NUCLEAR REACTION RATES AND CARBON STAR FORMATION

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ABSTRACT

We have studied how the third dredge-up and the carbon star formation in low-mass asymptotic giant branch stars depend on certain key nuclear reaction rates. From a set of complete stellar evolution calculations of a 2 $M_\odot$ model with $Z = 0.01$ including mass loss, we find that varying either the $^{14}\text{N}(p, \gamma)^{15}\text{O}$ or the triple-$\alpha$ reaction rate within their uncertainties as given in the NACRE compilation results in dredge-up and yields that differ by a factor of 2. Model tracks with a higher rate for the triple-$\alpha$ rate and a lower rate for the $^{14}\text{N}(p, \gamma)^{15}\text{O}$ reaction both show more efficient third dredge-up. New experimental results for the $^{14}\text{N}(p, \gamma)^{15}\text{O}$ reaction rates are surveyed, yielding a rate that is about 40% lower than the tabulated NACRE rate and smaller than NACRE’s lower limit. We discuss the possible implications of the revised nuclear reaction rate for stellar evolution calculations that aim to reproduce the observed carbon star formation at low mass, which requires efficient third dredge-up.

Subject headings: nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: AGB and post-AGB — stars: carbon

1. INTRODUCTION

Low-mass stars evolve through the core H- and He-burning stages before finally entering into the asymptotic giant branch (AGB) phase of evolution (Iben & Renzini 1983). In this terminal phase, most of the nuclear processing that is relevant for Galactic chemical evolution is taking place. Two shells on top of the electron-degenerate C/O core are burning H and He, respectively. Due to the different energy generations per mass unit, the shells have different Lagrangian speeds, and eventually shell burning becomes unstable. He-shell flashes occur that prompt a series of convective mixing episodes. First, the region between the H shell and the He shell becomes convectively unstable because of the large energy generation in the thermonuclear runaway of the He shell. Then the layer at the bottom and below the convective envelope expands and cools, making this region unstable against convection. Layers previously covered by the He-shell flash convection zone will become part of the convective envelope, and processed material from the core (or intershell to be more precise) will be mixed to the surface. This process is called the third dredge-up. Repeated dredge-up events will turn the initially O-rich giant into a C star with C/O > 1.

More than 20 years ago, Iben (1981) pointed out that observed and theoretically predicted parameters of C stars disagree. On the one hand, models predict more C star formation (i.e., efficient third dredge-up) for large (core) masses, thus implying large stellar luminosities. But no C stars were observed at such high luminosities. Instead, observations showed that C stars have low luminosities. But stellar models of low mass were not able to reproduce the required efficiency of dredge-up or any dredge-up at all. In subsequent years, some progress has been made. The first disagreement has been resolved by the discovery that the envelope of massive AGB stars is nuclear processed by CNO cycling because the bottom of the envelope convection zone reaches into the H shell (Boothroyd et al. 1993).

For the second disagreement concerning the low-mass stars, no final solution has been agreed on. The most recent work by Karakas et al. (2002) gives a detailed account of the dependence of dredge-up on mass and metallicity. However, they conclude that some scaling of their dredge-up law is still required as their models likely are not able to reproduce directly either the Galactic or the LMC or SMC C star luminosity function. Although much work has been published, no real consensus has been reached. The main focus has been on the numerical and physical treatment of convective boundaries (Frost & Lattanzio 1996; Mowlavi 1999). Herwig et al. (1997) and Herwig (2000) showed that even a small amount of exponential mixing beyond convective boundaries, including those of the He-shell flash convection zone, can greatly increase the model’s dredge-up efficiency, maybe even to the extent that carbon star models of sufficiently low mass can be constructed. However, it is impossible at this time to know from first principles how large this convective overshooting really is, and all implications of this proposition have not yet been evaluated.

Understanding the dredge-up properties of AGB stars is of great importance for current astrophysical research. Yield predictions for low-mass stars enter into models for Galactic chemical evolution. AGB stars serve as diagnostics for extragalactic populations, and for this purpose the conditions of the O-rich to C-rich transitions are crucial to know. In fact, C-rich giants are the brightest infrared population in extragalactic systems, and new space-based infrared observatories like the Spitzer Space Telescope emphasize the importance of improved stellar models in this regard. Finally, the envelope enrichment of AGB stars with the s-process elements is intimately related to the dredge-up properties of the models.

We will in the next section describe the results of model calculations that show the sensitivity of dredge-up predictions to changes in published nuclear reaction rates, within their uncertainties (§ 2). In § 3 we will present our assessment of
recent work on the $^{14}\text{N}(p, \gamma)^{15}\text{O}$ reaction rate. Finally, we will discuss the results for dredge-up modeling of AGB stars (§ 4).

2. STELLAR EVOLUTION WITH VARYING NUCLEAR PHYSICS INPUT

We present here the first systematic study based on complete stellar evolution calculations of how changed nuclear reaction rates affect the dredge-up and envelope abundance evolution of AGB stars. Earlier studies have indicated that stronger He-shell flashes are followed by deeper dredge-up (Boothroyd & Sackmann 1988) and that a decreased energy generation in the H shell leads to stronger He-shell flashes (Despain & Scalo 1976). A decrease in the $^{14}\text{N}(p, \gamma)^{15}\text{O}$ reaction rate leads to a smaller energy generation and thereby to a stronger He-shell flash and increased dredge-up. These earlier findings can be understood qualitatively in the following way.

A less effective H shell will cause a slower He accretion onto the C/O core, and it will take somewhat longer to reach the He-buffer mass required to ignite the He shell and initiate the He-shell flash. In that case, the density will be higher in the He shell, and thus the thermonuclear runaway will be larger because the shell is thinner and partial degeneracy is higher. During H-core burning, the published uncertainties of the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ rate are usually not influential because the thermodynamic conditions will adjust slightly to generate the energy rate required by the stellar mass. In the case of shell burning on degenerate cores, this is different. The core is electron-degenerate, and it largely determines the thermodynamic conditions in the H shell. Thus, a decrease in the nuclear reaction rate does lead to a smaller He production rate, with the consequences of a stronger He-shell flash and more efficient dredge-up.

Two reactions are important in the He-shell burning. The triple-$\alpha$ reaction with its large temperature exponent drives the thermonuclear runaway of the He shell. The $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ rate produces oxygen, mainly in the hotter and deeper layers of the He shell. The rate uncertainties of both reactions have been considered.

We have used the stellar evolution code EVOL, which is equipped with up-to-date input physics (see Herwig 2004 for details). We have calculated seven AGB evolution tracks from a common starting model with a mass of 2 $M_\odot$ and metallicity $Z = 0.01$ at the end of the core He-burning phase. Mass loss is included according to the formula given by Blöcker (1995) with a scaling factor $\eta_\text{m} = 0.1$. All calculations are evolved until all envelope mass is lost. We assume exponential, time- and depth-dependent overshooting at the bottom of the convective envelope ($f_\text{ov} = 0.016$). At the bottom of the He-shell flash convection zone, no overshooting is allowed in this study.

For the benchmark sequence (ET2), we used the NACRE (Angulo et al. 1999) recommended values for all three reactions. In addition, for each reaction, one sequence has been calculated for the lower and for the upper limit from the NACRE recommendation. We found that the uncertainty in the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction has only a marginal influence on the evolution and dredge-up, and we will not discuss this case any further here. A summary of the remaining five calculations is given in Table 1. The factors listed are those that apply to the analytical reaction rate fits in the temperature range relevant for H-shell burning ($5 \times 10^6 \text{K} < T < 8 \times 10^7 \text{K}$) and He-shell burning ($1 \times 10^8 \text{K} < T < 3 \times 10^8 \text{K}$), respectively (see Herwig et al. 2004 for details).

The stellar evolution calculations show that the published reaction rate uncertainties for both the triple-$\alpha$ and the $^{14}\text{N}(p, \gamma)^{15}\text{O}$ reaction have a substantial influence on the third dredge-up and, consequently, on the formation of carbon stars and the yields from low-mass AGB stars, as exemplified by carbon. As shown in Figure 1 for the $^{14}\text{N}(p, \gamma)^{15}\text{O}$ reaction, dredge-up starts at a lower core mass and is larger for a given core mass if this rate is lower. It is interesting to note that dredge-up efficiency and derivative quantities (like the yields) depend in a highly nonlinear way on the reaction rate. For both reactions, the rate uncertainties are individually responsible for the carbon yield being uncertain by more than a factor of 2 (Table 1). The cases with the higher triple-$\alpha$ rate and with the lower $^{14}\text{N}(p, \gamma)^{15}\text{O}$ rate lead to carbon star formation at a lower luminosity (Fig. 2). In both these cases, the stellar model spends five to six thermal pulse (TP) cycles in the C-rich stage, whereas the other sequences are only able to reach the C star regime at about two TPs before the end of the evolution when the envelope mass is already low.

Modeling of the third dredge-up and comparison with observations are plagued by a number of theoretical uncertainties, including the assumptions about mixing processes and mass loss. Modifications like those proposed with respect to the C/O ratio–dependent molecular opacities (Marigo 2002) are important in this regard too. It is evident from this differential study that the uncertainties in the two key nuclear reactions discussed here have a profound impact on the dredge-up modeling as well.

3. RATE REVISION FOR THE $^{14}\text{N}(p, \gamma)^{15}\text{O}$ REACTION

NACRE rates for the $3\alpha$ reaction reflect present values of the nuclear parameters and seem reliable for the present temperature range. The situation is different for $^{14}\text{N}(p, \gamma)^{15}\text{O}$.

| ID | $^{14}\text{N}(p, \gamma)^{15}\text{O}$ | Triple-$\alpha$ | $^{14}\text{N}(p, \gamma)^{15}\text{O}$ |
|----|---------------------------------|---------------|---------------------------------|
| ET2 | 1.00                            | 1.00          | 2.19                            |
| ET5 | 1.33                            | 1.00          | 1.95                            |
| ET8 | 0.75                            | 1.00          | 4.27                            |
| ET6 | 1.00                            | 1.13          | 5.42                            |
| ET9 | 1.00                            | 0.82          | 1.79                            |

* Carbon yields are in units of solar mass: $\rho_i = \frac{1}{2} \left[ X_i(m) - X_{i,0}\right] \text{dm}$. 

![Graph](image)
The NACRE tabulation for $^{14}\text{N}(\rho, \gamma)^{15}\text{O}$ is based primarily on fits to the data of Schroeder et al. (1987). The resulting capture reaction to the ground state of $^{15}\text{O}$ contributed almost half of the total cross section at low energies. This led to a total $S$-factor $S(0) = 3.2 \pm 0.8$ keV barns and to the NACRE reaction rates (Angulo et al. 1999). However, there was a concern about this result (Adelburger et al. 1998) because the fit to the ground-state cross section yielded a surprisingly large value of the gamma width of a (subthreshold) $3/2^+$ state at $E_\gamma = 6.793$ MeV in $^{14}\text{O}$, about 7 times the value for the isospin-analog transition in $^{15}\text{N}$. Such large differences are rarely, if ever, seen (Adelburger et al. 1998; B. A. Brown 2004, private communication). A more detailed reanalysis (Angulo & Descouvemont 2001) of the same data found that the ground-state transition was small and that $S(0) = 1.77 \pm 0.2$ keV barns. Direct measurements of the 6.793 state’s lifetime (Bertone et al. 2001; Yamada et al. 2004) yielded much smaller gamma widths; these results and determinations of asymptotic normalization coefficients for the relevant transitions using nuclear transfer reactions (Mukhamedzhanov et al. 2003; A. M. Mukhamedzhanov 2003, private communication) led to a similar conclusion and $S(0) = 1.7 \pm 0.41$ keV barns. All these investigations show that the ground-state transition is small and that the resulting total $S$-factor is reduced by about a factor of 2 from the NACRE result. Recently, additional $^{14}\text{N}(\rho, \gamma)^{15}\text{O}$ data and corrected data from Schroeder et al. (1987) were analyzed to yield $S(0) = 1.70 \pm 0.22$ keV barns (Formicola et al. 2004). An independent measurement at the Triangle Universities Nuclear Laboratory (Runkle et al. 2004) yielded $S(0) = 1.66 \pm 0.20$ keV barns. Because some of the most accurate results exist only in preprint form, and because of unresolved issues involving M1 contributions to the ground-state transition (Nelson et al. 2003), we have chosen to use an unweighted average of the four recent results and a conservative error to obtain $S(0) = 1.70 \pm 0.25$ keV barns. This can be expressed as a factor in the analytical fit of the NACRE rate in the relevant temperature range, for easy employment in the stellar evolution code, and this factor is 0.64 $\pm$ 0.1. 

4. DISCUSSION AND CONCLUSIONS

We have shown in § 2 that the reaction rate uncertainties for the key rates $^{14}\text{N}(\rho, \gamma)$ and triple-$\alpha$ have significant influence on the dredge-up and yield predictions of low-mass AGB stars. Within the recommended uncertainties, both a 13% larger triple-$\alpha$ rate and/or a 25% lower $p$-capture rate of $^{14}\text{N}$ than adopted by NACRE give $^{13}\text{C}$ yield predictions that are higher by a factor of 2 (Table 1). Preliminary tests indicate that the superposition of these two uncertainties is nonlinear and leads only to a moderate further increase of the dredge-up and yields.

Clearly a detailed study of the superposition of nuclear reaction rate uncertainties is desirable. Such studies are computationally expensive and time-consuming and are therefore postponed (Herwig et al. 2004).

The new $^{14}\text{N}(\rho, \gamma)^{15}\text{O}$ rate resulting from recent work (§ 3) is even smaller than the NACRE lower limit used in our calculation ET8. Thus, the yields and dredge-up efficiency are likely to be somewhat larger in a model with the new recommendation compared to those from calculation ET8. In addition, the uncertainty in the triple-$\alpha$ reaction has to be factored in as well, allowing a range of possible solutions that may extend to still more efficient dredge-up. Preliminary analysis of our ongoing calculations suggests that a case with the NACRE-recommended upper limit of the triple-$\alpha$ rate and the lower limit adopted in § 3 for the $^{14}\text{N}(\rho, \gamma)^{15}\text{O}$ rate produces about 3.2 times more carbon than sequence ET2 (both rates are NACRE-recommended).

Finally, as one of us has argued previously (Herwig 2000), a small amount of overshooting at the bottom of the He-shell flash convection zone can accommodate some convincing observational constraints related to H-deficient central stars of planetary nebulae, which are the progeny of the AGB stars. This overshooting might further improve the agreement of models and observations.

We have shown that nuclear reaction rates are an important physics input when modeling the third dredge-up. We have no indication that suggests that a dependence of dredge-up on these nuclear reaction rates is not a universal feature with respect to models of different mass and metallicity.

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