Escape fraction of ionizing photons from high-redshift galaxies in cosmological SPH simulations

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Abstract

Combing the three-dimensional radiative transfer (RT) calculation and cosmological SPH simulations, we study the escape fraction of ionizing photons \( f_{\text{esc}} \) of high-redshift galaxies at \( z = 3 - 6 \). Our simulations cover the halo mass range of \( M_h = 10^9 - 10^{12} M_\odot \). We postprocess several hundred simulated galaxies with the Authentic Radiative Transfer (ART) code to study the halo mass dependence of \( f_{\text{esc}} \). In this paper, we restrict ourselves to the transfer of stellar radiation from local stellar population in each dark matter halo. We find that the average \( f_{\text{esc}} \) steeply decreases as the halo mass increases, with a large scatter for the lower mass haloes. The low mass haloes with \( M_h \sim 10^9 M_\odot \) have large values of \( f_{\text{esc}} \) (with an average of \( \sim 0.4 \)), whereas the massive haloes with \( M_h \sim 10^{11} M_\odot \) show small values of \( f_{\text{esc}} \) (with an average of \( \sim 0.07 \)). This is because in our simulations, the massive haloes show more clumpy structure in gas distribution, and star-forming regions are embedded inside these clumps, making it more difficult for the ionizing photons to escape. On the other hand, in low mass haloes, there are often conical regions of highly ionized gas due to the shifted location of young star clusters from the center of dark matter halo, which allows the ionizing photons to escape more easily than in the high-mass haloes. By counting the number of escaped ionizing photons, we show that the star-forming galaxies can ionize the intergalactic medium at \( z = 3 - 6 \). The main contributor to the ionizing photons is the haloes with \( M_h \lesssim 10^{10} M_\odot \) owing to their high \( f_{\text{esc}} \). The large dispersion in \( f_{\text{esc}} \) suggests that there may be various sizes of H\( \text{ii} \) bubbles around the haloes even with the same mass in the early stages of reionization. We also examine the effect of UV background radiation field on \( f_{\text{esc}} \) using simple, four different treatment of UV background.

Key words: radiative transfer – ISM: dust, extinction – galaxies: evolution – galaxies: formation – galaxies: high-redshift – methods: numerical

1 Introduction

Observations of cosmic microwave background radiation provides a wealth of information on the cosmic reionization history (e.g., Page et al. 2007; Dunkley et al. 2008). For example, Komatsu et al. (2010) showed that the reionization occurred at \( z \sim 10.5 \) assuming an instantaneous reionization scenario. However, the detailed history of reionization and the nature of ionizing sources are not yet fully understood. Since the UV background (UVB) radiation can heat up the interstellar medium (ISM) to \( \sim 10^4 \)K and disturb star formation, UVB coupled with the ionization history of the universe significantly influences the galaxy formation (e.g., Susa & Umemura 2008; Umemura et al. 2001; Susa & Umemura 2004; Okamoto et al. 2008; Hasegawa et al. 2009). Therefore it is very important to study the UVB intensity and the nature of ionizing sources.

Haardt & Madau (1996) pointed out that the UVB is dominated by quasars at \( z < 4 \). Using the SDSS sample, Fan et al. (2001) showed that the bright-end slope of the quasar luminosity function at \( z \gtrsim 4 \) are considerably steeper than that at lower redshifts, and concluded that the quasars cannot maintain the ionization of IGM at \( z \gtrsim 4 \). Subsequently, much argument have been focused on the possibility that the IGM is ionized mainly by the UV radiation from high-redshift (hereafter high-\( z \)) star-forming galaxies (e.g., Fan et al. 2006; Bouwens et al. 2007).
The key quantity in determining the IGM ionization rate is the escape fraction of ionizing photons (e.g., Razoumov & Sommer-Larsen 2006, Gnedin et al. 2008), which is the number ratio of photons escaping from a galaxy to the intrinsically radiated photons by stars. This parameter controls the contribution to the UVB intensity from star-forming galaxies. In this work, we examine the values of $f_{\text{esc}}$ in high-$z$ star-forming galaxies.

There are several observational constraints on $f_{\text{esc}}$ at $z \sim 3$. Steidel et al. (2001) found $f_{\text{esc,rel}} \gtrsim 0.5$ from the composite spectrum of 29 Lyman Break Galaxies (LBGs) at $z \sim 3$, where $f_{\text{esc,rel}}$ is the relative fraction of escaping Lyman continuum (900 Å) photons relative to the fraction of escaping non-ionizing UV (1500 Å) photons. It is usually defined as

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

where $(F_{1500}/F_{900})_{\text{obs}}, (L_{1500}/L_{900})_{\text{int}}$ and $\tau_{900}$ 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 (1) compares the observed flux density ratio (corrected for the IGM opacity) with the models of UV spectral energy distribution of star-forming galaxies.

Giallongo et al. (2002) and Inoue et al. (2005) estimated the upper limit of $f_{\text{esc,rel}} \lesssim 0.1 - 0.4$ for some LBGs at $z \sim 3$. Shapley et al. (2006) directly detected the escaping ionized photons from 2 LBGs in the SSA22 field at $z = 3.1$, and estimated the average value of $f_{\text{esc,rel}} = 0.14$. Moreover, Iwata et al. (2000) successfully detected the Lyman continuum 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 $f_{\text{esc,rel}}$ for the 7 LBGs is 0.11 after correcting for dust extinction, and 0.20 if the IGM absorption is taken into account.

In the early theoretical works, some authors studied the $f_{\text{esc}}$ with ideally modelled galaxies. For example, Dove & Shull (1994) estimated the $f_{\text{esc}}$ of Milky Way type galaxy using a semi-analytic method, and reported $f_{\text{esc}} \sim 0.07$. Ricotti & Shull (2000) investigated the dependence of $f_{\text{esc}}$ on various physical quantities, such as the collapse redshift and star formation efficiency using a semi-analytic method. Wood & Loeb (2000) and Cardi et al. (2002) studied the effect of inhomogeneous structure of gas on $f_{\text{esc}}$, and showed that $f_{\text{esc}}$ increases in clumpy systems by a factor of $> 2$ than in a homogeneous gas distribution. Dove et al. (2000) investigated the influence of bubbles made by supernovae on $f_{\text{esc}}$ using a semi-analytic method. Using numerical simulations, Fujita et al. (2003) studied the effect of supernovae feedback, and reported a high $f_{\text{esc}} (> 0.2)$ for a disk galaxy with $M_h = 10^8 - 10^{10}M_\odot$.

Theoretical studies in a more fully cosmological environment can be performed by combining cosmological hydrodynamic simulations of galaxy formation and a three-dimensional radiative transfer calculation. For example, Yajima et al. (2009, hereafter Y09) post-processed the eulerian hydrodynamic simulation of Mori & Umemura (2006) with RT, and showed that the galaxies in an isolated halo of $M_h = 10^{11}M_\odot$ can have relatively large values of $f_{\text{esc}} = 0.17 - 0.47$. Moreover they found that $f_{\text{esc}}$ decreases gradually as a function of time owing to the dust pollution and the shifting star formation sites.

On the other hand, Razoumov & Sommer-Larsen (2006) examined the escape fractions of two galaxies in a cosmological SPH simulation from $z = 3.8$ to 2.4, which later become Milky Way type disk galaxies at $z = 0$. They found small values of $f_{\text{esc}} < 0.1$, in disagreement with Y09. However they also reported that $f_{\text{esc}}$ decreases with redshift from $z = 3.8$ to 2.4, in qualitative agreement with Y09.

Razoumov & Sommer-Larsen (2010) further examined the $f_{\text{esc}}$ of star-forming galaxies in a wide mass range ($M_h = 10^{7.8} - 10^{11.5}M_\odot$) at $z = 4 - 10$, and found that $f_{\text{esc}}$ decreases steeply as the halo mass increases in their cosmological SPH simulations, in contrast to the work by Gnedin et al. (2008) and Wise & Cen (2009).

Using cosmological AMR simulations, Gnedin et al. (2008) reported that haloes with $M_h = 10^{11} - 10^{12}M_\odot$ have $f_{\text{esc}} = 0.01 - 0.03$, and much lower $f_{\text{esc}}$ for lower mass haloes with $M_h = 10^9 - 10^{11}M_\odot$. Their results suggest that $f_{\text{esc}}$ increases with halo mass, at least in the range of $M_h = 10^{10} - 10^{11}M_\odot$.

Wise & Cen (2009) extracted 10 haloes with masses $M_h = 3 \times 10^6 - 3 \times 10^8M_\odot$ at $z = 8$ from cosmological AMR radiation hydrodynamical simulations, and examined the escape fraction of ionizing photons. They found that $f_{\text{esc}}$ fluctuates rapidly on a time-scale of a few to 10 Myrs depending on the star formation rates, and varies widely from almost zero to nearly unity. They found $f_{\text{esc}} \sim 0.4$ for a normal IMF for the haloes with $M_h = 10^{7.5} - 10^{9.5}M_\odot$, but $f_{\text{esc}} = 0.05 - 0.1$ for lower mass haloes, disregarding the effect of dust.

Although the halo mass dependence of $f_{\text{esc}}$ is very important for the study of cosmic reionization, there are significant differences in the theoretical estimates from cosmological hydrodynamical simulations as described above. In particular, in these previous works, the number of studied haloes has been very small ($\sim 10$), therefore it has been difficult to gauge the halo mass dependence of $f_{\text{esc}}$. In the present paper, we calculate the values of $f_{\text{esc}}$ for a much larger number of haloes (several hundreds) in cosmological volumes of comoving $10 - 100h^{-1}$Mpc, and examine its halo mass dependence. In addition, we study the effects of interstellar dust and UVB radiation on $f_{\text{esc}}$.

The outline of the paper is as follows. In §2 the models and numerical methods are described. We present the results on escape fractions in §3 and discuss the dust effect and the contribution of star-forming galaxies to the reionization of the universe in §4. We then summarise in §5.

## 2 MODEL AND METHOD

### 2.1 Simulations

We use an updated and modified version of the Tree-particle-mesh (TreePM) smoothed particle hydrodynamics (SPH) code GADGET-3 (originally described in Springel 2001). The SPH calculation is performed based on the entropy conservative formulation (Springel & Hernquist 2002). Our fiducial code includes radiative cooling by H, He, and metals (Choi & Nagamine 2009), star formation, supernova feedback, a phenomenological model for galactic winds
Table 1. Series of simulations employed for the present study. The box-size is given in units of $h^{-1}$Mpc, $N_p$ is the particle number of dark matter and gas (hence $\times 2$), $m_{DM}$ and $m_{gas}$ are the masses of dark matter and gas particles in units of $h^{-1}M_{\odot}$, respectively, $\epsilon$ is the comoving gravitational softening length in units of $h^{-1}$kpc, and $z_{\text{end}}$ is the ending redshift of the simulation. The value of $\epsilon$ is a measure of spatial resolution.

| Series       | Box-size | $N_p$ | $m_{DM}$     | $m_{gas}$     | $\epsilon$ | $z_{\text{end}}$ |
|--------------|----------|-------|--------------|--------------|-------------|-----------------|
| N144L10      | 10.00    | $2 \times 144^3$ | $1.97 \times 10^7$ | $4.94 \times 10^6$ | 2.78        | 2.75            |
| N216L10      | 10.0     | $2 \times 216^3$  | $5.96 \times 10^6$  | $1.21 \times 10^6$  | 1.85        | 2.75            |
| N400L100     | 100.0    | $2 \times 400^3$  | $1.12 \times 10^8$  | $1.91 \times 10^8$  | 6.45        | 0.0             |

In this paper, the RT equation is solved along a uniform grid of $N^2_k$ rays with uniform angular resolution from each source. The number of ionizing photons emitted from the source stars is computed based on the theoretical spectral energy distribution (SED) given by the population synthesis code PÉGASE v2.0 (Fioc & Rocca 1997). We take only the star particles that are younger than $10^7$ yrs as the sources of ionizing photons, and consider the effect of age and metallicity of the stellar population by interpolating the table generated from the result of PÉGASE. We shoot the radiation rays in a radial fashion from each star particles. We assume the Salpeter (1955) initial mass function with the mass range of $0.1 - 50M_{\odot}$.

Typically the post-processing RT calculation takes about 100 hours for a large grid of $300^3$, and 1 hour for a small grid of $70^3$ on a single CPU. Our ART code is paral-
lelized by MPI, and has a high parallelization efficiency. We process each star particle in parallel, and each CPU calculates the radiation field from each star particle. In practice, we use $\sim 1 - 128$ CPUs simultaneously to process one halo with RT.

### 2.3 Dust Attenuation

We also include the effect of dust attenuation by distributing the interstellar dust proportionally to the metallicity, with a size distribution of $n_d(a_d) \propto a_d^{-3.5}$ (Mathis et al. 1977), where $a_d$ is the radius of a dust grain. We adopt the dust grain size range of $0.1 - 1.0 \mu$m as our fiducial model. The dust mass is calculated as $m_d = 0.01 m_\odot (Z/Z_\odot)$ (Draine et al. 2007), where $m_d$, $m_\odot$, and $Z$ are the dust mass, gas mass, and metallicity in a grid. The density of a dust grain is assumed to be $3 \text{ g/cm}^3$ like silicates. The dust opacity is given by $d\tau_{\text{dust}} = Q(\nu)\pi a_d^2 n_d d\ell$, where $Q(\nu)$, $a_d$, $n_d$, and $d\ell$ are the absorption efficiency factor, dust size, number density of dust grains, and path length, respectively. Since the assumed range of dust size is larger than the wavelength of Lyman limit, we assume $Q(\nu) = 1$ for ionizing photons (Draine & Lee 1984).

### 2.4 UV Background Radiation

The baryonic gas in galaxies can be ionized by the UVB, and heated up to $\sim 10^4 \text{ K}$. It would be ideal to compute the RT of UVB as well as the stellar radiation, but in practice it is a very expensive calculation.

Let us briefly explain why the UVB RT calculation is much heavier than the stellar radiation transfer. For stellar radiation, using on-the-spot approximation, we only calculate the RT along the angular rays between stars and grids with the dilution factor by the distance, whereas for UVB we have to calculate the RT of all angular rays. Therefore in the ART method, the number of rays that we have to calculate is $N_{\text{star}} \times N_\odot \times N_\delta \times N_{\text{path}} \approx N_{\text{star}} \times N_\delta^2$ for stellar radiation, and $N_\delta^2$ for UVB. If $N_\delta^2 > N_{\text{star}}$, the calculation amount for UVB is larger than the stellar radiation. In practice, $N_\delta^2$ is greater than $N_{\text{star}}$ by $\sim 2 - 4$ orders of magnitude.

Due to this difficulty of UVB RT, usually a uniform UVB radiation field with an optically thin approximation is assumed across the simulation box as a simple approximation. Our fiducial simulation also includes a uniform UVB with a modified Haardt & Madau (1996) spectrum (see Davé et al. 1999), where the reionization takes place at $z \simeq 6$ as suggested by the quasar observations (e.g., Becker et al. 2001) and stellar radiative transfer calculations (e.g., Solasian et al. 2003).

However, the optically thin approximation is very crude, and the effects of different UVB has not been explored very much. Here we use following four N144L10 simulations with different treatment of UVB to examine the effects of UVB:

(i) **Fiducial**: A uniform UVB radiation field with an optically thin approximation is assumed as stated above.

(ii) **MH0.5** (modified Haardt 0.5): The ISM is optically thin to the same UVB, however the intensity of UVB is reduced to the half of the Fiducial run.

(iii) **OTUV** (optically thick UV): The ISM is optically thin to the UVB in the lower density regions with $n_{\text{HI}} < 0.01 \rho_{\text{th}} = 6.34 \times 10^{-3} \text{ cm}^{-3}$, but completely optically thick in higher density region ($n_{\text{HI}} \geq 0.01 \rho_{\text{th}}$), where $\rho_{\text{th}}$ is the threshold density, above which star formation is allowed. The value of $\rho_{\text{th}}$ was determined by Choi & Nagamine (2009a) based on the observed SF cut-off column density of the Kennicutt law. The OTUV method implicitly assumes that the UVB cannot penetrate into the high density regions by self-shielding. We find that this treatment reproduces the observed H I column density distribution function very well (Nagamine et al. 2011), and more detailed analyses using RT calculation supports this self-shielding density (Yajima et al. 2010, in preparation).

(iv) **no-UVB**: UVB does not exist at all.

We compute the ionization structure in each halo by solving the equation of ionization equilibrium as follows:

$$
(\Gamma_{\text{UVB}}^i + \Gamma_{\text{star}}^i) n_{\text{HI}} + \Gamma_{\text{C}}^i n_{\text{HI}} n_e = \alpha_{\text{B}} n_{\text{HI}} n_e,
$$

where $\Gamma_{\text{UVB}}^i$ and $\Gamma_{\text{star}}^i$ are the photoionization rate by UVB and stellar radiation; $\Gamma_{\text{C}}^i$ is the collisional ionization rate; $n_e$, $n_{\text{HI}}$ and $n_{\text{HI}}$ are the number density of free-electron, neutral and ionized hydrogen, respectively; $\alpha_{\text{B}}$ is the total recombination coefficient to all bound excitation levels. The value of $\Gamma_{\text{star}}^i$ is estimated by the full RT calculation, but $\Gamma_{\text{UVB}}^i$ is computed with the optically thin approximation.

### 3 RESULTS

#### 3.1 Ionization Structure

Figure 1 shows the ionization structure of gas in a high-mass halo (Halo “A”) and a low-mass halo (Halo “B”) in the N144L10 Fiducial UVB run.

The gas in Halo-A shows very complex and clumpy structure, going through continuous merging processes. The young star clusters are born in dense, neutral clumpy regions and irradiate the ambient ISM. However, the dense neutral gas clumps survive owing to high recombination rates.

On the other hand, the Halo-B shows more or less spherical gas distribution before we process it with RT. Star clusters are born near the central high-density region. Once the halo is processed with RT, most of the low density gas on the right-hand-side is ionized by the UVB and stellar radiation.

In particular, when the location of a young star cluster is slightly off-center, it can ionize one side of the halo preferentially, and creates a conical region of highly ionized region.

The high density gas on the left-hand-side of the star cluster remains neutral, and the ionizing photons cannot escape to the left-hand-side. The value of angle-averaged $f_{\text{esc}}$ of each halo is basically determined by the covering fraction of these highly ionized region.

#### 3.2 Escape Fraction

We estimate the average value of $f_{\text{esc}}$ for each dark matter halo as follows. For each light ray from each star particle in the halo, we count up the number of escaped ionizing photons by integrating the transferred spectrum as a function...
of wavelength, and then divide it by the total number of intrinsically radiated ionizing photons. Then the values of \(f_{\text{esc}}\) are averaged over all the rays coming out from the halo at the surface of the grid that was set up around the halo. Hereafter \(f_{\text{esc}}\) denotes the angle-averaged value for each halo most of the time.

### 3.2.1 Halo Mass and Redshift Dependence

Figure 2 shows the \(f_{\text{esc}}\) as a function of halo mass at \(z = 3 - 6\) for the N144L10 Fiducial UVB run. The solid triangles are the average values of \(f_{\text{esc}}\) in each mass bin with 1-\(\sigma\) error bars. We first take the average in the linear scale, and then take the logarithm for the data points (i.e., \(\log(f_{\text{esc}})\)). At all redshifts, we find a clear qualitative trend that the mean \(f_{\text{esc}}\) declines with increasing halo mass.

Our results are similar to the trend reported by Razoumov & Sommer-Larsen (2010), although our \(f_{\text{esc}}\) values are lower than theirs. Our results show the opposite trend to Gnedin et al. (2008), although for high-mass galaxies, our \(f_{\text{esc}}\) is similar to theirs. In Gnedin et al. (2008), most of the simulated galaxies show a disk-like structure. In their scenario, for low mass galaxies, stars are born after the disk is formed, and most young stars are embedded deep inside the disk. As a result, most of the ionizing photons are absorbed in the disk, and \(f_{\text{esc}}\) is low. However in more massive galaxies, some star-clusters can form near the edge of dense disk, and they can be exposed by the mergers of galaxies. As a result of this effect, they argued that more ionizing photons can escape from higher mass haloes. Therefore the geometry of simulated galaxies may cause the difference in the halo mass dependence of \(f_{\text{esc}}\).

The galaxy sample size in Gnedin et al. (2008) and Razoumov & Sommer-Larsen (2010) is \(\sim 10 - 20\), and it is somewhat small to discuss the systematic trend of \(f_{\text{esc}}\) as a function of halo mass. The spatial resolution of Gnedin et al. (2008), which is adaptively refined depending on the gas density, is from \(\sim 17\) kpc to 260 pc. Although this resolution of maximum refinement level is better than that of ours, their RT scheme (OTVET) is coarser in estimating the ionization structure (Iliev et al. 2006). These differences in the accuracy and resolution of fluid and RT calculations may have caused the difference in \(f_{\text{esc}}\). We will further discuss the possible resolution effects in Section 5.

Figure 3 shows the redshift evolution of mean \(f_{\text{esc}}\) in each halo mass bin. In Razoumov & Sommer-Larsen (2010),
the $f_{\text{esc}}$ of high-mass haloes with $M_h > 10^{10} M_\odot$ clearly decreases with redshift (blue open circles), and that of the low-mass haloes does not change largely. On the other hand, our results and Gnedin et al. (2008) indicate that $f_{\text{esc}}$ of high-mass haloes with $M_h > 10^{10} M_\odot$ does not change largely with redshift. For low-mass haloes with $M_h < 10^{10} M_\odot$, it seems that $f_{\text{esc}}$ is increasing slightly with decreasing redshift in our simulations. This might be due to the increasing cosmic SFR density and increasing UVB intensity from $z = 6$ to $z = 3$. Indeed, we calculate the radiative transfer without the contribution of UVB in Eq. (2) for the Fiducial run at $z = 3$ with the same gas and stellar distribution, $f_{\text{esc}}$ decreases by $\sim 10 - 20$ per cent. In addition, the mass fraction of gas with $\log n_H > 6.0$ within haloes increases with increasing redshift, which leads to lower escape fraction due to higher recombination rate.

Figure 4 shows the probability distribution function (PDF) of star particles as a function of $f_{\text{esc}}$ in haloes with $M_h \leq 10^{11} M_\odot$ (top panel) and $M_h > 10^{11} M_\odot$ (bottom panel). The probability is defined by $P(f_{\text{esc}}) = N_{\text{star}}(f_{\text{esc}})/(N_{\text{star, total}}(\Delta f_{\text{esc}}))$, where $N_{\text{star}}$ is the number of star particles that have the value of $f_{\text{esc}}$, $N_{\text{star, total}}$ is the total number of source star particles, and $\Delta f_{\text{esc}}$ is the bin width. The figure shows that the lower mass haloes have a longer tail towards higher values of $f_{\text{esc}}$. Since the ionization structure in low-mass haloes shows conical regions of highly ionized gas, ionizing photons can escape easily through these ionized cones, but not through other angular directions covered by highly neutral gas. This allows for some star particles in lower mass haloes to have high $f_{\text{esc}}$. On the other hand, the higher mass haloes show very complex and clumpy distribution of highly neutral gas, therefore it is more difficult for the ionizing photons to escape, and there are no star particles with $f_{\text{esc}} > 0.6$. Thus the PDF for higher mass haloes is concentrated at $f_{\text{esc}} < 0.1$.

We also find that there is a large dispersion in $f_{\text{esc}}$ for the low-mass haloes with $M_h \leq 10^{11} M_\odot$. This result may explain some of the recent observations. For example, Shapley et al. (2004) and Iwata et al. (2004) detected ionizing radiation from high-$z$ galaxies, with a detection rate of about 10 per cent. The detected galaxies show extremely high $f_{\text{esc}}$ ($\sim 100$ per cent). Our results do not show such high values of $f_{\text{esc}}$, however the $f_{\text{esc}}$ derived by Shapley et al. (2004) and Iwata et al. (2009) are estimated from the flux ratio at the Lyman limit and UV continuum. Recently Inoue (2010) pointed out that the nebulae emission lines can boost the above flux ratio, leading to a very high $f_{\text{esc}}$ with an assumption that the $f_{\text{esc}}$ of nebular and stellar emission is a few tens of per cent.

In our simulation sample, about 10 per cent show high $f_{\text{esc}}$ ($> 0.4$). These galaxies may corresponding to the recently observed objects with very high $f_{\text{esc}}$. Furthermore, Iwata et al. (2004) showed that $f_{\text{esc}}$ decreases with increasing UV flux. In our simulations, SFR is positively correlated with halo mass, therefore our result of decreasing $f_{\text{esc}}$ with increasing halo mass is consistent with that of Iwata et al. (2004).
3.2.2 Dependence on the UVB Models

Figure 4 shows $f_{\text{esc}}$ as a function of halo masses for different UVB model runs at $z = 3$. Similarly to the Fiducial UVB model run, $f_{\text{esc}}$ decreases as the halo mass increases in all UVB models. Since the ionization fraction of gas should increase with the increasing UVB intensity, one would naively expect a higher $f_{\text{esc}}$ for the runs with stronger UVB intensities. However, when the UVB intensity increases, the stronger gas heating results in less efficient cooling of gas and hence less star formation. This reduces the number of ionizing photons, and decreases the ionization fraction around the star-forming regions. Therefore these two competing effects counteract each other and self-regulate the ionization fraction described in the text.

We also considered the possibility that the sites of star formation might be different depending on the UVB intensity. Figure 4 shows the probability distribution function (PDF) of star particles as a function of $f_{\text{esc}}$ at $z = 3$ in the N144L10 Fiducial UVB run. The top panel shows the PDF of all star particles in haloes with $M_h < 10^{11} M_\odot$, and the bottom panel is for haloes with $M_h > 10^{11} M_\odot$. Lower mass haloes contain more star particles with larger $f_{\text{esc}}$. The probability in the extended tail is very small. If a star cluster is farther away from the gas density peak, the value of $f_{\text{esc}}$ would increase because the solid angle subtended by the high-density neutral clouds would become smaller.

3.2.3 Origin of Scatter in $f_{\text{esc}}$

To further investigate the effect of star cluster locations on $f_{\text{esc}}$, we plot $f_{\text{esc}}$ as a function of $R_{\text{rel}}$ for each halo in different UVB models in Figure 5. Here again, we selected only the low-mass haloes that include only one young star particle to focus on the scatter in $f_{\text{esc}}$ of the low-mass haloes. The gas near the density peak has high recombination rate, and therefore optically thick. The value of $f_{\text{esc}}$ strongly depends on the size of viewing angle to optically thick cloud from the source. As the source deviates from the central density peak, the viewing angle towards optically thick clouds decreases. Thus, $f_{\text{esc}}$ increases with increasing $R_{\text{rel}}$. Moreover, the mean value of $f_{\text{esc}}$ does not depend on the UVB models very much, although the scatter is somewhat larger at larger $R_{\text{rel}}$ values owing to the small sampling. At the lower values of $R_{\text{rel}}$, the scatter among different UVB models is smaller, because UVB cannot penetrate into the high-density cloud by the self-shielding effect. The results shown in Figures 4 and 5 suggest that the variation in $R_{\text{rel}}$ is one of the key factors that determines the scatter in $f_{\text{esc}}$ for low-mass haloes.

Furthermore $f_{\text{esc}}$ may depend on the hydrogen number density at the location of star clusters, because the neutral hydrogen gas near the star clusters can effectively absorb...
ionizing photons. Figure 6 shows the $f_{\text{esc}}$ of low-mass haloes as a function of hydrogen number density $n_\text{H}$ at the location of star clusters in different UVB models. In this figure we use only the low-mass haloes that include only one young star particle. The result of the Fiducial UVB run is shown by the dashed histogram in other panels for comparison. The runs with a weaker UVB have more young star particles at larger distances from the density peak.

3.2.4 Dependence on Other Physical Quantities

We also examine the dependence of $f_{\text{esc}}$ on other physical quantities, such as metallicity, SFR, and specific SFR ($\equiv \text{SFR/stellar mass}$) in Figure 6. This figure includes all star-forming haloes, just like Figure 2. We find that $f_{\text{esc}}$ decreases with increasing metallicity and SFR, and vice versa for specific SFR. These correlations are expected, because the metallicity and SFR are both positively correlated with galaxy stellar mass and halo mass. However, if the metallicity increases, the dust attenuation could have an extra effect on $f_{\text{esc}}$, which we will discuss in the next section.

4 DISCUSSION

4.1 Dust Attenuation Effect

Interstellar dust can decrease the $f_{\text{esc}}$ by absorbing the ionizing photons. We evaluate the effect of dust attenuation on $f_{\text{esc}}$ by comparing the RT result with and without the dust treatment, as described in § 2.3. Figure 6 shows the values of $f_{\text{esc}}$ with and without the treatment of dust extinction, as a function of halo mass at $z = 3$. The reduction rate of $f_{\text{esc}}$ does not depend on the halo masses very much, and ranges from 0 to 20 per cent, with an average of 14 per cent.

If the dust-to-gas ratio is the same, the optical depth is roughly proportional to $a_\text{d}^{-1}$, where $a_\text{d}$ is typical dust size. Note that $d\tau = [Q\pi a_\text{d}^2 m_\text{d}/(4\pi a_\text{d}^2 \rho/3)]d\ell \propto a_\text{d}^{-1}$, where $m_\text{d}$ and $\rho$ are dust mass and dust density. If we change the dust grain size distribution to a smaller size range of 0.03–0.3 $\mu$m, the mean reduction rate increases to $\approx 38$ per cent at $z = 3$. The weak dependence on halo mass is perhaps because most of the star-forming regions are enriched close to the solar metallicity, irrespective of the host halo masses.

Our reduction rate is somewhat smaller than that reported by Y09, which is probably owing to the difference in the volume occupied by the metal rich gas. In Y09, the model galaxy was an isolated system, and the ISM was globally mixed by the shock from supernova explosion, because there were no further infall of pristine gas from intergalactic space. On the other hand, in the present work, pristine gas can accrete onto the haloes from intergalactic space, which reduces the volume fraction occupied by the metal rich gas.
Figure 8. Escape fraction of the low-mass haloes as a function of hydrogen number density at the location of the star particle in different UVB models at $z = 3$. Similarly to Figure 8 only the low-mass haloes that include only one young star cluster are used. Different colors indicate different UVB models (red: Fiducial, blue: MH0.5, green: OTUV, and magenta: no-UVB). The triangles show the mean values in each mass bin with 1-$\sigma$ error bars. The data points with $\log f_{\text{esc}} < -2.5$ are set to $\log f_{\text{esc}} = -2.5$ for plotting purposes.

Figure 9. Escape fraction as a function of metallicity (upper panel), SFR (lower left panel), and specific SFR (lower right panel) for all the star-forming galaxies in the N144L10 Fiducial UVB run at $z = 3$. The negative correlation between $f_{\text{esc}}$ and metallicity is mainly caused by the positive correlation between halo mass and metallicity. It is not the metals that directly controls $f_{\text{esc}}$. The data points with $\log f_{\text{esc}} < -2.5$ are set to $\log f_{\text{esc}} = -2.5$ for plotting purposes.

Escape of ionizing photons

As a result of our RT calculation presented in the earlier sections, we are able to estimate the total number of ionizing photons that escape from all the star-forming galaxies in the entire simulation box. Our calculation includes haloes with $M_h \gtrsim 10^{9.4} M_\odot$ at $z = 3$, and those with $M_h \gtrsim 10^{9} M_\odot$ at $z = 6$. Figure 11 compares the comoving emission rate density of ionizing photons $N_{\text{ion}}$ (i.e., the number of ionizing photons emitted per unit time and per unit volume) in our N144L10 Fiducial UVB run to the required $N_{\text{ion}}$ to reionize the universe (Madau et al. 1999), which is shown by the black solid curves for the clumping factors of $C = 1, 3, 10$, and 30. The blue solid circles are for the intrinsically radiated photons from all star-forming galaxies in our simulation, and the red circles are for the escaped photons after the RT calculation.

The clumping factor of IGM at $z > 6$ is still very uncertain, and the results from numerical simulations vary depending on the resolution and the treatment of physical processes such as star formation and radiation transfer. Earlier, Gnedin & Ostriker (1997) suggested $C = 30$ at $z \sim 6$, however Iliev et al. (2007) reported $C = 10$ using higher
Figure 10. Upper panel: Comparison of $f_{\text{esc}}$ with and without dust extinction in the Fiducial N144L10 UVB model at $z = 3$. Open black circles show $f_{\text{esc}}$ without dust extinction, and the filled red circles show $f_{\text{esc}}$ with dust extinction. Magenta crosses show the case when the dust grain size range is changed to $0.03 - 0.3 \mu m$. The triangles indicate the mean values in each mass bin with 1-$\sigma$ error bars. The data points with log $f_{\text{esc}} < -2.5$ are set to log $f_{\text{esc}} = -2.5$ for plotting purposes. Lower panel: Mean reduction rate of $f_{\text{esc}}$ for each mass bin when including dust extinction. Different colors show different redshifts (red: $z = 3$, blue: $z = 5$ and green: $z = 6$). The dashed magenta result is when the dust grain size range is changed to $0.03 - 0.3 \mu m$. The error bars are 1-$\sigma$.

Long resolution simulations with a RT treatment. More recently, Pawlik et al. (2009) reported $C \sim 3 - 6$ using a cosmological SPH simulation with an optically thin approximation.

Our results show that $N_{\text{ion}}$ of escaped ionizing photons after the RT calculation is greater than the required $N_{\text{ion}}$ to ionize the universe at $z = 6$ if $C = 10$, but below the required value if $C = 30$. Therefore our fiducial simulation suggests that the star-forming galaxies can ionize the IGM as long as $C \leq 10$.

Our results on $N_{\text{ion}}$ is higher than those derived by Bolton & Haehnelt (2007), which was derived by using the results of cosmological SPH simulations and observational data of Ly$\alpha$ forest. Although the error bars of their data points look very small, it represents only the dispersion of Ly$\alpha$ opacity data. There are still significant uncertainties in the spectral shape and the mean free path of ionizing photons in Bolton & Haehnelt (2007). In their calculation, they use the distance between Lyman limit systems as a mean free path of ionizing photons. However many low density H I gas clouds can decrease the mean free path, and hence increase $N_{\text{ion}}$. Together with the uncertainties in our simulation such as the resolution and the details of star formation and feedback models, the differences between our results and that of Bolton & Haehnelt (2007) can be accounted for.

We also study the fractional contribution to the ionizing photons by the haloes with different masses, as shown in Figure 12. For the intrinsically radiated photons (blue lines), there is no clear trend with the halo mass, and all the haloes contribute roughly equal number of ionizing photons. However, the figure shows that most of the escaped ionizing photons (red histograms) come from the lower mass haloes ($\lesssim 10^{10} M_{\odot}$). This is because in our simulations, higher mass haloes have lower $f_{\text{esc}}$.

Earlier in Section 3.2.1 we discussed the large variation of $f_{\text{esc}}$ derived by Shapley et al. (2006). Based on a clustering analysis, Adelberger et al. (2003) reported that the sample in Shapley et al. (2006) are hosted by haloes with $M_{h} > 10^{11} M_{\odot}$. When compared with our results in Figure 12 it suggests that the sample of Shapley et al. (2006) might not be tracing the bulk of ionizing sources at $z = 3$, and only sampling the massive end of the distribution.

In addition, the detected sample in Iwata et al. (2009) is brighter than $\sim 27$ mag in R band. If we use the equation in Madau et al. (1998) and the relation between halo mass and SFR ($M_{h} \sim SFR \times 10^{10} M_{\odot}$), the limiting magnitude of Iwata’s sample corresponds to $M_{h} \sim 1.5 \times 10^{10} M_{\odot}$ (SFR $\sim 1.5 M_{\odot} yr^{-1}$). Therefore they are also tracing only the massive end of the distribution, although one order of magnitude deeper in halo mass than Shapley et al. (2006). Observations of fainter sources are needed to capture the entire ionizing radiation from lower mass haloes.

In the SPH simulations used for this work, haloes with $M_{h} \lesssim 10^{9} M_{\odot}$ are not resolved well. For example, in the
case of the Fiducial N144L10 run, the halo with \( M_h = 2 \times 10^9 h^{-1} M_\odot \) consists of 100 dark matter particles. In the future, we plan to study \( f_{\text{esc}} \) of even lower mass haloes using higher resolution simulations. If these low-mass haloes are the primary sources of ionizing photons at \( z > 6 \), the \( \text{H}\,\text{II} \) bubbles during the reionization epoch will be produced by numerous low mass haloes. In addition, the large dispersion in \( f_{\text{esc}} \) that we found in this work suggests that the sizes of the \( \text{H}\,\text{II} \) bubbles may have a large variety in the early stages of reionization.

### 4.3 Resolution Test

In the present work, we find that the value of \( f_{\text{esc}} \) depends strongly on the distribution of star particles with respect to the high density gas. However, the clumpiness of ISM around the star-forming regions could strongly depend on the resolution limit of simulations, therefore it is important to evaluate the resolution effects on \( f_{\text{esc}} \). In particular, the cosmological SPH simulations have a difficulty in resolving the clumpy structure of ISM when the number of SPH particles is very small, and the values of \( f_{\text{esc}} \) for low-mass haloes may be more strongly affected by the limited resolution. When the clumpiness of ISM is very high, it may have both positive and negative effect on \( f_{\text{esc}} \): the positive effect is that the ionizing photons may be able to escape through the void regions more easily, however those photons soon may be absorbed by the nearby high-density neutral clumps, which would be a negative effect.

To study the resolution effect, Figure 13 compares \( f_{\text{esc}} \) in the three runs with different resolution, as described in Table 1. The lower right panel compares the mean \( f_{\text{esc}} \) in each mass bins for the three runs with 1-\( \sigma \) error bars. The points with \( \log f_{\text{esc}} < -2.5 \) are set to \( \log f_{\text{esc}} = -2.5 \) for plotting purposes.

For the low-mass haloes, and that \( f_{\text{esc}} \) decreases on average with increasing halo masses.

In Figure 13 for the N216L10 run, we had to confine the sample to the low-mass haloes with \( M_h < 10^{11} M_\odot \), because of the heavy computational load. In the N216L10 run, we need to set up a large grid of \( > 500^3 \) for the high-mass haloes with \( M_h \sim 10^{12} M_\odot \), and these grids take too long to process with RT when we want to process a large sample. We will tackle the systematic study of haloes with higher resolution simulations using the next generation of supercomputers.

For the low-mass haloes, the \( f_{\text{esc}} \) of N216L10 run is smaller by a factor of \( \sim 2 \) than in the N144L10 run. If we assume that \( f_{\text{esc}} \) of all haloes becomes one half, the resulting \( N_{\text{ion}} \) also becomes a half. Then the red circles in Figure 13 would decrease by 0.3 dex for the N216L10 run, and the threshold clumpiness factor for IGM reionization changes to \( \sim 10(3) \) at \( z = 3(6) \).

### 5 SUMMARY

We have performed three-dimensional radiation transfer calculations of stellar radiation for a large number of high-\( z \) star-forming galaxies in cosmological SPH simulations to explore the escape fraction of ionizing photons. Our major findings are as follows:

- The value of \( f_{\text{esc}} \) decreases steeply with increasing halo mass, irrespective of numerical resolution.
- There is a large dispersion in \( f_{\text{esc}} \) for low-mass haloes.
with $M_h \lesssim 10^{11} M_\odot$.

- The values of $f_{\text{esc}}$ do not vary much with redshift and different UVB models.
- The average reduction rate of $f_{\text{esc}}$ owing to the dust attenuation effect is $\sim 14\%$ with a large dispersion.
- The results of our Fiducial N144L10 run suggests that the star-forming galaxies can ionize the IGM at $z = 3 - 6$, if the clumping factor is $C \lesssim 30$ (10) at $z = 3$ (6). If we use the results of the N216L10 run, we roughly estimate that the above threshold values would change to $C \lesssim 10$ (3) at $z = 3$ (6). Our results suggest that the star-forming galaxies become the main contributor of IGM ionization at $3 \lesssim z \lesssim 6$.
- The low mass haloes with $M_h \lesssim 10^{10} M_\odot$ are the main ionizing sources of IGM in our simulations owing to their high $f_{\text{esc}}$. The fraction of escaped ionizing photons coming from the haloes with $M_h \lesssim 10^{10} M_\odot$ at $z = 3 - 6$ is 70 per cent for the Fiducial N144L10 run.

As we summarised in Section 1 the current results on the escape fraction of ionizing photons are confusing, as different results are obtained from different simulations. For example, Gnedin et al. (2008) argued that $f_{\text{esc}}$ increases with increasing halo mass in the range of $M_h = 10^{10} - 10^{12} M_\odot$, and their values of $f_{\text{esc}}$ were mostly less than a few per cent, much smaller than the other published work. The trend found in our simulations (decreasing $f_{\text{esc}}$ with increasing halo mass) is similar to that found by Razoumov & Sommer-Larsen (2010), but we find lower $f_{\text{esc}}$ values despite of the fact that our simulations have lower resolution than their zoom-resimulations. Therefore the differences in $f_{\text{esc}}$ between our work and Razoumov & Sommer-Larsen (2010) cannot be explained simply by the resolution effect.

We also note that Wise & Cen (2004) obtained much higher values of $f_{\text{esc}}$ ($\sim$0.4) than Gnedin et al. (2008) did, using the same AMR method, but for a different halo mass range. Considering these facts, the differences that we see now in the results of $f_{\text{esc}}$ may have to do more with the different treatment of radiation transfer and the UV background radiation, rather than the resolution or numerical technique. However, more detailed comparisons are needed to make more definite statements.

One of our main points is that the variation in $f_{\text{esc}}$ is caused by the different geometry of ISM distribution in the halo. Recently Agertz et al. (2010) suggested that supernovae feedback and star formation efficiency can determine the geometry of a disk galaxy (see also Sales et al. 2010). Therefore the uncertainties in the treatment of star formation, feedback, and radiation transfer are all important for the calculations of $f_{\text{esc}}$, and we need to continue to improve these models through comparisons with future observations of high-z galaxies.

If we allow ourselves to speculate even further and combine all the current results mentioned above, it is possible that $f_{\text{esc}}$ has a peak at $M_h \approx 10^9 - 10^{10} M_\odot$ as a function of halo mass at $z = 3 - 6$. But this is highly speculative and by no means based on any definite physical arguments.

The strength of our current work is the large sample size of galaxies that we processed with RT. Our simulations also adopt a new galactic wind model which produces more favorable results on the cosmic star formation rate and the IGM statistics such as CIV mass density (Choi & Nagamine 2010). Although it is difficult to address the exact effect of our wind model on $f_{\text{esc}}$ unless we process simulations with different wind models with RT calculation, our test calculations showed that the effect is not so strong, and our main conclusions of this paper should remain unchanged even if we modify the wind model slightly. We consider that the most significant results in the current work are the large scatter of $f_{\text{esc}}$ for the low mass haloes, and its decline with the increasing halo mass. The earlier works by other authors did not discuss the scatter among different haloes with a wide range of mass owing to their small sample size.

At $z \gtrsim 7$, even lower mass haloes with $M_h \lesssim 10^9 M_\odot$ may become the main sources of IGM ionization. However in such low-mass systems, the UV radiation of massive stars may influence the gas dynamics significantly (Wise & Cen 2000). Simulations with higher resolution than presented in this paper are needed to follow the star formation in such low-mass systems, and we need to solve the hydrodynamics and radiation transfer simultaneously to examine the effect of radiative feedback. In the future, we plan to couple the RT with hydrodynamics and study the effects of radiative feedback by young stars and AGNs.

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