Massive Star Evolution: Nucleosynthesis and Nuclear Reaction Rate Uncertainties

A. Heger [a], S.E. Woosley [a], T. Rauscher [b], R.D. Hoffman [c], & M.M. Boyes [a]

[a] *Department of Astronomy and Astropyhsics, University of California, Santa Cruz, CA 95064*

[b] *Department of Physics and Astronomy, University of Basel, Basel, Switzerland*

[c] *Nuclear Theory and Modeling Group, Lawrence Livermore National Laboratory, Livermore, CA 94550*

Abstract

We present a nucleosynthesis calculation of a $25\,\mathrm{M}_\odot$ star of solar composition that includes all relevant isotopes up to polonium. In particular, all *stable* isotopes and necessary nuclear reaction rates are covered. We follow the stellar evolution from hydrogen burning till iron core collapse and simulate the explosion using a "piston" approach. We discuss the influence of two key nuclear reaction rates, $^{12}\mathrm{C}(\alpha,\gamma)$ and $^{22}\mathrm{Ne}(\alpha,\mathrm{n})$, on stellar evolution and nucleosynthesis. The former significantly influences the resulting core sizes (iron, silicon, oxygen) and the overall presupernova structure of the star. It thus has significant consequences for the supernova explosion itself and the compact remnant formed. The later rate considerably affects the *s*-process in massive stars and we demonstrate the changes that different currently suggested values for this rate cause.

Key words: stars: massive, evolution, nucleosynthesis, nuclear physics: uncertainties

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1 Introduction

Massive stars of more than $8\,\mathrm{M}_\odot$ are the main source of oxygen and heavier elements in the universe. Availability of (theoretical and experimental) reaction rate data and computational resources make it now possible to follow

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Email address: `alex@ucolick.org` (A. Heger).

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the complete nucleosynthesis in massive stars from hydrogen burning till core collapse and through the supernova explosion (§2). However, significant uncertainties in several key nuclear reaction rates still exist. In §3 we discuss the influence of the $^{22}\mathrm{Ne}(\alpha,\mathrm{n})$ rate on the *s*-process in massive stars and in §4 we demonstrate the influence of the $^{12}\mathrm{C}(\alpha,\gamma)$ rate on the presupernova structure.

2 Complete nucleosynthesis study

We present the first calculations to follow the complete nucleosynthesis in massive stars from hydrogen ignition till onset of iron core collapse and through the supernova explosion. Figure 1 shows the average abundance of all ejecta, including stellar wind mass loss, relative to their solar values (production factor). The dashed line indicates the production factor for $^{16}\mathrm{O}$, the dominant "metal" produced by massive stars, and the dotted lines indicate twice and half the production factor. The supernova explosion is simulated by a piston that resulted in $\sim 1.7\times10^{52}\,\mathrm{erg}$ kinetic energy of the ejecta. The mass cut is then determined self-consistently from the hydrodynamical simulation. Note that Fig. 1 does not include a possible *r*-process contribution due to the neutrino wind from the nascent neutron star.

In the $25\,\mathrm{M}_\odot$ star of Fig. 1, most isotopes from oxygen to the iron group are produced in about solar ratios relative to oxygen. The iron group itself is somewhat underproduced, due to fall-back during the explosion. Stars of $\sim 15\,\mathrm{M}_\odot$ typically contribute more here and Type Ia supernovae have added to the solar abundance in the region. The *s*-process isotopes above the iron group till $\sim A = 90$ are slightly overproduced. Stars of lower mass and/or lower metallicity produce less here. Therefore these high yields are required to produce the solar abundances over the lifetime of the Galaxy. Above $A \gtrsim 100$ many *p*-isotopes are produced by the γ-process in about solar abundances relative to $^{16}\mathrm{O}$. For more details please refer to Rauscher et al. (2001).

3 The $^{22}\mathrm{Ne}(\alpha,\mathrm{n})$ rate

The $^{22}\mathrm{Ne}(\alpha,\mathrm{n})$ rate is the most important source of neutrons for the *s*-process in massive stars in the region $60 \lesssim A \lesssim 90$. Figure 1 shows the result for the lower limit given by Käppeler et al. (1994) (as used by Hoffman et al., 2000). In Fig. 2 we show the results for the same star, except that we use the low, high, and recommended values by Jaeger et al. (2001). The abundance ratio of the *s*-process does not change much by this; the abundances only shifting to a slightly higher absolute value. The lower panel shows the result when using the high limit given by Angulo et al. (1999) (and the rest of their rate set as well,

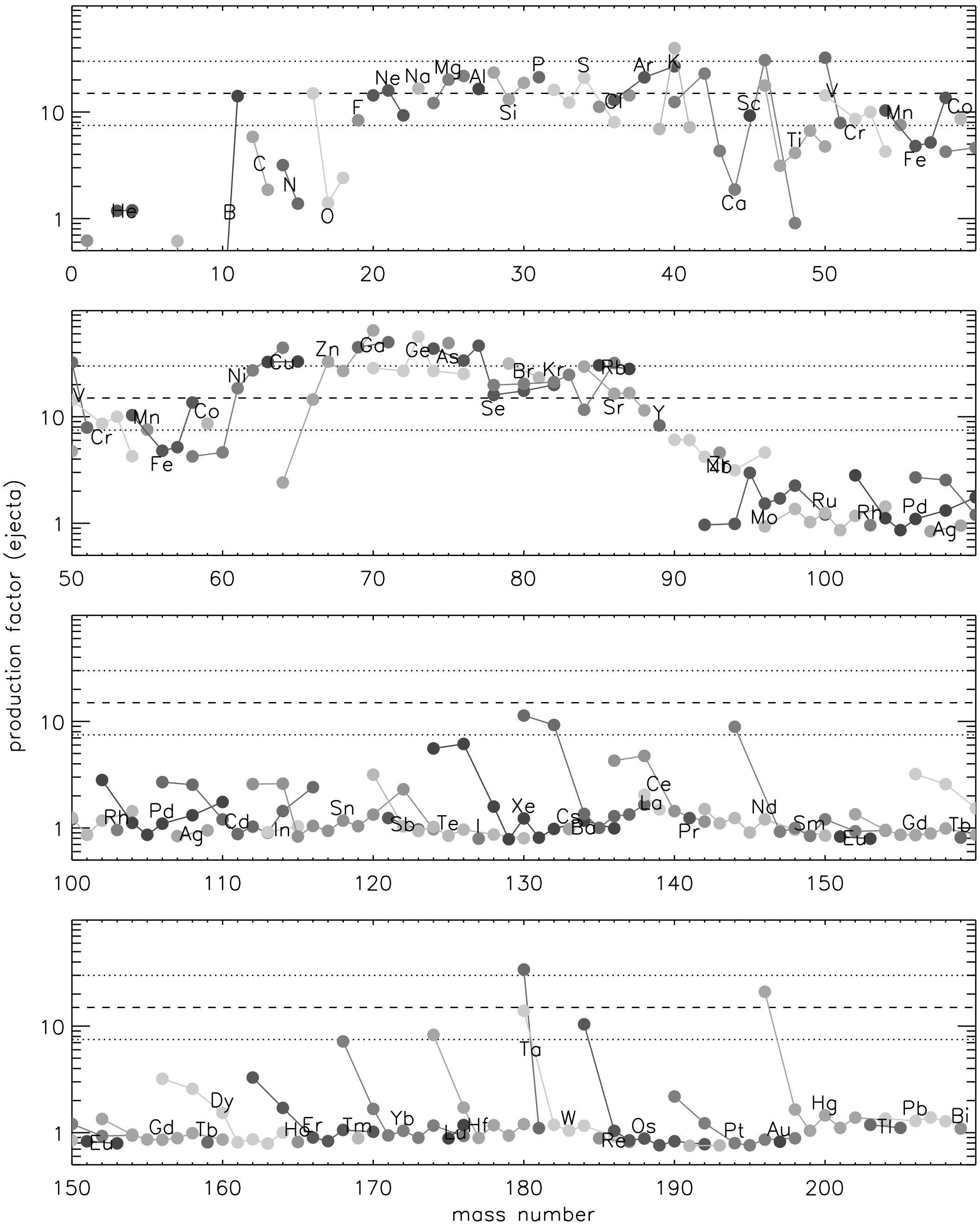

Fig. 1. Production factors of isotopes in ejecta, including wind, relative to solar abundances for a $25\,\mathrm{M}_\odot$ star of solar composition. We use $1.2\times$ the $^{12}\mathrm{C}(\alpha,\gamma)$ rate of Buchmann (1996) (cf. Kunz et al., 2001) and the low $^{22}\mathrm{Ne}(\alpha,\mathrm{n})$ rate of Käppeler et al. (1994); (as used by Hoffman et al., 2000).

which makes only a minor difference as compared to $^{22}\mathrm{Ne}(\alpha,\mathrm{n})$). The large overproduction of the *s*-process here cannot be balanced by galactochemical evolution. Even so, we do not find significant production of *p*-isotopes of Mo and Ru (cf. Costa, 2000). For more details please refer to Heger et al. (2001).

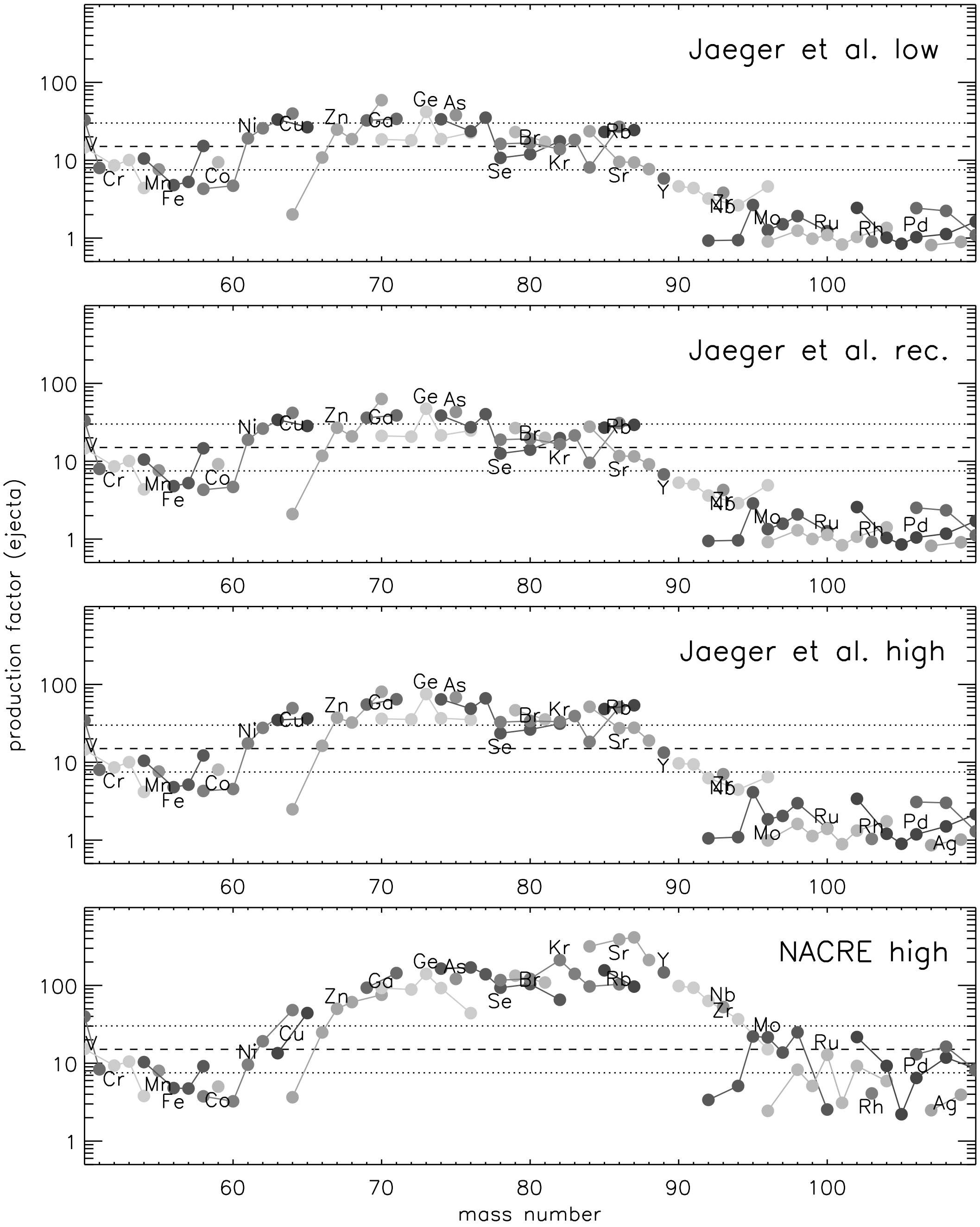

Fig. 2. Comparison of the production factors (see Fig. 1) for different ^{22}Ne(α,n) rates. The first three panels give the results for the lower limit, recommended value, and upper limit of Jaeger et al. (2001). The bottom panel uses the reaction rate set by Angulo et al. (1999) with their upper limit for the ^{22}Ne(α,n) rate.

4 The ^{12}C(α,γ) rate

The uncertainty of the ^{12}C(α,γ) rate has significant influence on the late time evolution of massive stars (cf. Imbriani et al., 2001). It determines how much ^{12}C is left after core helium exhaustion (Fig. 3). Only for a sufficiently high

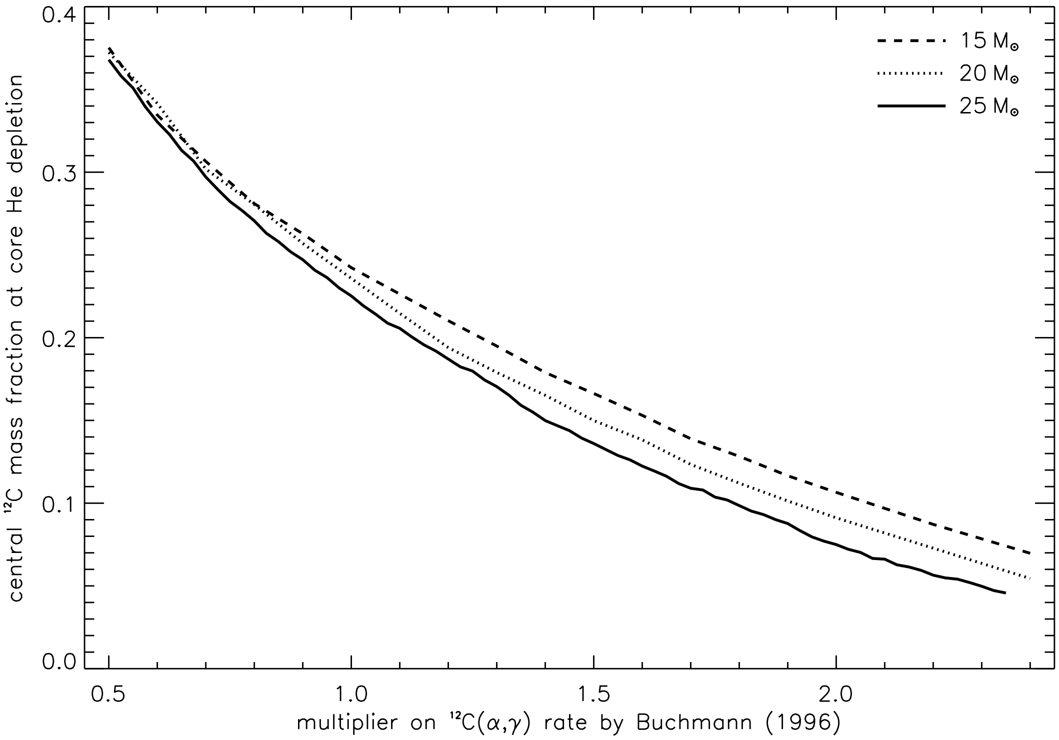

Fig. 3. Central carbon mass fraction after core helium exhaustion as a function of a multiplier on the ^{12}C(α,γ) rate of Buchmann (1996, , 2000 priv. com.) for 15 M$_\odot$ (*dashed line*), 20 M$_\odot$ (*dotted line*), and 25 M$_\odot$ (*solid line*) stars.

value central carbon burning proceeds convectively while otherwise it burns radiatively. Similarly, the extent and duration of the carbon shell burning phases are affected. They set the stage for the later burning phases in that they produce carbon-free cores of different sizes, as a non-monotonous function of the carbon abundance. In Fig. 4 the iron core size varies by up to 30 %! Therefore the ^{12}C(α,γ) rate determines whether a neutron star or a black hole is formed. For more details please refer to Boyes et al. (2001).

5 Conclusions & outlook

The current extent of uncertainties in key nuclear reaction rates still has significant influence on stellar evolution and nucleosynthesis. Other major uncertainties comprise our understanding of mixing processes, rotation, and magnetic fields in stars. Some of these uncertainties are currently under re-investigation. The combined effort of refined rate determinations and stellar modeling allows both fields to profit from the synergy effects.

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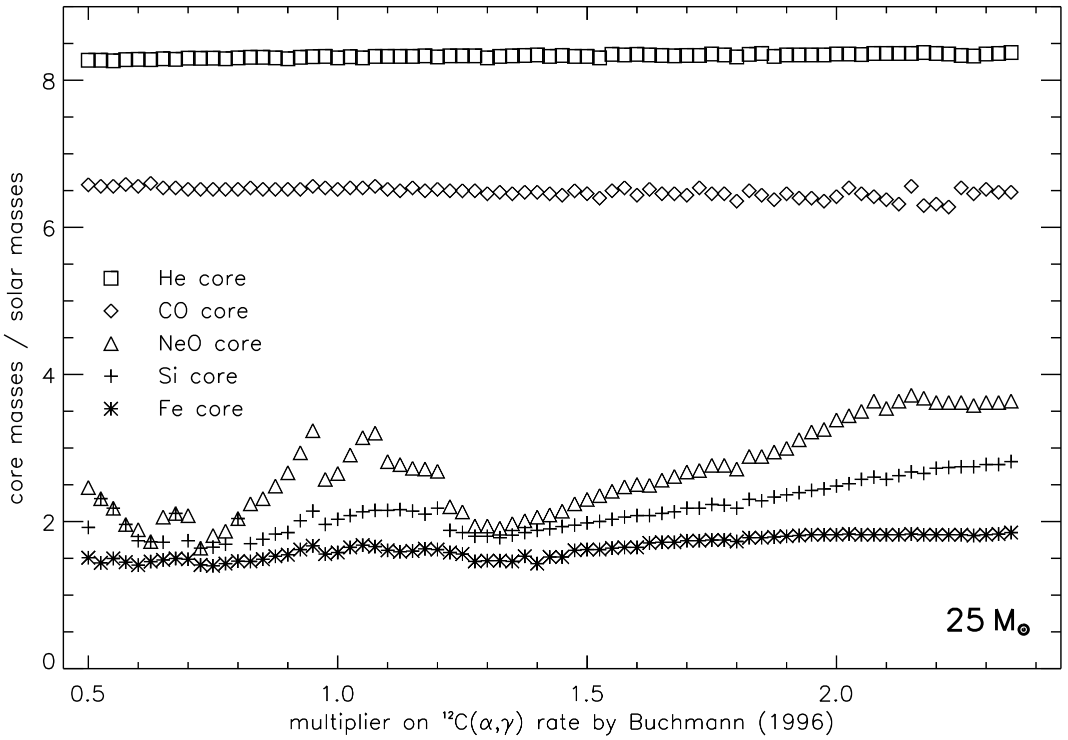

Fig. 4. Helium (*squares*), carbon-oxygen (*rotated squares*), neon-oxygen (*triangles*), silicon (*crosses*), and "iron" (*asterisks*) core masses as a function of a multiplier on the ^{12}C(α, γ) rate of Buchmann (1996)

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