THE FATE OF THE FIRST GALAXIES. II. EFFECTS OF RADIATIVE FEEDBACK

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ABSTRACT

We use three-dimensional cosmological simulations with radiative transfer to study the formation and evolution of the first galaxies in a ΛCDM cosmology. The simulations include continuum radiative transfer using the optically thin variable Eddington tensor (OTVET) approximation and line radiative transfer in the H2 Lyman-Werner bands of the UV background radiation. Chemical and thermal processes are treated in detail, particularly the ones relevant for H2 formation and destruction. We find that the first luminous objects ("small-halo objects") are characterized by bursting star formation (SF) that is self-regulated by a feedback process acting on cosmological instead of galactic scales. The global SF history is regulated by the mean number of ionizing photons that escape from each source, $\epsilon_{UV}$ ($f_{esc}$). It is almost independent of the assumed SF efficiency parameter, $\epsilon_s$, and the intensity of the dissociating background. The main feedback process that regulates the SF is the reformation of H2 in front of H ii regions and inside relic H ii regions. The H ii regions remain confined inside filaments, maximizing the production of H2 in overdense regions through cyclic destruction/reformation of H2. If $\epsilon_{UV}(f_{esc}) > 10^{-7}$/s, the SF is self-regulated, photoevaporation of small-halo objects dominates the metal pollution of the low-density intergalactic medium, and the mass of produced metals depends only on $f_{esc}$. If $\epsilon_{UV}(f_{esc}) \leq 10^{-7}$/s, positive feedback dominates, and small-halo objects constitute the bulk of the mass in stars and metals until at least redshift $z \sim 10$. Small-halo objects cannot reionize the universe because the feedback mechanism confines the H ii regions inside the large-scale structure filaments. In contrast to massive objects ("large halos"), which can reionize voids, small-halo objects partially ionize only the dense filaments while leaving the voids mostly neutral.

Subject headings: cosmology: theory — galaxies: dwarf — galaxies: evolution — galaxies: formation — galaxies: high-redshift — intergalactic medium

On-line material: color figures, mpg animation

1. INTRODUCTION

In cold dark matter (CDM) cosmologies, "small-halo" galaxies are believed to be the first luminous objects formed in the universe. Defined as small-mass protogalaxies, small-halo objects have virial temperature $T_{vir} < 10^4$ K and rely on H2 line cooling to form stars. The first generation of stars is necessarily metal-free, as all elements heavier than Li are produced in the cores of stars or by supernova (SN) explosions. In the literature, Population III is often used to refer to both metal-free stars and protogalaxies with $T_{vir} < 10^4$ K. In order to avoid this confusion, we use the term "small-halo objects" instead of the widely used "Population III objects" throughout our paper. For instance, the stars in a small-halo object are not necessarily Population III because the interstellar medium (ISM) could be polluted by metals rather quickly. In this paper we use synthetic stellar energy distributions (SEDs) calculated for metal-free stars, which for brevity we call Population III SEDs, and SEDs typical of low-metallicity stars, which we call Population II SEDs. Although the SED does not change the star formation (SF) history, we find that the H2 abundance in the intergalactic medium (IGM) depends on it.

In this paper, the second in a series on the formation and evolution of the first galaxies, we focus on the mechanisms responsible for the self-regulation of SF in small-halo objects. In Ricotti, Gnedin, & Shull (2002, hereafter Paper I) we discussed the numerical methods and the physics included in the simulations used in this paper. From resolution studies we found that our largest simulations seem to be close to numerical convergence. These models are the first three-dimensional cosmological simulations to include the physics necessary to study the formation of small-halo objects and their radiative feedback self-consistently. Mechanical feedback from SN explosions and stellar winds is not included, as it is the subject of a separate paper. The main new ingredients are the inclusion of continuum radiative transfer and line radiative transfer in the Lyman-Werner bands. A number of potentially relevant physical processes are included as well: secondary ionizations of H and He, detailed H2 chemistry and cooling processes, heating by Lyα resonant scattering, H and He recombination lines, metal production, and radiative cooling. The SED of the sources is consistent with the choice of the escape fraction of ionizing radiation ($f_{esc}$). The results of our simulations are considerably different from previous models of the formation of small-halo objects. These previous works were semianalytic treatments (Haiman, Rees, & Loeb 1997; Haiman, Abel, & Rees 2000; Ciardi et al. 2000) or three-dimensional simulations (Machacek, Bryan, & Abel 2001) without radiative transfer. In contrast to previous studies, we find that the formation of small-halo objects is not suppressed by the H2 dissociating background. The reason for this difference is that these earlier studies did not include a primary mechanism of positive feedback for the formation of small-halo objects.

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Prior to our work, it was widely thought that the main feedback mechanism that regulates small-halo formation is the buildup of the H$_2$ dissociating background. Indeed, the dissociating background can suppress or delay the formation of small-halo objects if H$_2$ is not reformed efficiently. Because of these results, small-halo objects were believed to be unimportant for subsequent cosmic evolution, metal enrichment of the IGM, and reionization. However, our recent work (Ricotti, Gnedin, & Shull 2001) pointed out a new radiative feedback mechanism that turns out to provide the dominant regulation for the formation of small-halo objects. A large amount of H$_2$ is naturally reformed in shells (positive feedback regions [PFRs]) in front of the halo regions or inside recombined fossil H II regions. The H$_2$ formation rate is proportional to the density squared of the gas and is very efficient in the filaments and inside galaxies. The bursting mode of SF observed in simulations produces fossil H II regions and therefore allows H$_2$ to be continuously reformed.

Contrary to the initial ideas in Ricotti et al. (2001), the volume filling factor of PFRs has to remain small to maximize the positive feedback. Therefore, we do not require the ionizing escape fraction ($f_{esc}$) $\sim$ 1 to maximize the IGM volume occupied by PFRs with respect to the volume occupied by the dissociating spheres (or with respect to the intensity of the dissociating background). Instead, small-halo formation is possible if $f_{esc} < 1$; inside the dense filaments, the positive feedback of H$_2$ reformation always dominates the negative feedback of the dissociating background and of the local dissociating radiation. This, together with the clustering of dark matter (DM) halos in the overdense regions, maintains a sufficiently high H$_2$ abundance inside the filaments to allow small-halo objects to cool and form stars. On the other hand, if the star formation rate (SFR) is too high (and $f_{esc} \sim 1$), the filaments become highly ionized by the Strömgren spheres and the H$_2$ is destroyed by direct ionization. This produces a local and temporary halt of SF until the Strömgren spheres recombine. Shells of H$_2$ then reform inside the H II regions and a new burst of SF occurs.

In Ricotti et al. (2001) we emphasized the importance of PFRs in reducing the dissociating background. In some simulations, the production of H$_2$ is high enough to reduce the dissociating background intensity by a factor of 10, but this does not affect the SF history. In the same paper, we pointed out that enhanced galaxy formation is possible if it happens inside a PFR. Indeed, in this work we find that this is the most important mechanism that regulates the formation of small-halo objects. Another positive feedback mechanism proposed by Ferrara (1998) involves local production of H$_2$ in shells produced by SN explosions. In the simulations presented in this paper, we do not include feedback from SN explosions, although we plan to address this problem in a subsequent paper.

In Ricotti & Shull (2000) we studied $\langle f_{esc} \rangle$ for small-halo objects, assuming a spherical halo geometry. The high merger rate in the early universe should favor the formation of spheroidal galaxies instead of disks. We have found that $\langle f_{esc} \rangle$ is small at high redshift, $\langle f_{esc} \rangle \propto \exp[-(1 + z_{vir})]$. This supports the theory that small-halo objects formed copiously in the early universe, and their existence could be directly or indirectly observed today. Metals in the Ly$_\alpha$ forest and dwarf spheroidal galaxies in the Local Group are two examples of observations that can test our models. In Paper III, currently in preparation, we will study the properties of small-halo galaxies and try to make a connection with available observational data on the dwarf spheroidal galaxies in the Local Group.

This paper is organized in the following manner. In §2 we briefly review the physics included in the code and the free parameters. This section serves as a quick reference of arguments treated extensively in Paper I. The results of the simulations are shown and discussed in §3. In §4 we provide a summary and final comments.

2. THE CODE

The simulations were performed with the softened Lagrangian hydrodynamics particle-particle-particle-mesh (SLH-P^3M) code described in detail in Gnedin (1995, 1996) and Gnedin & Bertschinger (1996). The simulation evolves collisionless DM particles, gas particles, “star particles” formed using the Schmidt law in resolution elements that sink below the numerical resolution of the code, and radiation, whose transfer is treated self-consistently with the optically thin variable Eddington tensor (OTVET) approximation of Gnedin & Abel (2001). We also include line radiative transfer in the H$_2$ Lyman-Werner bands of the background radiation, secondary ionization of H and He, heating by Ly$_\alpha$ scattering, detailed H$_2$ chemistry and cooling, and a self-consistent SED of the sources (Paper I).

We adopt a ΛCDM cosmological model with parameters $\Omega_0 = 0.3$, $\Omega_L = 0.7$, $h = 0.7$, and $\Omega_b = 0.04$. The initial spectrum of perturbations has $a$$_g$ = 0.91 and $n = 1$. All simulations start at $a = 100$ and finish at $a \leq 9$. We use box sizes $L_{box} = 0.5$, 1, and 2 comoving $h^{-1}$ Mpc and grids with $N_{cell} = 256^3$, $128^3$, and $64^3$ cells. We achieve the maximum mass resolution of $M_{DM} = 4.93 \times 10^3$ $h^{-1} M_\odot$ and spatial resolution of 156 comoving $h^{-1}$ pc in our biggest run. We fully resolve the SF in objects within the mass range $5 \times 10^5$ $M_\odot \leq M_{DM} \leq 10^9$ $M_\odot$.

In Paper I we discussed extensively the details of the code and the physics included in the simulation. We also studied the numerical convergence of the simulations that is especially crucial in the study of the first objects. High mass resolution is needed because the objects that we want to resolve have small masses ($10^5 M_\odot \lesssim M_{DM} \lesssim 10^9 M_\odot$). Moreover, the box size has to be large enough in order to include at least a few of the rare first objects. The first small-halo objects should form at $z \sim 30$ from 3 $\sigma$ density perturbations; the first large-halo objects (with $M_{DM} \sim 5 \times 10^7$ $h^{-1} M_\odot$) should form at $z \sim 20$, also from 3 $\sigma$ perturbations.

The reader interested in numerical issues or in the details of the physics included in the simulation should refer to Paper I. We summarize the meaning of the four free parameters in the simulations as follows:

1. $\epsilon_*$.—SF efficiency in the Schmidt law ($d\rho_\star / dt = \epsilon_* \rho_\star / t_\star$, where $\rho_\star$ and $t_\star$ are the stellar and gas density, respectively, and $t_\star$ is the maximum between the dynamical and cooling time).

2. $\epsilon_{LV}$.—Energy in ionizing photons per rest mass energy of H atoms ($m_H c^2$) transformed into stars. This parameter depends on the initial mass function (IMF) and stellar metallicity.

3. $\langle f_{esc} \rangle$.—Escape fraction of ionizing photons from the resolution element.

4. $g_{\nu}$.—Normalized SED. We use Population III and Population II SEDs with a Salpeter ($1 M_\odot < M_\star < 100$...
$M_\odot$) IMF, and we modify $g_e$ according to the value of $\langle f_{\text{esc}} \rangle$.

3. RESULTS

In this section we discuss the main physical processes that regulate the formation and evolution of small-halo objects. We ran a large set ($\sim 20$) of simulations in order to explore the dependence of the results on free parameters in the simulation. We ran the simulations on the Origins 2000 supercomputer at the National Center for Supercomputing Applications in Urbana-Champaign, Illinois. The typical clock times to run 64, 128, and 256 simulations from $z = 100$ to $z = 10$ are about 50, 1000, and more than 23,000 hr, respectively. The total computational time used to run the simulations presented in this work is about 44,000 hr. In Table 1, as a quick reference, we list the simulations with

\[ \text{radiative transfer discussed in this section. Each simulation is named (e.g., 64L05p2noLW+1) using the following convention:} \]

1. $N_{\text{box}}^3$ is the number of cells in the box (e.g., 64).
2. $L_{\text{box}}$ is the comoving size of the box in units of $h^{-1}$ Mpc (e.g., L05).
3. Population II (metallicity $Z = 0.04 Z_\odot$) stars are denoted by “p2” and Population III (metal-free) stars by “p3.” This and the following parts of the name are optional.
4. The comment “noLW” indicates that the sources emit no Lyman-Werner H$_2$ photons, “noRAD” is used for simulations without radiative transfer, and “noCID” indicates that radiative transfer and H$_2$ cooling are not included in the simulation.
5. The third optional part of the name is \( \text{log}(\langle \epsilon_{\text{UV}}/4\pi \rangle f_{\text{esc}})/1.6 \times 10^{-5} \) (e.g., “+1”).

Values of zero are omitted from the name. We will attempt to make clear the parameters of each simulation in the text. Therefore, a reader does not need to memorize the notation or repeatedly refer to Table 1.

### TABLE 1

| Run        | $N_{\text{box}}$ | $L_{\text{box}}$ ($h^{-1}$ Mpc) | $\epsilon$ | $\epsilon_{\text{UV}}$ | \( \langle f_{\text{esc}} \rangle \) |
|------------|------------------|-------------------------------|------------|------------------|------------------|
| 64L05p2noRAD...  | 64               | 0.5                           | 3.94 x 10^4 | 10...            | 1                | 0.2              | 0               |
| 64L05p2noLW-2... | 64               | 0.5                           | 3.94 x 10^4 | 10...            | 1                | 0.2              | 0               |
| 64L05p2noLW...   | 64               | 0.5                           | 3.94 x 10^4 | 10...            | 1                | 0.2              | 0               |
| 64L05p2noLW+1... | 64               | 0.5                           | 3.94 x 10^4 | 10...            | 1                | 0.2              | 0               |
| 64L05p2-1...     | 64               | 0.5                           | 3.94 x 10^4 | 10...            | 1                | 0.2              | 0               |
| 64L05p2-2...     | 64               | 0.5                           | 3.94 x 10^4 | 10...            | 1                | 0.2              | 0               |
| 64L05p2-3...     | 64               | 0.5                           | 3.94 x 10^4 | 10...            | 1                | 0.2              | 0               |
| 64L05p2-4...     | 64               | 0.5                           | 3.94 x 10^4 | 10...            | 1                | 0.2              | 0               |
| 64L05p2-5...     | 64               | 0.5                           | 3.94 x 10^4 | 10...            | 1                | 0.2              | 0               |
| 64L05p2-6...     | 64               | 0.5                           | 3.94 x 10^4 | 10...            | 1                | 0.2              | 0               |
| 64L05p2-7...     | 64               | 0.5                           | 3.94 x 10^4 | 10...            | 1                | 0.2              | 0               |

Note.—These values were calculated with the following parameters. Numerical parameters: $N_{\text{box}}^3$ is the number of grid cells, $L_{\text{box}}$ is the box size in comoving $h^{-1}$ Mpc, $B_z$ is the parameter that regulates the maximum deformation of the Lagrangian mesh: the spatial resolution is $\sim L_{\text{box}}/(N_{\text{box}} B_z)$. Physical parameters: $g_e$ is the normalized SED (II = Population II and III = Population III), $\epsilon$ is the SF efficiency, $\epsilon_{\text{UV}}$ is the ratio of energy density of the ionizing radiation field to the gas rest mass energy density converted into stars (depends on the IMF), and $\langle f_{\text{esc}} \rangle$ is the escape fraction of ionizing photons from the resolution element.

a Variable $g_e$ is modified assuming $a_0 = N_{\text{HI}}/N_{\text{HI}} = 0.1$ and $a_1 = N_{\text{HII}}/N_{\text{HI}} = 10$, where $N_i$ is the column density of the species/ion $i$ (see Paper I).

b Variable $g_e$ is modified assuming $a_0 = 0.01$, $a_1 = 10$.

c Secondary ionizations included.
In the left panel of Figure 1 we show the comoving SFR ($M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$) for the 64L05noRAD, 64L05noC, 64L05p2, 128L05noRAD, and 128L05p2 runs. These simulations have $L_{\text{box}} = 0.5 h^{-1} \text{ Mpc}$ and $\epsilon = 0.2$. The two solid lines show the SFR in the $128^3$ box (thick line) and in the $64^3$ box (thin line) without radiative transfer. In the higher mass resolution simulation, the SFR is larger since more small-mass objects are formed. The short-dashed line shows the $64^3$ simulation without radiative transfer and H$_2$ cooling. By definition, this simulation does not form any small-halo objects. Comparing the short-dashed line with the solid lines, we see that small-halo objects dominate the SFR down to $z \approx 10$ if we do not include radiative feedback. The two long-dashed lines show the SFR including radiative transfer [using the Population II SED and $(\epsilon_{\text{UV}}/4\pi)(f_{\text{esc}}) = 1.6 \times 10^{-5}$]. Again, the thick line is for the $128^3$ box and the thin line for the $64^3$ box. From Figure 1 it is clear that SF is bursting and is suppressed with respect to the simulations without radiative transfer.

The right panel of Figure 1 shows the analogous simulations to the left panel of Figure 1, but for box size $L_{\text{box}} = 1 h^{-1} \text{ Mpc}$. The three thin lines show the SFR for the $64^3$ box: without radiative transfer (solid line), without radiative transfer and H$_2$ cooling (dashed line), and with radiative transfer (long-dashed line). The lines are almost indistinguishable, showing that we are forming only large-halo objects and that radiative feedback has no effect on their SFR. The DM mass resolution of these simulations, $M_{\text{DM}} = 3.15 \times 10^5 h^{-1} M_{\odot}$, is not sufficient to fully resolve the first small-halo objects, with typical masses $M_{\text{DM}} \sim 10^8-10^9 h^{-1} M_{\odot}$. In Paper I we showed that we need to resolve each object with at least 100 DM particles. The two thick lines show the SFR for the $128^3$ boxes without radiative transfer (solid line) and including radiative transfer (long-dashed line). For the simulation with radiative transfer, we use the Population II SED and $(\epsilon_{\text{UV}}/4\pi)(f_{\text{esc}}) = 1.6 \times 10^{-5}$. This simulation has mass resolution $M_{\text{DM}} = 3.94 \times 10^4 h^{-1} M_{\odot}$, sufficient to resolve small-halo objects, and box size large enough to include the first large-halo objects that form at $z \sim 20$. It is clearly shown that the SF is bursting at $z \lesssim 20$ when it is dominated by small-halo objects. In this simulation, large-halo objects dominate the SFR as soon as they form, producing the continuous SF mode observed at $z \gtrsim 20$.

In summary, simulations with mass resolution $M_{\text{DM}} < 3.15 \times 10^5 h^{-1} M_{\odot}$ (such as the 64L1 runs) do not form small-halo objects and therefore are not well suited for this study. On the other hand, if the box is much smaller than $1 h^{-1} \text{ Mpc}$ (comoving), the formation of the first large-halo objects is delayed considerably. If $L_{\text{box}} \gtrsim 1 h^{-1} \text{ Mpc}$, the first rare massive objects form at $z \sim 20$. From the results of other simulations, not shown here, we have verified that the global SFR does not change if we increase the box size from $L_{\text{box}} = 1$ to $8 h^{-1} \text{ Mpc}$, keeping the mass resolution constant (for redshifts $z > 4$). The bursting SF mode of small-halo objects is not synchronized throughout the whole universe. Therefore, the strong oscillations of the SFR observed in some of our simulations are an artifact of the finite (actually quite small) size of the simulation box.

In Figure 2 we show a sequence of four three-dimensional views of the cube for the 128L1p2 run at $z = 21.2$, 17.2, 15.7, and 13.3. The rendering of the volume is obtained by assigning quadratic opacity to the logarithm of the gas density and linear opacity to the $x_{\text{HI}}$ fraction. The colors show the $x_{\text{HI}}$ fraction. The cosmological H II regions expand quickly in the IGM, but when their size becomes on the order of the filamentary structure, the expansion stops (in comoving coordinates). The filaments become partially ionized, but the voids remain neutral and reionization cannot occur. At redshift $z \sim 20$ the first large-halo objects form.
For large-halo objects, there is no feedback process that can stop the H\textsc{ii} region from expanding into the low-density IGM. Indeed, these H\textsc{ii} regions never stop expanding and eventually reionize the universe. Figure 3 is analogous to the previous figure, but here we show the H\textsubscript{2} abundance for the 64L05p3 run. The H\textsubscript{2} is quickly destroyed in the low-density IGM by the buildup of the dissociating background, but new H\textsubscript{2} is continuously reformed in the filaments. Therefore, in the dense regions where galaxy formation occurs, positive feedback dominates over the negative feedback of the dissociating background. In the following sections, we will show that the main mechanisms that regulate galaxy formation of small-halo objects are the two positive feedback processes found by Ricotti et al. (2001). In that paper, we discussed the importance of H\textsubscript{2} shells (PFRs) that form just in front of each Strömgren sphere and inside relic (recombining) H\textsc{ii} regions.

Since the 128\textsuperscript{3} and 256\textsuperscript{3} cubes are computationally intensive, in §3.1–3.3 we will try to understand the feedback mechanism that regulates the SF of small-halo objects using 64\textsuperscript{3} cubes with $L_{\text{box}} = 0.5\, h^{-1}\, \text{Mpc}$. We are aware, however, that after $z \sim 20$ we are not properly including the formation of the first large-halo objects. In §3.4 we present the results of our largest simulations that include detailed physics and realistic values of the free parameters.

3.1. Negative and Positive Feedback

The background intensity in the Lyman-Werner bands determines the redshift at which H\textsubscript{2} is destroyed in the low-density IGM. In the left panel of Figure 4 we show the mean mass- and volume-weighted molecular abundances $\langle x_{\text{H}_2} \rangle$, $\langle x_{\text{H}_1} \rangle$, and $\langle x_{\text{H}^-} \rangle$ as a function of redshift for the 64L05p2noLW, 64L05p2, and 64L05p3 runs. These runs have the same parameters [$\epsilon_\text{ion} = 0.2$, $(\epsilon_{\text{LW}}/4\pi) = 1.6 \times 10^{-5}$, and $(f_{\text{esc}}) = 1$] except for a different flux in the Lyman-Werner bands.\textsuperscript{3} The solid line shows the 64L05p2noLW run for which the stars do not emit Lyman-Werner photons, the short-dashed line shows the 64L05p2 run, which has a Population II SED, and the long-dashed line shows the 64L05p3 run, which has a Population III SED (zero metallicity). The Population II SED emits about 100 times more photons (per $M_\odot$ of SF) in the Lyman-Werner bands than

\textsuperscript{3} The SED $g_x$ of ionizing radiation is different for Population III and Population II, but since $\epsilon_{\text{UV}}$ is fixed, the H\textsc{i} ionization rate is the same.
the Population III SED. Indeed, in the 64L05p2 run, the dissociating background reduces the H$_2$ abundance in the low-density IGM to a value 1/100 of the H$_2$ abundance in the 64L05p3 run. In the 64L05p2noLW run the H$_2$ is not destroyed. In the right panel of Figure 4 we show the SFR as a function of redshift for the same simulations. Surprisingly, the SFR does not depend appreciably on the intensity of the dissociating background. It is evident that the destruction of H$_2$ in the low-density IGM does not affect the global SFR. The only difference in SF history is the run with a Population II SED, which has the higher background in the Lyman-Werner bands. Here the SFR decreases more than in the other two runs before a new burst occurs. However, on average, also taking into account numerical errors, the SFR is indistinguishable in these three runs.

When the background in the Lyman-Werner bands (averaged over 1000–1100 Å) builds up to $J_{LW} \gtrsim 10^{-25}$ ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$ (at $z \approx 20$), it starts to dissociate the H$_2$ in the IGM. It is evident (Fig. 4) that H$_2$ is continuously destroyed and reformed. The H$_2$ abundance peaks are slightly delayed with respect to the SFR minima. Since SF is self-regulated, the dissociating background intensity, after a rapid buildup phase, reaches an almost constant value. Depending on the SED of the sources and $\langle f_{esc} \rangle$, the equilibrium value of the background can be small (e.g., Population III and high $\langle f_{esc} \rangle$) or large (e.g., Population II and small $\langle f_{esc} \rangle$). Consequently, the H$_2$ abundance in the IGM can assume either a large or small quasi-constant value during the self-regulated SF phase.

In the Population III SED run (long-dashed line), the molecular abundance in the IGM is 100 times higher than in the Population II run, and the mass-weighted abundance becomes $\langle x_{H_2} \rangle_M \approx 2 \times 10^{-6}$ at $z \sim 12$. This means that the positive feedback produced essentially the same mass of H$_2$ destroyed by negative feedback.

The opacity of the IGM in the Lyman-Werner bands is proportional to the mean H$_2$ number density. In Figure 5 we show the background-specific intensity in $10^{-21}$ ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$ units, $J_{21}(\nu)$, as a function of frequency for the 64L05p3 run. We show $J_{21}(\nu)$ at redshift $z = 12$ when $\langle x_{H_2} \rangle_M \approx 2 \times 10^{-6}$. In the top panel, it is interesting to note the importance of the spectral features caused by H I, He I, and He II Ly$\alpha$ emission lines. The bottom panel shows a zoom at the frequencies of the Lyman-Werner bands; the upper line shows the intensity of the background without line radiative transfer, while the lower line shows it with line
The H$_2$ and resonant H i Lyman series line opacities reduce the background intensity by about 1 order of magnitude.

In Figure 6 we show a time sequence of two slices through the most massive object for the 64L05p2 simulation at $z = 19.4$ and 18.5. This simulation has $\epsilon_b = 0.2$, $\epsilon_{UV}/4\pi = 1.6 \times 10^{-5}$, and $f_{esc} = 1$ except for a different flux in the Lyman-Werner bands. The two top panels show the volume-(left) and mass-weighted (right) H$_2$ abundance in the box. The middle and bottom panels show the analogous quantities for H$_2$ and H$^+$, respectively. Right: Comoving SFR for the same three runs. Despite the fact that the dissociating background flux in these three simulations differs by several orders of magnitude, the SFRs are almost identical. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 4.—Left: Species abundances for the 64L05p2noLW (solid line), 64L05p2 (short-dashed line), and 64L05p3 (long-dashed line) runs. These runs have the same parameters [$s_b = 0.2$, $\epsilon_{UV}/4\pi = 1.6 \times 10^{-5}$, and $f_{esc} = 1$] except for a different flux in the Lyman-Werner bands. The two top panels show the volume-(left) and mass-weighted (right) H$_2$ abundance in the box. The middle and bottom panels show the analogous quantities for H$_2$ and H$^+$, respectively.

Right: Comoving SFR for the same three runs. Despite the fact that the dissociating background flux in these three simulations differs by several orders of magnitude, the SFRs are almost identical. [See the electronic edition of the Journal for a color version of this figure.]

In Figure 6 we show a time sequence of two slices through the most massive object for the 64L05p2 simulation at $z = 19.4$ and 18.5. This simulation has $\epsilon_b = 0.2$, $\epsilon_{UV}/4\pi = 1.6 \times 10^{-5}$, $f_{esc} = 1$, and sources with a Population II SED. Each one of the two panels shows $\log(x_{H_2})$, $\log(x_{H_2})$, $\log (1 + \delta)$, and $\log T$, where $\delta = (\rho - \rho_0)/\rho_0$ is the baryon overdensity with respect to the mean IGM density $\rho_0$. At $z = 19.4$, the H$_2$ has its relic abundance everywhere in the IGM except in the dissociation spheres around the first objects, where it is destroyed. At $z = 18.5$, the dissociation spheres are still visible, but the UV background starts to dissociate H$_2$ everywhere in the IGM except in the filaments. Finally, at $z = 18.5$, the dissociation spheres overlap, the background has destroyed all the relic H$_2$. The H$_2$ is still present in the filaments where the gas is partially ionized by stars and positive feedback dominates. In the analogous simulation, where the sources have a Population III SED, the dissociation spheres never appear around the source. The dissociating background destroys the H$_2$ in the IGM before the dissociation spheres grow larger than the PFRs. Finally, if $f_{esc} < 1$ and we use a Population II SED for the sources, the dissociation spheres around the sources almost overlap before the background dominates the H$_2$ dissociation rate. If the dissociating radiation emitted by each source, $S_{LW}$, is large, the dissociating background intensity rises quickly above $J_{LW} \approx 10^{-25}$ ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$ and the dissociation of H$_2$ in the IGM happens abruptly. In radiative transfer. The H$_2$ and resonant H i Lyman series line opacities reduce the background intensity by about 1 order of magnitude.

Fig. 5.—Background-specific intensity in $10^{-21}$ ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$ units, $J_{LW}(\nu)$, as a function of photon energy for the 64L05p3 run (Population III) at $z = 12$. The bottom panel shows a zoom of the spectrum in the Lyman-Werner bands. In this example, H$_2$ and H Lyman series line opacities reduce the intensity of the dissociating background in the Lyman-Werner bands by about 1 order of magnitude (lower line compared to the upper one). [See the electronic edition of the Journal for a color version of this figure.]
this case, the dissociation spheres grow fast enough\(^4\) to cover a large volume of the IGM before the contribution of distant sources to the dissociating background builds up substantially. In contrast, if the dissociating radiation emitted by the sources is small, the dissociation spheres grow slowly, while the additive contribution of distant sources builds up the intensity of the dissociating background more quickly. In this case, the dissociation spheres remain smaller than the PFRs (and therefore invisible) until the dissociating background has destroyed all the \(\text{H}_2\) in the IGM.

Figure 7 is analogous to Figure 6, except that we now show a zoomed region (0.125 \(\times\) 0.125 \(h^{-1}\) Mpc) around the most massive object in the 64L05p3 box. This simulation has \(L_{\text{box}} = 0.5 \ h^{-1}\) Mpc, \(\epsilon_\nu = 0.2\), (\(\epsilon_{\text{UV}}/4\pi\)) = \(1.6 \times 10^{-5}\), \(<f_{\text{esc}}>=1\), and sources with a Population III SED. In this sequence of four slices (at \(z = 17.3, 12.2, 11.3,\) and 10.2) we recognize the two main processes that create \(\text{H}_2\) in the filaments. In the top left frame at \(z = 17.3\) we can recognize a PFR as a shell of \(\text{H}_2\) surrounding the \(\text{H}\) II region that is barely intersected by the slice. In the bottom left frame (\(z = 11.3\)) two \(\text{H}\) II regions are clearly visible. Inside the \(\text{H}\) II regions, the \(\text{H}_2\) is destroyed. In the bottom right frame (\(z = 10.2\)) the \(\text{H}\) II regions are recombing (demonstrating that the SF is bursting) and new \(\text{H}_2\) is being reformed inside the relic \(\text{H}\) II regions. A more fine inspection\(^5\) of the time evolution of this slice shows that at least five \(\text{H}\) II regions form and recombine between \(z = 20\) and 10 in this small region of the simulation.

\(^4\) In Ricotti et al. (2001) we provide an analytic expression for the comoving radius \(R_\text{D}\) of the dissociation sphere produced by a source that turns on at \(z = z_i\) as a function of time: \(R_\text{D} \propto (z + 1)/(\Delta t)^{1/2}\).

\(^5\) Movies of two-dimensional slices and three-dimensional rendering of the simulations are publicly available on the World Wide Web at http://casa.colorado.edu/~ricotti/MOVIES.html.

In the left panel of Figure 8 we compare the SFR of three simulations with \(L_{\text{box}} = 0.5 \ h^{-1}\) Mpc, \((\epsilon_{\text{UV}}/4\pi) = 1.6 \times 10^{-5}\), \(<f_{\text{esc}}>=1\), and a Population III SED (64L05p3, 64L05p3b, 64L05p3c), when we reduce \(\epsilon_\nu = 0.2\) by a factor of 10 and 100. It appears that the SFR is fairly insensitive to the value of \(\epsilon_\nu\) if we consider a realistic range of values \(0.2 < \epsilon_\nu < 0.02\). As \(\epsilon_\nu\) is reduced from 0.2 to 0.02, the oscillations of the global SFR with redshift become more smooth, but its redshift-averaged value gets only a factor of 2 smaller. When we reduce \(\epsilon_\nu\) from 0.02 to 0.002, the global SFR gets a factor of 5 smaller. It is important to note that when the SFR is dominated by large-halo objects, the global SFR is proportional to \(\epsilon_\nu\). This result is based on the comparison of several simulations that differ only on the value of \(\epsilon_\nu\), some presented here and some presented in Gnedin (2000).

The \(\text{H}\) I ionizing background, \(J_{\text{HI}}\), has the same behavior as the SFR (i.e., is insensitive to \(\epsilon_\nu\)). In the right panel of Figure 8 we show the comoving mean free path\(^6\) of \(\text{H}\) I ionizing photons \(\lambda_{\text{com}}\) for the same simulations shown in the left panel of Figure 8. It is striking that even if we change \(\epsilon_\nu\) by 2 orders of magnitude, the mean free path of ionizing photons oscillates around a constant value \(\lambda_{\text{com}}^\text{cr}\), shown in the figure.

\(^6\) By definition, \(\lambda_{\text{com}} = |r/\bar{J}_{\text{HI}}(1 + z)|\), where \(\bar{J}_{\text{HI}}\) is the mean absorption coefficient weighted by the photoionization rate. Neglecting the terms on the left-hand side of eq. (4) in Paper I, we have \(\bar{J}_{\text{HI}} = S_{\text{HI}}/J_{\text{HI}}\). Therefore, we can derive \(\lambda_{\text{com}}\) from the emissivity \(S_{\text{HI}}\) (which is proportional to the SFR, \(<f_{\text{esc}}>\), and \(\epsilon_{\text{UV}}\)) and the ionizing background intensity \(J_{\text{HI}}\).
by the solid line given by

$$\lambda_{\text{com}}^{cr} = 0.55 \, h^{-1} \, \text{kpc} \left( \frac{20}{1 + z} \right)^2.$$  

(1)

Figure 9 is analogous to Figure 8 but compares simulations varying the value of $\epsilon_{UV}$. The first three runs of the list shown in the figure (thick lines) have the same $\langle f_{\text{esc}} \rangle = 1$ and $\epsilon_* = 0.2$, but $\epsilon_{UV}$ is reduced by factors of 10 and 100; the solid, short-dashed, and long-dashed lines have $\langle \epsilon_{UV}/4\pi \rangle = 1.6 \times 10^{-7}, 1.6 \times 10^{-6},$ and $1.6 \times 10^{-5}$, respectively. The last three runs of the list (thin lines) have $\epsilon_* = 0.02$ and varying $\epsilon_{UV}$; the solid, short-dashed, and long-dashed lines have $\langle \epsilon_{UV}/4\pi \rangle = 1.6 \times 10^{-6}, 1.6 \times 10^{-5},$ and $1.6 \times 10^{-4}$, respectively. The left panel of Figure 9 shows that the SFR is approximately inversely proportional to $\epsilon_{UV}$ and insensitive to $\epsilon_\star$. The inverse proportionality relation is evident when the SF is smooth (compare the thick and thin solid lines). When the SF is bursting, the comparison of different simulations is more difficult, but the inverse relation appears to hold at least in a limited range of the parameter space. The right panel of Figure 9 shows that $\lambda_{\text{com}}$ is constrained to not exceed a critical value $\lambda_{\text{com}}^{cr}$, shown by the solid line of equation (1). Analogous to $\lambda_{\text{com}}$, $J_{HI}$ is insensitive to the choice of the free parameters of the simulations. The number of ionizing photons that escape in the IGM is proportional to the parameter combination $\epsilon_{UV} \langle f_{\text{esc}} \rangle$. Therefore, changing $\epsilon_{UV}$ is the same as changing $\langle f_{\text{esc}} \rangle$. The only difference is that the SED has more dissociating photons if we reduce $\epsilon_{\text{esc}}$ instead of $\epsilon_{UV}$. In § 3.2.1 we show that unless $\langle f_{\text{esc}} \rangle$ is very small, the dissociating radiation does not affect the SFR. In this regime it is the value of the parameter combination $\epsilon_{UV} \langle f_{\text{esc}} \rangle$ that regulates the SFR.

If the product $\epsilon \epsilon_{UV} \langle f_{\text{esc}} \rangle$ is large, $\lambda_{\text{com}}$ has large oscillations around the critical value, and when the product is small, the oscillations are small. Large oscillations of $\lambda_{\text{com}}$ are associated with a strong bursting SF mode. The feedback works in such a way that when $\lambda_{\text{com}}$ exceeds the critical...
value, the SF is suppressed, and consequently $\lambda_{\text{com}}$ becomes smaller than the critical value. It is easy to show that $\lambda_{\text{com}}$ is related to the H$\text{ii}$ region radii. Therefore, the mechanism that self-regulates the SF in small-halo objects is related to the size of H$\text{ii}$ regions, rather than to the intensity of the dissociating background as previously thought.

Following Gnedin (2000), we can express $\lambda_{\text{com}}$ as a function of the mean radius $R_{\text{Hii}}$ of the H$\text{ii}$ regions well before the overlap phase. By definition, $\lambda_{\text{com}} = \frac{c}{k(1+z)}$, where $k$ is the mean absorption coefficient weighted by the photo-ionization rate $\Gamma$. The mean optical depth for H$\text{i}$ ionizing radiation inside an H$\text{ii}$ region is $\tau = \frac{R_{\text{Hii}}}{\lambda_{\text{com}}} = \frac{R_{\text{Hii}}}{\lambda_{\text{com}}}$. 

Fig. 8.—Global SFR (left) and comoving mean free path of H$\text{i}$ ionizing photons $\lambda_{\text{com}}$ (right) as a function of redshift for the 64L05p3, 64L05p3b, and 64L05p3c runs. The solid, short-dashed, and long-dashed lines have $\epsilon_{\text{s}} = 0.2$, 0.02, and 0.002, respectively. The three simulations have $L_{\text{box}} = 0.5 h^{-1}$ Mpc, $(e_{\text{UV}}/4\pi) = 1.6 \times 10^{-5}$, $(f_{\text{esc}}) = 1$, and a Population III SED. The global SFR, $J_{\text{HI}}$, and $\lambda_{\text{com}}$ are almost insensitive to $\epsilon_{\text{s}}$ for a reasonable range of SF efficiencies ($0.2 < \epsilon_{\text{s}} < 0.02$). [See the electronic edition of the Journal for a color version of this figure.]

Fig. 9.—Same as in Fig. 8, but for the 64L05p2noLW-2 (thick solid line), 64L05p2-1 (short-dashed line), and 64L05p2 (long-dashed line) runs with $\epsilon_{\text{s}} = 0.2$, $(f_{\text{esc}}) = 1$, and $(e_{\text{UV}}/4\pi) = 1.6 \times 10^{-7}$, $1.6 \times 10^{-8}$, and $1.6 \times 10^{-9}$. The thin solid, short-dashed, and long-dashed lines show the 64L05p3b-1, 64L05p3b, and 64L05p2noLW+1 runs that have $\epsilon_{\text{s}} = 0.02$, $(f_{\text{esc}}) = 1$, and $(e_{\text{UV}}/4\pi) = 1.6 \times 10^{-6}$, $1.6 \times 10^{-7}$, and $1.6 \times 10^{-8}$. The three curves in each set of simulations have values of $e_{\text{UV}}$ increased by 1 order of magnitude. It appears that the SFR is about inversely proportional to $e_{\text{UV}}$ and independent of $\epsilon_{\text{s}}$. The comoving mean free path of H$\text{i}$ ionizing photons, $\lambda_{\text{com}}$, and $J_{\text{HI}}$, instead, remain constant. [See the electronic edition of the Journal for a color version of this figure.]
density of a virialized halo is

\[ N_{\text{H}i} = \frac{\sigma_{\text{H}i}}{n_{\text{vir}}} R_{\text{vir}} \sim 10^{19} \text{ cm}^{-2} \left( \frac{1 + z}{20} \right)^2. \]

Here \( n_{\text{vir}} \) is the virial density, \( R_{\text{vir}} \) is the virial radius of an DM halo, and \( \sigma_{\text{H}i} \) is the neutral hydrogen fraction. Assuming a frequency-averaged value of the H I photoionization cross section \( \sigma_{\text{H}i} \sim 10^{-18} \text{ cm}^2 \), we have

\[ \lambda_{\text{com}} = \frac{R_{\text{H}ii}^\text{com}}{r_{\text{Hi}}} = \frac{R_{\text{H}ii}^\text{com}}{\sigma_{\text{H}i} N_{\text{H}i}} \approx 0.1 R_{\text{H}ii}^\text{com} \left( h^{-1} \text{ kpc} \right) \left( \frac{20}{1 + z} \right)^2, \tag{2} \]

where \( R_{\text{H}ii}^\text{com} \left( h^{-1} \text{ kpc} \right) \) is the mean free path of ionizing photons. Comparing equation (2) with equation (1), we find that the mean radius of the H II regions produced by small-halo objects is \( R_{\text{H}ii} \approx 5 \left( 1 + z \right) h^{-1} \text{ kpc} \), about the size of the dense filaments and the virial radii of the halos.

Qualitatively, this result is already evident in Figure 2, which shows that the H II regions remain confined inside the filaments. The PFRs produced ahead of ionization fronts and the relic H II regions continuously reform H II inside the filaments. The H II abundance remains high in the filaments, even when the dissociating background intensity is sufficiently strong to dissociate all the H II in the lower density IGM.

### 3.2.1. Star Formation History: A Function of \( \langle f_{\text{esc}} \rangle \)

We have seen in the previous section that the SFR is fairly insensitive to \( \epsilon_s \) over the range \( 0.02 < \epsilon_s < 0.2 \) and inversely proportional to \( \epsilon_{\text{UV}} \langle f_{\text{esc}} \rangle \). The free parameter \( \epsilon_{\text{UV}} \) depends mainly on the stellar IMF and slightly on the stellar metallicity. Assuming a Salpeter IMF, we find \( \epsilon_{\text{UV}} = 1.1 \times 10^{-5} \) for a Population II SED and \( \epsilon_{\text{UV}} = 2.5 \times 10^{-5} \) for a Population III SED. Some theoretical arguments suggest that at high redshift, the IMF could be flatter than a Salpeter IMF. If this is the case, we would have \( \epsilon_{\text{UV}} < 10^{-5} \). The possibility of having a steeper IMF, and therefore \( \epsilon_{\text{UV}} < 10^{-5} \), is not supported by any theoretical work or observation.

The value of \( \langle f_{\text{esc}} \rangle \) is unknown and has been an argument of debate for many years. In literature, values of \( \langle f_{\text{esc}} \rangle \) between 0.5 and 0.0 have been proposed. Theoretical work on \( \langle f_{\text{esc}} \rangle \) for small-halo objects at high redshift (Ricotti & Shull 2000; Wood & Loeb 2000) finds that \( \langle f_{\text{esc}} \rangle \) should be very small \( 10^{-5} < \langle f_{\text{esc}} \rangle < 10^{-3} \) and decreasing with increasing halo masses. Observations of \( \langle f_{\text{esc}} \rangle \) in nearby starburst galaxies find values of \( \langle f_{\text{esc}} \rangle \sim 10^{-3} \) (Leitherer et al. 1995; Hurwitz, Jelinsky, & Dixon 1997; Heckman et al. 2001; Deharveng et al. 2001), in agreement with theoretical studies (Dove, Shull, & Ferrara 2000). Numerical simulations of the reionization of the IGM usually adopt a value of \( \langle f_{\text{esc}} \rangle \sim 1 \) in order to reionize the universe before redshift \( z \sim 6 \). A recent study on Lyman break galaxies (Steidel, Pettini, & Adelberger 2001) agrees with numerical simulations in finding \( \langle f_{\text{esc}} \rangle \approx 0.5 \). However, there is no observational constraint on the value of \( \langle f_{\text{esc}} \rangle \) for small-halo objects. Reasonably, small-halo objects should have smaller \( \langle f_{\text{esc}} \rangle \) than large-halo objects (normal galaxies) since their halos are not collisionally ionized. On the other hand, if a substantial fraction of the ISM is photoevaporated or blown away by stellar winds and SNe, \( \langle f_{\text{esc}} \rangle \) could be larger. We note that \( \langle f_{\text{esc}} \rangle \) in this paper is defined as the escape fraction of ionizing photons from the resolution element; therefore, it is resolution dependent and generally larger than \( \langle f_{\text{esc}} \rangle \) from the galactic halos.

In the previous section we showed that if \( \epsilon_{\text{UV}} / 4 \pi \langle f_{\text{esc}} \rangle \gtrsim 10^{-3} \) and \( \epsilon_s \gtrsim 0.02 \), the SFR is suppressed by the feedback of ionizing radiation (but not from the dissociating background). Since it is unlikely that \( \epsilon_{\text{UV}} / 4 \pi \langle f_{\text{esc}} \rangle < 10^{-5} \), the SFR can be increased if \( \langle f_{\text{esc}} \rangle < 1 \). As we decrease \( \langle f_{\text{esc}} \rangle \), the SFR increases almost linearly up to a maximum value determined by the SFR without any feedback. This value is proportional to \( \epsilon_s \) and to the mass resolution of the simulation. In higher mass resolution simulations, the number of small-halo objects that form stars is larger since we resolve many more small-mass objects. We believe that our higher resolution simulation, with \( L_{\text{box}} = 20 h^{-1} \text{ Mpc}, 256^3 \text{ cells}, \) and mass resolution \( \Delta M = 4.93 \times 10^5 M_\odot \), is close to fully resolving SF for the case without radiative feedback (we need to resolve each halo with about 100 DM particles).

Clearly, if \( \langle f_{\text{esc}} \rangle = 0 \), there should be no positive feedback, but only the negative feedback of the dissociating background, which should determine the SFR. Indeed, if we decrease the value of \( \langle f_{\text{esc}} \rangle \) below a critical value, the SFR, after reaching the maximum, starts to decrease. This effect is shown in the left panel of Figure 10, where the lines show simulations with \( \epsilon_s = 0.2 \). Population II SED, and \( \langle f_{\text{esc}} \rangle = 1, 0.1, 0.01, 10^{-3} \), and \( 10^{-5} \) (runs 64L05p2, 64L05p2-1f, 64L05p2-2f, 64L05p2-3f, and 64L05p2-5f, respectively). At \( z = 15.5 \), in the simulation with \( \langle f_{\text{esc}} \rangle = 0.01 \), the intensity of the dissociating background is about \( J_{\text{LW}} \sim 5 \times 10^{-21} \text{ ergs cm}^{-2} s^{-1} \text{ Hz}^{-1} \text{ sr}^{-1} \). The value of \( J_{\text{LW}} \) is high enough to decrease the SFR with respect to the case without radiative feedback by about a factor of 2. In the right panel of Figure 10, we show the different importance of the dissociating radiation feedback for a Population II and a Population III SED. All the simulations in the right panel of Figure 10 have \( \langle f_{\text{esc}} \rangle = 0.01 \) (runs 64L05p2-2f, 64L05p2-3f, 64L05p2-2fa, and 64L05p3-2fa in Table 1).

The effect of decreasing excessively the value of \( \langle f_{\text{esc}} \rangle \) on the SFR is twofold: (1) it reduces the positive feedback of the EUV radiation and (2) it increases the relative importance of the dissociating radiation over the ionizing radiation by modifying the SED, \( \alpha_{\nu} \). The negative feedback of the dissociating background starts to affect the SFR, depending on the magnitude of the jump, \( \beta \), at the Lyman continuum frequency of the SED and the magnitude of the positive feedback. The jump \( \beta \) is inversely proportional to \( \langle f_{\text{esc}} \rangle \) and depends on the SED (intrinsic jump). For the same \( \langle f_{\text{esc}} \rangle \), the Population II SED produces a jump 10 times larger than the Population III SED. We find that if \( 0.02 \gtrsim \epsilon_s \lesssim 0.2 \), the critical value for which the negative feedback of the dissociating background starts to affect the SFR is \( \langle f_{\text{esc}} \rangle \lesssim 10^{-2} \) for the Population II SED and \( \langle f_{\text{esc}} \rangle \lesssim 10^{-3} \) for the Population III SED.

In Figure 11 we show a case in which the positive feedback produces enhanced global SFR with respect to the case without radiative feedback. The simulation (thick dashed line) has \( \epsilon_s = 0.02 \), \( \langle f_{\text{esc}} \rangle = 1 \), \( \epsilon_{\text{UV}} / 4 \pi \langle f_{\text{esc}} \rangle = 1.6 \times 10^{-3} \), and a Population III SED (64L05p3b-3 run). The thin solid line shows the analogous simulation without radiative transfer.
The thick dashed line shows a simulation with the same value of the parameter combination $C_{UV}C_{h_{esc}}$ as the 64L05p3b-3 run, but with a Salpeter IMF $\left(\frac{C_{UV}}{C_{15}}\right) = 1.6 \times 10^{-2}$ and $h_{esc} = 1$. The SFR in these two simulations should be identical, since it depends on the parameter combination $C_{UV}C_{h_{esc}}$. Instead, the negative feedback of the dissociating background reduces the SFR by a factor of 3 with respect to the 64L05p3b-3 run.

The dissociating background in the simulation with $h_{esc} = 10^{3}$ is 3 orders of magnitude higher ($J_{LW} = 0.5 \times 10^{-21}$ ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$ at $z = 11.5$) than in the simulation with $h_{esc} = 1$.

The simulations presented in this section have mass resolution $M_{DM} = 3.94 \times 10^{4} h^{-1} M_{\odot}$. The global SFR (without radiative feedback) is underestimated because we do not resolve the lowest mass objects that can form stars. Higher resolution simulations could produce an enhanced SFR with respect to the case without including any feedback. Indeed, positive feedback can trigger SF in halos with a mass smaller than the minimum mass derived in the absence of feedback. Theoretically, the lower limit for the DM mass of an object that could form stars is determined by the filtering mass, which is $M_{F} = 10^{5} - 10^{6} h^{-1} M_{\odot}$ in the redshift range $20 < z < 100$. In objects with DM masses smaller than $M_{F}$, the baryons cannot virialize.

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3.2.2. How Does the Self-Regulation Work?

Summarizing, the feedback prevents the size of H II regions from exceeding \( R_{\text{esc}}^{\text{UV}} \approx 5 \, h^{-1} \, \text{kpc} \) (about the size of the dense filaments). Indeed, when the H II regions get bigger than the filaments, molecular hydrogen is destroyed and the SF is suppressed. On the contrary, when the H II regions are smaller than the filaments or when they recombine after a burst of SF, the dense filaments are only partially ionized and the formation rate of molecular hydrogen is maximized. Since galaxy formation takes place only in overdense regions, the SF is self-regulated to maximize H2 formation in the filaments. Thus, the volume filling factor of the H II regions remains small. As a result, small-halo objects cannot reionize the universe. Molecular hydrogen is continuously reformed, in shells preceding the H II regions and in shells inside relic H II regions, the PFRs found by Ricotti et al. (2001). SF is bursting, since it is self-regulated by the two above-mentioned feedback mechanisms. The SFR does not depend on \( \epsilon_{s} \) or on the source SED, but only on \( \langle f_{\text{esc}} \rangle \) and the IMF through \( \epsilon_{\text{UV}} \). If \( \epsilon_{\text{UV}} \langle f_{\text{esc}} \rangle \) is small, the SFR is high, and vice versa. Indeed, if few ionizing photons (per each baryon converted into stars) escape from the halo, more stars have to be formed in order to produce H II regions of the size of the filaments. If the product \( \epsilon_{s} \epsilon_{\text{UV}} \langle f_{\text{esc}} \rangle \) is large, the SF burst is so fast that H II regions will expand outside the filaments before recombining. This produces a temporary halt in the global SF, which appears as a sequence of strong bursts. It is fascinating that the SF history of small-halo objects depends primarily on a single parameter, \( \epsilon_{\text{UV}} \langle f_{\text{esc}} \rangle \). This happens because the feedback mechanism acts on a cosmological (rather than galactic) scale. We notice, though, that \( \langle f_{\text{esc}} \rangle \) should depend slightly on \( \epsilon_{s} \) (Ricotti & Shull 2000).

In Figure 12 we show a sketch of the relative importance of positive and negative feedback from EUV (ionizing) and far-ultraviolet (FUV) (dissociating) radiation on the SFR. The thick and thin solid curves show the SFR with and without radiative transfer, respectively, for a simulation with \( \epsilon_{s} = 0.2 \), Population II SED \([\langle \epsilon_{\text{UV}}/4\pi \rangle = 1.1 \times 10^{-3}\), and \( \langle f_{\text{esc}} \rangle = 0.01 \). Without radiative feedback, the SFR is proportional to \( \epsilon_{s} \). Therefore, for a simulation with \( \epsilon_{s} = 0.02 \), for instance, the SFR shown by the thin solid curve would be a factor of 10 smaller. The solid line shows the region where the positive feedback from EUV radiation is maximum. The SFR of this line is inversely proportional to the parameter combination \( \epsilon_{\text{UV}} \langle f_{\text{esc}} \rangle \). Above the solid line, we have increasing negative feedback from EUV radiation (H II regions become larger than the filaments), and below the line the positive feedback from EUV radiation becomes increasingly weak. If the parameter combination \( \epsilon_{s} \epsilon_{\text{UV}} \langle f_{\text{esc}} \rangle \approx 10^{-6} \) to \( 10^{-7} \), the SFR is not suppressed by EUV radiative feedback (in this case the solid line ties above the thin solid curve). When the flux of ionizing photons in the filaments is too small, either because \( \langle f_{\text{esc}} \rangle \) is small or because of a low SFR, positive feedback effects are weak. The negative feedback of the dissociating background becomes, therefore, important. Below the thin dashed line, the negative feedback from FUV radiation starts to dominate the positive feedback from EUV radiation. The region between the solid and dashed lines is where the positive feedback dominates over negative feedback, and its size is inversely proportional to the jump \( \beta \) at the Lyman continuum of the source SED. The effect of the FUV negative feedback is usually to delay SF at high redshift, when the SFR, and therefore the ionizing photon flux, is lower. At higher redshift, as the number of small-halo objects increases, the positive feedback dominates and the SFR becomes self-regulated by the EUV radiation. In the extreme case of a very small \( \langle f_{\text{esc}} \rangle \) \( \langle f_{\text{esc}} \rangle \approx 10^{-3} \) for a Population II SED and \( \langle f_{\text{esc}} \rangle \approx 10^{-4} \) for a Population III SED, the negative feedback of the dissociating background can suppress small-halo object formation.

3.3. Metal Enrichment of the IGM

Metals are produced by the same massive stars that produce ionizing radiation. Understanding the metal enrichment of the low-density IGM is a challenging task. Observational constraints from the metallicity evolution of the Ly\( \alpha \) forest allow us to test the models. In Figure 13 we show a three-dimensional rendering of the IGM metallicity (in solar units) for the 64L05p3 run \([L_{\text{box}} = 0.5 \, h^{-1} \, \text{Mpc}, \epsilon_{s} = 0.2, \epsilon_{\text{UV}} \langle 4\pi \rangle = 1.6 \times 10^{-5}, \langle f_{\text{esc}} \rangle = 1, \text{and a Population III SED}]\). The opacity and the color coding are proportional to the logarithm of the metallicity \( (Z/Z_{\odot}) \). The comoving volume filling factor of the metal-enriched gas increases quickly at high redshift and slows down as the redshift decreases.

In the left panel of Figure 14 we show the ratio \( (Z/Z_{\odot}) \) for the volume- to mass-weighted mean metallicities as a function of redshift. This ratio is proportional to the filling factor of the metal-enriched gas. The solid line shows the 64L05n0RAD run \([L_{\text{box}} = 0.5 \, h^{-1} \, \text{Mpc}, \epsilon_{s} = 0.2, \epsilon_{\text{UV}} \langle 4\pi \rangle = 1.6 \times 10^{-5}, \text{without radiative transfer}]\). The dotted, dashed, and long-dashed lines show simulations with \( \langle f_{\text{esc}} \rangle = 1 \) and an increasing value of the parameter combination \( \epsilon_{s} \epsilon_{\text{UV}} \langle 4\pi \rangle \langle f_{\text{esc}} \rangle \approx 3.2 \times 10^{-8} \).
3.2 \times 10^{-7}, and 3.2 \times 10^{-6}, respectively. We remind the reader that if the value of this parameter combination is high, the global SF, $J_{\mathrm{HI}}$, and $\lambda_{\mathrm{com}}$ are strongly oscillating (bursting SF). The filling factor of metal-enriched gas is larger in the simulations with strongly bursting SF. This suggests that photoevaporation of high-redshift small-halo galaxies is an important mechanism for transporting metals in the low-density IGM (voids).

The right panel of Figure 14 shows the mass-weighted metallicity $\langle Z/Z_\odot \rangle_M$ for the four simulations in the left panel of Figure 14. It can be easily shown that $\langle Z/Z_\odot \rangle_M \propto \epsilon_{\mathrm{UV}} f_{\mathrm{star}}$, where $f_{\mathrm{star}}$ is the mass fraction in stars and $\epsilon_{\mathrm{UV}}$ is the energy in ionizing photons per rest mass energy of H atoms ($m_H c^2$) transformed into stars (the number of ionizing photons emitted by a population of stars is proportional to the number of heavy elements released in the ISM). The parameter $\epsilon_{\mathrm{UV}}$ depends on the IMF and stellar metallicity. If the feedback of the EUV radiation regulates the SFR, we have $f_{\mathrm{star}} \propto \langle \epsilon_{\mathrm{UV}} f_{\mathrm{esc}} \rangle^{-1}$. In this case, we expect $\langle Z/Z_\odot \rangle_M \propto \langle f_{\mathrm{esc}} \rangle^{-1}$, independent of the stellar metallicity and IMF. We conclude that while the SFR and $f_{\mathrm{star}}$ are inversely proportional to the parameter combination $\epsilon_{\mathrm{UV}} f_{\mathrm{esc}}$, the mass of metals produced by small-halo objects depends only on $f_{\mathrm{esc}}$. In Figure 14 we have used $\langle f_{\mathrm{esc}} \rangle = 1$.

### 3.4. Realistic Scenarios of Cosmic Evolution during the “Dark Ages”

In this section we show the evolution of the global properties of the universe in our three most realistic simulations: the 128L1p2, 128L1p2-2, and 256L1p3 runs. The mass resolution ($M_{\mathrm{DM}} = 4.93 \times 10^3 h^{-1} M_\odot$ for the 256$^3$ and $3.94 \times 10^4 h^{-1} M_\odot$ for the 128$^3$ runs) and box size, $L_{\mathrm{box}} = 1 h^{-1}$ Mpc, of these simulations are sufficiently large to resolve the formation of the first small-halo and large-halo objects. In particular, the 128L1p2-2 and 256L1p3 simulations include the effects of secondary electrons and the SED modification caused by assuming realistic values of $f_{\mathrm{esc}}$. We have $\langle f_{\mathrm{esc}} \rangle = 0.1$, $\epsilon_* = 0.1$, and a metal-free SED [$(\epsilon_{\mathrm{UV}}/4\pi) = 2.5 \times 10^{-4}$] for the 256L1p3 run. For the 128L1p2-2 run we assume $\langle f_{\mathrm{esc}} \rangle = 0.01$, $\epsilon_* = 0.05$, and $Z = 0.05 Z_\odot$ with a Population II SED [$(\epsilon_{\mathrm{UV}}/4\pi) = 1.1 \times 10^{-5}$]. The 128L1p2 run has $\langle f_{\mathrm{esc}} \rangle = 1$, $\epsilon_* = 0.2$, $(\epsilon_{\mathrm{UV}}/4\pi) = 1.6 \times 10^{-3}$, and a Population II SED.
We believe that the 2563 run is very close to the limit of numerical convergence. Finally, the formal spatial resolution is 156 $h^{-1}$ pc comoving ($B_h = 25$ is the parameter that regulates the maximum deformation of the Lagrangian mesh: the spatial resolution is $\sim L_{\text{box}}/(N_{\text{box}}B_h)$) in the 256L1p3 run, 488 $h^{-1}$ pc comoving ($B_h = 16$) in the 128L1p2-2 run, and 781 $h^{-1}$ pc comoving ($B_h = 10$) in the 128L1p2 run. To give a better idea of the scales resolved by the simulations, we remind the reader that the comoving core radius of a just-virialized DM halo of mass $M_{\text{DM}}$ is $R_c \approx 300$ pc ($M_{\text{DM}}/10^9 M_\odot$)$^{1/3}$ (we have assumed a halo concentration parameter $c = R_{\text{vir}}/R_c = 10$). We refer the reader to Paper I for details on the physics included in the code and in our convergence studies.

The thick solid lines in Figure 15 show the comoving SFR and fraction of baryons in stars, $f_{\text{star}}$, as a function of redshift for the 256L1p3 run (left panels), 128L1p2-2 run (middle panels), and 128L1p2 run (right panels). As a comparison we plot the same runs without radiative transfer (dashed lines) and the 64L1noC run (643 cells and $L_{\text{box}} = 1$ $h^{-1}$ Mpc), excluding both radiative transfer and H2 cooling (thin solid lines). Therefore, thin solid lines show the contribution to the global SFR of large-halo objects only, and the dashed lines show the SFR of small-halo and large-halo objects without any feedback effect. The main result shown in this figure is that small-halo objects are an extremely important (or dominant) fraction of the galaxies until at least redshift $z \sim 10$. Contrary to what is widely believed, their formation is not severely suppressed by the dissociating background. We showed in § 3.1 that the dissociating background has little influence in determining the SF history. In § 3.2 we demonstrated that the mass fraction of small-halo objects formed depends, instead, only on the value of $\langle f_{\text{esc}} \rangle$ and the stellar IMF.

The two panels on the left of Figure 15 show the SFR and $f_{\text{star}}$ for the 2563 cell simulation, which has $\langle f_{\text{esc}} \rangle = 0.1$; in this simulation the first stars form at $z = 30$. At $z = 15$ the fraction of stars in small-halo objects is $f_{\text{star}} \approx 2 \times 10^{-4}$, about 5 times the mass of stars in large-halo objects. The radiative feedback has reduced $f_{\text{star}}$ by a factor of 10. Note that $f_{\text{star}}$ for large-halo objects (thin solid line) and for small-halo objects without feedback (thin long-dashed line) scales with $\epsilon_*$. The fraction of baryons transformed into stars of small-halo objects, including radiative feedback effects, does not depend on $\epsilon_*$ as long as it is smaller than the value without radiative transfer. Since for large-halo objects $f_{\text{star}} \propto \epsilon_*$, the relative importance of small-halo to large-halo objects is inversely proportional to $\epsilon_*$ (which here is 0.1). For instance, if we had chosen $\epsilon_* < 0.1$ for this simulation, $f_{\text{star}}$ of small-halo objects would have been as large as 50 times $f_{\text{star}}$ of large-halo objects at $z = 15$, and the radiative feedback would have suppressed the SF by only a small factor.

We show an example of such a case in the two central panels of Figure 15. In this 1283 simulation we use $\langle f_{\text{esc}} \rangle = 0.01$ and $\epsilon_* = 0.05$. Here the first stars form at $z = 26$ because of the lower mass resolution. Radiative feedback suppresses the SFR only by a factor of 2. At $z = 15$, $f_{\text{star}} \approx 3 \times 10^{-4}$, and the contribution of small-halo objects to SF is about 10 times the contribution of large-halo objects. At $z = 10$, small-halo objects still dominate $f_{\text{star}}$ by a factor of 3. Note that in this simulation the dissociating background intensity is very high and, as shown by the short-dashed lines in Figure 16, the H+ and H2 abundances in the IGM are extremely small ($\sim 10^{-12}$ relative to H).

The two panels on the right show the SFR and $f_{\text{star}}$ for the 1283 simulation, which has $\langle f_{\text{esc}} \rangle = 1$ and $\epsilon_* = 0.2$. At $z = 15$, the fraction of stars in small-halo objects is $f_{\text{star}} \approx 2 \times 10^{-5}$, about one-fifth the mass of stars in large-
halo objects. The radiative feedback has reduced \( f_{\text{star}} \) by a factor of 100.

In Figure 16 we show the mass- and volume-weighted mean molecular abundances \( \langle \chi_{\text{H}_2} \rangle \), \( \langle \chi_{\text{H}_1} \rangle \), and \( \langle \chi_{\text{He}^-} \rangle \) as a function of redshift for the three simulations with radiative transfer shown in Figure 15. The volume-weighted abundances are about 2 orders of magnitude smaller than the mass-weighted abundance. This shows that \( \text{H}_2 \) is much more abundant in dense regions. The dissociating background destroys the \( \text{H}_2 \) in the low-density IGM in the redshift range \( 20 < z < 25 \), depending on the choice of the free parameters in the simulation. In the dense regions, the production/destruction of \( \text{H}_2 \) sets its abundance to a quasi-constant value that depends on the SED of the sources. At redshift \( z \sim 15 \), the abundance of \( \text{H}^- \), the main catalyst for \( \text{H}_2 \) production, reaches its maximum value and starts to decrease. Consequently, the \( \text{H}_2 \) abundance also decreases after \( z \sim 15 \).

Figure 17 is analogous to Figure 16, but here we show the mass- and volume-weighted ionized H and He mean abundances \( \langle \chi_{\text{H}_1} \rangle \), \( \langle \chi_{\text{He}^0} \rangle \), and \( \langle \chi_{\text{He}^+} \rangle \) (left panels), as well as the metallicity \( \langle Z/Z_{\odot} \rangle \) and temperature \( \langle T \rangle \) (right panel). If reionization takes place at redshift \( z \sim 6 \), as recent high-redshift quasar observations seem to suggest (Becker et al. 2001; Djorgovski et al. 2001), the run shown by the long-dashed line reionizes the universe too early, while the run shown by the short-dashed line reionizes the universe too late. This observation does not constrain the value of \( \langle f_{\text{esc}} \rangle \) or \( \epsilon_* \) for small-halo objects, since we expect that \( \langle f_{\text{esc}} \rangle \), at least, will vary as a function of redshift. In this paper, we assume for simplicity that \( \langle f_{\text{esc}} \rangle \), \( \epsilon_* \), \( \epsilon_{\text{UV}} \), and \( g_{\nu} \) are constants.

The mass-weighted metallicity \( \langle Z/Z_{\odot} \rangle M \) is proportional to the total mass of metals produced by the stars and therefore is proportional to the SFR. Since we have shown that small-halo objects dominate the SFR if \( \langle f_{\text{esc}} \rangle \ll 1 \), at least before redshift \( z \sim 10 \), their metal production dominates by the same amount. Moreover, we have shown in § 3.3 that if SF is bursting, photodestruction of small galaxies is the main process that pollutes the low-density IGM (voids) with...
metals. Finally, SN explosions, not yet included in the simulations, can transport metals into the voids efficiently, since small-halo objects are numerous and the voids are small at high redshift.

In the left panel of Figure 18 we show the evolution of the \( \text{H} \) \( \text{i} \) ionizing background \( J_{\text{H}i} \) (thick lines) and the \( \text{He} \) \( \text{ii} \) ionizing background \( J_{\text{He}ii} \) (thin lines) for the same three simulations shown in the previous figure. In the right panel of Figure 18 we show the comoving mean free path of the \( \text{H} \) \( \text{i} \) ionizing photons \( \lambda_{\text{H}i} \) (thick lines) and of the \( \text{He} \) \( \text{ii} \) ionizing photons \( \lambda_{\text{He}ii} \) (thin lines). Reionization, defined as the overlap of \( \text{H} \) \( \text{ii} \) regions, occurs when \( \lambda_{\text{H}i} D_s/2 \sim 0.1 \) \( h^{-1} \) Mpc, where \( D_s \) is the mean comoving distance between the ionizing sources (Gnedin 2000).

4. DISCUSSION AND SUMMARY

In this paper we studied the formation and evolution of the first galaxies in a \( \Lambda \)CDM cosmology. Our results are based on three-dimensional cosmological simulations that include, for the first time, a self-consistent treatment of radiative transfer. The simulations include continuum radiative transfer using the OTVET approximation and line radiative transfer in the \( \text{H}_2 \) Lyman-Werner bands of the background radiation. Chemical and thermal processes are treated in detail, particularly the ones relevant for \( \text{H}_2 \) formation and destruction. The details about the numerical methods and the physics included in the simulations are treated in a companion paper (Paper I). In Paper I we have also performed a careful convergence analysis. It appears that we are very close to the convergence limit when we use a 256\(^3\) box. In smaller simulations the SF is underestimated.

The main result is that positive feedback processes dominate negative feedback of the dissociating background, and therefore SF in small-halo objects is not suppressed. The main parameter that determines the importance of small-halo objects is \( \langle f_{\text{esc}} \rangle \). If \( \langle f_{\text{esc}} \rangle \sim 0.01 \), small-halo objects dominate the galaxy mass function until at least redshift \( z \sim 9 \), and feedback produces a bursting SF in these objects. Because the ionization fronts are confined to the dense fila-
ments, reionization of the IGM cannot be produced by small-halo objects. However, we find that small-halo objects are important in enriching the low-density IGM with heavy elements.

The main processes that are not included in our simulations are H\textsubscript{2} self-shielding and mechanical and thermal energy injection caused by SN explosions. H\textsubscript{2} self-shielding, depending on the choice of the free parameters, could be relevant and should reduce the effects of the dissociating radiation. Since we have found that the dissociating radiation has a negligible role in regulating SF, we expect that the results of our simulations should not be modified by H\textsubscript{2} self-shielding. The effects of dissociating radiation become important when \( f_{\text{esc}} \lesssim 10^{-3} \). H\textsubscript{2} self-shielding effects probably reduce the value of \( f_{\text{esc}} \) for which dissociating radiation becomes important to a smaller value. Although we have not included them in our simulations, SN explosions can be important; their feedback could be responsible for a self-regulating global SF and contribute to spreading metals into the low-density IGM. Unfortunately, the dynamical and thermal effects of SN explosions on the ISM of galaxies and IGM are not fully understood. The investigation of the effects of mechanical feedback from SN explosions will be the subject of our future work.

We cannot rule out alternative cosmologies, in which small-halo objects do not form. For example, in warm dark matter (WDM) cosmologies, the free-streaming of the DM particles is large enough to suppress the formation of dwarf galaxies at high redshift. It is also possible that the initial power spectrum does not have enough power on small scales to form small-halo objects. Theoretical arguments based on observations of the Ly\textalpha\, forest, quasars at high redshift, and stellar populations in dwarf galaxies pose some constraints on the mass of WDM particle candidates \( m_{\text{WDM}} \gtrsim 1 \text{ keV} \). Current observations do not rule out these alternative cosmological models, but they may not solve the problems faced by CDM.

In the following list we summarize the results of this work in more detail:

1. The SFR in small-halo objects is self-regulated and depends only on \( f_{\text{esc}} \), for fixed \( \epsilon_{\text{UV}} \) (known IMF). The SFR is almost independent of the SF efficiency \( \epsilon_{*} \), the dissociating background, and the SED (metal-free or metal-rich objects) of the sources. It depends only on \( f_{\text{esc}} \) and the IMF (number of ionizing photons per baryon converted into stars). If \( f_{\text{esc}} \) is small, the SFR is high, while if \( f_{\text{esc}} \sim 0.01 \), the SF is only slightly suppressed by radiative feedback. In this case, the maximum SFR is proportional to \( \epsilon_{*} \), and small-halo objects dominate the galaxy mass function until at least redshift \( z \sim 10 \).

2. Small-halo SF is intrinsically "bursting." SF is regulated by competing negative and positive feedback from EUV (ionizing) radiation. The H\textalpha\, regions produced by small-halo objects are confined to the dense IGM filaments. Reionization of the IGM cannot happen until massive galaxies are formed. In contrast to massive objects, which reionize voids first, small-halo objects partially ionize only the dense filaments while leaving the voids neutral.

3. Galaxy formation is triggered by the presence of neighboring galaxies. The SFR does not depend strongly on the dissociating background intensity or on the H\textsubscript{2} abundance in the IGM. The self-regulation of SF relies on H\textsubscript{2} being continuously reformed in positive feedback regions. The H\textsubscript{2} formation happens only in the filaments, both inside relic H\textalpha\, regions that never expand into the low-density IGM and in the H\textsubscript{2} shells just in front of the H\textalpha\, regions (Ricotti et al. 2001).

4. The dissociating (FUV) radiation reduces the SFR only if \( f_{\text{esc}} \) is very small. If \( f_{\text{esc}} \lesssim 10^{-3} \) for a Population II
SED or $\langle f_{\text{esc}} \rangle \lesssim 10^{-4}$ for a Population III SED, the negative feedback of the dissociating background suppresses small-halo object formation, more efficiently at high redshift.

5. Small-halo objects dominate the metal pollution of the low-density IGM. The transport of metals from the galaxies to the low-density IGM happens because of the continuous formation and photoevaporation of small-mass halos. The metal production, if the SF is self-regulated by EUV radiation, is independent of the SF efficiency, SED, and IMF but depends only on $\langle f_{\text{esc}} \rangle$.

In conclusion, we have shown that if SN explosions do not suppress the formation of small-halo objects and CDM cosmogonies prove to be correct, small-halo objects should have profound effects on cosmic evolution. Observations of dwarf spheroidal galaxies, metallicity of the Ly$\alpha$ forest, and stellar populations in the halo of the Milky Way could verify this model. Computational limitations prevent us from evolving a representative sample of the universe to redshifts $z < 9$. At lower redshifts, the bulk of small-halo objects merge, forming larger mass galaxies, but some of them might survive almost unaffected by the environment. Reionization is probably affecting the ISM of these small galaxies quite substantially, photoevaporating the remaining unshielded gas. These “fossil” small-halo objects could be identified with at least some dwarf spheroidal galaxies in the Local Group. In a paper currently in preparation, we study the properties of the simulated small-halo objects in order to understand whether this link is real. The prediction of a large population of small-halo objects offers a challenging test to verify CDM cosmogonies. We speculate that in the near future, given the rapid progress of computational power and the rapid growth of observational data of cosmological interest, detailed cosmological simulations will allow us to constrain the evolution of our free parameters, $\langle f_{\text{esc}} \rangle$, $\epsilon_{\text{UV}}$, and $\epsilon_*$, or possibly the nature of the dark matter.

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REFERENCES

Becker, R. H., et al. 2001, AJ, 122, 2850
Ciardi, B., Ferrara, A., Governato, F., & Jenkins, A. 2000, MNRAS, 314, 611
Deharveng, J.-M., Buat, V., Le Brun, V., Milliard, B., Kunth, D., Shull, J. M., & Gry, C. 2001, A&A, 375, 805
Djorgovski, S. G., Castro, S. M., Stern, D., & Mahabal, A. 2001, ApJ, 560, L5
Dove, J. B., Shull, J. M., & Ferrara, A. 2000, ApJ, 531, 846
Ferrara, A. 1998, ApJ, 499, L17
Gnedin, N. Y. 1995, ApJS, 97, 231
———. 1996, ApJ, 456, 1
———. 2000, ApJ, 535, 530
Gnedin, N. Y., & Abel, T. 2001, NewA, 6, 437
Gnedin, N. Y., & Bertschinger, E. 1996, ApJ, 470, 115
Haiman, Z., Abel, T., & Rees, M. J. 2000, ApJ, 534, 11
Haiman, Z., Rees, M. J., & Loeb, A. 1997, ApJ, 476, 458
Heckman, T. M., Sembach, K. R., Meurer, G. R., Leitherer, C., Calzetti, D., & Martin, C. L. 2001, ApJ, 558, 56
Hurwitz, M., Jelinsky, P., & Dixon, W. V. D. 1997, ApJ, 481, L31
Leitherer, C., Ferguson, H. C., Heckman, T. M., & Lowenthal, J. D. 1995, ApJ, 454, L19
Machacek, M. E., Bryan, G. L., & Abel, T. 2001, ApJ, 548, 509
Ricotti, M., & Shull, J. M. 2001, ApJ, 560, 580
———. 2002, ApJ, 575, 33 (Paper I)
Ricotti, M., & Shull, J. M. 2000, ApJ, 542, 548
Steidel, C. C., Pettini, M., & Adelberger, K. L. 2001, ApJ, 546, 665
Wood, K., & Loeb, A. 2000, ApJ, 545, 86