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Theoretical stellar ΔY/ΔO in the early Universe

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Abstract. Population III stars initiated the chemical enrichment of the Universe. Chemical evolution models seem to favour fast rotators among the very low-metallicity population. When a star rotates fast, it ejects significant quantities of He and its nucleosynthesic products are modified compared to the case without rotation. The value of ΔY/ΔO is explored from a theoretical point of view through stellar models of zero- or very low-metallicity.

Keywords. nucleosynthesis, stars: rotation, early universe

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1. Introduction

About a quarter of an hour after the Big Bang, the Universe has finished all possible nucleosynthesis leaving its chemical composition devoid of metals (see for example Iocco *et al.* 2007). Only when the first stars form does nucleosynthesis take place again, in their cores and envelopes, and the enrichment of the Universe in heavy elements can start.

In the very early Universe, the chemical enrichment follows the nucleosynthetic path of massive stars for the first few millions of years. Of course, in the galaxies we can observe now, the contribution of the first generations of stars has been overwhelmed by the following generations, where intermediate- or low-mass stars contribute actively to the nucleosynthesis. However, should we be able one day to observe galaxies with metallicities as low as $Z = 10^{-8}$, we would certainly observe a medium enriched only by massive stars and it is interesting to study how this enrichment would take place. Currently it is in the Milky Way halo that the most metal poor objects are observed. These low-mass, second generation stars retain the memory of the unique nucleosynthesis in the first generations of massive stars.

We have recently shown that only chemical evolution models adopting stellar yields from rotating star models can successfully explain some of the puzzling imprints of the first stellar generations, such as the production of primary nitrogen and ^{13}C in the early Universe (before intermediate-mass stars have had time to contribute to the chemical enrichment - see Chiappini *et al.* 2008, 2006). Here we address the following question: would fast rotators eject significant larger quantities of helium in the early chemical enrichment than present-day massive stars? Here, we explore the theoretical dY/dO value obtained by massive star models with rotation at extremely low or zero metallicities. We consider only stellar model results, since at those extreme metallicities only a few massive stars would have had time to contribute to the chemical enrichment.

2. Stellar models

In the present study, we use the same fast-rotating models of extremely-low metallicity ($Z = 0$ and $Z = 10^{-8}$) massive stars considered in our previous papers (Chiappini *et al.* 2008, 2006). The stellar models are described in Hirschi (2007) for $Z = 10^{-8}$ and in Ekström *et al.* (2008) for $Z = 0$. The mass range covered goes from 9 to 85 $M_\odot$. We let the interested reader refer to the original papers for the detailed physics of the models, we will just summarize here the main ingredients of the calculation:

- non-solid rotation is treated as in Hirschi *et al.* (2004), with the horizontal turbulence coefficient from Zahn (1992) and the shear diffusion coefficient from Talon & Zahn (1997);
- the radiative mass loss prescription is Kudritzki (2002) for the $Z = 0$ models, with the same adaptations as in Marigo *et al.* (2003), and Vink *et al.* (2001) for the $Z = 10^{-8}$ models;
- when (if) the star reaches the critical velocity†, a mechanical mass loss is applied as in Meynet *et al.* (2006), so the supercritical layers are removed;
- an important reaction rate for the results of $\Delta Y/\Delta O$ is the $^{12}C(\alpha,\gamma)^{16}O$ rate, which is still a subject of controversy. Here the models are computed with the NACRE recommanded rate;
- the convection criterion applied is the Schwarzschild (1958) criterion.

The models start on the ZAMS with a ratio $\upsilon/\upsilon_{\rm crit}$ around 0.5.

2.1. *Nucleosynthesis*

There are some peculiarities of the nucleosynthesis at extremely-low or zero metallicity. The stars are very compact, because of the lack of metals in their envelope, thus the hydrogen burning takes place at higher temperature in the core. Pop III stars even burn some helium during the main sequence. The compactness favours a mixing between the different burning zones, for example between the helium-burning convective core and the hydrogen burning radiative shell. This leads to the production of primordial nitrogen, for example (see Meynet & Maeder 2002). While the non-rotating models undergo this phenomenon only at specific mass domains (~ 25 and ~ 85 $M_\odot$), the rotating models present the primary nitrogen production at all masses. Later, some of this nitrogen can diffuse towards the core and increase the production of ^{22}Ne, which is an interesting source of neutrons for the $s-$process nucleosynthesis (Pignatari *et al.* 2008).

Rotation also leads to modifications in the yields of the elements that interest us here. At non-zero metallicity, the mass loss is enhanced, saving some helium from further burning. Fast rotators are thus expected to be strong helium producers (see the contribution of G. Meynet in this proceedings). When some C and O are diffused from the core to the H-burning shell, it drives a boost of the energy production in it (passing suddenly from the $pp-$chains to the CNO cycle). The boost of energy reduces the size of the core, and since the O yield is closely related to the core size, the O production is reduced in this case.

2.2. *Yields*

Figure 1 and Table 1 present the yields of O and He of all the models. The $Z = 0$ very massive (above 40 $M_\odot$) models produce more O and less He than the $Z = 10^{-8}$ models.

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† *i.e.* the velocity at which the centrifugal force counterbalances exactly the gravitational force at the surface

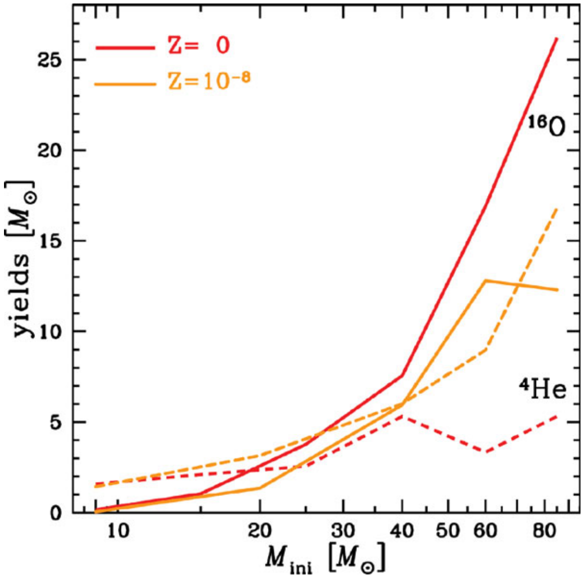

Figure 1. Yields in He (dashed lines) and O (solid lines): $Z = 0$ models (dark grey) and $Z = 10^{-8}$ (light grey).

This is mainly due to the difference in the mass loss rate: the Pop III models lose almost no mass at all while the $Z = 10^{-8}$ models experience a strong surface enrichment and the mass loss is largely increased thanks to the diffused metals. The evolution at almost constant mass and the extreme compactness of Pop III stars lead to very large CO cores, which favours a high O production at the expense of He.

As we mentioned previously, rotation enhances the mass loss. This is particularly interesting at very low metallicity, where radiative mass loss is supposed to be extremely weak. Also, according to Heger *et al.* (2003), some of the low-metallicity massive stars could end their life without the explosion of a supernova. The formation of a direct black hole would swallow the whole star without any ejection, except the winds the star lost during its life. In this case, the chemical contribution of the star would be of the 'wind-only' type. Table 1 shows the 'wind-only' contribution in parenthesis. We see that the wind is rich in He and very poor in O, as expected.

3. ΔY/ΔO

Figure 2 shows the dY/dO values obtained by stellar models. The more massive the model, the earlier the contribution is expected. Since high-mass models yield a low dY/dO value, the dY/dO ratio increases with time. The range of ΔY/ΔO values observed in the most metal-poor HII regions of the present-day Universe is indicated on the figure. Though metal-poor, those regions already bear the imprint of many stellar generations, including intermediate- and low-mass stars. The values are deduced from observations under the hypothesis that the IMF doesn't change at low metallicity (see Izotov *et al.* 2007). This hypothesis needs yet to be ascertained. In the very early Universe, it is thought that either the slope of the IMF is still valid but there is a mass-cut under $\simeq 10\ M_\odot$ (Nakamura & Umemura 1999), either the IMF is flat, or it is doubled-peaked (Nakamura & Umemura 2001).

If we assume that all the stars die at the same moment (which is reasonnable given that the less massive stars live less than 30 million years), we can integrate their yields

Table 1. Yields in He and O for the $Z = 0$ and $Z = 10^{-8}$ models. All masses are in $M_\odot$. The values given in parenthesis are the 'wind-only' contribution (see text).

	$Z = 0$			$Z = 10^{-8}$		
Mass	^{4}He	^{16}O	dY/dO	^{4}He	^{16}O	dY/dO
9	1.59	0.17	9.35	1.43	0.06	24.2
				(2.80e-5)	(2.33e-8)	(1200)
15	2.10	1.05	2.00			
	(3.59e-4)	(1.79e-15)	(2.0e11)			
20				3.15	1.35	2.33
				(2.36e-4)	(2.54e-10)	(9.3e5)
25	2.57	3.76	0.68			
	(2.13e-3)	(2.06e-13)	(1.0e10)			
40	5.32	7.57	0.70	6.01	5.94	1.01
	(5.48e-2)	(4.09e-8)	(1.3e6)	(0.33)	(2.42e-3)	(136)
60	3.37	16.90	0.20	8.97	12.80	0.70
	(4.11e-2)	(8.88e-8)	(4.6e5)	(1.21)	(5.48e-5)	(2.2e4)
85	7.09	26.20	0.27	16.80	12.30	1.37
	(1.78)	(5.98e-5)	(3.0e4)	(20.0)	(3.02)	(6.62)
IMF integrated						
S55†			1.39			2.82
MS79‡			2.14			4.18
IMF integrated, with 'realistic' fate¶ for the stars						
S55			2.36			5.16
MS79			3.51			7.28

† Salpeter (1955)
‡ Miller & Scalo (1979)
¶ Heger *et al.* (2003)

with an IMF and get a mean value for a first burst of primordial stars. For this, we use the following formula:

$$\frac{\mathrm{dY}}{\mathrm{dO}} = \frac{\int_{M_\mathrm{down}}^{M_\mathrm{up}} \mathrm{dY}\ \Phi(M)\ \mathrm{d}M}{\int_{M_\mathrm{down}}^{M_\mathrm{up}} \mathrm{dO}\ \Phi(M)\ \mathrm{d}M}$$

where $\Phi(M) = AM^{-(1+x)}$ is the IMF. Since we consider only massive stars, we use $M_\mathrm{down} = 9\,M_\odot$ and $M_\mathrm{up} = 120\,M_\odot$.

The results are given in the middle panel of Table 1. Depending on the IMF used, the results change because different mass domains are favoured. Compared to Salpeter's, the slope $x = 2.30$ (for $M > 10\,M_\odot$) of Miller & Scalo is steeper and favours the lowest masses, leading to a higher value of dY/dO. The case of Pop III stars seems very peculiar, lower dY/dO values than the case of $Z = 10^{-8}$ stars. It reflects the peculiarities of the yields commented in section 2.2. When the metallicity grows slightly, the nucleosynthesis changes, and even with a metallicity as low as $Z = 10^{-8}$, the stars present a higher dY/dO value. The 'wind-only' case leads to extremely high dY/dO values.

Now let us take into account the 'realistic' fate of the star as determined by Heger *et al.* (2003). According to these authors, all stars with M_α† between 9 and 40 $M_\odot$ are supposed to end their life by collapsing into a black hole, without a supernova explosion. For such stars, the only contribution to the chemical enrichment of the Universe would

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† M_α, the He core mass at the end of a star's evolution, is the mass coordinate at which the hydrogen abundance drops below 10^{-3}.

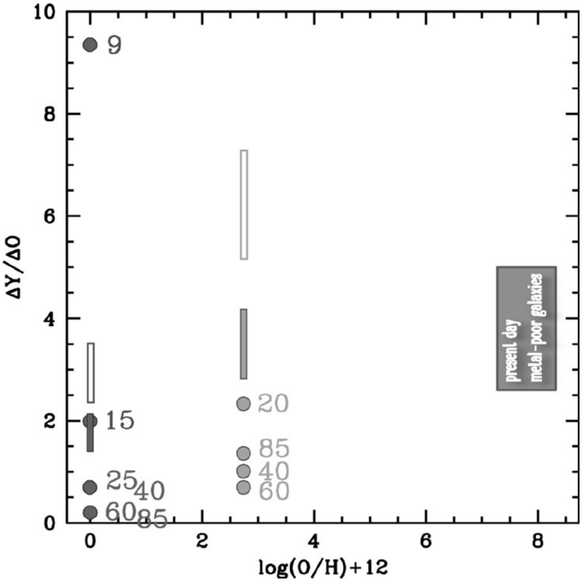

Figure 2. ΔY/ΔO values obtained with the total yields of the models as a function of the oxygen abundance: $Z = 0$ models (dark grey) and $Z = 10^{-8}$ (light grey). The IMF integrated values are given as a filled rectangle (range of values between S55 and MS79), and the ones obtained by taking into account the supposed fate of the models are shown with an empty rectangle. The range of values for the most metal-poor HII regions observed in the present-day Universe is also shown (data from Olive & Skillman 2004, Izotov *et al.* 2007 and Peimbert *et al.* 2007).

be made by the winds they experienced during their life. At $Z = 0$ the 25, 40, and 60 $M_\odot$ come into this category. At $Z = 10^{-8}$ the 40, 60, and 85 $M_\odot$ are concerned. Using these limits, we can compute more realistic dY/dO stellar ratios, which are given in the bottom panel of Table 1. Because of the high He and low O content of the winds, the dY/dO is much larger in this mixed case (i.e. winds+SN yields for stars with He core mass below $9 M_\odot$ and only winds above that value).

4. Discussion

Here we computed the expected ΔY/ΔO ratio from a generation of Z=0 and ultra metal poor (Z=10^{-8}) massive stars. The stellar values presented here give the starting point for the further evolution of the ΔY/ΔO ratio. With time, the ΔY/ΔO ratio will increase thanks to the contribution to the helium of intermediate and low-mass stars. The evolution of ΔY/ΔO will depend on the star formation history, IMF and selective outflows of the particular galaxy under study.

We show how the initial ΔY/ΔO obtained from the first stars depend upon the fate of these stars. If the most massive stars do contribute to the chemical enrichment only via their stellar winds, the expected ΔY/ΔO ratio is larger due to the high helium and low oxygen content of the stellar winds. Under the hypothesis that all massive Z=0 stars ended up into black holes, contributing to the chemical enrichment only via their stellar winds, we get unrealistic high ΔY/ΔO ratios (due to a very low contribution to oxygen). A mixed scenario where, even at Z=0, only stars with helium core mass between 9 and 40 $M_\odot$ do implode directly as black holes seems more likely.

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