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Influence of the ^{12}C$(\alpha,\gamma)^{16}$O reaction rate on the evolution of a 15 $M_\odot$ star

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In this paper we present the evolution of various 15$M_\odot$ stellar models of solar and sub-solar chemical composition, calculated using different values for the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate. This process influences the evolution of a star because it directly operates during the helium burning and it determines the final abundances of ^{12}C and ^{16}O left by this burning. Since this reaction works in a convective environment an analysis of its influence on the evolution of a star cannot be disentangled by the behavior of the convective core. Indeed the final ^{12}C and ^{16}O abundances largely depend on a delicate balance between the efficiency of this rate and the treatment of the convective core. We will show some tests which indicate quantitavely this interplay.

1. INTRODUCTION

The $^{12}C(\alpha,\gamma)^{16}O$ process influences the evolution of a star essentially in two respects: first, it affects the He burning because it directly operates in this evolutionary phase, and, second, it determines all the further evolution of a star because it controls the chemical composition of the matter left by the He burning. Since all stars more massive than, say, $0.55M_\odot$ burn He, it is clear that the $^{12}C(\alpha,\gamma)^{16}O$ process will affect the evolution of stars in a very large mass interval. Moreover, since the dominant (energetic) process during almost all the helium burning is the triple-α reaction, a changing of the $^{12}C(\alpha,\gamma)^{16}O$ rate is not counterbalanced by a thermal readjustment of the core but, instead, it fully reflects on the evolution of a stellar model.

From an experimental point of view, despite the enormous efforts devoted to the measurement of this cross section, the corresponding rate at astrophysical energies is still

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far from being well established. In the past twenty-five years many experiments have been performed, most of them based on the detection of γ-rays from α capture in direct or inverse kinematics [1][2][3][4][5][6][7][8][9]. All these measurements extend to a minimum energy of about 1 MeV: below this energy, the extremely small value of the cross section ($< 10pb$) hampers direct detection of γ-rays. Then extrapolation procedures have to be used in order to extract the astrophysical S-factor at the relevant energies ($E_0 = 300keV$ for $T_9 = 0.18$). The cross section around the Gamow peak is dominated by four contributions: the E1 amplitudes due to the low-energy tail of the 1^- resonance at $E_{cm} = 2.42\,MeV$ and to the subthreshold resonance at $-45\,keV$, and the E2 amplitudes due to the 2^+ subthreshold resonance at -245 keV and to the direct capture to the ^{16}O ground state, both with the corresponding interference terms.

A global analysis [10] of all available data (surface fit) including γ decay following α capture from ^{12}C, elastic scattering of α particles from ^{12}C [4] and α emission following β^- decay of ^{16}N [11][12] yielded a wide range (from $62\,keV \cdot b$ to $270\,keV \cdot b$) for the extrapolated S-factor. These values, for $T_9 = 0.18$, correspond to a minimum and maximum reaction rates of $0.5 * 10^{-15}$ and $2.2 * 10^{-15} cm^3/(mol \cdot s)$, which can be compared to the data reported in the compilations of Caughlan & Fowler of 1988 [13] ($N_A\sigma v = 0.8 * 10^{-15} cm^3/(mol \cdot s)$) and of 1985 [14] ($N_A\sigma v = 1.9 * 10^{-15} cm^3/(mol \cdot s)$), which are generally used in stellar evolution calculations. Finally, a recent compilation [15] yields $N_A\sigma v = 0.9 * 10^{-15} cm^3/(mol \cdot s)$ and $N_A\sigma v = 2.1 * 10^{-15} cm^3/(mol \cdot s)$ as lower and upper bounds for the reaction rate, whose adopted value is $N_A\sigma v = 1.5 * 10^{-15} cm^3/(mol \cdot s)$.

Theoretical efforts devoted to constrain the rate of this process on the basis of some "observables" have been initiated by Arnett, first, and by Weaver and Woosley, later. Arnett [16] was the first to point out that the observed solar abundances of C and O could be used to constrain the efficiency of the $^{12}C(\alpha,\gamma)^{16}O$ cross section. On the same guideline, Weaver and Woosley [17] also tried to fix this rate by comparing the yields obtained by adopting different rates for this process to the solar chemical composition. Both these approaches require, among other things, that the final abundances of ^{12}C and ^{16}O depend only on the efficiency of $^{12}C(\alpha,\gamma)^{16}O$ reaction rate. Unfortunately this is not necessarily the case, since this process works in a convective environment which may alter, also significantly, the final abundances of ^{12}C and ^{16}O. In the following we will explore such a possibility and we will present a preliminary analysis of the interplay between mixing and $^{12}C(\alpha,\gamma)^{16}O$ rate in determining the ashes of the He burning.

All the evolutionary tracks have been computed with the latest release (4.8) of FRANEC (Frascati RAphson Newton Evolutionary Code) whose earliest and latest version have been presented by Chieffi and Straniero (1989)[18] and Chieffi, Limongi and Straniero (1998)[19]. All the latest available input physics have been adopted as discussed in Straniero, Chieffi and Limongi (1997)[20]. The network adopted in the present sets of models includes 19 isotopes. No mass loss has been included.

2. THE HELIUM BURNING

We followed the evolution of stellar models of $15M_\odot$ having Z=0.02 and Y=0.285 and Z=0.001 Y=0.23 from the MS up to the central He exhaustion. These evolutions have been computed for two choises of the $^{12}C(\alpha,\gamma)^{16}O$ rate, i.e., the one computed by Caughlan &

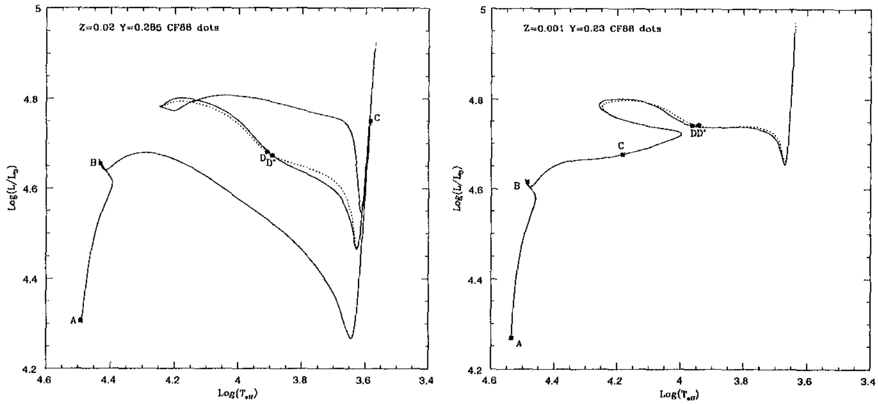

Figure 1. Path followed by the $15M_\odot$ in the HR diagram: the solid and dotted lines represent the evolutions obtained by adopting, respectively, the CF85 and CF88 rates of the $^{12}C(\alpha,\gamma)^{16}O$. The left and right panels refer, respectively, to the solar (Z=0.02) and subsolar (Z=0.001) cases. Points **A** and **B** represent the beginning and the end of the H burning, **C** the beginning of the He burning, while **D** and **D*** mark the end of the He burning for the CF88 and CF85 rates, respectively

Fowler in 1988 [13] (here and after CF88) and the one in 1985 [14] (here and after CF85) respectively. In both cases the Schwarzschild criterion was adopted with the inclusion of both the "induced" overshooting and semiconvection [21] during the central He burning phase; the possible occurrence of the so called Breathing Pulses (BP) has been inhibited according to [21].

Table 1 summarizes for both metallicities, solar (Z=0.02) and subsolar (Z=0.001), and for the low (CF88) and high (CF85) values of the reaction rate, the main evolutionary properties. Starting from the first row we report: the central He burning lifetime, the Carbon and Oxygen abundances left by the He burning, the maximum size of the convective core and the final He core mass at the He exhaustion. Fig. 1 shows the path followed by the $15M_\odot$ solar (left panel) and sub solar (right panel) stellar models in the HR diagram: the solid and dotted lines refer to models computed, respectively, with the CF85 and CF88 rates.

The direct effect of the $^{12}C(\alpha,\gamma)^{16}O$ rate on the He burning phase is essentially threefold: first of all it affects the "lifetime"; second it may alter the path followed by the stellar model in the HR diagram; and, third, it may change the time spent by the model on the different parts of the HR diagram. From Table 1 and Figure 1 it can be easily seen that a) for both metallicities the influence on the lifetime never exceeds 9%; b) the path followed by these models in the HR diagram is essentially unaffected by the quoted changing of this rate; and c) also the time spent by the models in the different parts of HR diagram is only very marginally affected. The last, but not least, thing worth noting is that, for both metallicities, a variation of the $^{12}C(\alpha,\gamma)^{16}O$ from the CF88 rate to the CF85 one leads to a reduction of more than a factor of two in the final Carbon abundance.

Table 1
Main evolutionary properties of the tests discussed in the text. Starting from the first row we report: the central He burning lifetime, the Carbon and Oxygen abundances left by the He burning, the maximum size of the convective core and the final He core mass at the He exhaustion. Test "A" refers to a run without "induced" overshooting and semiconvection, test "B" refers to a run computed by artificially increasing the size of the convective core by **1 $\mathbf{H_p}$** while test "C" refers to a run in which a small amount of overshooting (0.1 H_p) is imposed only when the central He abundance drops below 0.075 by mass fraction.

	$Z = 0.02$		$Z = 0.001$		$TestA$	$TestB$	$TestC$
	CF88	CF85	CF88	CF85	CF88	CF88	CF88
$t_{He}(Myr)$	1.21	1.32	1.26	1.37	1.14	1.57	1.47
X_{12C}	0.487	0.220	0.480	0.214	0.501	0.480	0.256
X_{16O}	0.491	0.761	0.509	0.778	0.485	0.495	0.723
$M_{CC}^{He}(M_\odot)$	2.28	2.39	2.46	2.57	2.12	3.28	2.63
$M_{He}^{fin}(M_\odot)$	4.31	4.37	4.47	4.52	4.31	4.45	4.36

Once this classical "reference" scenario is set up, it is possible to explore if, and at what extent, these results depend on the adopted treatment of convection. The starting reference model is the 15 $M_\odot$ of solar metallicity computed by adopting the CF88 rate and by including both the "induced" overshooting and semiconvection during the central He burning phase. In order to study the dependence of the final C abundance on the size of the convective core we have computed two additional models: in the first one we have adopted strictly the Schwarzschild criterion (no "induced" overshooting and no semiconvection), see column 5 in tab.1 (test A), while in the second one we adopted a large mechanical overshooting ($1H_p$) (test B), see column 6. In spite of the big difference in the size of the convective cores, the final carbon abundance left at the central He exhaustion is in both cases very similar to the one obtained in the "standard" case (column 1 in table 1). This is not a surprising result because a simple changing of the size of the convective core does not alter appreciably the run of neither the central temperature nor the density versus the central He abundance, and hence the rate at which He is converted in C, and C in O, is not significantly altered by such a change. The only thing which changes in these tests is the total burning time because the available "reservoir" grows with the size of the convective core (see first row of the table). However, this picture changes drastically if one allows the convective core to grow just when most of the conversion from C to O occurs, i.e. when the He drops below, say, 0.1 by mass fraction. In fact in this situation the helium ingested by the advancing convective core is mostly captured by carbon due to more efficiency of the $^{12}C(\alpha,\gamma)^{16}O$ rate with respect to the 3α one. This occurs if one does not manually inhibit the BPs, whose main effect is that of redusing the final Carbon abundance by almost 0.1 by mass fraction. Of course the inclusion of the BP is not the only way in which one may have an ingestion of small quantities of fresh He towards the end of the He burning. Another possibility could come from the use of the Ledoux criterion coupled to a specific (and arbitrary) treatment of the region in which the radiative stability is granted only by the existence of a gradient of molecular weight. In order to mimic such an occurrence we show as an example (test C) in table 1 a test evolution in which 0.1 H_p of overshooting has been included just when the central He burning drops below 0.075 by mass fraction. In this case the final carbon abundance closely resembles the one obtained by adopting the CF85 rate.

We conclude that the details of the mixing technique adopted to treat the mixing in the last part of the central He burning may drastically affect the final Carbon abundance. Hence a better experimental knowledge of this cross section will also help to shed light on the efficiency of the convective instabilities which may or may not occur during the latest phases of the He burning.

In a forthcoming paper we will provide a much deeper insight in this problem together with a discussion of the dependence of the explosive yields (of a 25 $M_\odot$) on the Carbon abundance left by the He burning.

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