

## Reaction Rate Uncertainties: NeNa and MgAl in AGB Stars

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We study the effect of uncertainties in the proton-capture reaction rates of the NeNa and MgAl chains on nucleosynthesis due to the operation of hot bottom burning (HBB) in intermediate-mass asymptotic giant branch (AGB) stars. HBB nucleosynthesis is associated with the production of sodium, radioactive  $^{26}\text{Al}$  and the heavy magnesium isotopes, and it is possibly responsible for the O, Na, Mg and Al abundance anomalies observed in globular cluster stars.

We model HBB with an analytic code based on full stellar evolution models so we can quickly cover a large parameter space. The reaction rates are varied first individually, then all together. This creates a knock-on effect, where an increase of one reaction rate affects production of an isotope further down the reaction chain. We find the yields of  $^{22}\text{Ne}$ ,  $^{23}\text{Na}$  and  $^{26}\text{Al}$  to be the most susceptible to current nuclear reaction rate uncertainties.

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## 1. Introduction

The Asymptotic Giant Branch (AGB) is the final evolutionary phase of stars with a mass less than about  $8M_{\odot}$ . The core of an AGB star has exhausted its supply of hydrogen and helium by nuclear burning and is made of carbon, oxygen, neon and perhaps magnesium, the main helium-burning products. A thin helium layer separates it from the convective stellar envelope which is mostly hydrogen. Hydrogen burning in a shell at the base of the envelope dominates the stellar luminosity, which is many thousands of times that of the Sun, but is punctuated by thermal pulses due to ignition of the helium layer. At each pulse the third dredge-up may occur, in which helium-burnt material is mixed into the stellar envelope, polluting it with helium, carbon,  $^{22}\text{Ne}$  and heavy *s*-process elements. The lifetime of an AGB star is dominated by rapid mass-loss which limits it to about a million years, after which the stellar envelope is ejected into the interstellar medium and a CO white dwarf remains.

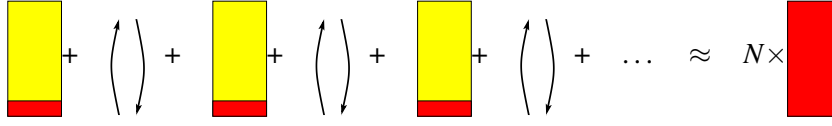
In AGB stars more massive than about  $4M_{\odot}$  the hydrogen burning shell, at a temperature of 60 to 100 million K, extends into the convective envelope, a process called *hot-bottom burning* (HBB). The envelope composition is directly affected by the various hydrogen-burning cycles: CNO, NeNa and MgAl. The effect is to convert carbon and oxygen to nitrogen, neon to sodium and magnesium to aluminium. The abundance anomalies seen in globular cluster stars, for example the oxygen-sodium anticorrelation, may be due to HBB in AGB stars [1]. The combination of third dredge-up of carbon with HBB is an important source of primary nitrogen, especially at low-metallicity.

Stellar models of hot-bottom burning rely on nuclear reaction rates that are inherently uncertain due to both experimental limits and extrapolation into the low-energy stellar regime. Our aim is to determine the effect of considering the rate uncertainties on the stellar abundances, and hence the chemical yields from AGB stars undergoing HBB. We have selected the NeNa and MgAl proton capture reactions primarily because these are modelled directly by our synthetic AGB model. It is not possible to vary the CNO reactions because they contribute significantly to the stellar luminosity, so affect the stellar structure, while we are assuming that changes in the NeNa/MgAl reaction rates do *not* affect the stellar structure.

## 2. Model

Our synthetic AGB model is described in detail in [2] but has been extended to include the NeNa and MgAl cycles (Izzard et al 2006, *in preparation*) as well as the CNO cycle. We model burning in the convective envelope by replacing the burn/mix/burn/mix... cycle with a single burn/mix event (see Figure 1) where the amount of material burnt, and the time it is burnt for, is calibrated to detailed AGB models [3].

We analytically solve the differential equations for the abundances of  $^{20,21,22}\text{Ne}$ ,  $^{23}\text{Na}$ ,  $^{24,25,26}\text{Mg}$  and  $^{26g,26m,27}\text{Al}$  in the burning region so we can follow the surface abundances as a function of time. The NeNa cycle is solved by an eigenvalue method (assuming no input to or output from the cycle, which is justified as  $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$  is usually slow and input from  $^{19}\text{F}$  is negligible compared to the amount of  $^{20}\text{Ne}$  present), then  $^{23}\text{Na}$  is decayed explicitly into  $^{24}\text{Mg}$ . The MgAl cycle then consists only of forward reactions if we ignore  $^{27}\text{Al}(p,\alpha)^{24}\text{Mg}$ , which is always justified at the temperature of HBB ( $\log_{10} T/\text{K} \sim 7.7 - 8.0$ ), so each rate equation is easily solved analytically.



**Figure 1:** Schematic view of our hot-bottom burning model. The detailed stellar models show that only a thin layer at the base of the convective envelope is hot enough to burn. In reality, and in the detailed models, the thin layer is continuously mixed over hundreds of convective turnover timescales, but our synthetic model can reproduce the effect by burning a large fraction of the stellar envelope for a short time.

Reaction	Lower limit	Upper limit	Reference
$^{20}\text{Ne}(p, \gamma)^{21}\text{Na}(\beta^+)^{21}\text{Ne}$	-50%	+50%	Iliadis et al. 2001 [5]=NACRE [4]
$^{21}\text{Ne}(p, \gamma)^{22}\text{Na}(\beta^+)^{22}\text{Ne}$	-20%	+20%	Iliadis et al. 2001 [5]
$^{22}\text{Ne}(p, \gamma)^{23}\text{Na}$	-50%	$\times 2000$	Hale et al. 2001 [5]
$^{23}\text{Na}(p, \alpha)^{20}\text{Ne}$	-30%	+30%	Rowland et al. 2004 [6]
$^{23}\text{Na}(p, \gamma)^{24}\text{Mg}$	/40	$\times 10$	Rowland et al. 2004 [6]
$^{24}\text{Mg}(p, \gamma)^{25}\text{Al}(\beta^+)^{25}\text{Mg}$	-17%	+20%	Iliadis et al. 2001 [5] = Powell et al. 1999 [7]
$^{25}\text{Mg}(p, \gamma)^{26}\text{Al}^g(\beta^+)^{26}\text{Mg}$	-50%	$\times 1.5$	Iliadis et al. 2001 [5]
$^{26}\text{Mg}(p, \gamma)^{27}\text{Al}$	/4	$\times 10$	Iliadis et al. 2001[5]
$^{26}\text{Mg}(p, \gamma)^{27}\text{Al}$	-25%	$\times 3$	Iliadis et al. 2001[5]
$^{26}\text{Al}^g(p, \gamma)^{27}\text{Si}(\beta^+)^{27}\text{Al}$	-50%	$\times 600$	Iliadis et al. 2001[5]

**Table 1:** Nuclear reaction rates in our network and their uncertainties. The effective stellar energy window for the reactions listed above is about 85-140 keV.

Beta-decays except that of  $^{26}\text{Al}^g$  are treated as instantaneous, we do allow for  $^{27}\text{Al}(p, \alpha)^{24}\text{Mg}$  by explicit decay of  $^{27}\text{Al}$  (the rate of this reaction is always negligible) and the chain is terminated at  $^{27}\text{Al}$  because  $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$  is very slow. The nuclear reactions, rate uncertainties in the HBB temperature range and references are found in Table 1.

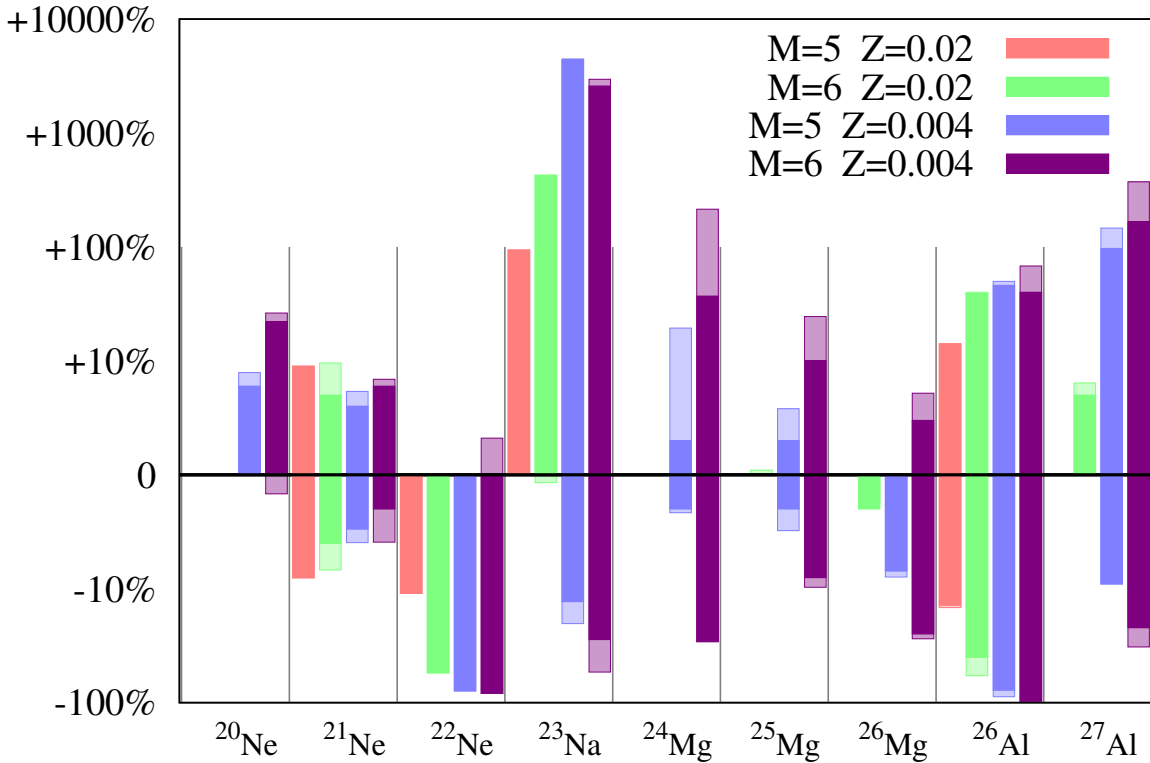
We have constructed two sets of models in which:

1. Each reaction is varied individually,
2. All reactions are varied at the same time.

When comparing the yield of an isotope, which we define simply as the mass ejected as that isotope, we use a control model where all the reaction rates are set to their recommended values (i.e. their rate multipliers are all 1.0). We use  $M = 5, 6M_{\odot}$  and  $Z = 0.02, 0.004$  to test the effect of increasing mass and decreasing metallicity, both of which increase the amount of hot-bottom burning.

### 3. Results

Figure 2 shows the effect on chemical yields of the NeNa and MgAl isotopes of varying the proton-capture nuclear reaction rates. The values shown are percentage differences from the control values, where positive values indicate extra production, negative values extra destruction, and zero means no change.



**Figure 2:** Uncertainty ranges for chemical yields as the difference from the control value as a function of isotope for our four sets of model. Dark colours are the maximum uncertainty ranges for varying each reaction individually, the light colours give the uncertainty when all the reactions are varied together.

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The main effects are:

- Complete conversion of  $^{22}\text{Ne}$  to  $^{23}\text{Na}$ , or not, due to the large uncertainty in the  $^{22}\text{Ne}(p, \gamma)^{23}\text{Na}$  rate. The yield of  $^{23}\text{Na}$  can be boosted by a factor of about 40 at  $Z = 0.004$ , in both the 5 and  $6M_{\odot}$  models. This sodium is *primary*;
- A potential increase or decrease by a factor of 2 in the yield of  $^{24}\text{Mg}$  and an uncertainty of 10% in  $^{25}\text{Mg}$ , but only in our  $Z = 0.004$  models;
- A very large uncertainty in  $^{26}\text{Al}$  production, ranging from  $\times 0$  to  $\times 2$ . This stems from the  $\times 600$  range of the  $^{26}\text{Al}(p, \gamma)^{27}\text{Si}$  rate. There is a corresponding knock-on effect on  $^{27}\text{Al}$ ;
- Most other isotopes vary by at most about 10 – 20%.

It is sometimes necessary to consider changing all the reaction rates together. The yields of the magnesium isotopes at  $Z = 0.004$  show this clearly, as they are affected by the preceding NeNa cycle rate changes followed by  $^{23}\text{Na}(p, \gamma)^{24}\text{Mg} \dots (p, \gamma)^{25}\text{Al}(\beta^+)^{25}\text{Mg} \dots (p, \gamma)^{26}\text{Al}(\beta^+)^{26}\text{Mg}$ .

## 4. Conclusions

We have showed that changes in yields from hot-bottom burning stars due to nuclear reaction rate uncertainties can be significant, particularly for  $^{22}\text{Ne}$ ,  $^{23}\text{Na}$ , the magnesium isotopes and aluminium. The effect of reaction rate uncertainty becomes stronger as the hydrogen burning temperature increases i.e. at higher mass and/or lower metallicity. For some isotopes, especially those of magnesium, it is important to consider changing *all* the uncertain reaction rates at the same time, as simply changing the proton capture rate on each isotope does not give an accurate error range for the yield.

It remains to be seen if, say, a higher  $^{22}\text{Ne}(p, \gamma)^{23}\text{Na}$  rate can help to solve the problem of the globular cluster abundance anomalies, which show excessive sodium and lower oxygen, particularly as we have not tried to change the CNO cycle rates here. It is also possible that the yields of primary sodium could be constrained by galactic chemical evolution models, which in turn would give us an upper limit for the  $^{22}\text{Ne}(p, \gamma)^{23}\text{Na}$  rate, although we will also have to examine carefully the role of massive stars in  $^{23}\text{Na}$  production.

Factor of two changes in the magnesium yields in our low-metallicity models may be important for fine-structure constant ( $\alpha$ ) variation studies because  $\Delta\alpha/\alpha$  is a steep function of  $(^{25}\text{Mg} + ^{26}\text{Mg})/^{24}\text{Mg}$  (see Fig. 1 of [8]).

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