EVOLUTION OF THE FIRST STELLAR GENERATIONS

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Abstract. Although the theoretical study of very low metallicity ($Z$) and metal–free stars is not new, their importance has recently greatly increased since two related fields have been developing rapidly. The first is cosmological simulations of the formation of the first stars and of the reionisation period. The second is the observations of extremely metal poor stars. In this paper, we present pre–supernova evolution models of massive rotating stars at very low $Z$ ($Z = 10^{-8}$) and at $Z = 0$. Rotation has a strong impact on mass loss and nucleosynthesis. Models reaching break–up velocities lose up to ten percents of their initial mass. In very low $Z$ models, rotational and convective mixing enhances significantly the surface content in carbon, nitrogen and oxygen (CNO) when the star becomes a red supergiant. This induces a strong mass loss for stars more massive than about 60 $M_\odot$. Our models predict type Ib,c supernovae and gamma–ray bursts at very low $Z$. Rotational mixing also induces a large production of CNO elements, in particular of primary nitrogen. The stellar wind chemical composition is compatible with the most metal–poor star known to date, HE 1327–2326, for CNO elements. Our models reproduce the early evolution of nitrogen in the Milky Way.

1 Physics and models at very low metallicities

What is the difference between very low $Z$ stars compared to solar metallicity stars? Lower $Z$ stars are more compact due to lower opacities. For example, the radius of a 20 $M_\odot$ star at $Z = 10^{-8}$ is about 1/4 of a 20 $M_\odot$ star at solar metallicity. It is also more difficult for very low $Z$ stars to reach the red supergiant (RSG) stage.

For metal–free stars ($Z \lesssim 10^{-10}$), the CNO cycle cannot operate at the start of H–burning. At the end of its formation, the star contracts until it starts He–
burning because the pp–chains cannot balance the effect of the gravitational force. Once enough carbon and oxygen are produced, the CNO cycle can operate and the star behaves like stars with $Z > 10^{-10}$ for the rest of the MS. Shell H–burning still differs between $Z > 10^{-10}$ and metal–free stars.

Due to fragmentation and cooling properties of metal–free gas, the first stars formed are thought to have been more massive than solar metallicity stars but by how much and for how long is still debated (Bromm and Larson, 2004; Schneider et al., 2006; Silk and Langer, 2006). In particular, the nucleosynthetic products of pair–instability SNe are not seen at the surface of extremely metal poor stars observed in the halo of our galaxy (Chieffi and Limongi, 2004; Heger and Woosley, 2002; Umeda and Nomoto, 2005).

Since mass loss depends on metallicity one expects to have much weaker winds at very low $Z$. However, the important point is to know which elements contribute the most to opacities and mass loss. Are these the iron group elements or light elements like CNO? In this work, it was assumed that all elements have the same importance. Theoretical studies have started answering this question (Vink et al., 2001; Vink and de Koter, 2005; van Loon, 2006) and this topic will be studied further in a future work.

The stellar evolution code used to calculate the stellar models is described in detail in Hirschi et al. (2004). Convective stability is determined by the Schwarzschild criterion. Convection is no longer treated as an instantaneous mixing but as a diffusive process from oxygen burning onwards. The overshooting parameter is 0.1–0.2 $H_P$ for H– and He–burning cores and 0 otherwise. The reaction rates are taken from the NACRE (Angulo et al., 1999) compilation. The mass loss is proportional to the square root of the metallicity. It is also dependent on the surface rotation velocity. The centrifugal force is included in the structure equations. The processes taken into account, which induce transport and mixing of angular momentum and matter, are meridional circulation and dynamical and secular shears.

Stellar evolution models studying the metallicity dependence were calculated (Hirschi, 2006; Meynet et al., 2006). In addition, two grids of models were calculated, one for metal–free stars (Ekström et al., 2006) and one for very low $Z$ stars at $Z = 10^{-8}$, which corresponds to the second stellar generation (Hirschi, 2006). The initial velocity of the models range between 500 and 800 km s$^{-1}$ and were chosen such that the angular momentum (and ratio of the initial velocity to the critical velocity) of the models are similar to solar metallicity models with an initial velocity of 300 km s$^{-1}$. The fact that stars are much more compact at very low $Z$ explains why initial surface velocities are higher at very low $Z$. The choice of velocity is supported by the fact that our models can reproduce the evolution of the N/O ratio (See Sect. 3.2).

2 Evolution at very low metallicities

The standard picture is that very low $Z$ and metal–free stars do not lose any mass before they collapse. Rotation however changes this picture. First, very low $Z$ stars reach break–up velocities (centrifugal force added to the radiative force balancing the gravitational force) during the main sequence. Second, rotational
and convective mixing enriches the surface in primary CNO elements and therefore enhances mass loss. Metal–free models reach break–up velocities and lose between 1 (25 $M_\odot$) and 10 percents (200 $M_\odot$) of their initial mass. Note that this fraction may be higher in more massive stars. In metal–free models, the surface does not become enriched significantly in CNO elements before the end of He–burning and the second effect cited above is not important. However, models at $Z = 10^{-8}$ experience a strong enrichment in primary CNO and lose a large fraction of their initial mass for masses larger than about 60 $M_\odot$. The surface enrichment starts when the model enters the RSG stage and the surface metallicity becomes almost solar for CNO elements. Since we considered that all elements are important for mass loss, the mass loss is very high during the rest of the RSG stage. Figure 1 (left) shows the structure evolution of the 85 $M_\odot$ model. The top solid line represents the total mass of the model. The model loses about 10 percents of its initial mass due to the break-up phenomenon during H–burning and then more than half of its initial mass during the RSG stage. This model produces a WO–type WR star and retains enough angular momentum in its core (Fig. 1 right) to produce a gamma–ray burst (GRB) via the collapsar model. Therefore, from the second stellar generation, our models predict important mass loss and SNIc–GRB events. This is in stark contrast with the standard picture where this model would
The empty triangles and the red stars correspond to the observed surface abundances of G77-61 (Plez and Cohen, 2005) and to the new (3D/NLTE corrected) estimates for HE1327-2326 (Frebel et al., 2006), respectively. These are both unevolved stars. The abundances of HE1327-2326 are best reproduced by the wind composition of the $40 \, M_\odot$, diluted by a factor 600 with pristine gas. This figures are taken from Hirschi (2006).

Rotationally induced mixing has an important impact on nucleosynthesis. Carbon and oxygen produced into the He–burning core are mixed in the H–burning shell and large amounts of primary nitrogen are produced. At very low $Z$, rotationally induced mixing may increase the nitrogen production by a factor 1000 or more. Part of the nitrogen is transformed into $^{22}$Ne and other intermediate mass elements via double alpha capture during shell He–burning. $^{22}$Ne is a neutron source for s–process in massive stars. In metal–free stars, s–process is inefficient because it has to start from carbon. However, in very low $Z$ stars, small amounts of iron group elements are present and s–process may produce interesting results since there is a high neutron to seed ratio. We will calculate s–process nucleosynthesis in future studies. In this section, we compare our models to observations of extremely metal poor (EMP) stars.

### 3.1 Carbon–rich EMP stars

About one quarter of EMP stars are carbon rich. One quarter of the carbon–rich EMP stars are thought to have been enriched by a weak s–process probably
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Fig. 3. Upper panel: Solar vicinity diagram log(N/O) vs. log(O/H)+12. Lower panel: Solar vicinity diagram log(C/O) vs. log(O/H)+12. The symbols are observations (Spite et al., 2005; Israeli et al., 2004; Akerman et al., 2004; Nissen, 2003). The black dashed line represents the chemical evolution model including the very low Z stellar yields. It fits both the evolution of N/O and C/O. This figure is taken from Chiappini et al. (2006).

taking place in massive stars (Ryan et al., 2005). The most metal poor star known to date ([Fe/H]~5.5), HE1327-2326, belongs to this last group. It is thought that its material has been enriched by only one or a few massive stars. It is therefore possible to compare directly the chemical output of our models to such a star. Figure 2 shows that the best fit for this star is obtained by diluting the composition of the 40 $M_\odot$ models at $Z = 10^{-8}$ by a factor 600 within interstellar medium (ISM) gas. In this scenario, HE1327-2326 is a third generation star. First, a metal–free star polluted the ISM to very low $Z$. Then a second generation star, like the 40 $M_\odot$ model at $Z = 10^{-8}$, polluted (only through its stellar wind) the ISM, out of which HE1327-2326 formed.

3.2 Primary nitrogen

The stellar yields of the very low $Z$ stars were used in a galactic chemical evolution model (Chiappini et al., 2006). The evolution of CNO elements is shown in Fig. 3. The previous models (solid black line) clearly underproduced nitrogen at very low metallicities. Using our models at $Z = 10^{-8}$, the evolution of nitrogen for log(O/H)+12 < 7 (or [Fe/H]< −3) is much better reproduced (black dashed line).
Our models also predicted an increase of the C/O ratio towards very low metallicities (Fig. 3 lower panel), which also fits the observations. These results give further support to the idea that stars at very low metallicities had high surface rotational velocities, of the order of 500-800 km s$^{-1}$.

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