THE IMPACT OF POPULATION III OBJECTS ON THE EARLY UNIVERSE

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Abstract

We study the effects of the ionizing and dissociating photons produced by Pop III objects on the surrounding intergalactic medium. We find that the typical size of a H$_2$ photodissociated region is smaller than the mean distance between sources at $z \approx 20-30$, but larger than the ionized region. This implies that clearing of intergalactic H$_2$ occurs before reionization of the universe is complete. In the same redshift range, the soft-UV background in the Lyman-Werner bands, when the intergalactic H and H$_2$ opacity is included, is found to be $J_{LW} \approx 10^{-28} - 10^{-26}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$. This value is well below the threshold required for the negative feedback of Pop III objects on the subsequent galaxy formation to be effective. We have combined these semi-analytical results with high resolution N-body simulations, to study the topological structure of photoionization and photodissociation and the evolution of the H$^+$ and H$_2$ filling factor.

1 Introduction

At $z \approx 1100$ the intergalactic medium (IGM) is expected to recombine and remain neutral until the first sources of ionizing radiation form and reionize it. Until recently, QSOs were thought to be the main source of ionizing photons, but observational constraints suggest the existence of an early population of pregalactic objects (Pop III hereafter) which could have contributed to the reheating, reionization and metal enrichment of the IGM at high redshift.

In order to virialize in the potential well of dark matter halos, the gas must have a mass greater than the Jeans mass, which, at $z \approx 30$, is $\approx 10^5 M_\odot$, corresponding to virial temperatures $< 10^4$ K. To have a fragmentation of the gas and ignite star formation, additional cooling is required. It is well known that in these conditions the only efficient coolant for a plasma of primordial composition is molecular hydrogen ([1]; [8]). As the first stars form, their photons in the energy range 11.26-13.6 eV are able to penetrate the gas and photodissociate H$_2$ molecules both in the IGM and in the nearest collapsing structures, if they can propagate that far from their source, thus inhibiting subsequent formation of small mass objects through the so called ”negative feedback”, as Haiman, Rees & Loeb ([3], HRL) have argued. It is therefore important to assess the impact of these objects on their surroundings through detailed calculations of the various influence spheres, i.e. ionization, photodissociation, and eventually also supernova metal enriched ([2]) spheres, produced by Pop IIIs. In this talk we will briefly present the main results and a progress report on these topics. A detailed derivation can be found in [3].
2 Analytical estimates

If massive stars form in Pop IIIs, their photons with $h\nu > 13.6$ eV create a cosmological HII region in the surrounding IGM. Its radius, $R_\text{i}$, can be estimated by solving the standard equation for the evolution of the ionization front ([4]; [7]). If steady-state is assumed and the cosmological expansion is neglected (since $R_\text{i} \ll c/H$), then $R_\text{i}$ is approximately equal to the Strömgren radius, $R_\text{S}$, that, in general, represents an upper limit for $R_\text{i}$. For our reference parameters it is:

$$R_\text{i} < \sim R_\text{S} = 0.05 \left( \Omega_b h^2 \right)^{-2/3} (1+z)^{-2/3} S_{47}^{1/3} \text{kpc},$$

where $S_{47} = S_i(0)/(10^{47} \text{ s}^{-1})$ and $S_i(0)$ is the ionizing photon rate.

In analogy with the cosmological HII region, photons in the energy range $11.26 \text{ eV} < h\nu < 13.6 \text{ eV}$, create a photodissociated sphere in the surrounding IGM. The main difference with the ionization spheres evolution is that there is no efficient mechanism to re-form the destroyed H$_2$, analogous to H recombination. As a consequence, it is impossible to define a photo-dissociation Strömgren radius. However, given a point source that radiates $S_{\text{LW}}$ photons per second in the LW bands, an estimate of the maximum radius of the H$_2$ photodissociated sphere, $R_\text{d}$, is the distance at which the photo–dissociation time becomes longer than the Hubble time:

$$R_\text{d} < \sim 2.5 h^{-1/2} (1+z)^{-3/4} S_{\text{LW,47}}^{1/2} \text{kpc},$$

where $S_{\text{LW,47}} = S_{\text{LW}}/(10^{47} \text{ s}^{-1})$.

To substantiate the above analytical estimates we have developed a non–equilibrium multifrequency radiative transfer code to study the evolution of ionization and dissociation fronts produced by a point source of baryonic mass $M_b \sim 10^5 M_\odot$ forming at redshift $z = 30$. We have adopted a standard CDM model ($\Omega_m = 1$, $h = 0.5$, $\sigma_8 = 0.6$), with $\Omega_b = 0.06$. The program evolves the energy equation and the chemical network equations, including 27 chemical processes and 9 species (H, H$^-$, H$^+$, He, He$^+$, He$^{++}$, H$_2$, H$_2^+$ and free electrons). The cooling model includes, among other processes, hydrogen, helium and molecular line cooling, Compton cooling on the CMB, recombination cooling and all relevant photoionization heating mechanisms.

3 Results and implications

In Fig. 1 we plot the numerical values of $R_\text{i}$ and $R_\text{d}$ as function of redshift, for $\beta = 1$, where $\beta$ is the ratio between the flux produced by the object just below and above the Lyman limit. Also shown are the upper limits to the radii, given by eq. (1) and eq. (2) (with $S_{\text{LW}} = \beta S_i(0)$).

To determine if the surviving intergalactic H$_2$ can build up a non-negligible optical depth to LW photons, it is important to compare the size of the dissociated regions around PopIIIs with their average interdistance, $d \sim \left[ n(v_c, z) \right]^{-1/3}$, where $n(v_c, z)$ is the proper number density distribution of dark matter halos and $v_c$ is their circular velocity ([6]). As in the redshift interval 20-30 $d$ is bigger than the typical derived $R_\text{d}$ ($d \approx 0.01 - 0.1 \text{ Mpc}$), the H$_2$ regions can hardly overlap and completely destroy the primordial H$_2$ molecules, and the H$_2$ photodissociated sphere overlapping will become important at $z \leq 20$.

3.1 Soft-UV background

In the calculation of the "soft-UV background" (SUVB), $J_{\text{LW}}$, produced by PopIIIs, we have included the intergalactic H$_2$ attenuation due to the LW absorption lines, as well as the neutral H lines absorption. The H lines are optically thick at their center; this, combined with the effect
Figure 1: Ionization radius, $R_i$ (open circles) and photodissociation radius, $R_d$ (filled) of the regions produced by a Pop III of total mass $M \approx 10^6 M_\odot$, turning on at $z \approx 30$, as a function of redshift. Also shown is the maximum radius of the dissociated region (solid line), given by eq. (2), the Strömgren radius $R_s$ (dotted), given by eq. (1), and the solution of the standard equation for the evolution of the ionization front (dashed).

of the cosmological expansion, produces the typical sawtooth modulation of the spectrum. We find that typically, a SUVB intensity $J_{LW} \approx 10^{-28} - 10^{-26}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ is produced by Pop III objects in the redshift range 20-30.

These results are particularly important when the effects of the possible "negative feedback" are to be considered. HRL concluded that in principle a SUVB created by pregalactic objects, would be able to penetrate large clouds, and, by suppressing their H$_2$ abundance, prevent the collapse of the gas. We find that the intensity of the SUVB is well below the threshold required for the negative feedback to be effective. Clearly, if at redshift $\approx 20$ complete overlapping of photodissociated regions occurs, as previously suggested, the SUVB intensity can be increased to interesting values for negative feedback effects. However, by that time a considerable fraction of the objects in the universe that must rely on H$_2$ cooling for collapse might be already in an advanced evolutionary stage and actively forming stars. To confirm this hypothesis, that depends on the details of structure formation, numerical simulations are required.

4 Numerical simulation

We have been provided by F. Governato & A. Jenkins of the Virgo Consortium with very high-resolution N-body simulations (halos with masses as low as $10^6 M_\odot$ are resolved) showing the dark matter halos distribution from $z \approx 30$. The simulations have been performed by using a $\mathbb{P}^3\!M$ parallel code, in a 5 Mpc box size (comoving) and $253^3$ cells, for a CDM cosmology with $\Omega_m = 1$, $h = 0.5$ and $\sigma_8 = 0.6$. We have combined the numerical results with the semi-analytical...
Figure 2: Evolution of the H\(_2\) (upper curves) and HII (lower curves) filling factor, for two different choices of \(f_b\), the fraction of virialized baryons able to cool and be available to form stars.

calculations, assigning to each halo the ionized and dissociated spheres produced by the host PopIII, as computed above. This allows the study of the evolution of the topological structure of photoionized/dissociated regions. As a preliminary result, we show here the evolution of the filling factor (Fig. 2). As expected, clearing of H\(_2\) occurs before reionization is completed. On the other hand the reionization epoch ranges from \(z \approx 8\) to \(z \approx 12\) depending on the cooling efficiency \(f_b\) of the collapsing halos.

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