Presupernova evolution and explosion of massive stars

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Presupernova Evolution and Explosion of Massive Stars

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Abstract. We review our recent progresses on the presupernova evolution of massive stars in the range 11-120 $M_\odot$ of solar metallicity. Special attention will be devoted to the effect of the mass loss rate during the Wolf-Rayet stages in determining the structure and the physical properties of the star prior the supernova explosion. We also discuss the explosive yields and the initial mass-remnant mass relation in the framework of the kinetic bomb induced explosion and hence the contribution of these stars to the global chemical enrichment of the interstellar medium

1. Introduction

Massive stars, i.e. those stars exploding as core collapse supernovae, play a pivotal role in the chemical and dynamical evolution of the galaxies. In fact, among the other things, they provide most of the mechanical energy input into the interstellar medium via strong stellar winds and supernova explosions [1] and also synthesize most of the elements (with $4<Z<38$), especially those necessary to life. The interiors of massive stars, also, constitute invaluable laboratories with physical conditions not seen elsewhere in the universe. All these issues make the understanding of the evolution and the explosion of massive stars of paramount importance in astrophysics.

We review here our recent progresses on the presupernova evolution, the explosion and mostly the nucleosynthesis of massive stars. We mainly focus on the advanced evolutionary phases prior to the explosion, i.e. from the core He exhaustion up to the onset of the iron core collapse. However, since the advanced burning phases strongly depends on the evolutionary history of the star during the H- and He-burning stages, here we address only the aspects of these phases relevant for the further evolution of the star up to the explosion. In particular we discuss in some detail the effect of mass loss during H- and He-burning and its implications on the more advanced burning phases. The explosive nucleosynthesis as well as the contribution of massive stars to the global enrichment of the interstellar

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medium and their role in the chemical evolution of the galaxies is, on the contrary, described in some detail.

2. Stellar Models

The models presented in this paper are the ones discussed in [2] and the computations were done with the latest release of the stellar evolutionary code FRANEC (5.050218). In particular, the interaction between convection and local nuclear burning has been taken into account by the coupling together and the simultaneous solution of the set of equations controlling the local nuclear burning and those describing the convective mixing. The convective mixing is treated by means of a diffusion equation in which the diffusion coefficient is computed by means of the mixing-length theory. The nuclear network is the same as the one adopted in [3] while the nuclear cross sections have been updated whenever possible (see Table 1 in [2]). A moderate amount of overshooting of 0.2 H_P has been included in the calculation only for central H burning. Mass loss has been taken into account following the prescriptions of [4] for the blue supergiant phase (T_{eff}>12000 K) and of [5] for the red supergiant phase (T_{eff}<12000 K). The Wolf-Rayet (WR) phase has been followed in the Late Nitrogen rich phase (WNL) by adopting [6] and [7] in the following Early Nitrogen rich (WNE) and Carbon and Oxygen rich (WCO) Wolf-Rayet stages.

We asssume that the star enters the WR phase when Log(T_{eff})>4 and the surface H mass fraction is H_{surf}<0.4, and we adopt the following usual definitions for the various WR phases: WNL (10^{-5}<H_{surf}<0.4), WNE (H_{surf}<10^{-5} and $(C/N)_{surf}$<0.1), Carbon and Nitron rich (WNC - 0.1<$(C/N)_{surf}$<10), and WCO ($(C/N)_{surf}$>10).

3. Core H and He burning

The core H burning is the first nuclear burning stage and, in massive stars, it is powered by the CNO cycle. For these stars the central temperature is high enough (7.5<log T_c<7.8) for both the Ne-Na and the Mg-Al cycles to become efficient. The strong dependence of this cycle on the temperature implies the presence of a convective core, which 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 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 blue supergiant phase (BSG) 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 core H exhaustion all the models expand and move in the red portion of the HR diagram. At the same time the more internal zones contract until the core He burning is activated. The further fate of the models is largely driven by the competition between the efficiency of mass loss in reducing the H rich envelope and the core He burning timescale. In stars with initial mass M<30 $M_\odot$ mass loss is not so efficient hence these stars do not loose most of their H rich mantle. As a consequence they will likely explode as red supergiants (RSGs). On the contrary in stars with M>30 $M_\odot$ mass loss is efficient enough to induce the total ejection of the H rich envelope. These stars will eventually explode as WR stars. In particular, we find that (1) stars with initial mass $M \geq 30\ M_\odot$ become (and explode as) WNL stars; (2) stars with initial mass $M \geq 35\ M_\odot$ become (and explode as) WNE stars; (3) stars with initial mass $M > 40\ M_\odot$ become (and explode as) WC stars.

Once the full H rich mantle is lost, the further evolution of the stellar model depends on the actual He core mass. Stars initially less massive than the minimum mass that completely loses its H-rich mantle develop a central He burning within the He core that never recedes in mass; it either advances or, at least, remains constant in mass. In this case, the He convective core never recedes and the reason is that the conversion of He to C and O increases the opacity in the entire convective core so that its outer border is continuously pushed outward rather than inward. Hence, a strong chemical discontinuity forms at the border of the He convective core where the He abundance changes from roughly zero to roughly one at central He exhaustion. Hence, a He convective shell will form outside the maximum extension of the convective core in a region whose chemical composition is still the one left by H burning.

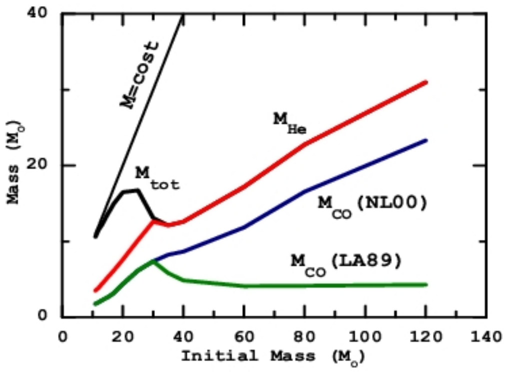

Figure 1. Total mass (black), He core mass (red) and CO core mass (blue for NL00 and grenn for LA89) at core He exhaustion as a function of the initial mass for two different prescription of the mass loss rate during the WNE/WCO stages (see text).

Vice versa, stars whose initial mass exceeds this threshold value not only lose their whole H-rich envelope but also a fraction of their He core mass. In this mass interval, therefore, central He burning occurs, partly or even completely, in the He core mass, which progressively decreases. Such an occurrence has a profound impact on the central He burning itself and, therefore, on all advanced burnings. As the He core mass decreases because of the mass loss, the central He burning readjusts on a physical structure and, hence, on a convective core size, which would compete for the current He core mass. Since the size of the convective core scales directly with that of the He core, the convective core recedes progressively in mass, leaving behind a He profile. In this case, a He convective shell will form in a region with a He profile whose steepness reflects the speed at which the He core mass has been eroded in He burning. In addition to that, the amount of carbon left in the He-exhausted core is affected by the mass loss because the central physical conditions readjust continuously to the ones proper for a star of progressively smaller He core mass. Since the C abundance left by He burning scales inversely with the He core mass, the smaller the final He core mass, the larger the abundance of C. The relevance of these effects, is very sensitive to the mass loss rate during the Wolf-Rayet stage.

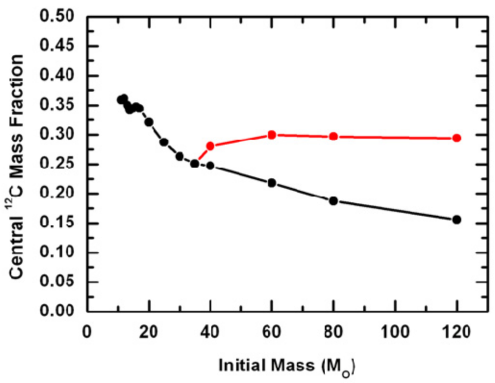

Figure 2. ^{12}C mass fraction at core He exhaustion as a function of the initial mass: the black line corresponds to NL00 models while the red line to LA89 models.

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 [6] (NL00) and the one provided by [7] (LA89), the second one being higher by about 0.2-0.6 dex on average compared to the first one. Inspection of the figure shows 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 develop a very similar structure that resembles that of a lower mass model. Moreover, Figure 2 shows that the ^{12}C left by over at core He exhaustion by the LA89 models is similar to that of the star with a similar CO core mass (in this case a 20 $M_\odot$). Since the evolution of a massive star after core He burning is mainly driven by both the CO core mass and its chemical composition (C and O constitute the basic fuel for all the further nuclear burning), it is clear that 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).

4. Advanced burning stages: C, Ne, O and Si burning

The evolution of a massive star during the advanced burning stages is mainly driven by the size and by the composition of the CO core. The CO core mass determines the thermodynamical history of the centre, while ^{12}C and ^{16}O constitute the basic fuel for all the following nuclear burning.

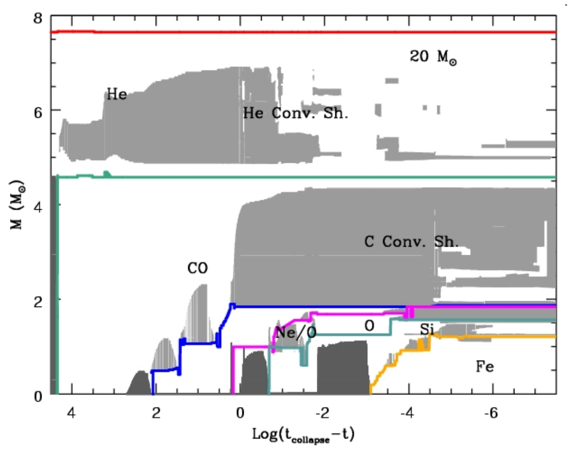

Figure 3. Convective history of a 20 $M_\odot$ model. The grey areas correspond to the convective regions. The solid line mark the nuclear burning shells.

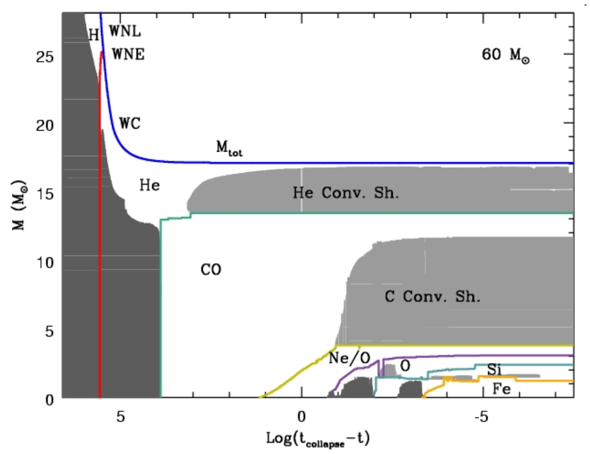

Figure 4. Convective history of a 60 $M_\odot$ model. The grey areas correspond to the convective regions. The solid line mark the nuclear burning shells.

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, which can partially overlap. The general trend is that the number of convective shells scales inversely with the mass size of the CO core (Figure 3 and Figure 4).

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). Figure 5 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

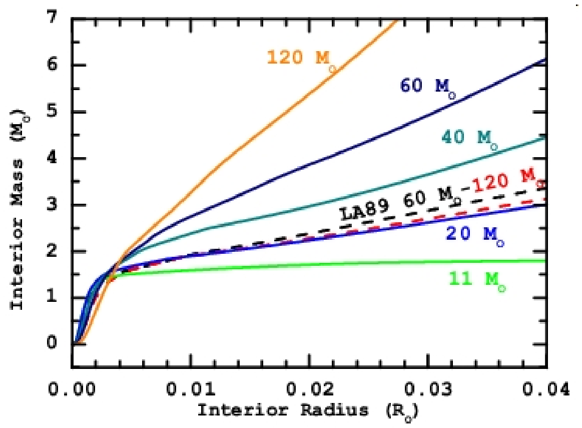

Figure 5. Mass-Radius relation for a subset of massive star models at the presupernova stage. The solid lines refer to the NL00 models while the dashed lines to the LA89 models.

(similar to that of a 20 $M_{\odot}$). The distribution of the most abundant chemical species at the presupernova stage is shown in Figure 6 for some selected NL00 models.

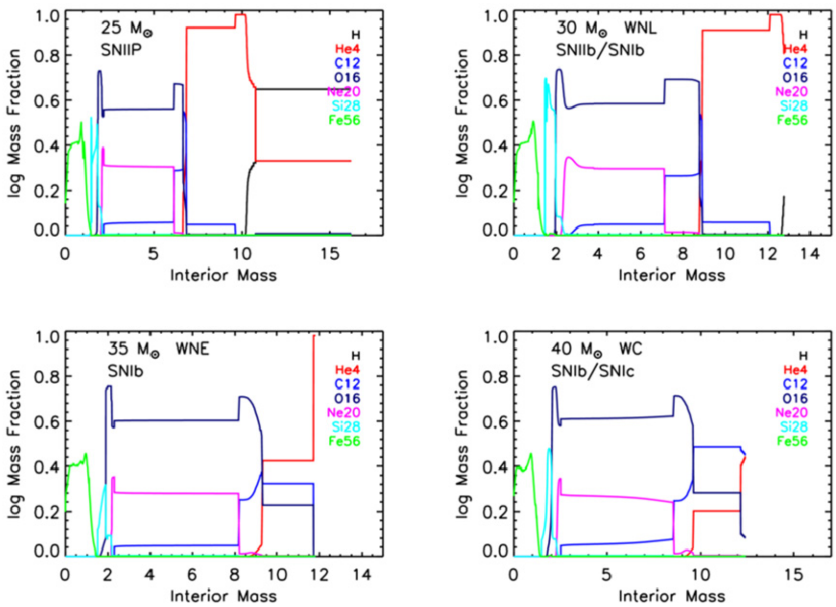

Figure 6. Presupernova distribution of the most abundant chemical species for a selected number of NL00 massive star models.

In the 25 $M_{\odot}$ the mass loss does not play a crucial role, most of the H rich envelope is retained and the star will eventually explode as SNII. On the contrary, the effect of mass loss is readily evident in the more massive stars that will explode as SNIIb, SNIb or SNIc depending on the efficiency of the mass loss in removing the H rich envelope as well as the He rich zones. In general the presupernova star consists of an iron core of mass in the range between 1.2 and 1.8 $M_{\odot}$, the higher is the mass of the star 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.

5. Explosive nucleosynthesis and initial mass-remnant mass relation

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, at present, explosive nucleosynthesis calculations are based on simulated explosions. The basic 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). 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 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, 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.

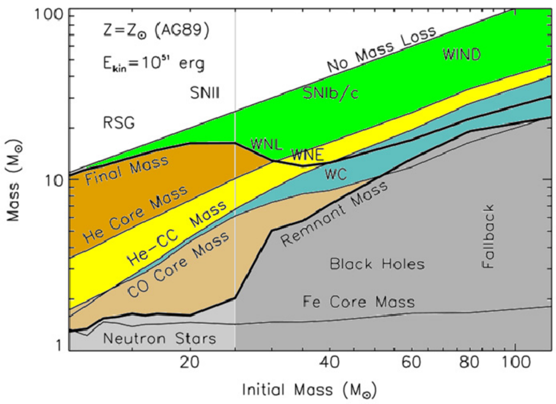

Figure 7. Characteristic masses as a function of the initial mass for the NL00 models. The final kinetic energy at infinity is set to Ekin=1 foe (see text).

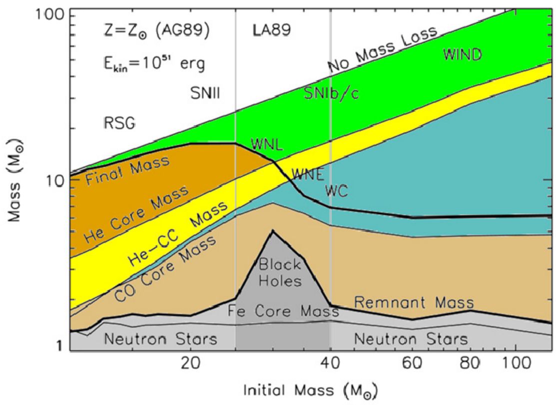

Figure 8. Same as Figure 7 but for the LA89 models.

Figure 7 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 (the explosions have been computed by means of the hydro code described in [2]). This choice implies that in stars with initial mass larger than 25-30 $M_\odot$ all the CO core, or a great fraction of it, fall back onto the compact remnant. This is due to 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) (Figure 5), 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 figure 7 are also shown the limiting masses that enter the various WR stages (WNL, WNE and WC) 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 (Figure 8) is completely different because their binding energy is much smaller than their corresponding NL00 models due to the much smaller He core masses (Figure 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.

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