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Do we really know M_{up} (i.e. the transition mass between Type Ia and core-collapse supernova progenitors)?

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Do we really know M_{up} (i.e. the transition mass between Type Ia and core-collapse supernova progenitors)?

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Abstract. M_{up} is the minimum stellar mass that, after the core-helium burning, develops temperature and density conditions for the occurrence of a hydrostatic carbon burning. Stars whose mass is lower than this limit are the progenitors of C-O white dwarfs and, when belong to a close binary system, may give rise to explosive phenomena, such as novae or type Ia supernovae. Stars whose mass is only slightly larger than M_{up} ignite C in a degenerate core and, in turn, experience a thermonuclear runaway. Their final fate may be a massive O-Ne WDs or, if the core mass approaches the Chandrasekhar limit, an e-capture SNe. More massive objects ignite C in non-degenerate conditions. These "massive " stars are the progenitors of various kind of core-collapse supernovae (type IIp. IIL, IIN, Ib, Ic). It goes without saying that M_{up} is a fundamental astrophysical parameter. From its knowledge depends our understanding of the SNe progenitors, of their rates, of the chemical evolution, of the WD luminosity functions and much more. A precise evaluation of M_{up} relies on our knowledge of various input physics used in stellar modeling, such as the plasma neutrino rate, responsible of the cooling of the core, the equation of state of high density plasma, which affects the heating of the contracting core and its compressibility, and some key nuclear reaction rates, such as, in particular, the $^{12}C+^{12}C$ and the $^{12}C+\alpha$. In this paper we review the efforts made to determine this important parameter and we provide an up-to-date evaluation of the uncertainties due to the relevant nuclear physics inputs.

1. Introduction

At the end of the core-He burning, stars with $M \leq 10\ M_{\odot}$ develop a degenerate C-O core surrounded by a He-burning shell. While the He burning moves progressively outward, the core becomes more massive, contracts and heats up. Owing to the progressive increase of the pressure of the degenerate electrons, the contraction rate slows down. Meanwhile, plasma neutrinos are efficiently produced near the centre, so that the central temperature reaches a maximum and, then, decreases. As a consequence, the highest temperature within the star moves outward, toward the external border of the C-O core. In intermediate mass stars the growth of the C-O core is stopped by the occurrence of the second dredge up, when the convective envelope penetrates into the H-exhausted core attaining layers located immediately above the shell He-burning. In summary, owing to the simultaneous actions of i) electron degeneracy, ii) neutrino cooling and iii) the second dredge up, only the more massive stars, those with a sufficiently large C-O core, may attain the physical conditions for the C ignition. In practice, the C ignition must occur before that the second dredge up is completed, otherwise temperature and density remain below the critical values.

The minimum initial mass of a single star able to experience a C-burning phase is called M_{up} [1]. If the initial mass is lower than M_{up}, after the second dredge up a star enters the AGB phase, during which the H-rich envelope is almost completely eroded by a huge stellar wind. These stars end their life as C-O white dwarfs (WDs). If they belong to a close binary system, the interaction with the companion stars may lead to explosive phenomena like Novae, cataclysm variables, low-mass X-ray binaries or type Ia supernovae. On the contrary, if the mass is slightly larger than M_{up}, an off-centre C ignition takes place in degenerate conditions, giving rise to a thermonuclear runaway followed by a quiescent C burning [2]. As a consequence, the star develops a degenerate O-Ne core and enters a super-AGB phase. The final fate of super-AGB stars is not very well known. Depending on the mass loss rate, they may lose the whole envelope ending their life as massive O-Ne WDs [3]. Alternatively, if the core attains the Chandrasekhar mass limit before the end of the super-AGB phase, a supernova triggered by electron captures may occur. Finally, more massive objects ignite carbon in the centre of a non-degenerate core. After the C burning, they experience the well-known sequence of central burnings (O, Ne, Si) until the formation of an iron core. These stars are the progenitors of "normal" core-collapse supernovae (type IIp, IIL, IIN, Ib, Ic). The scenario described so far is summarized in Figure 1.

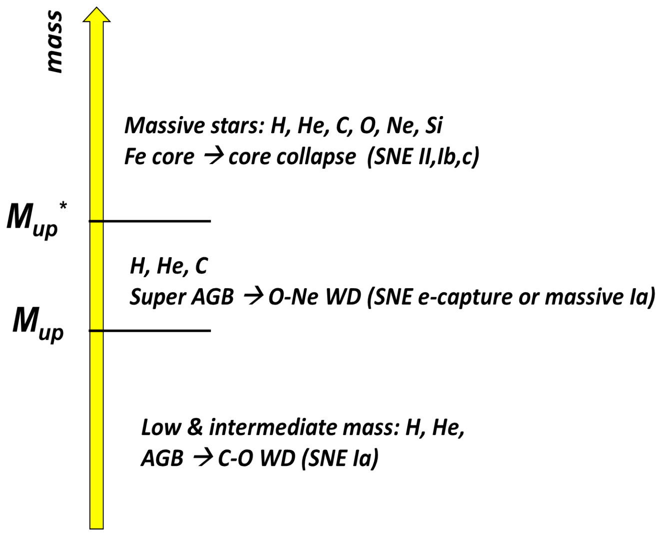

Figure 1. A scheme showing how the evolution of a star and its final fate change with the initial mass. M_{up} is the minimum initial mass of the stars that ignited C in a degenerate C-O core, while M_{up}^* is the minimum mass for a non-degenerate C ignition.

The first systematic attempt to determine the value of M_{up} was done by [1]. They provided an analytical relation between M_{up}, the metallicity (Z) and the initial helium content (Y). For a nearly solar composition, i.e. Z=0.02 and Y=0.28, this relation gives M_{up} = 9 $M_{\odot}$. In the last 20 years many improvements in the physics inputs needed to derive this relations have been obtained. In particular, we have now a much better knowledge of the equation of state [4, 5], of the radiative opacity [6] or of the neutrinos production rate [7, 8, 9]. An up-to-date version of this relation is plotted in Figure 2. The corresponding value of M_{up} for the revised solar composition is 7.8 $M_{\odot}$.

In this paper we analyse the uncertainties affecting such a relation. First of all, M_{up} depends on the relation between the initial mass and the mass of the H-exhausted core at the end of the core-He burning (M_H). The larger this core mass, the larger the maximum temperature attained within the core during the post core-He burning phase. M_{up} also depends on the amount of C left in the core at the end of the He burning, a quantity that directly affect the carbon burning rate. Both this quantities are the

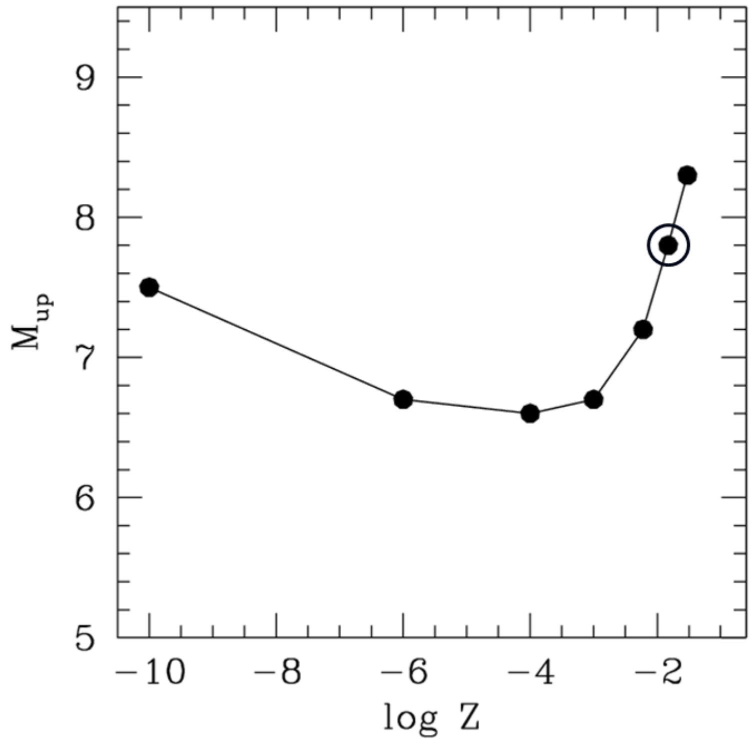

Figure 2. Variation of M_{up} with Z. The circled point corresponds to the solar metallicity

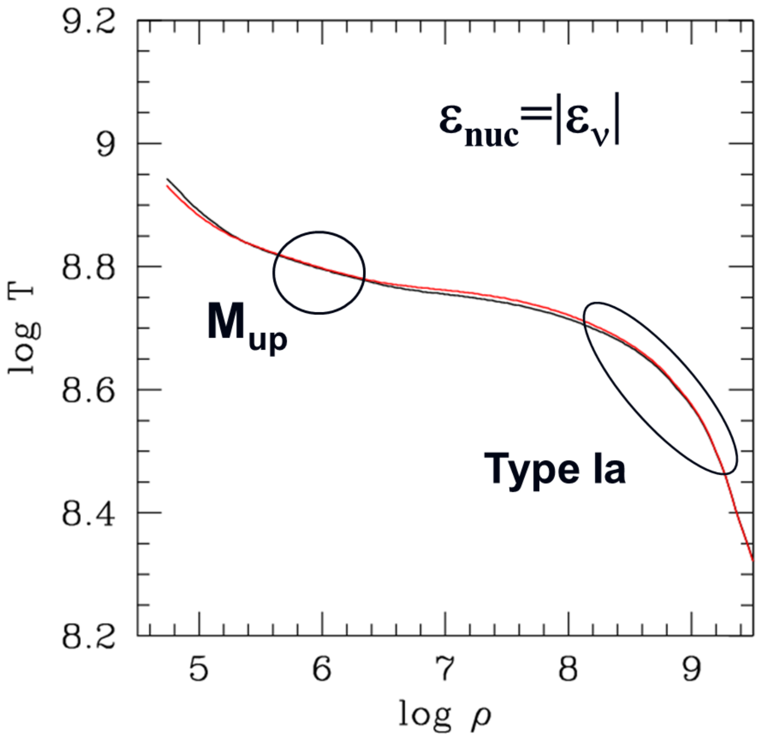

Figure 3. The carbon ignition curve (see text for the definition). The red and the black curves have been obtained under different assumptions for the neutrinos production rate, namely: [8] (red) and [9] (black). The two circled regions correspond to the typical ignition conditions for core-C burning in single massive stars and type Ia supernovae, respectively.

legacy of the evolutionary phases preceding the C burning. The core mass developed by a star with a given initial mass, for example, is affected by uncertainties in the determination of the extension of the convective core during both the core-H and the core-He burnings. On the other hand, the amount of carbon left in the core by the He burning depends on the adopted rate of the $^{12}C(\alpha,\gamma)^{16}O$ reaction.

Other uncertainties are directly connected to the physical description of the structure of the degenerate C-O core when the star approaches the C ignition. Figure 3 show the so-called ignition curve, i.e a line in the log T – log ρ plane on which the nuclear energy production rate is equal to the neutrinos energy loss rate. In stars with $M< M_{up}$ the core peak temperature always remain below this curve so that they skip the C burning. The locations of the C ignition in stars with $M>M_{up}$ as well as in progenitors of type Ia SNe are also shown. The following sections are mainly focused on the possible variations of the estimated value of M_{up} due to uncertainties affecting some key reaction rates, namely the $^{12}C(\alpha,\gamma)^{16}O$, the $^{12}C(^{12}C,\alpha)^{20}Ne$ and the $^{12}C(^{12}C,p)^{23}Na$.

2. The $^{12}C(\alpha,\gamma)^{16}O$ reaction rate and its impact on M_{up}

This reaction plays a fundamental role during the late part of the He-burning phase [10, 11]. In particular, its competition with the 3α reaction determines the amount of C (and O) left in to the core. Since the carbon-burning rate depends by the square of the C abundance, this quantity directly affects the value of M_{up}. However, a change of the $^{12}C(\alpha,\gamma)^{16}O$ rate also affect the core-He-burning lifetime and, in turn the final value of M_H.

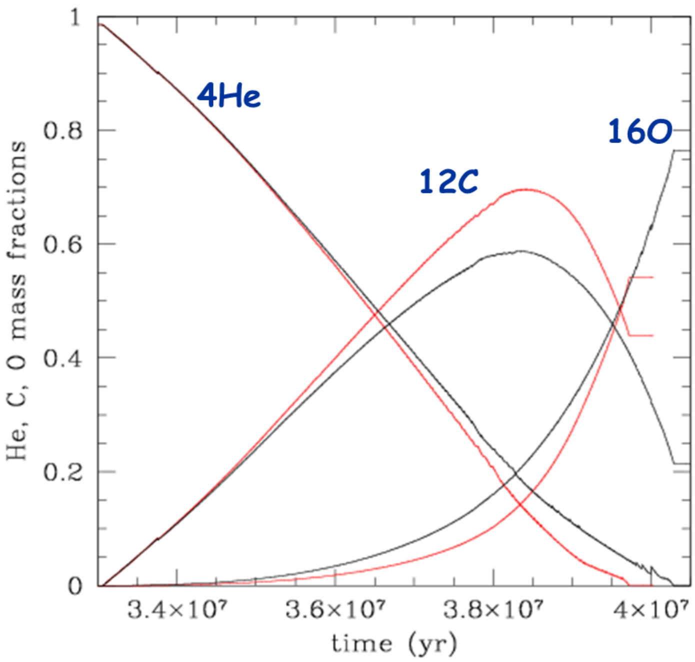

Figure 4. Core-He burning phase in a 7.6 $M_{\odot}$ model (solar composition). Evolution of the central mass fractions of ^{4}He, ^{12}C and ^{16}O. The black lines correspond to the model computed with S(300)=160 keVb for the $^{12}C(\alpha,\gamma)^{16}O$, while the red lines correspond to the model with S(300)=80 keVb.

The He burning in intermediate mass stars occurs at a temperature of about 100-200 MK corresponding to a Gamow's peak energy of about 300 keV. The latest experimental investigations on this reaction rate (see [12, 13] and references therein) converge on an S(300 keV) ~160 keVb. However, the available measurements con not definitely exclude a destructive resonant configuration for this reaction. In that case, the E1 contribution, which account for about half of the total astrophysical factor at 300 keV would be fully suppressed.

According to such a consideration, we have compared stellar models obtained under opposite assumptions for the S(300) , namely 160 and 80 keVb. The result is illustrated in Figure 4.

The final central C mass fraction scales inversely with S(300), namely $X(^{12}C)=0.42$, in the S(300)=80 keVb model (red lines), and $X(^{12}C)=0.21$, in the S(300)=160 keVb model (black lines). On the contrary, the higher the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate, the longer the He-burning lifetime, and, in turn, the larger the final core mass. As a result, M_H at the end of the core-He burning is 1.66 and 1.77 $M_\odot$ for the 80 and 160 keVb model, respectively. In practice, the increase of the core mass compensates the decrease of the C mass fraction within the core, so that M_{up} remains almost unaffected by the change of the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate.

3. The $^{12}C+^{12}C$ reaction rate and its impact on M_{up}

A change of this reaction directly affects the C ignition curve (see section 1). The Gamow's peak energy for the C burning in massive stars is about 1.5 MeV, while the available experimental investigations barely attain a lower limit of about 2.5 MeV (see [14, 15] and references therein). In the last years it has been speculated about the occurrence of a narrow resonance between 1.3 and 1.7 MeV [16, 17]. The effect of such a resonance on the estimated value of M_{up} would be dramatic.

Table 1. Variations of M_{up} with the $^{12}C+^{12}C$ rate at different Z

Z	M_{up} ($M_\odot$)	
	CF88	CF88 + 1.4 MeV res.
0.0001	6.6	4.5
0.0010	6.7	4.7
0.0060	7.2	5.3
0.0149	7.8	5.8
0.0300	8.3	6.1

Figure 5 illustrate the resulting variation of the ignition curve. The black curve has been obtained by using the rate published in [14] (CF88), whereas an additional contribution due to a narrow resonance at 1.4 MeV has been added in the red curve calculation (for the details see section 2 in [17]). The corresponding values of M_{up} are reported in Table 1. If such a resonance really exists, M_{up} would be up to 2 $M_\odot$ smaller.

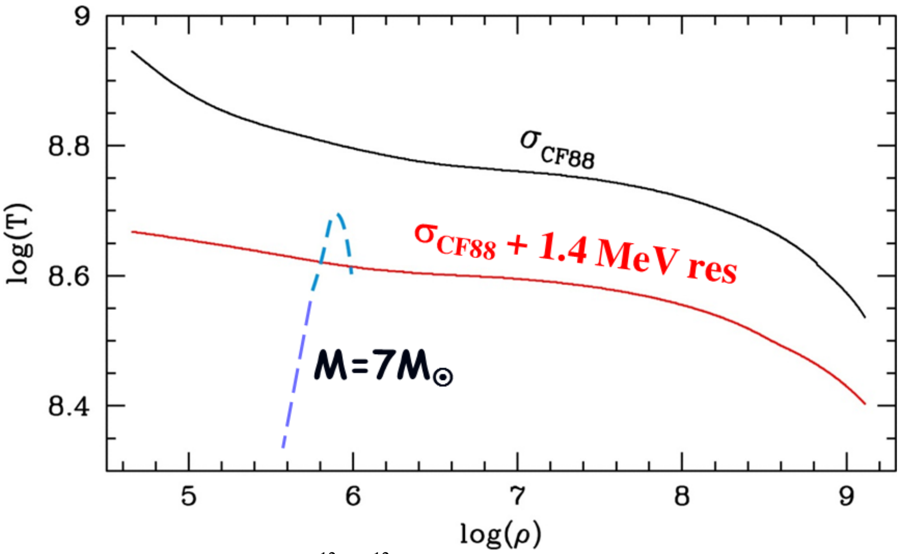

Figure 5. Carbon ignition curve and the $^{12}C+^{12}C$ reaction. Effects of a hypothetical narrow resonance at E=1.4 MeV. The dashed line represents the evolution of the maximum temperature within the core of a 7 $M_\odot$ model, when the additional resonant contribution is 0.

4. Conclusions

In spite of the many progresses made in our understanding of stellar physics, a precise evaluation of M_{up} is still missing. In this paper we have shown how a change of the $^{12}C+^{12}C$ reaction rate may substantially affect M_{up}.

The astrophysical consequences would be extremely important. Moving up or down the M_{up} value, a change of the mass range of supernova progenitors is expected. Depending on the steepness of the mass function, e.g. a power law MF with exponent 2.35 is adequate for the galactic disk [18], the supernova rate would drastically change. For example, we have calculated that a reduction of about 2 $M_\odot$ of M_{up} would reduce the type Ia frequency up to a factor of 4, either in single or double degenerate scenarios. Since in this case the promptest SNe are suppressed, i.e. those with more massive progenitors, the onset of the SNe Ia chemical pollution would be significantly delayed.

Concerning core-collapse SNe (e-capture SNe included), the minimum mass of the progenitors would be significantly reduced. For example, if M_{up}=6 $M_\odot$, the smallest "normal" core-collapse progenitor, i.e. the supernovae powered by the collapse of an iron core, is about 8 $M_\odot$, in good agreement with recent surveys devoted to the search of SNe IIp progenitors which found 8.5 ($_{-1.5}^{+1}$) $M_\odot$ [19]. By adopting a Salpeter's MF, the ratio between super-AGB stars, possible progenitors of e-capture SNe, and the more massive stars progenitors of "normal" core collapse SNe is 0.57, 0.45 or <0.45 when M_{up} is 6, 8 or >8 $M_\odot$, respectively[1].

A reduction of M_{up} of about 2 $M_\odot$, as due to a substantial increase of the $^{12}C+^{12}C$ rate, would reduce the maximum C-O white dwarf mass from 1.1 down to 0.95 $M_\odot$. Accordingly, the minimum mass for a O-Ne WD would be significantly reduced, while their fraction with respect to the total number of WDs would increase.

[1]These calculations have been made by assuming that the mass range of super–AGB stars is 6-8 or 8-10 $M_\odot$, while the mass range of core-collapse SNe progenitors is 8-30 or 10-30 $M_\odot$. In both cases *dN/dm* is proportional to $m^{-2.35}$.

Finally, the maximum mass of the stars that experience an AGB phase follows the variations of M_{up}. This occurrence have relevant effects on the contribution of massive AGB to the galactic chemical evolution. Indeed, only the more massive AGB stars develop the high temperature at the base of the convective envelope required for the activation of proton capture reactions (the so called *hot bottom burning*, HBB). Therefore, a reduction of the maximum AGB mass would imply a reduction of the number of stars undergoing hot bottom burning.

In summary, a precise evaluation of the $^{12}C+^{12}C$ rate at E ≈1.5 MeV is a necessary condition to improve our knowledge of M_{up} and of many related astrophysical open issues. On the contrary, we have shown that M_{up} is almost insensitive to a variation of the $^{12}C+\alpha$ reaction rate.

On the other hand, a reliable evaluation of M_{up} also requires a better understanding of the initial-mass to final-core-mass relation. This task implies an adequate evaluation of the effects of rotation on the evolution of intermediate mass stars and, in particular, an improved comprehension of the mechanisms controlling angular momentum transport and rotational induced mixings. As a matter of fact, larger stellar lifetime might result when rotation is included in stellar models, thus leading to larger core masses. In addition, as shown by [20], the onset of the second dredge up is delayed in fast rotating models. These occurrences may obviously affect the estimated value of M_{up}. Finally, deviations from the *standard model* of the particle physics may also modify the derived value of M_{up}. For example, axions are elementary particles introduced by Peccei and Quinn to solve the strong CP violation problem and are considered possible dark matter candidates. They may be produced within the degenerate C-O core of a star approaching the C burning [21]. Like neutrinos, axions cool down the core, thus preventing the C ignition.

From the discussion presented in this paper, we may conclude that M_{up} is the astrophysical *Saint Graal*[2]. Its search would imply a synergy between theoretical and observational astrophysics, nuclear physics and theoretical physics.

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