Impact of nuclear reactions on the fate of intermediate-mass stars*

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The evolution of intermediate-mass stars (8 - 12 $M_\odot$) represents one of the most challenging subjects in nuclear astrophysics (see e.g. [1,2]). Their final fate is still uncertain and strongly model dependent. They can become white dwarfs, undergo electron-capture or core-collapse supernovae or even proceed towards explosive oxygen-burning and a subsequent thermonuclear explosion. An accurate description of the involved nuclear reactions is crucial for the determination of the pre-supernova structure of these stars. We argue that due to the possible development of an oxygen-deflagration, a hydrodynamic description coupled to a nuclear reaction network has to be used. For selected nuclear species, we include a set of updated reaction rates, for which we discuss their role for the evolution of the stellar core, at the example of SAGB-star models from [2].

In this report, we want to point out the recent advances that we made in understanding the key nuclear reactions that are relevant for the proper modeling of the late stages of these stars. Compared to massive stars, nuclear reactions will operate at much higher densities (10^9 compared to 10^6 g cm^{-3}), where electron-capture (EC) reactions can already operate and influence the evolution of the star. As pointed out in [2], the O-Ne-core of such stars may first undergo a phase of URCA-cooling due to EC on odd-A nuclei and then a phase of rapid energy release due to double-EC on even-A nuclei, rising the temperature in the stellar core.

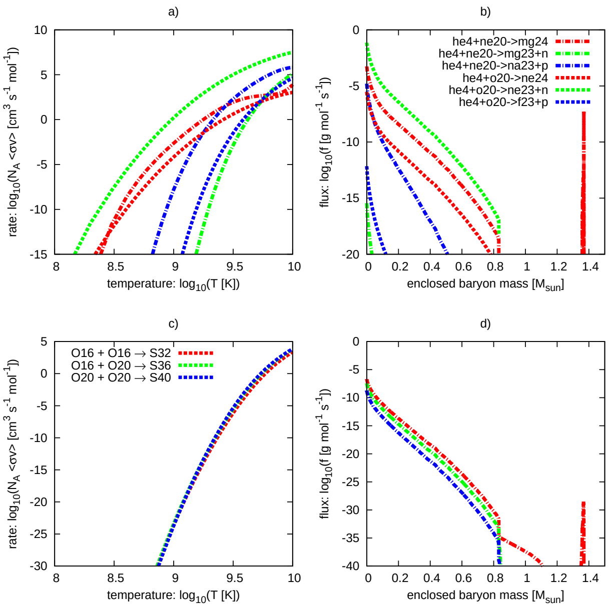

Figure 1: Rates and fluxes for the Ne- and O-burning phase

Prior to the Ne-burning phase, ^{24}Mg is converted into ^{24}Ne and later ^{20}Ne into ^{20}O by EC. Hence, the center of the core consists mainly of ^{16}O and ^{20}Ne but also up to 4% of ^{20}O. This opens new reaction channels that have so far not been considered. They modify the Ne-burning that now proceeds by the reactions $^{20}\mathrm{Ne}\,(\gamma,\alpha)\,^{16}\mathrm{O}$, followed by $^{20}\mathrm{O}\,(\alpha,\gamma)\,^{24}\mathrm{Ne}$. The JINA reaclib rates [3] are displayed in panel a) of Figure 1. Here, we compare the rates of the different reaction channels for the α-capture on ^{20}Ne and ^{20}O. The reaction $^{20}\mathrm{O}\,(\alpha,n)\,^{23}\mathrm{Ne}$ is dominating and we argue that the α-capture on ^{20}O is a competitive process that should be considered in future calculations. This can be seen even better in panel b) where we look at the reaction fluxes for conditions of stellar models from [2] prior to Ne-burning. For a binary rate, the flux is defined as: $f_{\mathrm{AB}\rightarrow\mathrm{X}} = \rho N_{\mathrm{A}}\,\langle\sigma v\rangle_{\mathrm{AB}\rightarrow\mathrm{X}}\,Y_{\mathrm{A}} Y_{\mathrm{B}}$, with density ρ, projectile abundances Y_{A} and Y_{B} and reaction rate $N_{\mathrm{A}}\,\langle\sigma v\rangle_{\mathrm{AB}\rightarrow\mathrm{X}}$.

Once the core reaches temperatures $\gtrsim$ 1.7 GK, the fusion reactions of neutron-rich oxygen isotopes, $^{16,20}\mathrm{O} + {}^{20}\mathrm{O} \rightarrow {}^{36,40}\mathrm{S}^*$ may become important (besides $^{16}\mathrm{O} + {}^{16}\mathrm{O} \rightarrow {}^{32}\mathrm{S}^*$). Due to the lack of experimental data, we rely on a model by [4] for the calculation of the astrophysical S-factors and calculate the reaction rate, taking into account the different branching ratios. In panels c) and d) of Figure 1, it can be seen that the reaction rates are actually very comparable. In panel d) are shown again the reaction fluxes for the same conditions as in panel b). We find that the contribution of the $^{16}\mathrm{O} + {}^{20}\mathrm{O}$-channel reaches up to 15% of the $^{16}\mathrm{O} + {}^{16}\mathrm{O}$-channel, while the $^{20}\mathrm{O} + {}^{20}\mathrm{O}$-channel is much less important. Considering the uncertainties present in all of these reactions, it is important to perform a careful evaluation of the corresponding S-factors as they can substantially affect oxygen burning in intermediate-mass stars. In addition to that, the fusion involving ^{20}O has Q-values of $\sim$ 30 MeV. This does not only increase the rate of energy release during the fusion phase of oxygen by up 30%, but it also allows for exotic decay channels including the emission of up to 5 neutrons. See [5] for more details.

References

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