The $^{12}C(\alpha,\gamma)^{16}O$ Reaction Rate: Evolution & Nucleosynthesis of Massive Stars

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Abstract

We investigate the effect of the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate on central helium burning, presupernova structure, and nucleosynthesis in massive stars of 15-25 $M_\odot$ by varying the rate given by Buchmann (1996) with a multiplier of 0.5 - 2.4. This changes the carbon abundance at central helium depletion, which in turn affects the remaining evolution stages. We find that while the helium burning phase itself is only slightly affected, later phases are changed more. In particular, the presupernova entropy and core masses are all significantly affected. Thus the value of this rate has important consequences for the supernova explosion and whether a neutron star or a black hole is formed.

Introduction

The $^{12}C(\alpha,\gamma)^{16}O$ reaction is one of two principal reactions that compete during helium burning to determine the relative yields of carbon and oxygen. The other, the 3α reaction, has a relatively well known cross section. The problem with $^{12}C(\alpha,\gamma)^{16}O$ is that its cross section is dominated by the interplay of several resonances, the two main ones lying below the particle threshold, and non-resonant direct capture which gives rise to the interferences within the excitation function (Kunz et al. 2001). The cross section of the $^{12}C(\alpha,\gamma)^{16}O$ reaction is extremely small at energies appropriate to stellar helium burning (of order 10^{-17} barns) and difficult to measure with present techniques. It is also not accurately predicted by theory. Yet it has been known for some time that the value one employs for $^{12}C(\alpha,\gamma)^{16}O$ significantly affects nucleosynthesis in massive stars (Weaver & Woosley 1993; Heger et al. 2001). Weaver & Woosley (1993) found agreement between calculated and observed nucleosynthetic yields of massive stars only if the previously accepted rate of Caughlan & Fowler (1988) was raised by a factor of 1.7 (corresponding to an S-factor at 300 keV of 170 keV barns). Recently Buchmann (1996) has revised the rate and given an analytic expression. Current nucleosynthesis studies (Rauscher et al. 2001) still find better agreement when the Buchmann (1996) rate is raised by a factor $\sim$1.2, which is similar to 1.7 times the Caughlan & Fowler (1988) rate and in agreement with Kunz et al. (2001).

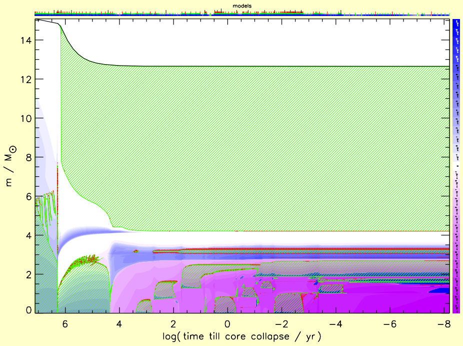

Figure 1: This plot shows the evolution of a 15 $M_\odot$ star, with a $^{12}C(\alpha,\gamma)^{16}O$ multiplier of 0.8, from the main sequence till iron core collapse. Convection is shown as green hatching, semiconvection as red cross hatching. Energy generation (blue) and energy losses (pink; mostly by plasma neutrinos) are shown as color shading and each "level" of higher color intensity represents an order of magnitude higher value, in erg $g^{-1}\,s^{-1}$, starting at 1/10 erg $g^{-1}\,s^{-1}$.

Here we have examined the sensitivity of stellar *structure* to variation of the $^{12}C(\alpha,\gamma)^{16}O$ rate using a much finer grid of rates than previously employed. This fine grid is necessary because, as we shall see, small changes in this rate can sometimes have a discontinuous effect on the results. We also examine the nucleosynthesis that comes from exploding our models in order to provide a more modern and precise nucleosynthesis-based limit on the rate than Weaver and Woosley (1993). We have included mass loss and many other improvements to other nuclear reaction rates and opacities that became available after 1993.

A detailed study of the pre-explosive evolution of three massive stars was conducted using the computer code KEPLER, originally developed by Weaver, Zimmerman, & Woosley (1978) and improved by Heger et al. (2001). Our studies assume spherical symmetry and neglect magnetic fields and rotation. By changing the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate while keeping all other stellar physics constant the overall effects of the uncertainties may be investigated. Stars are evolved from the zero age main sequence to presupernova, i.e., from central hydrogen ignition to iron core collapse (Figure 1).

Initial Models

All of the results presented in this work are for stars of 15, 20, and 25 solar masses, each initially having a solar chemical composition. The mass fraction of hydrogen (X) was set to X=0.7. The mass fraction of all elements heavier than helium (Z), normally referred to as "metals" in astrophysics, was set to Z=0.02. The mass fraction of helium (Y) consequently was Y=1-X-Z=0.28, in accordance with Anders & Grevess (1989).

Method and Procedure

All of the models for each mass were computed using exactly the same stellar physics except the Buchmann (1996) $^{12}C(\alpha,\gamma)^{16}O$ reaction rate multiplier. The 15, 20 and 25 solar mass stars were all studied on a grid with the $^{12}C(\alpha,\gamma)^{16}O$ multiplier ranging from 0.5 to 2.4 with steps of 0.025.

Results

The uncertainty of the $^{12}C(\alpha,\gamma)^{16}O$ rate has significant influence on the late time evolution of massive stars (cf. Imbriani et al., 2001). The $^{12}C(\alpha,\gamma)^{16}O$ rate determines how much ^{12}C is left in the core after helium depletion (Figure 2). We find that the $^{12}C(\alpha,\gamma)^{16}O$ rate affects the extent and the duration of the core and the shell burning phases, which has a ripple effect on later burning phases.

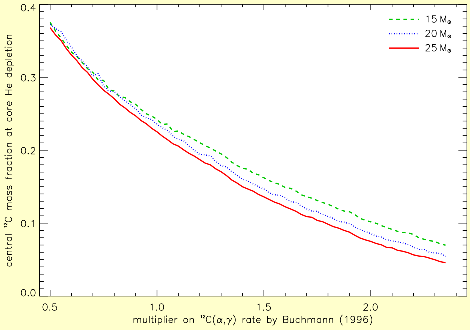

Figure 2: Central carbon mass fraction after core helium exhaustion as a function of the multiplier on the $^{12}C(\alpha,\gamma)^{16}O$ rate of Buchmann (1996) for 15 $M_\odot$ (*dashed line*), 20 $M_\odot$ (*dotted line*), and 25 $M_\odot$ (*solid line*) stars. A multiplier of 1.2 corresponds approximately to an S-factor at 300 keV of 170 keV barns.

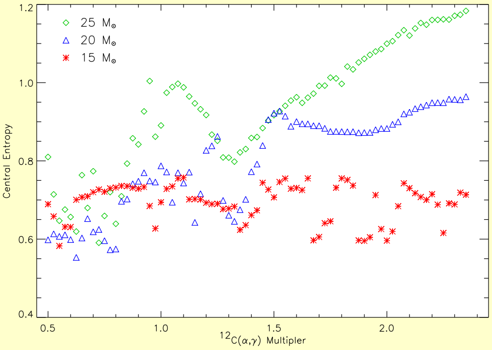

Figure 3: Presupernova central entropy as a function of the multiplier on the $^{12}C(\alpha,\gamma)^{16}O$ rate of Buchmann (1996) for 15 $M_\odot$ (*triangles*), 20 $M_\odot$ (*asterisks*), and 25 $M_\odot$ (*diamonds*) stars.

A key physical quantity that reflects stellar structure is the entropy. In general, presupernova stars with lower entropy in their centers have smaller more compact cores because the "effective Chandrasekhar mass" is smaller (in fact, the traditional Chandrasekhar mass is for zero entropy). During the late stages of stellar evolution, the iron core needs to exceed this mass just prior to collapse.

The $^{12}C(\alpha,\gamma)^{16}O$ multiplier affects the final central entropy of the presupernova star in a very complex way (see Figure 3). If a star lacks sufficient carbon after helium burning, then carbon and neon burning never become convective episodes in the middle of the star. The number and placement of convective carbon *shells* is also affected as is their propensity for merging with other burning shells of neon and oxygen. It seems that when carbon and oxygen shells merge, the central entropy is driven down. Shells merge, or combine, when convection from one shell extends into the other shell. This allows the two shells to mix, allowing an increase in fuel to be accessible. The drop in entropy is most noticeable when the energy production decreases in the merged shell. The $^{12}C(\alpha,\gamma)^{16}O$ multiplier also affects the central electron fraction per nucleon (Y_e) much the same way as it does for central entropy. The Chandrasekhar mass depends on both Y_e^2 and the entropy.

Effects on the Presupernova Core Structure

The final core masses are thus significantly influenced by the multiplier. In some cases where the core mass is large (greater than about 2.0 solar masses), a black hole may result. Smaller iron cores, on the other hand, make the star easier to explode and will probably lead to the formation of neutron stars (Figures 4). Those $^{12}C(\alpha,\gamma)^{16}O$ multiplier values which led to shells merging had a smaller final entropy. In all three stars the masses of the helium and helium-free cores were virtually unaffected, while the iron core mass varied dramatically. The variation in the iron core size for the 25 $M_\odot$ case was up to 30%.

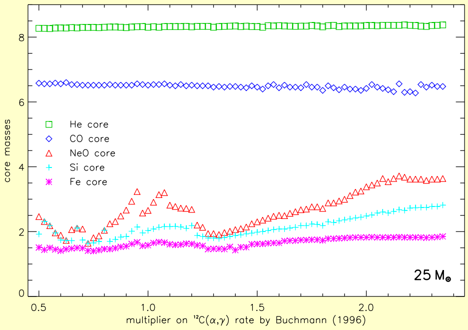

Figure 4: Helium (*squares*), carbon-oxygen (*diamonds*), neon-oxygen (*triangles*), silicon (*crosses*), and "iron" (*asterisks*) core masses as a function of the $^{12}C(\alpha,\gamma)^{16}O$ rate multiplier of Buchmann (1996).

Supernova Production Factors

The production factor is defined by the ratio of the abundance of isotopes produced to their solar abundance. We find that the nucleosynthesis agrees best with observed nucleosynthetic yields if the Buchmann (1996) rate is raised by a factor of 1.2 (Figure 5), which is in agreement with the most recent measurements by Kunz et al. (2002).

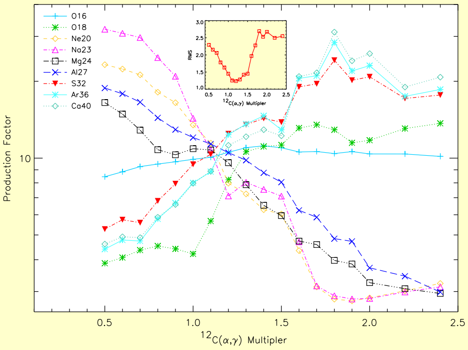

Figure 5: Supernovae production factors for selected isotopes as a function of the $^{12}C(\alpha,\gamma)^{16}O$ rate multiplier on the Buchmann (1996) rate. The production factors shown here result from integrating the yields of our model stars over an initial mass function of slope -2.35. The small figure shows the RMS deviation of the production factors from that of ^{16}O.

Conclusions

Current uncertainties in the $^{12}C(\alpha,\gamma)^{16}O$ rate have considerable influence on stellar evolution and nucleosynthesis of massive stars. Our best estimates place the $^{12}C(\alpha,\gamma)^{16}O$ rate at 1.2 ±0.2 times the Buchmann (1996) rate. Future experiments should help to refine the value of the rate even more. For the time being though, astrophysicists will have to live with an experimental uncertainty of at least 20% in this rate. The present study indicates that large changes in the presupernova structure and nucleosynthesis of a given star are caused by this degree of variation.

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