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Massive stars: presupernova evolution and explosive nucleosynthesis ⋆,⋆⋆

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Abstract. We review the current status of the research for the presupernova evolution of massive stars and their related explosive nucleosynthesis. We also discuss in detail some observational diagnostics for solar and zero metallicity massive star models.

Key words. nuclear reactions, nucleosynthesis, abundances – stars: evolution – stars: interiors – stars: supernovae

1. Introduction

Massive stars, those massive enough to explode as supernovae, play a key role in many fields of astrophysics. They are crucial in determining the evolution of the galaxies because: 1) light up regions of stellar birth and hence induce star formation; 2) are responsible for the production of most of the elements (among which those necessary to life); 3) induce mixing of the interstellar medium through stellar winds and radiation; 4) leave, as remnant, exotic objects like neutron stars and black holes. Massive Population III Stars could play an important role in Cosmology because they contribute to 1) the reionization of the universe ad $z > 5$, 2) the production of massive black holes that could have been the progenitors of active galactic nuclei, 3) the pregalactic metal enrichment. Finally Massive Stars play an important role in the field of high energy astrophysics because 1) they are responsible for the production of some long-lived γ-ray emitter nuclei as ^{26}Al, ^{56}Co, ^{57}Co, ^{44}Ti and ^{60}Fe and 2) they are likely connected to the Gamma Ray Bursts.

As a consequence, the understanding of these stars, i.e., their presupernova evolution, their explosion as supernovae and especially their nucleosynthesis, is crucial for the interpretation of many astrophysical objects.

In spite of this astrophysical relevance there are only few groups producing theoretical presupernova models of massive

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stars and associated explosive nucleosynthesis whose latest set of models are presented by Limongi & Chieffi (2003) (LC03 hereinafter), Umeda & Nomoto (2002) (UN02 hereinafter) and Rausher et al. (2002) (RHHW02 hereinafter). In this review we will try to put in evidence the difficulties related to the computation of presupernova evolution of massive stars and the following explosive nucleosynthesis and we will outline the different approaches followed by these three groups to overcome such a problems. In the final section we will present some observational diagnostics that can serve as guidance to check the theoretical predictions.

2. Computation of presupernova evolution of massive stars: Nuclear Network, Convection and Input Physics

The computation of the presupernova evolution of massive stars requires the adoption of very extended nuclear network, a special treatment of the interaction between the two systems of equations describing the physical structure of the star and the chemical evolution of the matter, a time dependent convective mixing and the inclusion of adequate input physics.

2.1. Nuclear Network

The advanced burning stages of massive stars, i.e. those following the central He exhaustion, are characterized by the release of light particles (p, α, n) that, in the physical conditions of temperature and density typical of these evolutionary phases can be captured by almost every nuclei. Therefore the computation of the advanced burning stages of massive stars requires the adoption of a very extended nuclear network including lots of isotopes and nuclear reactions among which, all possible strong binary interactions involving a single neutron, proton, α-particle or photon in entrance or exit channel and all possibile links due to the weak interactions (e-capture and β-decays). In their last computations LC03 adopted a 300 isotopes network from neutrons to ^{98}Mo, UN02 a 240 isotopes network from neutron to ^{71}Ge while RHHW02 an adaptive 700-2200 isotopes network (depending weather during hydrostatic or explosive nucleosynthesis) from neutrons to Polonium.

2.2. Interaction between physical and chemical evolution systems

The structure and evolution of a star in spherical symmetry and lagrangean coordinate is usually described by a set of 4 equations describing the structure of the star, supplemented by N equations (where N is the number of isotopes included into the network) describing the chemical evolution of the matter due to the nuclear reactions (see Chieffi, Limongi & Straniero 1998 for more details). In H and He burnings these two systems of equations can be solved in two separate and subsequent steps because the quantities that in principle depend on both the physical and chemical variables show a very mild dependence on the chemical composition. Such an occurrence is not valid anymore during the more advanced burnings - in particular the nuclear energy generation rate is strongly dependent on temperature, density and chemical composition. As a consequence one could not be allowed to solve separately the systems of equations but, on the contrary, should couple together and solve simultaneously all the equations. Such a full coupling, however, requires lot of computer time and memory hence the three abovementioned groups followed three different approaches to overcome the problem. LC03 developed a numerical technique that allows the full coupling and simultaneously solution of all the equations without the need of huge memory and computer time. Both UN02 and RHHW02 solve separately the two systems; the first group uses a tabulated energy generation rate as a function of temperature, density and electron fraction while the second one uses a very small

Table 1. Main presupernova evolutionary properties of a 25 $M_\odot$ star of solar composition

Phase	Time	L_ν	T_c (^oK)	ρ_c (g/cm^3)	Fuel	Main Prod.	Sec.Prod.	MainUncertainties
H	$\sim 10^7$yr		$\sim 7 10^7$	~ 10	^{1}H	^{4}He	^{13}C,^{14}N ^{17}O,^{23}Na ^{26}Al	Extension of the Convective Core Semiconvection
He	$\sim 10^6$yr		$\sim 2 10^8$	$\sim 2 10^3$	^{4}He	^{12}C ^{16}O	^{18}O,^{22}Ne $s-proc.$	Convection Semiconvection $^{12}C(\alpha,\gamma)^{16}O$
C	$\sim 10^3$yr	$\sim L_{ph}$	$\sim 8 10^8$	$\sim 10^6$	^{12}C	^{20}Ne, ^{23}Na ^{24}Mg, ^{27}Al	^{25}Mg $s-proc.$	Abundance of ^{12}C $\rightarrow^{12}C(\alpha,\gamma)^{16}O$
Ne	~ 3yr	$\sim 10^3 L_{ph}$	$\sim 1.6 10^9$	$\sim 10^7$	^{20}Ne	^{20}Ne ^{24}Mg	^{29}Si,^{30}Si	Abundance of ^{12}C $\rightarrow^{12}C(\alpha,\gamma)^{16}O$
O	~ 0.3yr	$\sim 10^5 L_{ph}$	$\sim 1.8 10^9$	$\sim 10^7$	^{16}O	^{28}Si, ^{32}S ^{36}Ar, ^{40}Ca	Cl, Ar K, Ca	Weak Interactions Coupling of the systems Time Dep. Convection
Si	~ 5days	$\sim 10^5 L_{ph}$	$\sim 2.5 10^9$	$\sim 10^8$	^{28}Si ^{30}Si	^{54}Fe ^{56}Fe ^{55}Fe	Ti, V, Cr Cr, Mn Co, Ni	Weak Interactions Coupling of the systems Time Dep. Convection Coulomb Corrections

reaction network for the energy generation and carry a larger nuclear network in a separate step (postprocessing).

2.3. Convection

During the advanced burning stages of massive stars a first problem connected with convection is the inability of convective mixing to fully homogenize the matter within a single timestep. Such an occurrence appears when the mixing timescale ($\tau_{\rm mix}$) becomes of the same order of magnitude of the timestep (Δt). In this case one should take into account for a time dependent mixing. A diffusion equation is used by all the three groups to properly treat such a phenomenon. The only uncertain quantity is the diffusion coefficient that is usually evaluated by means of the mixing-length theory ($D = 1/3 v_c l$).

The other problem that arises when trying to compute the advanced burning stages of massive stars is the need to properly treat the interaction between the local burning and the convective mixing. Such a problems occurs when the mixing turnover time $\tau_{\rm mix}$ becomes of the same order (or even lower) than the nuclear burning timescale $\tau_{\rm nuc}$. To overcome such a problem LC03 have developed a numerical technique, based on the iterative solution of the sparse matrices, that allows for the full coupling of convection to the system of equations describing the chemical evolution of the matter due to the nuclear reactions. On the contrary, both UN02 and RHHW02 carry out the nuclear burning first and then mix the stellar zones in a separate and subsequent step in the converged model.

Last problem is the choice of the stability criterion for convection. Both LC03 and UN02 adopt the Schwarzshild criterion and do not take into account neither Semiconvection nor mechanical overshooting. The only difference between the two groups is that LC03 adopt the Ledoux criterion for convection for the H convective shell that forms toward the end of central H burning. At variance with LC03 and UN02, RHHW02 adopt the Ledoux criterion for convection and include some amount of semiconvection and mechanical overshooting in their computations. The choice for all these convection parameters (stability criterion, semiconvection, overshooting) should be based on the observations. Unfortunately, no single choice of the convection parameters is able to explain all the available observations (Langer & Maeder 1995).

3. The hydrostatic evolution of a typical massive star

All stars more massive than ~ 12 M$_\odot$ complete all the nuclear burning stages, from H to Si burning, in hydrostatic equilibrium and in non degenerate conditions prior to collapse.

In general the presupernova evolution of a massive star is characterized by a complex interplay among: 1) the nuclear energy generation, 2) the neutrino losses (mainly due to pair annihilation) and 3) location and timings of numerous episodes of convective burnings.

Table 1 summarizes the main evolutionary properties of a typical massive star, i.e. a 25 M$_\odot$ of initial solar chemical composition, from the H burning to the onset of the iron core collapse. For each burning stage (Col. 1) the various columns of Table 1 refer to: the nuclear burning lifetime (Col.2), the neutrino luminosity (Col.3), the central temperature (Col.4), the central density (Col.5), the fuel for nuclear burning (Col.6), the main and secondary products of nuclear burning (Col.7 and Col.8 respectively) and the main theoretical uncertainties (Col.9).

Table 2. Induced explosion parameters

LC03	UN02	RHHW02
Prompt	Delayed (0.5 s)	Delayed (0.45 s)
Piston	Thermal Bomb	Piston
~ 1 M$_\odot$	Fe core	Fe core
$\sim 1.2 10^{51}$ erg	$\sim 1.2 10^{51}$ erg	$\sim 1.2 10^{51}$ erg

4. Induced explosions and associated nucleosynthesis

A more quantitative prediction of the chemical composition actually ejected in the interstellar medium by a massive star after the explosion should rely on a self consistent treatment of the core collapse to central nuclear densities, the bounce and then the propagation of the shock wave through the exploding mantle. Unfortunately, the present modeling of core collapse supernovae does not yield to successful explosions yet. As a consequence the explosive nucleosynthesis calculations for core collapse supernovae are still based on explosions induced by injecting an arbitrary amount of energy in a (also arbitrary) mass location of the presupernova model and then by following the development of the blast wave by means of a hydro code. Such a scheme, however, requires some choices, reported in Table 2 for each group, about: 1) the kind of explosion (Row 2), i.e., prompt or delayed; 2) the way in which the blast wave is induced (Row 3), i.e., thermal bomb, kinetic bomb or piston; 3) the mass location where to inject the energy (Row 4); 4) the final kinetic energy at the infinity.

5. Observational diagnostics for solar and zero metallicity models

In this section we will present some possibile diagnostics that can be used to check the reliability of the theoretical yields of solar and zero metallicity massive star models.

5.1. Solar metallicity models

The yields provided by a generation of solar metallicity model stars should be used, in principle, to interpret the ejecta of a single core collapse supernova of similar initial metallicity or as an input data for galactic chemical evolutionary codes. Although there is no reason, in principle, to require that the ejecta of a generation of solar metallicity massive stars preserve the solar distribution (that is the result of a cumulative contribution of several generations of stars), it is generally assumed that the production factors (PFs) of a generation of solar metallicity massive stars are essentially flat. The PF of a given element/isotope is defined as the ratio between the amount of that element/isotope ejected by the star and the amount of that element/isotope that would be present in the ejecta if the ejecta would have the solar composition. As a consequence the requirement that the PFs are constant implies that the ejecta preserve the solar distribution. Such a requirement is based on the reasonable assumption that the average metallicity Z grows slowly and continuously compared to the evolutionary lifetimes of the stars that actually contribute to the enrichment of the environment. Hence the solar system distribution constitutes a very powerful observational diagnostic to test the reliability of the theoretical yields of a solar metallicity generation of massive stars.

Once the yields of a generation of massive stars are integrated over a Salpter mass function the mass of the star that mostly contribute to the enrichment of the interstellar medium is $\sim$ 25 $M_\odot$ (see LC03). Hence for sake of simplicity we have compared the PFs, obtained by means of the latest theoretical yields, for a solar metallicity 25 $M_\odot$ star model (i.e. LC03 and RHWW02) with the solar distribution (Figure 1). By looking at Figure 1 we can recognize that the PFs of most of the isotopes are compatible with a flat distribution, within a factor of 2 arbitrarily taken as a suitable "theoretical" error bar. There are, however, some exceptions that deserve a closer scrutiny and may potentially constitute a problem. We recall the paper by LC03 for a more detailed discussion about this.

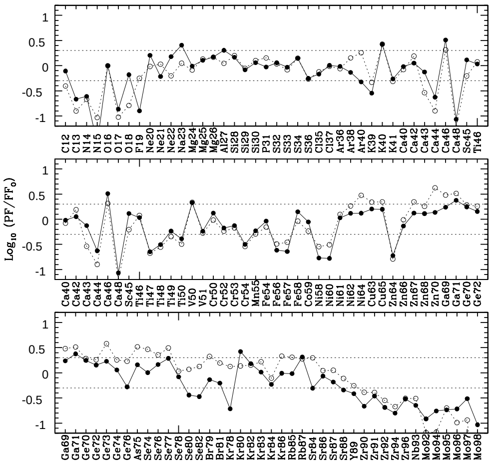

Fig. 1. Production factors (PFs) of all isotopes from ^{12}C to ^{98}Mo normalized to the PF(^{16}O). The *filled circles* connected by *solid line* refer to LC03 while the *open circles* connected by *dotted line* refer to RHWW02.

5.2. Zero metallicity models

Extremely metal poor stars (EMPS), those having [Fe/H] $\leq$ -3 (here [A/B] $=$ $\mathrm{Log_{10}}(X_A/X_B) - \mathrm{Log_{10}}(X_A/X_B)_\odot$, where X_A and X_B are the abundances of elements A and B respectively), formed in the very early epochs of Galaxy formation by gas clouds chemically enriched by just the very first stellar generation, i.e. the generation of PopIII massive stars. Hence they preserved up to the present time the fingerprints of this primordial population. In the hypothesis that during the early times of evolution of the Galaxy the matter was not enough homogenized, it is reasonable to assume that the EMPS formed in clouds of

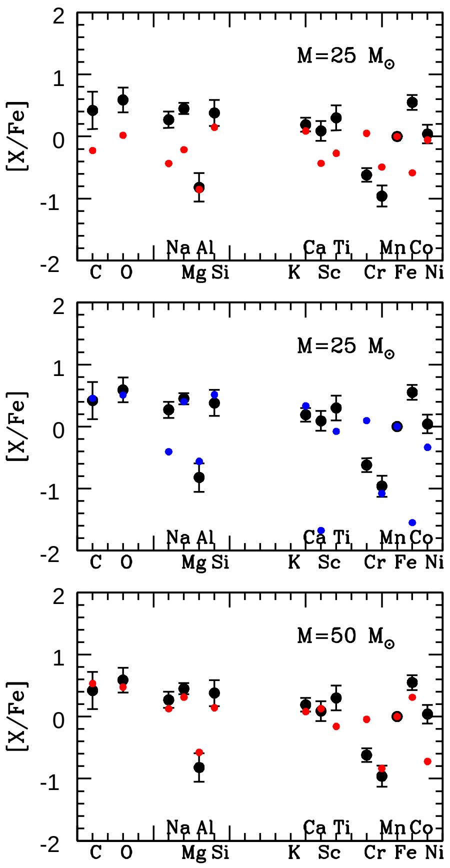

Fig. 2. Comparison between the AVG star (filled circles with error bars) and the ejecta of a 25 M$_\odot$ by WW95 (*upper panel*), a 25 M$_\odot$ by UN02 (*middle panel*) and a 50 M$_\odot$ by CL02 (*lower panel*).

gas enriched by very few PopIII supernovae (SNe), at least even only one. In this case the element abundance ratios observed in EMPS can be directly compared with theoretical yields of metal free SNII of different masses to determine which have contributed to the Galactic chemical enrichment and when. As a feedback they can be used to constrain theoretical models and nucleosynthesis when unexpected elemental ratios are found.

Among the EMPS we can identify essentially two groups: the first one showing a very similar abundance pattern for all the elements, the second one characterized by large enhancements of the light elements relative to iron and showing a rather high star to star scatter.

Since the stars belonging to the first group show a very similar abundance pattern we can define an "average" (hereafter AVG) star that represents all of them. Hence, the AVG star can be considered as a "template" of the majority of the EMPS and is worth being compared with the theoretical predictions. Figure 2 shows the best fit to the AVG star obtained by using the zero metallicity models computed by the three theoretical groups, namely, Woosley & Weaver (1995) (hereafter WW95) in the upper panel, UN02 in the middle panel and Chieffi & Limongi (2002) (hereafter CL02) in the lower panel. By looking at Figure 2 we can recognize that 1) WW95 yields do not provide a good fit to the observations; 2) UN02 yields provide a good fit to the light elements (below Ca) except Na - no fit is found for the iron peak elements; 3) CL02 yields allow for a good fit to 10 of the 13 observed element abundance ratios - among the iron peak elements no fit is found to Ti, Cr and Ni. We recall the CL02 paper for a deep and comprehensive discussion about the fit to the AVG star.

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