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The $^{12}C+^{12}C$ reaction and its astrophysical implications

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The $^{12}C+^{12}C$ reaction plays a pivotal role in the development of carbon burning in stars. Thus, the cross section of this reaction should be known with high accuracy down to the Gamow energy, which is E_G=1.5±0.3 MeV for the typical temperatures of carbon burning in stars. At present the lower limit of E_{cm} reached experimentally is 2.10 MeV where a strong resonance has been found at E_R = 2.14 MeV (Spillane et al. 2007). The high number of resonances measured so far led, in the last years, to speculation about a hypothetical presence of a resonance within the Gamow energy range that could completely dominate the reaction rate at the densities and temperatures typical of core carbon burning. In this paper we will show the effects that such a kind of resonance would have on the evolution of intermediate and massive stars and the following astrophysical implications.

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1. Introduction

Carbon burning in stars takes place when the temperature exceeds T~7×10^8 K and is triggered by the two reactions ^{12}C(^{12}C,α)^{20}Ne and ^{12}C(^{12}C,p)^{23}Na that occur with almost equal branching (Figure 1).

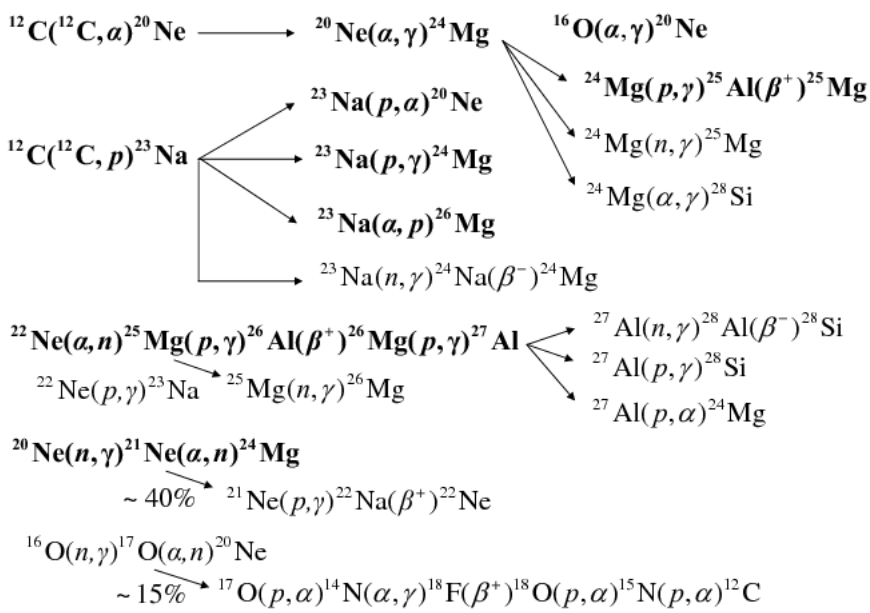

Figure 1. Most important nuclear reactions during C burning in massive stars.

The free protons liberated by the ^{12}C(^{12}C,p)^{23}Na are mainly captured by ^{23}Na through the ^{23}Na(p,α)^{20}Ne and ^{23}Na(p,γ)^{24}Mg reactions. As a consequence ^{23}Na is mainly transformed into ^{20}Ne and ^{24}Mg (Figure 1). Other efficient sequences involving proton captures are ^{24}Mg(p,γ)^{25}Al(β$^+$)^{25}Mg followed by ^{25}Mg(p,γ)^{26}Al(β$^+$)^{26}Mg and ^{26}Mg(p,γ)^{27}Al. At the same time most of the α-particles liberated by the ^{12}C(^{12}C,α)^{20}Ne are captured by ^{16}O, the most abundant product of He burning, through the ^{16}O(α,γ)^{20}Ne, and by ^{20}Ne and ^{23}Na, freshly synthesized, through the reactions ^{20}Ne(α,γ)^{24}Mg and ^{23}Na(α,p)^{26}Mg. As a result, the main products of carbon burning are ^{20}Ne, ^{23}Na and ^{24}Mg and a smaller amount of ^{25,26}Mg and ^{27}Al.

In spite of the key role the ^{12}C(^{12}C,p)^{23}Na and the ^{12}C(^{12}C,α)^{20}Ne play in Carbon burning, the cross section of these reactions is not yet known with high accuracy down the Gamow energy (E_G=1.5±0.3 MeV for a temperature of 5×10^8 K). The most recent investigation of the ^{12}C(^{12}C,p)^{23}Na and the ^{12}C(^{12}C,α)^{20}Ne reactions are those of Spillane et al. (2007) who studied these reactions from E=2.10 MeV to E=4.75 MeV. They found a strong resonance at E=2.14 MeV, which lies at the high-energy tail of the Gamow peak and that would increase the present non resonant reaction rate of the α channel by a factor of ~5 for T=8×10^8 K.

The pronounced resonances throughout the measured energy range shown by present day data and confirmed by the results obtained by Spillane et al. (2007), led to a number of speculations, in the last few years, about a possible presence of a strong resonance within the Gamow energy range (E_{cm}~1.5 MeV) which should completely dominate the reaction rate at the densities and temperatures typical of carbon burning in stars.

In this paper we want to explore the impact of such an hypothetical strong resonance at E_{cm}~1.5 MeV on the general behavior of carbon burning in stars.

First of all, we want to explore the regimes during which carbon ignition occurs in the core of stars as a function of the main sequence mass. As it is well known, carbon ignition may occur in the center, under non degenerate conditions, or off-center, under mildly degenerate conditions. Massive stars, by definition, never experience a significant electron degeneracy in the core during all their nuclear burning stages hence they evolve to higher and higher temperatures, fusing heavier and heavier elements under non degenerate conditions, until a iron core is formed. On the contrary, intermediate mass stars develope, after core He depletion, a degenerate CO core which is small enough to cool down before the ignition temperature for C burning is reached. In a narrow "transition region" between intermediate mass stars and massive stars, C burning is ignited off-center, in a mildly degenerate core. The minimum mass for off-center carbon ignition defines the upper mass limit of the intermediate mass stars (M_{up}) (see Becker and Iben 1979, Becker and Iben 1980), while the minimum mass for central non degenerate C ignition defines the minimum mass of the massive stars (M_{up}'). Stars with mass $M<M_{up}$ reach a point where the internal structure is fully supported by the electron degeneracy and the contraction of the degenerate core is slowed down. In these stars, mass loss prevents the degenerate core to reach the Chandrasekhar mass and the star to explode as supernova. These stars end their evolution as CO white dwarfs. Stars with mass $M>M_{up}'$ form an iron core which becomes unstable and trigger the explosion of the structure giving rise to the classical core collapse supernova event. Stars in the transition region $M_{up}<M<M_{up}'$ develope, after off-center C ignition, an ONeMg core whose fate has been studied by Nomoto (1984) and still remain quite uncertain. In general if the mass of the ONeMg core is high enough for Ne iginition the fate of the star is an electron capture supernova while, on the contrary, the star will end its evolution as an ONeMg white dwarf. The limiting mass between these two different evolutionary channels is defined as M_{up}''. Figure 2 shows schematically the summary of the evolutionary paths and critical masses discussed above. A reliable determination of M_{up} is crucial for several astrophysical problems, among which we recall the following. (1) The chemical enrichment of the interstellar matter due to different type of supernova explosions, since M_{up} marks the transition mass between thermonuclear and core collapse supernovae (for sake simplicity we neglect the very small mass intervall leading to ONeMg WDs) that, in turn, contribute to the chemical evolution with a completely different nucleosynthetic yields. (2) The ratio between core collapse supernovae (Tpye II, Ib, Ic, IIn and so on) and thermonuclear supernovae (Type Ia). (3) The luminosity function of M and C AGB stars in the Milky Way, LMC and SMC and, in particular, their tail at high luminosities. (4) The ratio between ONeMg and CO WDs.

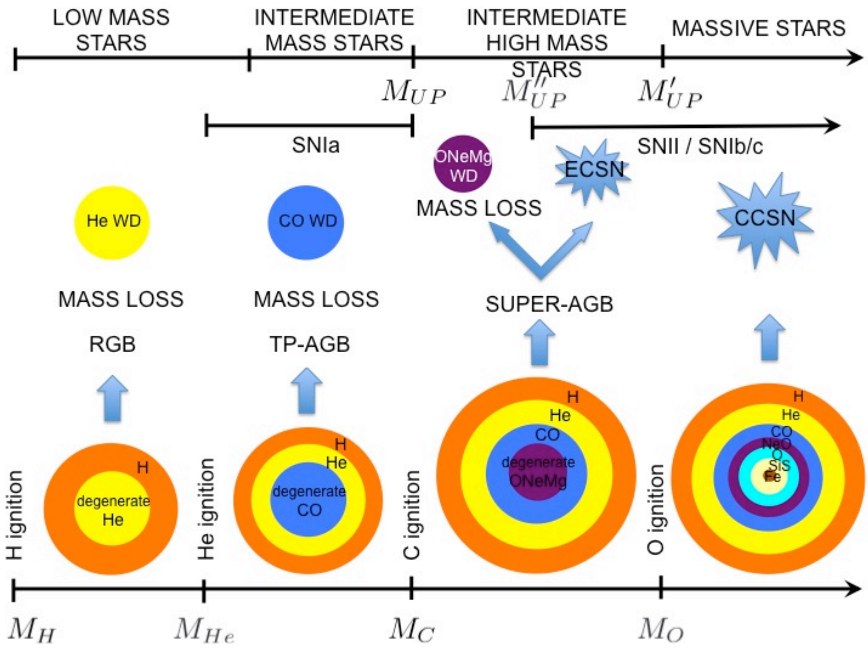

Figure 2. Schematic evolutionary paths of stars with different initial mass.

The other issue we want to address in this paper is the influence of the $^{12}C+^{12}C$ reaction on the presupernova evolution and on the following explosion of massive stars. Since carbon burning in shell drives the evolution of the CO core (mainly its gravitational contraction), we expect that a variation of the $^{12}C+^{12}C$ cross section could alter, even significantly, the final properties of a massive star at the presupernova stage as well as the basic behavior of its explosion.

2. Strong resonance at low energies

In this paper we study the consequences of a hypothetical strong resonance corresponding to the energy E=1.7 MeV with a maximum strength compatible with the measured cross section at low energy. The procedure adopted here in order to take into account of such a resonance is the one proposed by Bravo et al. (2011), hence we remind the reader to that paper for more detailed information. Thus, our "modified" $^{12}C+^{12}C$ cross section is the sum of the non resonant contribution (Caughlan and Fowler 1988, CF88) plus a resonant one that takes into account of the resonance found by Spillane et al. (2007) at E_{CM}=2.14 MeV and the assumed low-energy resonance at E_{CM}=1.7 MeV.

$$< \sigma v >^{\rm tot}_{^{12}C^{12}C} = < \sigma v >^{\rm CF88}_{^{12}C^{12}C} + < \sigma v >^{\rm R}_{^{12}C^{12}C}$$

where

$$< \sigma v >^{\rm R}_{^{12}{\rm C}^{12}{\rm C}} = 2.28{\cdot}10^{-24} T_9^{-3/2} \left[exp(-24.8/T_9) + \frac{(\omega\gamma)_R}{0.13{\rm MeV}} exp(-11.6 E_R/T_9) \right]$$

Moreover we require that the assumed resonance contributes to the cross section at E_{CM}=2.10 MeV less than 10% of the value measured by Spillane et al. (2007) at the same energy. In this case, assuming a resonance width of 10 keV, the resonance strength is limited to 4.1 MeV for E=1.7 MeV (see Bravo et al. 2011 for more details).

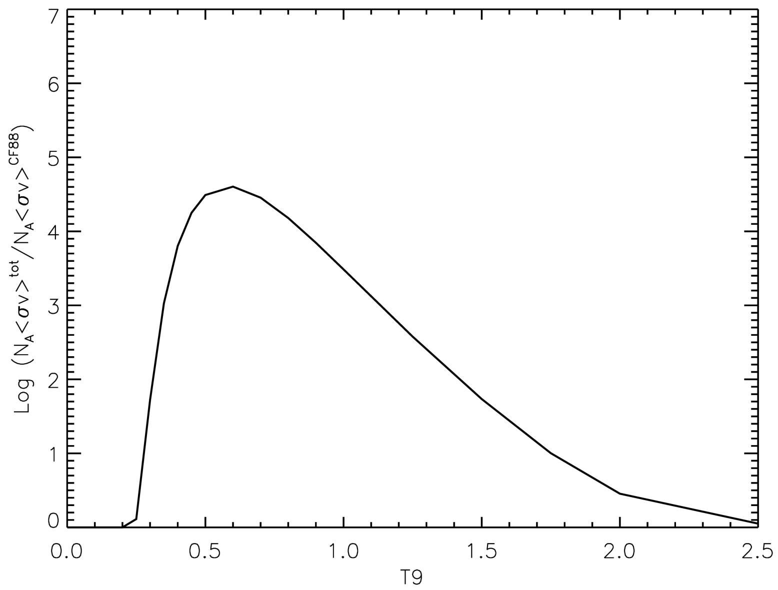

Figure 3. Comparison between the Caughlan and Fowler 1988 (CF88) and the "modified" (see section 2) $^{12}C+^{12}C$ cross sections.

A comparison between the "standard" (CF88) and the "modified" $^{12}C+^{12}C$ cross sections is shown in Figure 3. Note that the modified cross section is larger than the standard one by up to about 5 order of magnitudes for temperatures of the order of 6×10^8 K.

3. Stellar models

All the results presented in this paper are based on stellar models computed by means of the FRANEC code which is described in Limongi and Chieffi (2006) and Chieffi and Limongi (2012). In this last version of the code the set of equations formed by the four ones that describe the physical structure of the star plus the "N" ones describing the total chemical evolution (i.e. due to the nuclear reactions plus the various kind of mixing: convection, semiconvection, diffusion, rotational induced, etc.) are coupled together and solved simultaneously by means of a relaxation technique. Mass loss has been included following the prescriptions of Vink et al. (2000, 2001) for the blue supergiant phase (Teff>12000 K), de Jager et al. (1988) for the red supergiant phase (Teff<12000 K) and Nugis and Lamers (2000) for the Wolf-Rayet phase. The enhancement of the mass loss due to the formation of dust during the red supergiant phase has been included following the prescriptions of van Loon et al. (2005). The nuclear network includes 163 isotopes (from H to ^{98}Mo) and 448 reactions for H and He burning, and 282 isotopes (from H to ^{98}Mo) and 2928 reactions for the more advanced nuclear burning stages up to the procollapse phase. In total 293 isotopes and about 3000 processes were explicitly included in the various nuclear burning stages. The database of the cross sections adopted is the same reported in Limongi and Chieffi (2006). The stability criterion for convection is the Ledoux one; a moderate amount of convective overshoot (0.2 H_P) is assumed during core H burning; the efficiency of semiconvective mixing is set by choosing α_{semi}=0.02 (see Langer et al. 1985 for the meaning of α_{semi}). The mixing lenght is fixed at α=2.1. The initial solar composition is the one reported by Asplund et al. (2009).

4. The critical mass M_{up}

In this section we want to study the sensitivity of the critical mass M_{UP} to the $^{12}C+^{12}C$ cross section. It is well known the M_{UP} may depend on many quantities like, e.g., the overshooting the initial composition and so on. Here we want to study only its dependence on the $^{12}C+^{12}C$ cross section, regardless of the other uncertainties.

In this section we will firstly derive the value of the critical mass M_{UP} obtained by adopting the standard $^{12}C+^{12}C$ cross section (standard casem CF88). Then we will show how this value changes by adopting the $^{12}C+^{12}C$ cross section modified according to the procedure described in section 2 (test case).

Since we want to determine M_{UP}, which is by definition the the minimum mass for off-center C ignition, let us start by describing the evolution of a 7 $M_\odot$ star with initial solar composition ($Z=Z_\odot$, Y=0.26) after core He depletion.

As He is depleted at the center and a CO core is formed, the He burning shifts in a shell that sourrounds the CO core and progressively advances in mass. Since the central temperature is much lower than the one required for ignite the C burning reactions, the CO contracts and heats up in order to maintain the hydrostatic equilibrium. The physical conditions are such that degeneracy effects begin to take place in the central zones of the core and tend to propagate to an increasing fraction of the CO. As a consequence both the gravitational contraction and heating of a progressively larger fraction of the CO slow down. When the central temperatures (Log T~8.6) and densities (Log ρ~6.0) are high enough, neutrino cooling becomes efficient. From this time onward, the CO splits in two zones; the inner one, where the neutrino cooling exceeds the rate of heating by gravitational contration, that progressively cool down; the outer one, where the gravitational heating due to the advancing of the He burning shell exceeds the neutrino cooling that progressively heats up. Thus an off-center maximum of temperature naturally developes which progressively increases and moves outward in mass. However, when the convective envelope forms and penetrate deep in the star (second dredge-up), within the He core, the advancing of the He burning shell stops. From this time onward the gravitational heating of the outer cores becomes progressively less efficient until it lowers below the neutrino cooling. Once this happens the off-center maximum of temperature begins to decrease and the whole CO starts to cool down. Since during this sequence of events the off-center maximum of temperature never reached the critical value for C ignition, no off-center C burning is triggered. Thus, the following evolution of the star is throught the termally pulsing asymptotic giant branch phase (TP-AGB).

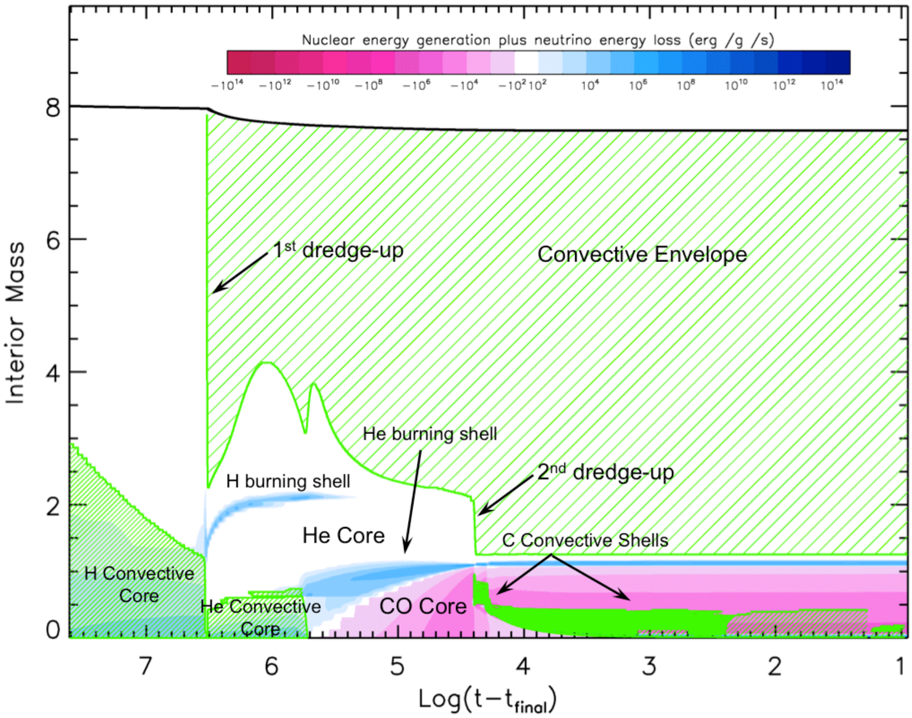

Figure 4. Convective history of a 8 M⊙solar composition. Shaded areas refer to the convective zones. Different colors identify zones where neutrino energy loss (magenta) and nuclear energy generation are efficient.

The evolution of a 8 M⊙ is similar to that of the 7 M⊙ but, in this case, the maximum off center temperature reaches the critical value for C ignition. Once C is ignited off-center the local temperature increases rapidly because, due to the degeneracy, the local pressure does not increase and there is no consumption of energy through expansion. As a consequence a strong flash occurs. The high local energy release, that is not counterbalanced by gravitational expansion, leads to the formation of a convective shell and the matter is continuously heated up at constant density. The dramatic increase of the temperature at constant density progressively reduces the degree of degeneracy. Once the degeneracy is almost completely removed all the zones start to expand. Because of the local energy release, the maximum temperature shifts inward in mass and a second C flash occurs. The following evolution proceeds through a number of C flashes (and convective shells) progressively more internal in mass until the carbon shell is able to lift the degeneracy of the whole core, the maximum cabon burning rate shifts to the center of the star and a quiescent core C burning settles on (Figure 4). After core C depletion an ONeMg core is formed. Whether the ONeMg core will eventually be able to start core Ne burning or to evolve toward a ONeMg white dwarf configuration is still highly uncertain. The knowledge of its following fate would require detailed and extremely tough calculations that, at present, are not available.

One of the consequences of the calculations described above is that the value of M_{UP} in the reference case is between 7 and 8 $M_{\odot}$ which is the typical value that can be found in literature.

The adoption of the $^{12}C+^{12}C$ cross section, modified as discussed in section 2, should imply a carbon ignition at lower temperatures. This can be cleary see in Figure 5 which shows a comparison between the standard (CF88) and the modified (Resonant) $^{12}C+^{12}C$ cross sections.

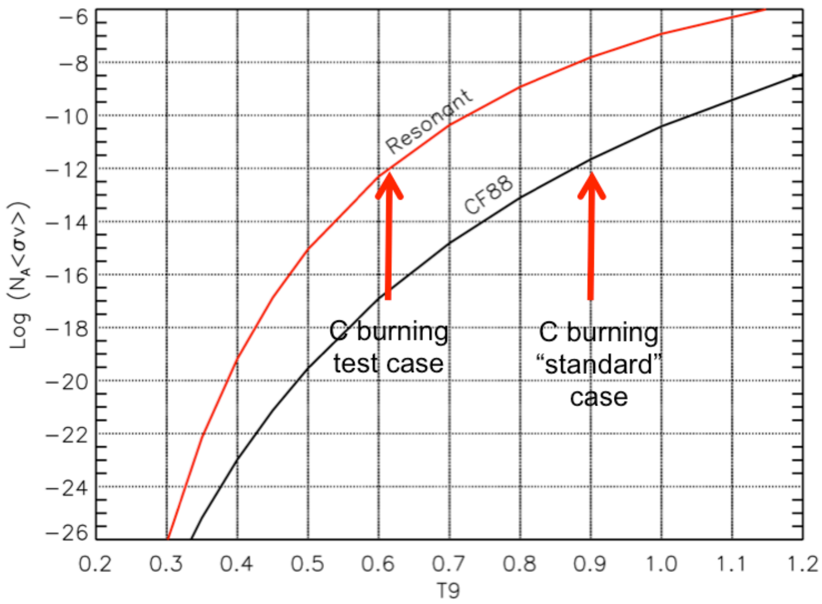

Figure 5. Comparison between the CF88 and the resonant $^{12}C+^{12}C$ cross section (see text).

Since in the standard case C burning occurs at a temperature of T_9~0.9 K, which corresponds to a value of the cross section Log(N_A<σv>)~-12, we expect that in the test case it should start at a temperature of T_9~0.6 K. This would ultimately implies a reduction of the value of M_{UP}.

Figure 6 shows the convective history of 5 $M_{\odot}$ computed with the modified $^{12}C+^{12}C$ cross section. The figure clearly shows an off-center C ignition, similar to the one described in the 8 $M_{\odot}$ starndard model. On the contrary in the 4 $M_{\odot}$ the maximum off-center temperature never reaches the critial value for the off-center C ignition. Therefore the adoption of the modified $^{12}C+^{12}C$ cross section would reduce the value of M_{UP} from 7÷8 $M_{\odot}$ (in the standard case) to 4÷5 $M_{\odot}$ (in the test case).

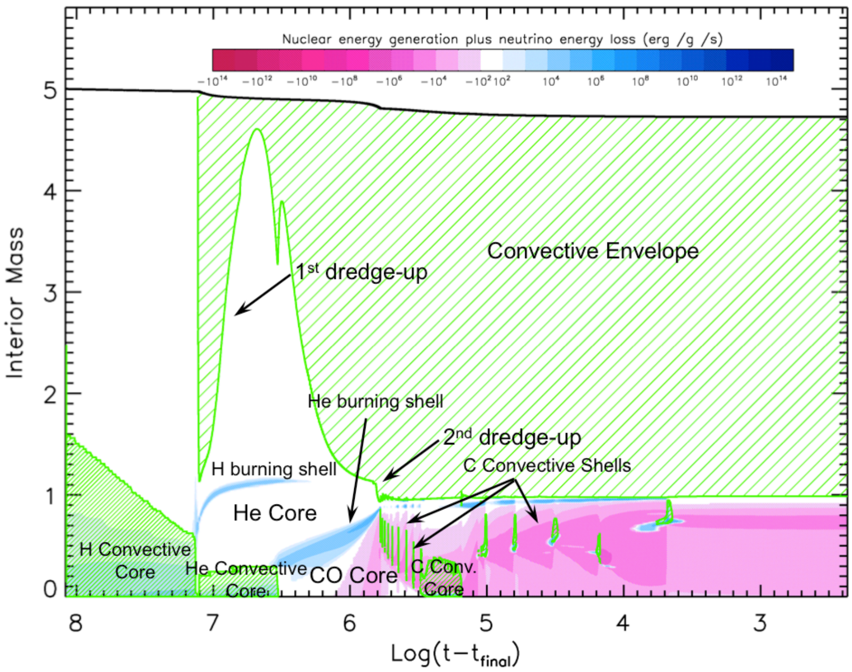

Figure 6. Same as Figure 4 but for a 5 $M_\odot$.

5. Presupernova evolution and explosion of massive stars

As it is already mentioned in the introduction, stars with mass larger than M_{up}' (massive stars) never experience a significant electron degeneracy in the core during all their nuclear burning stages hence they evolve to higher and higher temperatures, fusing heavier and heavier elements until a iron core is formed. After core He depletion a CO core is formed the He burning shifts in shell while the CO core contracts in order to ignite the next fuel. The advanced evolutionary phases of massive stars are characterized by four major burnings, i.e., carbon, neon, oxygen and silicon. In general each burning stage begins at the center and induces the formation of a convective core (Figure 7). The convective core increases in mass, reaches a maximum and then disappears as the nuclear fuel is exhausted - the only exception to this general rule being core C burning that in the more massive stars ($M > 20\ M_\odot$) occurs in a radiative environment due to the low ^{12}C mass fraction left by core He burning. Once the nuclear fuel is exhausted at the center, the burning shifts in a shell, which in general is efficient enough to induce the formation of a convective zone above it (Figure 7). Once the convective zone forms, the advancing of the shell stops and the burning proceeds within the convective shell. When the nuclear fuel is exhausted within the entire convective zone, the burning shell quickly shifts outward in mass, where the main fuel is more abundant and eventually another convective zone forms. By the way, two successive convective shells may also partially overlap in mass and this may have some impact on the local nucleosynthesis. The details of this general behavior, i.e. number, timing and overlap of the convective zones formed in each burning stage, depend on both the mass of the CO core (and hence the mass of the star) and its chemical composition (mainly the ^{12}C and ^{16}O left over at core He depletion). In general, one to four carbon convective shells and two to three convective shell episodes for each of the neon, oxygen and silicon burning occur. The basic rule is that the higher is the mass of the CO core, the lower is the ^{12}C left over by core He burning, the less efficient is the C shell burning and hence the lower is the number of C convective shells (Figure 8).

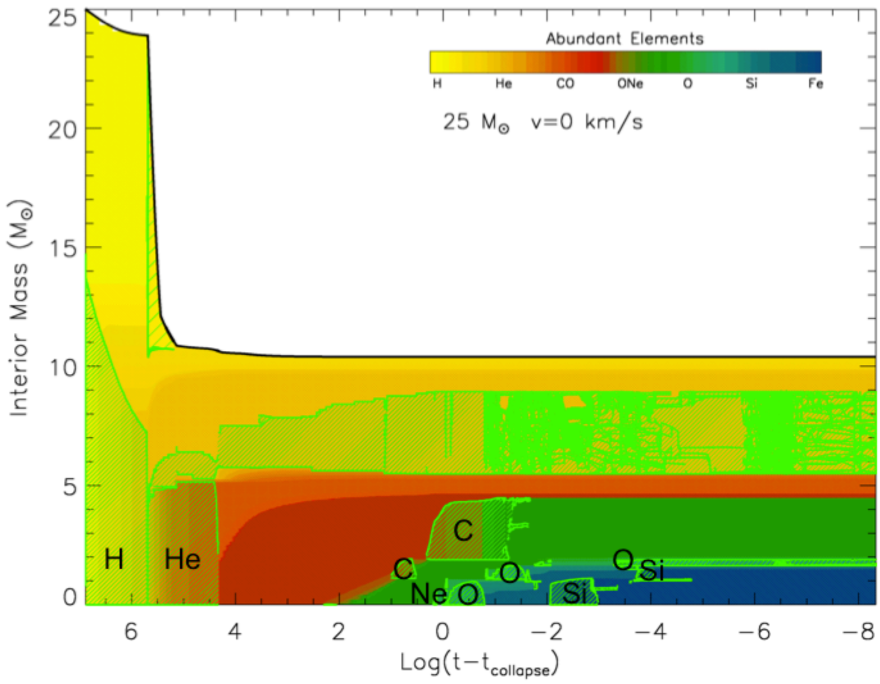

Figure 7. Convective history of a 25 $M_\odot$. Shaded areas correspond to convective zones. Different colors refer to different chemical compositions as indicated in the colorbar.

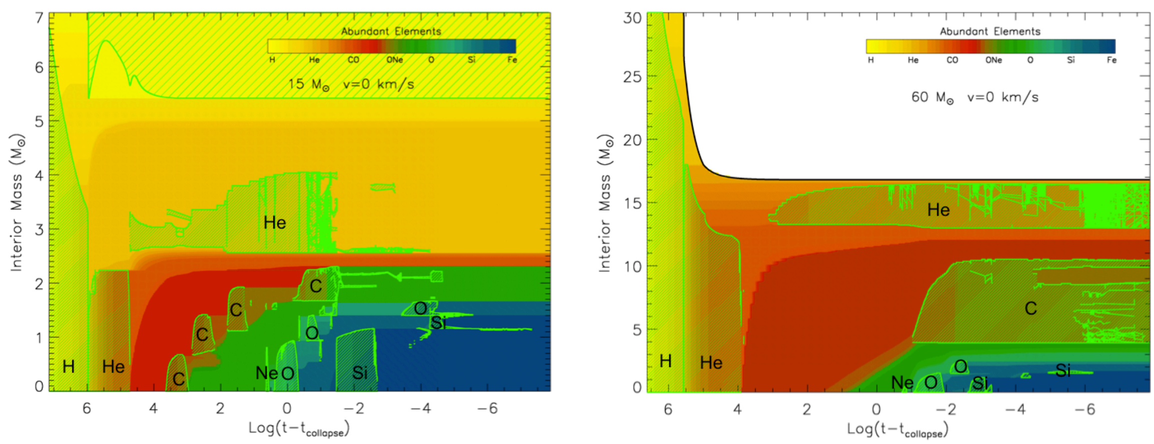

Figure 8. Same as Figure 7 for a 15 $M_\odot$ (left panel) and for a a 60 $M_\odot$ (right panel).

On the other hand, a less efficient nuclear burning implies a stronger gravitational contraction of the CO core and hence a steeper density profile at the presupernova stage. Since the CO mass increases with the initial mass, the higher is the initial mass the more compact is the presupernova structure (Figure 9).

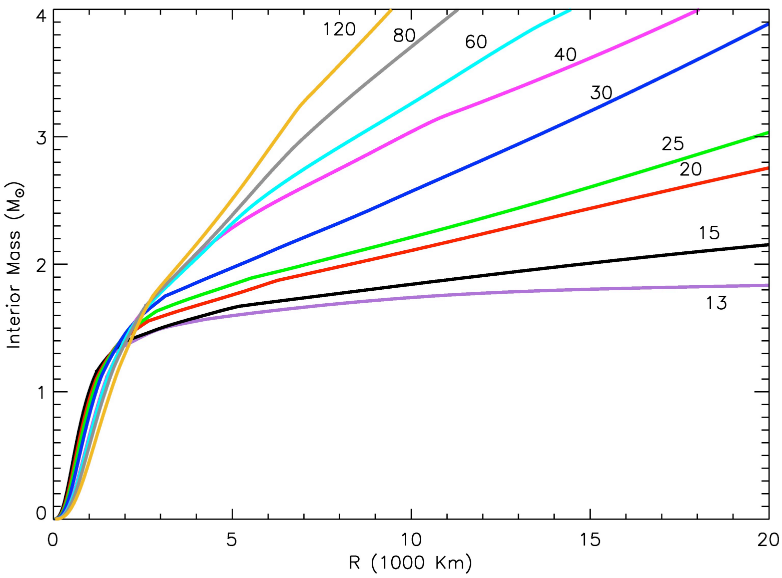

Figure 9. Mass-Radius relation at the presupernova stage for the various models. The initial mass is reported close to the line.

After the iron core and the well-known "onion" structure are formed, these stars will end their life through an explosive event. Such an explosion results from the collapse of the iron core to nuclear densities and its following re-bounce which launch a shock wave which will ultimately be responsible for propagating outward through the mantle, disrupting the star in a core collapse supernova. If the shock were to propagate outward without stalling, we would have what has been called a "prompt explosion". All of the realistic models completed to date suggest that this does not occur. The reason is that the shock wave forms within the iron core at a mass coordinate of 0.6-0.8 $M_\odot$ with an initial energy of ~ $4 \div 10 \cdot 10^{51}$ erg, but, during its propagation within the remaining part of the iron core, it looses ~ $1.7 \cdot 10^{51}$ erg/0.1 $M_\odot$ crossed due to dissociation of the iron peak nuclei into free nucleons and copious neutrino emission. As a result, the shock wave consumes its entire kinetic energy still within the iron core, turns into an accretion shock at a radius between 100 and 200 km and the prompt explosion fails. How the shock is revived in a delayed explosion mechanism is currently the central question in core collapse supernova theory. It must be reminded that the ultimate source of energy in a core collapse supernova is the ~ 10^{53} erg of gravitational binding energy associated with the formation of the neutron star. This gravitational binding energy is released after core bounce over 10 s in the form of a three-flavor neutrino pulse by the proto-neutrons star which forms at the center of the core at the time the shock stalls. The stalled supernova shock is though to be revived by such an electron neutrinos and antineutrinos that emerge from the proto-neutron star, a fraction of which are absorbed by free protons and neutrons just behind the shock. This is known as the "delayed shock mechanism" or "neutrino-heating mechanism", which was originally proposed by Wilson (1985) and Bethe and Wilson (1985). Although the total energy emitted in neutrinos is two orders of magnitude greater than what is required for the generation of a typical core collapse supernova explosion ($\sim 10^{51}$ erg), obtaining a successful supernova explosion is not an easy task. Indeed, although after two decades of research the paradigm of the neutrino heating explosion mechanism is widely accepted, at present there is no self-consistent model of core collapse supernova explosion that is able to obtain naturally the explosion with the typical energetic display.

The lack of such a self-consistent model implies that a number of fundamental questions remain opened, among the others: how much is the energy of the shock wave at the time it crosses the outer edge of the iron core and enters the mantle of the star? how much is the delay (if it exists) between the first re-bounce and the rejuvenation of the shock front? is there a fall back and at what extent? Moreover, the propagation of the shock wave through the mantle of the star induces locally compression and heating and hence, since nuclear reactions are very temperature sensitive, this causes (explosive) nucleosynthesis to occur within few seconds that might otherwise have taken days or years in the presupernova evolution. Such an explosive nucleosynthesis is responsible for the production of many isotopes that are not produced at all during the hydrostatic burning stages (e.g. ^{56}Ni, see below) and hence its modeling is fundamental to determine the chemical composition of the ejecta.

For all these reasons, at present, the explosive nucleosynthesis calculations for core collapse supernovae are still based on simulated explosions where an arbitrary amount of energy is injected in a (also arbitrary) mass location of the presupernova model. This extra energy immediately induces the formation of a shock wave whose propagation through the mantle is followed by means of a hydro code. Whichever is the way in which the energy is deposited into the presupernova model, the typical evolution of the explosion involves (1) an initial remnant; (2) a shock wave propagating through the mantle and inducing compression, heating, explosive nuclesynthesis and expansion of the shocked material; (3) a fallback of deepest layers of the expanding mantle because of the gravitational field of the compact initial remnant; (4) a mass cut which is the mass separation between the ejecta, which will have a given final kinetic energy, and the final remnant, which in general will be larger than the initial one (Figure 10). The amount of extra energy deposited at the border of the iron core mass is tuned in order to obtain a given final total kinetic energy of the ejecta, usually of the order of $1 \div 2$ foes (where 1 foe = 10^{51} ergs).

Quite obviously both the density structure at the presupernova stage and the hydrodynamical evolution of the shock wave play a fundamental role in determining both the amount of fall back and the chemical composition of the ejecta.

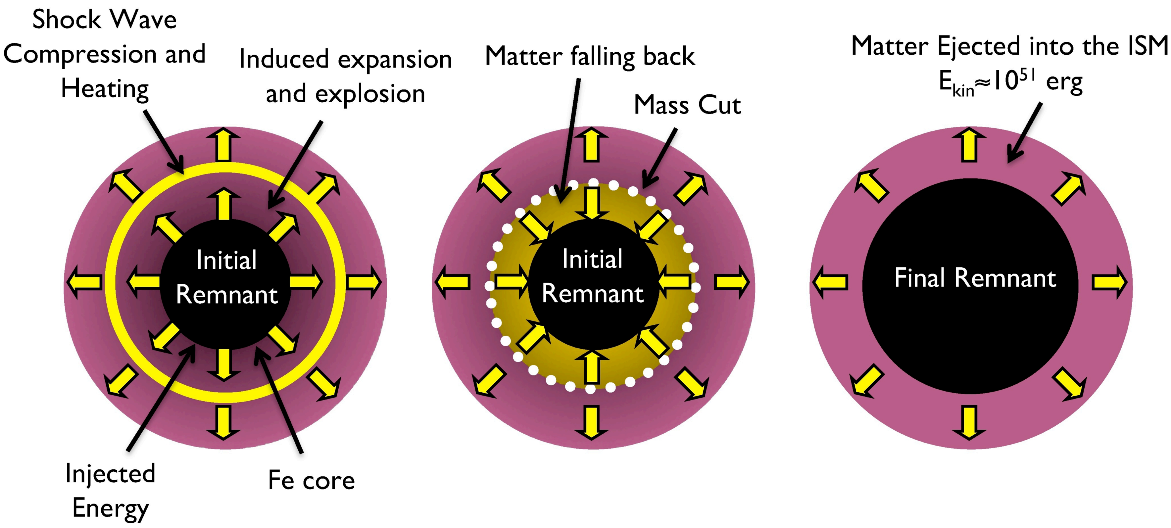

Figure 10. Schematic evolution of the star during the explosion.

Figure 11 shows, among the other properties, the initial mass-final mass relation 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 M-R relation (Figure 9) (i.e. the more compact is the structure), 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 20 $M_\odot$.

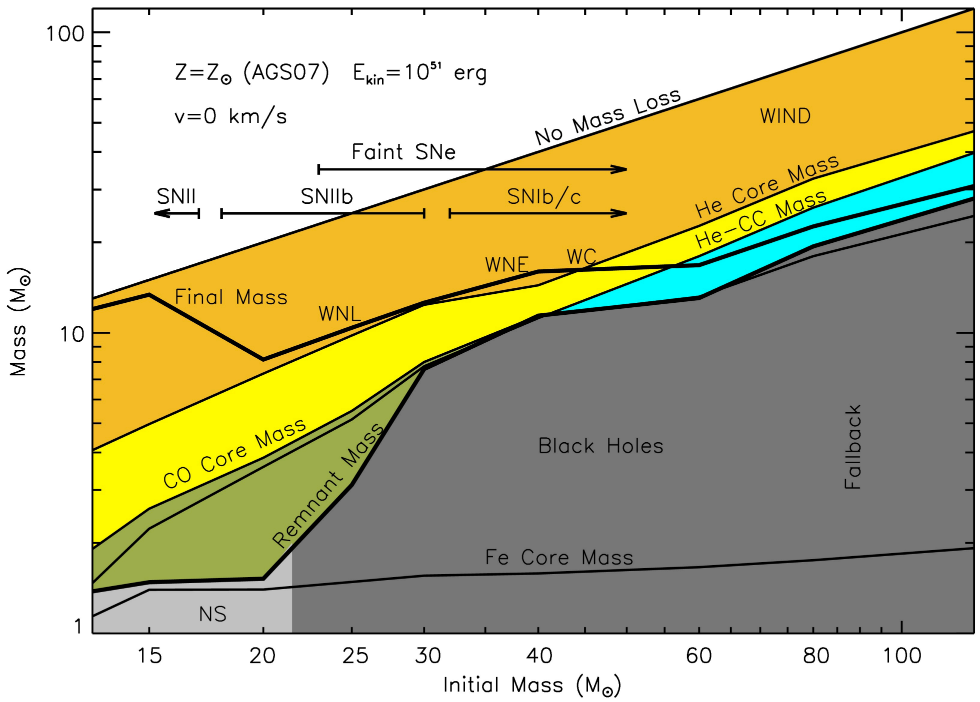

Figure 11. Final masses and remnant masses (thick−solid lines) as a function of the initial mass by assuming that all the models have E_{kin} = 1 foe at infinity. Also shown are the maximum He core, He convective core and CO core masses, the minimum masses that enter the various stages of WR, the limiting mass between stars exploding as SNII and SNIb/c, the limiting mass between stars forming neutron stars and black holes after the explosion.

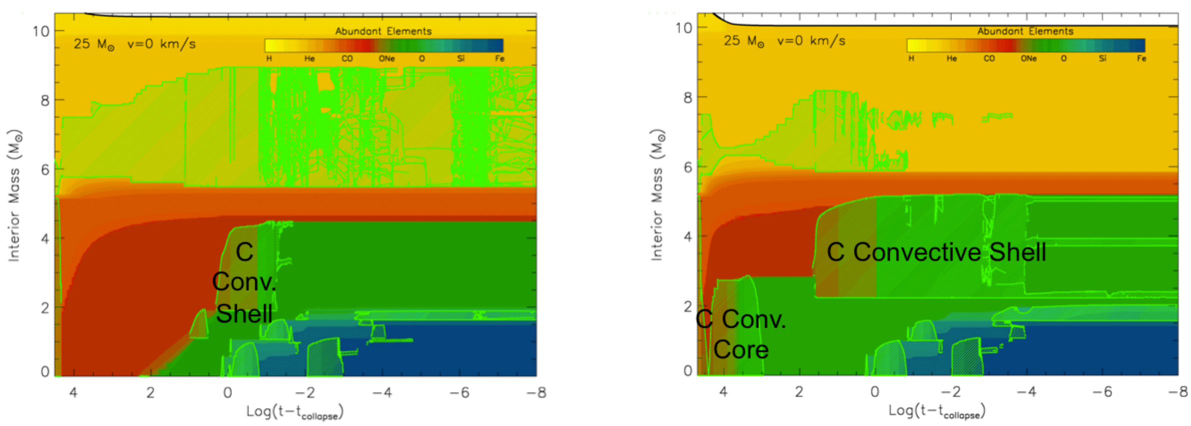

Figure 12. Convective history within the CO of two 25 $M_{\odot}$. The left panel refers to the model computed with the stabdard $^{12}C+^{12}C$ cross sections, while the right panel shows the evolutionary results obtaine with the $^{12}C+^{12}C$ cross sections properly modified in order to take into account of a hypothetical strong resonance close to the Gamow energy (see text).

An hypothetical strong resonance at E_{cm}~1.5 MeV in the cross section of the $^{12}C+^{12}C$ reaction makes the C burning more efficient, hence we expect substantial differences in the evolution of the zones interior to the CO core. Figure 12 shows a comparison between two 25 $M_\odot$ models: the first one (left panel) computed with the standard $^{12}C+^{12}C$ cross section (and already shown in figure 7, see above), the second one (right panel and "test model" hereafter) computed with the $^{12}C+^{12}C$ cross section properly modified in order to take into account of the strong resonance close to the Gamow energy (as discussed above).

Figure 12 clearly shows that C burning is much more efficient in the test model rather than in the standard one. In particular, core C burning occurs, in the test model, in a convective core and only one, very efficient and extended C shell forms. This prevents a strong gravitational contraction of the CO core and makes the test model less compact than the standard one. This is clearly shown in figure 13.

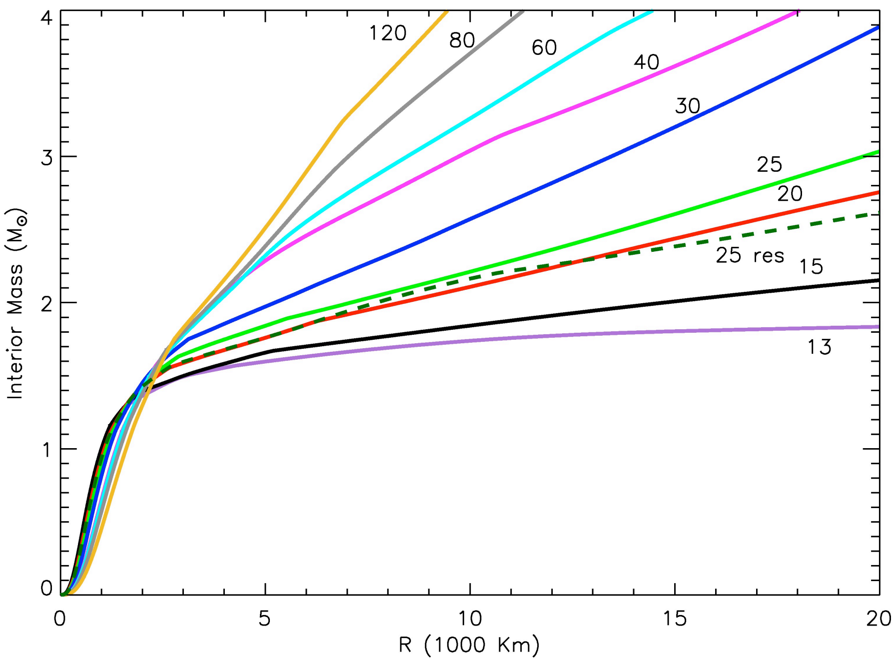

Figure 13. Same as Figure 9. The black dashed line and the label "25 res" refer to the "test" 25 $M_\odot$ model.

Moreover, the lower binding energy of the test model allows, for the same explosion energy, the ejection of a substantial amount of the CO core, and hence heavy elements, compared to the standard case (see Figure 14 and 15).

Summarizing, the hypothetical presence of a strong resonance at E~1.7 MeV, with a maximum strength limited by the measured cross section at low energy (2.10 MeV), has a strong impact on the presupernova evolution and explosion of massive stars. In particular, making the C burning more efficient it would produce less compact presupernova structures that, in turn, would have smaller remnants than their corresponding standard models. Thus, for the same explosion energy, it would increase the limiting mass between neutron star and black hole forming supernovae compared to the standard case. Moreover, the reduction of the fallback mass would imply the increase of the maximum mass contributing to the enrichment of the interstellar medium with heavy elements. In this paper we have presented only one test case. In order to have quantitative information on these two quantities, the calculation of the presupernova evolution and the associated explosion of a full set of models in a wide range of masses are required. We will present such a calculations in a forthcoming paper.

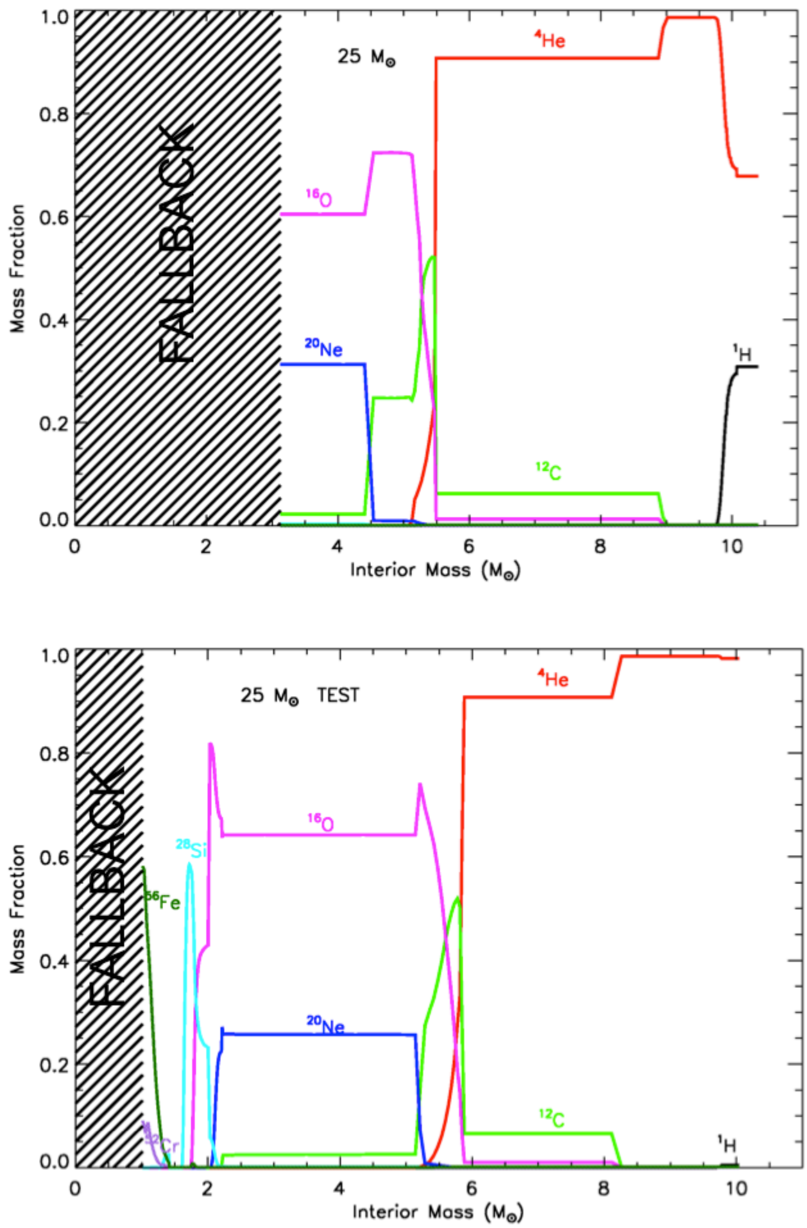

Figure 14. Comparison between the post-explosion chemical composition for the standard and the test 25 M⊙ models. The shaded area refers to the mass that fallback onto the compact remnant during the explosion.

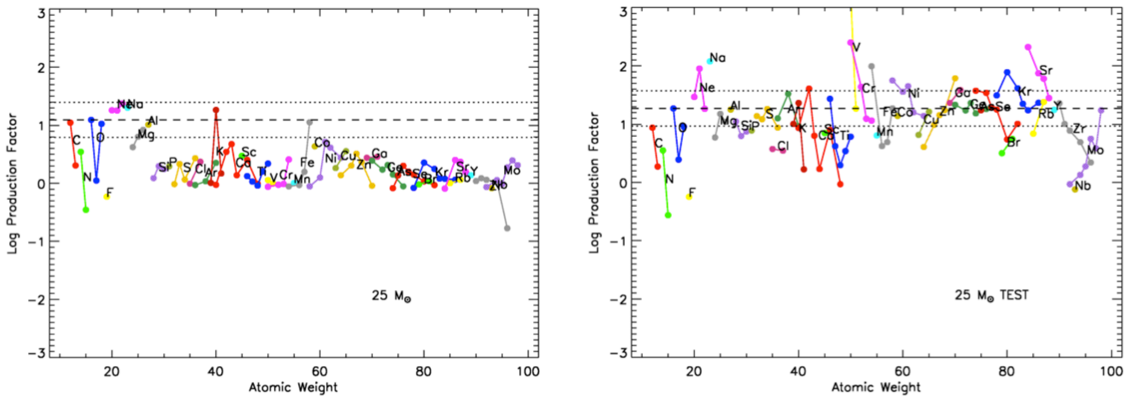

Figure 15. Comparison between the production factors (ratio of each isotope's mass fraction in the total ejecta divided by its corresponding initial mass fraction, i.e., PF=$X_{ejected}$ =X_{ini}) for the standard and the test 25 M⊙ models.

6. Summary and Conclusions

The $^{12}C+^{12}C$ reaction plays a pivotal role in the development of carbon burning in stars. The pronounced resonances throughout the measured energy range shown by present day data, led to a number of speculations about a possible presence of a strong resonance within the Gamow energy range (E_{cm}~1.5 MeV) which should completely dominate the reaction rate at the densities and temperatures typical of carbon burning in stars. In this paper we explored the impact of such an hypothetical strong resonance at E_{cm}~1.5 MeV on the general behavior of carbon burning in stars and in particular its impact on the value M_{UP} (the maximum mass of the AGB stars) and on the presupernova evolution and the following explosion of massive stars. We found that the presence of an hypothetical resonance in the cross section of the $^{12}C+^{12}C$ reaction at E_{CM}=1.7 MeV, with a maximum strength limited by the presently measured value low energy (2.10 MeV), has the following consequences.

1) Carbon burning in massive stars is more efficient than in the standard case, therefore it would produce less compact presupernova structures that, in turn, would have smaller remnants than their corresponding standard models. Thus, for the same explosion energy, the limiting mass between neutron star and black hole forming supernovae is increased compared to the standard case. Moreover, the reduction of the fallback mass would imply the increase of the maximum mass contributing to the enrichment of the interstellar medium with heavy elements. A quantitative determination of these two quantities would require the calculation of a full set of presupernova models and their associated explosions.

2) A higher value of the $^{12}C+^{12}C$ cross section implies that C burning is ignited at lower temperatures. Therefore, the maximum mass able to ignite C off-center is lowered from M_{UP}=7÷8 M⊙ (in the standard case) to M_{UP}=4÷5 M⊙ (in the test case). This, in turn, would

imply i) a reduction of the maximum mass exploding as Type Ia SN; ii) the increase of the CCSNe/SNIa ratio (CCSNe means Core Collapse Supernovae); iii) a changing of the history of galactic chemical enrichment, and in particular that of the alpha elements (mainly produced by CCSNe) realtive to Fe (mainly produced by SNIa); iv) an increase of the ONeMg WD/CO WD ratio.

All these effects clearly demonstrate the astrophysical relevance of the $^{12}C+^{12}C$ reaction and hence that reliable measurements of the cross section of this process down to the Gamow energies are strongly needed.

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