Zero metallicity stellar sources and the reionization epoch

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ABSTRACT

We reconsider the problem of the cosmological reionization due to stellar sources. Using a method similar to that developed by Haiman & Loeb (1997), we investigate the effect of changing the stellar models and the stellar spectra adopted for deriving the ionizing photon production rate. In particular, we study the consequences of adopting zero metallicity stars, which is the natural choice for the first stellar populations. We construct young isochrones representative of Population III stars from existing sets of evolutionary models (Forieri 1982; Cassisi & Castellani 1993) and calculate a suitable library of zero metallicity model atmospheres. The number of ionizing photons emitted by such a zero metal population is about 40% higher than that produced by standard metal poor isochrones. We find that adopting suitable zero metallicity models modifies the reionization epoch. However the latter is still largely affected by current uncertainties in other important physical processes such as the efficiency of the star formation and the fraction of escaping UV photons.

Key words: Cosmology: theory – intergalactic medium

1 INTRODUCTION

In the recent years there has been a lot of theoretical work related to the cosmological reionization. The source of the ionizing UV background is still uncertain: the more studied scenarios are those connected to a first generation of stars in mini–galaxies or to the radiation from massive black holes in small halos. The Next Generation Space Telescope will be able to observe directly the first luminous objects and discriminate between the previous scenarios. In addition, future satellite experiments (such as MAP and PLANCK) are likely to detect the CMB secondary anisotropies due to the reionized intergalactic medium.

Detailed numerical simulations of the reionization phenomena requires a suitable treatment of different physical phenomena: gas dynamics, cooling processes and radiative transport (Abel et al. 1998, Norman et al. 1998, Razoumov & Scott 1999, Gnedin 1999). However, the complete study of the formation of first objects and the feedback effect on the surrounding medium is still out of the possibility of the present numerical approaches. For this reason a number of analytical or semianalytical methods (e. g. Fukugita & Kawasaki 1994, Liddle & Lyth 1995, Tegmark, Silk & Blanchard 1994, Haiman & Loeb 1997, hereafter HL97, Valageas & Silk 1999, Ciardi et al. 1999, Chiu & Ostriker 1999) have been used for estimating the reionization epoch and how this depends on the cosmological model and on the formation history of ionizing sources. The effect related to the cosmological parameters are relatively understood in comparison to those used for estimating stellar feedback.

In this paper we focus mainly on how the properties of the stars, in particular the metallicity and stellar winds, could affect the reionization epoch. In section 2 we briefly describe the reionization model. In section 3 we discuss the peculiarity of the Population III (hereafter PopIII) stars and present our isochrones and our spectral library. Finally, in section 4 we present and discuss our results.

2 THE REIONIZATION MODEL

To study the process of the cosmological reionization we have developed a code based on the analytical method described in HL97. The mass function of the dark matter halos is computed according to the Press–Schechter theory (Press & Schechter 1974). The formation of a stellar population is allowed in any halo with a total mass $M \geq 10^9 [(1 + z)/10]^{-3/2} M_{\odot}$, assuming that all the H$_2$ is
dissociated by the very first radiation sources as soon as reionization begins.

In such halos a fraction $f_*$ of the gas is converted into stars in a single instantaneous burst (simple stellar population model, hereafter SSP). Given the lack of complete theory of star formation, this fraction is assumed to be a universal constant and it is fixed on the base of the metallicity observed in the Lyman-α forest. If we assume that the carbon observed in these systems is produced by the same primordial mini-galaxies we are considering here, the efficiency of star formation is likely confined in the range $0.015 \leq f_* \leq 0.15$ (see HLM97 for more details). We use the Salpeter IMF, with a low mass limit equal to $0.024 M_\odot$. Given such a limit, the mass fraction of stars of the range $3 - 8 M_\odot$ is the same as that given by the Scalo IMF, used by HLM97, so that we can refer to their values for $f_*$.

Part of the ionizing photons (with energy $\geq 13.6$ eV) is absorbed by the gas in the mini-galaxies. This effect is described by introducing a factor which represents the escape fraction $f_{esc}$ of photons. Due to the incertitude in the estimate of this parameter, we explore the range $f_{esc} = 0.2 \div 1$.

We assume that the emission is isotropic and that the intergalactic medium is homogeneous; in this case the volume of the spherical HII region formed around each galaxy may be computed analytically (see Shapiro & Giroux 1987). Integrating over all the sources, we can calculate, at any redshift, the filling factor of the HII regions ($F_{HII}$). The reionization redshift $z_{rei}$ is defined by $F_{HII}(z_{rei}) = 1$.

### 3 STELLAR POPULATIONS OF ZERO METALLICITY

In order to compute the SSP photon rate production $\epsilon_\nu(t, Z)$, we integrate the contribution of stars along an isochrone of given age, $t$ and metallicity, $Z$. If $f_\nu[L(M, t, Z), g(M, t, Z), T_{eff}(M, t, Z)]$ is the spectrum of the star with initial mass $M$, luminosity $L$, surface gravity $g$ and effective temperature $T_{eff}$ along the isochrone of age $t$ and metallicity $Z$, and $\psi(M)$ is the initial mass function, then the emissivity is given by

$$\epsilon_\nu(t, Z) = \int_{M_{inf}}^{M_{sup}} f_\nu[L(M), g(M), T_{eff}(M)] \psi(M) dM . \quad (1)$$

We have neglected, for simplicity, the dependence from age and metallicity while the dependence on the gravity has been explicitly included because, in general, the initial mass is different from the current stellar mass due to mass-loss along the isochrone. The procedure is similar to the one adopted in Bressan, Chiosi & Fagotto (1994, hereafter BCF94).

Equation (1) requires the knowledge of the theoretical isochrone $\{(L(M), g(M), T_{eff}(M))\}$ and of suitable model atmospheres. In the following we discuss our choice for the zero metallicity stellar populations.

#### 3.1 Theoretical isochrones for zero metallicity stars

The first generation of stars forms from the primordial material, whose chemical composition is entirely dictated by the cosmological nucleosynthesis. Detailed computations of primordial nucleosynthesis set an upper limit for the CNO mass abundance $Z_{CNO} \leq 10^{-12}$ (Applegate, Hogan & Scherrer 1987). Only in the case of inhomogeneous nucleosynthesis and baryonic matter density parameter $\Omega_b=1$, significantly higher values, $Z_{CNO} \leq 10^{-9}$, are predicted (Kawano et al. 1991). These extreme models will not be considered here.

The very low abundance of CNO elements affects both the radiative opacity and the rate of nuclear energy production, as shown in early studies by Ezer (1961), Ezer & Cameron (1971), Hartquist & Cameron (1977), Bond, Carr & Arnett (1983), El Eid, Fricke & Ober (1983) and Castellani, Chieffi & Tornambè (1983).

For very young stellar populations, which are most interesting here, the largest effect is due to the lack of the CNO cycle in the most massive stars because, due to the very shallow temperature dependence of the proton-proton reaction rates, very high central temperatures and densities are needed in order to halt the gravitational contraction and set the star onto the ZAMS. Eventually, in stars more massive than a critical mass ($10 M_\odot \div 20 M_\odot$), depending on the assumed initial helium abundance), the central temperature overcomes $10^8$ K, where the triple alpha reaction becomes effective in producing fresh carbon ($^{12}$C). The new synthesized $^{12}$C immediately feeds the CNO cycle which begins to compete with the p-p cycle and becomes the dominant process when the CNO abundance reaches a few times $10^{-11}$. Because of the steep temperature dependence of the CNO reaction rate, the central temperature and density start decreasing, but the former never falls below $10^8$ K, so that the CNO abundance keeps growing under the effect of the triple alpha reaction. At the end of the central hydrogen burning phase the CNO abundance in massive stars is of the order of a few times $10^{-9}$, still some orders of magnitude less than that typical in the most metal poor stars in our Galaxy. As a consequence the main sequence of zero metallicity massive stars is definitely hotter (and slightly more luminous) than that obtained by adopting the lowest abundance found in the metal poor globular clusters.

In this paper zero metallicity isochrones were constructed by combining sets of stellar evolutionary tracks computed by several authors. The first set is by Cassisi & Castellani (1993) and refers to stars between 1.0 $M_\odot$ and 30 $M_\odot$, for a chemical composition $Z=10^{-10}$. Models of higher mass have been computed by Forieri (1982) (20 $M_\odot$, 60 $M_\odot$ and 100 $M_\odot$ with $Z=0$) and by El Eid et al. (1983) ($M \geq 80 M_\odot$). Here we use stellar evolution tracks computed by the former author because of the finer time resolution of the corresponding tables. Slightly bluer isochrones are obtained by using the tracks of El Eid et al. 1983 instead of those by Forieri 1982 (Cojazzi et al. 2000).

Isochrones were computed by considering equivalent evolutionary phases along tracks of different mass, as described in García-Vargas, Bressan & Díaz (1995), in order to carefully follow the ionizing photon output rate from the most massive stars. The resulting zero metallicity isochrones are shown in Figs. 2a and 2b for two selected ages, $t=0$ and $t=2$ Myr, respectively. In the figures we also show for comparison the isochrones of non zero metallicity (Bertelli et. al 1994, Girardi et. al 1996) in order to highlight the large effect produced by the lack of the CNO cycle mainly in the range of massive zero metallicity stars. In both figures the metallicity increases from left to right and it is $Z=0$, $Z=0.0001$, $Z=0.0004$, $Z=0.004$ and $Z=0.02$, respectively.

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Figure 1. Zero age main sequence for different initial chemical composition. Starting from the rightmost one, the initial composition is $Z=0.02$, $Y=0.28$; $Z=0.004$, $Y=0.24$; $Z=0.0004$, $Y=0.23$ (Bertelli et al. 1994) and $Z=0.0001$, $Y=0.23$ (Girardi et al. 1996). The leftmost line is our $Z=0$ isochrone.

Figure 2. As in Fig. 1 but for a time $t=2\,\text{Myr}$.

3.2 Spectral library

To compute the emissivity of PopIII stellar population we need a grid of suitable atmospheric models. Existing models of very low metallicity have been computed by several authors (see e.g. Kurucz 1993 and later revisions and Schmutz et al. 1992). The lowest metallicity in the LTE plane parallel models computed by Kurucz corresponds to $[\text{M/H}]=-5$. The highest temperature in this library is 50000K and it is significantly lower than that reached by our main sequence models. On the other hand, Schmutz et al. (1992) computed non LTE wind models of pure helium stars with temperature ranging from about 30000K to 150000K. The latter models were meant to represent the atmospheres of Wolf-Rayet stars which are characterized by large mass outflows. However, if the mass loss rate decreases with the metallicity as discussed by Kudritzki et al. (1987), it should have a negligible effect in the case of zero metallicity stars and high temperature plane parallel models should be preferred.

Given the lack of such models, we computed a grid of fluxes for zero metallicity atmospheres using the code developed by Auer & Heasley (1971). The parameter space covered by the new grid extends from 10000 to 140000 K in effective temperature and from 4.0 dex to 6.0 dex in surface gravity. The code is based on the classical assumptions of radiative and local thermodynamic equilibria, and the plane parallel approximation. For the computation we have considered 71 optical depth points, ranging from $-7.0 < \tau_{\text{ROSS}} < 2.4$. A total of 45 wavelength points have been considered extending from 113 $\AA$ to about 4.5 $\mu$m. The coverage in wavelength is sufficient to make the grid suitable for continuum studies since the Balmer and Lyman breaks at 3646 and 912 $\AA$ are among the most prominent features on the spectral energy distributions in the parameter space covered by the grid. For a more detailed description of the grid the reader is referred to Chavez & Cardona (2000; in preparation).

We also extended the $[\text{M/H}]=-5$ Kurucz grid to higher temperatures, in order to highlight possible differences between true zero metal atmospheres and very metal poor ones. Fig. 3 compares very hot spectra ($T_{\text{eff}}=90000$K) in the region near and below the Lyman break, from the different sets of atmospheric models. The model computed with the Kurucz code (solid line) and the model computed with the Auer & Heasley (1971) code (dotted line) are almost superimposed. At this temperature the Lyman break is practically absent. Also the blanketing by metals in the $[\text{M/H}]=-5$ Kurucz grid is very inefficient. Moreover in both models the flux below about 228 $\AA$ falls rapidly because, in those models, the abundance of HeII ions is always high enough to block the corresponding ionizing radiation.

To illustrate this point we plot in the same figure the models of Schmutz et al. (1992). These pure helium non LTE models account for the effect of stellar wind and show that enough HII ionizing radiation can escape the star in the case of strong mass-loss (model 1), the opposite of what occurs in plane parallel models. In the case of a less strong wind (model 2), the spectrum is more similar to the plane parallel case, with a lack of photons shortward of 228 $\AA$.

Because very low metallicity stars considered here likely do not suffer of strong mass-loss rates, the use of plane parallel atmospheres seems thus justified. In any case the only significant difference would be in the amount of HeII ionizing radiation which is able to escape the stellar photosphere, which is not relevant in the present context. By contrast, the possibility that PopIII stars may significantly ionize HeII (e.g. Tumlinson & Shull 2000) must be considered with some caution.

Finally we remark that we have also considered, for sake of comparison, two cases with non zero metal content, namely $Z=0.0001$ and $Z=0.004$. In both cases we used the Padova theoretical isochrones, but Kurucz atmospheres for the former and the CoStar library (Schaerer & De Koter 1997) for the latter.
4 DISCUSSION AND CONCLUSIONS

We now consider the effects of zero metallicity stars on the reionization redshift adopting the model described in section 2 and the library of stellar isochrones obtained in section 3.

According to our assumptions, we model a galaxy with an instantaneous burst of star formation and neglect the local metal enrichment. Therefore the metallicity is kept constant during the whole process of reionization. The effect of metal enrichment due to merging with already evolved systems where the gas has been polluted by previous stellar generations, it is not considered here and, in this respect, the results obtained with zero metallicity stars must be considered as upper limits to the reionization redshift.

Fig. 4 compares the evolution of the ionizing photon production rate of an instantaneous burst of star formation at different metallicities. It can be seen from the figure that the number of ionizing photons emitted by young zero metallicity SSPs is always from 30% to 40% higher than that obtained with typical low metallicity populations.

As far as the assumptions underlying the cosmological model are concerned, we considered two typical cases: a standard CDM model with parameters and a flat CDM model with non zero cosmological constant. The former is taken as reference model while the latter is suggested by observations (Viana & Liddle 1996). The characteristic parameters of the models are: $(\Omega_0, \Omega_{\Lambda}, \Omega_b, h, \sigma_{8\text{h}^{-1}\text{Mpc}}, n, \Gamma) = (1, 0, 0.05, 0.5, 0.52, 1, 0.45)$ for the CDM and $(\Omega_0, \Omega_{\Lambda}, \Omega_b, h, \sigma_{8\text{h}^{-1}\text{Mpc}}, n, \Gamma) = (0.3, 0.7, 0.03, 0.83, 0.93, 1, 0.21)$ for the ΛCDM.

In both models, the power spectrum of primordial fluctuations has been normalized to fit the present cluster abundance (Eke, Cole & Frenk 1996). For each cosmological model, we investigated two extreme values of the gas conversion fraction, $f_*=0.015$ and $f_*=0.15$, and of the photon escape fraction, $f_{esc}=0.2$ and $f_{esc}=1$. These values can be considered as representative of the uncertainty with which the corresponding processes are known.

The results are summarized in Table 1 for the CDM model and in Table 2 for the ΛCDM model. Because of the enhanced ionizing photons production rate, the reionization is faster when PopIII stars are included, leaving all the others parameters unchanged. In particular, comparing the case of PopIII stars with that of $Z=0.004$ stars we see that the

Table 1. Reionization redshifts $z_{rei}$ in a CDM model $(\Omega_0, \Omega_{\Lambda}, \Omega_b, h, \sigma_{8\text{h}^{-1}\text{Mpc}}, n, \Gamma) = (1, 0, 0.05, 0.5, 0.52, 1, 0.45)$ for different values for $Z, f_*$ and $f_{esc}$.

| $f_*$ | 0.015 | 0.150 |
|-------|-------|-------|
| $f_{esc}$ | 0.2  | 1     | 0.2  | 1     |
| $Z$   | 0.004 |   4.9 |   8.6 |  9.9 | 12.7 |
|       | 0.0001 | 5.2  | 8.8   | 10.1 | 12.8 |
|       | 0     | 6.2  | 9.5   | 10.8 | 13.4 |

Table 2. As in Table 1 in a ΛCDM model $(\Omega_0, \Omega_{\Lambda}, \Omega_b, h, \sigma_{8\text{h}^{-1}\text{Mpc}}, n, \Gamma) = (0.3, 0.7, 0.03, 0.83, 0.93, 1, 0.21)$.

| $f_*$ | 0.015 | 0.150 |
|-------|-------|-------|
| $f_{esc}$ | 0.2  | 1     | 0.2  | 1     |
| $Z$   | 0.004 | 7.1  | 11.9  | 13.6 | 17.2 |
|       | 0.0001 | 7.5  | 12.1  | 13.8 | 17.4 |
|       | 0     | 8.7  | 13.0  | 14.7 | 18.1 |
relative variation in the reionization redshift \( z_{\text{rei}} \) is about 20% in the models with a late reionization and reduces to about 5% in the case of an early reionization. In some cases the late reionization obtained with low metallicity SSPs is not compatible with the lower limit on \( z_{\text{rei}} \) inferred from observations of recent limits on the Gunn-Peterson effect at redshift \( z \leq 5 \) (e.g. Songaila et al. 1999), and observations of high redshift Lyman-\( \alpha \) emitters (Hu, Cowie & McMahon 1998) that would not be detected in presence of a neutral intergalactic medium (Miralda-Escudé 1998). We notice that, in such cases, the adoption of PopIII stars alone is sufficient to reconcile the models with the observations.

Turning now to the favorite cosmological model (\( \Lambda \)CDM) we see that the redshift of reionization is confined in the range between \( 9 \leq z \leq 18 \). The main uncertainties are introduced by the parameters \( f_* \) and \( f_{\text{esc}} \), which roughly imply a variation of the photon production rate by a factor of 10 and 5, respectively. From our analysis it appears that, for a given cosmological model, these are the factors which actually define the reionization epoch from stellar sources.

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