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Challenges for nuclear astrophysics: low mass stars

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Abstract. Our understanding the evolution of galaxies in terms of energetic outputs (brightness), colors (temperature) and chemistry depends on the precise knowledge of the cross sections of the key nuclear processes controlling the rate of H and He burning in stars. The importance of the recent developments in nuclear astrophysics studies devoted to the comprehension of these reactions and their relevance for astrophysics, from the age of the oldest stellar population of the Milky Way to the yields of core-collapse supernovae, are reviewed.

Key words. stellar physics – H burning stars He burning stars

1. Introduction

The majority of the stars seen from Earth are low mass H-burning stars. In the core of Sirius, the brightest star in the north hemisphere, or in a thin shell surrounding the H-exhausted core of Arcturus, a red giant template, hydrogen is burned via the CNO cycle, whereas in sub-dwarf stars, like the Sun or α-Cen, the pp chain is the main source of energy. Modelling these stellar structures implies the precise knowledge of a few nuclear processes, the bottlenecks, which controls the rate of energy production, namely: the p(p,$e^+\nu$)d, for the pp chain, and the ^{14}N(p,γ)^{15}O, for the CNO cycle. More rare in the night sky, core He burning stars can be easily identified in the color-magnitude diagrams of Globular Clusters belonging to the Galaxy or to the Magellanic Clouds: they populate the so called horizontal branch. Asymptotic Giant Branch (AGB) stars are even more rare objects. In these bright red giants, the He burning takes place in a shell located immediately outside their carbon- and oxygen-rich core. In all cases, the energy production of core- and shell-He burning is controlled by two competing processes, the 3α and the ^{12}C$(\alpha,\gamma)^{16}$O.

Huge efforts have been done in experimental and theoretical nuclear astrophysics studies to evaluate the rates of these key reactions. In stellar environments, H and He burning occur at energy ranging between 10 and 300 KeV and only underground laboratories, where the cosmic background is significantly reduced, provide favorable conditions for the direct measurements of the relevant reaction rates. In some cases, however, the contamination from terrestrial radioactive decays makes more difficult to attain such a low energy range, even in underground measurements.

In this paper, we discuss the astrophysical implications of recent progresses in the determination of these reaction rates.

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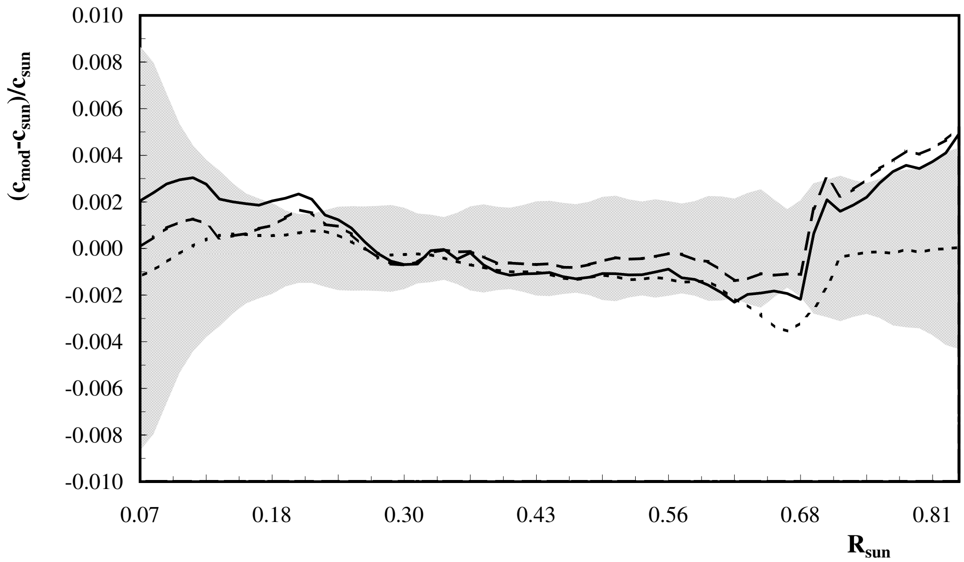

Fig. 1. Comparison between measured and predicted sound velocity profiles in the solar interior. This figure shows the power of helioseismology to constrain the relevant nuclear reaction rate of the pp-chain. The different lines represent models obtained by using different compilations of nuclear astrophysics data. The dashed area represents the allowed values, according to seismic solar measurements.

2. p(p,$e^+\nu$)d

The rate of the slower reaction of the pp chain is so low that, at present, it cannot be directly measured in laboratory. Few experimental indications are derived from the measured properties of deuteron and from proton-proton scattering. In practice, however, only theoretical evaluations are available for stellar model calculations.

It exists a substantial agreement among the different theoretical approaches on the value of the astrophysical factor at 0 energy, i.e. $4.05(\pm 0.16) \times 10^{-25}$ MeV b (see e.g. Bahcall & Pinsonneault 1992). The best indirect constraints come from helioseismology. In particular, the temperature in the core of the Sun is highly sensitive to the p(p,$e^+\nu$)d reaction rate (see Straniero et al. 1997). According to Degl'Innocenti, Fiorentini & Ricci (1998), the astrophysical factor for the bottleneck of the pp chain cannot differ by more than 15% from that obtained by the extant theoretical calculations.

3. ^{14}N$(p,\gamma)^{15}$O

The bottleneck of the CNO cycle has been recently investigated by the LUNA collaboration in the underground laboratory at LNGS. Measurements have been firstly extended down to about 100 KeV (Imbriani et al. 2005), by using a solid target, and then down to 70 KeV, by means of a gas target (LUNA Collaboration 2006). Note that this measurements covers the Gamow-peak energy of shell-H burning in red giant stars and provide stringent constraints for the evaluation of the CNO rate at the lower energies of the core-H burning (main sequence stars). As a results, the new rate is 40% lower than previously estimated.

The first important application concerns the evaluation of the age of Globular Clusters, representing the oldest stellar population of the Milky Way (Imbriani et al. 2004). Stellar clusters are groups of stars with similar ages and chemical compositions, but different masses. It was early recognized that the older the clus-

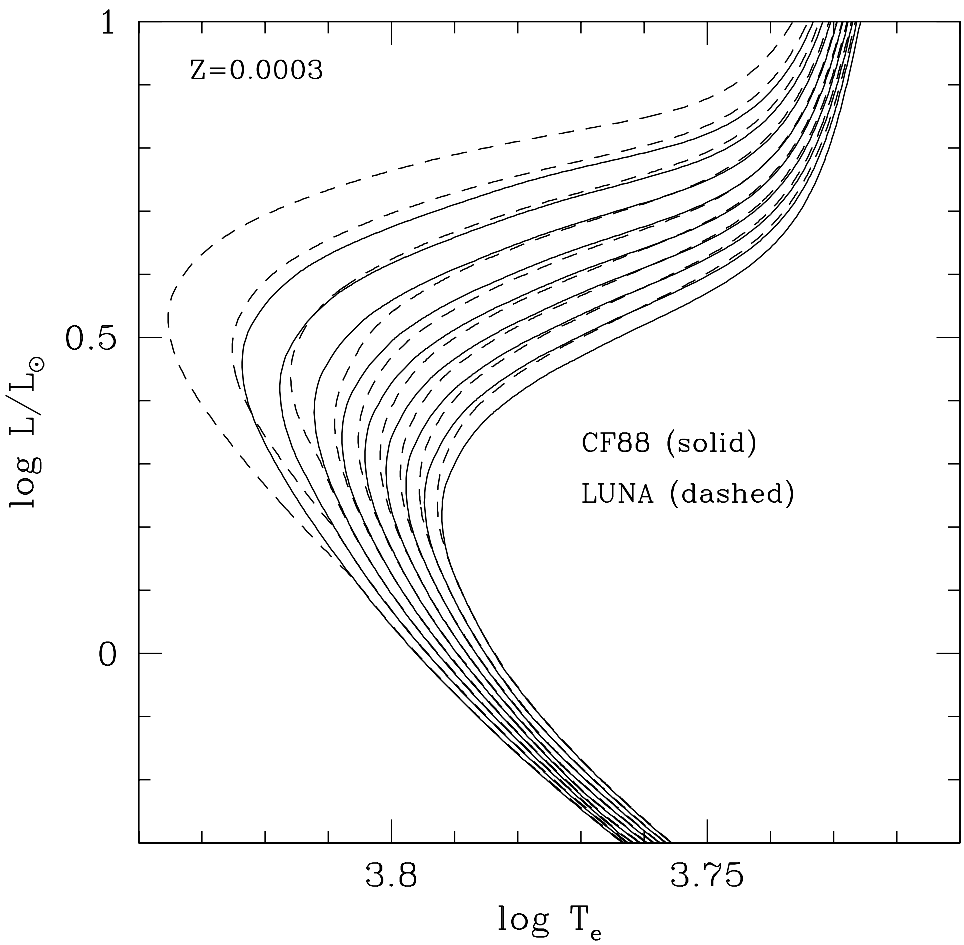

Fig. 2. Isochrones for Globular Cluster Stars, as obtained by using the old and the new rate of the $^{14}N(p,\gamma)^{15}O$ reaction.

ter, the fainter the tip of the main sequence in the observed color-magnitude diagrams. This occurs because the H-burning is faster in massive stars, so that the main sequence of a stellar cluster becomes progressively depopulated of the brightest (more massive) stars. For this reason, the turn off luminosity, namely the luminosity of the bluest point of the main sequence, is a fundamental age indicator for these group of stars. The method used to date these stellar systems requires the knowledge of the distance, the light extinction along the line of sight and the original chemical composition of the stars. The measure of these parameters is matter for astronomers. In addition to that, we need a reliable theoretical calibration of the age-turnoff luminosity relation. This relays on our knowledge of the physical processes of energy generation and transport taking place in H-burning low mass stars.

By comparing our latest theoretical isochrones (Imbriani et al. 2004), based on the $^{14}N(p,\gamma)^{15}O$ reaction rate provided by LUNA, with the color magnitude diagrams of

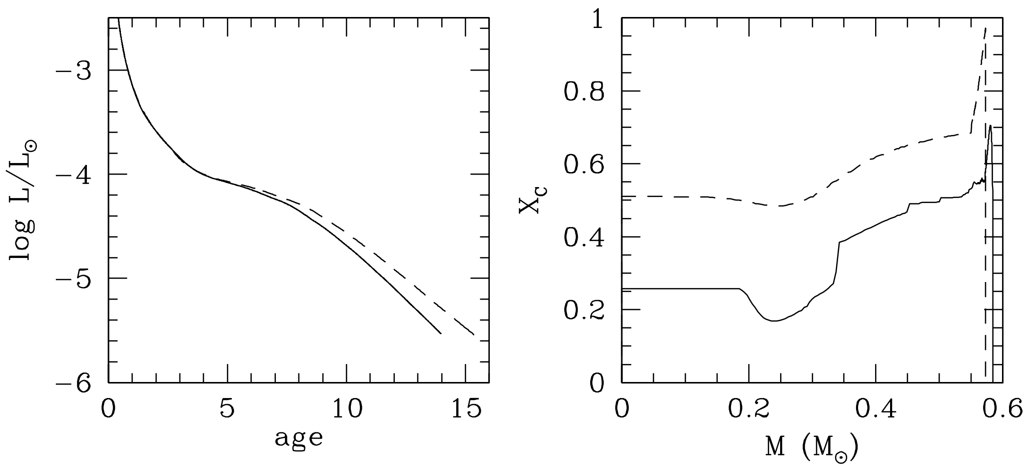

Fig. 3. Left panel: cooling time scale of a White Dwarf (0.6 $M_\odot$) under different assumption on the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate. Right panel: corresponding internal profiles of the carbon mass fraction.

35 GCs belonging to the Milky Way, we found that the bulk of the GCs is coeval (within a bona fide error of ±1 Gyr), with interesting exceptions at large metallicity ([Fe/H]>1.2). Once the five metal-rich Clusters whose age differs by more than 2 Gyr from that of M15 are excluded, an average age of 13.9 ± 0.7 Gyr is found. Note that the quoted error is a bare standard deviation; it does not include possible systematic errors, as for example those due to the adopted distance scale.

The Globular Clusters age represents a lower limit for the age of the Universe (their formation started about 0.5 − 1 Gyr after the big bang). In that context, the revised value of this age strengthens the need of a positive cosmological constant. Assuming flat geometry (Ω = 1) and $H_0 = 0.72\ Kms^{-1}Mpc^{-1}$ (according to Freedman et al. 2001), a Universe older than 14 Gyr would imply $\Omega_M < 0.22$ ($\Omega_M < 0.35$ within 1 σ error). Note that this upper limit for the matter density is independent of the SNe Ia distance scale. Alternatively, by coupling our result with the constraint derived from high redshift SNe Ia surveys, we may relax the assumption on the geometry of the Universe to derive a stringent upper limit for the Hubble constant. So doing, taking $H_0t_0 = 0.96 \pm 0.04$ (Tonry et al. 2003), the present lower limit for the age of the oldest GB stars would imply $H_O < 67\ Kms^{-1}Mpc^{-1}$ ($H_0 < 77$ within 1 σ), in good agreement with 72 ± 8 obtained by the HST Key Project (Freedman et al. 2001).

A second important result concerns the thermally pulsing asymptotic giant branch stars. In these stars the interplay of H and He burning, coupled with extended convective episodes, leads to the enrichment of the stellar surface with ashes of thermonuclear processes, in particular He, C and s-process elements. As a matter of fact, these stars are considered among the most important chemical polluters in the Galaxy.

In between two subsequent thermal pulses (He-shell flashes), the intermediate He-rich layer increases in mass, as a consequence of the shell- H burning. Then, the rate of CNO cycle affects the thermodynamic properties of the He-rich intershell. In particular, the lower the rate, the larger the density attained within the He intershell. As a result, the ignition of the 3α reactions in a denser environment produces stronger thermal pulses and, in turn, larger carbon dredge up (Straniero et al. 2000; Herwig & Austin 2004).

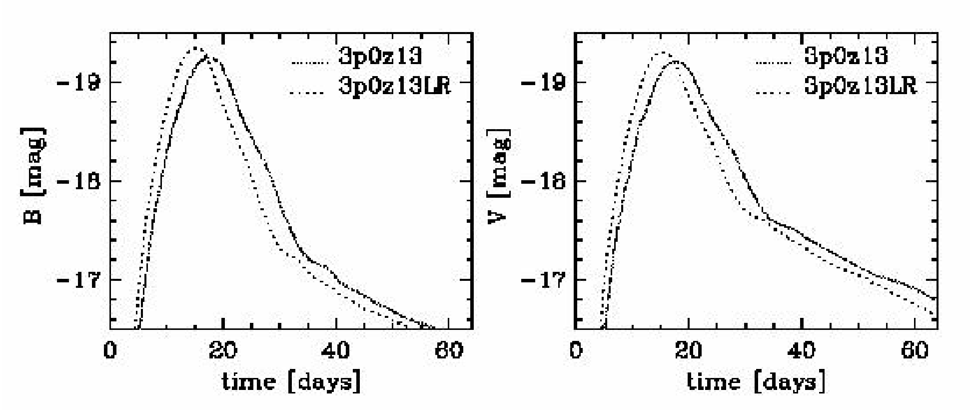

Fig. 4. Theoretical light curves for SNe Ia, under different assumption for the progenitor: in the 3p0z13 case the progenitor is a 3 $M_\odot$, Z=0.001 computed by assuming a high rate for the $^{12}C(\alpha,\gamma)^{16}O$ reaction, while in the 3p0z13low we used a low rate (see Domínguez, Höflich & Straniero 2001).

4. 3α

The triple-α reaction is the main process of He burning within stars of any mass and composition. It concurs with the $^{12}C(\alpha,\gamma)^{16}O$ in the late part of the core He burning. Initially, when the mass fraction of C is low, the triple α dominates the He consumption. Later on, when the central helium mass fraction decreases below 20%, the production of ^{16}O via the $^{12}C(\alpha,\gamma)^{16}O$ becomes a competitive process.

A change in the reaction rate would imply a change in the He-burning lifetime as well as a variation of the amount of C and O produced in the deep stellar interior. Recent re-analysis of this rate found important variations with respect to previous estimations, mainly at low (below 100 KeV) and large (above 1 MeV) energy, but smaller changes (less then 20%) at the relevant astrophysical energy (200-300 KeV). Our checks of the importance of this revised reaction rate show only negligible effects on the calculated He-burning lifetime. It may be possible that more important effects could be found in the evolution of very metal poor massive stars.

5. $^{12}C(\alpha,\gamma)^{16}O$

The importance of the $^{12}C(\alpha,\gamma)^{16}O$ reaction in stellar evolution concerns the fact that it determines the abundances of Carbon and Oxygen within the stellar core at the end of Helium burning (Imbriani et al. 2001; Straniero et al. 2003). For instance, the physical structure of the progenitors of core-collapse SNe depends on the composition of the core after the He burning. For this reason, the resulting explosive nucleosynthesis is affected by the uncertainty on the $^{12}C(\alpha,\gamma)^{16}O$ reaction. On the other hand, the cooling rate of CO White Dwarfs, the end point of the evolution of low and intermediate mass stars, significantly depends on the actual internal distribution of C and O (Prada Moroni & Straniero 2002, 2007). In addition, since CO WDs attaining the Chandrasekhar mass limit are the progenitors of SNe Ia, and since carbon is the main fuel for this thermonuclear explosions, a precise determination of the rate of the $^{12}C(\alpha,\gamma)^{16}O$ is also important to understand the physics of these supernovae (see Domínguez, Höflich & Straniero 2003).

The attempts to constraint the effective rate of this reaction by using astrophysical arguments are limited by the fact that the core He

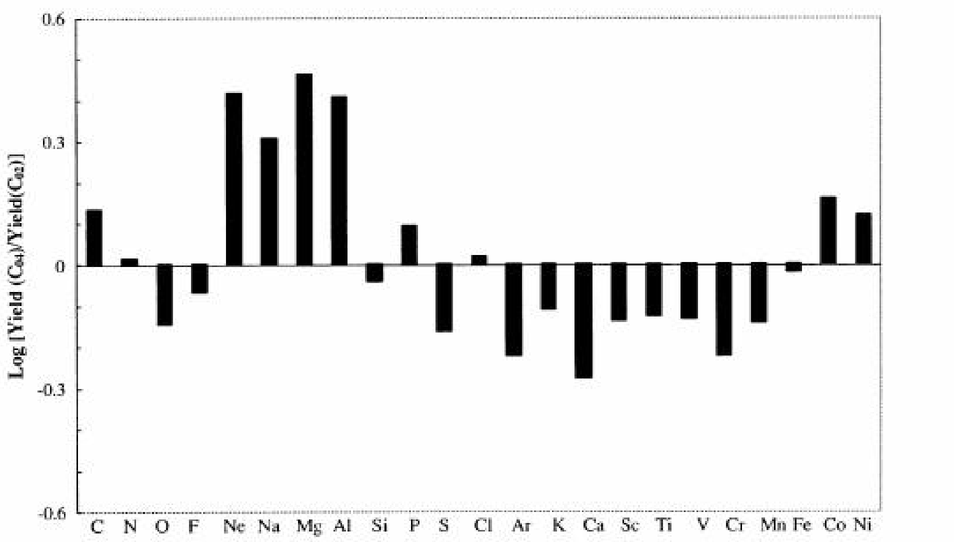

Fig. 5. Logarithm of the ratio between the explosive yields produced by a progenitor (initial mass 25 $M_{\odot}$) computed by using a low rate for the $^{12}C(\alpha, \gamma)^{16}O$ reaction and those obtained by using a high rate.

burning occurs in a convective layer. As a matter of fact, differences in the C/O ratio induced by changing the reaction rate can be equally reproduced by changing the efficiency of the convective mixing (within the present uncertainty of the theory). From an experimental point of view, the rate at astrophysical energies is far from being well established. The cross section around the Gamow peak is dominated by ground-state transitions through four different processes: the two E1 amplitudes due to the low-energy tail of the 1 resonance at Ecm=2.42 MeV and to the subthreshold resonance at -45 keV, the E2 amplitude due to the 2+ subthreshold resonance at -245 keV, and the direct capture to the 16O ground state (plus the relevant interference terms). In addition to ground-state transitions, also cascades, mainly through the E2 direct capture to the 6.05 MeV 0+ and 6.92 MeV 2+ states, should be considered. In the past 30 years many experiments have been set up, most of them based on the detection of γ-rays produced by captures in direct or inverse kinematics (see Kunz et al. 2002,for a recent review). New hints have bee recently obtained by means of a recoil mass separator (Schürmann et al. 2005). All these measures extend to a minimum energy of about 1 MeV and show systematic differences. Below this energy, extrapolations have to be used in order to extract the astrophysical S-factor.

The present uncertainty, around 300 KeV, is not less than 30% (Kunz et al. 2002). The corresponding uncertainties for stellar evolution are very important. First of all, the final chemical yields of massive stars, which undergoes a core collapse supernova explosion, are significantly affected by the amount of C left by the He burning (see Figure 5). In particular, intermediate-light elements, Ne, Na, Mg and Al, which are produced in the C convective shell, scale directly with the C abundance, because they descend directly from the amount of fuel available (i.e C and or Ne). On the contrary, the elements whose final yield is builded up by any of the four explosive burnings (namely, complete explosive Si burning, incomplete explosive Si burning, explosive O burning and explosive Ne burning) scale inversely with the C abundance left by the He burning. Indeed, when the amount of C left by the He burning is low, the pre-explosive structure is more compact and the mass of the collapsing core is smaller. In this condition, less material falls back after the shock is passed through.

By combining the uncertainty on the relevant reaction rate with that of the convective-induced mixing, the present theoretical prediction for the central oxygen mass fraction in white dwarfs varies between 0.3 and 0.9 (Straniero et al. 2003). This large uncertainty effects the prediction of the White Dwarf cooling time scale, which could be used as alternative method to date Globular Cluster (see Figure 3). In particular, for an age of 10 Gyr the uncertainty in the predicted cooling time is of the order of 25% (Prada Moroni & Straniero 2002).

Finally, the outcomes of type Ia SNe – namely, stellar explosion caused by the ignition of C in the degenerate core of CO WDs with mass close to the Chandrasekhar limit – are affected by the uncertainty on the amount of C left by the He burning. The abundance of the resulting ^{56}Ni scales with the abundance of C (Figure 4). It affects the absolute brightness and the kinetic energy of the expelled material (Domínguez, Höflich & Straniero 2001). Figure 3 to 5 illustrate the influence of the $^{12}C(\alpha,\gamma)^{16}O$ in all these cases.

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