MODELING LYMAN CONTINUUM EMISSION FROM YOUNG GALAXIES

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ABSTRACT

Based on cosmological simulations, we model Lyman continuum emission from a sample of 11 high-redshift star-forming galaxies spanning a mass range of a factor 20. Each of the 11 galaxies has been simulated both with a Salpeter and a Kroupa initial mass function (IMF). We find that the Lyman continuum luminosity of an average star-forming galaxy in our sample declines from \( z = 3.6 \) to 2.4 due to the steady gas infall and higher gas clumping at lower redshifts, increasingly hampering the escape of ionizing radiation. The galaxy-to-galaxy variation of apparent Lyman continuum emission at a fixed redshift is caused in approximately equal parts by the intrinsic variations in the Lyman continuum emission and by orientation effects. The combined scatter of an order of magnitude can explain the variance in the far-UV spectra of high-redshift galaxies detected by Shapley and coworkers. Our results imply that the cosmic galactic ionizing UV luminosity is monotonically decreasing from \( z = 3.6 \) to 2.4, curiously anti-correlated with the star formation rate in the smaller galaxies, which on average rises during this redshift interval.

Subject headings: galaxies: formation — H II regions — intergalactic medium — radiative transfer

Online material: color figures

1. INTRODUCTION

Recent spectroscopic detection of Lyman continuum emission from individual \( z \sim 3 \) galaxies (Shapley et al. 2006) represents a major step forward in analyzing the stellar contribution to the ionizing background at high redshifts. In a study of 14 \( z \sim 3 \) star-forming (SF) galaxies Shapley et al. (2006) have detected escaping ionizing radiation from two objects, concluding that there is significant variance in the emergent Lyman continuum spectrum. The nature of this variance is currently not understood, although it is undoubtedly linked to the physical conditions in the interstellar medium (ISM) at these high redshifts. Comparison of observed Lyman continuum emission to theoretical models should in principle allow us to put constraints on the physics of star formation in young galaxies and study the effect of stellar radiation on the thermal properties of high-redshift gas, including its role in maintaining cosmic reionization. One of the main parameters in this study is the escape fraction of ionizing photons from the clumpy ISM, a quantity of primary importance in determining the contribution of the volumetric stellar luminosity to the ionizing background.

In Razoumov & Sommer-Larsen (2006, hereafter Paper I) we presented calculations of the escape fraction of Lyman continuum photons from a large number of SF regions in two simulated high-redshift protogalaxies. We found that the modeled redshift evolution of \( f_{\text{esc}} \) matches the observational findings of Inoue et al. (2006), namely, the decline from \( f_{\text{esc}} \sim 6\% - 10\% \) at \( z \geq 3.6 \) to \( f_{\text{esc}} \sim 1\% - 2\% \) at \( z = 2.4 \). This decline is attributed to a much higher clumping of gas around the SF regions at lower redshifts, due to accretion of the interstellar gas onto growing protogalaxies. In this paper we extend these calculations to a larger set of (proto-) spiral galaxies covering a range of masses and study the dependence of our results on the amount of feedback per unit stellar mass encoded in the initial mass function (IMF). We moreover determine galaxy-to-galaxy Lyman continuum emission variations at a given redshift and galaxy mass, as well as variations for a given galaxy along different lines of sight.

2. MODELS

We use results of high-resolution galaxy formation simulations in a standard ΛCDM cosmology done with a significantly improved version of the TreeSPH code described by Sommer-Larsen et al. (2003). The code uses the “conservative” entropy formulation (Springel & Hernquist 2002), noninstantaneous gas recycling and chemical evolution with 10 elements (Lia et al. 2002), metallicity-dependent atomic radiative cooling, and self-shielding in regions with the mean free path of Lyman limit photons below 1 kpc. All galaxies for this project were selected from a dark matter—only run of box length 10 h\(^{-1}\) Mpc, which was then resimulated with the TreeSPH code at higher resolution in Lagrangian regions enclosing the galaxies. Further details on this simulation set can be found in Sommer-Larsen (2006). Table 1 lists 11 galaxies, in order of increasing mass, for which we performed radiative transfer calculations around all their SF regions at \( z = 3.6, 2.95, \) and 2.39. The first 5 are fairly small (\( V_c \leq 130 \text{ km s}^{-1} \); see below), gas-rich galaxies that exhibit relatively little star formation. Galaxy 41 is an intermediate-size system with \( V_c = 150 \text{ km s}^{-1} \), whereas the rest are larger (\( V_c \gtrsim 180 \text{ km s}^{-1} \)) disk galaxies. The most massive galaxies were computed at “normal” resolution, with SPH (and star) particle masses of \( 1.1 \times 10^6 M_\odot \) and interpolated grid resolution of 30 pc; the smaller galaxies were simulated with 8 times higher mass resolution and twice the force resolution. The only “low”-resolution simulation was the \( V_c = 310 \text{ km s}^{-1} \) galaxy with particle masses of \( 3.1 \times 10^6 M_\odot \).

All galaxies in Table 1 are labeled by their \( z = 0 \) characteristic circular velocities, which were calculated using the technique described in Sommer-Larsen & Dolgov (2001). For our purpose, the present-day \( V_c \) is a good measure of \( z \sim 3 \) galaxy dynamical masses for a number of reasons. First, galaxies tend to grow in size from \( z = 3 \) to 0, but not so much in \( V_c \). In addition, there is a fairly tight relation between the \( z = 3 \) stellar and virial masses and the \( z = 0 \) ones. This is simply explained by the fact that our
sample contains only field galaxies, which become disks by $z = 0$. All of them have relatively quiet $z < 3$ merging histories; in fact, at $z = 3$ it is already fairly easy to identify the main protogalaxy. Finally, most of our $z = 3$ systems have several protogalactic components, and our results at $r = 100$ kpc account for absorption and stellar emission in all of these components, not just the main protogalaxy. Note that stellar masses, on the other hand, are sensitive to the feedback scenario, as we show in § 3.1, and cannot be uniquely described by $V_c$, which is rather the measure of the galaxy’s dynamical mass.

We model star formation with a set of discrete star “particles,” which represent a population of stars born at almost the same time in accordance with a given IMF. The stellar UV luminosity is determined using the population synthesis package Starburst99 (Leitherer et al. 1999), with continuous star formation distributed among all stars younger than 34 Myr. To compute the time-dependent ionization by stellar photons, we use the point-source radiative transfer algorithm on adaptively refined meshes first employed in Paper I. This algorithm extends the adaptive ray-splitting scheme of Abel & Wandelt (2002) to a model with variable grid resolution. Around each SF region we build a system of 12 high-resolution region. In each cell we accumulate the ionization and heating rates due to photons traveling along ray segments passing through that cell. These rates are then used to update temperature and the ionization state of hydrogen and helium as a function of time.

To study the sensitivity of our results to the strength of stellar feedback, which is in turn a function of the number of massive stars in our SF regions, we adopt two different but widely used IMFs, the standard Salpeter (1955) and the triple-interval Kroupa (1998) IMF. The Salpeter IMF produces approximately twice as much SN II feedback and stellar ionizing radiation per unit stellar mass compared to the Kroupa IMF. However, both IMFs result in less feedback than the more top-heavy IMF used in Paper I. The SN II feedback and chemical enrichment are included into the hydrodynamical models, whereas the propagation of ionizing stellar photons is traced with postprocess radiative transfer, as detailed in Paper I.

We do not include the effects of dust in our current calculations. The fact that our models in Paper I, which did not include dust, matched well the observationally determined escape fractions of Inoue et al. (2006) as a function of $z$ (for $z \sim 2.4–3.6$) can be taken as indirect evidence that dust may be not of primary importance in controlling Lyman continuum escape fractions and luminosities of young galaxies. On the other hand, a number of physical processes such as cooling and molecule formation depend on dust density and composition. Dust forms from heavier elements, and the metallicity of our galaxies is fairly high; e.g., iron abundances range from $[\text{Fe/H}] \sim -1.2$ for the smallest galaxies to $[\text{Fe/H}] \sim -0.4$ for the largest. Unfortunately, the physics of dust grain growth and destruction is extremely complicated and is well beyond the scope of the present paper, although we are
planning to include a simple parametric description into our future simulations.

3. RESULTS

3.1. Redshift Evolution and the Effect of the IMF

Following Paper I, we define $f_{\text{esc}}$ simply as the fraction of (ionizing) stellar photons of a given frequency that reach distance $r$ from the SF regions. Here all our results are computed at $r = 100$ kpc, i.e., on a sphere that encompasses all absorbing clouds associated with each galaxy, at $t = 10$ Myr after the stellar sources were switched on. However, to obtain these results, the full three-dimensional time-dependent ionization structure of the gas was computed.

In Figure 1 we plot the angle- and source-averaged escape fractions for all galaxies from Table 1 as a function of the photon energy, at $z = 3.6$, $2.95$, and $2.39$. The PDF is the fraction of total volume for gas and the fraction of total number for stars in a given density interval $\Delta \log \rho$. [See the electronic edition of the Journal for a color version of this figure.]

In Figure 2 we plot the PDF of gas (solid lines) and stars (dashed lines) in galaxies 93 (top, evolved with Salpeter IMF) and 15 (bottom, evolved with Kroupa IMF) at $z = 3.6$ (thick), $z = 2.95$ (medium-thick), and $z = 2.39$ (thin). The PDF is the fraction of total volume for gas and the fraction of total number for stars in a given density interval $\Delta \log \rho$. [See the electronic edition of the Journal for a color version of this figure.]

Figure 3 shows on a linear scale the fraction of stellar particles younger than 34 Myr, as a function of the refinement level, for the same two galaxies. The nested grid structure was created from the SPH particle distribution using the gas density as a refinement criterion. Stars form in highly overdense regions, the average density of which increases with time as more gas accretes onto growing protogalaxies from the intergalactic medium. This phenomenon is particularly evident in small galaxies such as 93, which shows a gradual rise in the average density of SF regions from $z = 3.6$ to 2.39, leading to a decline in ionizing UV output. Note that all lower mass galaxies in Figure 1 display a drop in $f_{\text{esc}}$ in this redshift interval. Larger field galaxies such as 15 have already accumulated a massive amount of gas by $z = 3.6$ and exhibit somewhat more limited growth at lower redshifts, while their SF regions are skewed to more dense environments. Consequently, massive galaxies have already fairly small $f_{\text{esc}}$ even at early times, and in some cases they can even show a rise in $f_{\text{esc}}$ at lower redshifts, such as...
in galaxies 33, 29, and 26 with the Salpeter IMF. Overall, we find significant variations from galaxy to galaxy, especially in the lower mass systems, with the Salpeter IMF Lyman-limit \( f_{\text{esc}} \) varying from 3% in galaxy 115 to 33% in galaxy 87.

Sommer-Larsen et al. (2003) found that early, fairly strong bursts of star formation converting several percent of the initial gas mass into stars with the Salpeter IMF can substantially alleviate the disk galaxy angular momentum problem, as feedback from these starbursts can blow a larger fraction of the remaining gas out of the small protogalactic clumps, with this gas later gradually settling to form extended disks. These models were later expanded to include the Kroupa IMF (Sommer-Larsen 2006), and at the moment they still underpredict the observed angular momenta of galaxies at \( z = 0 \) disk galaxies by approximately a factor of 1.5. On the other hand, these models feature fairly realistic high-redshift systems that reproduce the submillimeter properties of Lyman break galaxies (Greve & Sommer-Larsen 2006), show extended \( \text{Ly}\alpha \) emission (Laursen & Sommer-Larsen 2007), and have fairly small stellar cores at \( z = 3 \), consistent with observations (Trujillo et al. 2006; Dahlen et al. 2007).

We now focus on the effect of the IMF on Lyman continuum emission. With the Salpeter IMF the stronger feedback at early

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**Fig. 5.**—Ratio \( f_{\text{esc}}^{\text{S}}/f_{\text{esc}}^{\text{K}} \) of the Lyman-limit escape fractions for models with the Salpeter and Kroupa IMFs vs. ratio \( N_{s}/N_{K} \) of the number of young (\( t_{\text{age}} < 34 \) Myr) stellar particles in each pair of models, at \( z = 3.6 \) (triangles), \( z = 2.95 \) (squares), and \( z = 2.39 \) (crosses). [See the electronic edition of the Journal for a color version of this figure.]

**Fig. 6.**—Ratio \( f_{\text{esc}}^{\text{S}}/f_{\text{esc}}^{\text{K}} \) of the Lyman-limit escape fractions (top) and the Lyman-limit specific luminosities (bottom) for models with the Salpeter and Kroupa IMFs vs. characteristic circular velocity, at \( z = 3.6 \) (triangles), \( z = 2.95 \) (squares), and \( z = 2.39 \) (crosses). [See the electronic edition of the Journal for a color version of this figure.]

**Fig. 7.**—Lyman-limit specific luminosity vs. characteristic circular velocity, at \( z = 3.6 \) (triangles), \( z = 2.95 \) (squares), and \( z = 2.39 \) (crosses), for Salpeter (top) and Kroupa (bottom) galaxies. [See the electronic edition of the Journal for a color version of this figure.]

**Fig. 8.**—Lyman-limit specific luminosity at \( z = 2.95 \) vs. optical luminosity. The dotted lines connect a pair of models of each galaxy evolved with the Salpeter (filled circles) and Kroupa (open triangles) IMFs, respectively. The logarithmic scale is the same on the vertical and horizontal axes.
times suppresses star formation relative to the Kroupa case, yielding less massive $z \sim 3$ stellar components (Fig. 4) and building up a larger reservoir of hot gas around the galaxy. This results in an anticorrelation between $f_{\text{esc}}$ and the number of young ($t_{\text{age}} < 34$ Myr) stars at $z = 3.6$ (Fig. 5): the stronger the feedback is in a galaxy, the fewer stars it forms, but also the higher $f_{\text{esc}}$ it gets, as the same amount of gas is being dispersed over a larger volume and more neutral gas is ionized per unit stellar mass. This anticorrelation reduces the sensitivity of the absolute UV luminosity to the fraction of massive stars encoded in the IMF. For example, in galaxy 87 ($v_c = 132$ km s$^{-1}$) at $z = 3.6$ the Salpeter $f_{\text{esc}}$ is about 10 higher than the Kroupa $f_{\text{esc}}$ (Fig. 6a); however, it has 93 young stellar particles with the Salpeter IMF, while the Kroupa IMF results in 444 particles. The result is that its Salpeter luminosity is only $\sim 3$ times higher than its Kroupa luminosity (Fig. 6b).

Ultimately, the feedback cannot prevent the cool-out of hot gas, which sooner or later leads to a rise in star formation. In fact, Salpeter galaxies tend to produce more stars than Kroupa galaxies at later times, as can be seen in the number of young stars along the horizontal axis in Figure 5 at $z = 2.39$. By this time, however, there is no correlation between the escape fractions and the number of recent starbursts, as consistently stronger feedback has a very nonlinear effect on the gas distribution at lower redshift. On the one hand, models with higher feedback rates per unit stellar mass generally have more gas left over for star formation from earlier times, and by $z = 2.39$ some of this gas might have cooled back into dense clouds in the disk ISM. Therefore, combined supernova winds now have to push through a thicker layer of material, unless all of this cool-out gas has been efficiently converted into stars on a short timescale, which is unlikely. On the other hand, irrespective of the earlier star formation history, stronger feedback might still clear channels through which ionizing photons escape into the intergalactic medium. The end result is that all these processes create a very complex, porous ISM, with lower average $f_{\text{esc}}$, but higher variations from galaxy to galaxy, and a larger scatter when we vary the IMF (Figs. 6a, 6b), as by now many effects contribute to the value of $f_{\text{esc}}$.

Gas blowout is expected to be less efficient in already formed disk galaxies, as it drives a typically much smaller fraction of interstellar gas in bipolar outflows perpendicular to the disk (Mac Low & Ferrara 1999). As one would expect, in our models the escape
fractions show a weaker dependence on the feedback strength in the most massive galaxies (Fig. 6a).

It is interesting that in two galaxies (29 and 33) stronger feedback leads to lower \( f_{\text{esc}} \) even at \( z = 3.6 \). Close examination reveals that with the Salpeter IMF these fairly massive galaxies expelled a large amount of gas prior to this epoch, whereas in the Kroupa IMF case a noticeable fraction of this gas was converted into stars early in the run. With the Salpeter IMF, by \( z = 3.6 \) this gas is falling back onto the galaxies supplying cold material to the SF regions. In addition, galaxy 29 has two components very close to each other, and some of the expelled gas is actually trapped in the common gravitational field before accreting back onto both components.

The luminosity of each galaxy is a product of the original IMF spectrum, the number of SF regions in the galaxy, the star formation rate of each region, which depends on the mass of a stellar particle, and the escape fraction. In Figure 7 we plot the specific (per unit frequency) Lyman-limit luminosity \( L_{912} \) of each galaxy versus its circular velocity at all three redshifts. Overall, the Lyman-limit luminosities of galaxies simulated using the two different IMFs follow similar trends with \( V_c \) and \( z \). Note that for most systems \( L_{912} \) is higher at earlier times, meaning that galaxies become an increasingly more important source of ionizing photons relative to quasars, the number density of which declines rapidly at \( z \gtrsim 3 \) (Richards et al. 2006). Therefore, the results shown in Figure 7 are of great importance in relation to the ionization history of the universe, and we shall return to this topic in a forthcoming paper.

We also find that the average cosmic galactic Lyman continuum luminosity, which in our models decreases monotonically from \( z = 3.6 \) to 2.4, most notably in the low-mass galaxies, is anticorrelated with the star formation rate in the same galaxies, which rises during this redshift interval. For the five small (\( V_c < 150 \) km s\(^{-1}\)) galaxies in our sample, the average star formation rates are 1.8, 2.6, and 2.7 \( M_\odot \) yr\(^{-1}\) at \( z = 3.6, 2.95, \) and 2.39 for the Kroupa galaxies, and 0.6, 1.4, and 2.8 \( M_\odot \) yr\(^{-1}\) for the Salpeter galaxies, respectively. For the larger galaxies, the evolution of the star formation rate with redshift is more flat in the \( z = 3.6-2.4 \) interval. Both of these findings are in qualitative agreement with the observational result of Sawicki & Thompson (2006) that the galaxy (nonionizing) UV luminosity function gradually rises at the faint end from \( z = 4 \) to 2, while the bright end of the luminosity function exhibits virtually no evolution.

In Figure 8 we plot the Lyman-limit luminosities of all galaxies in our sample versus their optical luminosities, at \( z = 2.95 \). The optical luminosity is tightly coupled to the number of bright stars, whereas the ionizing luminosity also depends on the amount of absorbing neutral gas in the vicinity of SF regions. As gas blowout is less efficient in more massive galaxies, the supply of material available for star formation does not depend so strongly on the feedback strength, and the optical luminosity of such galaxies is less affected when varying the IMF. The ionizing luminosities, on the other hand, are sensitive to the conditions near SF regions and show variations even in already formed massive systems. It is also seen from Figure 8 that the effects of changing the IMF on the Lyman continuum and optical luminosities, respectively, are essentially uncorrelated.
orientation of galaxies with respect to an observer. The source-to-source scatter in $f_{\text{esc}}$ (Fig. 9) and a nonuniform gas distribution in host galaxies invariably translate into angular variations. In Figures 10–11 we plot the angular dependence of $f_{\text{esc}}$ for two galaxies, the more massive 15 and the small 93, at three different redshifts, both galaxies computed with the Kroupa IMF. For Salpeter galaxies the behavior is qualitatively the same. In both plots the $x$-axis gives the index of the angular pixel in the HEALPix (Górski et al. 2002) notation, covering the entire $4\pi$ in 768 = $12 \times 4^3$ bins. Essentially, it is as an index along a fractal space-filling curve going through all bins on the sky (as seen from the galaxy) in which $f_{\text{esc}}$ was computed, with each bin covering the same solid angle. For the more massive galaxy 15, especially with the Kroupa IMF, we can see two spikes corresponding to the face-on orientation of the galaxy, with $f_{\text{esc}} \sim 2–3$ times the average.

In Figure 12 we plot the angular probability distribution function of $f_{\text{esc}}$ for two Salpeter and two Kroupa galaxies, at all three redshifts. The vertical axis shows the fraction of angular bins per unit log $f_{\text{esc}}$, such that the area under each curve is exactly unity. The decline of $f_{\text{esc}}$ with time is evident in all four panels, but more interesting is the scatter of about an order of magnitude in $f_{\text{esc}}$, depending on orientation to the observer. This, together with the intrinsic Lyman continuum luminosity variation from galaxy to galaxy (Fig. 7), explains why in magnitude-limited surveys only a fraction of galaxies are detected in direct Lyman continuum emission (Shapley et al. 2006).

4. Conclusions

In conclusion, we present calculations of the Lyman continuum emission from 11 (proto-) disk galaxies in the redshift range $z = 3.6–2.4$, modeled with the standard Salpeter and Kroupa IMFs. To calculate the ionization structure of the interstellar medium in each galaxy, we performed time-dependent numerical radiative transfer around a large number (up to $10^4$) of SF regions modeled with discrete star particles. Our findings are as follows:

1. Although we find significant variations in the escape fraction of ionizing photons from galaxy to galaxy, we confirm our earlier results on the average decrease of $f_{\text{esc}}$ from $z = 3.6$ to 2.4 for the entire range of galaxy masses, as more gas cools and accretes onto galaxies, forming stars in progressively clumpier environments. The resulting Lyman continuum luminosity of individual galaxies declines gradually over this redshift interval, by nearly an order of magnitude for lower mass galaxies and by a smaller factor for more massive objects. We also note that this result is not sensitive to the assumed IMF, at least within the range of feedback parameters normally associated with the widely used Salpeter and Kroupa IMFs.

2. The observed galaxy-to-galaxy scatter in Lyman continuum emission is caused in approximately equal parts by the inclination effects and the intrinsic variations in the $4\pi$-averaged UV luminosities, for galaxies of a fixed mass.

3. We predict that the cosmic galactic ionizing UV luminosity would decrease monotonically from $z = 3.6$ to 2.4. Some fraction of smaller galaxies in clusters can turn on their star formation for the first time during this redshift interval due to tidal effects, although the intrinsic changes in most field galaxies associated with continuous gas infall would lead to a decline in the Lyman continuum comoving luminosity density.

On the other hand, there is evidence that the galaxy nonionizing UV luminosity function gradually rises at the faint end from $z = 4$ to 2 (Sawicki & Thompson 2006). We want to stress that our findings do not contradict these data, as indeed we see a rise by a factor of $\sim 2–4$ in the number of young stars from $z = 3.6$ to 2.4 in all

3.2. Radial Dependence of the Escape Fraction

To probe conditions inside the ISM, it is instructive to look at the radial dependence of absorption as a function of redshift in one of our galaxies. In Figure 9 we show the $4\pi$-averaged distribution of $f_{\text{esc}}$ for all star particles in the more massive galaxy 15, computed with the Kroupa IMF, as a function of redshift and the distance from these particles. At all five redshifts a significant fraction of photons reach the radius $r = 100$ pc, although this fraction decreases with time as more gas is clustered around the SF regions. At $r = 1$ kpc the redshift evolution is more noticeable, as very few sources have $f_{\text{esc}} > 0.1$ at $z = 2.39$. In other words, a random observer sitting inside this galaxy would see Lyman continuum emission directly from 15%–20% of the young stars in that galaxy at $z = 3.8$ and from only a few percent of the stars at $z = 2.39$. For a distant observer beyond this galaxy’s virial radius of $r \sim 45$ kpc, the average Lyman-limit escape fraction drops from $\sim 4\%$ to $\sim 0.4\%$ in the above redshift interval.

3.3. Orientation Effects

In § 3.1 we show that for galaxies of a given mass the galaxy-to-galaxy scatter in the Lyman continuum emission can be partially attributed to variations in the physical conditions in the clumpy ISM surrounding the SF regions (by a factor of $\sim 2–3$ for either of the selected IMFs in Fig. 7).

In this section we examine variations in apparent Lyman continuum luminosities caused by orientation effects, i.e., the random
our small galaxies, consistent with continuous gas infall. We are planning to study the nonionizing UV luminosity function in the same set of galaxies in the future.

4. The higher escape fractions, as well as Lyman continuum luminosities found at $z = 3.6$ compared to the lower redshifts, also support the notion that galaxies become a progressively more important source of ionizing photons as one goes back in time, as the comoving number density of quasars declines rapidly at $z \gtrsim 3$ (Richards et al. 2006).

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