DETECTIONS OF LYMAN CONTINUUM FROM STAR-FORMING GALAXIES AT Z \simeq 3 THROUGH SUBARU/SUPRIME-CAM NARROW-BAND IMAGING

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Submitted to ApJL

ABSTRACT

Knowing the amount of ionizing photons from young star-forming galaxies is of particular importance to understanding the reionization process. Here we report initial results of Subaru/Suprime-Cam deep imaging observation with a special narrow-band filter to optimally trace ionizing radiation from galaxies at z > 3. The unique wide field-of-view of Suprime-Cam enabled us to search for ionizing photons from 198 galaxies with spectroscopically measured redshifts z \simeq 3.1. We detected ionizing radiation from 7 Lyman break galaxies (LBGs), as well as from 10 Ly-\alpha emitter (LAE) candidates. Some of the detected galaxies show significant offsets of ionizing radiation from non-ionizing UV emission. As an average of the 7 detected LBGs, the observed flux density ratio of non-ionizing UV to ionizing radiation is estimated to be 4.9, which is smaller than values expected from population synthesis models with a standard Salpeter initial mass function (IMF) and dust attenuation. This implies an intrinsically bluer spectral energy distribution, e.g. that produced by a top-heavy IMF, for these LBGs. The observed flux density ratios of the detected LAEs are even smaller than those expected from a top-heavy IMF and QSOs if they are truly at z \simeq 3.1. We find that the average escape fraction of ionizing photons for the detected LBGs should be higher than 15%.

Subject headings: galaxies: evolution — galaxies: high-redshift — cosmology: observations — intergalactic medium — diffuse radiation

1. INTRODUCTION

Ionizing radiation from star-forming galaxies is a likely primary source of cosmic reionization. Although the ratio of the flux density of Lyman continuum escaping from a galaxy to that produced in the galaxy, the so-called escape fraction (f_{esc}), is a key parameter for evaluating the contribution of galaxies to cosmic reionization, it has been poorly constrained due to the fact that Lyman continuum photons are easily absorbed by the intergalactic medium (IGM). Direct observations of Lyman continuum from z > 4 are virtually impossible because of a rapid increase in the number density of Lyman limit systems toward high redshifts (Inoue & Iwata 2008). Therefore, we must focus on z \simeq 3 where the IGM optical depth is still about unity on average. Steidel et al. (2001) detected Lyman continuum in a composite spectrum of 29 Lyman break galaxies (LBGs) at \langle z \rangle = 3.4. The observed flux density ratio was f_{1500}/f_{900} = 17.7 \pm 3.8.

Shapley et al. (2006, hereafter S06) detected Lyman continuum individually from two out of 14 observed LBGs at z \simeq 3 through a deep long-slit spectroscopy, and derived f_{1500}/f_{900} = 12.7 \pm 1.8 and 7.5 \pm 1.0 for the two LBGs. So far the number of galaxies with direct observation of Lyman continuum is too small to find common properties shared by galaxies with large f_{esc}, or to estimate a typical value of f_{esc}.

In this letter we report the initial results of the observations of Lyman continuum from galaxies at z \simeq 3 with Subaru/Suprime-cam (S-Cam; Miyazaki et al. 2002). A narrow-band filter imaging was adopted to search for Lyman continuum, as pioneered by Inoue et al. (2005). The use of narrow-band imaging instead of slit spectroscopy enables us to examine ionizing radiation from a large number of galaxies simultaneously, as well as to examine emission offsets from rest-frame non-ionizing UV radiation. The target field of the present study is the SSA22 field where the prominent proto-cluster of galaxies at z = 3.09 has been discovered (Steidel et al. 1998, 2000; Shapley et al. 2004, hereafter H04). We adopt a cosmology with the parameters $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$ and $H_0 = 70 \text{ km/s/Mpc}$. All magnitudes are measured in the AB system.

2. OBSERVATIONS AND DATA REDUCTION

We produced a special narrow-band filter NB359 which has a central wavelength of 359 nm with a FWHM of 15 nm (and \geq 10% transmittance between 350 nm and 371 nm). This filter is designed to trace Lyman continuum of galaxies at z \gtrsim 3.06 with contamination from non-ionizing radiation at less than 1% for a typical star-forming galaxy. In the laboratory measurement it was verified that the transmission of the filter is less than 0.01% in the wavelength range of 400 nm–1200 nm. We
also confirmed that the central wavelength is stable with rms=0.47 nm at every position on the filter.

The imaging observations using Subaru/S-Cam with the NB359 filter were carried out in 2007 September 10−14 (UT). Three nights were photometric while in the other two nights cloud coverage was relatively high. The seeing condition was good throughout the observing dates, with a FWHM of 0.′′5−0.′′9 in NB359 images. The pointing center (α = 22°17′26.1, δ = +00°16′11″ [J2000]) is aligned to the previous Subaru/S-Cam observations of the SSA22 field (Matsuda et al. 2004, hereafter M04; H04). For half of the shots the position angle was switched from 90° to 270°, in order to reduce the effect of chip-to-chip sensitivity variation.

The data reduction was made using SDFRED version 1.2.5 (Yagi et al. 2002; Ouchi et al. 2004). The rejection of frames under poor sky condition led a selection of 45 frames with 1,800 sec exposures to produce the mosaic image. The flux calibration was made using measurements of spectroscopic standard stars. The 3 σ limiting magnitude of the final mosaic image is estimated to be 27.33 AB mag for 1.′′2 diameter aperture.

Source detection and photometry were done using SExtractor (Bertin & Arnouts 1996) version 2.5.0 in the double-image mode; source detection was performed with the R-band image, and photometry in other band images was done at each position of a source detected in the R-band. Galactic extinction has been corrected using the dust map by Schlegel, Finkbeiner & Davis (1998). As described below, there are objects detected in NB359 but their positions in NB359 are slightly offset from those in the R-band. In such cases we performed source detection and photometry with the NB359 image.

3. RESULTS

There are 198 objects with spectroscopically measured redshifts larger than 3.0 in the S-Cam field-of-view (32′ × 26′). Ten objects classified as QSOs/AGNs from optical spectra and/or X-ray observation have been excluded. Among the 198 objects there are 44 LBGs reported in the literature (Steidel et al. 2003; S06), 29 LBGs selected as U-dropout galaxies and identified spectroscopically with VLT/VIMOS (Kousai et al., in preparation), and 125 Ly-α emitters (LAEs) and Ly-α ‘blobs’ selected through a narrow-band (NB497) imaging with Subaru/S-Cam (H04, M04) and identified spectroscopically with Subaru/FOCAS and Keck/DEIMOS (Matsuda et al. 2006; Matsuda et al., in preparation).

We detected 16 objects with secure detection (>3σ) within 1.′′2 diameter apertures in NB359: 6 are LBGs and 10 are LAEs. The redshift range of the LBGs is 3.04 < z < 3.31, while for the LAEs it is 3.07 < z < 3.10. In order to eliminate a possibility of spurious detections, we split the frames used to create the final NB359 image into two sets and generated two mosaic images. All 16 objects were detected in both images at ≥2σ level. We also executed a detection test using a negative image in NB359 and found that a probability of spurious detection at >3σ level is ∼0.4%. Therefore, we are confident in the reality of source detection in NB359. In Figure 1 we show four postage stamp images as examples.

In addition, SSA22a-C49, from which S06 detected Lyman continuum, has 2.95σ significance in our image. The measured flux density within the 1.′′2 aperture (5.5 ± 1.0 × 10⁻² μJy) is consistent with that measured with a long-slit spectroscopy by S06 (6.9 ± 1.0 × 10⁻² μJy). We add this object to the detection list in NB359, bringing the total number of detected objects to 17 (7 LBGs and 10 LAEs). On the other hand, we could not find any significant signal in NB359 at the position of SSA22a-D3 which is another object detected in Lyman continuum by S06 Since the 3σ detection limit within 1.′′2 aperture at the position of this object (5.8 × 10⁻² μJy) is well below the flux density reported by S06 (11.8 ± 1.1 × 10⁻² μJy), it is not clear why the object is not visible in our NB359 image. In Figure 1 images of SSA22a-C49 and D3 are also shown.

All of the 10 LAEs detected in NB359 show a prominent emission line around 497 nm in their spectra taken with FOCAS and DEIMOS, but continua are not well detected due to their faintness. All but one spectrum of these 10 objects have a resolution high enough to distinguish the doublet if the emission line detected with the NB497 filter is [O ii] λ3727 at z = 0.33, and we find no such feature. However, there is still a possibility that they are AGNs at lower redshifts if the emission line is C iv λ1549 at z = 2.21 or Mg ii λ2798 at z = 0.78, although some of them show a spatially extended emission in the NB497 image. Unfortunately, the wavelength coverage of the spectra obtained so far is too narrow to definitely rule out the low redshift possibility. Follow-up spectroscopy would be required to clarify whether these objects are really LAEs at z ∼ 3.09.

If a faint foreground object lies very close to an object at z ∼ 3.1, it might mimic Lyman continuum in our NB359, and it would be difficult to distinguish it at longer wavelengths if the object at z ∼ 3.1 is brighter than the foreground object. Siana et al. (2007) discussed such a possibility of contamination by faint foreground objects in the z ∼ 3 Lyman continuum survey. Following Siana et al. (2007), we roughly estimate the probability of such a case by assuming a surface density of faint galaxies and their spatial distribution to be purely random. The apparent magnitudes of galaxies detected in NB359 range from 26.5 mag to 27.5 mag. The surface number density of galaxies in this magnitude range from U-band number count by Williams et al. (1996) is ∼ 10⁵ mag⁻¹ deg⁻². If we consider that a foreground ob-
ject within a 0.′′5 radius cannot be distinguished in our NB359 image, each object has ∼0.6% chance of such foreground contamination. Since we have 198 spectroscopic sample galaxies, one or two objects among the galaxies detected in NB359 may be explained by contamination by such a foreground object. However, it would be difficult to imagine that all 17 detections could be due to foreground contamination.

4. DISCUSSION

4.1. Properties of Detected Objects

As seen in Figure [1] shapes and positions of the emitting regions in the 17 detected galaxies in NB359 are quite different from those in the R-band in many cases. The rms of positional offsets between the NB359 and the R-band images for foreground objects is ∼ 0.′′25. The offsets of 4 LBGs among the 7 LBGs detected in Lyman continuum exceed 3σ, and the average offset is 0.′′97 (3.8σ, corresponding to 7.4 kpc at z = 3.09). Such differences in the shape and the position between the emitting regions of ionizing radiation and those of non-ionizing UV may give us a clue to understand how Lyman continuum escapes from galaxies. For instance, Lyman continuum may escape through a chimney-like structure in the interstellar medium [Razoumov & Sommer-Larsen 2007], and we may see the emission only from some limited regions. Another possibility is that the spatial distribution of the Lyman continuum sources is different from that of the non-ionizing UV emitting stars. For some detected galaxies, high resolution images taken with the HST/ACS using the F814W filter are available. We find that many of them show multiple knotty structures and the Lyman continuum emission appears to be associated with one of such knots. We will discuss these geometrical features further in a future publication. Note that at the moment with the F814W image we cannot distinguish between superposition of a foreground object and multiple knotty substructures frequently seen in LBGs (e.g., Lowenthal et al. 1997). The position offsets of Lyman continuum from non-ionizing UV peak also imply a possibility that long-slit spectroscopy may miss Lyman continuum.

In Figure 2 the NB359−R colors of the 198 objects with spectroscopic redshifts larger than 3.0 are plotted against their R-band magnitudes. The NB359−R color corresponds to the apparent flux density ratio of ionizing to non-ionizing UV photons for objects at z ∼ 3. We find that luminous (R < 25) objects, which roughly correspond to those with L > L* of LBGs at z ∼ 3 [Sawicki & Thompson 2000], show relatively red colors of NB359−R ≥ 2. On the other hand, some of the less luminous objects show bluer colors, 0 < NB359 − R < 2. If the IGM opacity does not depend on the source luminosity, this suggests that the ionizing-to-non-ionizing UV escape flux density ratio (a proxy of f_{esc}; see Inoue, Iwata & Deharveng 2006) is lower in relatively luminous objects. Interestingly, this appears contrary to the argument by Gnedin, Kravtsov, & Chen (2008) that f_{esc} is smaller for galaxies with smaller star formation rates (or mass).

We use deep multi-band optical imaging data (H04) to investigate spectral energy distribution (SED) of the detected sample. The UV spectral slopes of the detected LBGs are flat (0 < V − i′ < 0.5). There are two clearly distinctive sub-groups of the detected LAEs from their V − i′ colors: one is red (0.5 < V − i′ < 1.0), and the other is blue (−0.5 < V − i′ < 0). In Figure 2 different symbols are used for different types of SEDs. Blue LAEs show extremely blue NB359−R colors (< 0.3), while LBGs have NB359−R larger than 0.7. The difference between these three types becomes clear if we place them into the NB359−R and V − i′ two-color plane, as shown in Figure 3. To compare with these observed colors we calculated predictions of colors for young star-forming galaxies with a population synthesis code (Starburst99 version 5.1; Leitherer et al. 1999). A model at zero age, with the Salpeter IMF (0.1–120M⊙; Salpeter 1955) and Padova evolutionary tracks with metallicity Z = 4×10^{-4} is used as a fiducial one. Since models with higher metallicity or older age have redder colors, this model has the bluest SED under an assumption of the Salpeter IMF. The colors of the model without IGM and dust attenuation and assuming f_{esc} = 1 at z = 3.0 and 3.3 are shown as filled and open circles connected with a solid line in Figure 3. An arrow indicates the direction of dust attenuation following a prescription by Calzetti et al. (2000) for a galaxy at z = 3. For λ < 1200Å we simply extrapolated their attenuation law. Such smooth extrapolation toward extreme-UV may be reasonable up to λ ∼ 800 Å [Draine 2003]. IGM attenuation has a large dispersion for different lines of sight. We show colors with a median value of IGM attenuation for z = 3.0 and z = 3.2 cases, with the optical depth range containing 68% of all sightlines of Monte-Carlo simulations [Inoue & Iwata 2008]. The shaded area shows colors of model galaxies which can be explained with dust and/or IGM attenuation. The dashed line in the area indicates colors with IGM opacity with 1% probability of occurrence (i.e., very rare transparent sight-lines); 99% of objects with the bluest SED with the Salpeter IMF at z ∼ 3 should show redder NB359−R colors than this dashed line. However, all but one object of the detected sample show bluer NB359−R colors.

The V − i′ colors of the detected LBGs suggest moderate attenuation by dust, E(B−V) ∼ 0.1−0.3, consistent with previous studies (e.g., Iwata, Inoue & Burgarella 2008).
Fig. 3.— NB359−R and V − i′ colors of objects detected in NB359. LBGs detected in NB359 are shown with squares, and two LAE sub-groups divided by their UV slopes are shown with open circles and triangles. Solid line is the color track of a model galaxy with the bluest SED with the Salpeter IMF from $z = 3.0$ to 3.3. The shaded area indicates a color range which can be explained with attenuation by dust and IGM. See text for details. The cross indicates the expected color of a model QSO with a folded SED with attenuation by dust and IGM. See text for details. The cross shows a color range which can be explained by dust and IGM. The shaded area indicates a color range which can be explained with attenuation by dust and IGM. See text for details.

However, the NB359−R colors of the detected LBGs are difficult to explain with these models. Even if we assume no IGM attenuation for these objects, colors of four LBGs bluest in NB359−R cannot be explained. A QSO-like spectrum may be able to explain these objects (see a cross shown in the figure), although these objects are not classified as AGNs, according to the catalog (Steidel et al. 2003). To explain these strong emission in Lyman continuum, models which can produce much bluer intrinsic colors – such as those with a top-heavy IMF – would be required. Indeed, model SEDs with a top-heavy IMF have $\nu \propto \nu^3$ for $\lambda < 1100$ Å and $\nu \geq 1100$ Å, respectively, $f_s \propto \nu^3$, without IGM attenuation.

4.2. Constraints on the Escape Fraction

The relative escape fraction is defined as (Steidel et al. 2001):

$$f_{esc, rel} = \frac{(f_{1500}/f_{900})_{int}}{(f_{1500}/f_{900})_{obs}} \exp(\tau_{IGM, 900})$$

where $(f_{1500}/f_{900})_{int}$ and $(f_{1500}/f_{900})_{obs}$ are the intrinsic and observed UV to Lyman continuum flux density ratios, respectively, and $\tau_{IGM, 900}$ is the IGM optical depth for Lyman continuum photons along the line of sight. For $(f_{1500}/f_{900})_{int}$ we use 3.0, following previous studies on Lyman continuum at $z \sim 3$ (Steidel et al. 2001; Inoue et al. 2005; S06). If the dust attenuation at 1500 Å is known, $f_{esc, rel}$ can be converted to $f_{esc}$ as $f_{esc} = 10^{-0.4A_{1500}/f_{esc, rel}}$ (Inoue et al. 2005; Siana et al. 2007). We calculate the observed flux densities at rest-frame 1500 Å by interpolating flux densities in $V$ and $R$-bands, and use flux densities with the NB359 filter as $f_{900, obs}$. Values measured with a 1/2 diameter aperture are used. For the seven detected LBGs, the average $(f_{1500}/f_{900})_{obs}$ is 4.9±2.9. If we consider the case without IGM attenuation it corresponds to $f_{esc, rel} = 0.61$, and it is a lower limit of $f_{esc, rel}$ for the detected LBGs. Under the assumption of average dust attenuation $E(B−V) = 0.15$, which would be reasonable to explain $V − i′$ colors of these objects (see Figure 2), a lower limit of $f_{esc}$ is 0.15. If a correction for the IGM attenuation for a median opacity $\tau_{IGM} = 0.59$ (for $z = 3.0$) is applied, $f_{esc} = 0.26$. A use of opacity for very rare (1% probability) transparent sight-lines ($\tau_{IGM} = 0.31$) gives $f_{esc} = 0.20$. These values increase if $(f_{1500}/f_{900})_{int}$ is larger than 3.0. Thus we conclude that for the detected LBGs the average $f_{esc}$ should be higher than 15% and it is quite likely that $f_{esc}$ is higher than 20%. This high $f_{esc}$ makes a clear contrast with a stringent upper limits $f_{esc, rel} < 0.08$ for stacked images of $z \sim 1.3$ galaxies (Siana et al. 2007). However, we should emphasize that, as it is seen in Figure 2, these LBGs should be the systems with highest $(f_{900}/f_{1500})_{obs}$ among luminous galaxies at $z \sim 3$. The average $f_{esc}$ of the entire galaxy populations (at least for $L > L^*$ galaxies) should be much lower than the value derived for our detected LBG sample. The constraints on $f_{esc}$ for UV-magnitude limited sample with the present data will be discussed in the forthcoming paper.

We thank Alex Razoumov for a careful read of the manuscript and discussions. II and AKI acknowledge Grant-in-Aid for Young Scientists (B: 18740114) from Japan Society for the Promotion of Science (JSPS) and support by the Institute for Industrial Research, Osaka Sangyo University. We would like to express our acknowledgment to the indigenous Hawaiian community for understanding of the significant role of the summit of Mauna Kea in astronomical research.

REFERENCES

Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Calzetti, D., Armus, L., Bohlin, R. C., Kinney, A. L., Koornneef, J., & Storchi-Bergmann, T. 2000, ApJ, 533, 682
Draine, B. T. 2003, ApJ, 598, 1017
Gnedin, N. Y., Kravtsov, A. V., & Chen, H.-W. 2008, ApJ, 672, 765
Hayashino, T., et al. 2004, AJ, 128, 2073 (H04)
Inoue, A. K., Iwata, I., Deharveng, J.-M., Buat, V., & Burgarella, D. 2005, A&A, 435, 471
Inoue, A. K., Iwata, I., & Deharveng, J.-M. 2006, MNRAS, in press (arXiv:0804.2951)
Iwata, I., Inoue, A. K., & Burgarella, D. 2005, A&A, 440, 881
Leitherer, C., et al. 1999, ApJS, 123, 3
Lowenthal, J. D., et al. 1997, ApJ, 481, 673
Matsuda, Y., et al. 2004, AJ, 128, 569 (M04)
Matsuda, Y., Yamada, T., Hayashino, T., Yamauchi, R., & Nakamura, Y. 2006, ApJ, 640, L123
Miyazaki, S., et al. 2002, PASJ, 54, 833
Ouchi, M., et al. 2004, ApJ, 611, 660
Razoumov, A. O., & Sommer-Larsen, J. 2007, ApJ668, 674
Salpeter E. E. 1955, ApJ, 121, 161
Sawicki, M., & Thompson, D. 2006, ApJ642, 653
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ500, 525
Shapley, A. E., Steidel, C. C., Pettini, M., Adelberger, K. L., & Erb, D. K. 2006, ApJ, 651, 688 (S06)
Siana, B., et al. 2007, ApJ, 668, 62

Steidel, C. C., Adelberger, K. L., Dickinson, M., Giavalisco, M., Pettini, M., & Kellogg, M. 1998, ApJ, 492, 428
Steidel, C. C., Adelberger, K. L., Shapley, A. E., Pettini, M., Dickinson, M., & Giavalisco, M. 2000, ApJ, 532, 170
Steidel, C. C., Pettini, M., & Adelberger, K. L. 2001, ApJ, 546, 665
Steidel, C. C., Adelberger, K. L., Shapley, A. E., Pettini, M., Dickinson, M., & Giavalisco, M. 2003, ApJ, 592, 728
Williams, R. E., et al. 1996, AJ, 112, 1335
Yagi, M., et al. 2002, AJ, 123, 66