QUANTIFYING DISTRIBUTIONS OF THE LYMAN CONTINUUM ESCAPE FRACTION

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ABSTRACT

Simulations have indicated that most of the escaped Lyman continuum (LyC) photons escape through a minority of solid angles with near complete transparency, with the remaining majority of the solid angles largely opaque, resulting in a very broad and skewed probability distribution function (PDF) of the escape fraction when viewed at different angles. Thus, the escape fraction of LyC photons of a galaxy observed along a line of sight merely represents the properties of the interstellar medium along that line of sight, which may be an ill-representation of the true escape fraction of the galaxy averaged over its full sky. Here we study how LyC photons escape from galaxies at $z = 4 - 6$, utilizing high-resolution large-scale cosmological radiation-hydrodynamic simulations. We compute the PDF of the mean escape fraction ($\langle f_{\text{esc,1D}} \rangle$) averaged over mock observational samples, as a function of the sample size, compared to the true mean (if an infinite sample size is used). We find that, when the sample size is small, the apparent mean skews to the low end. For example, for a true mean of 6.7%, an observational sample of (2,10,50) galaxies at $z = 4$ would have have a 2.5% probability of obtaining the sample mean lower than $\langle f_{\text{esc,1D}} \rangle = (0.007\%, 1.8\%, 4.1\%)$ and a 2.5% probability of obtaining the sample mean greater than (43%, 18%, 11%). Our simulations suggest that at least ~100 galaxies should be stacked in order to constrain the true escape fraction within 20% uncertainty.

Key words: cosmic background radiation – dark ages, reionization, first stars – galaxies: high-redshift – large-scale structure of universe – radiative transfer – ultraviolet: galaxies

1. INTRODUCTION

A fraction of the Lyman continuum (LyC) photons generated by young massive stars is believed to escape from the host galaxies to enter the intergalactic space. This is a fundamental quantity to determine the epoch and pace of cosmological reionization, provided that the universe is reionized by stars (e.g., Gnedin 2000; Cen 2003). After the completion of cosmological reionization, it plays another important role in determining the ultraviolet (UV) radiation background (on both sides of the Lyman limit) in conjunction with another major source of UV photons—quasars—that progressively gains importance at lower redshift (e.g., Faucher-Giguère et al. 2008; Fontanot et al. 2014).

Observations of star-forming galaxies at high redshifts ($z \sim 3$) suggest a wide range of the escape fraction of ionizing photons. While only a small fraction of LyC photons ($\lesssim$ a few percent) escapes from their host galaxies in the majority of the Lyman break galaxy samples, a non-negligible number of them ($\sim 10\%$) shows high levels of LyC flux corresponding to $\langle f_{\text{esc,1D}} \rangle \sim 10\%$ (Shapley et al. 2006; Iwata et al. 2009; Nestor et al. 2011, 2013; Mostardi et al. 2013). Cooke et al. (2014) claim that the mean escape fraction may be even higher ($\langle f_{\text{esc,1D}} \rangle \sim 16\%$) if the observational sample is not biased toward the galaxies with a strong Lyman limit break. It is not well understood quantitatively, however, what the probability distribution function (PDF) of the LyC escape fraction is and how a limited observational sample size with individually measured escape fractions can be properly interpreted, because of both possible large variations of the escape fraction from sightline to sightline for a given galaxy and possible large variations from galaxy to galaxy. The purpose of this Letter is to quantify how LyC photons escape in order to provide a useful framework for interpreting and understanding the true photon escape fraction given limited observational sample sizes.

2. SIMULATIONS

To investigate how LyC photons escape from their host halos, we make use of the cosmological radiation hydrodynamic simulation performed using the Eulerian adaptive mesh refinement code, RAMSES (Teyssier 2002; Rosdahl et al. 2013, ver. 3.07). The reader is referred to Kimm & Cen (2014, the FRU run) for details, where a detailed prescription for a new, greatly improved treatment of stellar feedback in the form of supernova (SN) explosion is given. Specifically, the new feedback model follows the dynamics of the explosion blast waves that capture the solution for all phases (from early free expansion to late snowplow), independent of simulation resolution, and allow for anisotropic propagation.

The initial condition for the simulation is generated using the MUSIC software (Hahn & Abel 2011) with WMAP7 parameters (Komatsu et al. 2011): $(\Omega_m, \Omega_{\Lambda}, \Omega_b, h, \sigma_8, n_s) = (0.272, 0.728, 0.045, 0.702, 0.82, 0.96)$. We adopt a large volume of (25 Mpc/hr$^3$) (comoving) to include the effect of large-scale tidal fields on the galaxy assembly. The entire box is covered with 256$^3$ root grids, and high-resolution dark matter particles of mass $M_{\text{dm}} = 1.6 \times 10^5 M_\odot$ are employed in the zoomed-in region of $3.8 \times 4.8 \times 9.6$ Mpc$^3$. We allow for 12 more levels of grid refinement based on the density and mass enclosed within a cell in the zoomed-in region to have a maximum spatial resolution of 4.2 pc (physical). Star formation is modeled by creating normal and runaway particles in a dense cell ($n_H > 100$ cm$^{-3}$) with the convergent flow condition (Kimm & Cen 2014, the FRU run). The minimum mass of a normal (runaway) star particle is $34.2 M_\odot$ ($14.6 M_\odot$). We use the mean specific frequency of SN II explosions of 0.02 $M_\odot^{-1}$,
assuming the Chabrier initial mass function. Dark matter halos are identified using the HaloMaker (Tweed et al. 2009).

Eight consecutive snapshots are analyzed at each redshift (\(3.96 \leq z \leq 4.00\), \(4.92 \leq z \leq 5.12\), and \(5.91 \leq z \leq 6.00\)) to increase the sample size in our calculations. At each snapshot there are \(\approx 142\), 137, and 104 halos in the halo mass range of \(10^9 \leq M_{\text{vir}} < 10^{10} M_\odot\), and 15, 10, and 7 halos with mass \(M_{\text{vir}} \geq 10^{10} M_\odot\). The most massive galaxy at \(z = 4\) (5, 6) has a stellar mass of \(1.6 \times 10^9 M_\odot\) \((6.0 \times 10^8, 2.5 \times 10^9 M_\odot)\), and host halo mass \(8.8 \times 10^{10} M_\odot\) \((5.2 \times 10^{10}, 4.1 \times 10^{11} M_\odot)\).

The escape fraction is computed as follows. We cast 768 rays per star particle and follow their propagation through the galaxy. Each ray carries the spectral energy distribution (SED), including its LyC emission, determined using STARBURST99 (Leitherer et al. 1999), given the age, metallicity, and mass of the star particle. The LyC photons are attenuated by neutral hydrogen (Osterbrock & Ferland 2006) and SMC-type dust (Draine et al. 2007) in the process of propagation. For a conservative estimate, we assume the dust-to-metal ratio of 0.4. We also simply assume that dust is destroyed in hot gas \((T > 10^6\ \text{K})\). We note that attenuation due to dust is only significant in the most massive galaxy \((M_{\text{star}} = 1.1 \times 10^9 M_\odot, \tau_d = 0.58)\) in our sample. The second most massive galaxy \((M_{\text{star}} = 3.6 \times 10^8 M_\odot)\) shows \(\tau_d = 0.29\), meaning that it reduces the number of photons by only \(<30\%\). Given that the dust-to-metal ratio is even smaller than \(0.4\) in low-metallicity systems (Lisenfeld & Ferrara 1998; Engelbracht et al. 2008; Galametz et al. 2011; Fisher et al. 2014), it is likely that the attenuation by dust is even less significant in our simulated galaxies. We define the true escape fraction of the galaxy as the ratio of the sum of all outward fluxes at the virial sphere to the sum of the initially emitted fluxes of all stellar particles in the galaxy; we shall call this \(f_{\text{esc},1D}\). In addition, an observer at infinity at a random point in the sky of the galaxy collects all LyC fluxes and defines the escape fraction along that particular line of sight; this is called \(f_{\text{esc},3D}\).

3. PROBABILITY DISTRIBUTION FUNCTIONS OF LyC PHOTON ESCAPE FRACTION

It is useful to give a qualitative visual illustration of how LyC photons may escape from galaxies at \(z = 4\). Figure 1 shows three examples of an all-sky map—the sky an observer sitting at the center of the galaxy would see—of the neutral hydrogen for the most massive \((M_{\text{vir}} = 7.8 \times 10^9 M_\odot\), top left panel), second massive \((6.1 \times 10^9 M_\odot\), top right panel), and a smaller halo \((1.8 \times 10^9 M_\odot\), bottom). The observer is placed at the center of the halo. Note that the actual escape fraction presented later is computed by ray-tracing LyC photons of all stellar particles spatially distributed through the clumpy interstellar medium until escaping through the virial sphere. The true escape fraction of LyC photons of these halos is 5.4%, 12%, and 5.0%, respectively.

![Figure 1](image-url)
This qualitative behavior has also been found earlier in independent simulations by Wise & Cen (2009).

Let us now turn to more quantitative results. Figure 2 shows the probability distribution of the apparent escape fraction for massive halos (top panel) and less massive halos (bottom panel) at $z = 4$ (left column) and $z = 6$ (right column). Black histograms show the distribution of the true escape fraction of each sample, while red histograms show the PDF of the apparent escape fraction. The median of the distributions is shown as arrows.

Figure 2. Probability distribution of the apparent escape fraction for massive halos (top panel) and less massive halos (bottom panel) for $z = 4$ (left column) and $z = 6$ (right column). Black histograms show the distribution of the true escape fraction of each sample, while red histograms show the PDF of the apparent escape fraction.

Figure 3. Similar to Figure 2, except the galaxy sample is subdivided according to their star formation rates, SFR = 0.3–10 $M_\odot$ yr$^{-1}$ (top panel), 0.01 to 0.3 $M_\odot$ yr$^{-1}$ (middle panel), and < 0.01 $M_\odot$ yr$^{-1}$ (bottom panel).

Cen 2014). This qualitative behavior has also been found earlier in independent simulations by Wise & Cen (2009).

Let us now turn to more quantitative results. Figure 2 shows the probability distribution of the apparent escape fraction for massive halos (top) and less massive halos (bottom) at $z = 4$ (left column) and $z = 6$ (right column). Black histograms show the distribution of the true (3D) escape fraction of each sample (i.e., from the viewpoint of the overall intergalactic medium), while red histograms show the PDF of the apparent escape fraction (i.e., from the point of view of observers placed at a far distance). Note that the distribution of the true escape fraction is noisier than that of the apparent escape fraction due to the smaller sample size for the former, because for the 3D escape fraction each galaxy is counted once but for the apparent escape fraction each galaxy is sampled many times. In terms of the mean escape fraction, there is a trend that, at a given redshift, the galaxies embedded in more massive halos tend to have a lower mean escape fraction.

There is also a weak trend that the escape fraction increases with redshift. For example, the true (3D) median escape
fractions are (7.0%, 9.5%) for the halos of masses ($\geq 10^{10}, 10^{9} - 10^{10}$) $M_\odot$, respectively, at $z = 4$; the true (3D) median escape fractions are (8.8%, 29%) for halos of masses ($\geq 10^{10}, 10^{9} - 10^{10}$) $M_\odot$, respectively, at $z = 6$. Upon close examination we suggest that the redshift dependence can be attributed, in part, to the following findings. At a given halo mass, the specific star formation rate (SFR) decreases with decreasing redshift at $\leq z \leq 6$. As star formation becomes less episodic at lower redshifts, it takes longer to blow out the star-forming clouds via SNe. Consequently, a larger fraction of LyC photons is absorbed by their birth clouds. We also find that the specific SFR does not change notably at $z > 6$ while the mean density of the halo increases with redshifts, explaining an opposite trend found in Kimm & Cen (2014) at $7 \leq z \leq 11$. The predicted median escape fraction for halos with $10^9 \leq M_{\text{halo}} \leq 10^{11} M_\odot$ at $4 \leq z \leq 6$ is generally smaller than the previous studies (10%–30%; Razoumov & Sommer-Larsen 2010; Yajima et al. 2014), although the trend at $z < 6$ is broadly consistent with Razoumov & Sommer-Larsen (2010). Nevertheless, it is prudent to bear in mind that the sometimes conflicting results and trends among studies with respect to redshift may be in part due to still limited galaxy sample sizes.

Figure 3 is similar to Figure 2, except the galaxy sample is subdivided according to their SFRs. We note that this division according to SFRs introduces subtle degeneracies. For example, a lower SFR does not necessarily correspond to a
less massive galaxy; instead, a lower SFR may correspond to the phase of a galaxy between two star formation bursts. The significantly higher escape fraction for the lowest SFR bin (bottom panels) is, for the most part, due to a post-starburst phase when the interstellar medium has been cleared out by the preceding burst and SFR has abated, as noted in Kimm & Cen (2014). Thus, if we do not consider the lowest SFR bin, it seems that the mean escape fraction does not strongly depend on SFR at $z = 4–6$. The escape fraction from the most actively star-forming galaxy sample with $0.3 < \text{SFR} < 10 \, M_{\odot} \, \text{yr}^{-1}$ may be compared with that of Lyman alpha emitters or faint LBGs. Our simulations suggest that the median $f_{\text{esc},1D}$ of the sample is 5.1%, which is consistent with $f_{\text{esc},1D} = 5 - 15\%$ inferred from narrow-band filter imaging observations of 91 LAEs (Mostardi et al. 2013). We note that, given the wide distribution of the simulated apparent escape fraction ($0.1\% \lesssim f_{\text{esc},1D} \lesssim 23\%$ or $0.001\% \lesssim f_{\text{esc},1D} \lesssim 47\%$ for the 1σ and 1.5σ range, respectively), our results are also compatible with the individual detection of LyC fluxes from.

### Table 1

| $N_{\text{stack}}$ | $z = 4$ | $z = 5$ | $z = 6$ |
|---------------------|---------|---------|---------|
|                     | $(f_{\text{esc},1D}^1, f_{\text{esc},1D}^2, f_{\text{esc},1D}^3, f_{\text{esc},1D}^4)^{\text{median}}$ | $(f_{\text{esc},1D}^1, f_{\text{esc},1D}^2, f_{\text{esc},1D}^3, f_{\text{esc},1D}^4)^{\text{median}}$ | $(f_{\text{esc},1D}^1, f_{\text{esc},1D}^2, f_{\text{esc},1D}^3, f_{\text{esc},1D}^4)^{\text{median}}$ |
| 1                   | (0.001, 0.004, 3.21, 12.4) | (0.002, 0.097, 4.57, 14.6) | (0.004, 0.162, 3.19, 7.16) |
| 2                   | (0.001, 0.091, 2.34, 6.14) | (0.011, 0.231, 2.56, 7.45) | (0.092, 0.358, 2.41, 4.58) |
| 5                   | (0.091, 0.552, 1.81, 3.48) | (0.151, 0.470, 1.87, 3.36) | (0.311, 0.577, 1.65, 2.63) |
| 10                  | (0.251, 0.509, 1.59, 2.56) | (0.317, 0.601, 1.59, 2.48) | (0.460, 0.682, 1.42, 1.96) |
| 20                  | (0.405, 0.634, 1.53, 2.02) | (0.460, 0.703, 1.39, 1.92) | (0.588, 0.763, 1.28, 1.61) |
| 50                  | (0.580, 0.755, 1.27, 1.59) | (0.624, 0.805, 1.24, 1.51) | (0.717, 0.848, 1.17, 1.36) |
| 100                 | (0.684, 0.823, 1.18, 1.40) | (0.738, 0.859, 1.16, 1.34) | (0.795, 0.889, 1.12, 1.24) |
| 1000                | (0.892, 0.942, 1.05, 1.11) | (0.910, 0.951, 1.05, 1.10) | (0.930, 0.965, 1.03, 1.07) |

### 1σ and 2σ Ranges of LyC Escape Fraction in Terms of Sample Size, Stellar Mass, and Redshift

- $10^0 \leq M_{\odot}/M_{\odot} < 10^1$
- $10^0 \leq M_{\odot}/M_{\odot} < 10^{10}$
- $0.3 \leq \text{SFR} < 10$
- $0.1 \% \leq f_{\text{esc,1D}} \leq 47\%$
- $0.1 \% \leq f_{\text{esc,1D}} \leq 47\%$
- $0.01 \% \leq f_{\text{esc,1D}} \leq 47\%$
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seven LBGs (Iwata et al. 2009) 5.5 \lesssim f_{esc,1D} \lesssim 55\% for the intrinsic UV to LyC flux ratio of 3).

Evidently, the distribution of the apparent LyC escape fraction is very broad and skewed toward the lower end. The reason for this behavior is understandable. In the case of galaxies with low $f_{esc,1D}$ values, the LyC photons escape normally through transparent holes with small solid angles. Since not all of these holes are seen by an observer, the distribution of $f_{esc,1D}$ for individual galaxies tends to get skewed toward the lower end of the distribution. As a result, the medians of the two distributions, shown as arrows in Figure 2, are about a factor of ~2 smaller than the mean. More importantly, it suggests that an observational sample of limited size may underestimate the true mean escape fraction. The top two panels of Figure 4 show the PDF of the apparent mean for a given observational sample size $N_{stack}$ for the high mass (top) and low mass (bottom) sample, respectively. We compute the apparent mean of a sample of galaxies using LyC photon (or SFR)-weighted mean escape fraction, which is exactly equivalent to stacking the galaxies. The bottom two panels of Figure 4 are similar to the top two panels in Figure 4 for subsamples with different SFRs. What we see in these figures is that the probability distribution is rather broad. It is thus clear that it is not a robust exercise to try to infer the mean escape fraction based on a small sample (<10) of galaxies, whether individually measured or through stacking.

Table 1 provides a quantitative assessment of the uncertainties, which shows the 1σ and 2σ probability intervals of fractional lower and upper deviations from the true mean escape fraction. Some relatively mild trends that are consistent with earlier observations of the figures are seen. Specifically, the convergence to the true mean escape fraction in terms of sample sizes is faster toward high redshift, toward higher halo mass, and toward higher SFRs. Let us take a few numerical examples. We see that with a sample of 50 galaxies of halo mass in the range of $(10^{10} - 10^{11}) M_\odot$ at $z = 4$ the 2σ fractional range of the escape fraction is 58%–159%, which improves to a range of 68%–140% when a sample of 100 galaxies is used. Note that the observations of Mostardi et al. (2013) have 49 Lyman break galaxies and 91 Lyman alpha emitters at $z \sim 2.85$. At $z = 6$ for the $(10^{10} - 10^{11}) M_\odot$ halo mass range, we see that with a sample of 20 galaxies, the 2σ fractional range of the escape fraction is 59%–161%, comparable to that of a sample of 50 galaxies at $z = 4$, as a result of benefiting from faster convergence at higher redshift. On the other hand, at $z = 5$ for the $(0.3 - 10) M_\odot$ yr$^{-1}$ SFR range, the 2σ fractional range of the escape fraction is 56%–163% with a sample of 20 galaxies, which is improved to 71%–137% with a sample of 50 galaxies.

Finally, we note that the actual observed LyC escape fraction has additionally suffered from possible absorbers in the intergalactic medium, primarily Lyman limit systems. Since the background galaxy and the foreground absorbers are physically unrelated, we may consider the effects from the internal factors in galaxies and those from the intergalactic medium to be completely independent. Thus, in this case, assuming no knowledge of the foreground absorbers, the overall distribution would be the convolution of the two, resulting in a still broader overall distribution than derived above when considering internal factors alone. In reality, however, one may be able to remove, to a large degree, the LyC opacity due to intergalactic absorbers by making use of a tight correlation between Ly$\alpha$ and LyC absorption (Inoue & Iwata 2008).

4. CONCLUSIONS

We have simulated a significant sample of galaxies that are resolved at 4 parsec scales, important for capturing the structure of the interstellar medium (e.g., Joung & Mac Low 2006). We have also implemented a much improved SN feedback method that captures all phases of the Sedov–Taylor explosion solution and has been shown to yield the correct final momentum driven by the explosion regardless of the numerical resolution (Kimm & Cen 2014). An adequate treatment of both these two requirements is imperative, before one can start properly addressing the issue of LyC escape, because most of the escape LyC photons escape through “holes” in the interstellar medium, instead of them uniformly leaking out in a “translucent” medium. In Kimm & Cen (2014) we address the escape fraction for galaxies at the epoch of reionization to provide the physical basis for stellar reionization.

Here we quantify the distribution of escape fraction for galaxies as a whole, at a range of redshift from $z = 4$ to $z = 6$. In general, it is found that the LyC escape fraction depends strongly on the view angle of the observer and the overall distribution of the escape fraction sampled over many sightlines is very broad. The distribution narrows with increasing halo mass or SFR or redshift. This broad distribution introduces large sampling uncertainties, when the galaxy sample size is limited. For example, a sample of 50 galaxies of halo mass in the range of $(10^{10} - 10^{11}) M_\odot$ at $z = 4$ produces the 2σ fractional range of the escape fraction of 58%–159%. At $z = 5$, a sample of 20 galaxies with SFR in the range of $(0.3 - 10) M_\odot$ yr$^{-1}$ gives the 2σ fractional range of the escape fraction to be 56%–163%. Our analysis suggests that at least on order of tens of galaxies is needed before one is confident at the 2σ level that the mean escape fraction measured does not deviate from reality by 30%–50% at $z = 4 – 6$ for galaxies hosted by halos of mass in the range of $(10^{10} - 10^{11}) M_\odot$.

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