Mem. S.A.It. Vol. 80, 151

**Memorie** della

# Presupernova evolution and explosion of massive stars: the role of mass loss during the Wolf-Rayet stage

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**Abstract.** We review the presupernova evolution, the explosion and mostly the nucleosynthesis of massive stars in the range $11 - 120$ $M_\odot$ of solar metallicity. Among the various sources of uncertainties in the models that still prevent a full understanding of the whole evolution of these objects, we will discuss the effect of the mass loss during the various Wolf-Rayet stages.

**Key words.** Stellar Evolution – Nucleosynthesis – Supernovae

## 1. Introduction

Massive stars, exploding as core collapse supernovae, play a pivotal role in the chemical and dynamical evolution of the galaxies. In fact, they (1) provide most of the mechanical energy input into the interstellar medium via strong stellar winds and supernova explosions (Abbott 1982) that, in turn, induce star formation and mixing of the interstellar matter; (2) generate most of the ultraviolet ionizing radiation and power the far-infrared luminosities of galaxies through the heating of the dust; (3) contribute significantly to the integrated luminosity of the unresolved galaxies (since they are very luminous objects); (4) synthesize most of the elements (with $4 < Z < 38$), especially those necessary to life; (5) produce some long-lived radioactive nuclei like, e.g., $^{26}$Al, $^{60}$Fe and $^{44}$Ti that provide important information on the ongoing nucleosynthesis in the Galaxy - these gamma ray emitters constitute the main observational targets of the gamma ray satellites presently in space, i.e., INTEGRAL, RHESSI, (Limongi & Chieffi 2006); (6) constitute the most energetic phenomenon yet found, emitting gamma-ray bursts as they collapse into black holes (Woosley 1993; Bethe & Wilson 1985). Moreover, the interiors of massive stars constitute invaluable laboratories with physical conditions not seen elsewhere in the Universe. For example, the neutrino burst occurring few seconds prior their explosion is one of the most powerful events in the Universe. Then, the understanding of the evolution and the explosion of massive stars is of paramount importance in many fields of astrophysics.

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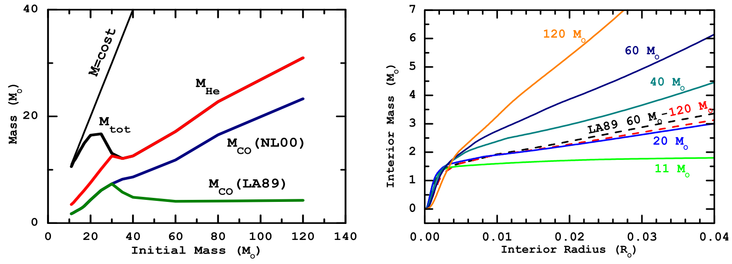


**Fig. 1.** Left panel: total mass, He core mass and CO core mass at core He exhaustion as a function of the initial mass for two different prescriptions of the mass loss rate during the WNE/WCO stages (see text). Right panel: M-R relation for a subset of massive star models at the presupernova stage. The solid lines refer to the NL00 models while the dashed lines to the LA89 models respectively.

We review the presupernova evolution, the explosion and mostly the nucleosynthesis of massive stars. Among the various sources of uncertainties in the models that still prevent a full understanding of the whole evolution of these objects, we will discuss the effect of the mass loss during the various Wolf-Rayet stages.

## 2. Presupernova evolution of massive stars: overview

The main presupernova evolutionary properties of massive stars presented in this paper are based on a set of models that have been computed by means of the latest version of the FRANEC, which is described in detail in Limongi & Chieffi (2006). Let us just mention here that mass loss is included following Vink et al. (2000) for the blue supergiant (BSG) phase, and de Jager et al. (1989) for the red supergiant (RSG) phase. For the Wolf-Rayet (WR) phase the mass loss rate provided by Nugis & Lamers (2000, NL00) has been adopted. The models have initial solar composition (Anders & Grevesse 1989) and range in mass between 11 and 120 $M_\odot$.

### 2.1. Core H and He burning and the effect of mass loss

The core H burning is the first nuclear burning stage and, in these stars, is powered by the CNO cycle. The strong dependence of this cycle on the temperature implies the presence of a convective core, that reaches its maximum extension just at the beginning of the central H burning and then recedes in mass as the central H is burnt. Mass loss is rather efficient during this phase and increases substantially with the luminosity of the star (i.e. the initial mass). In stars more massive than $\sim 40\ M_\odot$ it leads to a significant reduction of the total mass. The H exhausted core (He core) that forms at the central H exhaustion scales (in mass) directly with the initial mass. It is worth noting here that the presently adopted mass-loss rates in the BSG phase do not alter too much the initial mass-He core mass relation at the core H exhaustion, compared to the one obtained in absence of mass loss. On the contrary the size of the H convective core, which in turn may be affected by the overshooting and/or semiconvection, has a strong impact on the initial mass-He core mass relation and hence constitutes the greatest uncertainty in the computation of the core H burning phase.

At the core H exhaustion all the models move toward the red side of the HR diagram while the center contracts until the core He burning begins. The further fate of the models is largely driven by the competition between the efficiency of mass loss in reducing the H rich envelope during the RSG phase and the core He burning timescale. Stars initially less massive than 30 $M_\odot$ do not loose most of their H rich mantle hence they will become and eventually explode as RSGs. Vice versa stars initially more massive than this threshold value loose enough mass to explode as WR stars. In particular, we find that (1) stars with mass $M \geq 30\ M_{\odot}$ become WNL WR stars (i.e., stars with $10^{-5} < X_{sup} < 0.4$); (2) stars with mass $M \geq 35\ M_{\odot}$ become WNE WR stars (i.e., stars with $X_{sup} < 10^{-5}$ and $(C/N)_{sup} < 0.1$); (3) stars with mass $M \geq 40\ M_{\odot}$ become WC Wolf-Rayet star (i.e., stars with $X_{sup} < 10^{-5}$ and $(C/N)_{sup} > 10$).

It is worth noting that, once the full H rich mantle is lost, the further evolution of the stellar model depends on the actual He core mass. In fact, as the He core is reduced by mass loss the star feels this reduction and tends to behave like a star of a smaller mass (i.e., a star having the same actual He core mass). Hence, the reduction of the He core (i.e. the total mass) during the core He burning has the following effects: 1) the He convective core reduces progressively in mass, 2) the He burning lifetime increases, 3) the luminosity progressively decreases, 4) the $^{12}$C mass fraction at core He exhaustion is higher than it would be without mass loss and 5) the CO core at the core He exhaustion resemble that of other stars having similar He core masses independently on the initial mass of the star.

The importance of these effects, is very sensitive to the mass-loss rate during the Wolf-Rayet stage. Figure 1 (left panel) shows the CO core mass at core He exhaustion as a function of the initial mass for two different prescriptions of the mass loss during the WNE/WCO WR stages, i.e., the one provided by NL00 and the one provided by (Langer 1989, LA89), the second one being higher by about 0.2-0.6 dex on average compared to the first one. From the figure it is clear that while in the case of the NL00 mass-loss rate the CO core mass preserves a clear trend with the initial mass, in the case of the LA89 mass-loss rate all the models show a very similar structure that resembles that of a lower mass models. Another important difference between models computed with these two different prescriptions for the mass loss is the trend of the central $^{12}$C mass fraction at core He exhaustion with the initial mass. As for the CO core, also in this case, the LA89 models tend to behave like models having a similar final He core mass. Since the evolution of a massive star after core He burning is mainly driven by both the CO core mass and its chemical composition (mainly the C/O ratio), it is clear that the mass loss during the WR stage is fundamental in determining the evolutionary properties of these stars during the more advanced burning stages and also their final fate (see below).

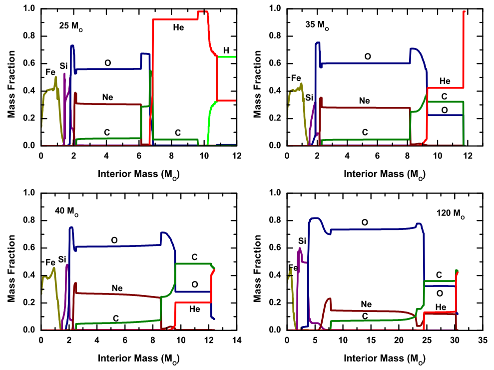


**Fig. 2.** Presupernova distribution of the most abundant chemical species for a selected number of NL00 massive star models.

### 2.2. Advanced burning stages

The evolution of the star during the advanced burning stages is mainly driven by the size and the composition ($^{12}$C/$^{16}$O) of the CO core. The CO core mass defines the thermodynamical history of the center, while $^{12}$C and $^{16}$O constitute the basic fuel for all the following burning stages. In general each burning stage, from the C burning up to the Si burning, occurs first at the center and then, as the fuel is completely burnt, it shifts in a shell. The nuclear burning shell, then, may induce the formation of one of more successive convective zones, that can partially overlap. The general trend is that the number of convective shells scales inversely with the mass size of the CO core.

The complex interplay among the shell nuclear burnings and the timing of the convective zones determines in a direct way the distribution of the chemical composition and the mass-radius (M-R) relation of the star at the presupernova stage (the relevance of the M-R relation for the explosive nucleosynthesis is discussed in the next section). In general, the more efficient is the nuclear burning (i.e., the higher is the $^{12}$C mass fraction left by core He burning), the higher is the number of the convective zones and the earlier is their formation, the slower is the contraction of the CO core and the shallower is the final M-R relation. This means that the higher is the mass of the CO core, the more compact is the structure at the presupernova stage. In general the mass of the CO core scales directly with the mass, but if the mass loss is so strong to significantly reduce the He core during core He burning, this scaling could not be preserved anymore (Fig. 1). The different scaling of the CO core mass with the initial mass directly reflects on the scaling between the initial mass and the final M-R relation. Figure 1 (right panel) clearly shows that for the NL00 models the larger is the initial mass the more compact is the presupernova structure while, on the contrary, all the LA89 models have a very similar M-R relation at the presupernova stage. This is the consequence of the fact that the NL00 mass loss preserves a direct scaling between the initial mass and the CO core mass while, on the contrary, the LA89 mass loss is so strong that all the LA89 models converge toward a very similar structure. By the way, all the LA89 models have a CO core mass similar to that of the 20 $M_\odot$ computed with the NL00 mass loss. As a consequence all the LA89 models develop a final M-R relation close to that of the 20 $M_\odot$ NL00 model.

The distribution of the most abundant chemical species at the presupernova stage is shown in Fig. 2 for some selected NL00 models. The 25 $M_\odot$ can be taken as representative of all the models in which the mass loss does not play a crucial role. On the contrary, the effect of mass loss is readily evident in the more massive stars. In general the presupernova star consists of an iron core of mass in the range between $\sim$ 1.2 and $\sim$ 1.8 $M_\odot$, the higher is the mass of the star the higher is the iron core mass, surrounded by active burning shells located at the base of zones loaded in the main products of silicon, oxygen, neon, carbon, helium and hydrogen burnings, i.e., the classical "onion structure". Thus, each zone keeps memory of the nucleosynthesis produced by the various central and/or shell burnings occurring either in a radiative environment or in a convective zone.

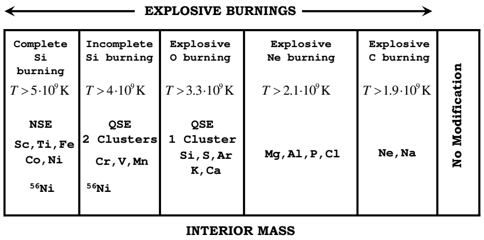


**Fig. 3.** Schematic representation of the zones undergoing the various explosive burnings and their corresponding chemical composition .

## 3. Simulated explosion: explosive nucleosynthesis and initial mass-remnant mass relation. The role of mass loss

The chemical composition left by the hydrostatic evolution is partially modified by the explosion, especially that of the more internal zones. At present there is no self consistent hydrodynamical model for core collapse supernovae and consequently we are forced to simulate the explosion in some way in order to compute the explosive yields. The idea is to deposit a given amount of energy at the base of the exploding envelope and to follow the propagation of the shock wave that forms by means of a hydro code. The initial amount of energy is fixed by requiring a given amount of kinetic energy at the infinity (typically of the order of $10^{51}$ erg = 1 foe). The propagation of the shock wave into the exploding envelope induces compression and local heating and hence explosive nucleosynthesis. Zones heated up to different peak temperatures undergo different kind of explosive nucleosynthesis and hence will be characterized by different compositions (Fig. 3).

Whichever is the technique adopted to deposit the energy into the presupernova model (piston, kinetic bomb or thermal bomb), in general the result is that some amount of material (the innermost one) will fall back onto the compact remnant while most of the envelope

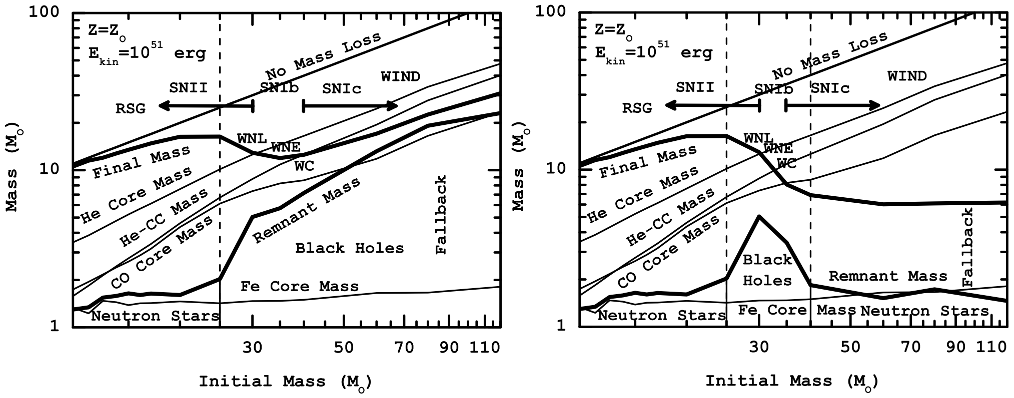


**Fig. 4.** Left Panel: characteristic masses as a function of the initial mass for the NL00 models. The final kinetic energy at infinity is set to $E_{kin}$ = 1 foe. Right Panel: same as left panel but for the LA89 models.

will be ejected with the desired final kinetic energy. The mass separation between remnant and ejecta is always referred to as the mass cut. This quantity strongly depends on the details of the explosive calculations, i.e., the mass location and the way in which the energy is deposited, the inner and the outer boundary conditions, and so on, hence it constitutes the most uncertain and free parameter in the explosive nucleosynthesis calculations for core collapse supernovae. The mass cut strongly affects not only the chemical yields of all those isotopes that are produced in the innermost zones of the exploding mantle, mainly $^{56}$Ni and also all the iron peak elements (Fig. 3), but also the relation between the initial mass and the final remnant mass, i.e., which is the mass limit or the mass interval between stars forming neutron stars and stars forming black holes after the explosion.

Figure 4 (left panel) shows the the initial-final mass relation for the NL00 models, in the assumption that the ejecta have 1 foe of kinetic energy at infinity. This choice (i.e., $E_{kin}$ = 1 foe for all the models) implies that in stars with masses above 25-30 $M_{\odot}$ all the CO core, or a great fraction of it, fall back onto the compact remnant. Such a behavior is the consequence of the fact that the higher is the mass of the star the steeper is the mass-radius relation, i.e. the more compact is the structure, (Fig. 1, left panel), the higher is the binding energy and hence the larger is, in general, the mass falling back onto the compact remnant. As a consequence these stars would not eject any product of the explosive burnings, as well as those of the C convective shell, and will leave, after the explosion, black holes with masses ranging between 3 and 11 $M_{\odot}$. In Fig. 4 (left panel) the limiting masses that enter the various WR stages are also shown, i.e., WNL (30 $M_{\odot}$), WNE (35 $M_{\odot}$) and WC (40 $M_{\odot}$), as well as the limiting mass (30- 35 $M_{\odot}$) between stars exploding as Type II SNe and those exploding as Type Ib/c supernovae.

The behavior of the LA89 models is completely different because their binding energy is much smaller than their corresponding NL00 models due to the much smaller He core masses (Fig. 1). In this case, the choice of a final kinetic energy of 1 foe allows, even in the more massive stars, the ejection of a substantial amount of the CO core, and hence heavy elements, leaving neutron stars as remnants (Fig. 4, right panel).

The first products of the calculations described above are the yields of the various isotopes, i.e., the amount of mass of each isotope ejected by each star in the interstellar medium. The integration of these yields over an initial mass function (IMF) provide the chemical composition of the ejecta of a generation of massive stars. Figure 5 shows the production factors of all the elements obtained by assuming a Salpeter IMF ($dn/dm = km^{-2.35}$) provided by a generation of massive stars in the

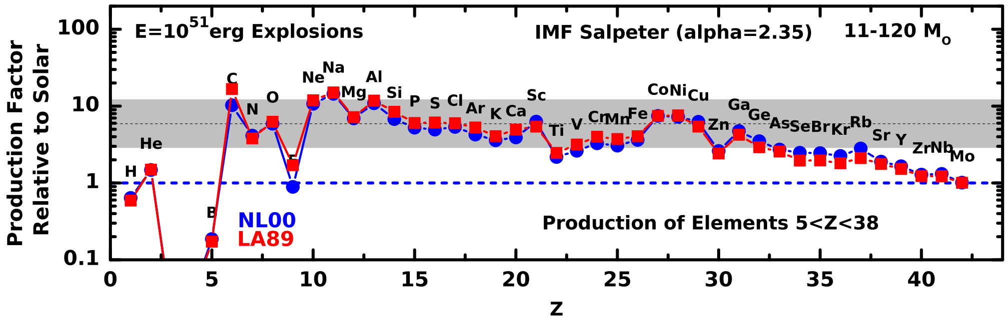


**Fig. 5.** Production factor of the elements from H to Mo for a generation of massive stars in the range 11-120 $M_\odot$ (NL00 blue filled circles, LA89 red filled squares) averaged over a Salpeter IMF. The horizontal black dashed line refers to the production factor of Oxygen, PF(O), and the shaded area corresponds to a difference less than factor of 2 with respect to PF(O).

range 11-120 $M_\odot$ for the two cases, i.e., NL00 and LA89. This figure clearly shows that, in both cases, these stars are responsible for producing all the elements with $4 < Z < 38$. Moreover, the majority of the elements preserve a scaled solar distribution relative to O. Other sources, like, e.g. AGB stars and Type Ia SNe, must contribute to all the elements that are under produced by massive stars (e.g., the iron peak elements and the s-process elements above Ge). In addition, since the main difference between the two set of yields is that in the NL00 case the contribution of stars with $M > 35\ M_\odot$ is severely suppressed, the similarity between the two set of production factors implies that these stars do not produce any specific signature on the relative distribution of the integrated yields.

The contribution of stars with $M \geq 35\ M_\odot$, to the total yield of each element is completely different between the NL00 and LA89 cases. In the NL00 case, these more massive stars produce roughly $\sim$ 60% of the total yields of C and N and about $\sim$ 40% of Sc and s-process elements. This is the result of the strong mass loss experienced by these stars that allows the ejection of these elements, synthesized during H (N) and He burning (C, Sc and s-process elements), before their destruction during the more advanced burning stages and/or during the explosion. The contribution of these stars to the intermediate mass and iron peak elements is negligible because of their large remnant masses. The adoption of the LA89 modifies substantially this result. In particular, in this case stars with $M \geq 35\ M_\odot$ contribute for $\sim$ 30% to the production of most of the elements and for $\sim$ 80%, $\sim$ 55% and more than $\sim$ 100% (this means that stars with $M < 35\ M_\odot$ destroy this element) to the production of C, N and F, respectively. The non negligible contribution to the majority of the elements is due to the rather small amount of fall back that allows the ejection of a substantial amount of elements produced in the innermost zones of the exploding mantle. The large contribution to C, N and F is due to the very efficient mass loss that preserves them from further destruction.

## References

Abbott, D. C. 1982, ApJ, 263, 723
Anders, E. & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Bethe, H. A. & Wilson, J. R. 1985, ApJ, 295, 14
de Jager, C. S. , Nieuwenhuijzen, H. & Lamers, H. J. G. L. M. 1989, A&A, 72, 259
Langer, N. 1989, A&A, 220, 135 (LA89)
Limongi, M. & Chieffi, A. 2006, ApJ, 647, 483
Nugis, T. & Lamers, H. J. G. L. M. 2000, A&A, 362, 295 (NL00)
Vink, J. S. et al. 2000, A&A, 362, 295
Woosley, S. E. 1993, ApJ, 405, 273