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The uncertainties in the ^{22}Ne $+\alpha$-capture reactions and magnesium production in intermediate-mass AGB stars

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Abstract. We study how the production of the neutron-rich magnesium isotopes in intermediate mass Asymptotic Giant Branch stars is affected by uncertainties in the neutron-capture reactions involving the Mg isotopes and uncertainties in the ^{22}Ne $+\alpha$-capture reaction rates. We examine how uncertainties in these rates affect the stellar yields of species from ^{22}Ne through to ^{31}P, which is important for chemical evolution models. We also compare our results to data from pre-solar spinel grains, where the magnesium isotopic ratios have been accurately measured.

Key words. stars: AGB and post-AGB – nuclear reactions, nucleosynthesis, abundances, magnesium

1. Introduction

The neutron-rich magnesium isotopes can be produced (and destroyed!) inside intermediate mass Asymptotic Giant Branch (AGB) stars (Karakas & Lattanzio 2003). Many of the reaction rates which are involved in Mg production in the He-shell have large uncertainties, the effect of which are mostly untested in stellar models of AGB stars. Briefly, during thermal pulses, the neutron-rich Mg isotopes can be produced by the chain of reactions: ^{14}N$(\alpha,\gamma)^{18}$F$(\beta^{+}\nu)^{18}$O$(\alpha,\gamma)^{22}$Ne followed by ^{22}Ne$(\alpha$,n$)^{25}$Mg and ^{22}Ne$(\alpha,\gamma)^{26}$Mg when the temperature exceeds about 300 $\times 10^{6}$ K. The amount of ^{22}Ne, ^{25}Mg and ^{26}Mg produced in the intershell depends on the temperature in the helium-shell during the thermal pulse (TP) and the amount of ^{14}N left by the hydrogen shell during the preceding interpulse period. In AGB stars with deep third dredge-up and hot bottom burning (HBB), primary ^{14}N is produced from the primary ^{12}C dredged into the envelope. Note that HBB can also alter the abundance of all Mg isotopes, including ^{24}Mg, which is destroyed when the temperature exceeds 90×10^{6} K.

While the rates of the ^{14}N$(\alpha,\gamma)^{18}$F and ^{18}O$(\alpha,\gamma)^{22}$Ne reactions are well de-

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termined (Görres et al. 2000; Dababneh et al. 2003), the rates of the ^{22}Ne(α,n)^{25}Mg and ^{22}Ne(α,γ)^{26}Mg reactions are not well known and suffer from large uncertainties (Koehler 2002). Neutrons liberated by the ^{22}Ne(α,n)^{25}Mg reaction can be captured by ^{24}Mg and ^{25}Mg, which will also affect the distribution of these species in the He-rich intershell. In this study we are concerned with how uncertainties in these reaction rates affect the production of the Mg isotopes in intermediate mass AGB stars of various initial compositions.

This is of interest in relation to the problem of the apparent time variation of the fine structure constant (Ashenfelter, Mathews & Olive 2004), to anomalies observed in some globular clusters stars (Yong et al. 2003a), observations of fields stars of different metallicities (Yong et al. 2003b) and measurements of the Mg isotopic ratios in pre-solar grains (Zinner et al. 2004).

2. The stellar models

We calculate the structure models first and perform detailed nucleosynthesis calculations afterward, using a post-processing algorithm. The stellar structure models were calculated with the Monash version of the Mount Stromlo Stellar Structure Program; see Karakas & Lattanzio (2003) and references therein for details. For the present study we used a 6.5M$_\odot$, Z = 0.02 model and 5M$_\odot$ models with Z = 0.02, 0.004 and 0.0001. Mass loss on the first giant branch is included using the Reimer's mass-loss prescription (Reimers 1975) with the parameter η = 0.4 and on the AGB we use the formulation given by Vassiliadis & Wood (1993). The models were calculated from the pre-main sequence to near the end of the thermally-pulsing AGB phase. In all models we found HBB and deep third dredge-up (TDU) to occur self-consistently. In Table 1 we present some details of the models relevant for the nucleosynthesis including the number of thermal pulses, the number of TDU episodes, the core mass at the beginning of the TP-AGB, the maximum temperature at the base of the convective envelope, the maximum temperature in the He-shell during a TP and the maximum dredge-up efficiency, $\lambda_{\rm max}$[1]. We note that the 5M$_\odot$, Z = 0.02 only experienced HBB for about 10 thermal pulses whereas the other models experienced very efficient HBB from about the second TP until about the fifth-to-last TP.

We performed detailed nucleosynthesis calculations using a post-processing code which includes 74 species and time-dependent mixing in all convective zones. In the nucleosynthesis network there are 59 nuclei from neutrons and protons up to sulphur, with another 14 iron group species to allow neutron capture on iron seed nuclei. Initial abundances were taken from Anders & Grevesse (1989) for the Z = 0.02 models and we assumed scaled-solar for most of the Z = 0.004 and Z = 0.0001 models. We also calculated 5M$_\odot$, Z = 0.004 models with an initially α-enhanced mixture typical of thin disk stars (Reddy et al. 2003).

The inclusion of a partial mixing zone at the deepest penetration of the TDU will mix protons from the envelope into the He-intershell, producing a ^{13}C pocket. The ^{13}C burns radiatively via ^{13}C(α,n)^{16}O, liberating free neutrons that can be captured by ^{24}Mg and ^{25}Mg, further altering the distribution of the Mg isotopic ratios in this region. The details of how the ^{13}C pocket forms is still unknown though various mechanisms have been proposed including diffusive convective overshoot (Herwig et al. 1997), rotational shear (Langer et al. 1999) and internal gravity waves (Denissenkov & Tout 2003). In nucleosynthesis studies the extent of the pocket is usually set as a free parameter, with typical values ~ 1/15$^{\rm th}$ the mass of the He-intershell (Gallino et al. 1998; Goriely & Mowlavi 2000). In intermediate mass stars, the mass of the He-intershell is smaller by about an order of magnitude compared to lower mass stars and hence the importance of the ^{13}C pocket may be lessened. For example, the mass of the He-intershell in the 5M$_\odot$, Z = 0.02 model varies from about 0.004M$_\odot$ near the beginning of the TP-AGB to 0.001M$_\odot$ near the end (compared to about 0.02M$_\odot$ in a $M \approx$ 3M$_\odot$ model). We test the ef-

[1] where $\lambda = \Delta M_{\rm dredge}/\Delta M_{\rm core}$

Table 1. Some details of the AGB models used for the present study:

Mass ($M_\odot$)	Z	No. TP	No. TDU	$M_c(1)$ ($M_\odot$)	T^{max}_{BCE} (in 10^6K)	T^{max}_{He} (in 10^6K)	λ_{max}
5.0	0.02	24	20	0.861	64	352	0.961
6.5	0.02	40	36	0.951	87	372	0.910
5.0	0.004	83	81	0.888	85	379	0.959
5.0	0.0001	94	92	0.910	92	380	0.980

fect of adding in a ^{13}C pocket in one model of 5$M_\odot$, Z = 0.02, by adding in a partial mixing zone with an extent in mass equal to 0.001$M_\odot$ at the end of each TDU episode. This will result in a larger ^{13}C pocket than used in previous simulations and the results can be considered a qualitative upper limit. Further work will be to investigate models of lower mass.

2.1. The reaction rates

The bulk of the 506 reaction rates are from the REACLIB data tables (Thielemann et al. 1986), based on the 1991 updated version. Some of the reaction rates have been updated according to the latest experimental results, see Lugaro et al. (2004) for details. In this study, we adopt the NACRE rates (Angulo et al. 1999) for the Ne-Na and Mg-Al chains. For our *standard* case, we adopt the NACRE recommended rates for the ^{22}Ne(α,n)^{25}Mg and ^{22}Ne(α,γ)^{26}Mg reactions. We also calculated models using both the NACRE upper and lower limits of these rates. For the M = 5 and 6.5$M_\odot$, Z = 0.02 cases, we calculate sequences using the NACRE upper limit of the ^{22}Ne(α,γ)^{26}Mg rate and the NACRE lower limit of the ^{22}Ne(α,n)^{25}Mg reaction rate. These combinations were chosen to try and match the composition of the grain OC2.

The NACRE upper limits to the two ^{22}Ne + α reactions are higher than the recommended values by a couple orders of magnitude at the temperatures relevant for He-shell burning in AGB stars (between 100 to 400 million K). There are more recent estimates of the ^{22}Ne(α,n)^{25}Mg reaction rate than given by NACRE. Both Koehler (2002) and Jaeger et al. (2001) point out the large upper uncertainty given by the NACRE compilation can be ruled out and provide new estimates of this rate with much smaller uncertainties (about a factor of 5 from Jaeger et al. (2001)). We should point out that the Jaeger et al. (2001) is based on experimental data which still suffers from too much background noise to measure the hypothetical resonance at 635 keV.

We calculate further models with the ^{25}Mg(n,γ)^{26}Mg rate or the ^{24}Mg(n,γ)^{25}Mg rate (Weigmann et al. 1976) varied by a factor of two either way. The neutron capture cross sections of ^{24}Mg, ^{25}Mg and ^{26}Mg have been recently re-measured at CERN (The n-TOF Collaboration 2004).

3. Results and discussion

3.1. The stellar yields

In Figure 1 we present the percentage difference between the stellar yields calculated from models using our *standard* reaction rates and five other cases. We do not include results from models which varied the ^{24}Mg(n,γ)^{25}Mg reaction rate owing to differences of less than 2% for all species but ^{24}Mg, where the differences were less than 15%. From Figure 1 we show that the ^{22}Ne + α-capture reactions are important for the production of a number of species besides ^{22}Ne and the heavy Mg isotopes. This is because of the feedback between the TDU and other nucleosynthesis sites but also because extra free neutrons are available for neutron-capture, so the production of the heavy Si-isotopes and ^{31}P are affected. Hence it is very important that these rates be constrained at the temperatures relevant for He-shell burning in AGB stars. The largest yield changes are observed in models that use the NACRE upper limits for the ^{22}Ne α-capture reactions and these results will have to be tested against observations using chemical evolution models such as those employed by Fenner et al. (2003). Even if we can rule out the NACRE upper limits to these reactions, varying the ^{25}Mg(n, γ)^{26}Mg rate by a factor of two resulted in fairly significant changes to the production of some isotopes, notably ^{25}Mg, ^{26}Mg, ^{29}Si, ^{30}Si and ^{31}P, with the largest differences of the order of 50%.

From Figure 1 we observe that the inclusion of a large ^{13}C pocket in the 5M$_\odot$, Z = 0.02 model resulted in large changes to the stellar yields, with differences of up to 190% for ^{31}P compared to the standard case without a pocket. Whilst the size of the partial mixing zone at the end of the TDU is unknown, it will probably be smaller than the entire He-rich intershell which we assumed in this calculation near the end of the TP-AGB phase. Hence the inclusion of a more realistic pocket ($\approx 2 \times 10^{-4}$M$_\odot$) might result in less significant changes perhaps making the inclusion of a pocket unimportant.

3.2. The pre-solar grain OC2

In Figure 2 we present the Mg isotopic ratios plotted as δ-values, defined according to δ^{26}Mg/^{24}Mg = ((^{26}Mg/^{24}Mg)/(^{26}Mg/^{24}Mg)$_{\rm solar}$)×1000. Note that the δ^{26}Mg/^{24}Mg ratio includes the radiogenic contribution from ^{26}Al. The models start the TP-AGB with the Mg isotopic ratios shifted by the second dredge-up (SDU); some of the grains with enhanced ^{26}Mg and depleted ^{25}Mg could be the result of SDU nucleosynthesis.

From Figure 2 we see that the 5M$_\odot$, Z = 0.004 (with [Fe/H] $\sim$ −0.7) can explain the Mg isotopic ratios measured in the grain OC2. However, the composition of the grain was reached relatively early on in the evolution along the TP-AGB before most of the mass is lost from the envelope. It is also unlikely that a presolar grain produced in a star of such low metallicity could survive in the interstellar medium for so long and end up in our solar system. The 6.5M$_\odot$, Z = 0.02 model is also relatively close to the composition of this grain, in particular the case where the ^{25}Mg(n, γ)^{26}Mg reaction was multiplied by two; the cases using the NACRE upper limit of the ^{22}Ne(α, γ) reaction and the lower limit of the ^{22}Ne(α,n) overproduced the amount of ^{26}Mg, compared to the grain OC2 (see the left panel of Figure 2). The uncertainties in the rates of production and destruction of ^{26}Al by proton-capture should also be considered.

Moreover, there are a number of other constraints that must be met, including the oxygen and aluminium isotopic ratios. For example, the ^{18}O/^{16}O ratio presents a serious problem since very efficient HBB destroys ^{18}O. In OC2 the ^{18}O/^{16}O = 7×10^{-5} whereas in the 6.5M$_\odot$, Z = 0.02 model this ratio $\approx 1.8 \times 10^{-6}$ when δ^{26}Mg/^{24}Mg $\approx$ 1100. However, it is likely that the ^{18}O/^{16}O ratio measured in OC2 is an upper limit, as some contamination with solar material, rich in ^{16}O, likely occurred (Zinner, private communication). All the models produce larger ^{17}O/^{16}O ratios than found for OC2 (1.25×10^{-3}) however the 6.5M$_\odot$, Z = 0.02 models came closest to matching this composition, where the ratio ranged from 1.53×10^{-3} at the beginning of the TP-AGB to 2.29×10^{-3} near the end. Both of the ^{17}O destruction rates are still quite uncertain and further tests using new rate estimates from Iliadis et al. (2001) are needed. We should also examine models of intermediate metallicity between solar and Z = 0.004, such as Z = 0.008 (with [Fe/H] $\sim$ −0.3). A detailed study is needed to address the composition of this grain.

4. Conclusions

The production of the heavy magnesium isotopes inside intermediate mass AGB stars is sensitive to the nucleosynthetic conditions inside thermal pulses as well the choice of nuclear reaction rates. We have shown that the large uncertainties that exist for the ^{22}Ne $+\alpha$-capture reactions have a dramatic impact on the production of species from ^{22}Ne through to ^{31}P. The inclusion of a ^{13}C pocket also affects the nucleosynthesis of these intermediate-mass isotopes during the TP-AGB. The stellar yields from these calculations should be tested with a chemical evolution model of the Mg isotopes.

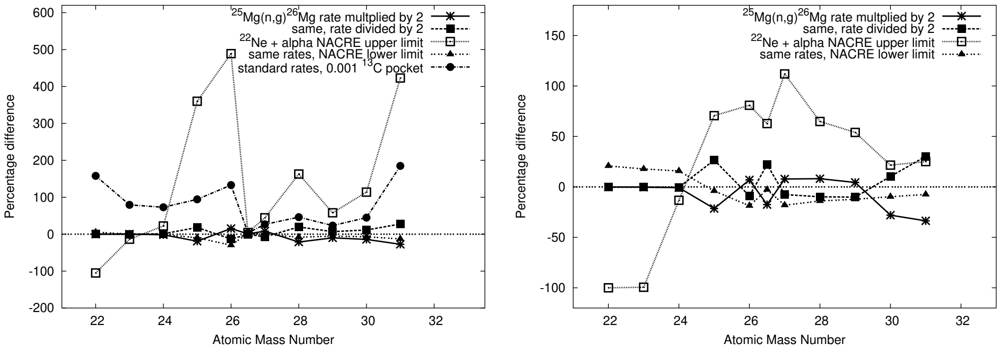

Fig. 1. Percentage difference between stellar yields calculated from models using our *standard* reaction rates and a number of other cases. Results for the $5M_{\odot}$, $Z = 0.02$ model are shown on the left and results for the $5M_{\odot}$, $Z = 0.0001$ model on the right. We present results for isotopes from ^{22}Ne to ^{31}P.

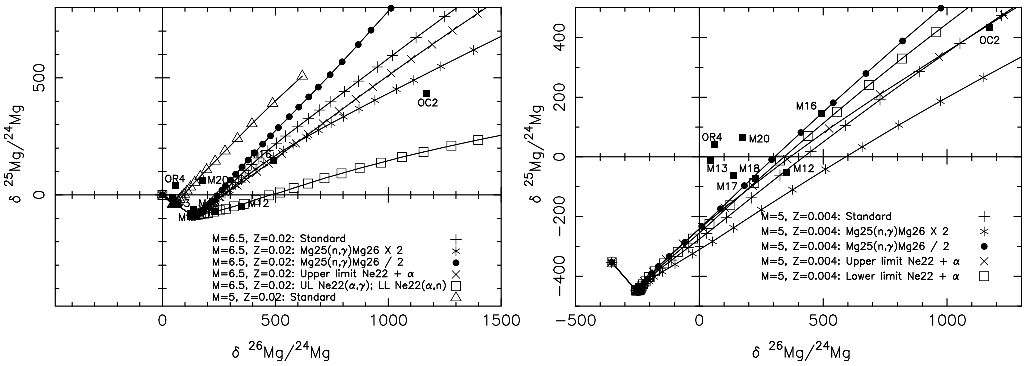

Fig. 2. Magnesium isotopic ratios plotted as δ-values for a number of selected models. (Left) from $Z = 0.02$ models and (right) from the $5M_{\odot}$, $Z = 0.004$ models with α-enhanced initial abundances. Also included are Mg isotopic ratios from pre-solar spinel grains (Zinner et al. 2004).

The presolar spinel grain OC2 was likely produced inside an intermediate mass AGB star with hot bottom burning. Our results suggest a star of sub-solar metallicity; we find a match to the Mg isotopic composition of this grain for a model with $5M_{\odot}$, $Z = 0.004$. There are other constraints that must be met, including the oxygen isotopic ratios. A detailed study is needed to address the composition of this grain.

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