DEEP SPECTROSCOPIC SURVEY OF LYMAN BREAK GALAXIES AT Z ∼ 5

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Abstract. We report results of deep optical spectroscopy with Subaru/FOC AS for Lyman Break Galaxy (LBG) candidates at z ∼ 5. So far, we made spectroscopic observations for 24 LBG candidates among ∼ 200 bright (z′ < 25.0) LBG sample and confirmed 9 objects to be LBGs at z ∼ 5. Intriguingly, these bright LBGs show no or a weak Lyα emission and relatively strong low ionization interstellar metal absorption lines. We also identified 2 faint (z′ > 25.0) objects to be at z ∼ 5 with their strong (EW rest > 20 Å) Lyα emission. Combining our results with other spectroscopic observations of galaxies at the similar redshift range, we found a clear luminosity dependence of EW rest of Lyα emission, i.e., the lack of strong Lyα emission in bright LBGs. If the absence of Lyα emission is due to dust absorption, these results suggest that bright LBGs at z ∼ 5 are in dusty and more chemically evolved environment than faint ones. This interpretation implies that bright LBGs started star formation earlier than faint ones, suggesting biased star formation.

1 Introduction

A survey of galaxies at high redshift is a direct approach to understand formation and evolution of galaxies. In this decade, the color selection technique utilizing blue UV continuum slope and Lyman break of star-forming galaxies has found so-called Lyman Break Galaxies (LBGs; e.g., [1]) at z ∼ 3 (~2 Gyr after big bang). Then various studies have been revealing their detailed properties such as UV luminosity function (UVLF) [2], UV spectroscopic features (e.g., [3]), and stellar population (e.g., [4, 5]) etc, opening the new era to understand galaxies at high redshift.

As a next step, a survey for LBGs at higher redshift is required. We focused on redshift 5, because it is ~1 Gyr (corresponding to the maximum age estimation of LBGs at z ∼ 3) earlier than z ∼ 3 and the highest redshift at which the two-color (secure) Lyman Break selection using standard optical bands can be applied. We have obtained deep and wide V, Ic and z′-bands images with Subaru [3] and Suprime-Cam [4] in/around the GOODS-N field and the J0053+1234 field (Iwata et al. 2005 in prep.) and successfully constructed a large, ~1000 galaxies with z′ < 26.5, sample of LBG candidates at z ∼ 5 among other similar surveys [2, 10, 11].

Now we investigate properties of these LBGs at z ∼ 5. Their statistical and photometric properties such as UVLF rest-frame UV to optical color, etc. are presented and discussed in Iwata’s contribution in this proceedings (see also [3]). In this paper, we report the results of spectroscopic observations of our LBGs at z ∼ 5 and discuss their UV spectroscopic features. Throughout this paper, we adopt flat Λ cosmology, Ω_M = 0.3, Ω_{Λ} = 0.7, and H_0 = 70 km s^{-1} Mpc^{-1}). The magnitude system is based on AB magnitude.

2 Observations

We made optical spectroscopy for a part of our LBG sample in the GOODS-N field and the J0053+1234 field using multi-object-spectroscopy (MOS) mode of the Faint Object Camera and Spectrograph (FOCAS; [12]) attached to the Subaru Telescope. Spectroscopic targets were selected from photometric catalog of our survey for LBGs at z ∼ 5. Details of imaging observation and color selection are described in [3] and Iwata et al. (2005 in prep.). Main spectroscopic targets are our LBG candidates brighter than z′ = 25.0 mag. Since one mask of
FOCAS MOS covers a 6′φ aperture diameter field of view, we designed MOS masks to contain main targets as many as possible on each MOS field. So far, we observed four MOS fields: three masks in the GOODS-N field and one mask in the J0053 +1234 field which contain 24 bright targets. We also included faint LBG candidates (z′ ≥ 25.0 mag) as many as possible in each mask.

Spectroscopic observations were made in 2003 and 2004 under a clear condition. We used the grism of 300 lines/mm blazed at 7500 Å and the SO58 order cut filter. This setting gave wavelength coverage from 5800 Å to 10000 Å depending on a slit position on a mask. The MOS slit widths were fixed to be 0.′′8, giving a spectral resolution of R ∼ 700 which was measured by night sky emission. An exposure time of each frame was 0.5 hours, and a total effective exposure time was 5−6 hours. This exposure time was set to detect continuum feature of main targets. Seeings during the observing runs were ∼0.′′6−0.′′8.

3 Results

Among 24 main targets, we identified 9 objects to be LBGs at z ∼ 5. Examples of resultant spectra are shown in Figure 1. Redshifts of these objects are confirmed with continuum depression shortward of redshifted Lyα and some line features such as Lyα emission and low ionized interstellar (LIS) metal absorption lines which are characteristic features of nearby starburst galaxies (e.g., [13]) and LBGs (e.g., [3, 14, 15]). Intriguingly, these bright LBGs generally show no or a weak Lyα emission and relatively strong LIS absorption lines, though the sample size is still small. Figure 2 presents the composite spectra of bright LBGs at z ∼ 5 (thick line: [16]) and LBGs at z ∼ 3 (thin line: [3]) for comparison. The average rest-frame equivalent widths of Lyα and three LIS absorption lines (SiII λ1260, OI+SiII λ1303, and CII λ1334) of these bright LBGs at z ∼ 5 are 5.9Å and −2.6Å, respectively. The value of EW of Lyα emission is small by considering that Lyα emission is often seen in LBGs at z ∼ 3 and more than 1/4 of them have strong (EWrest >20Å) Lyα emission. The average value of EW of three LIS absorption lines is stronger than that of LBGs at z ∼ 3 (−1.8Å: [3]). Assuming the local relation between LIS absorption and metallicity by [13], we can estimate their metallicity of 12+log(O/H)∼ 8.0 (1/5 solar). We also found a velocity offset between the peak of Lyα emission with respect to that of average of LIS lines; peaks of Lyα emission are redshifted 300−700 km s−1 to LIS absorption for five objects. Similar velocity offsets were also reported in LBGs at z = 3 ∼ 4 (e.g.,[3, 15]) which may be related to a large scale outflow.

Reminders of spectroscopic main sample are not identified because of their low S/N, but we found 2 objects among them to be possible elliptical galaxies at foreground redshift (z ∼ 1) from their continuum features like 4000 Å break.

Besides main targets, we confirmed 2 objects among faint bonus targets with z′ > 25.0 to be LBGs at z ∼ 5 using their strong and asymmetric Lyα emission line, though LIS absorptions were not seen due to low continuum S/N. In contrast to the result for main, bright, targets describe above, Lyα emissions of these faint LBGs are quite strong (average EWrest ∼ 58.5Å), and these are expected to be detected as Lyα emitters (LAEs). This result suggests that EW of Lyα emission of LBGs at z ∼ 5 depends on the UV luminosity.

Figure 3 shows the positions of identified objects in the V − Ic and Ic − z′ two color diagram. Filled circles show LBGs at z ∼ 5 (7 bright objects as large circles and 2 faint objects as small ones), and crosses
show foreground objects. In order to examine our color selection criteria, we also observed some objects located outside but close to the criteria. As a result, four objects were identified to be Galactic M stars which are also plotted as crosses in Figure 3. These results suggest that our selection criteria for LBGs at \( z \sim 5 \) are reasonable.

4 Discussions

We found the sign of luminosity dependence of EW of Ly\( \alpha \) emission in LBGs at \( z \sim 5 \): the lack of strong (EW\(_{\text{rest}} \) > 20\( \AA \)) Ly\( \alpha \) emission in bright LBGs at \( z \sim 5 \). In order to examine this trend, we compiled past results of the spectroscopy of galaxies at similar redshift. Figure 4 shows the EW\(_{\text{rest}} \) of Ly\( \alpha \) emission against the rest-frame UV absolute magnitude. Filled circles show our results and filled squares are the results of spectroscopies of galaxies at \( z = 4 - 5 \) \cite{9, 17, 18, 19, 20}. We also show the SFR estimated from UV absolute magnitude using the relation by \cite{21}. This figure clearly shows that there are no UV luminous LBGs at \( z \sim 5 \) with strong (EW\(_{\text{rest}} \) > 20\( \AA \)) Ly\( \alpha \) emission, while UV faint ones tend to have strong Ly\( \alpha \) emission. In addition, there seems to be a UV magnitude threshold for LBGs with strong Ly\( \alpha \) emission around \( M_{1400} \sim -21.5 \) mag which is almost the same as the \( M_\star \) magnitude of UV luminosity function of our \( z \sim 5 \) LBG sample \cite{8}. In Figure 4, crosses show Lyman \( \alpha \) emitters (LAEs) at \( z \sim 5.8 \) from narrow-band imaging data \cite{22}. The EW distribution of LAEs is similar to that of faint LBGs with strong Ly\( \alpha \) emission, suggesting the fraction of LAEs to LBGs changes with the UV luminosity at \( z \sim 5 \) universe. This is consistent with past result of \cite{23}, a number ratio of LAEs to LBGs at \( z \sim 5 \) decreases with increasing UV luminosity.

If the absence of strong Ly\( \alpha \) emission is due to the dust extinction, luminous LBGs at \( z \sim 5 \) may have chemically evolved to some extent. Presence of strong LIS absorption and the estimated metallicity (~1/5 solar) also support this idea. It seems that luminous LBGs at \( z \sim 5 \) started star formation relatively earlier than faint ones. Further, results of clustering analysis of LBGs at \( z \sim 5 \) show bright LBGs have a larger correlation length than faint ones, suggesting bright LBGs reside in more massive dark halos \cite{24}; see also the contribution by Iwata et al. in this proceedings). This fact also implies that bright LBGs at \( z \sim 5 \) have experienced star formation earlier than faint ones, i.e., biased star formation in the early universe.

Of course, velocity structure and distribution of HI gas (including dust) in/around the galaxy also affect the strength of Ly\( \alpha \) emission and its profile. We found asymmetry of Ly\( \alpha \) emission line and the velocity offset between Ly\( \alpha \) emission and LIS absorption lines in a part of our sample, which implies the presence of a large scale motion of the neutral gas in/around LBGs at \( z \sim 5 \). Thus we cannot rule out the possibility that the effect of gas geometry and kinematics for the EW and profile of Ly\( \alpha \) emission.

In any case, more spectroscopic sample of LBGs at \( z \sim 5 \) is needed to study their spectroscopic features and discuss their luminosity dependence presented in this paper, which would give clues to understand evolution of galaxies in the early universe.

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1 In order to derive UV absolute magnitudes and the SFR, we assumed continuum slope \( \beta \) of \(-1\) which is a typical value of LBGs at \( z \sim 3 \).
Figure 3: Positions of identified objects in two-color diagram. Our color selection criteria [8] for LBGs at $z \sim 5$ are indicated by thick lines. Filled circles represent the objects confirmed to be at $z \sim 5$ (7 bright objects as big circles and 2 faint objects as small ones). Crosses show objects identified to be foreground objects (Galactic M stars and possible ellipticals at $z \sim 1$). A dashed (a dot-dashed) line represents a color track of a model LBG spectrum with the $E(B-V) = 0.0$ mag ($E(B-V) = 0.4$ mag) from [8]. A dotted line refers to a color track of an elliptical galaxy [25]. Small open pentagons indicate the colors of A0 – M9 stars calculated based on the library by [26].

Figure 4: Rest-frame EWs of Ly$\alpha$ emission vs. absolute magnitude at rest-frame 1400Å for galaxies at $z \sim 5$. Filled circles show our spectroscopic results and filled squares show results from [9] and serendipitously discovered objects at $z \sim 5$ [17, 18, 19, 20]. Crosses represent LAEs at $z = 5.8$ [22] obtained from narrow-band imaging. SFR estimated from UV absolute magnitude with the relation by [21] are also shown.
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