ESCAPE OF IONIZING RADIATION FROM HIGH-REDSHIFT GALAXIES

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Received 2007 July 6, accepted 2007 September 23

ABSTRACT

We model the escape of ionizing radiation from high-redshift galaxies using high-resolution adaptive mesh refinement N-body + hydrodynamics simulations. Our simulations include the time-dependent and spatially resolved transfer of ionizing radiation in three dimensions, including the effects of dust absorption. For galaxies of total mass \( M \gtrsim 10^{11} M_\odot \), and star formation rates SFR \( \approx 1-5 M_\odot \, \text{yr}^{-1} \), we find angular averaged escape fractions of 1\%–3\% over the entire redshift interval studied (3 < \( z \) < 9). In addition, we find that the escape fraction varies by more than an order of magnitude along different lines of sight within individual galaxies, from the largest values near galactic poles to the smallest along the galactic disk. The escape fraction declines steeply at lower masses and SFR. We show that the low values of escape fractions are due to a small fraction of young stars located just outside the edge of the \( H_\text{i} \) disk. This fraction, and hence the escape fraction, is progressively smaller in disks of smaller galaxies because their \( H_\text{i} \) disks are thicker and more extended relative to the distribution of young stars compared to massive galaxies. We compare our predicted escape fraction of ionizing photons with previous results and find a general agreement with both other simulation results and available direct detection measurements at \( z \sim 3 \). We also compare our simulations with a novel method to estimate the escape fraction in galaxies from the observed distribution of neutral hydrogen column densities along the lines of sight to long-duration \( \gamma \)-ray bursts (GRBs). Using this method we find escape fractions of the GRB host galaxies of 2\%–3\%, consistent with our theoretical predictions. Our results thus suggest that high-redshift galaxies are inefficient in releasing ionizing radiation produced by young stars into the intergalactic medium.

Subject headings: cosmology: theory — galaxies: dwarf — galaxies: evolution — galaxies: formation — methods: numerical — stars: formation

Online material: color figures

1. INTRODUCTION

Star-forming galaxies have a number of important effects on the surrounding intergalactic medium (IGM) and subsequent gas accretion. The ionizing radiation from galaxies is thought to be responsible for the reionization of the universe (e.g., Madau et al. 1999; Bolton et al. 2005), altering the thermal state of the IGM (Gnedin & Hui 1998; Gnedin 2000; Ricotti et al. 2000; Schaye et al. 2000; McDonald et al. 2001; Fechner & Reimers 2007), reducing gas accretion onto small dwarf galaxies (Efstathiou 1992; Thoul & Weinberg 1996; Dijkstra et al. 2004), and evaporating the existing gas in small halos (Barkana & Loeb 1999; Shaviv & Dekel 2003; Shapiro et al. 2004). The amount of radiation emitted by galaxies into the IGM depends not only on the abundance of hot, young stars but also on the spatial distribution of absorbing gas and dust in individual galaxies and their immediate surroundings. The escape of ionizing radiation from galaxies is therefore the focus of a number of observational and theoretical studies. Nevertheless, the “escape fraction,” \( f_{\text{esc}} \), that characterizes the fraction of total ionizing radiation released into the IGM from individual galaxies remains poorly constrained.

Recent empirical measurements of the escape fraction from normal galaxies in the local universe (Leitherer et al. 1995; Bland-Hawthorn & Maloney 1999; Heckman et al. 2001; Bergvall et al. 2006) and at high redshifts (Giallongo et al. 2002; Fernández-Soto et al. 2003; Shapley et al. 2006)\(^5\) have generally produced modest values in the range of a few percent. In contrast, theoretical studies of the escape of ionizing radiation from high-redshift galaxies have largely been inconclusive. Many of the previous studies have applied simplified analytic models (Dove & Shull 1994; Haiman & Loeb 1997; Dove et al. 2000; Ricotti & Shull 2000; Wood & Loeb 2000; Clarke & Oey 2002; Fujita et al. 2003) that predicted a wide range of values for \( f_{\text{esc}} \).

A more reliable estimate can be derived from self-consistent cosmological numerical simulations of galaxy formation that include three-dimensional radiative transfer and model the three-dimensional distribution of absorbing gas in and around individual galaxies. This approach is computationally challenging and has been attempted only recently at a range of redshifts, from \( z \sim 2 \) (Alvarez et al. 2006) to more modest redshifts, \( z \gtrsim 2 \) (Razoumov & Sommer-Larsen 2006, 2007), where a comparison with the observations is possible.

In this paper, we continue this line of work using fully self-consistent cosmological numerical simulations of galaxy formation that include radiative transfer and model the three-dimensional distribution of absorbing gas in and around individual galaxies. This approach is computationally challenging and has been attempted only recently at a range of redshifts, from \( z \sim 20 \) (Alvarez et al. 2006) to more modest redshifts, \( z \gtrsim 2 \) (Razoumov & Sommer-Larsen 2006, 2007), where a comparison with the observations is possible.

\(^5\) Note that both Giallongo et al. (2002) and Shapley et al. (2006) quote larger values, up to 15\%. However, the quoted numbers are for relative escape fractions between 1500 Å and the Lyman limit. The absolute escape fractions are actually about 3\%–4\%, as we discuss in more detail in § 6.
smaller galaxies spanning a wide range of masses. We use all these systems to estimate the escape fraction of ionizing radiation from star-forming regions for galaxies of different masses and star formation rates (SFRs).

3. METHOD

Because our simulation includes an approximate treatment of the radiative transfer self-consistently, the nonequilibrium abundances of all ions for each cell in the AMR grid hierarchy are available throughout the calculation. We can thus measure the opacity at a given frequency along a given direction from any point in the simulation volume to any other point.

Since the opacity can only increase along a given line of sight, the escape fraction is, in general, a function of the distance from the source. We choose to measure this distance in units of the virial radius of a given galaxy, and we measure the escape fraction at 0.5, 1, and 2 virial radii from the center of the galaxy (defined as the peak of the dark matter density). Unless specified otherwise, hereafter we use the escape fraction at 1 virial radius as our fiducial working definition of the escape fraction.

In computing the escape fraction, it is important to separate satellite galaxies from isolated ones. When a small satellite galaxy is located within a larger galaxy, the concept of virial radius and escape fraction becomes ambiguous. Therefore, we only consider isolated galaxies and only include sources that actually reside in (i.e., are gravitationally bound to) the main galaxy, thus excluding the satellites. In computing the continuum absorption by atomic species we include the detailed velocity structure of the galactic and infalling gas, although we find that ignoring the gas velocity field makes no measurable difference on the escape fraction.

Operationally, the escape fraction $f_{esc}$ of a specific galaxy at a given redshift is then a function of two variables, the frequency and the direction of propagation of escaping radiation:

$$f_{esc} \equiv f_{esc}(\nu, \theta).$$

It is measured as a fraction of all photons with frequency $\nu$ emitted by all stars within a given galaxy in the direction $\theta$ on the sky that reach a given distance (1 virial radius for our fiducial definition) from the center of the galaxy.

For studies of reionization of the universe and the Lyα forest, the most important quantity is the escape fraction of ionizing radiation,

$$f_{esc}^{\mathrm{Ly} \alpha}(\theta) = \frac{\int d\nu f_{esc}(\nu, \theta) \sigma_j' S_{\nu}}{\int d\nu \sigma_j S_{\nu}},$$

where $\sigma_j'$ is the photoionization cross section for the species $j$ ($j = \mathrm{H\,i}, \mathrm{He\,i}, \mathrm{He\,ii}$) and $S_{\nu}$ is the spectrum of the sources of radiation. This quantity enters the radiative transfer equation as a multiplier to the source term and is therefore the most relevant quantity. An alternative definition of escape fraction that does not include weighting by the photoionization cross section is discussed in the Appendix.

In our simulation, we include only stellar sources and compute the ionizing radiation spectra using the Starburst99 package (Leitherer et al. 1999). We assume continuous star formation, 0.04 solar metallicity (typical of galaxies in our simulation), and a Salpeter initial mass function over a mass range from 1 to 100 $M_\odot$.

The spectral shape is shown in Figure 4 of Ricotti et al. (2002). Note that the Starburst99 spectral shape is computed for the unobscured stellar population, which is the appropriate spectral shape to use in equation (2), which explicitly includes the $f_{esc}$ factor.
However, observationally the escape fraction of ionizing radiation is difficult to determine, since it requires measuring the whole ionizing spectrum. Instead, the escape fraction at the hydrogen ionization edge (Lyman limit), \( f_{\text{esc}}(\nu_0) \), is usually measured in observational studies. We present the relationship between these two quantities in the Appendix.

### 4. ABSORPTION BY DUST

Incorporating dust absorption into the simulations for calculating the escape fraction is critical, because dust may contribute significantly to the absorption of ionizing radiation (e.g., Weingartner & Draine 2001). Unfortunately, properties of dust in high-redshift galaxies are not well known. In particular, the dust absorption cross section depends on the dust composition and grain size distribution, which is measured only in nearby galaxies. In our analysis, we adopt the dust extinction curves for Large and Small Magellanic Clouds (LMC and SMC, respectively) from Weingartner & Draine (2001) as representative of high-redshift galaxies, because low metallicities of these galaxies are closer to typical metallicities of high-redshift galaxies in our simulation.

A convenient parameterization for the dust extinction law in the LMC and SMC is given by Pei (1992) based on the earlier data,

\[
\alpha_{\nu}^d &= \alpha_0 \sum_{i=1}^{7} f(x_i/\bar{x}_i, a_i, b_i, p_i, q_i),
\]

where the fitting function \( f \) has the form

\[
f(x, a, b, p, q) = \frac{a}{x^p + x^{-q} + b}.
\]

We correct the fits of Pei (1992) using the newer data from Weingartner & Draine (2001) by adding the seventh term in equation (3) in order to account for the narrow and asymmetric shape of the far-UV peak in the dust extinction law. We also change values for some parameters from those adopted by Pei (1992). The values for the parameters we use are listed in Table 1, and we show changes from Pei (1992) in bold.

#### TABLE 1

| Term | \( \bar{x}_i \) (\( \mu \)m) | \( a_i \) | \( b_i \) | \( p_i \) | \( q_i \) |
|------|-----------------|--------|--------|--------|--------|
| SMC Dust Model |
| 1........... | 0.042 | 185 | 90 | 2 | 2 |
| 2........... | 0.08 | 27 | 15.5 | 4 | 4 |
| 3........... | 0.22 | 0.005 | -1.95 | 2 | 2 |
| 4........... | 9.7 | 0.010 | -1.95 | 2 | 2 |
| 5........... | 18 | 0.012 | -1.8 | 2 | 2 |
| 6........... | 25 | 0.030 | 0 | 2 | 2 |
| 7........... | 0.067 | 10 | 1.9 | 4 | 15 |
| LMC Dust Model |
| 1........... | 0.046 | 90 | 90 | 2 | 2 |
| 2........... | 0.08 | 19 | 21 | 4.5 | 4.5 |
| 3........... | 0.22 | 0.023 | -1.95 | 2 | 2 |
| 4........... | 9.7 | 0.005 | -1.95 | 2 | 2 |
| 5........... | 18 | 0.006 | -1.8 | 2 | 2 |
| 6........... | 25 | 0.02 | 0 | 2 | 2 |
| 7........... | 0.067 | 10 | 1.9 | 4 | 15 |

Note.—Values changed from Pei (1992) are shown in bold.

The overall normalization for the dust cross section is determined by parameters \( \sigma_{0,\text{LMC}} = 3.0 \times 10^{-22} \text{ cm}^2 \) and \( \sigma_{0,\text{SMC}} = 1.0 \times 10^{-22} \text{ cm}^2 \). With these functional forms, the dust cross sections for both the LMC and SMC fit the plotted curves of Weingartner & Draine (2001) to a few percent accuracy.

In order to limit the range of possible dust effects, we consider three extreme dust models: (1) a model with no dust at all, (2) a model in which we assume that the dust column density scales with neutral (atomic and molecular) gas column density,

\[
N_{\text{dust}} = \frac{Z}{Z_0} (N_{\text{H}_1} + 2N_{\text{H}_2}),
\]

where \( Z \) is the gas metallicity), and (3) a model where the dust column density scales with the total gas column density (both neutral and ionized).

\[
N_{\text{dust}} = \frac{Z}{Z_0} N_{\text{H}_1},
\]

where \( Z_0 = 0.32 \) (0.2) is the gas-phase metallicity of the LMC (or SMC; Welty et al. 1997, 1999). Note that emission-line studies (Peimbert et al. 2000; Keller & Wood 2006) usually indicate somewhat larger values for both metallicities than the absorption-line metallicities that we adopt. If we adopted larger values for the LMC and SMC metallicities, the dust effect on our measured escape fractions would be even smaller.

Physically, equation (5) implies a complete instant sublimation of dust in the ionized gas, while equation (6) implies no dust sublimation at all. Of course, the truth lies somewhere in between, but these two extreme cases bracket the range of possibilities.

Figure 1 shows the angular averaged escape fraction for the Milky Way progenitor galaxy at \( z = 3 \) as a function of frequency. We show several dust models, together with typical reddening correction for Lyman break galaxies from Adelberger & Steidel (2000). We also show the SMC no-sublimation dust model with a dust cross section arbitrarily increased by a factor of 3. As we have mentioned above, the no-sublimation model is likely to
overestimate the effect of dust absorption. Since it is highly unlikely that uncertainties in our adopted value for the SMC metallicity and the dust extinction curve are as large as a factor of 3, this latter model serves as an absolute (and, likely, implausibly high) upper limit for the dust absorption.

A rather unexpected feature of Figure 1 is that the escape fraction above the Lyman limit is almost independent of the dust absorption. In order to understand this phenomenon, we show in Figure 2 the distributions of escape fractions from individual stellar particles within the central galaxy in a fixed, randomly selected direction on the sky. The distributions have similar shapes: they are weak functions of $f_{\text{esc}}$ for $0 < f_{\text{esc}} < 1$ and exhibit a primary peak at $f_{\text{esc}} \approx 0$ and a secondary peak at $f_{\text{esc}} \approx 1$. Thus, the escaping radiation is produced not by sources in a semipaque medium, with each source attenuated by a similar amount, but by a small fraction of essentially unobscured sources. We discuss this point in detail in §5 (see Fig. 9, discussed in that section).

For a distribution like those in Figure 2, the effects of dust absorption can be easily understood if we ignore the “translucent points” at $0 < f_{\text{esc}} < 1$ and use a toy model distribution for the gas-only $f_{\text{esc}}$,

$$p(f_{\text{esc}, H_1}) = \alpha(1 - f_{\text{esc}, H_1}) + (1 - \alpha)\delta(f_{\text{esc}, H_1}),$$

(7)

where $\alpha \ll 1$ is constant and $\delta(x)$ is a Dirac delta function. The average escape fraction in this model is simply

$$\langle f_{\text{esc}, H_1} \rangle = \int_0^1 f_{\text{esc}, H_1} p(f_{\text{esc}, H_1}) \, df_{\text{esc}, H_1} = \alpha.$$  

(8)

If the dust absorption is included, then the escape fraction at each location is changed by a factor that depends on the dust opacity,

$$f_{\text{esc}} = f_{\text{esc}, H_1} e^{-\tau_d} \equiv e^{-\tau_{H_1} - \tau_d}.$$ 

At locations where $f_{\text{esc}, H_1} \approx 1$ ($\tau_{H_1} \ll 1$), the effect of dust is negligible (since $\tau_d \ll \tau_{H_1}$). At locations where $\tau_d \gtrsim 1$, the hydrogen opacity is already so large that no radiation escapes from this position, irrespective of how much dust is mixed with the gas. As the result, the escape fraction does not change at all.

In reality, “translucent points” with $0 < f_{\text{esc}} < 1$ are affected by dust, but their integrated contribution to the average escape fraction remains small. In the no-sublimation dust model, the situation may be more complex, since there is dust absorption in the ionized gas. However, Figure 1 demonstrates that this is not a large effect.

At frequencies below the Lyman limit the distribution of $f_{\text{esc}}$ from dust is similar to Figure 2, but there is no gas absorption. Because dust absorption is weaker than gas absorption, the average escape fraction at these frequencies is much larger and increases to unity as the frequency decreases down to infrared.

The important result of this section is that, while dust absorption is the dominant effect for UV radiation below the Lyman limit, it does not substantially affect the escape fraction of ionizing radiation in our model galaxies, as Figure 1 demonstrates. In the rest of this paper, we adopt the SMC instant sublimation model as our fiducial dust model, but we note that our final results are not sensitive to this particular choice.

5. RESULTS

Figure 3 shows the escape fraction of hydrogen ionizing radiation $f_{\text{esc}, H_1}$ (eq. [2]) as seen from the center of the central galaxy (the Milky Way progenitor) at three different redshifts. The celestial coordinates in Figure 3 are aligned with the principal axes of the galaxy (“galactic” coordinates), with the plane of the disk of the galaxy crossing the middle of the plot. Typically, the escape fraction is close to zero along the plane of the disk and approaches maximum values near the poles, although there are significant small-scale variations at all redshifts that underscore the complex, perturbed nature of high-redshift disk galaxies. At $z = 5$ the galaxy is experiencing a substantial major merger (and a lesser one at $z = 3$), so the angular distribution of escape fractions is more irregular at these epochs.

Another interesting feature of the $f_{\text{esc}}$ distribution shown in Figure 3 is a few small very opaque (dark blue) clouds of gas that block ionizing radiation at larger distances. These clouds can be counterparts of the Lyman limit absorbers observed in the spectra of distant quasars. Previous studies, based on lower resolution simulations, have indicated that Lyman limit systems tend to cluster around large galaxies (Kohler & Gnedin 2007). Our simulations confirm that such clouds do exist around high-redshift galaxies.

We have checked that, as we integrate further in distance, more of the Lyman limit systems fall inside the radius of integration, and the “sky,” as seen from the center of the galaxy, appears progressively more opaque. The sky should become completely opaque at a distance of a few mean free paths for ionizing radiation. At $z = 4$ the mean free path for ionizing radiation is about $85 \, h^{-1}$ comoving Mpc (Miralda-Escudé 2003), much larger than the size of our computational box. Thus, we cannot actually reach full opacity with our current simulation. However, the important point to make is that the mean free path is much larger than a virial radius of any galaxy at these redshifts, so the concept of the “escape fraction” is well defined and robust at intermediate redshifts.

Figure 4 illustrates this point in a quantitative way. It shows the probability of having a specific value of the escape fraction on a celestial sphere at different distances from the center of the main progenitor of the Milky Way–sized galaxy. As the distance from the galaxy increases, the tail of the distribution at low escape fractions grows, as Lyman limit systems cover a progressively larger fraction of the sky. However, at a distance comparable to
the virial radius of the galaxy the effect of Lyman limit systems is small, as can be seen from the plot; the fraction of the sky below $f_{esc}^\text{HI} = 0.003$ increases from 3% to only 6% as the distance increases from $0.5R_{\text{vir}}$ to $2R_{\text{vir}}$.

Poisson errors on the probability density shown in Figure 4 remain small for escape fractions well below $10^{-3}$, indicating that angular maps from Figure 3 resolve the structure in the gas down to that level. Of course, the small-scale structure in the gas is limited by the finite resolution of our simulation.

Figure 5 presents the main result of this paper: the angular averaged escape fraction for hydrogen ionizing radiation as a function of galaxy mass or SFR at a range of redshifts. We only show results for the galaxies which are resolved down to the maximum ninth level of refinement. This resolution criterion corresponds approximately to a minimum mass of $10^{10} M_\odot$ (or $\gtrsim 10^4$ dark matter particles). A general trend of increasing escape fraction...
with increasing galaxy mass and SFR is clearly observed: the escape fraction changes by approximately 2 orders of magnitude from \(10^{-4}\) to \(10^{-2}\) for total masses between \(10^{10}\) and \(4 \times 10^{11} \, M_\odot\) (or SFR from 0.1 to \(7 \, M_\odot \, yr^{-1}\)). The same time, the figure also shows that there is little change with redshift, from \(z = 5\) to 3, either in the values of the escape fraction or in the dominant trend with mass or SFR.

Figure 6 further illustrates the lack of redshift evolution in the escape fraction found in our simulations. The figure shows the average escape fraction of the most massive Milky Way progenitor in the simulation at different redshifts, along with the variation in escape fraction in different directions. While the escape fraction fluctuates with redshift, a spread in the escape fraction in different directions at a given redshift is much larger than the variation in the average escape fraction with redshifts at \(z < 7\). A similarly weak trend is found by most well-resolved galaxies from our simulation.

There is a significant drop in the escape fraction at the He ii ionization threshold. This is further illustrated in Figure 7, which shows all three escape fractions for ionizing radiation as a function of total mass for the model galaxies. We note that H i and He i are invariably close to each other, while He ii escape fractions are systematically much lower. This behavior is again completely expected, as only active galactic nuclei are thought to fully (i.e., doubly) ionize helium.

It is interesting to explore the reasons behind the low values of the escape fractions of ionizing radiation from the galactic disk. As Figure 2 demonstrates, the ionizing radiation that escapes is emitted preferentially by unobscured sources, with only a small fraction of all sources being unobscured at any given time (rather than being emitted by the majority of sources, which are only partially obscured). The origin of these unobscured stars, of course, is in the relative spatial distribution of young, UV-emitting stars and neutral gas.

Figure 8 shows face- and edge-on views of two galaxies from our simulation: the largest one with \(f_{\text{esc}} \approx 2\%\) and a smaller one with negligible \(f_{\text{esc}}\). The cold H i disk, where young stars form, is very thin (~100–200 pc). Figure 8 shows that the H i disk for the smaller galaxy is somewhat puffier than the larger mass disk. Also, the young stars in the larger galaxy are distributed throughout the neutral disk, with some stars located just outside the disk edge. The escaped ionizing radiation is thus mostly due to a small fraction of stars in a thin shell surrounding the H i disk.

Why is a small fraction of young stars located outside of the cold disk? This can happen for several reasons. First, some of the stars have sufficient velocity to move outside the edge of the H i disk while they are still young, bright emitters of UV photons. For example, a star traveling at 10 km s\(^{-1}\) will move by \(\approx 100\) pc in 10\(^7\) yr. In addition, the outer edge of the H i disk is changing significantly on the same timescale. These changes can expose some of the young stars and clear the way for the ionizing radiation to leave the system. The stars can of course help this by ionizing the edge of the disk near their location even more.

In order to visualize the dynamics in the regions of a galaxy where these unobscured sources reside, Figure 9 shows a pseudo-color composite image of three different snapshots from the simulation closely spaced in time. The edge-on disk of the main galaxy is shown in the total gas density (top) and in the H i fraction (bottom). Three snapshots 10 Myr apart at \(z \sim 4\) are overlaid; the first snapshot is shown in red, the second in green, and the last in blue. If the gas distribution did not change between the snapshots, then the image would appear as an equal combination of red, green, and blue, i.e., as a pure gray scale. In reality, however, the upper surface of the disk appears purple (red plus blue), while the bottom surface is pure green. This means that the galactic disk oscillates with a period of about 20 Myr; the disk bent downward between the first (red) snapshot and the second (green) snapshot, but returned to the first configuration in the third (blue) snapshot, so that the first and third snapshots look almost identical, blending into a single color (purple). Oscillating modes with shorter wavelengths are also visible in the image.

This behavior is clearly visible in the total gas density image and in the H i fraction image within the inner 0.5–0.7 kpc; the H i disk oscillates much more violently at larger radii. This is not surprising, because the oscillations of the H i edge are subject to positive feedback. As the H i edge oscillates and uncovers ionizing sources, the ionizing intensity in a given point is likely to increase (similarly to how the ionizing intensity increases when isolated H ii regions merge during reionization).

The relative constancy of the escape fraction with redshift or SFR that we find could thus be a simple consequence of the galactic disks oscillating by a comparable amount on a 10 Myr timescale. Note that this timescale is close to the local dynamical timescale of the dense high-redshift disks and lifetime of massive, UV-bright stars. Such oscillations are thus likely dynamical.
in origin: the disk can be perturbed by mergers and interactions with satellites, which are only weakly correlated with SFR or redshift (unless a disk goes into a starburst phase).

In the smaller galaxy shown in Figure 8, on the other hand, the young stars are embedded deep in the neutral disk with no stars outside the edge. This is because the density and pressure required for star formation are reached only near the midplane of the disk. This is also the reason for lower star formation efficiency in dwarf galaxies in these simulations compared to massive galaxies (see Tassis et al. 2008 for detailed discussion). The outer, lower density H\textsc{i} disk is thus inert in terms of star formation. In bigger galaxies, the disk is denser and star formation is occurring closer to
Our simulation indicates that there is a characteristic mass below which the neutral disk becomes significantly larger than the disk of young stars. At $z/C_2^4/3$ this mass is $M_{\text{tot}} \sim 10^{11} M_\odot$.

This picture can thus explain why the escape fraction decreases steeply for lower mass galaxies. Young stars in dwarf galaxies are concentrated toward the central regions of the disk and the midplane, and a much smaller fraction of them can reach the edge of the $H\text{\textsc{i}}$ disk or get exposed by fluctuations of its boundary. Note, however, that resolution of dwarf galaxies in our simulations is considerably worse than for the massive galaxies. This explanation and the trend with mass will thus need to be verified in the future by higher resolution simulations.

6. DISCUSSION AND CONCLUSIONS

To summarize the current understanding of the escape fraction of photons at the ionizing threshold of hydrogen, we show in Figure 10 both simulation predictions and observational constraints available at $z = 3$. The simulation predictions are taken from Razoumov & Sommer-Larsen (2006) and our work. Observational constraints are from Giallongo et al. (2002) upper limits.
and Fernández-Soto et al. (2003), respectively, presented as average values for their triangle and circles show the observational measurements from Shapley et al. (2006) UV flux and corrected for dust extinction for the electronic edition of the Journal for a color version of this figure. Filled squares with error bars show our results, similar to Fig. 5. Open diamonds are the simulation results of Razoumov & Sommer-Larsen (2006). Filled downward-pointing triangles show the upper limits from Giallongo et al. (2002). Both the Shapley et al. (2006) and the Giallongo et al. (2002) data samples. The filled downward-pointing triangles show the upper limits from Giallongo et al. (2002). The measurements of Giallongo et al. (2002) are for individual galaxies, and the measurements of Fernández-Soto et al. (2003) are averaged over 14 (13) high- (low-) luminosity galaxies found at $z < 3$. The SFR is estimated based on the observed UV flux and corrected for dust extinction for $E(B - V) = 0.11$. Both the Carrera et al. (2002) and the Shapley et al. (2006) measurements are corrected from the relative measurements of the ratio $f_{esc}(912 \, \AA)/f_{esc}(1500 \, \AA)$ they report to the absolute measurement of $f_{esc}(912 \, \AA)$ by adopting a value of $f_{esc}(1500 \, \AA) = 0.2$ from Adelberger & Steidel (2000). This correction factor is also consistent with other observed estimates of reddening at 1500 Å (Pettini et al. 1998; Steidel et al. 2001; Shapley et al. 2006). The measurements of Fernández-Soto et al. (2003) are averaged over 14 (13) high- (low-) luminosity galaxies found at $1.9 < z < 3.5$ in the Hubble Deep Field (the second one is actually an upper limit). The SFRs are conversions of the observed UV flux using the scaling relation from Madau et al. (1998) and are corrected for dust extinction assuming $E(B - V) = 0.1$ and the extinction law from Calzetti et al. (2000). Fernández-Soto et al. (2003) measure the absolute escape fraction, so no correction is applied to their points.

There still exists a gap between simulations and observations in the luminosity and SFR parameter space. While our simulations model modest-mass galaxies, observational measurements are reported mostly for the brightest, $z \sim L_\ast$ galaxies. Nevertheless, the simulations are tantalizingly close to reaching a range of luminosity and SFR similar to that covered by the observations.

Both the observations and simulations indicate little (if any) trend in the absolute escape fraction with the galaxy mass or SFR, except for a rapid drop in $f_{esc}$ for smaller mass galaxies. Our simulations indicate that this characteristic scale corresponds to about SFR $\sim 1 M_\odot$ yr$^{-1}$ or $M_{tot} \sim 10^{11} M_\odot$, although an upper limit of $f_{esc} < 0.4\%$ from Fernández-Soto et al. (2003) at SFR $\sim 10 M_\odot$ yr$^{-1}$ may indicate that both our simulations and those of Razoumov & Sommer-Larsen (2006) overestimate escape fractions in galaxies with SFR $\lesssim 10 M_\odot$ yr$^{-1}$. The level of disagreement (if any) cannot yet be accurately deduced from the simulations, and, formally, the Fernández-Soto et al. (2003) upper limit is fully consistent with our results. Note also that Siana et al. (2007) in their recent study of the Lyman continuum escape fractions in galaxies at $z \sim 1$ also find small values ($f_{esc} \lesssim 0.1\%$), which is consistent with the weak evolution of escape fractions we find in our simulations.

We also notice that our results agree reasonably well with simulations of Razoumov & Sommer-Larsen (2006) despite the significant differences in numerical approaches. In particular, it appears that coupling of the radiative transfer to the gas dynamics, as is done in our simulation (as opposed to using the radiative transfer in a postprocessing stage, as has been done by Razoumov & Sommer-Larsen 2006), does not produce a large change in the modeled escape fractions.

The general agreement between our results, the Razoumov & Sommer-Larsen (2006) simulations, and the observations is definitely encouraging and may indicate that relative distribution of the young stars and UV absorbing gas is modeled faithfully in our high-resolution AMR simulations. An interesting alternative way of constraining the escape fraction observationally, independent of the observed UV light, is offered by the observed distribution of H$\alpha$ column densities toward ionizing sources from our simulation at $z = 3$ (dotted line) with that measured in the host galaxies of long-duration GRBs at $z > 2$ (solid histogram; see Chen et al. [2007] for the description of the observational data). [See the electronic edition of the Journal for a color version of this figure.]
Figure 11 shows the observed distribution of H i column densities in spectra of GRBs with confirmed redshifts of $z > 2$ (Chen et al. 2007), compared to the corresponding distribution in our simulation at $z = 3$. The simulated distribution is reasonably close to the observed distribution of $N_{\text{H}i}$ from GRBs for $N_{\text{H}i} < 3 \times 10^{21}$ cm$^{-2}$. At higher column density we do not expect a good agreement between our simulation and the data, because the simulation does not incorporate the physics of formation and self-shielding of molecular hydrogen correctly, which becomes important in that regime. Thus, the simulation is expected to overpredict $N_{\text{H}i}$, column densities, because in reality some of this H i is in molecular form. The value for the escape fraction from this method of $2\%$, quoted by Chen et al. (2007), is in remarkable agreement with our results.

While higher resolution simulations and deeper observations are needed to bridge the remaining small gap in the probed star formation regime between the data and the theory, our results suggest that average escape fractions from bright galaxies at intermediate redshifts do not depend strongly on galaxy properties or redshift. This is interesting because it implies that porosity of the interstellar medium in galaxies, and hence its opacity to ionizing radiation, does not dramatically change at higher SFRs, as expected in some of the theoretical models (e.g., Clarke & Oey 2002). Note that observed escape fractions at higher SFRs are consistent with being simply an extrapolation of the trend seen in simulations at lower rates. If this is indeed the case, it implies the absence of a well-defined critical SFR above which the escape fraction sharply increases to unity.

At the same time, the low values of escape fractions found in our simulations suggest that high-redshift galaxies are quite inefficient in emitting ionizing radiation produced by their young stars into the intergalactic medium, with escape fractions decreasing sharply for galaxies of $M_{\text{tot}} \leq 10^{11} M_\odot$ (or SFR $\leq 1 M_\odot$ yr$^{-1}$). This conclusion potentially has important implications for the contribution from normal galaxies to the early reionization of the universe and for the relative role of galaxies and quasars in keeping the universe ionized at intermediate redshifts.

We thank Alex Razoumov, Douglas Rudd, Alice Shapley, and the anonymous referee for constructive and useful comments on the draft of this paper. We also thank Alex for sending us values for the escape fractions from the Razoumov & Sommer-Larsen (2006) simulations, shown in Figure 10. This work was supported in part by the DOE and NASA grant NAG 5-10842 at Fermilab; by NSF grants AST 02-06216, AST 02-39759, and AST 05-07596; and by the Kavli Institute for Cosmological Physics at the University of Chicago. Supercomputer simulations were run on the IBM P690 array at the National Center for Supercomputing Applications and San Diego Supercomputing Center (under grant AST 02-0018N) and the Sanssouci computing cluster at the Astrophysikalisches Institut Potsdam. This work made extensive use of the NASA Astrophysics Data System, the http://arxiv.org preprint server, and the HEALPix (Górski et al. 2005) package (http://healpix.jpl.nasa.gov).

**APPENDIX**

**ALTERNATIVE DEFINITIONS OF THE ESCAPE FRACTION**

The definition of the escape fraction from equation (2) is not unique. For example, as we mentioned above, observational determinations usually measure the escape fraction at the hydrogen ionization edge $f_{\text{esc}(\nu_0)}$ rather than the full escape fraction of ionizing radiation. In order to facilitate comparison between the theoretical and observational results, in Figure 12 we show a relationship between the theoretically relevant escape fraction of ionizing radiation (i.e., an integral quantity, as defined in eq. [2], since it determines

![Figure 12](#)
the ionization state of the IGM) and the escape fraction at the hydrogen ionization edge (Lyman limit), which is usually measured in observational studies. We find a tight correlation between the two quantities in the form
\[ f_{\text{esc}}^\text{H} = 1.25 f_{\text{esc}}(v_0), \] (A1)
which is helpful for relating observationally measured and theoretically relevant quantities. We use this relation in Figure 10 when comparing observational and theoretical values on the same plot.

Alternatively, the integral escape fraction can be defined similarly to equation (2) but without the cross-section weighting,
\[ f_{\text{esc}}(\theta) = \int \frac{d\nu f_{\text{esc}}(\nu, \theta) S_{\nu}}{d\nu S_{\nu}}. \] (A2)

In principle, this quantity is less useful for reionization studies, since it does not determine the ionization state of the IGM. However, we find that in our simulation the two escape fractions are almost identical, as is illustrated in Figure 12 (right).

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