SUPPRESSION OF H\textsubscript{2} COOLING IN THE ULTRAVIOLET BACKGROUND

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Received 2007 April 26; accepted 2007 August 24

ABSTRACT

The first luminous objects in the concordance cosmology form by molecular hydrogen cooling in dark matter dominated halos of masses $\sim 10^6 M_\odot$. We use Eulerian adaptive mesh refinement simulations to demonstrate that in the presence of a large soft ultraviolet radiation background, molecular hydrogen is the dominant coolant. Even for very large radiation backgrounds, the halo masses that cool and collapse are up to 2 orders of magnitude smaller than the halos that cool via atomic hydrogen line cooling. The abundance of cooling halos and the cosmic mass fraction contained within them depends exponentially on this critical mass scale. Consequently, the majority of current models of cosmological reionization, chemical evolution, supermassive black hole formation, and galaxy formation underestimate the number of star-forming progenitors of a given system by orders of magnitude. At the highest redshifts, this disagreement is largest. We also show that even in the absence of residual electrons, collisional ionization in central shocks create a sufficient amount of electrons to form molecular hydrogen and cool the gas in halos of virial temperatures far below the atomic cooling limit.

Subject headings: early universe — Galaxy: formation — stars: formation

Online material: color figure

1. MOTIVATION

Cosmic structure forms hierarchically. Any object in the universe today started with copious numbers of small progenitors at redshifts currently inaccessible to direct observations. Traditionally, in galaxy formation (Rees & Ostriker 1977; White & Rees 1978; Dekel & Rees 1987; White & Frenk 1991; Baugh et al. 2003) $T_{\text{vir}} = 10^4$ K halos are assumed to be the first cooling halos. Nevertheless since the late 1960s it has been known that molecular hydrogen, formed in the gas phase, can dominate cooling in objects of smaller virial temperature and mass (Saslaw & Zipoy 1967; Peebles & Dicke 1968; Yoneyama 1972; Haiman et al. 1996; Tegmark et al. 1997; Abel et al. 1998, 2000). Neglecting this early phase of H\textsubscript{2} cooling halos has been justified by arguing that H\textsubscript{2} is destroyed via radiative feedback effects (see Dekel & Rees 1987; Haiman & Loeb 1997; Haiman et al. 2000; Glover & Brand 2001; Bromm & Loeb 2003). The photodissociation of H\textsubscript{2} via the Solomon process by an early soft ultraviolet background (UVB) is generally assumed as the main reason (Oh & Haiman 2002; Ciardi & Ferrara 2005; Haiman & Bryan 2006).

The mass scale of halos considered enters exponentially in the collapsed mass fraction and the abundance of halos. Figure 1 shows the predicted abundances of the earliest building blocks of galaxy formation as a function of redshift for the latest concordance cosmology using the Sheth-Tormen formalism (Press & Schechter 1974; Sheth & Tormen 2002). The different lines correspond to different virial masses. The solid line corresponds to halos with virial temperatures of $10^4$ K, the temperature at and above which atomic hydrogen line cooling is dominant. At redshift 30, e.g., the difference of abundances of $2 \times 10^5 M_\odot$ and $T_{\text{vir}} = 10^4$ K halos is 5 orders of magnitude. Even at redshift 10 this disparity is still a factor of a 1000. When studying reionization and chemical evolution of galaxies and the intergalactic medium, one needs to consider stellar feedback. The simple fact that the binding energy of the gas of smaller mass halos is even less than the kinetic energy deposited by even one supernova (SN) is illustrated in Figure 1b. Surely whether the atomic hydrogen line (Ly\textalpha) cooling halos are formed from pristine primordial gas or are mergers of many tens of progenitors that massive stars have enriched and expelled the gas from should make a significant change in their further evolution. The minimum mass of star-forming halos is undoubtedly an important issue independent of the techniques employed to study structure formation.

Advances in cosmological hydrodynamics and its numerical methods (Cen 1992; Zhang et al. 1995; Katz et al. 1996; Abel et al. 1997; Anninos et al. 1997; Bryan & Norman 1998; Gnedin & Abel 2001; Ricotti et al. 2002, 2002a) allow now detailed investigations of all the relevant physical processes. Modeling the expected negative feedback from an early soft UVB is straightforward as a background flux only causes a spatially constant photodissociation rate in the chemical reaction network being solved when H\textsubscript{2} does not exist at high enough abundances to self-shield. Machacek et al. (2001, hereafter MBA01) used Eulerian adaptive mesh refinement (AMR) simulations to investigate the role of such a H\textsubscript{2} dissociating (Lyman-Werner; LW) background on the minimum mass of halos within which primordial gas can first cool for a variety of radiation amplitudes. In addition to a LW background, the collapse of halos within relic H ii regions can be either delayed or catalyzed. Mesinger et al. (2006) used AMR simulations with a short-lived 3 Myr hydrogen ionizing UVB that simulates a nearby massive, metal-free (Population III) star. They found that halo collapses are prolonged if $J_{912} > 0.1$ and catalyzed if below this critical value, where $J_{912}$ is in units of $10^{-21}$ ergs s$^{-1}$ cm$^{-2}$ Hz$^{-1}$ sr$^{-1}$ at a wavelength of 912 Å. In the case of a large UVB, the collapse is delayed due to lower gas densities and higher cooling times. In the small UVB regime, excess free electrons in the relic H ii region accelerate H\textsubscript{2} formation. In both cases, feedback in relic H ii subsides after ~30% of a Hubble time. Strong suppression of H\textsubscript{2} formation also occurs in $10^6 M_\odot$ halos with a LW background $J_{21}^{\text{LW}} > 0.01$. Yoshida et al. (2003, hereafter YAH03) similarly addressed this issue using smoothed particle hydrodynamics (SPH). They found an additional effect on the minimum collapse mass of dynamical heating.
from the mass accretion history of the halo. As the heat input increases, the virial temperature must rise before $H_2$ cooling can start to dominate, and a cool phase develops in the center of the potential well.

Self-consistent calculations in which the sources produce the radiation backgrounds which in turn affect the number of new potential wells. As the heat input further with detailed higher resolution simulations to check whether their analytical expectation would hold.

We present a series of 14 very high resolution Eulerian AMR simulations designed to see how the largest possible feedback may raise the minimum mass in which primordial gas will cool by molecular hydrogen. The simulations techniques and details of the suite of calculations is the topic of the next section. In the following sections, we describe the results that show $H_2$ cooling cannot be neglected in early structure formation. In the discussion, we describe the nature of the UVB and why $H_2$ cooling can occur in such large radiation backgrounds. We also comment on the large range of questions in cosmological structure formation that this conclusion affects.

2. SIMULATIONS AND ASSUMPTIONS

We use the Eulerian AMR hydrodynamic code Enzo (Bryan & Norman 1997, 1999) to study the importance of $H_2$ cooling in early galaxy formation. Enzo uses an $n$-body adaptive particle-mesh solver (Couchman 1991) to follow the dark matter (DM) dynamics. We perform two cosmological realizations with different box sizes and random phases and Wilkinson Microwave Anisotropy

Table 1 summarizes them. We use a nine-species (H, H+, He, He++, H$_2$, H$_2^+$$^+$, H$^-$) nonequilibrium chemistry model (Abel et al. 1997; Anninos et al. 1997) for all runs except the $H_2$ dissociating LW. We perform each realization with seven sets of assumptions.

| Name          | $H_2$ | Residual $e^-$ | $F_{LW}$ | $z_a$ | $z_b$ |
|---------------|-------|--------------|----------|-------|-------|
| $H_2$         | Yes   | Yes          | $10^{-22}$ | 0     | 29.7  | 31.1 |
| $H_2$LW22     | Yes   | Yes          | $10^{-22}$ | 28.3  | 27.5  |
| $H_2$LW21     | Yes   | Yes          | $10^{-21}$ | 24.4  | 24.7  |
| $H_2$LW20     | Yes   | Yes          | $10^{-20}$ | 20.5  | 22.4  |
| $noe$-$H_2$   | No    | Yes          | 0        | 18.7  | 23.4  |
| $noe$-$H_2$LW20 | Yes | No          | $10^{-20}$ | 16.8  | 21.4  |
| $H$+$H_2$     | No    | Yes          | 0        | 15.9  | 16.8  |

Note.—These simulations are performed for both realizations.

![Figure 1](image-url)
by neglecting LW self-shielding. In addition, LW self-shielding may be unimportant up to column densities of $10^{20} - 10^{21}$ cm$^{-2}$ if the medium contains very large velocity gradients and anisotropies (Glover & Brand 2001).

Free electrons are necessary to form H$_2$ in the gas phase. In order to restrict H$_2$ formation to Ly$\alpha$ line cooling halos in our "noe-" calculations, we reduce the residual free electron fraction from $\sim 10^{-4}$ (Peebles 1968; Shapiro et al. 1994) to a physically low $10^{-12}$ at the initial redshift. This setup is designed to find the first halos that can collapse and form stars once free electrons from collisionally ionized hydrogen becomes available to catalyze H$_2$ formation (Shapiro & Kang 1987).

This work is an extension of the original work of MBA01, adding the calculations with $F_{LW} = 10^{-20}$ and ones in which H$_2$ cannot cool until Ly$\alpha$ cooling becomes efficient. We consider these extreme cases to strengthen the point made in MBA01, in which a UVB only increases the critical halo collapse mass, never completely suppressing the crucial importance of H$_2$ formation and cooling. Our maximum spatial resolution in the finest AMR level is a factor of 4 smaller than MBA01; however, this does not cause any differences between our work and MBA01 because these finest grid patches only exist in the dense, central core during the final 150 kyr of the collapse.

2.1. Virial Temperature

In galaxy formation models, the virial temperature is a key quantity as it controls the cooling and star formation rates in a given halo. We define a halo as the material contained in a sphere of radius $r_{200}$ enclosing an average DM overdensity $\Delta_0$ of 200. For an isothermal singular sphere, the virial temperature

$$T_{\text{vir}} = \frac{\mu m_p V^2_c}{2k},$$

where $V^2_c = GM/r_{200}$ is the circular velocity (see Bryan & Norman 1998 with $\beta = 1$). Here $\mu$ is the mean molecular weight in units of the proton mass $m_p$, and $k$ is Boltzmann’s constant. We use this definition of $T_{\text{vir}}$ in this paper with $\mu = 0.59$. We choose this value of $\mu$ to be consistent with the literature on galaxy formation even though the halos presented in this paper are neutral and have $\mu = 1.22$.

3. RESULTS

We first describe the halo properties at collapse. Then we compare them to previous studies of collapsing halos in the presence of a soft UVB.

3.1. Halo Properties

Figure 2 shows density-squared weighted projections of gas density and temperature when each calculation can cool and collapse to an overdensity of $10^7$. It illustrates the large difference in the sizes and morphologies of the collapsing halos in the various cases of negative feedback. All panels have the same field of view of 1.2 proper kpc and same color scales. It is clear from the relative sizes of the collapsing halos that the critical halo mass to cool increases with the amount of negative feedback. The virial shock and numerous central shocks heat the gas to the virial temperature. The central shocks create fine structure seen in the temperature projections. In all of the H$_2$ cases, we see neither fragmentation nor large-scale disk formation. The internal structures of the halos with H$_2$ cooling and residual free electrons are similar to previous studies of Population III star-forming halos (MBA01; Abel et al. 2000, 2002; Bromm et al. 2002; Yoshida et al. 2003), exhibiting a turbulent medium with a radially monotonically decreasing density profile and a cool central core.

Figure 3a depicts the halo mass and redshift when the halo collapses for all of the runs, and Figure 3b shows their central temperature at the same epoch. The collapse redshifts, $z_{\text{sh}}$ and $z_{\text{h}}$, are also listed in Table 1 for simulations A and B, respectively. As seen in other studies (MBA01, YAH503), the minimum DM halo mass to collapse increases with the background intensity. The H$^+$He case predictably collapses at $T_{\text{vir}} \sim 10^4$ K, and all of the halos with H$_2$ cooling collapse at much smaller masses. The temperature of the central core increases with halo mass from 300 to 1000 K for halo masses $4 \times 10^3$ and $10^4 M_\odot$. Restricting the data to models with residual electrons, the central temperature increases as a power law,

$$T_c = AM_{\text{vir}}^B,$$

where $A = 3.1^{+1.3}_{-0.9}$, $B = 0.355 \pm 0.024$, and $M_{\text{vir}}$ is in units of solar masses. This relationship is plotted in Figure 3.

With neither residual electrons nor an UVB (noe-H$_2$), the most massive halo collapses at 9.8 (6.2) $\times 10^6$ M$_\odot$ at $z = 18.7$ (23.4). Here H$_2$ formation in the gas phase can only become important when sufficient free electrons are created by collisional ionization. Virial heating in the central halos can increase temperatures up to twice the virial temperature (Wise & Abel 2007) that collisionally ionizes hydrogen in the central shocks and initiates H$_2$ cooling (Shapiro & Kang 1987) in halos well below virial temperatures of $10^4$ K. These shocks are abundant throughout the central regions. Figure 4 shows radial profiles of temperature and electron fraction for both simulations and depicts gas shock-heating up to $2 \times 10^4$ K and raising electron fractions up to $10^{-3}$. The electron fractions remain at unrealistically low values less than $10^{-6}$ in low-density regions where gas has not been collisionally ionized. The higher density regions have condensed to densities above $3 \times 10^5$ cm$^{-3}$ after free electrons in protogalactic shocks induced H$_2$ cooling.

A similar but extreme model, noe-H2LW20, demonstrates that even in the presence of a very large UVB of $F_{LW} = 10^{-20}$ gas is able to form a cool and dense central molecular core at a mass of $2.7 (1.1) \times 10^7$ M$_\odot$ at redshift 16.8 (21.4). Two major mergers in simulation A occur between $z = 17-21$, and the associated heating allows the halo to begin cooling by H$_2$. A central core only forms once the system is adequately relaxed after the mergers, which causes the collapse mass difference between the realizations.

By not fully resolving weak shocks in our main calculations, it is possible to underestimate the electron fraction. We performed SimB-H2LW20 with an additional refinement criterion that resolves the “cooling length,” $l_{\text{cool}} = l_{\text{cool}}/c_s$, by at least two cells. The large- and small-scale structure in the simulation is unchanged. When we resolve these weak shocks, the increased electron fraction marginally accelerates the collapse, which occurs 780 kyr earlier at $z = 22.5$. The virial mass at this time is $8.0 \times 10^6$ M$_\odot$ compared with $8.4 \times 10^6$ M$_\odot$. Hence we believe that the critical halo mass to collapse as a function of the LW background is independent of this refinement criterion.

The combination of a recent major merger and collisional ionization produces complex structures as seen in the density and temperature projections of the SimA-Noe-LW20 and SimB-Noe calculations in Figure 2, unlike the other H$_2$ models with a single cool central core.
Fig. 2.—Density-squared weighted projections in simulation A (left two columns) and B (right two columns) of the gas density (first and third columns) and temperature (second and fourth columns) at the times when the most massive halo starts to cool and collapse above an overdensity of $10^7$ in the models. The rows show the H$_2$, H$_2$LW21, H$_2$LW20, and noe-H$_2$, noe-H$_2$LW20, and H$^+$-He runs from top to bottom, respectively. Note the complex structure for the SimA-Noe-LW20 and SimB-Noe-H$_2$ run, in which central shocks lead to the formation of free electrons that promote the formation of H$_2$ and triggering the collapse. The field of view in all panels is 1.2 proper kpc. The color maps are equal for all images.
3.2. Comparison to Previous Studies

Through a series of AMR calculations with varying UVB intensities, MBA01 found the minimum DM halo mass

\[ M_{\text{crit}} = 2.5 \times 10^5 + 1.7 \times 10^6 (F_{\text{LW}}/10^{-21})^{0.47} M_\odot \]  

in order to cool and condense 4% of the baryons. This fraction of cool and dense gas agrees with simulations of the formation of Population III stars (Abel et al. 2002; Yoshida et al. 2006). There is some scatter of \( \sim 0.5 \) dex in this threshold mass (see also YAHS03). For the UVB intensities used in our models (\( F_{\text{LW}} = 0, 10^{-22}, 10^{-21}, 10^{-20} \)), the critical collapse masses are \( 2.5 \times 10^5, 8.4 \times 10^5, 2.0 \times 10^6, \) and \( 5.4 \times 10^6 \) \( M_\odot \). Our calculations with \( \text{H}_2 \) cooling and residual free electrons agree with the results of MBA01.

YAHS03 studied the minimum collapse mass but also included the effects of self-shielding. Through their SPH simulations and arguments using equilibrium \( \text{H}_2 \) abundances, they conclude that an UVB intensity of \( J_{21} = 0.1 \) nearly prevents halo collapses below \( T_{\text{vir}} \approx 7000 \) K where Ly\( \alpha \) cooling becomes efficient. They also deduce that \( J_{21} = 1.0 \) completely prevents any \( \text{H}_2 \) cooling in these low-mass halos, based on \( \text{H}_2 \) dissociation timescales. We find the contrary in our \( \text{H}_2 \text{LW21} \) and \( \text{H}_2 \text{LW20} \) calculations where the most massive halo collapses with masses of \( 4.5 (2.9) \times 10^5 \) and \( 8.4 (6.8) \times 10^6 \) \( M_\odot \), respectively. Even in our no- runs, the halo collapses when \( T_{\text{vir}} \approx 4000 \) K, i.e., before Ly\( \alpha \) cooling becomes important, which is around the same mass scale that the H2LW20 runs condense. We ignore self-shielding

Fig. 3.—(a) Halo masses of the most massive halos as function of redshift when they reach a central overdensity of \( 10^7 \). This allows to translate the mass values in panel b to be converted to cooling redshifts. It marks the runs with H/He (filled squares), H\(_2\) (open squares), \( F_{\text{LW}} = 10^{-22} \) (open diamonds), \( F_{\text{LW}} = 10^{-21} \) (filled diamonds), no residual electrons (open circles), and extreme feedback no-LW20 (filled circles) runs. The two data points for each symbol represent simulations A and B. Even for the most extreme cases of feedback cooling occurs much earlier than in the atomic line cooling only case. (b) Central temperatures of most massive halo in the simulation as a function of its mass at different redshifts. The virial temperature computed form the dark matter halo mass at redshift 20 is the solid line. The dotted line is the fitted relationship between the central gas temperatures and the halo mass in models with residual electrons and \( \text{H}_2 \) cooling.

Fig. 4.—Radial profiles of temperature (top) and electron fraction (bottom) colored by density for the “noe-“ simulations with no residual free electrons or UVB in simulation A (left) and B (right). The virial temperatures of these halos are 4600 and 4200 K for simulations A and B, respectively, using eq. (1) with \( \mu = 0.59 \).
in our calculations, but this would only decrease the critical collapse mass and strengthens our main conclusion that H$_2$ cooling is always dominant, even in the presence of a large LW flux.

YAH503 used cosmological SPH simulations and H$_2$ formation and dissociation timescales to argue that a LW background intensity of $J_{21}^{\text{LW}} > 0.1$ suppresses H$_2$ formation so halos cannot cool before virial temperatures of 7000 K are reached. Employing the same argument, we see that the H$_2$ formation timescale

$$ \tau_{\text{H}_2} = \frac{m_{\text{H}_2}}{k_{\text{H}_2} - m_{\text{He}}} = \frac{f_{\text{H}_2}}{0.92 k_{\text{H}_2} f_{\text{e}}} \approx 30 \text{ kyr}, \quad (4) $$

with typical central values found in high-redshift halos before any radiative cooling becomes efficient (see Wise & Abel 2007). Here $f_{\text{H}_2} = 10^{-6}$ and $f_{\text{e}} = 10^{-4}$ are the H$_2$ and electron number fraction, respectively, and $n = 10$ cm$^{-3}$ is the baryon number density. $k_{\text{H}_2} \approx 10^{-15}$ cm$^2$ s$^{-1}$ is the H$_2$ formation rate coefficient by electron photodetachment at $T = 1000$ K (Abel et al. 1997). This timescale is a factor of 1000 smaller than the value calculated in YAH503 because we use the quantities from the halo center as compared to the mean values. The H$_2$ dissociation timescale is $k_{\text{diss}}^{-1} = 23/J_{21}$ kyr, which is comparable with $\tau_{\text{H}_2}$ using the values above.

The halo characteristics and the collapse redshift will likely depend on halo merger histories as seen in these two realizations. The better statistics of MBA01 sampled this effect well. Here the scatter of threshold mass is $\sim 0.5$ dex and is smaller than the mass difference between halos with virial temperatures of 4000 and 10,000 K. Thus our limited sample of halos should not change our result of the importance of H$_2$ cooling in halos well below $T_{\text{vir}} = 10^4$ K, even with very large LW radiation backgrounds.

4. DISCUSSION

Structure formation in the high-redshift universe is contained within shallow potential wells that are sensitive to negative feedback from a UVB. In addition, local positive and negative feedback will influence star formation and further complicate estimates of halo mass scales. Some examples include the following:

1. **Positive feedback.**—Enhanced H$_2$ formation in relic H II regions (e.g., Ferrara 1998; O’Shea et al. 2005; Johnson et al. 2007) and ahead of the H II ionization front (Ricotti et al. 2001; Ahn & Shapiro 2007), dust and metal line cooling (Glover 2003; Schneider et al. 2006; Jappsen et al. 2007).

2. **Negative feedback.**—Baryonic expulsion from host halos (Whalen et al. 2004; Kitayama et al. 2004; Yoshida et al. 2007; Abel et al. 2007), photoevaporation (Susa & Umemura 2006), entropy floors (Oh & Haiman 2003).

These processes are not within the scope of this paper and will be considered in later publications that utilize three-dimensional radiation hydrodynamic simulations with Population III star formation. Here we only focused on the effects of a UVB on low-mass halos.

4.1. **The Nature of the UVB**

The intensity of the UVB is a monotonically increasing function of redshift as more halos form stars. The UVB increases on the order of a Hubble time, which is much shorter than a dynamical time of a collapsing halo and justifies the use of a constant intensity in our calculations.

Self-consistent studies that evolve the UVB according to star formation rates only find $J_{21}^{\text{LW}}$ to be in the range of 0.01–0.1 at redshifts 15–20 (YAH503; WA05). WA05 calibrated their model against the WMAP1 measurement of $\tau = 0.17$. With the WMAP3 result of the electron scattering optical depth $\tau = 0.09$ and less small-scale power, UVB intensities will be even lower at these redshifts.

We can relate reionization to LW radiation by equating $J_{21}$ in the LW band to a common quantity in reionization models, the ratio of emitted hydrogen ionizing photons to baryons, $n_{\gamma, \text{HI}}/\bar{n}_b$, where $\bar{n}_b \approx 2 \times 10^{-5}(1+z)^3$ cm$^{-3}$ is the cosmic mean of the baryon number density. Assuming that $J_{21}$ is constant in the LW band, the number density of LW photons is

$$ n_{\gamma, \text{LW}} = \frac{4\pi}{c} \int_{\nu_1}^{\nu_2} \frac{J_{21}^{\text{LW}}}{h_\nu} d\nu \approx 1.19 	imes 10^{-5} J_{21}^{\text{LW}} \text{ cm}^{-3}, \quad (5) $$

where $h_\nu$ is Planck’s constant and $\nu_1, \nu_2 = 2.70 \times 10^{15}$ Hz, $3.26 \times 10^{15}$ Hz bound the LW band. To relate $J_{21}$ to $n_{\gamma, \text{HI}}/\bar{n}_b$, we must consider the intrinsic ionizing spectrum and absorption from the IGM and host halo. At redshift 20, the majority of star-forming halos host Population III stars that emit a factor $\phi_{\text{HI}} \approx 10$ more hydrogen-ionizing photons than LW photons because of its $\sim 10^5$ K surface temperature. Since the number density of sources exponentially increases with redshift, the majority of the early UVB at a given redshift originates from cosmologically nearby $(\Delta z^2 \approx 0.1)$ sources. Lyman line resonances absorb a fraction $f_{\text{esc}} \approx 0.1$ of the LW radiation in the intergalactic medium in this redshift range, producing a sawtooth spectrum (Haiman et al. 1997). In addition, absorption in the host halo reduces the number of ionizing photons that escape into the IGM by a fraction $f_{\text{esc}}$. For Population III halos, this factor is close to unity (Yoshida et al. 2007; Abel et al. 2007). By considering these multiplicative processes, we now estimate

$$ \frac{n_{\gamma, \text{HI}}}{\bar{n}_b} = \frac{n_{\gamma, \text{LW}}}{\bar{n}_b} \left( \frac{1+z}{20} \right)^{-3} \phi_{\text{HI}} f_{\text{esc}} f_{\text{abs}}^{-1} = 0.64 J_{21} \left( \frac{1+z}{20} \right)^{-3} \phi_{\text{HI}} \left( \frac{f_{\text{esc}}}{10} \right) \left( \frac{f_{\text{abs}}}{0.1} \right)^{-1} \quad (6) $$

This estimate is in agreement with the reionization models of Haiman et al. (2000) and WA05 (see also Gnedin & Ostriker 1997). These models find that sources produce a large UVB of $J_{21} \approx 1$ prior to reionization. When Population III stars dominate the UVB, the LW radiation will be small in comparison to the volume averaged hydrogen ionizing emissivity because of the intrinsically hard Population III spectra that peaks at $\sim 300$ Å. Hence high-redshift halos should not be exposed to a large UVB, i.e., $J_{21} \lesssim 0.1$, and H$_2$ formation will remain important before reionization.

Nearby star formation can boost the LW radiation over its background value, but these bursts are short-lived as Population III lifetimes are only $\sim 3$ Myr (Schaerer 2002). For example, a 100 $M_\odot$ star produces $10^{50}$ LW photons s$^{-1}$ and will produce $J_{21}^{\text{LW}} > 0.1$ in the surrounding 3 proper kpc, neglecting any H$_2$ self-shielding.

The LW background is uniform outside these spheres of influence. The bursting nature of Population III star formation does not affect the time evolution of the background. The intensity only depends on the number of sources in a redshift range $\Delta z^2 = 13.6 \text{ eV}/11.18 \text{ eV}^{-1}$, where the two energies bound the LW band, because any radiation redward of the Lyman break contributes to the LW background. Using a conservative minimum halo mass for Population III star-forming halos of $3 \times 10^8 M_\odot$, at redshift 20, there are $\sim 42,000$ halos that have hosted a Population III star in the volume contained within $\Delta z$, using WMAP3 parameters with Sheth-Tormen formalism. Clearly the background is uniform considering the shear number of sources within this.
optically thin volume. Local perturbations from Population III star formation should only affect the timing of nearby star formation but not the global star formation rate.

4.2. \textit{H}_2 \text{ Cooling within a UVB}

Figure 5 shows SimB-LW20 20 million years before the central core condenses. At this time, the core is just beginning to cool by \textit{H}_2, catalyzed by the free electrons created in the central shocks. In these shocks, temperatures reach \(1.4 \times 10^4\) K and electron fractions up to \(10^{-3}\) exist there. These conditions result in \textit{H}_2 formation timescales less than 25 kyr, which is necessary to cool in a UVB of \(J_{21} \approx 1\). Within the central 10 pc, hot and cold gas phases exist. The hot phase exists behind the shocks that have lower densities around \(10 cm^{-3}\) and \(t_{H_2} < 25\) kyr. This is where \textit{H}_2 cooling is catalyzed by collisional ionization in these shocks. The cold phase has already cooled through \textit{H}_2 and has high densities and larger \(t_{H_2}\) values. Both phases are apparent in the panels of Figure 5. Similar conditions create \textit{H}_2 in the collapses in the \textit{“noe-”} calculations, which have sufficient gravitational potential energy, resulting in temperatures above \(10^4\) K in central shocks. Hence \textit{H}_2 formation is possible in the centers of high-redshift halos with virial temperatures below \(10^4\) K, even with a UVB of intensity \(J_{21}^{LW} \approx 1\), larger than expected from semianalytic models of reionization.

4.3. Impact on Semianalytic Models

Two consequences of a lower critical \textit{Ly} cooling halo mass are more frequent and earlier galaxy formation and higher mass fractions in cooling halos. At redshift 20, e.g., abundances of \(T_{vir} = 4000\) K halos are an order of magnitude larger than \(T_{vir} = 10^4\) K halos, resulting from the exponential nature of Press-Schechter formalism. The mass fraction contained in these halos is 3 times higher than \(10^4\) K halos. In semianalytic models of reionization and chemical enrichment, the star formation rate (SFR) is linearly dependent on the collapsed mass fraction since the SFR is usually a product of mass fraction and star formation efficiency, which is the fraction of gas collapsing into stars (e.g., Haiman et al. 1997). The star formation efficiency for primordial stars is \(\sim 10^{-3}\) with a single massive star forming in dark matter halos with mass \(\sim 10^6 M_\odot\) (Abel et al. 2002; Bromm et al. 2002; Yoshida et al. 2006). This fraction may rise to a few percent in dwarf galaxies as widespread star formation occurs (Taylor et al. 2007).
1999; Gnedin 2000; Walter et al. 2001). Various studies predict that a major fraction of the reionizing flux originates from dwarf galaxies (e.g., Cen 2003; Sokasian et al. 2004; Haiman & Bryan 2006). If the mass contained in star forming halos is 3 times greater than previously thought, some of the predicted attributes, e.g., photon escape fractions and star formation efficiencies, of high-redshift dwarf galaxy will require appropriate adjustments to match observations, such as the WMAP3 measurement of optical depth to electron scattering (Page et al. 2007) and Gunn-Peterson troughs at $z \sim 6$ (Becker et al. 2001; Fan et al. 2002).

5. SUMMARY

We conducted a suite of fourteen cosmology AMR simulations that focus on the importance of H$_2$ cooling with various degrees of negative feedback. We summarize the findings of each model below.

1. The calculations with a UVB of $F_{\text{LB}} = (0, 10^{-22}, 10^{-21})$ agree with the results of MBA01, where the critical collapse halo mass increases as a function of UVB intensity.

2. Above $F_{\text{LB}} = 10^{-21}$, it had been argued that an H$_2$ dissociating background would inhibit any H$_2$ formation until the halo could cool through Ly$\alpha$ cooling. We showed that central shocks provide sufficient free electrons from collisional ionization to drive H$_2$ formation faster than dissociation rates even in a $F_{\text{LB}} = 10^{-20}$ background.

3. In our “noe-” models, we explored when collisional ionization becomes important and conducive for H$_2$ formation. This occurs at $T_{\text{vir}} = 4000$ K. Recent major mergers above this mass scale create complex cooling structures, unlike the nonfragmented central cores in smaller halos.

4. Even our most extreme assumptions of $J_2 = 1(F_{\text{LB}} \approx 10^{-20})$ and no residual free electrons cannot defeat the importance of H$_2$ cooling in the early universe.

O’Shea & Norman (2007) independently studied halo collapses with Enzo and similarly considered primordial gas chemistry and nine different UVB intensities ranging from zero to $J_2 = 1$. They agree with our conclusions in that primordial gas in $T_{\text{vir}} < 10^4$ K halos can catastrophically cool and collapse even in models with $J_2 = 0.1$. They attribute the collapse to the increased H$_2$ cooling rates at higher temperatures that is caused by greater dynamical heating in halos with $M_{\text{h}} \gtrsim 10^7 M_\odot$. The cooling rate per molecule is 100 times larger at 2000 K than at 500 K, typical of Population III star-forming halos without an UVB. Most likely, the combination of the elevated H$_2$ cooling rates and electron fractions from internal protogalactic shocks instigate the halo collapses in a strong UVB ($J_2 > 0.1$).

In any case, H$_2$ cooling triggers collapses in halos with virial temperatures well below $10^4$ K. The lower critical halo mass, corresponding to $T_{\text{vir}} \approx 4000$ K, increases mass fraction contained in these halos by 3 times at redshift 20 and the number density of high-redshift star forming halos by an order of magnitude! By considering additional cases of extremely large negative feedback, we have strengthened the results of MBA01 that H$_2$ cooling plays a key role in high-redshift structure formation. We conclude that a UVB only delays and never completely suppresses H$_2$ formation and cooling and subsequent star formation in these low-mass halos.

This work was supported by NSF CAREER award AST 02-39709 from the National Science Foundation. We appreciate the helpful feedback, which enhanced the presentation of this paper, from the referee, Simon Glover. We thank Marcelo Alvarez, Greg Bryan, and Naoki Yoshida for providing constructive comments on an early draft. We are grateful for the continuous support from the computational team at SLAC. We performed these calculations on 16 processors of a SGI Altix 3700 Bx2 at KIPAC at Stanford University.

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