The Radiative Feedback from the First Stars and Quasars and the End of the Dark Age

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Abstract. In hierarchical models of structure formation, an early cosmic UV background (UVB) is produced by the small ($T_{\rm vir} \lesssim 10^4$K) halos that collapse before cosmological reionization. If the first collapsed halos harbor stars, then their UV flux below 13.6 eV photo–dissociates the molecular hydrogen H_2 in subsequently collapsing halos within a large sphere of influence. This causes a pause in the cosmic star–formation history: the buildup of the UVB and the epoch of reionization are delayed until larger halos ($T_{\rm vir} \gtrsim 10^4$K) collapse. In contrast, if the small halos harbor mini–quasars with hard spectra extending to ~1keV, then their X–rays balance the effects of the UVB, the negative feedback does not occur, and reionization can be caused early on by the small halos.

1 Introduction

Recent high redshift observations have yielded estimates of the global star–formation history of the universe to redshifts as high as $z \sim 5$ (Madau et al. 1996; Steidel et al. 1996). However, some stellar activity must have taken place even at $z > 5$: the enrichment by heavy elements, as well as the reionization of the intergalactic medium (IGM), hints at early sources of metals and ionizing photons. Such ultra–high redshift objects are indeed expected in popular cosmological cold dark matter (CDM) models, which predict that the first virialized halos appear at redshifts as high as $z \sim 30$. It is natural to identify these halos as sites where the first stars or massive black holes appear, forming the first generation of "mini–galaxies" or "mini–quasars".

Because of the low virial temperatures ($T < 10^4$K) of the first halos, their H_2 molecule fraction determines whether they are able to cool and form any stars or black holes. As a result, the H_2 abundance inside these halos determines when the "dark age" ends: if there is sufficient H_2, it ends earlier; if H_2 is absent, it ends at the later redshift when the ~ 1000 times more massive halos collapse and cool via atomic H. Here, we study the H_2 abundance inside halos collapsing in a ΛCDM cosmology. The main question we address is: *Could the first collapsed dark halos, with masses near the Jeans mass, contribute to the reionization of the universe?* For a more detailed report on this work, we refer the reader to Haiman, Abel & Rees (1999).

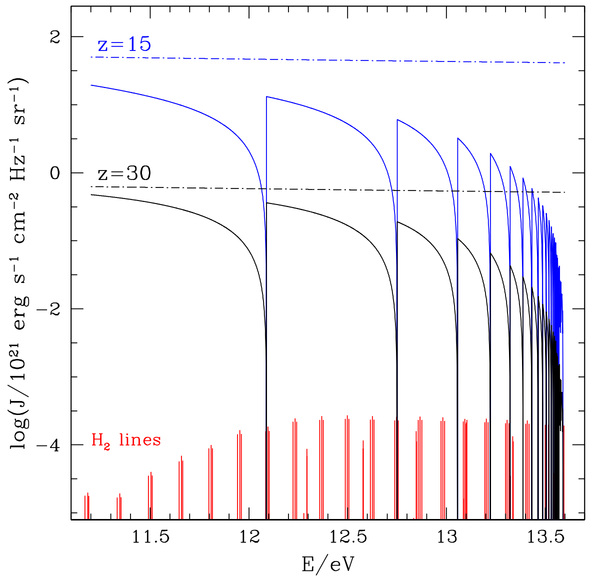

Fig. 1. The spectrum of the UV background at redshifts $z = 30$ and $z = 15$. The solid (dashed) lines show the spectrum after (without) absorption by neutral H in the high–redshift IGM. For reference, we show the location of the 76 lines of H_2.

2 Spectrum of the Early UV and X–ray Backgrounds

In any hierarchical model of structure formation, the radiation output associated with collapsed halos gradually builds up a cosmic UV background. If the first halos harbored black holes, in addition to (or instead of) stars, then the spectrum of the background extended into the X–ray regime (Haiman & Loeb 1998), producing an early X–ray background (XRB). UV photons in the 11.18–13.6eV range can travel to a large fraction of the Hubble length across the IGM, and photo–dissociate molecular H_2 both in the IGM and inside other collapsed halos (Field et al. 1966). X–ray photons with energies above a few keV also travel to large distances, and photo–ionize H and He, as well as produce collisional ionization of H by fast photo–electrons. The resulting extra free electrons catalyze the formation of H^-, and therefore tend to increase the H_2 abundance. In order to assess the molecular fraction inside collapsed halos, it is necessary to quantify the spectrum of the background in the soft UV and X–ray bands. Consider an observer at redshift $z_{\rm obs}$, measuring the UVB at the local frequency $\nu_{\rm obs}$, where $11.18{\rm eV} < h\nu_{\rm obs} < 13.6{\rm eV}$. The photons collected at the frequency $\nu_{\rm obs}$ are arriving from sources located at $z_{\rm s} > z_{\rm obs}$, and have redshifted their original frequency $\nu_{\rm s} > \nu_{\rm obs}$. Because of the large optical depth of the IGM in the atomic Lyman series, effectively a "dark screen" blocks the view of all sources at redshifts above $z_{\rm max}$, defined as $(1 + z_{\rm max})/(1 + z_{\rm obs}) = \nu_{\rm i}/\nu_{\rm obs}$, where $\nu_{\rm i}$ is the frequency of the Lyman line closest to $\nu_{\rm obs}$. The cumulative effect of this absorption leads to a characteristic spectral shape for the early UVB, resembling a "sawtooth"[1], shown in a specific model (described below) in Figure 1. The shape of the early XRB is obtained in a more straightforward manner, by summing the spectra of individual sources (here assumed to be a power law with index -1), and including the opacity of the intergalactic H and He, which exponentially suppresses the flux to $\sim$1 keV.

3 H_2 Cooling Inside the First Halos

The H_2 Abundance in Collapsed Clouds. The radiative efficiency of a gas cloud by collisional excitations of H_2 molecules depends on the gas temperature, density, and H_2 abundance. Here we consider spherical clouds with density profiles of truncated isothermal spheres (Shapiro et al. 1999), composed of primordial H+He gas, with the initial abundances given by their post–recombination values (Anninos and Norman 1996). We solve the time evolution of the chemical abundance profiles, when the cloud is illuminated by the external background. The initial conditions are specified by the virial temperature $T_{\rm vir}$, and collapse redshift $z_{\rm coll}$ of the cloud, and the amplitude of the UVB, J_{21}, as well as the XRB. The latter is obtained by assuming a power law spectrum above 13.6eV, including a multiplicative factor, $\epsilon_{\rm x}$, to characterize the ratio of X–ray to UV flux. For pure stellar sources, $\epsilon_{\rm x} = 0$; for typical quasar spectra (Elvis et al.), $\epsilon_{\rm x} \sim 1$. Values of $\epsilon_{\rm x}$ in–between 0 and 1 could describe either miniquasars with softer spectra, or a mixed population of stars and mini–quasars.

The evolution of $x_{\rm H_2}$ at the core of a cloud, chosen as an example, is shown by the solid curves in Figure 2. In the absence of any UVB, the H_2 fraction rises continuously, and reaches $10^{-3.5}$ in a Hubble time (top curve). When a UV flux with $J_{21} = 0.1$ is turned on (bottom solid curve), the H_2 fraction is suppressed. For higher fluxes, the suppression is even more pronounced. By performing similar calculations for clouds with virial temperatures and collapse redshifts in the ranges $10^2 < T_{\rm vir} < 10^4$K and $5 < z_{\rm coll} < 50$, we have found that the evolution shown in Figure 2 remains qualitatively the same. However, the level of flux required at which the H_2 molecules are photo–dissociated depends on the values of both $z_{\rm coll}$ and $T_{\rm vir}$. For defining a "critical flux" $J_{\rm crit}$, we assume that a cloud is able to form stars if the cooling time in the core becomes shorter than the time elapsed since the formation of the cloud.

If increasing amounts of X–rays are also added (middle two solid curves), then the H_2–suppression (relative to the dotted curve) is, as expected, less

[1] We find that the overall effect of intergalactic molecular absorption is negligible.

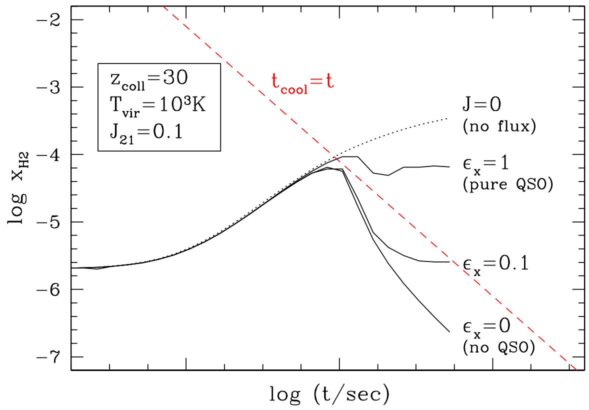

Fig. 2. Evolution of the H_2 abundance in the core of a truncated isothermal sphere. Also shown is the H_2 abundance at which the cooling time equals the time elapsed (short dashed line). The curve labeled J=0 shows the evolution in the absence of any flux. The label ϵ_x on the other curves is a measure of the X–ray/UV flux ratio, where $\epsilon_x = 0$ corresponds to a pure stellar spectrum with no X–rays, and $\epsilon_x = 1$ corresponds to a pure "mini–quasar" spectrum with a spectral index of -1.

pronounced. By experimenting with different combinations of $z_{\rm coll}$ and $T_{\rm vir}$, we have found that the situation shown in Figure 2 is typical: a $\sim 10\%$ contribution by X–rays to the flux (e.g. the curve labeled $\epsilon_x = 0.1$ in fig.2) is sufficient to keep the H_2 fraction high enough to allow star formation. We therefore expect that if the early background had a non–negligible contribution from "mini–quasars" with hard spectra, extending to ~ 1 keV, then the negative H_2 feedback described here would not occur.

The Minimum UV Flux for Negative Feedback. In the example shown in Figure 2, $(z_{\rm coll}, T_{\rm vir}) = (30, 10^3{\rm K})$, the critical value of the UV flux to suppress starformation, $J_{\rm crit}$ can be read off directly from Figure 2 to be $J_{\rm crit} = 0.1$. In order to be able to investigate the evolution of the UVB in the Press–Schechter cosmological models, we have computed the evolution of clouds for a grid of values for $5 < z_{\rm coll} < 50$, and $2 < \log(T_{\rm vir}/{\rm K}) < 4$. For each pair of values, we have found the critical flux. We find that the resulting values are relatively low, $J_{\rm crit} \sim 10^{-1} - 10^{-3}$, depending on the collapse redshift and virial temperature. *Since these values of the flux necessary to prevent star–formation are 2–4 orders of magnitude below the minimum flux necessary to reionize the universe (i.e. one photon/baryon), a negative feedback necessarily turns on prior to reionization.* This robust conclusion holds unless there is an early XRB, as described above.

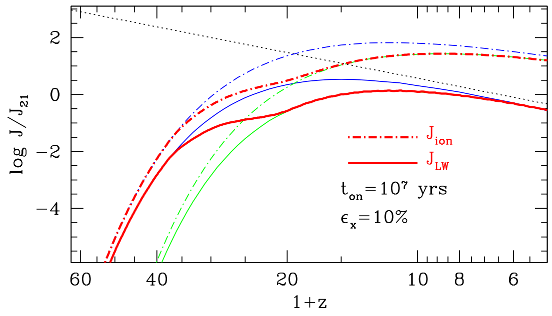

Fig. 3. Evolution of the background flux J at 13.6eV (dot–dashed lines) and the average flux in the LW bands (solid lines). In both cases, the bottom and top curve assume a constant $T_{\rm crit} = 10^{3.8}K$, and $10^{2.4}K$, respectively, and bracket our actual coupled solution, shown by the thick middle curve. The diagonal dotted line shows the minimum flux for reionization, corresponding to one photon per hydrogen atom. If early miniquasars produce an XRB, then the H_2 feedback does not occur.

4 H_2–Feedback and Cosmological Reionization

The next step is to compute the coupled redshift evolution of the background flux, the intergalactic H_2 fraction, and the mass–scale (expressed by the critical virial temperature $T_{\rm crit}[z]$) of the H_2 feedback. We assume that each halo that satisfies the star formation criterion has a constant star formation rate for $t_{\rm on}$ years, during which it turns a total fraction ϵ of its baryonic mass into stars with a Scalo IMF. We start from a high redshift, and take small redshift steps towards z=0. At each step, we sum the UV flux of all sources that are within the imaginary redshift screen $z_{\rm max}$, and satisfy our star formation criterion. Once the flux is obtained, we find the critical virial temperature numerically for the new flux J_{21} and redshift.

Our main results are shown in a model with ($t_{\rm on}$,ϵ) = (10^7 yr, 10%) in Figure 3. The figure shows the evolution of the total ionizing flux produced by all sources at 13.6 eV ($J_{\rm ion}$) and the average flux in the LW bands, ($J_{\rm LW}$) The three solid curves show the evolution of $J_{\rm LW}$ in our model with feedback (middle curve), assuming that the critical virial temperature is fixed at $T_{\rm vir} = 10^{2.4}$K (upper curve), and at $T_{\rm vir} = 10^{3.8}$K (lower curve). These curves demonstrate that initially the small halos are allowed to form stars, there is no feedback, and the flux builds up as in the constant $T_{\rm vir} = 10^{2.4}$K case. At redshift $z \approx 35$, the feedback starts to be noticeable, as the flux builds up to $J_{\rm LW} \approx 10^{-2}$, and $T_{\rm crit}$ rises above $10^{2.4}$K. By redshift $z = 20$, $T_{\rm crit}$ reaches $10^{3.8}$K. The dot–dashed lines show the evolution of the ionizing flux, $J_{\rm ion}$; and the dotted line shows the minimum flux required for reionization (corresponding to one photon per hydrogen atom). As the figure shows, reionization in this model occurs at $z \sim 15$, and at this redshift the contribution from the small halos to $J_{\rm ion}$ is only $\sim$10%.

We have found that different choices for $t_{\rm on}$ and ϵ yield similar conclusions: the H_2 feedback suppresses star formation inside the small halos, and the contribution of the small halos to the reionizing flux is always below 10%, unless we include an XRB in addition to the UVB. If reionization occurs late, then the H_2 feedback makes less of a difference to the overall ionizing flux. The contribution from small halos to the reionizing flux is then small in any case, since by this late time, the collapsed baryon fraction, as well as the UV background, is dominated by the large halos. There is an indication from 3–D simulations that the efficiency in small halos might be unusually small ($< 1\%$, Abel et al. 1998). If the efficiency in small halos was intrinsically indeed much smaller than in large halos, then the contribution to the flux from the small halos would be again small, regardless of the H_2–feedback. We emphasize that the H_2 feedback generically occurs in any model without an XRB that satisfies the reionization constraint by $z = 5$, because the suppression of the H_2 abundance and star formation inside clouds requires a UV flux that is only a fraction $10^{-2} - 10^{-4}$ of the reionizing flux. As the UVB builds up to the reionizing level, it must necessarily first reach the level at which the H_2 feedback sets in. However, we find that if early miniquasars produce an XRB, at a flux level of $\sim 10\%$ of the UVB, then the H_2 feedback does not occur, and reionization can be caused early on by the small halos. The evolution of the small early halos is therefore distinctly different in stellar and mini–quasar models: this may help shed light on the question of what type of sources were responsible for ending the “dark age”, and reionized the Universe.

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