, 635

Bouwens R. J. et al. 2004, ApJ 606, L25

Calzetti D., Armus L., Bohlin R. C., Kinney A. L., Koornneef J., Storchi-Bergmann T., 2000, ApJ, 533, 682

Connolly A. J., Szalay A. S., Dickinson M., Subbarao M. U., Brunner R. J. 1997, ApJ, 486, L11

Fynbo J. P. U., Ledoux C., Moller P., Thomsen B., Burud I., 2003, A&A 407, 147

Gabasch A. et al., 2004, A&A 421, 41

Giavalisco M. et al., 2004, ApJ 600, L103

Iwata I., Ohta K., Tamura N., Ando M., Wada S., Watanabe C., Akiyama M., Aoki K., 2003, PASJ 55, 415

Lehnert M. D., Bremer M. N., 2003, ApJ 593, 630

Lilly S. J., Le Fevre O., Hammer, F., Crampton D., 1996, ApJ 460, L1

Nagamine K., Cen R., Hernquist L., Ostriker J. P., Springel V. 2004, ApJ 610, 45

Ouchi M. et al. 2004, ApJ 611, 660

Shapley A. E., Steidel C. C., Pettini M., Adelberger K. L., 2003, ApJ, 588, 65

Somerville R. S., Primack J. R., Faber S. M., 2001, MNRAS, 320, 504

Steidel C. C., Adelberger K. L., Giavalisco M., Dickinson M., Pettini M. 1999, ApJ, 519, 1