DEFICIENCY OF LARGE EQUIVALENT WIDTH Lyα EMISSION IN LUMINOUS LYMAN BREAK GALAXIES AT z ∼ 5–6

Masataka Ando,1 Kouji Ohta,2 Ikuru Iwata,3 Masayuki Akiyama,4 Kentaro Aoki,4 and Naoyuki Tamura4,5

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ABSTRACT

We report a deficiency of luminous Lyman break galaxies (LBGs) with a large rest-frame equivalent width (EW$_{\text{rest}}$) of Lyα emission at z ∼ 5–6. Combining our spectroscopic sample of LBGs at z ∼ 5 and those from the literature, we found that luminous LBGs at z ∼ 5–6 generally show weak Lyα emissions, while faint LBGs show a wide range of Lyα EW$_{\text{rest}}$, and tend to have strong (EW$_{\text{rest}}$ ≳ 20 Å) Lyα emissions; i.e., there is a deficiency of strong Lyα emission in luminous LBGs. There seems to be a threshold UV luminosity for the deficiency; it is $M_{\text{UV}} = -21.5$ to $-21.0$ mag, which is close to or somewhat brighter than the $M_*$ of the UV luminosity function at z ∼ 5 and 6. Since the large EW$_{\text{rest}}$ of Lyα emission can be seen among the faint LBGs, the ratio of Lyα emitters to LBGs may change rather abruptly with the UV luminosity. If the weakness of Lyα emission is due to dust absorption, the deficiency suggests that luminous LBGs at z = 5–6 tend to be in dusty and more chemically evolved environments and that they begin star formation earlier than faint LBGs, although other causes cannot be ruled out.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: high-redshift

Online material: color figure

1. INTRODUCTION

Recently, a number of Lyman break galaxies (LBGs) at z ∼ 5–6 have been found, and their photometric properties and spatial distribution have been studied extensively. Studies have been made on a UV luminosity function (UVLF) as well as a star formation rate (SFR) density at the epoch (e.g., Iwata et al. 2003; Bunker et al. 2004; Yan & Windhorst 2003; Dickinson et al. 2004; Ouchi et al. 2004a; Shimasaku et al. 2005; Bouwens et al. 2006) and on a two-point correlation function that constrains the mass of the dark halo where an LBG or LBGs reside (e.g., Ouchi et al. 2004b; Kashikawa et al. 2006). Furthermore, analysis of spectral energy distributions (SEDs) has constrained their stellar masses, ages, degrees of extinction, and so on for the z ∼ 5 LBGs (e.g., Eyles et al. 2005; Yan et al. 2005; Chary et al. 2005).

However, the spectroscopic properties of LBGs at z ≥ 5 are still unknown. Only about a dozen spectra have been published so far (Spinrad et al. 1998; Dey et al. 1998; Weymann et al. 1998; Dawson et al. 2002; Lehner & Bremer 2003; Stanway et al. 2003, 2004; Nagao et al. 2004, 2005; Dow-Hygelund et al. 2005), and extensive follow-up spectroscopies have been currently made. Among these, most of the spectra show only Lyα emission, and virtually no information can be drawn from their continuum spectrum. Frye et al. (2002) successfully detected the continuum and line features of gravitationally lensed galaxies at z = 4–5 and have found the presence of interstellar absorption lines. More recently, Dow-Hygelund et al. (2005) detected the continuum and interstellar absorption lines of a gravitationally lensed LBG at z = 5.5 with a good signal-to-noise ratio (S/N) and with an extremely long (22.3 hr) exposure time.

We are also conducting a spectroscopic study of the LBGs at z ∼ 5 found by Iwata et al. (2003) and I. Iwata et al. (2006, in preparation), and Ando et al. (2004) present the first results. The obtained spectra show weak or no Lyα emission, in contrast to LBGs at z ∼ 3 (e.g., Shapley et al. 2003; Iwata et al. 2005a), and rather strong low-ionization interstellar (LIS) absorption lines of which equivalent widths (EWs) are comparable to those seen in LBGs at z ∼ 3 (Shapley et al. 2003). We also found that the Lyα emissions are redshifted by about 500–700 km s$^{-1}$ relative to the interstellar absorption lines in some of the LBGs, which suggests the presence of an outflow in the LBGs at z ∼ 5.

In this Letter, we report on the possible UV luminosity dependence of the Lyα emission of LBGs at z ∼ 5–6 using our previous and new spectroscopic samples together with those from the literature, and we discuss some possible causes. Throughout this Letter, we adopt a flat Λ cosmology, with $\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. The magnitude system is based on AB magnitude (Oke & Gunn 1983).

2. SPECTROSCOPIC SAMPLES OF LBGs AT z ∼ 5 AND z ∼ 6

The spectroscopic sample of LBGs at z ∼ 5 is taken mainly from Ando et al. (2004), and our recent results are taken with the Faint Object Camera and Spectrograph (FOCAS; Kashikawa et al. 2002) attached to the Subaru Telescope (Iye et al. 2002). The former sample is obtained around the GOODS-N field, and the latter one is obtained around the J0053+1234 field (see Ando et al. 2005). The LBG selection of our sample is based on $V - I_c$ and $I_c - z'$ colors, and the details are described in Iwata et al. (2003, 2005a) and I. Iwata et al. (2006, in preparation). Magnitudes of the spectroscopic sample in the $I_c$ band are 24.0–25.3, and the redshift coverage is $z = 4.3–5.2$. The spectroscopic observations and data reductions are achieved almost the same way for both samples, as described in Ando et al. (2004). For the sample in the GOODS-N field, resulting spectra of seven bright ($I_c \leq 25.0$) LBGs are
shown in Figure 1 of Ando et al. (2004). They show the continuum depression shortward of redshifted Lyα and some LLS metal absorption lines, indicating secure identifications of the redshifts. For the sample in the J0053+1234 field, two bright (I_c \leq 25.0) LBGs were confirmed with features similar to the GOODS-N sample, and two faint ones were identified with a strong (EW_{rest} \sim 40–80 \AA) Lyα emission line. The average Lyα EW_{rest} of our nine bright spectroscopic LBGs is \sim 6 \pm 7 \AA, and that of two faint ones is \sim 60 \pm 20 \AA. In addition to our sample, we take the spectral data of similar redshifts from the literature (Spinrad et al. 1998; Dey et al. 1998; Dawson et al. 2002; Lehnert & Bremer 2003). The number in the sample is six, and the redshift coverage is z = 4.8–5.3. Since the sample of Frye et al. (2002) is gravitationally lensed and since their magnitude correction contains a relatively large uncertainty (maximally 1.5 mag), it is excluded in the following discussion.

We also compiled spectroscopic results of LBGs at z \sim 6 (Weymann et al. 1998; Lehnert & Bremer 2003; Stanway et al. 2003, 2004; Nagao et al. 2004, 2005; Dow-Hygelund et al. 2005). The number of galaxies in the sample is nine, and the redshift coverage is z = 5.5–6.3. The object by Dow-Hygelund et al. (2005) is a gravitationally lensed galaxy, but its amplification effect (\sim 0.3 mag at most) is small; thus, we include it. Note that the objects by Nagao et al. (2004, 2005) are the i'-dropout objects with a narrowband (NB921) depression; a strong Lyα emission largely contributes to the z'-band light.

## 3. Result and Discussion

### 3.1. Deficiency of UV-luminous LBGs with a Large Lyα Equivalent Width

With the samples described in §2, we adopted the EWs of Lyα emission that appeared in each paper. For the objects of our spectroscopic sample of LBGs at z \sim 5 in the J0053+1234 field, we measured EWs in the same way used by Ando et al. (2004). The uncertainties of the EWs are estimated to be 30%–50%. For the sample of Lehnert & Bremer (2003), we measured the EWs from their Figure 4 because the EWs of individual objects were not presented. The uncertainties of the EWs are roughly 50%. For all these values of EWs, the absorption for the emission line by intergalactic matter (IGM) was not corrected, and the absorption component of Lyα was not included. Figure 1 shows rest EWs of Lyα emissions plotted against the rest-frame UV absolute magnitudes. The filled circles show our spectroscopic results, and the filled squares refer to the results from the literature. The open squares represent those of LBGs at z \sim 6. We converted the observed broadband magnitude to the rest-frame 1400 Å magnitude assuming a continuum slope β (f_λ \propto \lambda^{\beta}) of -1, which is a typical value for LBGs at z \sim 3 (Shapley et al. 2003). The effect of the uncertainty of the slope, which is estimated to be typically 0.1–0.2 mag, is small. For the objects whose adopted broad band contained the wavelength region shortward of Lyα, we corrected for the contributions by Lyα emission and IGM absorption (Madau 1995) to derive the UV absolute magnitudes. From the UV absolute magnitude, using the relation by Madau et al. (1998), we also show the SFR estimated at the upper abscissa.

As seen in Figure 1, there are no UV-luminous (M_{1400} \sim -21.0 mag) LBGs at z \sim 5 with strong (EW_{rest} \sim 20 \AA) Lyα emission, and the UV-faint LBGs show a wide range of EW_{rest} and tend to have stronger Lyα emission than UV-luminous LBGs, on average. In addition, there seems to be a UV magnitude threshold for LBGs with strong Lyα emission around M_{1400} \sim -21.0 mag that is almost the same as the M_∗ magnitude of the UVLF of our z \sim 5 LBG sample (Iwata et al. 2003) and that of Ouchi et al. (2004a). This trend still holds if the data by Frye et al. (2002) are considered.

A similar deficiency of the luminous LBGs with strong Lyα emission seems to hold at z \sim 6, although the sample size is quite small, especially for the luminous part (M_{1400} \sim -21.5 mag). There seems to be a threshold magnitude around M_{1400} \sim -21.5 mag that is close to the M_∗ of the UVLF at z \sim 6 of Bunker et al. (2004) and one \sim 1.4 mag brighter than that of Bouwens et al. (2006). The threshold magnitude is \sim 0.5 mag brighter than that of LBGs at z \sim 5, which might suggest its evolution. But the current sample number is not large enough to definitively illustrate the evolution of the threshold magnitude.

We note that the deficiency of the luminous LBGs with strong Lyα emission is not due to observational bias, at least for our spectroscopic sample. First, the minimum detectable EW_{rest} of the Lyα emission in our spectroscopic survey is \sim 10 Å for luminous (corresponding to I_c \leq 25.0) LBGs at z \sim 5 and \sim 30 Å for faint ones, in the wavelength regions where night-sky emission lines are not strong. Therefore, we should detect large EW Lyα emission lines among luminous LBGs, if there are such objects. Second, the number of observed luminous LBGs in our present spectroscopic sample (22 objects) is larger than the number of faint LBGs (12 objects). Thus, if the fraction of objects with strong Lyα emission is the same for UV-luminous and UV-faint LBGs, we should detect at least several luminous LBGs with strong Lyα emission, unless we happened to choose LBG candidates with a small EW_{rest} in luminous candidates selectively. The Kolmogorov-Smirnov test would not be useful because faint LBGs with a small EW_{rest} are expected to be missed in the present sample.

For the i'–z selected LBGs at z \sim 6, there may be a selection
bias that leads to the apparent deficiency of LBGs with strong Lyα emission because the strong Lyα emission contributes largely to the i-band flux and reduces the value of the $i-z$ color. Expected $i-z$ colors of the LBGs with EW$_{\text{rest}}$ of 20 Å (100 Å) are $\sim$0.2 mag ($\sim$0.7 mag) bluer than $i-z = 1.5$ mag, the color criterion to pick up i-dropout objects, in the redshift range between $z = 5.9$ and $z = 6.0$ ($\sim$5.9 and $\sim$6.1). Among the samples we used here, Stanway et al. (2003) and Dow-Hygelund et al. (2005) utilized the $i-z$ selection method, and the samples may suffer from selection bias. However, this bias should work independently of the UV luminosity; thus, it may not seriously affect the deficiency of luminous LBGs with strong Lyα. Note that the sample of LBGs at $z \sim 5$ does not suffer from this selection bias.

Since the EW$_{\text{rest}}$ increases with decreasing UV continuum luminosity for a constant Lyα luminosity, the deficiency may just reflect the distribution of a constant Lyα luminosity. In Figure 1, we show locations of constant Lyα luminosity corresponding to $5 \times 10^{43}$, $2 \times 10^{43}$, $10^{43}$, $5 \times 10^{42}$, and $10^{42}$ ergs s$^{-1}$ as dotted lines from top left to bottom right. All the luminous LBGs with small EWs have Lyα luminosity smaller than or equal to $10^{43}$ ergs s$^{-1}$, while about half of the faint LBGs show Lyα luminosity larger than $10^{43}$ ergs s$^{-1}$. Although the contrast is not so strong as compared with that seen in the EWs, again there are no UV-luminous LBGs with a large Lyα luminosity. In any case, the present sample is a combination of our spectroscopic data and data from the literature, and the sample size is small. A more homogeneous and larger spectroscopic sample is needed to examine whether this trend is definitive or not, although such data sets are hard to obtain even with currently available 8–10 m telescopes.

3.2. Lyα Emitters at $z \sim 6$

Since Lyα emitters (LAEs) are expected to have large rest EWs due to their selection method, LAEs may be located in the upper left part of the Figure 1. In this figure, we plot the LAEs at $z \sim 5.7$ and $z \sim 6.6$ detected from narrowband imaging data; the crosses and plus signs represent LAEs at $z \sim 5.7$ (Ajiki et al. 2003) and $z \sim 6.6$ (Taniguchi et al. 2005), respectively. We adopted the EW values from spectroscopic results for the LAEs at $z \sim 6.6$ (triangles; Taniguchi et al. 2005). The values of Lyα rest EWs are not corrected for IGM absorption for the emission. Most of the LAEs are UV-faint objects, and the rest EWs’ distribution is similar to that of faint LBGs. For the UV-luminous LAEs, Lyα rest EWs are relatively smaller than those of faint LAEs and faint LBGs, and again we can see the deficiency of the strong Lyα emission in UV-luminous LAEs. A recent survey of LAEs at $z = 5.7$ in the Subaru Deep Field (Shimasaku et al. 2006) also shows the same tendency (see their Fig. 16).

These results imply that the ratio of LAEs to LBGs changes with the UV luminosity at $z \sim 5$–6; among UV-luminous LBGs, there are only a few LAEs, while among faint LBGs, there are many LAEs with large EWs of Lyα emission. This fits the trend that the ratio of LAEs to LBGs at $z \sim 5$ decreases with increasing UV luminosity (Ouchi et al. 2003), although our results show a rather abrupt decrease of LAEs among luminous LBGs. Thus, the LAEs are presumably a subset of faint LBGs, and they are not the luminous LBGs at the redshift.

3.3. Possible Origins of the Deficiency

Although we need further studies to confirm the deficiency of luminous LBGs with large Lyα EW$_{\text{rest}}$, we try to find the possible causes for this trend and its implications. One possible cause is the systematic difference in the dust extinction between luminous and faint LBGs. Since there are significant correlations between gas metallicity, dust extinction, and the strength of LIS absorption lines in local star-forming galaxies (e.g., Heckman et al. 1998), the presence of strong LIS absorption lines in the luminous LBGs of our spectroscopic sample supports this possibility. If we assume the local relation between the EW of LIS absorptions and metallicity by Heckman et al. (1998), an estimated gas metallicity for our spectroscopic sample of luminous LBGs at $z \sim 5$ is $12 + \log (O/H) \sim 8.0$ ($\sim$1/3 solar), using the solar value from Allende Prieto et al. (2001). At this gas metallicity, the Lyα/Hβ ratio is reduced by a factor of about 30 from the case B assumption for local star-forming galaxies (Hartmann et al. 1988). If the luminous LBGs at $z \sim 5$ are more chemically evolved than the faint LBGs, it is suggested that the luminous LBGs at $z \sim 5$ will begin star formation relatively earlier than faint LBGs. The clustering analysis of LBGs at $z \sim 5$ shows that luminous LBGs have a larger correlation length than faint LBGs, suggesting that luminous LBGs reside in a more massive dark halo (e.g., Ouchi et al. 2004b; Iwata et al. 2006, in preparation). The suggestions seem to fit the biased star formation scenario in the early universe; UV-luminous LBGs at $z \sim 5$ are in a more massive dark halo and have experienced star formation earlier than faint LBGs residing in a less massive dark halo. We do not find a significant relation between the $L_\text{c} - z'$ color and the EW$_{\text{rest}}$ of Lyα emission for our spectroscopic sample. However, this is probably because the baseline separation between $L_\text{c}$ and $z'$ is too small to derive reliable $E(B-V)$ values under the current photometric uncertainty. In addition, the S/Ns of our spectra are too low, and the wavelength coverage too small, to reliably estimate the $E(B-V)$ values from their continuum.

The amount of H i gas in and surrounding the galaxy can affect the Lyα EWs. If luminous LBGs have much more H i gas than faint ones, it is possible that Lyα emission is selectively extinguished in luminous LBGs, resulting in small EWs. The presence of a large amount of H i gas in luminous LBGs seems to fit the biased galaxy formation scenario described above; luminous LBGs reside in a more massive dark halo and are expected to have more H i gas than faint LBGs in a less massive dark halo.

The age of a galaxy can also affect the EW of Lyα. A large Lyα EW$_{\text{rest}}$ (100–200 Å) is expected for very young (<10–100 Myr) galaxies (e.g., Charlot & Fall 1993). Thus, luminous LBGs may be older than faint LBGs. However, it is hard to claim this to be so if the dust exists in the galaxy. In fact, using the results of the SED fitting of LBGs at $z \sim 3$, Shapley et al. (2001) found that the composite spectrum of young (age ≤ 10 Myr) LBGs shows a small Lyα EW, while that of old (age ≥ 1 Gyr) LBGs shows a large one.

Another possibility is the velocity structure of the H i gas in/around the galaxy. From Lyα imaging and spectroscopy of nearby star-forming galaxies, EWs of Lyα do not necessarily depend on the gas metallicity. For example, Kunth et al. (1998, 2003) claim that the kinematical property of the gas is a dominant regulator of the Lyα escape probability; galaxies with outflowing neutral gas tend to have large Lyα EWs, while galaxies with static neutral gas tend to have small Lyα EWs. Shapley et al. (2003) also pointed out the importance of the
kinematical feature for the LBGs at \( z \sim 3 \), but their sense of its importance is opposite to that of Kunth et al. (1998). They found that LBGs with smaller \( \text{Ly}_\alpha \) EWs tend to have stronger LIS absorptions and large velocity offsets of \( \text{Ly}_\alpha \) emission relative to LIS absorption lines. These facts can be explained if the LBGs with smaller EWs have outflowing neutral gas with a larger velocity dispersion, because the gas causes a broader \( \text{Ly}_\alpha \) absorption for \( \text{Ly}_\alpha \) emission that results in a smaller EW of \( \text{Ly}_\alpha \), a more redshifted (asymmetric) \( \text{Ly}_\alpha \) peak that is seen as the larger velocity offset between \( \text{Ly}_\alpha \) and LIS absorption, and stronger LIS absorption lines (Shapley et al. 2003). We found the asymmetry of the \( \text{Ly}_\alpha \) emission line and the velocity offset of \( \text{Ly}_\alpha \) emission relative to LIS absorption lines in a part of our luminous spectroscopic sample, which implies the presence of the large-scale motion of the neutral gas of LBGs at \( z \sim 5 \) as well as at \( z \sim 3 \). Thus, there is a possibility that the gas kinematics affects the EW and the shape of profile of \( \text{Ly}_\alpha \) emission.

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