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IMPROVING STELLAR MODELING WITH NEW PRECISE NUCLEAR REACTION RATES DETERMINED FROM NUCLEAR EXPERIMENT

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Abstract. The origin of elements in the Universe is still a challenging question today. From the Big Bang nucleosynthesis that formed the lightest elements (essentially H and He), all the heavier were since synthesized through the stellar nucleosynthesis involving different processes with mainly nuclear fusion or particle capture and the subsequent reactions. The knowledge about nuclear reaction rates that drive these reactions is, however, still inaccurate. Their determination by new nuclear experiments is pursued for the main nuclear reactions of the stellar fusion phases, i.e. H- He-, C-burning phases. In order to improve stellar modelling, we now need to take into account these new results that might be key to understand stellar evolution. We implemented new $^{12}\mathrm{C} +^{12}\mathrm{C}$ nuclear reaction rates and explore their impact.

Keywords: Nuclear reactions, Stars: evolution, Star: interiors, Nucleosynthesis, Stars: rotation

1 Introduction

In recent years, numerous nuclear reaction rates relevant for astrophysics have been determined experimentally via direct and indirect methods, highlighting specific trends like the unexpected fusion hindrance phenomenon (steep fall of the fusion cross-section at very low energies) and multiple resonances. In particular, a precise determination of the nuclear reaction rates is a crucial ingredient in understanding stellar evolution. New nuclear reaction rates have been determined for the different cycles of H- He-, C-burning phases by nuclear experiments (e.g. Broggini et al. 2018), leading to significant changes in the nucleosynthesis. In particular, measurements for the $^{12}\mathrm{C} +^{12}\mathrm{C}$ nuclear reaction have been obtained at the low energies of astrophysical interest by the STELLA collaboration in France (Fruet et al. 2020) and open the way to improvements in stellar evolution modelling. This reaction is indeed the main nuclear reaction during the advanced C-burning phase of massive stars ($\geq$ 8 $\mathrm{M}_\odot$). Monpribat et al. (2022) showed these new rates impact the burning lifetime as well as the production of C-burning products and s-process elements changing later stages of the evolution. In continuation of this work, using the stellar evolution code GENEC (Ekström et al. 2012), we computed new models for a larger range of masses and metallicities, and including rotation-induced mixing ($\mathrm{V_{ini}/V_{crit}} = 0.4$).

2 Nuclear reaction rates $^{12}\mathrm{C} +^{12}\mathrm{C}$

$^{12}\mathrm{C} +^{12}\mathrm{C}$ nuclear rates are often taken from the so-called CF88 reference (Caughlan & Fowler 1988) in stellar evolution codes. New measurements are available for the p and α channels (Fruet et al. 2020) and for the n channel (Bucher et al. 2015). They consider the hindrance phenomenon (steep fall of the cross-section, HIN model) which is observed for certain energies in this reaction, as well as a resonance close to the astrophysics region of interest and observed for the α exit channel (HINRES model, Fruet et al. 2020). Figure 1, left panel, shows reaction rates normalised to the CF88 rates, as a function of the central temperature for these two new cases: HIN, HINRES. The temperature location of the resonance may impact differently the stars depending on their C-burning temperature, or in other words, depending on their mass and metallicity.

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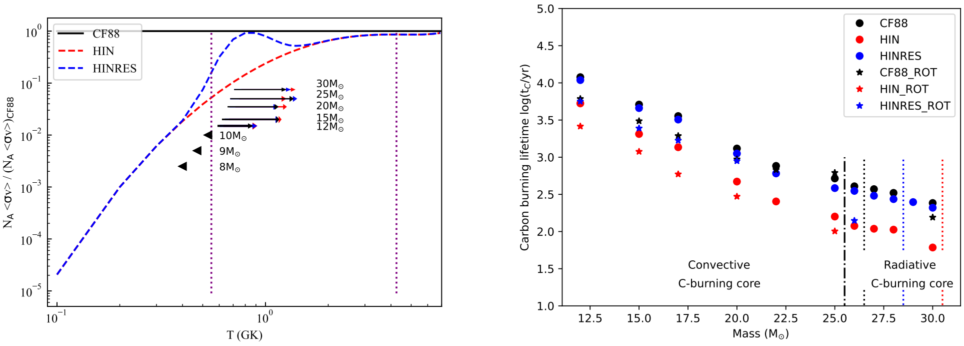

Fig. 1. Left: Reactions rates following CF88, HIN, and HINRES reference in black, red, and blue, respectively, and normalised to CF88 rates ($N_A < \sigma v >_{CF88}$). Black, red, and blue arrows show the temperature regions where carbon fusion takes place for classical models of 12, 15, 20, 25, and 30 $M_{\odot}$. Black triangles give the maximum core temperature reached by the 8, 9, and 10 $M_{\odot}$ stars. The area between purple dotted-lines was explored by the STELLA experiment. **Right:** Core C-burning lifetimes for stellar models of different masses without/with rotation (circle/star, respectively). Dotted-lines and dotted-dashed lines indicate the transitions between convective and radiative core for models without/with rotation, respectively.

A lower reaction rate (HIN) results in a higher central temperature and density, and a shorter lifetime during the C-burning phase (see right panel of Fig. 1). This trend was already shown by (Pignatari et al. 2013; Chieffi et al. 2021) for different rates. The difference between the HIN and HINRES models is due to the resonance observed in Fig. 1, left panel. Rotation leads in both cases to a shift to higher T_c/ρ_c and shorter lifetime. The effects on nucleosynthesis remain small on classical models but should be further explored for rotation models, as well as during the C-burning shell phase (Raiteri et al. 1991).

3 Conclusions

New nuclear reaction rates for $^{12}C + ^{12}C$ are driving changes in the C-ignition and C-burning in massive stars (core temperature, lifetime). Preliminary results show that the resulting effects are multiple impacting nucleosynthesis, intermediate/massive stars mass limit, core structure (convective or radiative), end-of-life (e.g. Chieffi et al. 2021; Monpribat et al. 2022; De Gerónimo et al. 2023). Thanks to new measurements, accurate nuclear rates are currently obtained for a large set of fundamental reactions. In this context, results for $^{12}C+^{12}C$ support the need to test and update stellar evolution codes for the different nuclear fusion phases. A better nuclear description is indeed one of the key for improving the stellar modelling and is especially relevant in the context of asteroseismic constraints on stellar interiors.

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