FEEDBACK FROM FIRST RADIATION SOURCES: H⁻ PHOTODISSOCIATION

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ABSTRACT

During the epoch of reionization, the formation of radiation sources is accompanied by the growth of a H⁻ photodissociating flux. We estimate the impact of this flux on the formation of molecular hydrogen and cooling in the first galaxies, assuming different types of radiation sources (e.g., Population II and Population III stars, miniquasars). We find that H⁻ photodissociation reduces the formation of H₂ molecules by a factor of \( F_f \approx 1 + 10^{-3} k_{\text{H}_2} \delta^{-1} \) where \( \chi \) is the mean ionized fraction in the intergalactic medium, \( f_{\gamma} \) is the fraction of ionizing photons that escape from their progenitor halos, \( \delta \) is the local gas overdensity, and \( k_{\text{H}_2} \) is an order unity constant that depends on the type of radiation source. By the time a significant fraction of the universe becomes ionized, H⁻ photodissociation may significantly reduce the H₂ abundance and, with it, the primordial star formation rate, delaying the progress of reionization.

Subject headings: cosmology: theory — early universe — galaxies: formation — galaxies: high-redshift

1. INTRODUCTION

The first stars in the ΛCDM universe are believed to have formed inside dark matter–dominated minihalos filled with mostly neutral, metal-free gas of virial temperature \( T_{\text{vir}} < 10^4 \) K, when \( \text{H}_2 \) molecules formed in sufficient abundance to cool the gas radiatively to \( \sim 10^2 \) K. If, as currently thought, these stars were massive, hot, and luminous, they may have contributed significantly to the reionization of the universe, which cosmic microwave background polarization observations by Wilkinson Microwave Anisotropy Probe (WMAP) indicate was highly ionized by \( z \sim 10 \) (Spergel et al. 2006). However, the release of ionizing UV radiation by minihalos and other sources (e.g., stars in more massive halos, with \( T_{\text{vir}} > 10^4 \) K, or miniquasars), required to explain reionization, must have been accompanied by radiation release at energies below the H Lyman limit as well. This may in turn have limited the H₂ abundance inside minihalos and their ability to form stars, thereby limiting their contribution to cosmic reionization.

In the absence of dust and at densities below the three-body formation regime \( (n \lesssim 10^{10} \text{ cm}^{-3}) \), the most important reaction for the production of H₂ is

\[
\text{H}^- + \text{H} \rightarrow \text{H}_2 + e^- \tag{1}
\]

(e.g., Shapiro & Kang 1987 and references therein), with a reaction rate \( k_\gamma = 1.3 \times 10^{-9} \text{ cm}^3 \text{ s}^{-1} \) (Schmetekopf et al. 1967). Once formed, H₂ can be destroyed by collisions with other species:

\[
\text{H}_2 + \text{H}^\rightarrow \text{H}_2^+ + \text{H}, \tag{2}
\]

\[
\text{H}_2 + \text{H} \rightarrow \text{H} + \text{H} + \text{H}, \tag{3}
\]

\[
\text{H}_2 + e^- \rightarrow \text{H} + \text{H} + e^-, \tag{4}
\]

or by photodissociation via Lyman-Werner band photon absorption:

\[
\text{H}_2 + \gamma \rightarrow \text{H} + \text{H}. \tag{5}
\]

The latter process becomes dominant once a substantial UV background is built up between 912 and 1110 Å, providing a feedback mechanism against the formation of new radiation sources (e.g., Haiman et al. 1997, 2000; Ciardi et al. 2000; Machacek et al. 2001; Mesinger et al. 2006).

In this Letter we explore the impact of another feedback mechanism, the photodissociation of \( \text{H}^- \),

\[
\text{H}^- + \gamma \rightarrow \text{H} + e^- \tag{6}
\]

The cross section for photodissociation of \( \text{H}^- \) is well fitted by (Wishart 1979)

\[
\sigma(\epsilon) = 2.1 \times 10^{-16} \left( \frac{\epsilon - 0.75}{0.75} \right)^{5/2} \text{ cm}^2, \tag{7}
\]

where \( \epsilon \) is the photon energy in units of eV. The cross section is zero below a threshold of \( \epsilon < 0.755 \) eV, the binding energy of the second electron. In the absence of the UV background, the primary mode of \( \text{H}^- \) destruction is the formation of \( \text{H}_2 \) (eq. [1]), so introducing the \( \text{H}^- \) photodissociating flux reduces the \( \text{H}_2 \) formation rate by a factor

\[
F_f = 1 + \frac{x}{k_{\text{H}_2} n_H}, \tag{8}
\]

where \( x = \int n_H(\epsilon) \sigma(\epsilon) d\epsilon \) is the photodissociation rate per \( \text{H}^- \) ion, \( n_H \) is the hydrogen atom number density, and \( n_H(\epsilon) \) is the number density of photons with energy \( \epsilon \). Hence, the importance of this mechanism depends primarily on the local density ratio of \( \text{H}^- \) photodissociating photons and hydrogen atoms.

The impact of \( \text{H}^- \) photodissociation differs from that of \( \text{H}_2 \) by two fundamental characteristics. First, the time required for \( \text{H}^- \) abundance to approach equilibrium is very short (typically less than 10,000 years), while for \( \text{H}_2 \) the equilibration time can

\[
\text{When gas fractional ionization is high (} \chi \gtrsim 0.01\text{), mutual neutralization with H}^- \text{can provide another efficient channel for H}^- \text{ destruction. However, typically the fractional ionization of minihalos is much lower.}
\]

\[
\text{This approximation for } F_f \text{ breaks down when its value exceeds } \sim 50, \text{ since for such UV intensities the H}^- + \text{H} \rightarrow \text{H}_2 + \gamma \text{ reaction becomes a dominant channel of } \text{H}_2 \text{ production (assuming reaction rates given by Shapiro & Kang 1987). Note also that } k_{\text{H}_2} \text{ is still uncertain to within a factor of a few (see Glover et al. 2006), and this uncertainty carries over to } F_f \text{ when } F_f \gg 1.
\]
that epoch is transparent to most nonionizing UV photons, almost all of them add to the H\textsuperscript{+} photodissociation background.

Neglecting recombinations in the diffuse IGM, the mean ionization is \( x = N_{ib} f_{esc} \), where \( N_{ib} \) is the total number of ionizing photons per baryon produced up to this point. Inside halos, the recombination time is quite short, and so the number of ionizations taking place there, \( N_{ib}(1 - f_{rec}) = x(1 - f_{rec}) f_{esc} \), is almost equal to the number of electron recombinations to \( n \geq 2 \) states (i.e., recombinations that do not result in emission of additional ionizing photons), \( N_{rec} \). Therefore, the average H\textsuperscript{+} photodissociating rate is given by

\[
\dot{x} = N_{rec} n_{ba} c(\sigma_\text{a}) = x n_{ba} c(\sigma_\text{a}) \left( \frac{1 - f_{esc}}{f_{rec}} \right),
\]

where \( n_{ba} \) is the mean baryon density and \( c(\sigma) \) is the average cross section per recombination photon times the average number of photons per recombination.

By combining equations (8) and (9), we can estimate the importance of the H\textsuperscript{+} photodissociation due to recombination radiation. Assuming that most of the recombinations occurred recently, we find that the recombination radiation alone will suppress the H\textsubscript{2} formation rate by

\[
F_r = 1 + 800 \delta^{-1} \left( \frac{c(\sigma)}{0.1} \right)^{-1} (1 - f_{esc}),
\]

where \( \delta = 1.08 n_{ib}/n_{ba} \) is the local overdensity. Here we have neglected recombinations in the diffuse IGM and the associated H\textsuperscript{+} dissociating photons from these recombinations, but these would only further increase \( F_r \).

Cosmological redshift can affect the photodissociation rate by shifting the spectrum to longer wavelengths. Initially this leads to an increase in \( c(\sigma) \) due to the \( \epsilon^{1/2} \) dependence of the cross section for \( \epsilon \gg 0.755 \) eV. Eventually, as more and more of the spectrum is shifted below the threshold, the cosmological redshift begins to decrease the dissociation rate. For recombination photons, this redshift effect is small, and the transition to \( (\sigma_\text{a}) \)-depression occurs at a redshift factor of \((1 + z)/(1 + \bar{z}) \approx 2.5 \) (see Fig. 1).

Fig. 1.—Redshift evolution of the average H\textsuperscript{+} photodissociation cross section of the UV photons produced by recombination (dotted line), excitations by nonthermal electrons (dashed line), and massive Population III stars (solid line).

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2. H\textsuperscript{+} PHOTODISSOCIATING BACKGROUND: UV SOURCES

2.1. Recombination Products

Since the first radiation sources are expected to form within overdense gas clouds, only the escaping fraction of their ionizing photons, \( f_{esc} \), was available for ionization of the diffuse intergalactic medium (IGM). The rest was absorbed within the host halos and, via the process of radiative recombination, converted into lower energy UV photons. Since the universe during
2.2. Direct Emission

Unlike ionizing photons, whose intensity is heavily attenuated both in stellar atmospheres and in their host galaxies, most of the photons with frequencies below the Lyman limit escape freely into the IGM. From then on, photons with frequency below Ly$\beta$ undergo no evolution apart from cosmological redshift. By contrast, within a small fraction of the Hubble time, most photons with frequency between Ly$\beta$ and the Lyman limit are split by cascade into two or more photons after being redshifted into one of the hydrogen resonances. Most of the cascade products, which include lines such as Ly$\alpha$, H$\alpha$, and H$\beta$ as well as a continuum spectrum produced by the two-photon transition $2s \rightarrow 1s$, are above the 0.755 eV threshold for H$^{-}$ photodissociation.

The relative importance of these directly emitted H$^{-}$ dissociating photons depends on the nature of the UV sources. Figure 2 shows the increase of the H$^{-}$ dissociation rate due to inclusion of direct emission from metal-poor Population III stars, which we calculated using the stellar atmosphere models of Schaerer (2002). Predictably, for very massive Population III stars, with surface temperatures $\sim 10^{7}$ K, adding the stellar continuum below the Lyman limit to the recombination spectrum increases the photodissociation rate by only $\sim 10\%$. If, on the other hand, most of the early ionizing flux was produced by stars with masses below $10 M_\odot$, whose continuum emission is stronger at lower frequencies, then the total H$^{-}$ dissociation rate would be tripled at least. Likewise, direct emission may be important if most of the UV photons were produced by miniquasars. For example, assuming that their spectrum can be approximated by a power law, $L_s \propto \nu^{-1.7}$, with a cutoff below 0.75 eV, adding the directly emitted photons to the recombination products increases the total photodissociation rate by a factor of $\sim 5$.

3. H$^{-}$ PHOTODISSOCIATING BACKGROUND: X-RAY SOURCES

It has been suggested that X-ray photons could contribute a large fraction of the energy emitted by the first radiation sources (e.g., Ricotti & Ostriker 2004). By increasing the number of free electrons, X-rays can boost the production of H$^{-}$, and thus of H$_2$, providing a positive feedback to the formation of new sources (Haiman et al. 2000; Kuhlen & Madau 2005). This effect, however, would be at least partially offset by an increase of the H$^{-}$ photodissociating background, caused by conversion of X-rays into UV photons.

The absorption of an X-ray photon is followed by the release of a nonthermal electron, which then loses some of its energy by inelastic collisions with atoms before it can thermalize its energy by elastic scattering with ions and other electrons. When the gas ionization fraction is low ($x \approx 0.05$), the photoelectron splits most of its energy evenly between collisional ionizations and excitations of hydrogen atoms (Shull & Van Steenberg 1985). Using electron-hydrogen excitation cross sections (Grafe et al. 2001; Stone et al. 2002), we find that around $5/6$ of the excitations are to the 2p level, which are followed by emission of a Ly$\alpha$ photon. Most of the remaining excitations are to the 3p level, which decays via emission of one H$\alpha$ photon and a subsequent two-photon decay from the 2s level. The Ly$\alpha$, H$\alpha$, and two-photon continuum each produce roughly equal contributions to H$^{-}$ photodissociation. Per ionization, the average intensity-weighted cross section for these photons is $\langle \sigma_r \rangle = 1.6 \times 10^{-17}$ cm$^2$. Due to the low number of UV photons produced during this phase, the formation of H$_2$ is not strongly affected:

$$F_x = 1 + 4 \delta^{-1} \left( \frac{x}{0.01} \right).$$  \hspace{1cm} (11)

After the ionized fraction climbs above $x \approx 0.05$, most of the energy of the nonthermal electrons is converted to heat. However, simultaneously with the growth of the ionized fraction, the temperature of the gas rises, and as it crosses $10^4$ K, the collisions between thermal electrons and atoms begin to dissipate the energy added by X-rays, mainly via emission of Ly$\alpha$ photons. Neglecting gas clumping, we find that the number of emitted Ly$\alpha$ photons per hydrogen atom is

$$N_\alpha = 4.6 \times 10^{-6} \text{ cm}^{-3} \text{ s}^{-1} \int x(1-x)e^{-1.18 \times 10^4 T} \eta_{\text{HeI}} \, dt. \hspace{1cm} (12)$$

Assuming for simplicity that $x$ and $T$ are constants, we can rewrite the equation (12) as

$$N_\alpha = 11.2 \left( \frac{\tau_{\alpha}}{0.05} \right) \frac{\int [1-x]e^{-1.18 \times 10^4 T} \eta_{\text{HeI}} \, dt}{10^{-4}}, \hspace{1cm} (13)$$

where $\tau_{\alpha} = \int x \sigma_x \, dt$ is the Thompson optical depth from the epoch of partial ionization by X-rays. If X-ray preionization contributes at least half of the $\tau \approx 0.1$ measured by WMAP (i.e., $\tau_{\alpha} \approx 0.05$), hydrogen atomic de-excitations in the diffuse IGM may produce $\geq 30$ Ly$\alpha$ photons per baryon.

The suppression of H$_2$ formation due to H$^{-}$ photodissociation by Ly$\alpha$ photons is

$$F_x \approx 1 + 100 N_\alpha \delta^{-1}. \hspace{1cm} (14)$$

Since the energy of Ly$\alpha$ photons (10.2 eV) is far above the H$^{-}$ photodissociation threshold (0.75 eV), the photodissociation rate grows roughly as $(1+z)^{5/3}(1+z)^{3/5}$, where $z$ is the redshift at which the photon was emitted. In the case of an extended period of partial ionization, $F_x$ may be increased by a factor of a few, possibly exceeding $10^5 \delta^{-1}$.

Since, when the IGM temperature rises above $10^4$ K, the...
formation of new minihalos is suppressed, the impact of $H^-$ photodissociating flux produced by X-ray conversion is relevant only for minihalos that have formed some time ago or for halos with $T_{\text{vir}} > 10^5$ K, which also rely on $H_2$ cooling to form stars.

4. DISCUSSION

As shown by our calculations, $H^-$ photodissociation reduces the formation of $H_2$ molecules by a factor of

$$F_s \sim 1 + 10^k \times \frac{1}{x_{\text{esc}}} \delta^{-1},$$

(15)

where $k_s$ is a constant of order a few, whose value depends on the type of radiation source and the growth history of the radiation background. Thus, by the time a significant fraction ($\gtrsim 0.1$) of the universe becomes ionized, $H^-$ photodissociation can significantly reduce the $H_2$ formation rate in regions with overdensities of up to a few thousand, i.e., in the interior regions of minihalos. The equilibrium abundance of molecular hydrogen during this stage would be determined by the balance between its formation and destruction rates (eqs. [1] and [5]):

$$n_{H_2} = \frac{k}{k_{\text{LW}}} \frac{n_H n_H}{n_H},$$

(16)

where $k_{\text{LW}}$ is the $H_2$ destruction rate by the Lyman-Werner photons. Thus, a reduction of $H^-$ abundance by a factor $F_s$ translates into the same reduction of the $H_2$ abundance and, in minihalos, a comparable increase of the cooling time.

Indirectly, $H^-$ photodissociation may affect the cooling in the central regions of minihalos even during the early stages of reionization. The maximum density that gas can reach in the core region of a minihalo is limited by the amount of entropy it is able to radiate away during collapse. The lower density gas prevalent during the early collapse phase would be susceptible to $H^-$ dissociation from even a relatively low intensity $H^-$ dissociating flux, and the resulting lowered $H_2$ abundance would limit its ability to radiate away entropy via $H_2$ cooling. Furthermore, the density and $H_2$ abundance at the center depend on the conditions in the low-density outer regions, through their contributions to both the total pressure and the self-shielding ability of the halo. We plan to investigate these effects further with numerical radiation-hydrodynamic simulations in the future.

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