THE GREAT OBSERVATORIES ORIGINS DEEP SURVEY: CONSTRAINTS ON THE LYMAN CONTINUUM ESCAPE FRACTION DISTRIBUTION OF LYMAN-BREAK GALAXIES AT 3.4 < z < 4.5

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ABSTRACT

We use ultra-deep ultraviolet VLT/VIMOS intermediate-band and VLT/FORS1 narrowband imaging in the GOODS Southern field to derive limits on the distribution of the escape fraction (fesc) of ionizing radiation for L > L*1, Lyman-break galaxies (LBGs) at redshift 3.4–4.5. Only one LBG, at redshift z = 3.795, is detected in its Lyman continuum (LyC; S/N ≳ 5.5), the highest redshift galaxy currently known with a direct detection. Its ultraviolet morphology is quite compact (R_{eff} = 0.8 kpc physical). Three out of seven active galactic nuclei are also detected in their LyC, including one at redshift z = 3.951 and z_{850} = 26.1. From stacked data (LBGs), we set an upper limit to the average fesc in the range 5%–20%, depending on how the data are selected (e.g., by magnitude and/or redshift). We undertake extensive Monte Carlo simulations that take into account intergalactic attenuation, stellar population synthesis models, dust extinction, and photometric noise in order to explore the moments of the distribution of the escaping radiation. Various distributions (exponential, log-normal, and Gaussian) are explored. We find that the median fesc is lower than ≲6% with an 84% percentile limit not larger than 20%. If this result remains valid for fainter LBGs down to current observational limits, then the LBG population might be not sufficient to account for the entire photoionization budget at the redshifts considered here, with the exact details dependent upon the assumed ionizing background and QSO contribution thereto. It is possible that fesc depends on the UV luminosity of the galaxies, with fainter galaxies having higher fesc and estimates of fesc from a sample of faint LBGs from HUDF (i_{775} ≤ 28.5) are in broad quantitative agreement with such a scenario.

Key words: diffuse radiation – galaxies: distances and redshifts – galaxies: evolution – galaxies: high-redshift – intergalactic medium

Online-only material: color figures

1 INTRODUCTION

The fraction of the metagalactic ionizing background contributed by star-forming galaxies remains poorly constrained by direct measures at every cosmic epoch because of the difficulty of the observations. In particular, we do not have direct empirical determinations of how the fraction of escaping ionizing radiation depends on the properties of the galaxies, nor how it evolves with redshift. Yet, the issue deserves attention, because it directly bears on fundamental problems of galaxy evolution, such as the evolution of the initial mass function (IMF) and the contribution of galaxies to cosmic re-ionization.

The latter problem is currently particularly timely since observations are starting to identify relatively large samples of galaxies at z > 7 (e.g., Bouwens et al. 2010a, 2010b; Finkelstein et al. 2010; Castellano et al. 2010), namely, during the epoch when cosmic re-ionization is believed to have completed (e.g., Fan et al. 2002). The ultraviolet background (UVB) radiation can significantly affect galaxy evolution by photoionizing and heating the interstellar medium (ISM) to ~10^4 K thereby decreasing gas accretion onto low-mass galaxies and evaporating the existing gas in small halos. Deriving empirical constraints to the nature and evolution of the cosmic UVB, as well as the nature of ionizing sources, remains a primary goal of many observations.

Faucher-Giguère et al. (2008a) analyzed the opacity of the Lyman alpha forest (LAF) of 86 high-resolution quasar (QSO) spectra and found that the hydrogen photoionization rate $\Gamma$ is remarkably flat in the redshift range 2–4.2. The quasar contribution to the hydrogen ionizing background increases toward z ~ 2 as the peak of the quasar luminosity function is approached (e.g., Hopkins et al. 2007); beyond redshift 2 their contribution significantly decreases (e.g., Fontanot et al. 2007; Siana et al. 2008; Faucher-Giguère et al. 2009; Prochaska et al. 2009). Glikman et al. (2010) calculate the faint-end slope of the QSO luminosity function and find that quasars might be able to ionize the intergalactic medium (IGM) at z ∼ 4. However, recent additional observations improve their constraints on the slope, bringing it into greater agreement with previous estimates...
and suggesting that QSOs may not be sufficient to account for the ionizing photons (E. Glikman et al. 2011, in preparation). Star-forming galaxies are now known to exist numerously at these redshifts and are therefore the leading candidates to account for the remaining ionizing photons (e.g., Siana et al. 2008; Faucher-Giguère et al. 2009).

From a theoretical point of view, current predictions of the escape fraction of ionizing photons from high-redshift galaxies are confusing, with different results obtained by different simulations. For example, Gnedin et al. (2008) argued that \( f_{\text{esc}} \), i.e., ratio of the flux density of Lyman continuum (LyC) escaping from a galaxy to that produced in the galaxy, increases with increasing halo mass in the range of \( M_h = 10^{10} - 10^{12} M_\odot \), and their values of \( f_{\text{esc}} \) are mostly less than a few percent. This is much lower than other published work; for example, Wise & Cen (2009) predict \( f_{\text{esc}} \sim 0.4 \). Yajima et al. (2010) found an opposite behavior such that \( f_{\text{esc}} \) decreases with increasing halo mass, with an average \( f_{\text{esc}} = 0.40 \) for \( M_h = 10^7 M_\odot \) dropping to \( f_{\text{esc}} = 0.07 \) for \( M_h = 10^{11} M_\odot \). A similar result was also found by Razoumov & Sommer-Larsen (2010). It is clear that the physical processes that modulate the escaping ionizing photons are not well understood.

From the observational point of view, \( f_{\text{esc}} \) has been poorly constrained due to the fact that LyC photons are easily absorbed by both the IGM and the ISM in a galaxy. The best way to investigate the LyC emissivity from high-redshift galaxies is to perform deep spectroscopic or narrowband observations focused on the peak of the LyC emission, e.g., 880–910 Å rest frame. Ultra-deep intermediate-band imaging can also give an important contribution, as we show in this work.

The LyC measure has been addressed in recent years by several authors. Malkan et al. (2003) and Siana et al. (2007, 2010) stacked tens of deep ultraviolet images of galaxies at \( z \sim 1 \) and report no detection. Similarly, Cowie et al. (2009) combined \( \sim 600 \) galaxies at \( z \sim 1 \) observed with the Galaxy Evolution Explorer (GALEX) and also report a non-detection. At higher redshift, Steidel et al. (2001) initially found \( f_{\text{esc}, \text{rel}} \gtrsim 0.5 \) from the composite spectrum of 29 Lyman-break galaxies (LBGs) at \( z \sim 3 \), where \( f_{\text{esc}, \text{rel}} \) is the relative fraction of escaping LyC (900 Å) photons relative to the fraction of escaping non-ionizing ultraviolet (1500 Å) photons. Giavalisco et al. (2002) and Inoue et al. (2005) estimated an upper limit of \( f_{\text{esc}, \text{rel}} \lesssim 0.1–0.4 \) for a sample of LBGs at \( z \sim 3 \). Shapley et al. (2006, S06 hereafter) directly detected the escaping photons from two LBGs in the SSA22 field at \( z = 3.1 \), and estimated the average value of \( f_{\text{esc}, \text{rel}} = 0.14 \). Chen et al. (2007) placed a 95% confidence level upper limit of 0.075 for the escaping radiation at \( z \gtrsim 2 \) of star-forming regions hosting gamma-ray bursts. More recently, Iwata et al. (2009) detected the LyC emission from 10 Ly\( \alpha \) emitters (LAEs) and 7 LBGs within a sample of 198 LAEs and LBGs in the SSA22 field. They showed that the mean value of \( f_{\text{esc}, \text{rel}} \) for the 7 LBGs is 0.11 after correcting for dust extinction, and 0.20 if IGM absorption is taken into account.

Current observations suggest that \( f_{\text{esc}} \) increases with increasing redshift: the fraction of direct LyC detection grows from 0% to \( \sim 10\% \) over the redshift range \( 0 < z < 3 \) (e.g., Inoue et al. 2006). Even though the trend is possibly present, the current fraction of direct LyC detections may be overestimated due to contamination by blue light coming from lower redshift sources superimposed on the targeted LBG. This has been investigated in detail by Vanzella et al. (2010a), exploiting the high-quality data of the Great Observatories Origins Deep Survey (GOODS; Giavalisco et al. 2004a) and Hubble Ultra Deep Field (HUDF) projects (Beckwith et al. 2006) in conjunction with ultra-deep VLT/VIMOS U-band imaging (Nonino et al. 2009). They find that the probability that at least \( \sim 1/3 \) of the direct detections reported in the literature are due to superposition of lower redshift sources (confused in the point-spread function of the image) is larger than 50%. Therefore, the observed evolution of \( f_{\text{esc}} \) with redshift may be less pronounced than currently believed.

It is therefore necessary to perform LyC measurements as free as possible from contamination by lower redshift sources. An ideal starting point is therefore deep, high-resolution, multi-wavelength (space-based) imaging. In the present work, we address this issue exploiting the extensive information (spectroscopy and photometry) available in the GOODS Southern field and HUDF. In particular, we take advantage of the deep VLT/FORS1 7′ × 7′ narrowband 3880 Å imaging centered on the HUDF and ultra-deep intermediate-band VLT/VIMOS U-band imaging of the entire GOODS-South (Nonino et al. 2009).

Throughout this paper, magnitudes are reported in the AB scale (Oke 1974), and the world model, when needed, is a flat universe with density parameters \( \Omega_m = 0.3 \), \( \Omega_\Lambda = 0.7 \), and Hubble constant \( H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

### Table 1

| Depth | \( U \)-VIMOS | NB-FORS1 |
|---|---|---|
| 5\( \sigma \) | 28.6 | 27.1 |
| 1\( \sigma \) | 30.5 | 29.0 |

**Note.** Magnitudes are reported within aperture diameters of 1′′.

## 2. DATA AND SAMPLE SELECTION

### 2.1. Intermediate-band (IB) Imaging

Ultra-deep \( U \) intermediate-band imaging in the GOODS-South field was performed with the VLT/VIMOS imaging spectrograph for a total integration time of \( \sim 40 \) hr. Nonino et al. (2009) described the reduction and characterization of the final image quality, which reaches a depth of magnitude 29.5, 29.1, and 28.6 at 2\( \sigma \), 3\( \sigma \), and 5\( \sigma \), respectively (see Table 1). Completeness and detection limit analyses have been performed by running Monte Carlo simulations and we refer the reader to Nonino et al. (2009) for details. The seeing of the co-added image is \( \simeq 0.8 \) and represents the deepest image currently available in the \( U \) band. The depth and the overall image quality of the co-added data, \( \sim 30 \) AB at 1\( \sigma \), are well matched to the impressive multi-wavelength data available in GOODS-South.

The transmission of the filter is shown in Figure 1. The filter probes the LyC region (\( \lambda < 912 \text{ Å} \)) for sources at redshift higher than 3.386. In the following, we only consider sources with redshift higher than 3.4, for which the Lyman limit is beyond the red limit of the filter. The transmission at \( \lambda > (912 \text{ Å} \times 4.4) \) decreases rapidly to zero, and is never higher than 1% of its peak at \( \sim 3900 \text{ Å} \). The filter has an FWHM of \( \sim 350 \text{ Å} \), corresponding to 80–60 Å rest frame for redshift 3.4–4.5, which makes it an intermediate-band filter (IB hereafter). While the lower limit of the redshift range investigated in this work is set by the filter transmission, the upper limit is given by the gradual increase of opacity of the IGM. Indeed, as we discuss
in detail in Section 4.1, the average transmission of the IGM decreases as redshift increases, reaching a transmission smaller than $3 \times 10^{-4}$ (1.0 means 100% transmission) at redshift beyond 4.5. Therefore, the transparency is too small at higher redshift to make analysis of $z > 4.5$ galaxies useful. In the following, we adopt redshift 4.5 as an upper limit.

2.2. Narrowband (NB) Imaging

Very deep VLT/FORS1 narrowband imaging (NB hereafter) has been performed in the GOODS-South field, including the HUDF, centered at $\alpha = 3^h 32^m 32^s$, $\delta = -27^d 47^m 16^s$ (J2000) with a total exposure time of 60,900 s. These data were obtained with the goal of detecting Lya emission at $z = 2.2$ (see Hayes et al. 2010 for details). The filter has a central wavelength ($\lambda_C$) of 3880 Å, a width (FWHM) of $\Delta \lambda = 37$ Å, and is sensitive to the LyC region for galaxies with redshift higher than 3.3. For the redshift range $3.3 < z < 4.5$, the NB filter probes rest-frame wavelengths $902 \, \text{Å} < \lambda < 700 \, \text{Å}$.

The data were reduced using standard tasks in NOAO/IRAF, including bias subtraction, flat-field correction, and sky subtraction. Images were then registered onto a common astrometric grid and co-added. The resulting magnitude limit of $\sim 26.5$ at $5\sigma$ within an aperture diameter of $2''$ and the median seeing of the final image of 0''85 are fully consistent with the reduction of Hayes et al. (2010). In particular, the NB image reaches the magnitude limit of $\sim 29.0$ at $1\sigma$ within a 1''2 diameter aperture (see Table 1). The observed field is a sub-region of the larger IB imaging, and therefore the available LBG sample with spectroscopic redshifts is smaller ($\simeq 1/4$ of the full sample used in the VIMOS IB image). However, useful constraints can be derived from a stacking analysis (see Section 5). In the following, we mainly exploit the deeper and wider IB imaging.

2.3. The Spectroscopic Sample

Extensive spectroscopic redshift surveys have been performed in the GOODS-South and surrounding fields (e.g.,

Cristiani et al. 2000b; Szokoly et al. 2004; Vanzella et al. 2006, 2008; Popesso et al. 2009; Balestra et al. 2010; D. Stern et al. 2011, in preparation). A collection of the published surveys is available at the ESO Web site. In the present work, only sources with secure redshifts are considered, i.e., those with the highest quality. All the spectra and the identified spectral features have been visually inspected.

The ESO/VIMOS spectroscopic survey extends beyond the deep GOODS-South area, where the IB photometry is also available. In this extended region, we find 13 galaxies with secure redshifts in the range $3.4 < z < 4.5$.

In total, 135 sources in the IB image (122 in the GOODS-South area and 13 outside) have secure redshifts in the range $3.4 < z < 4.5$. Their redshift and $i_{775}$ magnitude distributions are shown in Figure 2. The mean redshift and $i_{775}$ magnitude of the sample are $3.64 \pm 0.27$ and $24.85 \pm 0.58$, respectively.

3. THE IB PHOTOMETRY AND SELECTION OF THE CLEAN SAMPLE

Aperture photometry in the IB image was performed with the SExtractor (Bertin & Arnouts 1996) in the “double image” mode. To detect sources we have created a new, fake image based on the IB one with pixel values set to zero anywhere except at the positions of the LBGs satisfying our selection criteria, which were set to 10,000. Using these positions, photometry was then performed on the IB image. The accuracy in the centering of the apertures has been tested on a sample of 68 spectroscopically identified stars with magnitude $g_{850} = 25$ in the range 21–25 uniformly distributed across the IB image. The comparison between the original coordinates in the GOODS-South Advanced Camera for Surveys (ACS) catalog (v2.0) and those obtained by SExtractor on the corresponding “forced”

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Figure 1. Normalized transmissions of the VIMOS $U$ and narrowband FORS1/3880 filters.

Figure 2. Magnitude (top) and redshift (bottom) distributions of the 135 sources considered in this paper (7 AGNs and 128 galaxies). The vertical dotted line in the bottom panel illustrates the minimum redshift probed by the IB for the 912 Å limit. In both panels, blue crosses mark the AGNs. Those detected in their Lyman continuum are indicated in bold face (see also Figure 8).

(A color version of this figure is available in the online journal.)
positions in the IB image shows a mean deviation of \( \langle \Delta_{\text{R.A.}} \rangle = 0.001 \pm 0.133 \) and \( \langle \Delta_{\text{decl.}} \rangle = -0.009 \pm 0.136 \), which is significantly smaller than 1 pixel (0.′3). Flux measurements within increasing aperture diameters of 1′′2, 1′′5, 1′′8, and 2′′1 (4, 5, 6, and 7 pixels) have been computed. The same procedures have been executed for the NB image.

Figure 3 shows the distribution of the IB signal-to-noise ratios (S/Ns) for the 135 galaxies in 1′′2 and 2′′1 apertures. The distributions are asymmetric, peaked around zero, and have a wider dispersion for the larger aperture. In the positive tails of the distributions, there are possible direct LyC detections or intercepted foreground blue sources that mimic ionizing emission (we refer to the latter as contaminants, see the next section). Thirty-five out of 135 sources have an S/N in the IB image higher than 2 in either the 1′′2 or 2′′1 aperture. All have been visually inspected in the IB and the Hubble Space Telescope (HST) images (see Figures 4–6 and the Appendix for a description of the sample in the outer region of the GOODS-South area). The majority are due to offset faint or bright sources that boost the flux measure in the aperture centered on the LBG. In these cases, the S/N increases as the aperture diameter increases, because the contribution of the nearby source also increases. Relatedly, if the signal arises from the center of the aperture (i.e., at the LBG position), the S/N typically decreases as the aperture size increases. Illustrative examples of clear foreground contamination by bright, lower redshift galaxies include J033217.39-274142.4, J033212.98-274841.1, J033225.16-274852.6, and J033238.87-274908.7. Examples with a distinct and offset faint, blue source clearly visible in the ACS images that significantly (if not totally) contribute to the aperture photometry include J033204.87-274451.4, J033220.97-275022.3, J033226.49-274124.0, and J033236.83-274558.0; the last one is in HUDF and was discussed in Vanzella et al. (2010a; see Figure 7). Since we generally do not have the redshift of these faint, blue compact sources, it is not possible to guarantee that they are in the foreground. However, we note that the number of faint, nearby sources is consistent with the expected superposition probability (see the next section).

In the following, the 1′′2 apertures are used to derive constraints on the escaping LyC radiation from LBGs. Moreover, the 2σ limit has been adopted as the main IB detection threshold (results are also presented for 3σ and 5σ limits). We identify 27 out of 135 sources that most probably suffer contamination by an offset foreground source in the 1′′2 apertures. They are excluded in the following analysis. However, it is worth noting that we would tend to underestimate the derived constraints on the escape fraction if some of these offset sources are not foreground contamination.

We are most interested in investigating the contribution of stellar emission to the UVB. Therefore, active galactic nuclei (AGNs) are excluded from the sample as identified using either the 2 Ms Chandra image of GOODS-South (Luo et al. 2008) or by looking for typical AGN features like N v, Si iv, and C iv emission lines in the spectra. We find that 7 out of the 135 sources are AGNs, one of which is contaminated by a nearby foreground source (e.g., is one of the 27 sources mentioned above). The AGN image cutouts, photometric and spectroscopic information are reported in Figure 8. Ignoring the contaminated source, three out of the six remaining AGNs are detected in the IB image with an S/N > 2 (two with S/N \( \sim 3 \) and one with S/N \( \sim 2 \)), i.e., at wavelengths bluer than 896 Å rest frame. For the highest redshift source, GDS J033238.76-275121.6 at \( z = 3.951 \), the IB samples the rest-frame interval 700–808 Å.

In summary, among the 135 sources (122 in the GOODS-South area and 13 outside), 128 are LBGs and 7 are AGNs. Twenty-seven sources are contaminated (26 LBGs and 1 AGN); the distribution of IB flux densities of the uncontaminated sources is shown in Figure 9. Of the 102 isolated LBGs, 92 are from the GOODS-South area and 10 are from the surrounding region (see Figure 10). Images of the 26 contaminated LBGs (23 in the GOODS-South area and 3 in the outer region) are shown in Figures 6 and 11 (see Table 2 for a summary).

The sample of 102 clean LBGs is used to constrain the ionizing radiation escape fraction. In the following section, we briefly discuss the expected likelihood of foreground superposition that can contaminate LyC measurements.

### 3.1.Foreground Contamination

Vanzella et al. (2010a) discuss in detail the role of foreground contamination in estimating the LyC radiation from galaxies at redshift higher than 3. Taking advantage of the ultra-deep imaging available in the GOODS-South field, they show that the probability of a foreground source mimicking LyC emission is not negligible. For example, there is a 50% chance that at least 15% of a given sample is affected by superposition by lower redshift sources for 1′′ seeing and a U-band magnitude limit of 28.5 (Vanzella et al. 2010a). Comparisons with the observations of Steidel et al. (2001) and Shapley et al. (2006) have been performed using Monte Carlo simulations. Taking this contamination effect into account (which increases with redshift), Vanzella et al. (2010a) estimate that the escape fraction might be overestimated (amplified) by up to a factor of two.

In this work, we find contamination by both bright and faint sources (Figures 4 and 5). Considering the present spectroscopic sample of 135 sources, including the 7 AGNs, we find 27 sources (one AGN and 26 LBGs) are contaminated by lower redshift interlopers.
The probability that at least 13 high-redshift galaxies out of 135 are confused with a foreground object in a circle of 0.8′′ radius and $U$-band magnitude down to 29.5 is $\sim$50% (adopting the $U$-band number counts reported in Nonino et al. 2009 and Vanzella et al. 2010a). However, the present analysis finds 27 contaminations out of a sample of 135. The apparent inconsistency with the above calculation is solved if the size of the nearby sources is taken into account. Indeed, we clearly note from ACS and IB images that many extended foreground galaxies still pollute the photometry of the background LBG at separations even larger than 1′′. Looking carefully at Figure 11 (and Figures 4 and 5), it is apparent that $\sim$12 out of the 27 offset IB detections arise from relatively close, compact blue sources at separations of $\sim$1′′. This is fully consistent with the expected probability of a close superposition. The other superpositions are associated with tails of extended galaxies at larger separations.

If we relax the above calculation and adopt a circle of radius 1′′ to calculate the interloper rate, the probability that at least 27 galaxies out of 135 are polluted is $\sim$63%. A dedicated analysis should be performed to include the effect of size in

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**Table 2** Summary of the Sources Adopted

|        | AGNs [N/Detect/Cont] | LBG [N/Detect/Cont] | Isolated LBG |
|--------|----------------------|---------------------|--------------|
| GOODS-South | 7/3/1 | 115/1/23 | 92 |
| Ext GOODS-South | 0/0/0 | 13/0/3 | 10 |
| Total | 7/3/1 | 128/1/26 | 102 |

**Notes.** [N/Detect/Cont] indicates the number of sources (N), the number LyC detections (Detect), and the number affected by nearby sources (Cont). “Ext GOODS-South” indicates the extended GOODS-South region.
these calculations, but that is beyond the scope of the present work. The main aim here is to select a sample as \textit{clean} as possible and provide constraints on the escaping ionizing radiation.

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
GOODS ID & S/N 1\,\prime& S/N 2\,\prime & $i_{775}$ & $i_{775}$ & zspec & $\beta$ & Comment \\
\hline
J033204.94-274431.7 & 2.1 & 7.2 & 23.71 & 0.019 & 3.462 & −1.9 & AGN, N\,\textsc{v}, C\,\textsc{iv}; X-ray no \\
J033216.64-274253.3 & 5.2 & 4.4 & 24.86 & −0.015 & 3.795 & −2.1 & LBG, Si\,\textsc{iv}, C\,\textsc{iv} (abs); X-ray no \\
J033238.76-275121.6 & 3.3 & 3.4 & 26.09 & 0.11 & 3.951 & −1.5 & AGN, C\,\textsc{ii}, C\,\textsc{iv}; X-ray yes \\
J033244.31-275251.3 & 2.9 & 2.0 & 23.89 & −0.11 & 3.466 & −2.6 & AGN, N\,\textsc{v}, Si\,\textsc{iv}; X-ray yes \\
\hline
\end{tabular}
\caption{Spectroscopic Sample of Galaxies with a Detection in the IB Image with S/N > 2 in 1\,\prime 2 Diameter Aperture.}
\end{table}

\section{3.2. The LyC Detections}

Four sources have been detected in their LyC (see Table 3). Three out of four are AGNs, two of them are in the Szokoly et al. (2004, hereafter S04) spectroscopic catalog and one has been observed in Cristiani et al. (2000b, hereafter C00) and Balestra et al. (2010). The remaining source is an LBG observed with the Keck-DEIMOS spectrograph (D. Stern et al. 2011, in preparation). Summarizing the LyC detections:

1. J033204.94-274431.7: AGN. C\,\textsc{iv}, N\,\textsc{v} emission lines and X-ray emission is also measured.
2. J033216.64-274253.3: LBG. Ly\,\alpha, Si\,\textsc{iv}, and C\,\textsc{iv} (faint) absorption lines are detected.
3. J033238.76-275121.6: AGN. C\,\textsc{iv}, C\,\textsc{iii}], C\,\textsc{ii}, and X-ray emission is detected.
4. J033244.31-275251.3: AGN. Ly\,\alpha, N\,\textsc{v}, Si\,\textsc{iv}, and X-ray emission is detected.

\subsection{3.2.1. LyC Emission from LBG GDS J033216.64-274253.3}

Among the 102 LBGs in the \textit{clean} sample, only one is detected in the IB image (GDS J033216.64-274253.3 at $z = 3.795$; detected with S/N $\simeq 5.5$). The GOODS ACS images show that the source is quite compact, yet well resolved (SExtractor stellarity index of 0.43 in the $z_{850}$ band) with effective radius $R_{\text{eff}} = 0.8$ kpc physical ($R_{\text{eff}} = 0.114$), and has blue rest-frame ultraviolet continuum ($i_{775} - z_{850} = -0.015$ ($\beta = -2.1$). There are no close sources in the ACS images that might affect the IB signal. Since it is isolated and compact, the probability that another compact foreground source is superposed along the line of sight within a circle of radius $R_{\text{eff}}$ is lower than 0.1\%. This is the highest redshift LBG currently known with direct LyC detection. The Keck-DEIMOS spectrum (Figure 12) shows a clear Ly\,\alpha break with a mean continuum decrement $D_{\lambda} = 0.61 \pm 0.03$, consistent with the expected IGM transmission at redshift 3.8 (e.g., Inoue & Iwata 2008). The spectrum also shows faint Si\,\textsc{iv} and C\,\textsc{iv} absorption lines. Interestingly, the low and high ionization absorption lines are weak (or absent), in contrast to typical LBG spectra where weak interstellar absorption lines are often associated with strong Ly\,\alpha emission, and, conversely, Ly\,\alpha in absorption is often accompanied with strong interstellar absorption lines (e.g., Shapley et al. 2003; Vanzella et al. 2009; Balestra et al. 2010). This source appears to be the fortuitous combination of a relatively high escape fraction of ionizing radiation with low IGM attenuation. From the multi-wavelength information (MUSIC catalog; Grazian et al. 2006; Santini et al. 2009), we derive the following best-fit parameters for this galaxy using the main aim here is to select a sample as \textit{clean} as possible and provide constraints on the escaping ionizing radiation.
Figure 6. Images of the three $z > 3.4$ LBGs outside the ACS GOODS-South area with offset IB detections (S/N $\sim 2.5$). From left to right, ACS two-color images (from GEMS), IB, and VIMOS $R$-band images are shown. The dotted and solid lines indicate the possible nearby polluting source and the targeted LBG, respectively. In all three cases, the offset emission in the IB is consistent with the presence of a close source visible in the ACS images. In the middle $U$-band images, black circles outline the $1.2''$ diameter apertures, while in the $R$-band images white circles indicate the position of the spectroscopic target. Below the images, to the right of the GOODS ID, the separation between the LBG and the nearby source is reported. The spectrum of the top source is presented in Figure 23.

(A color version of this figure is available in the online journal.)

Figure 7. Three LBGs in the HUDF detected at S/N $> 1$ ($1.2''$ diameter) in the IB image. The $BVi$ color images at the HUDF depth are shown on the left of each panel. The position of the LBG is marked with a solid arrow in the color image and a circle in the IB (black/white) image. Blue compact sources detected in the IB images are visible, both close to the LBG and in the field. The box size of the IB cutouts is 6'' on a side.

(A color version of this figure is available in the online journal.)
Figure 8. HST/ACS BV$_i$ color images and the ultra-deep VLT/VIMOS IB cutouts for the seven AGNs with spectroscopic redshift higher than 3.4. The circles in the IB images have 1.2″ diameters and the box sizes are 4.5 on a side. For each pair, the GOODS ID, redshift, S/N within the 1.2″ diameter aperture, $i_{775}$ magnitude, and the information on the X-ray detection and spectral properties are reported. C00, B10, S04, and V08 correspond to Cristiani et al. (2000b), Balestra et al. (2010), Szokoly et al. (2004), and Vanzella et al. (2008), respectively. Three out of seven AGNs show an LyC detection at S/N > 2.

(A color version of this figure is available in the online journal.)

Figure 9. Flux distribution of the clean LBG sample (102) and AGNs (6) in AB units and within 1.2″ diameter aperture is shown. AGNs are marked with blue crosses, and the LBG with a red circle. Three AGNs (from right to left) and the LBG (circle) have been detected in their LyC with S/N higher than 2 (see also Table 3).

(A color version of this figure is available in the online journal.)

3.2.2. LyC Emission from AGNs and Their Influence on the IB Photometry

It is worth noting that the three AGNs with LyC detections are not likely to be altering the transmission of the IGM in their spatial proximity, including the volume probed by our $U$-band images. Following D’Odorico et al. (2008; see also Cen & Haiman 2000), we calculated the radius of the sphere of influence (or Strömgren sphere) of each of the detected AGN by relating the intensity of the ultraviolet ionizing background at the Lyman limit to the luminosity of the source at the same frequency. The resulting radius is smaller than 750 kpc (physical) for all three AGNs. In particular, the faintest and highest redshift of them, J033238.76-275121.6 at $z = 3.951$, is detected at S/N = 3.3 in the IB image (i.e., $i_{775} = 26.89$) at a rest-frame wavelength blueward of 808 Å. Its influence on the surrounding IGM reaches a radius of only $\sim 250$ kpc (physical).

Indeed, the flux in the $U$-band would be completely suppressed if a Lyman limit system was intercepted in the redshift range 3.386–3.951 (i.e., in the wavelength interval between the red edge of the $U$ filter and the Lyman limit of the source). Since the libraries of Bruzual & Charlot (2003) and a Salpeter IMF (similar values are obtained using the libraries of Charlot & Bruzual 2007): extinction $A_{1500} \sim 0.62$ (assuming a Calzetti et al. 2000 extinction law), age $\lesssim 0.1$ Gyr, star formation rate (SFR) $\sim 26 M_\odot$ yr$^{-1}$, and stellar mass $M_\ast \sim 2.7 \times 10^9 M_\odot$. On the one hand, if we assume an IGM transmission of 100%, a lower limit of 15% is obtained for $f_{\text{esc}}$. On the other hand, an $f_{\text{esc}}$ of 100% corresponds to an IGM transmission not lower than 0.15. We note that in this extreme case, no Ly$\alpha$ in emission is expected as all of the ionizing radiation escapes. Moreover, the lower limit on the transmission of 0.15 is higher than the expected average value at this redshift, 0.022, and the probability to have a transmission higher than 0.15 at $z = 3.8$ varies between 4.5% and 8% (see simulations in Section 4). This indicates a line of sight particularly free from Lyman limit systems.
Figure 10. VLT/VIMOS U-band cutouts of the sources adopted in the simulations (clean sample). The box sizes are 4.5′′ on a side. The sole LBG detected in LyC with S/N higher than 2 in the 1′′2 diameter aperture is marked with a dotted square (GDS J033216.64-274253.3 with S/N = 5.5, described in Section 3.2.1). Circles indicate the position of the 1′′2 diameter apertures.

Strömgren sphere radius is only 250 kpc (physical), the AGN is not influencing the IB observation, or in other words, the source must ionize the IGM at least down to redshift 3.386 to perturb the IB photometry (Δz ≥ 0.56), which clearly is not the case. Its LyC detection is therefore most probably due to an intrinsically high transmission of the IGM and/or escape fraction of ionizing radiation.

Similarly, if $f_{\text{esc}}$ is intrinsically high for the LBGs considered here as well, we expect a certain number of detections in the ultra-deep IB image (see below). In other words, the LyC detection of some of the AGNs validates the statistical method adopted here in constraining the $f_{\text{esc}}$ distribution for galaxies.

The next section describes Monte Carlo simulations performed with the aim of constraining the $f_{\text{esc}}$ distribution. A deeper limit on its average is given in Section 5 by stacking the sources.

4. CONSTRAINING THE DISTRIBUTION OF ESCAPING IONIZING RADIATION

In the following analysis, we refer to the clean spectroscopic sample described in the previous sections, composed by 102 galaxies with one LyC detection at S/N ≃ 5.5. Once this clean spectroscopic sample of LBGs has been identified, it is interesting to address the following question: how many sources do we expect to detect at a given depth in the IB survey assuming a distribution function of $f_{\text{esc}}$?

Allowing redshift to vary from 3.3 to 4.5, the IB filter probes rest-frame wavelengths far below 912 Å (e.g., down to ~700 Å), where the IGM transmission decreases rapidly to zero because of the increasing probability of intercepting Lyman limit systems and damped Lyα systems (hereafter LLSs and DLAs, respectively) as well as the decreasing free path of ionizing photons (see the next section). It is therefore necessary to estimate the expected LyC signal in our IB image adopting a model of the IGM transmission. This is also useful for the source stacking (Section 5).

4.1. Modeling the IGM Transmission

The effective optical depth through a clumpy IGM at the rest-frame frequency $\nu_S$ for a source at redshift $z_S$ is (e.g., Paresce et al. 1980):

$$\tau_{\text{eff}}(\nu_S, z_S) = \int_0^{z_S} dz \int_{N_i}^{N_c} dN_{\text{HI}} \frac{\partial^2 N}{\partial z \partial N_{\text{HI}}} (1 - e^{-\tau_i}) ,$$

(1)
Figure 11. VLT/VIMOS U-band cutouts of the sources excluded from the simulations because of the presence of a nearby blue object. The box sizes are 4′′×5 on a side (see the text for details).

Figure 12. Extracted Keck-DEIMOS spectrum of the LBG GDS J033216.64-274253.3 with LyC detection in the IB image (S/N ≥ 5.5). In the top and bottom panels, the blue and red parts of the spectrum are shown: Lyα, Si iv 1403 Å, and C iv 1548–1550 Å absorptions are clearly seen, and we marginally detect C ii 1335 Å absorption. Absorption from Si ii 1260, O i + Si ii 1302-1304, Si ii 1526, Fe ii 1608, and Al ii 1671 are not detected, nor are emission lines like Ni v] 1486 and He ii 1640 detected. A comparison with the cB58 spectrum with the IRAF task rvsao gives a good cross correlation coefficient (R = 3.34) and a redshift of 3.797.

(A color version of this figure is available in the online journal.)

\[ N_{\text{HI}} \text{ interval, and } \tau_{\text{cl}} = \sigma_{\text{HI}}(vS(1 + z)/(1 + z_S))N_{\text{HI}} \text{ is the optical depth of an absorber with } N_{\text{HI}} \text{ at } z, \] where \( \sigma_{\text{HI}}(v) \) is the H I cross section at frequency \( v \) in the absorber’s rest frame.\(^{11}\) If the column density distribution of the absorbers is a power law with index \(- \beta (\beta \approx 1.5; \text{e.g., Kim et al. 2002})\) independent of redshift, the maximum contribution to \( \tau_{\text{eff}} \) is made by absorbers with \( \tau_{\text{cl}} \sim 1 \). Therefore, the absorption of the LyC is mainly caused by LLSs and DLAs with \( N_{\text{HI}} > 10^{17} \text{ cm}^{-2} \) and not by the LAF, which has \( N_{\text{HI}} \sim 10^{13} \text{ cm}^{-2} \). This implies that LyC absorption is very stochastic because it is related to the probability of intercepting an LLS.

In this work, the intergalactic absorption derived from the Monte Carlo simulations of Inoue & Iwata (2008, hereafter IW08) is adopted. Briefly, we recall the main steps. The simulations are based on an empirical distribution function of intergalactic absorbers which reproduces the observational statistics of the LAF, LLSs, and DLAs simultaneously. From this assumed distribution function, a large number of absorbers have been generated (running suitable Monte Carlo simulations) along many lines of sight. The probability to encounter an absorber is assumed to follow a Poisson distribution, and for each one the column density and Doppler parameter are extracted randomly from their (empirical) probability distribution functions. Typically ~18,000 absorbers are generated for a line of sight in the redshift interval 0 < z < 6 (this number depends on the lower limit to the column density). As described in detail in IW08, 10,000 lines of sight have been calculated in the redshift interval 3.4 < z < 4.5 with step \( \Delta z = 0.1 \). The resulting

\(^{11}\) The frequency dependence of \( \sigma_{\text{HI}}(v) \) for LyC is approximately \( \propto v^{-3} \).
mean intergalactic transmission is comparable to that derived by Meiksin (2006) in the Lyman series regime ($\lambda > 912$ Å), though the IW08 transmissions are slightly lower in the LyC regime. This is due to the different number of LLSs considered by the two approaches (see IW08 for details).

Figure 13 shows examples of transmissions along different line of sights, extracted randomly from the 10,000 realizations at the three redshifts $z = 3.4$, 3.7, and 4.0. In some cases, the transmission drops to zero blueward of the redshift of LLSs; in others the signal coming from the source is transmitted down to $\lambda \lesssim 700$ Å. In general, as redshift increases, the IB filter used here is strongly penalized. This is shown in Figure 14, where the medians and 68% confidence interval of the transmissions of 10,000 different lines of sight calculated in the redshift range 3.4–4.5 are reported (the averages are also shown as open squares). The distributions are not symmetric because of intervening LLSs and DLAs. The transmissions have been convolved with the IB filter shape; therefore, they are calculated in the suitable wavelength interval covered by the filter at a given redshift. For comparison, the median transmissions calculated in the wavelength range 880–910 Å are also shown (it is identical to that reported in Figure 8 of IW08). Clearly, the transmissions calculated through the IB filter are systematically lower than the “optimal” case (880–910 Å). This is fully taken into account in the simulations we describe in the following section. We note that at redshifts beyond 4.0, the intergalactic absorption strongly attenuates the ionizing flux.

We briefly note the recent findings of Prochaska et al. (2010), in which they find a significantly lower incidence of LLSs at $z < 4$ compared with previous estimates. A similar result has been found by Songaila & Cowie (2010), even though this tendency is less pronounced. Qualitatively, if these results are correct then the transmission of the IGM derived here is underestimated; i.e., the number of expected LyC detections in our IB survey would increase, and given the observational constraint of only one out of 102 LBGs detected, this would imply that the upper limits we derive for $f_{\text{esc}}$ are further strengthened (see next section). Indeed, the fact that we detect two sources in their LyC (one LBG and one AGN) at relatively high redshift ($z \sim 4$) may support a higher average transmission than predicted from our simulations.

Quantitatively, the detailed inclusion of the results of Prochaska et al. (2010; and Prochaska et al. 2009; Songaila & Cowie 2010) in the modeling of the IGM (as in IW08) deserves a dedicated work that will be presented elsewhere (Inoue et al. 2010). However, a comparison between the observations of Péroux et al. (2005; e.g., those adopted in IW08), Prochaska et al. (2010), and Songaila & Cowie (2010), shows that decreasing the mean LyC optical depth (due to a lower number density of LLSs) increases the final IGM transmission by a factor of 1.5 (see Figure 15).

In Section 5, we report limits on $f_{\text{esc}}$ by stacking and considering previous and current statistics on LLSs.

### 4.2. Simulating the Expected Number of LyC Detections

The relative fraction of escaping LyC photons (at 900 Å) relative to the fraction of escaping non-ionizing ultraviolet
The averages calculated over the same lines of sight (shifted by 10,000 lines of sight generated with the IW08 simulations. Open squares indicate the median value and central 68% range of the transmission for the circles) as a function of source redshift. The filled circles and vertical error bars (1500 Å) photons is defined as (Steidel et al. 2001)

\[ f_{\text{esc,rel}} \equiv \frac{(L_{1500}/L_{900})_{\text{int}}}{(F_{1500}/F_{900})_{\text{obs}}} \exp(\tau_{900}^{\text{IGM}}), \]

where \((F_{1500}/F_{900})_{\text{obs}}\), \((L_{1500}/L_{900})_{\text{int}}\), and \(\tau_{900}^{\text{IGM}}\) represent the observed 1500 Å/900 Å flux density ratio, the intrinsic 1500 Å/900 Å luminosity density ratio, and the line-of-sight opacity of the IGM for 900 Å photons, respectively. Equation (2) compares the observed flux density ratio (corrected for the IGM opacity) with models of the ultraviolet spectral energy distribution (SED) of star-forming galaxies. If the dust attenuation \(A_{1500}\) is known, \(f_{\text{esc,rel}}\) can be converted to \(f_{\text{esc}}\) as

\[ f_{\text{esc}} = 10^{-0.4A_{1500}} f_{\text{esc,rel}} \] (e.g., Inoue et al. 2005; Siana et al. 2007).

We can rearrange the above equation to give an estimation of the observed flux at wavelengths smaller than the Lyman limit (i.e., \(F_{\text{LyC}}\) instead of \(F_{900\text{obs}}\)):

\[ F_{\text{LyC}} = \frac{(L_{\lambda_{\text{rest}}}/L_{1500})_{\text{int}}}{f_{\text{esc}} \times (F_{1500})_{\text{obs}} \times e^{-\tau_{900}^{\text{IGM}}} \times 10^{0.4A_{1500}}} \]

The quantities on the right-hand side of the equation have been modeled and inserted in a Monte Carlo simulation. They are described as follows.

1. \((L_{1500}/L_{\lambda_{\text{rest}}})_{\text{int}}\): Depending on the redshift, the wavelength range probed by the IB filter is included in the interval \(\lambda_{\text{rest}} \leq 908 \text{ Å} (= \lambda_{\text{rest}}(\max) - 4000 \text{ Å}/(1+z_{\text{min}}) \text{ with } z_{\text{min}} = 3.405)\). The value of the intrinsic luminosity density ratio \((L_{1500}/L_{\lambda_{\text{rest}}})_{\text{int}}\) is still very uncertain observationally; it must therefore be estimated from stellar population synthesis models. The LyC flux is emitted by O stars, whose lifetime is much shorter than the B and A stars that dominate the 1500 Å flux emission. Therefore, the luminosity ratio depends on the stellar population age, metallicity, star formation history (single burst, exponential decay, constant, or multi-bursts), and IMF (e.g., Bruzual & Charlot 2003; Leitherer et al. 1999). When the dying O stars are not replenished with new star formation, the ratio increases rapidly within a few million years (e.g., single burst). In the case of constant SFR, O stars are continually formed and the A and B stars accumulate, so the ratio slowly increases and saturates at later times, beyond 1 Gyr (Siana et al. 2007). Inoue et al. (2005), adopting the Starburst 99 models (Leitherer et al. 1999) and assuming a constant SFR, Salpeter IMF over the mass range 0.1–100 \(M_\odot\) and a metallicity \(Z\) of 0.001–0.02 (0.02 is the solar value), obtained ratios that lie in the 1.5 < \((L_{1500}/L_{900})_{\text{int}}\) < 5.5 interval. Depending on the time since the onset of star formation, they reported \((L_{1500}/L_{700})_{\text{int}} = 4.0 (7.0)\) in the case of 10 Myr (100 Myr) old stellar populations, with the value saturating at older ages. Here, wavelengths below 900 Å are observed (down to \(\sim 750 \text{ Å}\)) with the IB filter passing from redshift 3.4 to 4.5 and therefore a suitable ratio must be considered. Adopting an average age of \(\sim 300 \text{ Myr for our sample (derived by Pentericci et al. 2007, 2010), and following the calculations of Siana et al. (2007) that reported ratios between 6 and 8 for } (L_{1500}/L_{700})_{\text{int}} \text{ and } (L_{1500}/L_{700})_{\text{int}} \text{ for a similar age, respectively, and Inoue et al. (2005) that reported a ratio } \approx 7, \text{ we adopt a value of } (L_{1500}/L_{\text{LyC}})_{\text{int}} \approx 7 \text{ for the following analysis. This has been used in the Monte Carlo simulations described below, where we assume a Gaussian distribution with a mean of 7 and a standard deviation 50% of the mean. The 50% scatter includes the dispersion due to different physical properties of the LBGs in the sample as well as their redshift distribution. Results do not change significantly if we allow it to vary between 30% and 70%.)
2. $(F_{1500})_{\text{obs}}$. The $(F_{1500})_{\text{obs}}$ is derived from the observed $i_{775}$ magnitude of each source. That filter corresponds to $\lambda_{\text{eff}} \sim 1750$ Å, 1550 Å, and 1400 Å at redshift 3.4, 4.0, and 4.5, respectively. The average spectral slope of the sample is almost flat, $(\beta) = \sim 1.95 \pm 0.4$, so the estimated flux density deviates by only a small amount from the observed $i_{775}$ magnitude (less than 5% on average, $F_i \sim \lambda^{-2.95}$).

3. A1500. The correction for dust attenuation has been calculated assuming the empirical extinction relation $A_{1500} = 4.43 + \beta 1.99$, where the spectral index $\beta$ is derived from the observed $(i_{775} - z_{850})$ color following the prescription of Bouwens et al. (2009; see also Meurer et al. 1999). This technique has already been employed by several previous studies estimating the SFR density at $z \sim 2$–6 (e.g., Adelberger & Steidel 2000; Meurer et al. 1999; Bouwens et al. 2006; Stark et al. 2007). The dust correction has also been compared to the values derived from the standard SED fitting of a sub-sample of the 102 LBGs (80% of them) for which we have photometric multi-wavelength coverage from the MUSIC catalog. We refer the reader to Santini et al. (2009) for details of the SED fitting procedures. The median and standard deviation of A1500 from the SED fitting is 0.61$^{+0.93}_{-0.61}$, while from the ultraviolet spectral slope it is 0.58$^{+0.88}_{-0.58}$ assuming a Calzetti extinction law.

4. IGM attenuation. The transmission of the IGM ($T = e^{-\tau_{\text{IGM}}}$) between the observer and the source redshift has been inserted by adopting the models $\tau_{\text{IGM}}$ of IW08 (see previous section).

A Monte Carlo simulation that takes into account all of the above quantities has been performed and is described next. Random IGM transmissions have been associated with each object from the spectroscopic sample (102 galaxies) by extracting from the 10,000 different lines of sight at the closest redshift to the source and convolved with the IB filter. Similarly, a value of the intrinsic ratio of the luminosity density has been extracted randomly from the adopted distribution described above, then a correction for the dust absorption (A1500) has been calculated from the observed color. The $f_{\text{esc}}$ has been investigated by inserting various functional behaviors (see next section). An estimate of the flux $(F_{900})_{\text{obs}}$ is derived from Equation (3). If the estimated $(F_{900})_{\text{obs}}$ flux is brighter than the adopted threshold (i.e., the depth of the IB image), then it has been further perturbed according to the error of the image photometry for that flux level. The error as a function of the magnitude has been parameterized analytically by fitting an exponential function to the observed data.

Ten thousand simulated samples of 102 galaxies, each anchored to the observed quantities of the clean sample, i.e., the rest-frame ultraviolet colors, magnitudes, and redshift, have been generated for each $f_{\text{esc}}$ distribution. For each of the 10,000 extractions, the number of sources brighter than the chosen IB magnitude limit is recorded. At the end, for each assumed $f_{\text{esc}}$ distribution, 10,000 estimations of the expected number of “survived” sources are calculated, and the median and central 68 percentile range are derived.

Summarizing, the number of expected LyC detections in the IB image has been calculated performing Monte Carlo simulations that take into account the IGM transmission, the IB filter shape, the distribution of the intrinsic luminosity ratio $(L_{1500}/L_{\text{LyC}})$, dust attenuation by the ISM, photometric errors of the IB image, the observed redshift, and $i_{775}$ magnitude.

Once these effects are suitably modeled, the expected number of LyC detections in the IB image depends on the moments of the $f_{\text{esc}}$ distribution assumed. The aim of the next section is to investigate these dependences through comparison with the observed number.

4.3. The Tested Distributions

It is reasonable to believe that $f_{\text{esc}}$ varies from galaxy to galaxy with a distribution currently not known. Indeed, theoretical studies propose various behaviors for $f_{\text{esc}}$ as a function of the halo mass, luminosity, gas and dust content, geometry, etc. (Gnedin et al. 2008; Wise & Cen 2009; Yajima et al. 2010; Razoumov & Sommer-Larsen 2010). We have investigated which effect an assumed distribution of $f_{\text{esc}}$ would have on the expected number of LyC detections in our IB image. We assume that the distributions apply for all luminosities.

Before introducing the various functional forms adopted, we perform a similar check to what was done by Siana et al. (2007) in characterizing their null detection of LyC at $z \sim 1.3$. We assume a fraction ($Y$) of our sample has constant $f_{\text{esc}} (=X)$ and the rest (1-$Y$) has zero LyC emission ($X$ and $Y$ vary between 0 and 1). Monte Carlo simulations have been run in order to estimate the number of expected detections ($N$) in our IB survey as described in the previous section down to a 2σ limit and as a function of $X$ and $Y$. This has been done 30 times (1000 extractions each) on the clean sample randomly sorted at every time. The results are reported in Figure 16 where points (X, Y) with $N = 3$ belong to the black region; above it $N > 3$ and below $N < 3$. In our sample of 102 LBGs only one has been detected, $N = 1$. Very low $f_{\text{esc}} (<5\%$) are needed to reproduce the null or one LyC detection if all LBGs have the same $f_{\text{esc}}$ value. Conversely, a high $f_{\text{esc}} (>70\%)$ can reproduce a null
Figure 17. Monte Carlo simulations of the expected number of LyC detections in the ultra-deep VLT/VIMOS U-band imaging as a function of the median $f_{\text{esc}}$ (in the left panels $f_{\text{esc}}$ up to 30% is shown, in the middle and right panels it is shown up to 50%). From left to right, the expected number of LyC detections is presented for three IB depths, $2\sigma$ (29.5), $3\sigma$ (29.1), and $5\sigma$ (28.6), respectively. Solid lines show the median expected number, while the dotted lines and dashed line mark the 1$\sigma$ and 3$\sigma$ limits, respectively. In the top panels, a constant $f_{\text{esc}}$ value is assumed, from 1% to 100%. In the middle and bottom panels, Gaussian and exponential distributions of $f_{\text{esc}}$ with different medians are shown, respectively. The abscissa reports the median of the simulated distribution (see the text for details).

or one detection if it is associated with less than 10% of the LBG sample. This test suggests that high values of $f_{\text{esc}}$ are less probable in this luminosity regime (a feature already noted in other works; e.g., Giallongo et al. 2002; Inoue et al. 2005; Shapley et al. 2006; Iwata et al. 2009).

Having this result in mind, various continuous functions have been explored: flat, Gaussian, and asymmetric functions (exponential and log-normal). In detail, we test the following functional forms for $f_{\text{esc}}$.

1. **Constant value.** A constant value of $f_{\text{esc}}$ has been assumed for all galaxies, between 0.0 and 1.0 with an increment of 0.01. It is not realistic to assume a constant value of $f_{\text{esc}}$. However, it is useful as a check of the typical scatter due to solely Monte Carlo simulated effects like IGM, dust, photometric noise, intrinsic luminosity ratio distribution, etc.

2. **Gaussian distribution.** $f_{\text{esc}}$ is assumed to be distributed as a Gaussian form with a mean running from 0.0 to 1.0 (step 0.01) and standard deviation equal to half of the mean.

3. **Exponential distribution.** Exponential distributions ($e^{-K\times\text{Gauss}}$) with different slopes $\lambda$ have been considered, with $\lambda$ running from 1 to 100 with step $\Delta\lambda = 1$. This allows us to investigate the effect of asymmetric tails toward high $f_{\text{esc}}$ values.

4. **log-normal distribution.** log-normal distributions with various medians and scatter have been inserted, $e^{-K\times\text{Gauss}}$, where Gauss is extracted randomly from a Gaussian distribution with zero mean and standard deviation equal to 1. $K$ has been assumed to be 1, 2, 3, 4 and for each $\lambda$ parameter running from 0.1 to 10.0 (step 0.1). Varying $K$ allows us to change the average of the initial symmetric distribution (small $\lambda$). As $\lambda$ increases, the median of the distribution tends to zero and an asymmetric tail toward high values arises (see below).

In this way 100 constant, Gaussian, exponential, and 400 log-normal distributions of $f_{\text{esc}}$ have been calculated, each one extracted 10,000 times with the Monte Carlo simulation described above. We discuss the results in the following section.

### 4.4. Constraints on the Ionizing Radiation Fraction Distribution from the Spectroscopic Sample

The expected number of LyC detections has been explored as a function of the median and 68% interval of the assumed $f_{\text{esc}}$ distributions. Figures 17 and 18 show the results for constant, Gaussian, and exponential $f_{\text{esc}}$ behaviors. As expected, in all cases, if the median $f_{\text{esc}}$ increases the number of expected LyC detections also increases. Considering the IB depth at the $2\sigma$ level (left panels of Figure 17) and given the single LyC detection, the upper limit on the median $f_{\text{esc}}$ is $\simeq6(5)$% at $3\sigma$ for the Gaussian (exponential) distribution. Relating to a shallower IB depth, 29.1 ($3\sigma$) and 28.6 ($5\sigma$), the median of the
A Gaussian (exponential) $f_{\text{esc}}$ distribution is lower than 12(10)% and 20(15)% respectively.

Focusing on the exponential distribution, a median less than $\sim$5% and a scatter less than $\sim$15% are required to be compatible within $3\sigma$ to the observations. In other words, the very low number of LyC detections in the IB image down to 29.5 limit ($2\sigma$ within 1.2 diameter) implies an upper limit to the median $f_{\text{esc}}$ and the 84% percentile of the distribution of 5% and 15%, respectively. Figure 18 shows in more detail the exponential case reported in the lower left panel of Figure 17, i.e., IB depth at $2\sigma$ level. In particular, the distributions that lead, on average, to an expected number of LyC detections higher than 4 are highlighted in the [median–scatter] plane of all the log-normal distributions explored (see examples in the main box of Figure 19). Following the Poisson statistics, these are distributions for which the probability to have less than two LyC detections (our case) is lower than 5%. While in the above cases the dispersion decreases together with the median of the distribution and approaches zero as the median tends to zero, the effect of a relatively high scatter and very small median of $f_{\text{esc}}$ has been explored by adopting log-normal distributions as described in the previous section. The case with $K = 1$ and $\lambda$ running from 0.1 to 10.0 ($\Delta \lambda = 0.1$) is shown in Figure 19. As $\lambda$ increases, the distribution changes its shape from symmetric and centered at the initial value $e^{-1}$ ($K = 1$) to asymmetric with very small median and relatively high 84% scatter (see examples in the main box of Figure 19).

In the extreme case of very small medians (e.g., $\lambda = 100$, median $e^{-100}$), the scatter still allows a marginal LyC detection. This is the reason why in Figure 19 the expected number of LyC detections is different from zero even though the median is close to zero. Similarly, for the exponential case, the locus of points in the [median–scatter] plane of all the log-normal distributions (varying $\lambda$ and $K = 1$) is shown in the inner right box of Figure 19. Those excluded with a probability higher than 95% have been highlighted. In this case, log-normal distributions with a scatter lower than $\sim$18% are favored if compared with observations. Similar results have been found varying log-normal distributions with $K = 1, 2, 3, 4$ and $\lambda$ running from 0.1 to 10.0 (see Figure 20).

Summarizing, among the $f_{\text{esc}}$ distributions explored and from the comparison with the observed number of LyC detections (i.e., 1 out of 102), we find that the median fraction of ionizing radiation escaping from the LBG sample considered here is less than $\sim$5%–6% with a 1σ scatter (upper 84th percentile) not larger than $\sim$20% at the $2\sigma$ IB depth. These upper limits increase to $\sim$10%–12% and 20% (median and 1σ) if the 3σ IB depth is considered. In general, adopting the Poissonian statistics and considering the single LyC here reported, the distributions that predict more than 5 (10) LyC detections can be excluded with a probability higher than 95% (99%), respectively.
Figure 20. Same as shown in the inner right box of Figure 19, but calculated for different \( K \) values of the log-normal distributions \( e^{-K + \lambda \times \text{Gauss}} \). The black solid lines show the regions occupied by the 100 distributions for each \( K \) value. The distributions for which the expected number of LyC detection is larger or equal to 5 are shown with open circles. The single observed LyC detection reported in the present work suggests that \( f_{\text{esc}} \) is distributed with median and 1\( \sigma \) upper tail lower than \( \sim 6\% \) and 18\%, respectively, if a log-normal distribution is assumed. (A color version of this figure is available in the online journal.)

5. UPPER LIMITS ON THE IONIZING RADIATION FRACTION FROM STACKING

5.1. IB Imaging

The median and average stacks of all 102 galaxies are shown in the top part to Figure 21. No LyC detection is seen.

Similarly, the median and average stacks have been performed for the sub-sample of 45 LBG with redshift lower than 3.6, for which the mean IGM transmission is higher (see Figure 14). Median and averages have also been calculated for two sub-samples of these 45 galaxies, one of 22 LBG with \( i_{775} < 25 \) and the other for 23 LBG with \( i_{775} > 25 \) (they are shown in Figure 21). None of them show an LyC detection. It is worth noting that the individual LyC measure described in Section 3.2.1 (when included) does not provide enough counts to contribute to a significant stacked detection.

Following previous work in the literature (e.g., Steidel et al. 2001; Giallongo et al. 2002; Inoue et al. 2005; Shapley et al. 2006; Iwata et al. 2009), an upper limit on the \( f_{\text{esc}} \) can be calculated by assuming average values for the quantities in Equation (2) and correcting \( f_{\text{esc}, \text{rel}} \) for the average dust extinction at 1500 Å. Figure 9 shows the IB flux (AB) distribution within the 1\( \prime \).2 aperture of the sample of 102 LBGs plus 6 AGNs. Excluding the AGNs and the single LBG detected in its LyC, the distribution has a mean and standard deviation of \( \langle F(1.2) \rangle = -0.007 \pm 0.023 \times 10^{-30} \text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1} \). This 1\( \sigma \) dispersion corresponds to magnitude 30.50 AB, consistently with the 1\( \sigma \) limit described at the beginning, and can be adopted as the typical error of the single measure (assuming the flux distribution to be Gaussian and each measurement as independent). Therefore, the 1\( \sigma \) limit of the mean over \( N \) sources is \( 0.023 \times 10^{-30} \text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1} \) decreased by the square root of \( N \). In the case of 102 LBGs, this limit corresponds to magnitude 33. However, despite the very deep flux reached, the very low transmission of the IGM as redshift increase (\( z > 4 \)) weakens the constraints on \( f_{\text{esc}} \). In order to keep a relatively high IGM transmission and high magnitude contrast, galaxies with redshift lower than 3.75 and \( i_{775} < 25.5 \) have been selected (64 LBGs). The average \( i_{775} \) magnitude and redshift are 24.84 and 3.57, respectively, and the observed 1\( \sigma \) flux density ratio probed is \( (F_{1500}/F_{\text{rest}})_{\text{obs}} = 1473 \). The upper limit on \( f_{\text{esc}, \text{rel}} \) is

\[
f_{\text{esc}, \text{rel}} < \left[ \frac{7}{1473} \right] \times \frac{1}{0.09} = 0.05, \quad (4)
\]
where the average transmission is $\approx 0.09$ at redshift below $3.75$ (see Figure 14) and the intrinsic luminosity ratio has been fixed to 7 (see previous section). Assuming an average $A_{1500} = 0.65$ (flat spectral slope), the upper limit on total escape fraction $f_{esc} = f_{esc,rel} \times 10^{-0.4 \times A_{1500}}$ turns out to be 0.03.

Several further constraints on $f_{esc}$ can be calculated by selecting sub-samples in magnitude and redshift. Selecting brighter sources allows one to increase the magnitude contrast, and selecting lower redshift sources allows one to increase the average IGM transmission because the IB filter approaches rest-frame 900 Å. A summary of this is shown in Table 4 where upper limits on $f_{esc}$ are reported as a function of the magnitude threshold (columns) and redshift (rows). The upper limits on the (mean) escaping ionizing radiation $f_{esc}$ span the range 4%–60%. The values derived from the Monte Carlo simulations are consistent with this interval, in particular if the brighter (larger magnitude contrast) and lower redshift (higher IGM transmission) objects are considered in the grouping (see Table 4). Compared to the estimations appearing in the literature so far, these are the most constraining results on $f_{esc}$ in the redshift and magnitude range here considered.

As discussed at the end of Section 4.1, it is worth noting the effect of the recent findings of Prochaska et al. (2010) and Songaila & Cowie (2010) about the lower incidence of LLSs observed with respect to previous work (e.g., Péroux et al. 2005; also adopted in this work). Assuming these results to be correct, they imply a higher IGM transmission by a factor of 1.5 (this also adopted in this work). Assuming these results to be correct, they imply a higher IGM transmission by a factor of 1.5 (this also adopted in this work). Therefore, the upper limits we report in the above equation would further decrease by the same factor (Equation (4)). The same dimming factor would also apply to the upper limits reported in Table 4.

### 5.2. NB Imaging

The number of available sources of the clean sample in the FORS1 NB imaging is 30. There are two more LBGs in this sample (not considered in the IB calculations) since the NB imaging starts to probe the LyC at redshift beyond 3.3 (not 3.4 as for the IB). None of the LBGs show an LyC detection at $S/N > 2$, and again no detection is measured in the median (average) stacking. While the NB observations have the disadvantage of having smaller statistics and being shallower than the IB imaging, the narrow wavelength window helps to increase the average transmission of the IGM if a suitable selection in redshift is done (the limits calculated from the whole sample do not add any further constraint with respect to the IB derivations). Indeed, selecting sources with redshift below 3.65, the average transmission turns out to be 0.2 and the

| $\langle z \rangle < 24.75$ | $\langle z \rangle < 25.0$ | $\langle z \rangle < 25.25$ | $\langle z \rangle < 25.5$ | $\langle z \rangle < 25.75$ | Redshift (T) |
|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| 0.051(10)               | 0.047(17)               | 0.045(26)               | 0.045(28)               | 0.046(30)               | [3.40–3.55] 0.135       |
| 0.136(17)               | 0.130(21)               | 0.127(30)               | 0.127(36)               | 0.127(37)               | [3.35–3.75] 0.050       |
| 0.058(27)               | 0.054(38)               | 0.052(56)               | 0.053(64)               | 0.053(67)               | [3.40–3.75] 0.090       |
| 1.208(3)                | 1.012(6)                | 0.994(7)                | 0.994(9)                | 1.006(10)               | [3.75–4.05] 0.013       |

**Notes.** The 1σ limits on $f_{esc,rel}$ Values are reported as a function of redshift and magnitude bins. The average IGM transmission ($T$) in the middle of the redshift range and convolved with the IB VIMOS filter, the intrinsic luminosity ratio $L_{1500}/L_{\mathrm{LyC}} = 7$ is adopted. The total $f_{esc} (f_{esc} = f_{esc,rel} \times 10^{-0.4 \times A_{1500}})$ can be obtained by assuming the average dust absorption of the sample, $A_{1500} \geq 0.65$ (see the text). Within parenthesis the number of sources used in the calculation having magnitude less than the corresponding column head and belonging to the redshift interval (redshift column). These limits are further decreased by a factor of 1.5 if the recent results of Prochaska et al. (2010) and Songaila & Cowie (2010) on the LLSs statistics are considered (see the text).

### 6. Evidence for a Luminosity Dependency?

The limits on $f_{esc}$ derived from Monte Carlo simulations and from the stacking have been calculated from the spectroscopic sample of LBG, which is probing mainly $L \gtrsim L_{*}^{z=3}$ luminosities, i.e., galaxies hosted by relatively massive dark matter halos ($z \approx 10^{11} M_{\odot}$; e.g., Arnouts et al. 2002; Lee et al. 2009). The ionizing luminosity density at LyC ($\rho_{Lyc}$) can be calculated following Inoue et al. (2006). The luminosity density of non-ionizing radiation $\rho_{1500}$ has been derived from the luminosity function of Bouwens et al. (2007) at $z \approx 4$ integrated down to the faint limit $M_{1500} = -16 (0.02 L_{*}^{z=3})$, and $3.36 \times 10^{26}$ erg s$^{-1}$ Hz$^{-1}$ Mpc$^{-3}$. If we adopt the 1σ limit $f_{esc,rel} \approx 5%$ derived from the bright part of the sample here analyzed (see Section 5.1) and assumed valid for all luminosities, we find $\rho_{Lyc}$ provided by the LBG population to be $2.5 \times 10^{24}$ erg s$^{-1}$ Hz$^{-1}$ Mpc$^{-3}$.

Bolton et al. (2005) and Faucher-Giguère et al. (2008b) calculate the hydrogen ionization rate of the IGM at redshift 4 derived from the LAF analysis as $\Gamma_{12}$ of 0.9 and 0.5, respectively (where $\Gamma_{12} = \Gamma / 10^{12}$ s$^{-1}$ is the rate 10$^{-12}$ ionizations s$^{-1}$ atom$^{-1}$). We convert these values into luminosity density units by adopting the formulation in Schirber & Bullock (2003) assuming “local source” approximation (see also Hopkins et al. 2007): $\Gamma_{12} \approx 2(1 + z)^{-1.5} (\frac{\epsilon_{UV}}{\epsilon_{ion}})$, assuming an $\alpha_{UV}$ spectral slope of the background equal to 2.0 (e.g., Haehnelt et al. 2001). The $\epsilon_{UV}$ quantity is expressed in units of $10^{24}$ erg s$^{-1}$ Hz$^{-1}$ Mpc$^{-3}$.

The estimated luminosity density of the background turns out to be $\rho_{BG} = 22.9$ and $12.7 \times 10^{24}$ erg s$^{-1}$ Hz$^{-1}$ Mpc$^{-3}$ for Bolton et al. (2005) and Faucher-Giguère et al. (2008b), respectively. If we compare these values with the upper limit derived above from galaxies ($\rho_{Lyc}$), they then contribute to only

12 $\rho_{Lyc} = \rho_{1500} \frac{f_{esc}}{T_{1500}} \times f_{esc,rel} = \rho_{1500} \frac{f_{esc}}{T_{1500}} \times \exp \left( \frac{\epsilon_{LyC}}{\epsilon_{ion}} \right)$.
Therefore, star-forming galaxies alone may not be able to account for the entire ultraviolet ionizing budget. It is worth noting that, given the observed global non-detection here reported, a higher transmission of the IGM (Prochaska et al. 2010) would imply an even tighter constraint on the escaping radiation and therefore less contribution by (bright) LBGs. If galaxies only partially contribute, the remaining fraction presumably is provided by QSOs. However, several works agree on the fact that at redshift beyond 3, galaxies play a dominant role in the IGM ionization with QSOs contributing fractions of only 30%–10% in the redshift range 3.5–4.0 (e.g., Bolton et al. 2005; Siana et al. 2008; Faucher-Giguère et al. 2008b, 2009; Prochaska et al. 2009). If galaxies are responsible for the remaining ionizing budget, then the implication is that \( f_{\text{esc}} \) depends on the UV luminosity, with fainter galaxies having a larger escape fraction.

Such a relationship between \( f_{\text{esc}} \) and the UV luminosity has recently been suggested by simulations. Yajima et al. (2010) performed a three-dimensional radiation transfer calculation of stellar radiation for a large number of high-redshift, star-forming galaxies in cosmological simulations. One of their primary conclusions was that, in the redshift interval \( 3 < z < 6 \), galaxies become the main contributor to IGM ionization with the average (standard deviation) of the escape fraction of ionizing radiation increasing to \( \simeq 40\% \pm 20\% \) for low-mass halos, \( M_h < 10^{10} M_\odot \). For the larger halos, \( M_h \simeq 10^{11} M_\odot \), they predict an average \( f_{\text{esc}} \) of \( 7\% \) with a relatively small scatter, less than 20\% (see their Figure 2), in agreement with what we find here.

Sources at the fainter end of the magnitude distribution are underrepresented in our simulations, since the magnitude contrast reached between the ionizing and non-ionizing radiation (IB and \( f_{775} \)) is smaller. However, if there is a dependency of \( f_{\text{esc}} \) with the luminosity so that fainter galaxies have higher average \( f_{\text{esc}} \), this could partially compensate for the lower contrast. As mentioned above, Yajima et al. (2010) predict \( f_{\text{esc}} \) increases for lower halo masses, with \( \langle f_{\text{esc}} \rangle \) of 40\% ± 30\% and 15\% ± 20\% for \( M_h = 10^9 M_\odot \) and \( M_h = 10^{10} M_\odot \), respectively. Razoumov & Sommer-Larsen (2010) predict \( f_{\text{esc}} \) values that reach 70\%–80\% for \( M_h \) in the range \( 10^9–10^{10} M_\odot \) at redshift 4.4.

To investigate the IB emission in our data at fainter limits, we have selected a sample of 218 galaxies with photometric redshifts in the range \( 3.4 < z < 4.0 \) and magnitude \( 27 < i_{775} < 28.5 \) extracted from the public photometric redshift catalog of Coe et al. (2006). IB photometry has been performed at the positions of the galaxies in the four aperture diameters, as was done for the spectroscopic sample. Twenty-six out of 218 have a detection with S/N higher than 2 in the 1′2 diameter aperture; Figure 22 shows their IB cutouts and the list is reported in Table 5. Five out of 26 show an IB emission aligned with the LBG position (marked with black crosses in Figure 22). In the other cases, an offset is present and the LBG may suffer contamination by foreground sources.

From Monte Carlo simulations of the sample considered here we find that the expected median number of LyC detections at the 2\( \sigma \) IB depth is \( 6_{-3}^{+5} \) and \( 3_{-2}^{+3} \) for the case of constant and Gaussian distributions with median \( f_{\text{esc}} = 1.0 \) and 0.7, respectively. Exponential and log-normal distributions predict a comparable number (\( \simeq 3–6 \)) if the median of the \( f_{\text{esc}} \) distributions is larger than 60\%. This result is quantitatively consistent with the expectations if \( f_{\text{esc}} \) increases for less luminous galaxies.

Figure 22. VLT/VIMOS I′-band cutouts of the sources selected in the HUDF with magnitude \( 27 < i_{775} < 28.5 \), photometric redshifts in the range \( 3.4 < z_{\text{phot}} < 4.0 \), and S/N in the 1′2 diameter aperture higher than 2. The size of the boxes is 4′.5 on a side. Sources indicated with a black cross show a non-offset detection in the IB.

However, we stress that apart from the reduced magnitude contrast probed, the main disadvantage concerning these fainter sources is the reliance on photometric redshifts. If the sample includes some galaxies with true redshifts \( z < 3.4 \), the IB image would include light from wavelengths longward of the Lyman limit.
Table 5

| ID     | GOODS ID   | zphot | $i_{775}$ | S/N 1'2 | S/N 2'1 |
|--------|------------|-------|-----------|---------|---------|
| 1      | J033229.90-274721.5 | 3.559 | 28.10    | 4.6     | 7.0     |
| 2      | J033230.79-274740.6 | 3.495 | 27.63    | 3.6     | 10.1    |
| 3      | J033232.09-274726.9 | 3.777 | 27.21    | 2.7     | 5.5     |
| 4      | J033232.83-274630.0 | 3.619 | 27.78    | 3.6     | 11.0    |
| 5      | J033234.63-274819.4 | 3.487 | 27.78    | 2.4     | 1.8     |
| 6      | J033236.50-275500.8 | 3.650 | 27.80    | 2.9     | 3.5     |
| 7      | J033236.67-274802.9 | 3.764 | 27.83    | 2.2     | 7.6     |
| 8      | J033236.67-274743.4 | 3.681 | 27.85    | 4.7     | 14.0    |
| 9      | J033236.94-274757.5 | 3.507 | 28.43    | 2.6     | 5.9     |
| 10     | J033237.87-274552.9 | 3.562 | 27.21    | 3.7     | 7.2     |
| 11     | J033238.30-274728.7 | 3.488 | 28.15    | 3.8     | 5.6     |
| 12     | J033238.50-274902.6 | 3.592 | 28.03    | 9.2     | 9.5     |
| 13     | J033239.43-274956.6 | 3.546 | 28.36    | 2.6     | 5.0     |
| 14     | J033240.70-274936.8 | 3.830 | 27.05    | 3.1     | 9.4     |
| 15     | J033240.85-274912.0 | 3.699 | 27.91    | 4.4     | 6.1     |
| 16     | J033241.33-274548.2 | 3.425 | 28.23    | 4.6     | 9.4     |
| 17     | J033241.57-274604.1 | 3.497 | 27.93    | 3.1     | 9.4     |
| 18     | J033241.57-274728.7 | 3.488 | 28.15    | 3.8     | 5.6     |
| 19     | J033241.83-274819.4 | 3.487 | 27.78    | 2.4     | 1.8     |
| 20     | J033242.77-274743.4 | 3.681 | 27.85    | 4.7     | 14.0    |
| 21     | J033242.89-274854.5 | 3.460 | 27.57    | 21.0    | 33.9    |
| 22     | J033242.77-274618.1 | 3.416 | 28.45    | 2.9     | 6.6     |
| 23     | J033242.89-274845.7 | 3.761 | 28.19    | 3.5     | 3.2     |
| 24     | J033244.14-274737.7 | 3.780 | 28.45    | 2.0     | 3.9     |
| 25     | J033246.03-274752.8 | 3.854 | 27.98    | 2.4     | 2.9     |
| 26     | J033246.97-274730.5 | 3.610 | 27.15    | 4.4     | 7.3     |

7. CONCLUSIONS

Exploiting the ultra-deep VIMOS IB and deep FORS1 NB imaging of the GOODS-South field, new limits on the escape fraction of ionizing radiation from star-forming galaxies at redshift 3.4–4.5 have been derived. Particular care has been devoted to clean the spectroscopic sample from foreground contamination and AGN contributions. From a sample of 102 LBGs we derive the following results.

1. From Monte Carlo simulations and stacking of the IB and NB imaging, we find that $f_{\text{esc}}$ of $L > L_{\gamma}^* + 3$ LBG is distributed with a median lower than 5%-6% and 84 percentile scatter lower than 20% in all the distributions investigated (Gaussian, exponential, and log-normal). We note that the low upper limit on the median escape fraction is for the entire sample, independent of spectral properties. If the recent findings of Prochaska et al. (2010) and Songaila & Cowie (2010) are considered—i.e., the average IGM transmission is higher than that adopted here—then the limits we derive are further strengthened.

2. One star-forming galaxy is detected in its LyC region at 700–835 Å rest-frame. It is the highest redshift galaxy with such a detection currently known and is most probably due to a combination of high IGM transmission coupled with a relatively high $f_{\text{esc}}$. The lower limit on $f_{\text{esc}}$ is 15%; assuming $f_{\text{esc}} = 100\%$, the IGM transmission cannot be lower than 15%. This value is higher than the expected average value at this redshift (2.2%), implying that it is a particularly free line of sight. The galaxy shows a blue UV-continuum spectral slope ($\beta = -2.1$) and weak or absent interstellar absorption lines in the spectrum even though Ly$\alpha$ is in absorption. The ultraviolet morphology is quite compact, $R_{\text{eff}} = 0.8$ kpc (physical).

Adopting the observed photoionization rate of Bolton et al. (2005) or Faucher-Giguère et al. (2008b), star-forming galaxies contribute partially (< 5%) to the required ultraviolet ionizing budget if $f_{\text{esc,rel}}$ is constant and equal to 5%. On one hand, the contribution of QSOs may still be significant at the redshifts considered here, providing the ionizing fraction missed by galaxies. This strongly depends on the faint-end slope of the QSO luminosity function (Glikman et al. 2010; E. Glikman et al., in preparation). On the other hand, several works suggest that the QSO contribution to the UVB decreases significantly beyond redshift 2, reaching fractions lower than 50% (down to 10%) at redshift 4 (e.g., Fontanot et al. 2007; Siana et al. 2008; Faucher-Giguère et al. 2008b; Prochaska et al. 2009). In this case, galaxies would provide almost all of the ionizing radiation, which, as we have seen, requires that $f_{\text{esc}}$ depends on the UV luminosity. We remind, however, that these conclusions depend on both the total ionizing UVB and the QSO fractional contribution to it, quantities remain empirically poorly constrained at these redshifts.

If $f_{\text{esc}}$ does indeed depend on the UV luminosity, then we can speculate on the following scenario. Bouwens et al. (2009b), analyzing samples of LBGs in the redshift range $3 < z < 6$ show that there is a clear correlation between the UV-continuum slope $\beta$ and ultraviolet luminosity. In particular, for the $B$-band dropout sample also adopted here, more luminous LBGs have redder colors. Moreover, it is known from stacking tens and hundreds of LBG spectra at redshift 3–5 that the redder UV-continuum slopes are linked to low Ly$\alpha$ equivalent widths and stronger interstellar absorption lines, while LAEs are bluer and have weaker interstellar absorption lines (e.g., Shapley et al. 2003; Pentericci et al. 2007; Vanzella et al. 2009; Balestra et al. 2010).

Thus, if $f_{\text{esc}}$ is, on average, larger in galaxies with fainter UV luminosity then we would expect that the bulk of the ionizing radiation comes from faint LAEs, which are, in general, younger and less massive than their brighter LBG counterparts (e.g., Ono et al. 2010). On the one hand, this would be plausible and possible cases have been found by Iwata et al. (2009). On the other hand, we have shown an opposite example, in which LyC emission arises from a LBG without Ly$\alpha$ in emission (even though it has been detected in the bright $L_{\gamma}^*$ regime).

A direct investigation at fainter flux limits $(i_{775} > 27)$ is challenging because the magnitude contrast decreases and spectroscopic redshifts are difficult to obtain with current facilities. An analysis of faint galaxies from the HUDF, $27 < i_{775} < 28.5$ or $0.3L_{\gamma}^* = 0.04L_{\gamma}^*$, selected with photometric redshift is in broad quantitative agreement with the expectations if $f_{\text{esc}}$ depends on the UV luminosity, increasing for fainter galaxies.

A way to explore this faint luminosity regime (before the advent of future telescopes like the James Webb Space Telescope (JWST) and the Extremely Large Telescopes) is to analyze samples of spectroscopically confirmed LAEs selected through NB imaging (e.g., Iwata et al. 2009; Inoue et al. 2010), looking at peculiar spectroscopic features related to low-luminosity AGN or hot and massive stars (e.g., Vanzella et al. 2005) or using spectra of $\gamma$-ray burst afterglows (e.g., Chen et al. 2007), strategies that we plan to pursue in upcoming works.

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The ESO/VIMOS spectroscopic survey extends beyond the deep GOODS-South area, but where the IB photometry is still available. Thirteen galaxies with secure redshifts match the selection $3.4 < z < 4.5$. Three out of 13 show an IB detection with $S/N \simeq 2.5$. In all three cases, the IB emission is offset with respect to the position of the LBG. High-resolution imaging (HST/ACS) drawn from the Galaxy Evolution from Morphology and SEDs project (GEMS; Rix et al. 2004) has been used to check for the presence of close companions that may contaminate the IB photometry. Even though the GEMS survey is shallower than GOODS, in all cases there is a distinct faint source shifted in the direction consistent with the IB emission. Figure 6 shows the HST/ACS color ($V_{606}$ and $z_{850}$ combined), the VIMOS IB and $R$ images, where the deep $R$ data are described in Nonino et al. 2009. In particular for the source J033156.8-275151.9 (top panel), a distinct compact source at $\sim 0.6$ separation from the LBG is clearly present (marked with dotted lines in the figure). In this case, a signal bluer than the Lyman limit is also visible in the two-dimensional spectrum (see Figure 23). There is no spatial offset between the two traces in the spectrum because of the slit orientation over the sky superposes the two objects along the wavelength dispersion. It is further confused by the seeing conditions during the observations ($\sim 1^\prime$). No additional spectral features, possibly arising from the close source, have been detected. In the other two cases (middle and bottom panels of Figure 6) a similarly offset and faint close source is present that can be linked to the contamination.

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APPENDIX

THE SOURCES IN THE EXTENDED GOODS-SOUTH REGION

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