Mass loss and very low-metallicity stars

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Abstract. Mass loss plays a dominant role in the evolution of massive stars at solar metallicity. After discussing different mass loss mechanisms and their metallicity dependence, we present the possibility of strong mass loss at very low metallicity. Our models at $Z = 10^{-8}$ show that stars more massive than about 60 $M_\odot$ may lose a significant fraction of their initial mass in the red supergiant phase. This mass loss is due to the surface enrichment in CNO elements via rotational and convective mixing. Our 85 $M_\odot$ model ends its life as a fast rotating WO type Wolf-Rayet star. Therefore the models predict the existence of type Ic SNe and long and soft GRBs at very low metallicities. Such strong mass loss in the red supergiant phase or the $\Omega\Gamma$-limit could prevent the most massive stars from ending as pair-creation supernovae.

The very low metallicity models calculated are also very interesting from the nucleosynthesis point of view. Indeed, the wind of the massive star models can reproduce the CNO abundances of the most metal-poor carbon-rich star known to date, HE1327-2326. Finally, using chemical evolution models, we are able to reproduce the evolution of CNO elements as observed in the normal extremely metal poor stars.

Keywords: Massive stars, mass loss, rotation
PACS: —

INTRODUCTION

The first generations of stars took part in the re-ionisation of the universe at the end of the dark ages (roughly 400 million years after the Big Bang). They are therefore tightly linked to the formation of the first structures in the universe and can provide valuable information on the early evolution of the universe. The first stars are thought to be more massive than solar metallicity stars (Bromm & Larson, 2004; Schneider et al., 2006) and mass loss is expected to be very low at very low metallicities. The logical deduction from these two arguments is that a large fraction of the first stars were very massive at their death ($>100 \, M_\odot$) and therefore lead to the production of pair-creation supernovae (PCSNe). Unfortunately, the first massive stars died a long time ago and will probably never be detected directly (see however Scannapieco et al., 2005; Tornatore et al., 2007). There are nevertheless indirect observational constraints on the first stars coming from observations of the most metal poor halo stars (Beers & Christlieb, 2005). These observations do not show the peculiar chemical signature of PCSNe (strong odd-even effects and low zinc, see Heger & Woosley, 2002). This probably means that at most only a few of these very massive stars ($>100 \, M_\odot$) formed or that they lost a lot of mass even though their initial metal content was very low. In this paper, we discuss the possibility of strong mass loss at very low metallicities.
MASS LOSS AND ITS DEPENDENCE ON METALLICITY

At solar metallicity ($Z_{\odot}$), mass loss has a crucial impact on the evolution of massive stars. It affects evolutionary tracks, lifetimes and surface abundances. It also determines the population of massive stars (number of stars in each Wolf-Rayet subtype for example). It influences the type of supernova at the death of the star (SNII, Ib, Ic) and the final remnant (neutron star or black hole). Mass loss releases matter, containing newly produced helium and metals (see Chieffi & Limongi, 2006, for the impact of mass loss on yields), and energy back into the interstellar medium in amounts comparable to supernovae (for stars above 30 $M_{\odot}$). Finally, it affects the hardness of the ionizing radiation coming from massive stars. It is therefore very important to understand mass loss in order to understand and model the evolution of massive stars.

The metallicity ($Z$) dependence of mass loss rates is usually described using the formula:

$$\dot{M}(Z) = \dot{M}(Z_{\odot})(Z/Z_{\odot})^\alpha$$

The exponent $\alpha$ varies between 0.5-0.6 (Kudritzki & Puls, 2000; Kudritzki, 2002) and 0.7-0.86 (Vink et al., 2001; Vink & de Koter, 2005) for O-type and WR stars respectively (See Mokiem et al., 2007, for a recent comparison between mass loss prescriptions and observed mass loss rates). Until very recently, most models use at best the total metal content present at the surface of the star to determine the mass loss rate. However, the surface chemical composition becomes very different from the solar mixture, due either to mass loss in the WR stage or by internal mixing (convection and rotation) after the main sequence. It is therefore important to know the contribution from each chemical species to opacity and mass loss. Recent studies (Vink et al., 2000; Vink & de Koter, 2005) show that iron is the dominant element concerning radiation line-driven mass loss for O-type and WR stars. In the case of WR stars, there is however a plateau at low metallicity due to the contributions from light elements like carbon, nitrogen and oxygen (CNO). In the red supengiant (RSG) stage, the rates generally used are still those of Nieuwenhuijzen & de Jager (1990). More recent observations indicate that there is a very weak dependence of dust-driven mass loss on metallicity and that CNO elements and especially nucleation seed components like silicon and titanium are dominant (van Loon, 2000, 2006; Ferrarotti & Gail, 2006). See van Loon et al. (2005) for recent mass loss rate prescriptions in the RSG stage. In particular, the ratio of carbon to oxygen is important to determine which kind of molecules and dusts form. If the ratio of carbon to oxygen is larger than one, then carbon-rich dust would form, and more likely drive a wind since they are more opaque than oxygen-rich dust at low metallicity (Höfner & Andersen, 2007).

In between the hot and cool parts of the HR-diagram, mass loss is not well understood. Observations of the LBV stage indicate that several solar masses per year may be lost (Smith et al., 2003) and there is no indication of a metallicity dependence. Chromospheric activity could also play a role in stars having surface temperature similar to the Sun. Thermally driven winds (Schröder & Cuntz, 2007) and pulsations are still other ways to lose mass.

The mass loss prescriptions used in the Geneva stellar evolution code are described in detail in Meynet & Maeder (2005). In particular, the mass loss rates depend on
metallicity as $\dot{M} \sim (Z/Z_\odot)^{0.5}$, where $Z$ is the mass fraction of heavy elements at the surface of the star. Models including the effects of both mass loss and especially rotation better reproduce the WR/O ratio and also the ratio of type Ib+Ic to type II supernova as a function of metallicity compared to non-rotating models, which underestimate these ratios (Meynet & Maeder, 2005). Rotating models also better reproduce the ratio of blue to red supergiants at low metallicities and surface enrichments in nitrogen during the main sequence (Maeder & Meynet, 2000).

**FIRST STELLAR GENERATIONS**

As we saw in the previous sections, mass loss plays a crucial role in the evolution of solar metallicity stars. In this section, we discuss the importance of mass loss on the evolution of the first stellar generations. The first stellar generations are different from solar metallicity stars due to their low metal content or absence of it. First, very low-$Z$ stars are more compact due to lower opacity. Second, metal free stars burn hydrogen in a core, which is denser and hotter due to the lack of initial CNO elements. This implies that the transition between core hydrogen and helium burning is much shorter and smoother. Furthermore, hydrogen burns via the pp-chain in shell burning. These differences make the metal free (first) stars different from the second or later generation stars! (Ekström et al., 2007). Third, mass loss is metallicity dependent (at least for radiation-driven winds) and therefore is expected to become very weak at very low metallicity. Finally, the initial mass function of the first stellar generations is expected to be top heavy below a certain threshold (Bromm & Loeb, 2003).

Mass loss is expected to be very weak. What could change this expectation? In order to investigate this question, models at very low and zero metallicity were calculated with the same physics as in the models able to reproduce many observables around solar metallicity. These models were computed with an initial total angular momentum similar or slightly higher to the one contained in solar metallicity models with average initial rotational velocities of $300 \text{ km s}^{-1}$. Models of metal free stars including the effect of rotation (Ekström et al., 2006) show that stars may lose up to 10% of their initial mass due to the star rotating at its critical limit (also called break-up limit). The mass loss due to the star reaching the critical limit is non-negligible but not important enough to change drastically the fate of the first generation stars.

The situation is very different at very low but non-zero metallicity (Meynet et al., 2006; Hirschi, 2007). The total mass of an $85 \, M_\odot$ model at $Z = 10^{-8}$ is shown in Fig. 1 by the top solid line. This model, like metal free models, loses around 5% of its initial mass when its surface reaches break-up velocities in the second part of the main sequence. At the end of core H-burning, the core contracts and the envelope expands, thus decreasing the surface velocity and its ratio to the critical velocity. The mass loss rate becomes very low again until the star crosses the HR diagram and reaches the RSG stage. At this point the convective envelope dredges up CNO elements to the surface increasing its overall metallicity. The total metallicity, $Z$, is used in this model (including CNO elements) for the metallicity dependence of the mass loss. Therefore depending on how much CNO is brought up to the surface, the mass loss becomes very large again. The CNO brought to the surface comes from primary C and O produced in He-burning.
Rotational and convective mixing brings these elements into the H-burning shell. A large fraction of the C and O is then transformed into primary nitrogen via the CNO cycle. Additional convective and rotational mixing is necessary to bring the primary CNO to the surface of the star.

![Structure evolution diagram of the 85 $M_\odot$ model at Z = 10^{-8}](image)

**FIGURE 1.** Structure evolution diagram of the 85 $M_\odot$ model at Z = 10^{-8}. Coloured areas correspond to convective zones along the lagrangian mass coordinate as a function of the time left until the core collapse. The top solid line shows the total mass of the star. The burning stage abbreviations are given below the time axis.

The strongest mass loss occurs in these models in the cooler part of the HR diagram. Dust-driven winds appear to be metallicity independent as long as C-rich dust can form. For this to occur, the surface effective temperature needs to be low enough (log(T_{eff}) < 3.6) and carbon needs to be more abundant than oxygen. Note that nucleation seeds (probably involving titanium) are still necessary to form C-rich dust. It is not clear whether extremely low-Z stars will reach such low effective temperatures. This depends on the opacity and the opacity tables used in our calculations did not account for the non-standard mixture of metals (high CNO and low iron abundance, see Marigo, 2002, for possible effects). It is interesting to note that the wind of the 85 $M_\odot$ model is richer in carbon than oxygen, thus allowing C-rich dust to form if nucleation seeds are present. There may also be other important types of wind, like Chromospheric activity-driven, pulsation-driven, thermally-driven or continuum-driven winds.

**NUCLEOSYNTHESIS AND CHEMICAL EVOLUTION**

**The most metal poor star known to date, HE1327-2326**

Significant mass loss in very low-Z massive stars offers an interesting explanation for the strong enrichment in CNO elements of the most metal poor stars observed in the halo of the galaxy (see Meynet et al., 2006; Hirschi, 2007). The most metal poor stars known to date, HE1327-2326 (Frebel et al., 2006) is characterised by very high N, C and O abundances, high Na, Mg and Al abundances, a weak s-process enrichment and
depleted lithium. The star is not evolved so has not had time to bring self-produced CNO elements to its surface and is most likely a subgiant. By using one or a few SNe and using a very large mass cut, Limongi et al. (2003) and Iwamoto et al. (2005) are able to reproduce the abundance of most elements. However they are not able to reproduce the nitrogen surface abundance of HE1327-2326 without rotational mixing. A lot of the features of this star are similar to the properties of the stellar winds of very metal poor rotating stars. HE1327-2326 may therefore have formed from gas, which was mainly enriched by stellar winds of rotating very low metallicity stars. In this scenario, a first generation of stars (PopIII) pollutes the interstellar medium to very low metallicities ([Fe/H] \sim -6). Then a PopII.5 star (Hirschi, 2005) like the 40 \, M_\odot model calculated here pollutes (mainly through its wind) the interstellar medium out of which HE1327-2326 forms. This would mean that HE1327-2326 is a third generation star. In this scenario, the CNO abundances are well reproduced, in particular that of nitrogen, which according to the new values for a subgiant from Frebel et al. (2006) is 0.9 dex higher in [X/Fe] than oxygen. This is shown in Fig. 2 where the abundances of HE1327-2326 are represented by the red stars and the best fit is obtained by diluting the composition of the wind of the 40 \, M_\odot model by a factor 600. When the SN contribution is added, the [X/Fe] ratio is usually lower for nitrogen than for oxygen. It is interesting to note that the very high CNO yields of the 40 \, M_\odot stars brings the total metallicity Z above the limit for low mass star formation obtained in Bromm & Loeb (2003).

**Primary nitrogen**

One of the most stringent observational constraint at very low Z is a very high primary $^{14}$N production. This requires extremely high primary $^{14}$N production in massive stars,
FIGURE 3. Chemical evolution model predictions of the N/O and C/O evolution, in the galactic halo, for different stellar evolution inputs. The solid curves show the predictions of a model without fast rotators at low metallicities. The dashed and dotted lines, almost overlapping, show the effect of including a population of fast rotators at low metallicities (the dotted line includes also the Z=0 fast rotators). For the data see Chiappini et al. (2006) and references therein.

About 0.1 $M_\odot$ per star ($\sim$0.15 $M_\odot$ used in the heuristic model of Chiappini et al., 2005). Upon the inclusion of the new stellar calculations of Hirschi (2007) for Z=10$^{-8}$ in a chemical evolution model for the galactic halo with infall and outflow, both high N/O and C/O ratios are obtained in the very metal poor metallicity range in agreement with observations (see details in Chiappini et al., 2006b). This model is shown in Fig. 3 (dashed magenta curve). In the same figure, a model computed without fast rotators (solid black curve) is also shown. Fast rotation enhances the nitrogen production by $\sim$3 orders of magnitude. These results also offer a natural explanation for the large scatter observed in the N/O abundance ratio of normal metal-poor halo stars: given the strong dependency of the nitrogen yields on the rotational velocity of the star, we expect a scatter in the N/O ratio which could be the consequence of the distribution of the stellar rotational velocities as a function of metallicity. Furthermore, the strong production of primary nitrogen is linked to a very active H-burning shell which contributes a large part of the total luminosity of the star. Hence, the energy produced by the helium core is reduced, reducing the efficiency of the $^{12}$C($\alpha,\gamma$)$^{16}$O reaction. As a consequence, less carbon is turned into oxygen, producing high C/O ratios. Although the abundance data for C/O is still very uncertain, a C/O upturn at low metallicities is suggested by observations (see Asplund, 2005, and references therein).

GAMMA-RAY BURSTS AND PAIR-CREATION SUPERNOVAE

Long and soft gamma-ray bursts (GRBs) have now been firmly connected to the death of type Ic supernovae (see Woosley & Bloom, 2006, for a recent review). In one of the most promising models, the collapsar model (Woosley, 1993), GRB progenitors must
form a black hole, lose their hydrogen rich envelope (become a WR) and retain enough angular momentum in their core during the pre-supernova stages. The strong mass loss discussed in the previous section makes it possible for single massive stars in the first stellar generations to become WR stars and even to retain enough angular momentum to produce a GRB (Hirschi, 2007). A wide grid of models around $Z_{\odot}$ shows that the fast rotating WO stars are produced only at metallicities equal to or lower than that of the LMC, in agreement with observations (Stanek et al., 2006). These models predict that, at low $Z$, one GRB occurs for every 10 core collapse supernovae, which is in the upper limit of what is allowed by the observations (see Hirschi et al., 2005, for more details). More recent models including the effects of magnetic fields (Yoon & Langer, 2005) show that another mechanism is possible to produce GRBs at low $Z$. This mechanism is the quasi-homogeneous evolution of very fast rotating massive stars. In this scenario, WR stars are produced by mixing and not mass loss. This last scenario however does not predict GRB at metallicities equal or higher than the SMC. This upper limit is too low compared to recent observations (Stanek et al., 2006). Taking into account the anisotropy in the wind of these fast rotating stars (Meynet & Maeder, 2007) may help reduce the discrepancy between models and observations. Note that the downward revision of solar metallicity (Asplund, 2005) may help resolve the problem.

Apart from GRBs, pair-creation supernovae (PCSNe) are very energetic explosions, which could be observed up to very high redshifts (Scannapieco et al., 2005). PCSNe are expected to follow the death of stars in the mass range between 100 and 250 $M_{\odot}$, assuming that they do not lose a significant fraction of their mass during the presupernova stages. Amongst the very first stars formed in the Universe, one expects to have PCSN due to the lack of mass loss and to the low opacity unable to stop the accretion on the star during its formation. However, the EMP stars observed in the halo of the galaxy do not show the peculiar chemical signature of PCSN (strong odd-even effect, see Heger & Woosley, 2002). This means that either too few or even no PCSN existed. One possible explanation to avoid the production of very low-$Z$ or metal free PCSNe is the strong mass loss in the cool part of the HR diagram due to the surface enrichment in CNO elements induced by rotational and convective mixing (see previous section) or the star reaching the $\Omega\Gamma$-limit (Ekström et al., 2007).

**CONCLUSION**

For the most massive models ($M > 60 M_{\odot}$), significant mass loss occurs during the red supergiant stage assuming that CNO elements are important contributors to mass loss. This mass loss is due to the surface enrichment in CNO elements via rotational and convective mixing. The models predict the production of WR stars for an initial mass higher than $60 M_{\odot}$ at $Z = 10^{-8}$ and our 85 $M_{\odot}$ model with $v_{\text{ini}} = 800 \text{ km s}^{-1}$ becomes a WO. Therefore SNe of type Ib and Ic are predicted from single massive stars at these low metallicities. The 85 $M_{\odot}$ model retains enough angular momentum to produce a GRB but the calculations did not include the effects of magnetic fields.

The stellar yields were calculated for light elements. These yields were used in a galactic chemical evolution model and successfully reproduce the early evolution of CNO elements (Chiappini et al., 2006). Finally, a scenario is proposed to explain the
CNO abundances of the most metal poor star known to date HE1327-2326.

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