Testing an indirect method for identifying galaxies with high levels of Lyman continuum leakage

Satoshi Yamanaka,1,2⋆ Akio K. Inoue,1,2,3 Toru Yamada,4 Erik Zackrisson,5 Ikuru Iwata,6 Genoveva Micheva,7 Ken Mawatari,8 Takuya Hashimoto1,2,6,9 and Mariko Kubo6

1Waseda Research Institute for Science and Engineering, Faculty of Science and Engineering, Waseda University, 3-4-1, Okubo, Shinjuku, Tokyo 169-8555, Japan
2Department of Environmental Science and Technology, Faculty of Design Technology, Osaka Sangyo University, 3-1-1, Nakagaito, Daito, Osaka 574-8530, Japan
3Department of advanced Science and Engineering, Faculty of Science and Engineering, Waseda University, 3-4-1, Okubo, Shinjuku, Tokyo 169-8555, Japan
4Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1, Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan
5Department of Physics and Astronomy, Uppsala University, Box 515, SE-751 20 Uppsala, Sweden
6Institute for Cosmic Ray Research, The University of Tokyo, 3-1-3 Kashiwa-no-Ha, Kashiwa, Chiba 277-8582, Japan
7National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
8Leibniz-Institut für Astrophysik, An der Sternwarte 16, D-14482 Potsdam, Germany
9Tomonaga Center for the History of the Universe (TCHoU), Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Ibaraki 305-8571, Japan

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

Using a sample of galaxies at z ∼ 3 with detected Lyman Continuum (LyC) leakage in the SSA22 field, we attempt to verify a proposed indirect method for identifying cases with high LyC escape fraction fesc based on measurements of the Hβ equivalent width (EW) and the β slope of the UV continuum. To this end, we present Keck/MOSFIRE Hβ flux measurements of LyC galaxies (LCGs) at spectroscopic redshifts zspec ∼ 3.3, Lyman break galaxies (LBGs) at photometric redshifts zphot ∼ 2.7–3.7, and Lyα emitters at zphot = 3.1. We also reconfirm the spectroscopic redshifts and measure the Hβ emission line fluxes from 2 LCGs and 6 LBGs. For the LCG in our sample with the most extreme fesc, as revealed by the direct detection of LyC photons, we find that the EW(Hβ)−β method gives a broadly consistent estimate for fesc, although the error bars remain very large. We also discuss how a combination of fesc measurements based on direct and indirect methods can shed light on the LyC escape mechanism and the anisotropy of the leakage.

Key words: galaxies: high-redshift – galaxies: starburst – galaxies: ISM

1 INTRODUCTION

Cosmic reionization is a phase transition from the neutral to ionized state of the intergalactic medium (IGM), likely driven by ionizing radiation from star-forming galaxies (SFGs) and/or active galactic nuclei (AGNs; e.g. Madau et al. 1999; Madau & Haardt 2015; Robertson et al. 2015). Various observations indicate that the reionization process was completed by z ∼ 6; the Gunn–Peterson optical depth (e.g. Fan et al. 2002, 2006), the clustering of Lyα Emitters (LAEs; e.g. Ouchi et al. 2010, 2018), the evolution of the luminosity function of LAEs (e.g. Kashikawa et al. 2006, 2011; Itoh et al. 2018; Konno et al. 2018), the fraction of Lyα emitting galaxies in SFGs (e.g. Ono et al. 2012; Schenker et al. 2012), the Lyα damping wing in gamma-ray burst after-glow spectra (e.g. Totani et al. 2006, 2016; Greiner et al. 2009), and the kinetic Sunyaev–Zeldovich effect (e.g. Zahn et al. 2012; Planck Collaboration et al. 2016). However, despite a great deal of effort to understand cosmic reionization, the detailed history, sources, and topology of this epoch are not yet understood.

In order to understand the dominant sources of cosmic reionization, the fraction of ionizing photons (Lyman continuum, hereafter LyC, at λrest < 912 Å) that escapes from SFGs/AGNs into the surrounding IGM, fesc, is one of the most important physical quantities. For reionization by SFGs, a LyC escape fraction on the order of 10% seems to be required (e.g. Inoue et al. 2006; Finkelstein et al. 2015, 2019; Bouwens et al. 2016). Based on current constraints, the contribution from AGNs to the reionization process moreover appears to be subdominant compared to that of SFGs (e.g. Micheva et al. 2017a; Matsuoka et al. 2018; Kulkarni et al. 2019).

The simplest and most robust way to constrain fesc is direct imaging and/or direct spectroscopic observations of the escaping LyC photons. The standard procedure is to estimate fesc of SFGs/AGNs from their observed luminosity ratio of ionizing to non-ionizing ultraviolet (UV) radiation, LUV,obs/LLyC,obs, using

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assumptions on the intrinsic luminosity ratio of $L_{\text{UV, int}}/L_{\text{LYC, int}}$, the IGM absorption along its line of sight, and the dust attenuation (e.g. Steidel et al. 2001; Inoue et al. 2005; Siana et al. 2007).

Since it is next to impossible to directly observe the LyC photons escaping from SFGs/AGNs at $z > 5$ due to foreground IGM absorption (Inoue & Iwata 2008), the LyC observations for lower-$z$ analogs are important for inferring the likely $f_{\text{esc}}$ of SFGs/AGNs in the epoch of cosmic reionization, and to test indirect methods of estimating $f_{\text{esc}}$.

Numerous attempts have been made to estimate the LyC escape fractions of individual SFGs at $z < 4$. Since Earth’s atmosphere is very efficient in absorbing far-UV radiation, space telescopes such as the Far Ultraviolet Spectroscopic Explorer (FUSE) and the Hubble Space Telescope (HST) have been very important for studying the $f_{\text{esc}}$ of local and/or low-$z$ SFGs. Several detections of direct LyC radiation from $z < 1$ starburst galaxies have been made, typically with $f_{\text{esc}} \lesssim 10\%$ (e.g. Bergvall et al. 2006; Leitet et al. 2011, 2013; Borthakur et al. 2014; Izotov et al. 2016a,b), although some objects have been reported with $f_{\text{esc}} \sim 40$–70\% (Izotov et al. 2018a,b). At $z \approx 2–4$, the $f_{\text{esc}}$ values of SFGs have been investigated by both space and ground based telescopes. In this redshift range, many individual objects appear to show relatively high $f_{\text{esc}} (f_{\text{esc}} \gtrsim 10\%)$ compared to the local value (e.g. Steidel et al. 2001, 2018; Iwata et al. 2009, 2019; Mostardi et al. 2015; Shapley et al. 2016; Vanzella et al. 2016, 2018; Bian et al. 2017; Micheva et al. 2017b; Naidu et al. 2017; Fletcher et al. 2019).

At the same time, attempts to estimate the typical $f_{\text{esc}}$ using stacked samples at $z \approx 1–3$ indicate that this value may be much lower. These stacking analyses often result in non-detections of LyC, with corresponding upper limits at $f_{\text{esc}} < \text{several}\%$ (e.g. Siana et al. 2007, 2010; Vanzella et al. 2010b; Graziani et al. 2016; Micheva et al. 2017b). A very low typical $f_{\text{esc}} \approx 0.5\%$ has also been derived from the study of gamma-ray bursts at $z \approx 1.6–6.7$ (Tanvir et al. 2019). Hence, the average $f_{\text{esc}}$ at these intermediate redshifts may be on the low side of what would be required for cosmic reionization (but see Finkelstein et al. 2019, for an attempt to explain reionization with $f_{\text{esc}} \lesssim 5\%$). Whether the average $f_{\text{esc}}$ increases as one approaches the epoch of reionization ($z > 6$) remains an open question.

Since studies of individual objects with LyC detections report significant $f_{\text{esc}}$ values (from several \% at $z \approx 10$ to 60\% at $z \sim 3–4$), it is likely that the LyC escape depends strongly on physical quantities such as the properties of gas and dust in the ISM, the viewing angle, the star formation rate, and/or the stellar mass (e.g. Nestor et al. 2011, 2013; Mostardi et al. 2013). For a statistical discussion, it is important to collect data on LyC-detected SFGs which cover a wide parameter space in terms of physical characteristics. In numerical simulations, less-massive and/or UV fainter SFGs, which are more abundant than massive and/or UV brighter SFGs, are for instance often predicted to have high $f_{\text{esc}}$ and hence contribute significantly to cosmic reionization (e.g. Yajima et al. 2011; Wise et al. 2014; Paardekooper et al. 2015).

Depending on the physical mechanism behind the leakage, this can have number of distinct effects on various spectral features. When the escape path is optically thin to Ly$\alpha$ photons ($\tau_{\text{Ly}} \sim 1$ for log $N_{\text{H}} \sim 13$), the escape path is also optically thin to LyC photons ($\tau_{\text{LyC}} \sim 1$ for log $N_{\text{H}} \sim 17$). Hence, one expects a positive correlation between $f_{\text{esc}}$ and the emission-line equivalent width (EW) of Ly$\alpha$ (e.g. Micheva et al. 2017b; Steidel et al. 2018). When assuming the link of the escape path between LyC and Ly$\alpha$, the line profile of Ly$\alpha$ also becomes a probe for $f_{\text{esc}}$ (Verhamme et al. 2015, 2017; Dijkstra et al. 2016). The luminosity ratio of [O$\text{I}$] $\lambda\lambda$4959, 5007 and [O$\text{III}$] $\lambda\lambda$4372, 5007/[O$\text{II}$] has also been suggested as a probe for high-$f_{\text{esc}}$ SFGs (Nakajima et al. 2013; Nakajima & Ouchi 2014). Indeed, very high $f_{\text{esc}} (f_{\text{esc}} > 50\%)$ are found among SFGs with high [O$\text{II}$]/[O$\text{II}$] at both low and high $z$ (de Barros et al. 2016; Vanzella et al. 2016, 2018; Izotov et al. 2018a). Even so, Nakajima et al. (2019) report that no LyC escape is detected for some SFGs despite a high [O$\text{II}$]/[O$\text{II}$] ratio. Hence, it seems that a high [O$\text{II}$]/[O$\text{II}$] ratio may be necessary, but not sufficient condition for LyC leakage.

Although there have been attempts to determine $f_{\text{esc}}$ for SFGs at $z < 4$ from direct LyC measurements, our knowledge of $f_{\text{esc}}$ is still far from complete. There are essentially five difficulties in estimating $f_{\text{esc}}$ from direct LyC measurements. First of all, it is hard to directly observe the escaping LyC photons from high-$z$ SFGs (and almost impossible from SFGs at $z > 5$) due to the foreground absorption by H$\text{I}$ clouds in the IGM such as Lyman limit systems (e.g. Inoue & Iwata 2008; Inoue et al. 2014). Second, significant sightline-to-sightline variations in IGM absorption are predicted (Inoue & Iwata 2008; Vasei et al. 2016; Steidel et al. 2018), which may be difficult to assess for individual targets. In fact, Rivera-Thorsen et al. (2019) report on large variations among the multiply-imaged LyC spots from a gravitationally lensed SFG at $z = 2.4$. Third, it is possible that the observed flux, which is assumed to be due to escaping LyC photons, does not come from SFGs at high $z$ but from the foreground (low-$z$) interlopers (Vanzella et al. 2010a; Siana et al. 2015). Fourth, the leakage may be anisotropic, so that the $f_{\text{esc}}$ measured in our direction may deviate significantly from the total $f_{\text{esc}}$ of the target galaxy. Finally, because UV light is absorbed by Earth’s atmosphere, we need space telescopes for the direct LyC measurements of low-$z$ objects. In order to investigate the redshift evolution of $f_{\text{esc}}$ and the detailed correlations between $f_{\text{esc}}$ and other physical quantities, we would greatly benefit from an indirect method which can avoid these problems.

Zackrisson et al. (2013) have proposed a scheme to indirectly assess $f_{\text{esc}}$ from two observational quantities not affected by IGM attenuation – the H$\beta$ line equivalent width (EW) and the rest-frame intrinsic UV spectral slope $\beta$, defined as $f_{\gamma} \propto \lambda^{\beta}$ at $\lambda_{\text{rest}} \sim 1300–2500$\AA (Calzetti et al. 1994). This EW(H$\beta$)–$\beta$ method is based on the simple idea that a high fraction of LyC photons absorbed in H$\text{II}$ regions of SFGs should result in stronger nebular emission and a larger EW(H$\beta$). The equivalent width of nebular emission also depends on the production rate of LyC photons, but the UV spectral slope $\beta$ can potentially be used to gauge this, as a blue UV slope is expected to go hand in hand with a high production rate. As a consequence, the distribution of SFGs across the EW(H$\beta$)–$\beta$ diagram could make it possible to single out high-$f_{\text{esc}}$ cases.

This method was designed for identifying extreme cases of LyC leakage in the $z > 6$ galaxy population, which are out of reach of direct LyC detection methods, and originally based on simple toy models for such galaxies. However, Zackrisson et al. (2017) also show the validity of this idea for SFGs at $z > 6$ in cosmological simulations. If verified, this could be a useful tool for studying LyC leakage with the James Webb Space Telescope (JWST), which will be able to spectroscopically detect H$\beta$ in large samples of galaxies up to $z \approx 9$.

However, before attempting to apply the EW(H$\beta$)–$\beta$ method to SFGs at $z > 6$, it would be very useful to verify this method with SFGs for which the LyC has been measured through direct means, so that the $f_{\text{esc}}$ derived from the direct and indirect methods can be compared. This requires applying the method to galaxies at $z < 4$, and comes with a number of challenges. Observations have revealed that there is a trend in $\beta$ with redshift in the sense that...
Testing an indirect method for probing LyC leakage

In this paper, we present results of our $K$-band spectroscopic measurements of the $H\beta$ emission line flux from Lyman Continuum Galaxies (hereafter LCGs), which are SFGs with direct LyC detections at $z \sim 3$, as well as Lyman break galaxies (LBGs) and LAEs in the SSA22 field. In the end, we are able to identify one very blue LCG for which the EW($H\beta$)–$\beta$ method may be applied without modifications, and find that the $f_{\text{esc}}$ estimated from this technique is broadly consistent with $f_{\text{esc}}$ derived from the direct LyC measurement. Stronger constraints (and hence a more decisive test) would, however, require a significant reduction of the observational errors on both EW($H\beta$) and $\beta$.

In section 2, we describe the details of our sample of LCGs/LBGs/LAEs. In section 3, we describe the spectroscopic observations and the data reductions. In section 4, we explain the method used for measuring the UV spectral slope $\beta$, the emission line flux, and EW($H\beta$). In section 5, we show our main result, i.e., the EW($H\beta$)–$\beta$ diagram. In section 6, we discuss the EW($H\beta$)–$\beta$ method in comparison to the direct LyC measurement. Our results are summarized in section 7. In regard to the cosmological parameters, we assume $\Omega_m=0.3$, $\Omega_{\Lambda}=0.7$, $H_0=70$ km s$^{-1}$ Mpc$^{-1}$. Throughout this work, we adopt the AB magnitude system (Oke & Gunn 1983; Fukugita et al. 1996).

2 SAMPLE

2.1 Photometric catalog

In this work, we use the SSA22 H$\alpha$ Tomography (SSA22HIT) master catalog (Mawatari et al. in preparation). The purpose of the SSA22HIT project is to reveal the spatial distribution of H$\alpha$ gas in the SSA22 proto-cluster field through the use of Ly$\alpha$ forest tomography (Lee et al. 2014, 2018). For this purpose, they compile the photometry of available broad-band and narrow-band filters in the SSA22 field, and make a catalog of LAEs and LBGs in a range of photometric redshift ($z_{\text{phot}}$) 2.7–3.7. The catalog includes the photometry of broad-band and narrow-band filters of the Canada-France-Hawaii Telescope (CFHT)/Megacam (Boulade et al. 2003), Subaru/Suprime-Cam (Scam; Miyazaki et al. 2002), Subaru/Hyper Suprime-Cam (HSC; Miyazaki et al. 2012, 2016), Subaru/MORCS (Suzuki et al. 2003; Ichikawa et al. 2006), UKIRT/WFCAM (Casali et al. 2007), and Spitzer/IRAC (Fazio et al. 2004). The source detection on the Subaru/Scam $i'$-band image (Nakamura et al. 2011) and multi-band photometry are performed by using SExtractor1 ver 2.5.0 (Bertin & Arnouts 1996). Except for the Spitzer data, the point spread function (PSF)-matched images are created by convolving the original images with Gaussian kernels to match a PSF with full width at half maximum (FWHM) = 1.1". The 2.2"-diameter ($\pm 2\times$PSF) aperture flux is measured for the PSF-matched images.

In our analysis, we use the photometry measured for the PSF-matched images of Subaru/Scam R (Hayashino et al. 2004), Subaru/Scam i' and z' (Nakamura et al. 2011), Subaru/Scam NB359 (Iwata et al. 2009), Subaru/HSC y (HSC Subaru Strategic Program Public Data Release 1; Aihara et al. 2018), and UKIRT/WFCAM K (UKIRT Infrared Deep Sky Survey Data Release 10; Lawrence et al. 2007). We list the detail of the imaging data used in this work in Table 1.

2.2 Spectroscopic targets

Our spectroscopic sample consists of 42 galaxies in the SSA22 field. Two of them are LCGs at spectroscopic redshifts ($z_{\text{spec}}$) 3.3 and the main targets for our MOSFIRE observation. They are selected from a sample of the LyC sources reported by Iwata et al. (2009) and Micheva et al. (2017b). In this paper, we will refer to them as LCG-1 and LCG-2. In order to observe these main targets, we set two mask fields, Mask-1 and Mask-2. 37 objects are complementary LBGs at $z_{\text{phot}} \sim 3.2 \pm 0.3$, which are selected from the SSA22HIT master catalog. We will refer to these as SSA22-LBGs in this paper. The remaining three objects are LAEs at $z_{\text{phot}} = 3.1$ (Yamada et al. 2012a,b) which are observed as filler objects (hereafter Y12LAEs), Y12LAe-2 and Y12LAe-3 are taken from the LAE candidates studied in Yamada et al. (2012a) which show significant narrow-band excess but below their criteria for the robust LAE sample. Our sample is summarized in Table 2. The details are described in the following.

2.2.1 LCG-1 and LCG-2

LCG-1 is reported by Micheva et al. (2017b) as “LBG03” in their paper. In the LyC image (Subaru/NB359 filter), two small LyC clumps are observed, separated by $\Delta r \sim 0.8''$ (see figure 2 in Micheva et al. 2017b) from the peak of the rest-frame UV continuum (Subaru/R filter). We set the MOSFIRE slitlet on the peak of the UV continuum and we use the wider slit width due to the complex morphology of LyC and UV continuum. The spectroscopic redshift is $z_{\text{spec,LyC}} = 3.287$ which is measured from the optical low-resolution spectroscopy for the Ly$\alpha$ emission line (Micheva et al. 2017b). Due to the blue $NB359 - R$ color, we consider LCG-1 to be the primary high-$f_{\text{esc}}$ candidate in our sample.

LCG-2 is also reported by Micheva et al. (2017b) as “LBG04” in their paper. The LyC image reveals a single small LyC clump, with a spatial offset of $\Delta r \sim 0.8''$ from the peak of the rest-frame UV continuum (see figure 2 in Micheva et al. 2017b). In this case, we set the slitlet to simultaneously cover the peak of the UV continuum and the LyC clump. The spectroscopic redshift is measured by Steidel et al. (2003). In Steidel et al. (2003), LCG-2 is referred to as “SSA22b-oD8” and shows $z_{\text{spec,LyC}} = 3.323$ and $z_{\text{spec,abs}} = 3.311$. According to Steidel et al. (2003), $z_{\text{spec,LyC}}$ and $z_{\text{spec,abs}}$ are measured from the Ly$\alpha$ emission line and the average of some absorption lines, respectively. Due to the red $NB359 - R$ color, we consider LCG-2 to be the low-$f_{\text{esc}}$ candidate of our sample.

2.2.2 SSA22-LBGs and Y12LAEs

The SSA22-LBGs, selected from the SSA22HIT master catalog, all have $i' < 26.4$ (S/N > 5) at $z_{\text{phot}} = 2.7–3.7$. We set the slitlets on the peak of the UV continuum (Subaru/i' filter) for each
object. The SSA22-LBGs satisfy either the color-color selection (i.e., classical Lyman break technique) or the photometric redshift estimated by using Hyperz (Bolzonella et al. 2000), or both. For our MOSFIRE observation, we first choose the SSA22-LBGs with blue UV spectral slopes $\beta (\beta < -2.0)$ as the high-priority targets from the catalog. After that, we fix the two mask fields so as to maximize the number of high-priority targets. The remaining slitlets are set to other SSA22-LBGs. There is still a margin of slitlets which is used for the three Y12LAEs. Under the SSA22HIT project, some of the SSA22-LBGs are observed with the Deep Imaging Multi-Object Spectrograph (DEIMOS; Faber et al. 2003) mounted on the Keck-I telescope. In cases where the spectroscopic redshift has been successfully measured by the SSA22HIT project, we show the $z_{\text{spec}}$ value in Table 2.

There are some SSA22-LBGs significantly detected in the LyC image in our sample: 11 objects display a LyC detection at the $3\sigma$ level ($NB359 < 26.7$). 6 out of the 11 objects also exhibit a blue UV slope $\beta (\beta < -2.0)$, whereas the remaining 5 objects exhibit a red UV slope $\beta (\beta > -2.0)$. Initially, we considered them as possible LCG candidates. However, from our MOSFIRE observations, we cannot identify any emission lines in any of these targets. Therefore, we conclude that these LBGs are not LCG candidates. However, from our MOSFIRE observations, we do not use these object in the following analysis.

### 2.3 Rough estimation of LyC escape fraction

Fig. 1 shows an observed color-magnitude diagram which indicates a rough $f_{\text{esc}}$ value and UV flux for our LCGs/SSA22-LBGs. The Subaru/NB359 is a unique narrow-band filter which directly traces LyC photons from galaxies at $z \gtrsim 3.06$ (Iwata et al. 2009; Micheva et al. 2017b). Hence, the vertical axis represents the observed flux density ratio $f_{\text{L}}/f_{\text{LyC}}$. The horizontal magenta line indicates $f_{\text{esc}} = 0.5$ assuming a set of standard parameters: IGM transmission $T_{\text{IGM}} = 0.4$ (Inoue et al. 2014), UV dust attenuation $A_{\text{UV}} = 1.67$ (Micheva et al. 2017b), and the intrinsic LyC-to-UV luminosity ratio $L_{\text{UV}}/L_{\text{LyC}} = 3$, where $L$ is in units of erg s$^{-1}$ Hz$^{-1}$ (e.g. Steidel et al. 2001; Inoue et al. 2005). In general, the $T_{\text{IGM}}$, $A_{\text{UV}}$, and $L_{\text{LyC}}/L_{\text{UV}}$ values change from galaxy to galaxy. These parameters should be carefully estimated by the spectral energy distribution (SED) fitting analysis (e.g. Fletcher et al. 2019). In this paper, the rough $f_{\text{esc}}$ estimate provided by this figure will be used in an attempt to test the EW(H$\beta$)-$\beta$ method. However, we intend to carry out a more careful $f_{\text{esc}}$ estimation for each object in future works by using a $z_{\text{spec}}$ catalog for the SSA22HIT project.

As indicated by Fig. 1, LCG-1 appears to have $f_{\text{esc}} \gtrsim 0.5$, whereas LCG-2 and other SSA22-LBGs classified as sample A (H$\beta$-detected sample) and B (redshift-confirmed sample) appear to have $f_{\text{esc}} < 0.5$. The one exception is SSA22-LBG from sample B (SSA22-LBG-08). While this objects seems to have $f_{\text{esc}} \sim 0.5$, the Subaru/NB359 filter is contaminated by another object close to the SSA22-LBG-08. Therefore, we adopt $f_{\text{esc}} < 0.5$ for SSA22-LBG-08 as well. Some of the other SSA22-LBGs (grey crosses in Fig. 1) also show the significant detection with NB359 and a high $f_{\text{esc}}$ value. However, we are unable to confirm $z_{\text{spec}}$ of the NB359-detected SSA22-LBGs due to either a single or no emission line in our MOSFIRE observation. It is therefore likely that the Subaru/NB359 filter does not trace the LyC emission for these objects and we will not discuss these objects further.

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**Table 2.** Summary of the imaging data used for our analysis.

| Instrument/Scam | Filter | PSF FWHM (original, arcsec) | Limiting Mag. (smoothed, $2.2''\phi$, $5\sigma$) | Reference |
|-----------------|--------|-----------------------------|-----------------------------------------------|-----------|
| Subaru/HSC      | $y$    | 0.56                        | 24.1                                          | Aihara et al. (2018) |
| Subaru/Scam     | $R$    | 1.08                        | 26.5                                          | Hayashino et al. (2004) |
| $r'$            | 0.76   | 26.3                        |                                               | Nakamura et al. (2011) |
| $z'$            | 0.76   | 25.6                        |                                               | Nakamura et al. (2011) |
| $NB359$         | 0.84   | 26.1                        |                                               | Iwata et al. (2009) |
| Subaru/HSC      | $K$    | 0.86                        | 22.9                                          | Lawrence et al. (2007) |

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**Figure 1.** Observed color–magnitude diagram of $NB359-R$ vs $R$. The blue double circles show our main targets, LCG-1 and LCG-2. The grey crosses denote SSA22-LBGs. The green circles and orange diamond over-plotted on the grey crosses mark the H$\beta$-detected (sample A) and the redshift-confirmed sample (sample B), respectively, after MOSFIRE spectroscopy. The sample classification is described in Section 3.2.2. The black error-bars at top right indicate the average error of $NB359-R$ and $R$. The horizontal magenta line indicates $f_{\text{esc}} \sim 0.5$ under the assumption of a set of standard parameters (see section 2.3).
Testing an indirect method for probing LyC leakage

3 MOSFIRE OBSERVATIONS

3.1 Observation and data reduction

We conduct $K$-band multi-object spectroscopy with the Multi-Object Spectrometer For Infrared Exploration (MOSFIRE; McLean et al. 2010, 2012) on the Keck-I telescope. The purpose of these observations is to determine the spectroscopic redshift using strong emission lines such as $[\text{O} \text{iii}] \lambda \lambda 4959, 5007$, and to measure the $H\beta$ emission line flux. The data was obtained on August 27, 2016 during photometric conditions with seeing 0.4″–0.6″. We applied the ABA′B′′dithering pattern with a dither amplitude of 3.0″ (A-B) and 2.4″ (A′-B′). We mainly used slit widths of 0.7″, which corresponds to a spectral resolution $R \sim 3600$ in the $K$-band, although a slit width of 0.8″ was used for LCG-1 to cover the LyC emitting regions (see section 2.2.1).
We use two slit masks, Mask-1 and Mask-2, for our 42 LCGs/LBGs/LAEs. The field of view covered by the two slit-masks partially overlap, and SSA22-LBG-09 and SSA22-LBG-12 are observed using both slit masks. In addition to our LCGs/SSA22-LBGs targets, we also assign a slitlet on a bright and point-source like object ($K \sim 20$) in each slit mask to assess slit losses. The exposure time of Mask-1 and Mask-2 are 2.45h and 0.5h, respectively. Due to the short exposure time used for Mask-2, we fail to detect emission lines from most of the targets observe in this setting. We only use LCG-2 and SSA22-LBG-22 from Mask-2 for our following analysis.

The data reduction is performed by using the MOSFIRE data reduction pipeline (DRP)$^2$, which was developed by the MOSFIRE instrument team (Steidel et al. 2014). As a result, we obtain reduced 2-D spectra which are flat-fielded, wavelength calibrated, rectified, and sky subtracted. In the wavelength calibration procedure, we search for the best solution for each slitlet from the combination of OH night sky lines and arc lines of a neon lamp. According to Steidel et al. (2014), the wavelength of the final 2-D spectra are reduced to the vacuum wavelength and corrected for the heliocentric velocity. Therefore, we do not apply any additional correction to the reduced 2-D spectra. The 1-D spectra with their 1σ uncertainties are extracted from the reduced 2-D spectra by using the BMEP$^3$ software developed by the MOSFIRE Deep Field Evolution Team (MOSDEF; Freeman et al. 2019). For the flux calibration, we also observe a telluric standard A0V star, HIP 80974, when the star is at similar air mass as the science frames. Finally, we correct for slit losses by using the bright object in each slit mask. The total flux of the bright object is calculated from the UKIRT/K-band photometry after taking the filter response of the UKIRT/K-band into account.

We show the reduced 2-D and the extracted 1-D spectra of LCG-1 in Fig. 2 as an example. In this case, we can easily identify some emission lines, and we can extract the 1-D spectrum. In some cases, however, we are unable to identify any emission lines or the continuum from the 2-D spectrum at the object position, and hence refrain from extracting a 1-D spectrum. In Appendix, we summarize all the reduced 2-D spectra and the successfully extracted 1-D spectra.

3.2 Quick summary of MOSFIRE observations

3.2.1 LCG-1 and LCG-2

For LCG-1, we detect the three emission lines ([O III] λλ 4959, 5007 and Hβ), and then confirm its systemic spectroscopic redshift from [O III] λ 5007 to be $z_{\text{spec.sys}} = 3.2890$. This value is consistent with (or slightly larger than) that from the Ly$\alpha$ emission line inferred from optical low-resolution spectroscopy. Although the Ly$\alpha$ emission line may be blueshifted compared with its systemic redshift, we need the optical medium-/high-resolution spectroscopy to confirm the shift. As shown in Fig. 2, part of the Hβ emission line is affected by OH night sky lines. However, we judge their influence on the optical continuum is not large enough to be measured the peak of the Hβ emission line. Moreover, we do not find any other emission lines stemming from lower redshifts. Hence, there is no evidence that the LyC flux inferred for this target from the Subaru/NB3539 is contaminated by low-$z$ interlopers.

For LCG-2, we detect the three emission lines ([O III] λλ 4959, 5007 and Hβ). The systemic redshift estimated from [O III] λ 5007 is $z_{\text{spec.sys}} = 3.3152$, which is consistent with the redshifts reported by Steidel et al. (2003) and Micheva et al. (2017b) since $z_{\text{spec.sys}}$ typically lies somewhere between $z_{\text{spec.Lyα}}$ and $z_{\text{spec.abs}}$ (e.g. Steidel et al. 2010). Since we do not find any other suspicious emission lines, there is no evidence that the LyC photons detected in the Subaru/NB3539 filter stems from a low-$z$ interloper. The bright absolute UV magnitude of LCG-2 ($M_{UV} \sim -22.0$) could potentially indicate the existence of the faint AGN in this source. In fact, the observed line width of Hβ is relatively large (FWHM$_{raw} \sim 300$ km s$^{-1}$; Table A1). However, we do not find any other features of AGNs from our MOSFIRE observation. In order to conclude the existence of AGNs, we would need further follow-up observations such as optical spectra covering C iv λ1549 and He ii λ1640.

3.2.2 SSA22-LBGs and Y12LAEs

For SSA22-LBGs and Y12LAEs, 1–3 emission lines are confirmed for some of the targets after visual inspection of the 2-D images and the 1-D spectrum. The detection of the three emission lines ([O III] λλ 4959, 5007 and Hβ) places the object in the Hβ-detected sample (hereafter sample “A”), whereas the detection of two emission lines places the object in the redshift-confirmed sample (hereafter sample “B”). When we detect just a single or no emission line, the object is considered part of unidentifed sample (hereafter sample “C”).

After the visual inspection for SSA22-LBGs and Y12LAEs, the samples A, B, and C include 6, 5, and 29 objects, respectively. For our analysis, we use all of objects from sample A and only one object (SSA22-LBG-22) from sample B.

We here describe the details of the five objects in sample B to motivate the reason for using only SSA22-LBG-22 for our analysis. For SSA22-LBG-22, our observation significantly detects [O III] $\lambda$ 5007, and marginally detects [O III] $\lambda$ 4959 (S/N $\lesssim 5$) due to blending with OH night sky lines. It is in principle possible that the detection of [O III] $\lambda$ 4959 is spurious and SSA22-LBG-22 is actually a lower-$z$ object. However, the spectrum does not contain any further unidentified emission lines and the Hβ wavelength is not affected by the OH night sky lines. Therefore, we consider SSA22-LBG-22 as a robust member of the redshift-confirmed sample.

Three of the five objects are SSA22-LBG-06, 17, and Y12LAE-1. Their Hβ wavelengths are not covered by our observation due to...
the slitlet configuration. Because we cannot obtain any information about Hβ, we do not use these objects. The last of the five objects is SSA22-LBG-08, for which the region covering the expected Hβ wavelength is affected by OH sky lines. Due to the poor constraint on the Hβ emission, we refrain from using SSA22-LBG-08 in our analysis.

4 ANALYSIS

4.1 UV spectral slope

In this work, we measure the UV spectral slope β from the photometry of Subaru/R′, i′', z′', and HSC/y-band filters by using linear least-squares fitting. According to Finkelstein et al. (2012) and Rogers et al. (2013), we apply the following function to the observed photometry,

\[ m(λ_x) = -2.5(β + 2) \log λ_x + \text{Const} \]  

(1)

where \( m(λ_x) \) is the effective wavelength of \( x \)th broad-band filter, \( m(λ_x) \) is the measured magnitude at \( x \)th broad-band filter, and “Const” is a constant value. Our sample consists of LBGs at \( z \approx 3.2 \pm 0.3 \) and LAEs at \( z = 3.1 \). At these redshifts, the applied broad-band filters of \( R, i', z' \), and \( y \) in the fitting are optimal for avoiding redshifted strong spectral features such as the Lyβ break (\( λ_{\text{rest}} \approx 1216 \)Å) or the Balmer break (\( λ_{\text{rest}} \approx 3600 \)Å). Our \( β \) values are listed in Table 3.

4.2 Emission line measurement

We adopt a Monte Carlo method for measuring the line profile, the total flux, and the associated uncertainties for each emission line. We first perturb the 1-D spectrum according to its 1σ noise spectrum at each pixel (hereafter referred to as a fake spectrum). We then identify the brightest emission line as \([\text{O} \text{III} \lambda 5007]\) from the fake spectrum, and estimate the spectroscopic redshift, \( z_{\text{spec}} \), by fitting a single Gaussian profile to the line. If part of the emission line is strongly affected by the OH night sky lines, we mask the pixels in the fitting. We also calculate the total line flux by integrating the Gaussian profile. We repeat this procedure \( 10^5 \) times, and finally obtain the \( 10^5 \) measurements of the \( z_{\text{spec}} \) value, the FWHM of the line profile, and the total flux from the fake spectra. The mean and standard deviation of the distribution of the measurements are adopted as the best value and its uncertainty, respectively. By using the best \( z_{\text{spec}} \) value, we search for the redshifted emission lines of \([\text{O} \text{III}] \lambda 4959 \) and \( \text{Hβ} \) from each of the \( 10^5 \) fake spectra. When we identify the emission lines, we fit a single Gaussian profile, whose center is fixed based on the best \( z_{\text{spec}} \) value, to each line. In a similar way to \([\text{O} \text{III}] \lambda 5007 \), we obtain the best FWHM value and the best total flux of \([\text{O} \text{III}] \lambda 4959 \) and/or \( \text{Hβ} \) from the \( 10^5 \) fake spectra. For the line fitting, we adopt \( λ_{\text{rest, vac}} = 5008.240 \)Å, 4960.295Å, and 4862.683Å, which are obtained from the Atomic Line List ver. 2.04 4, as a vacuum wavelength of \([\text{O} \text{III}] \lambda λ 5007, 4959, \) and \( \text{Hβ} \), respectively.

As for SSA22-LBG-22 from sample B, we measure the 3σ upper-limit of the \( \text{Hβ} \) emission line. On the basis of the error propagation, we estimate a 1σ uncertainty in the Hβ emission line flux from \( \sqrt{\sum σ^2} \) where \( σ \) indicates the 1σ uncertainty per spectral element from the noise spectrum. For the range of the summation, we adopt

4 http://www.pa.uky.edu/~peter/atomic/

Figure 3. Illustration for estimating the permitted range of the continuum flux density. As an example, we show the spectral energy distribution of SSA22-LBG-01. The blue diamonds refer to broad-band photometry of \( B, V, R, i', z', y, J, \) and \( K \) from left to right. The red diamonds indicate narrow-band photometry of \( \text{NB} 497, \text{NB} 816, \) and \( \text{NB} 912 \) from left to right. The black dashed line, which shows the best-fit UV spectral slope \( β \), is extrapolated to longer wavelengths. The purple double arrow indicates the permitted range of the continuum flux density for SSA22-LBG-01.

\begin{align*}
\lambda &= \lambda_{\text{Hβ, vac}}(1+z_{\text{spec}}) \pm 3σ_{[\text{O} III]} \text{ where } σ_{[\text{O} III]} \text{ is the best standard deviation of } [\text{O} III] \lambda 5007 \text{ calculated by } σ_{[\text{O} III]} = \text{FWHM}/(2\sqrt{2}\ln 2). \\
\text{In the estimation for the upper-limit, we assume that the FWHM of } \text{Hβ} \text{ is similar to that of } [\text{O} III] \lambda 5007. \text{ We consider } ±3σ_{[\text{O} III]} \text{ to be optimal since a wider summation range results in an overestimation of the upper limit due to contamination of the OH night sky lines.}
\end{align*}

In Table 3, we show the \( Hβ \) total flux for LCG-1, LCG-2, and SSA22-LBGs from which we measure the best total flux of \( Hβ \). The detail results of the line measurements for our targets are described in Appendix A, and listed in Tables A1 and A2.

4.3 Equivalent width measurement

The equivalent width (EW) of \( Hβ \) is obtained by \( \text{EW}(Hβ) = F_{\text{Hβ}}/f_{\text{Lcont}} \) where \( F_{\text{Hβ}} \) is the total flux of \( \text{Hβ} \) and \( f_{\text{Lcont}} \) is the continuum flux density at the wavelength of \( \text{Hβ} \) in units of \( \text{erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1} \). While we obtain \( F_{\text{Hβ}} \) through our MOSFIRE observations, there are no objects detected at a significant level (> 3σ) in UKIRT/K among the sample A and B SSA22-LBGs due to the short exposure time of \( K (K_{\text{1σ}} \approx 23.5) \). However, two SSA22-LBGs of sample A are detected at a 2σ level (SSA22-LBG-10 and SSA22-LBG-12). For LCG-1, LCG-2, and the two SSA22-LBGs, therefore, we estimate \( f_{\text{Lcont}} \) from the \( K \)-band photometry as an average continuum flux density around the wavelength of \( \text{Hβ} \) after subtracting the contribution from the \( [\text{O} III] \) and \( \text{Hβ} \) emission lines to the filter. We simply estimate the uncertainty in \( \text{EW}(Hβ) \) from the uncertainty in the \( Hβ \) flux and the \( K \)-band magnitude on the basis of error propagation. The measured \( \text{EW}(Hβ) \) are summarized in Table 3.

For other SSA22-LBGs of sample A (and also SSA22-LBG-22), we regard them as the UKIRT/K non-detection sample. We estimate the permitted range of the continuum flux density as follows. Fig. 3 illustrates our idea. The upper limit of the flux density
is obtained from the 3σ limiting magnitude of the UKIRT/K-band image after correcting for the contribution of the [O\text{iii}] and H\beta emission lines to the filter. The lower limit of the flux density is obtained by extrapolating the UV spectral slope $\beta$ from rest-frame UV to rest-frame optical wavelength. Except for special cases, the continuum flux density in the $K$-band will be similar to or higher than the extrapolation due to the Balmer break which is prominent for old stellar populations. In case of a strong nebular continuum flux density in the UV to rest-frame optical wavelength. Except for special cases, the continuum flux density is obtained by extrapolating the UV spectral slope $\beta$ to the rest-frame optical wavelength. For SSA22-LBG-01, we estimate the lower limit of the flux density by using the upper and lower limits on the continuum flux density, we estimate the permitted range of flux density. By using the upper and lower limits on the continuum flux density, we estimate the permitted range of $EW(\text{H}\beta)$ for SSA22-LBGS of sample A without the K-band detection. For SSA22-LBG-22, we estimate the upper limit of $EW(\text{H}\beta)$ from the 3σ upper limit of the H\beta line flux and the lower limit of the continuum flux density. The permitted range and the upper limit on $EW(\text{H}\beta)$ are also summarized in Table 3.

5 RESULTS FROM THE $EW(\text{H}\beta)-\beta$ DIAGRAM

Fig. 4 shows the result of the $EW(\text{H}\beta)-\beta$ method to constrain $f_{\text{esc}}$. In this diagram, we include the data for LCG-1, LCG-2, the SSA22-LBGS of sample A along with SSA22-LBGS-22 from sample B. The blue circles filled with cyan show our main targets, LCG-1 and LCG-2. The green diamonds with error bars represent UKIRT/K-detected SSA22-LBGs of sample A (hereafter K-LBGS). The red error bars represent SSA22-LBGs of sample A which are undetected in K at the 2σ level (hereafter nK-LBGS), whereas the horizontal error bars of the nK-LBGS represent the permitted range of $EW(\text{H}\beta)$ described in Section 4.3. The uncertainty in $\beta$ is indicated by the vertical error bars. For the sake of clarity, the error bars for $\beta$ are placed at the left edge of the permitted range of $EW(\text{H}\beta)$. Therefore, the red error bars denote the expected regions in which the nK-LBGS are. The orange arrow with error bars represents SSA22-LBG-22 (sample B). The arrow denotes the upper limit on $EW(\text{H}\beta)$, estimated from the 3σ upper limit on the H\beta flux and the lower limit on the continuum flux density.

In Fig. 4, we also show the model tracks for radiation-bounded...
nebulae with various $f_{\text{esc}}$ and $Z = 0.004$ from Zackrisson et al. (2013). The black solid, dashed, dot-dashed, and two-dot-dashed lines represent the models with $f_{\text{esc}} = 0.0, 0.5, 0.7,$ and $0.9$, respectively. Each model track changes with the production rate of ionizing photons in a galaxy, namely, the age of the stellar population. Nebular continuum is already applied to these model tracks according to the $f_{\text{esc}}$ values. These models are for cases without any dust attenuation ($A_V = 0.0$), even though the observed LCGs/SSA22-LBGs are affected by dust, to various degree. The impact of dust on the EW(H$\beta$)–$\beta$ diagram depends on the dust attenuation curve and geometry of dust, gas and stars in the target galaxies (Zackrisson et al. 2013, 2017). The two black arrows on the right-hand side of Fig. 4 represent two simple models for dust attenuation effects. In these simple models, we assume the Calzetti et al. (2000) attenuation curve. The black solid arrow is the case where the dust attenuation of the stellar component is the same as the attenuation of the nebular component ($A_V = A_{V,\text{neb}}$). Because the dust attenuation of the continuum and the emission line flux are the same, the arrow runs parallel to the y-axis. The black dashed arrow represents an alternative scenario where the dust attenuation of the stellar component is 0.44x the dust attenuation of the nebular component ($A_V = 0.44A_{V,\text{neb}}$). The relation between $A_V$ and $A_{V,\text{neb}}$ has been discussed by e.g. Erb et al. (2006); Kashino et al. (2013). According to these studies, the proportionality constant of the relation seems to range between 0.44 and 1.0 for high-$z$ starbursts. Therefore, the two constant values adopted in our simple models represent reasonable assumptions.

Due to the blue UV spectral slope ($\beta \approx -2.5$) of LCG-1, we can directly compare its observed EW(H$\beta$) and $\beta$ values to the model prediction from Zackrisson et al. (2013) without considering the influence of dust attenuation. When taking the error bars in to account, we find that the EW(H$\beta$)–$\beta$ method indicates $f_{\text{esc}} = 0.0$–0.7 for the object LCG-1. As shown in Fig. 1, the direct LyC measurement also predicts a high $f_{\text{esc}}$ value, $f_{\text{esc}} \gtrsim 0.5$, for this object. Hence, the two methods give broadly consistent results. It is clear, however, that given the observational uncertainties, the EW(H$\beta$)–$\beta$ method would not be able to provide useful constraints on its own, as it is only able to rule out $f_{\text{esc}} > 0.7$ for this object.

For the remaining objects, it is difficult to directly apply the EW(H$\beta$)–$\beta$ method, since their UV slopes are redder and therefore likely more affected by dust. As an example, consider LCG-2, which displays $\beta \approx -1.4$. Because the EW(H$\beta$) value of LCG-2 formally allows $f_{\text{esc}} = 0.0$–0.9, the dust-corrected (intrinsic) UV spectral slope, $\beta_{\text{int}}$, would be required for a detailed constraint on $f_{\text{esc}}$ using the EW(H$\beta$)–$\beta$ model sequences.

In principle, the intrinsic UV slope $\beta_{\text{int}}$ could potentially be derived from SED fitting, although it would be premature to attempt this at the current time. For LBGs at $z \geq 4$, the SED-fitting analysis of Yamanaka & Yamada (2019) indicates $\beta_{\text{int}} \sim -2.5 \pm 0.3$ for objects with $\beta_{\text{obs}} \sim -1.4$. Since LBGs with the same $\beta$ value at $z = 3$ and $z = 4$ are, on average, expected to be similar in terms of stellar populations, one could be tempted to shift an object like LCG-2 to $\beta_{\text{int}} \sim -2.5 \pm 0.3$, in which case the EW(H$\beta$)–$\beta$ method would suggest $f_{\text{esc}} = 0.0$–0.5. While this is formally consistent with the prediction from the direct LyC measurement ($f_{\text{esc}} \sim 0.0$), this would place the dust-corrected position of LCG-2 in the EW(H$\beta$)–$\beta$ diagram very close to the observed position of LCG-1, which would seems contradictory given that the direct LyC observations indicate significantly different $f_{\text{esc}}$ for these two objects. Similar problems plague the EW(H$\beta$)–$\beta$ analysis of the other objects in Fig. 4 as well – the objects display UV slopes that are too red, and have too large error bars, to allow conclusions on $f_{\text{esc}}$ from their position in the EW(H$\beta$)–$\beta$ at this stage.

6 DISCUSSION

6.1 Probing the LyC escape mechanism

Throughout the paper, we have implicitly assumed $f_{\text{esc}}$ estimated by the EW(H$\beta$)–$\beta$ method to be the same as that estimated from the direct LyC measurement. It is, however, possible that this assumption may break down in the case where the escape of LyC photons is anisotropic.

Because the direct LyC measurement depends on the optical depth of neutral hydrogen along the line-of-sight, the direct method displays a dependence on the viewing angle. The EW(H$\beta$)–$\beta$ method, on the other hand, does not have the same angular dependence. In the scenario of a ‘radiation-bounded nebula with holes’ (Zackrisson et al. 2013), also known as the picket-fence model, the LyC photons escape from the galaxy through holes or tunnels of optically thin (or almost ionized) hydrogen gas. However, the distribution of these holes and their sizes may differ across the object, and the ones facing the observer (responsible for the leakage of LyC photons detected in direct observations) may not be representative of the average across the whole galaxy. If this is the case, direct and indirect methods may not necessarily result in comparable $f_{\text{esc}}$ estimates.

Indeed, recent observations indicate that the LyC photons from LCGs with high $f_{\text{esc}}$ may have escaped through low-density channels of the type envisioned in the radiation-bounded nebula with holes scenario (Vanzella et al. 2016, 2018, 2019; Izotov et al. 2018b). According to Verhamme et al. (2015) and Behrens et al. (2014), a triple-peaked Ly$\alpha$ emission profile with a peak at its systemic velocity (or a double-peaked Ly$\alpha$ emission profile with a small peak separation) is predicted for high $f_{\text{esc}}$ LCGs in this scenario, and such a spectral feature has indeed been observed in some previous works (Vanzella et al. 2018, 2019). Moreover, Rivera-Thorsen et al. (2019) report on the LyC properties and $f_{\text{esc}}$ properties of the multiple images from the gravitationally lensed SFG at $z = 2.4$. The individual images of the LyC source in this object are spatially unresolved within the high-resolution HST image, which may indicate narrow escape channels.

If LyC leakage through a radiation-bounded nebular with holes is a commonly occurring phenomenon, the EW(H$\beta$)–$\beta$ method could become an important tool for probing the “angle-averaged” (hereafter global) escape fraction. When assessing the role of galaxies in the reionization of the Universe, it is in fact the global $f_{\text{esc}}$ that matters, not $f_{\text{esc}}$ in the direction of the observer (which would be measured by the direct LyC measurements).

By combining direct measurements of LyC escape (which trace optically thin holes or regions) with indirect ones (which may potentially provide a better estimate of the global $f_{\text{esc}}$) for the same objects, it may be possible to quantitatively assess the anisotropy of the leakage, at least in the case of SFGs at $z = 3$–4 and for lower-redshift analogs. It should be stressed, however, that one can only hope to detect very extreme cases of LyC leakage ($f_{\text{esc}} \gtrsim 0.5$) using the EW(H$\beta$)–$\beta$ method. Similar indirect techniques that make use of a wider set of spectroscopic data could in principle do better (Jensen et al. 2016; Giri et al. 2020).
6.2 Uncertainties in EW(H\(\beta\))–\(\beta\) method

Here, we discuss the observational effects that dominate the uncertainties in the EW(H\(\beta\))–\(\beta\) method, and how the errors may potentially be reduced in the future. In our analysis, the errors on EW(H\(\beta\)) and \(\beta\) are dominated by the uncertainties in the broad-band photometry at the longer wavelengths, namely, in the Subaru/z\(\prime\), y, and UKIRT/K-band filters. Since the spectroscopic H\(\beta\) flux is well determined (with a typical uncertainty of \(<\pm 10\%\); Table 3), the uncertainty on EW(H\(\beta\)) is attributed to the large uncertainty in the continuum flux density estimated from the UKIRT/K-band photometry.

For blue UV spectral slopes (\(\beta < -2.0\)), the z\(\prime\)- and y-band fluxes become fainter than those of the R- and i'-bands. Therefore, the uncertainty on the z\(\prime\)- and y-band photometry is critical for the \(\beta\) estimation. If we were to obtain much deeper images of z\(\prime\), y-, and K-band in the SSA22 field, the EW(H\(\beta\))–\(\beta\) would be easier to apply.

A similar issue may also be important for attempts to apply the EW(H\(\beta\))–\(\beta\) method to SFGs at \(z > 6\). Since strong nebular emission lines are expected for SFGs at \(z > 6\) (e.g. Harikane et al. 2018), emission line identification may be easily accomplished by future instruments such as JWST. However, if the H\(\beta\) continuum is undetected in the spectroscopic data, as would be expected for very faint sources and/or observations at high spectral resolution, deep imaging observations may nonetheless be important to measure the continuum flux.

The complicated effects of dust on the EW(H\(\beta\))–\(\beta\) diagram also adds substantial uncertainty in the application of the EW(H\(\beta\))–\(\beta\) method for estimating \(f_{\text{esc}}\). The observational data in Fig. 4 are affected by dust, whereas the model sequences from Zackrisson et al. (2013) are for intrinsic EW(H\(\beta\)) and \(\beta\) prior to dust attenuation. Both the attenuation curve and the amount of dust attenuation are critical parameters in the exercise for applying the right corrections to EW(H\(\beta\)) and \(\beta\). As mentioned in section 5, if the dust attenuation applied for the nebular component is different from that for the stellar component, the observational data points of the EW(H\(\beta\))–\(\beta\) diagram shift diagonally from bottom left to top right as the amount of the dust attenuation is increased.

For LCG-1 (and some SSA22-LBGs), however, the observed UV spectral slope is \(\beta \approx -2.5\), which is quite blue compared to the average \(\beta\) value of LBGs/LAEs at similar redshifts (\(\beta \sim -1.7\) or \(-2.0\) for \(M_{\text{UV}} \sim -21.0\) at \(z \sim 3\); e.g. Bouwens et al. 2009; Santos et al. 2019). Due to the strong dependence of \(\beta\) on the dust attenuation (e.g. Meurer et al. 1999), these blue UV spectral slopes \(\beta\) indicate that dust reddening must be small. Therefore, the observed EW(H\(\beta\)) and \(\beta\) are expected to be close to their intrinsic values, at least for LCG-1 and possibly also for some of the other SSA22-LBGs in our sample.

7 CONCLUSION

In this work, we examine the validity of the EW(H\(\beta\))–\(\beta\) method proposed by Zackrisson et al. (2013) to indirectly estimate the escape fraction of LyC photons from individual galaxies. For this purpose, we conduct K-band multi-object spectroscopy with Keck/MOSFIRE to measure the H\(\beta\) emission line flux of LCGs, LBGs, and LAEs at \(z \approx 3.0–3.5\) in the SSA22 field. Thanks to the unique Subaru/NB359 filter, we can also directly detect the LyC flux from these objects and assess the associated escape fraction \(f_{\text{esc}}\). Finally, we compare the outcomes of these two methods and discuss the usefulness of combining direct and indirect methods for probing the astrophysical mechanism that allow LyC photons to escape from galaxies.

Our main conclusions can be summarized as:

(i) We reconfirm the spectroscopic redshift and measure the H\(\beta\) emission line flux from 2 LCGs and 6 SSA22-LBGs. The spectroscopic redshifts of our main targets, LCG-1 and LCG-2, are \(z_{\text{spec}} = 3.2890\) and 3.3152, in good agreement with the Ly\(\alpha\) redshift values reported by Micheva et al. (2017b).

(ii) When plotting our 8 LCGs/SSA22-LBGs onto the EW(H\(\beta\))–\(\beta\) diagram, we find LCG-1 to be suitably located for assessing \(f_{\text{esc}}\) using the Zackrisson et al. (2013) method. Based on the model predictions, we infer \(f_{\text{esc}} = 0.0–0.7\) for this object. While this is broadly consistent with the escape fraction estimated from the directly detected LyC flux of this object (\(f_{\text{esc}} \approx 0.5\)), the large error bars on \(\beta\) and EW(H\(\beta\)) prevent us from setting strong quantitative constraints on the agreement. The remaining objects display UV continuum slopes \(\beta\) that are too red to allow any meaningful comparison without the application of dust corrections to the \(\beta\) slopes.

(iii) We discuss the possibility that direct and indirect LyC leakage estimates could return discrepant estimates of \(f_{\text{esc}}\) in the case of anisotropic LyC leakage, as in the case where LyC leakage happens through a radiation-bounded nebula with holes. In this scenario, the direct LyC measurements trace the covering fraction along the line of sight. This quantity may differ from the angle-averaged, “global” escape fraction that matters for the role of galaxies in the reionization of the Universe, and which could potentially be better probed through indirect \(f_{\text{esc}}\)-estimation techniques like the EW(H\(\beta\))-\(\beta\) method. Hence, improved comparisons between these two techniques for SFGs at \(z = 3–4\) and low-\(z\) analogs could provide useful constraints on the anisotropy of LyC leakage.

ACKNOWLEDGEMENTS

SY and AKI were supported by JSPS KAKENHI Grant Number 17HO1114. TH was supported by Leading Initiative for Excellent Young Researchers, MEXT, Japan. EZ acknowledges funding from the Swedish National Space Board. The data presented herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation. This work is based on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan. The UKIDSS project is defined in Lawrence et al. (2007). UKIDSS uses the UKIRT Wide Field Camera (WFPCAM; Casali et al. 2007). The photometric system is described in Hewett et al. (2006), and the calibration is described in Hodgkin et al. (2009). The pipeline processing and science archive are described in Irwin et al. (2009, in prep) and Hambly et al. (2008). We use UKIDSS data release 10. Data analysis was in part carried out on the Multi-wavelength Data Analysis System operated by the Astronomy Data Center (ADC), National Astronomical Observatory of Japan. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.
APPENDIX A: REDUCED 2-D IMAGES AND 1-D SPECTRA OF ALL OUR TARGETS

We here show all the reduced 2-D spectra image and the successfully extracted 1-D spectra in Fig. A1. In cases where the 1-D spectrum is not extracted, we only show the 2-D spectral image. In Tables A1 and A2, we show the results of the flux measurements. The following is brief comments on some sample C objects, i.e. SSA22-LBG-05, SSA22-LBG-13, and Y12LAE-3.

SSA22-LBG-05. This object is observed by Keck/DEIMOS under the SSA22HIT project. The spectroscopic redshift is $z_{\text{spec, Ly\alpha}} = 3.112$ which is measured from the DEIMOS observation for the Ly\alpha emission line. If assuming the single emission line detected by our MOSFIRE observation is [O\III] $\lambda 5007$, the spectroscopic redshift is $z_{\text{spec, [O\III]}} = 3.1154$. Since the spectroscopic redshift is consistent with the photometric redshift, Y12LAE-3 is a new redshift-confirmed object by our observation. However, the H\beta wavelength is not covered by our observation due to the MOSFIRE slitlet configuration. Therefore, this object is not used for our analysis.

SSA22-LBG-13. This object is observed by Keck/DEIMOS under the SSA22HIT project. The spectroscopic redshift is $z_{\text{spec, Ly\alpha}} = 2.869$. If assuming the single emission line detected by our MOSFIRE observation is [O\III] $\lambda 5007$ or H\alpha ($\lambda_{\text{vac}} = 6564.61$), the spectroscopic redshift is $z_{\text{spec, [O\III]}} = 3.7322$ or $z_{\text{spec, H\alpha}} = 2.6103$, respectively. The spectroscopic redshift is not consistent in the observations. Therefore, this object is still a unidentified object.

Y12LAE-3. This object is taken from the LAE candidates at $z_{\text{phot}} = 3.1$ studied in Yamada et al. (2012a), although the narrow-band excess was below their criteria for the robust LAE sample. If assuming the single emission line detected by our MOSFIRE observation is [O\III] $\lambda 5007$, the spectroscopic redshift is $z_{\text{spec, [O\III]}} = 3.1147$. Since the spectroscopic redshift is consistent with the photometric redshift, Y12LAE-3 is a new redshift-confirmed object by our observation. However, the H\beta wavelength is not covered by our observation due to the MOSFIRE slitlet configuration. Therefore, this object is not used for our analysis.
Table A1. Summary of flux measurement for LCG-1, LCG-2, and the SSA22-LBGs classified as belonging to sample A and B.

| Name          | $z_{\text{spec}}$ | $\lambda^b$ | [O iii] $\lambda$5007 FWHM$^e$ | Total Flux$^d$ | [O iii] $\lambda$4959 FWHM$^e$ | Total Flux$^d$ | $\lambda^b$ | H$\beta$ $^f$ FWHM$^e$ | Total Flux$^d$ |
|---------------|-------------------|--------------|---------------------------------|----------------|---------------------------------|----------------|--------------|---------------------|----------------|
| SSA22-LBG-01  | 3.0892            | 20479.9      | 145.1                           | 72.91 ± 0.68  | 20283.9                         | 155.1          | 23.99 ± 1.11 | 19884.7            | 161.8          |
| SSA22-LBG-02  | 3.3437            | 21754.0      | 205.7                           | 60.36 ± 0.86  | 21545.8                         | 245.5          | 21.77 ± 1.13 | 21212.8            | 211.4          |
| SSA22-LBG-09  | 2.9768            | 19916.5      | 179.8                           | 121.30 ± 0.96 | 19725.9                         | 184.0          | 40.07 ± 0.99 | 19337.7            | 276.3          |
| SSA22-LBG-10  | 3.2013            | 21040.9      | 214.2                           | 44.14 ± 1.08  | 20839.4                         | 223.6          | 16.68 ± 0.85 | 20429.3            | 188.8          |
| SSA22-LBG-12  | 3.1118            | 20592.8      | 172.3                           | 171.40 ± 0.88 | 20395.7                         | 171.1          | 58.25 ± 0.68 | 19994.3            | 166.4          |
| SSA22-LBG-16  | 3.1041            | 20554.2      | 105.1                           | 13.24 ± 1.16  | 20357.5                         | 167.1          | 4.42 ± 0.42  | 19956.8            | 156.7          |
| SSA22-LBG-06  | 3.1098            | 20583.0      | 144.7                           | 15.78 ± 1.24  | 20386.0                         | 182.6          | 5.24 ± 0.51  | 19984.8            | –              |
| SSA22-LBG-08  | 3.3327            | 21699.3      | 131.6                           | 22.33 ± 0.64  | 21491.6                         | 112.5          | 6.26 ± 0.45  | 21068.6            | –99            |
| SSA22-LBG-17  | 3.0734            | 20400.3      | 166.3                           | 51.37 ± 0.75  | 20205.0                         | 186.9          | 18.78 ± 1.10 | 19807.4            | –              |
| Y12LAE-1      | 3.0824            | 20445.6      | 100.9                           | 8.14 ± 0.38   | 20249.8                         | 173.7          | 4.56 ± 0.56  | 19851.3            | –              |

Mask-2

| Name          | $z_{\text{spec}}$ | $\lambda^b$ | [O iii] $\lambda$5007 FWHM$^e$ | Total Flux$^d$ | [O iii] $\lambda$4959 FWHM$^e$ | Total Flux$^d$ | $\lambda^b$ | H$\beta$ $^f$ FWHM$^e$ | Total Flux$^d$ |
|---------------|-------------------|--------------|---------------------------------|----------------|---------------------------------|----------------|--------------|---------------------|----------------|
| SSA22-LBG-09  | 2.9772            | 19918.7      | 178.8                           | 117.95 ± 2.40  | 19728.0                         | 201.8          | 39.83 ± 3.05 | 19339.8            | –              |
| SSA22-LBG-12  | 3.1116            | 20591.9      | 210.4                           | 136.47 ± 2.19  | 20394.8                         | 118.1          | 26.19 ± 1.05 | 19995.5            | –              |
| SSA22-LBG-22  | 3.3490            | 21780.9      | 122.2                           | 16.37 ± 1.24   | 21572.4                         | 113.2          | 6.86 ± 1.44  | 21147.9            | < 2.19         |

$^a z_{\text{spec}}$ is estimated from the [O iii] $\lambda$5007 emission line.

$^b$ Center of Gaussian function in units of Å.

$^c$ FWHM of Gaussian function in units of km s$^{-1}$. FWHM is not corrected for the instrumental broadening.

$^d$ Total flux in units of 10$^{-18}$ erg s$^{-1}$ cm$^{-2}$.

$^e$ The center wavelength of [O iii] $\lambda$4959 and H$\beta$ is calculated from $z_{\text{spec}}$ and their vacuum wavelength. They are fixed in the flux measurement.

$^f$ “-99” indicates that the predicted wavelength is the outside of the wavelength coverage of our MOSFIRE observation.

$^*”-99"$ indicates that the predicted wavelength is strongly affected by OH night sky lines.

Table A2. Summary of flux measurement for SSA22-LBGs classified as belonging to sample C.

| Name          | Unidentified emission line | $\lambda^a$ | FWHM$^b$ | Total Flux$^c$ | Comment |
|---------------|----------------------------|--------------|-----------|----------------|---------|
| SSA22-LBG-04  | [O iii] $\lambda$4363       | 195.7        | 45.37 ± 1.69 | Line profile looks like [O iii] $\lambda$3726, 3729 doublet. |
| SSA22-LBG-05  | [O iii] $\lambda$4363       | 182.5        | 32.32 ± 0.54 | Observed by Keck/DEIMOS under SSA22HIT project. |
| SSA22-LBG-07  | [O iii] $\lambda$4363       | 235.9        | 59.75 ± 0.79 | |
| SSA22-LBG-13  | [O iii] $\lambda$4363       | 122.3        | 11.64 ± 1.99 | Observed by Keck/DEIMOS under SSA22HIT project. |
| SSA22-LBG-15  | [O iii] $\lambda$4363       | 281.1        | 15.09 ± 1.73 | |

$^a$ Center of Gaussian function in units of Å.

$^b$ FWHM of Gaussian function in units of km s$^{-1}$. FWHM is not corrected for the instrumental broadening.

$^c$ Total flux in units of 10$^{-18}$ erg s$^{-1}$ cm$^{-2}$.

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Figure A1. Reduced 2-D images and 1-D spectra.
Testing an indirect method for probing LyC leakage

Figure A1 – continued Reduced 2-D images and 1-D spectra.
Figure A1 – continued Reduced 2-D images and 1-D spectra.
Figure A1 – continued Reduced 2-D images and 1-D spectra.
Figure A1 – continued Reduced 2-D images and 1-D spectra.
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