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Light *s*-Process Element Production in Solar Metallicity AGB Stars

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Abstract. Spectral lines of highly ionized neutron-capture elements have recently been detected in planetary nebulae (PNe), with derived abundances ranging from solar to factors of 3 to ~ 30 above solar. These observations indicate that the *slow* neutron-capture process (*s* process) operated in the parent star during the thermally-pulsing asymptotic giant branch (TP-AGB) phase. We compute a number of solar metallicity AGB models to compare with these observations. Within the uncertainties allowed by the observations, the models produce a reasonable match to the composition of most PNe. Model uncertainties (e.g. convection, mass loss) affect the results and could account for the composition of the most *s*-process-enriched objects. The occurrence of third dredge-up episodes at the tip of the AGB, when the envelope mass is small, or a late thermal pulse on the post-AGB track, could provide further enrichment. Further study is required to better assess how the model uncertainties affect the predictions and, consequently, whether a late TP should be invoked.

1. Introduction

After the thermally-pulsing asymptotic giant branch phase is terminated, low to intermediate mass stars ($M_{\rm initial} \sim 0.8$ to $8\,{\rm M}_{\odot}$) evolve through the planetary nebula phase before finally ending their lives as white dwarfs (see Herwig 2005, for a recent review). The gaseous nebula is the remnant of the deep convective envelope that once surrounded the core, which is now exposed as the central star of the PN. Thus the composition of the nebula should reveal information about the chemical processing that took place during the AGB phase, and more precisely, information about the final thermal pulses.

Accurate abundances from PNe for helium, C, N, O, Ne, S, Cl and Ar have been available for some time (Dopita et al. 1997; Stanghellini et al. 2000). These abundances can be used as a powerful tool to constrain models of AGB stars (Karakas & Lattanzio 2003), in particular the amount of mixing that occurs during the third dredge-up (TDU) following a thermal pulse (TP). The discovery of lines of the light neutron-capture element Ge in PNe by Sterling, Dinerstein, & Bowers (2002) has been followed by the detection of more heavy elements

(Ga, Br, Kr, Se, Xe, Rb, Ba) that can be created by the *s*-process (Sterling & Dinerstein 2003; Sterling et al. 2007; Sharpee et al. 2007). Observations have revealed PNe compositions ranging from no enhancements to enhancements of factors of ∼3 to 30 above solar. Abundances of heavy elements in PNe are particularly interesting and important because they provide constraints on the amount of TDU and also on the operation of the *s*-process occurring in AGB stars of various masses.

In this contribution we report on the results of a study that compares model predictions from solar-metallicity AGB stars to PNe. In Karakas, Lugaro, & Gallino (2007) we also study the effect of metallicity by considering AGB models with $Z = 0.008$ and 0.004.

2. The Numerical Method

We compute the structure first and then perform detailed nucleosynthesis calculations in the manner described by Lugaro et al. (2004). The reaction network in the post-processing algorithm has been expanded from 74 species to 156, to include all stable isotopes up to ^{75}As.

We use a "double neutron-sink" description (Herwig, Langer, & Lugaro 2003) and include two artificial species which are linked by the following reactions: $^{75}\mathrm{As}(n,\gamma)^{76}\mathrm{g}$ and $^{76}\mathrm{g}(n,L)^{76}\mathrm{g}$, where ^{76}g replaces ^{76}As and has an initial abundance equal to the sum of solar abundances from Se to Bi. The second artificial particle, L, is equivalent to counting the number of neutrons captured beyond arsenic.

Most of the 1260 reaction rates are from the 1991 updated REACLIB Data Tables. Many of the proton, α and n capture reaction rates have been updated according to the latest experimental results; see Lugaro et al. (2004) and Karakas et al. (2006) for details. The cross-section of the $^{76}\mathrm{g}(n,L)^{76}\mathrm{g}$ reaction is a composite assuming a solar heavy-element distribution and thermodynamic conditions appropriate for low-mass AGB stars.

3. The Stellar Models

Stellar models of 1.5, 3 and 6.5 $\mathrm{M}_\odot$ with $Z = 0.012$ were computed with the revised solar abundances from Asplund, Grevesse, & Sauval (2005) for comparison to the $Z = 0.02$ models, with abundances from Anders & Grevesse (1989). Similar to the $Z = 0.02$ case (Karakas et al. 2002), the 1.5 $\mathrm{M}_\odot$, $Z = 0.012$ model did not experience any TDU and we do not consider it further. The 3 $\mathrm{M}_\odot$ $Z = 0.012$ model became a carbon star, reaching a final C/O ratio of 2.8, whereas the 6.5 $\mathrm{M}_\odot$ model experienced efficient HBB with peak temperatures of $\sim 90 \times 10^6$ K, thus retaining an O-rich atmospheric composition. The 3 and 6.5 $\mathrm{M}_\odot$, $Z = 0.012$ models were similar to their $Z = 0.02$ counterparts when comparing the initial/final masses and the total number of TPs during the TP-AGB phase (see Table 1 of Karakas et al. 2007). The behavior of the $Z = 0.012$ models was that of slightly lower metallicity models where we observed somewhat deeper TDU and hotter burning shells. In Figure 1 we show the comparison at 3 $\mathrm{M}_\odot$ where the final masses are 0.68 $\mathrm{M}_\odot$ and 0.69 $\mathrm{M}_\odot$, respectively, for the $Z = 0.02$ and $Z = 0.012$ models.

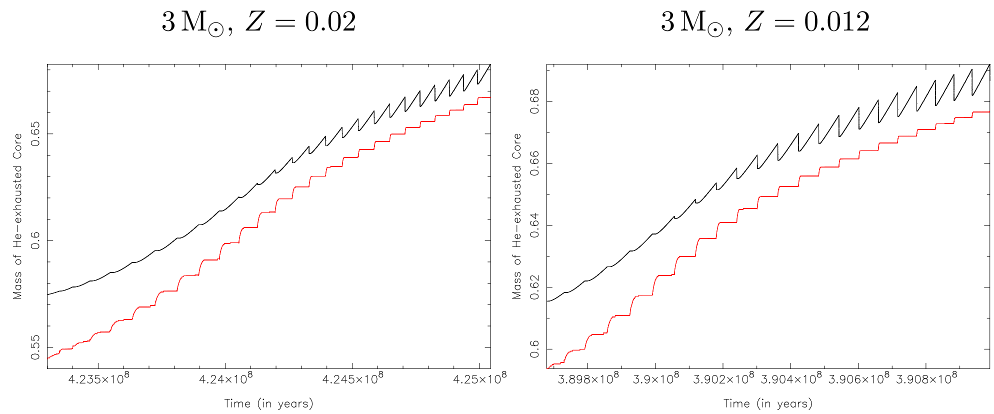

Figure 1. The time evolution of the H and He-exhausted cores for the $3\,M_\odot$ models, where the figure on the *left* was computed with solar abundances from Anders & Grevesse (1989) and the figure on the *right* with solar abundances from Asplund et al. (2005).

The results found in this study are subject to many model uncertainties including convection and mass loss which effect both the structure and nucleosynthesis. We refer to Herwig (2005) for a discussion on this topic.

3.1. The Inclusion of a Partial–Mixing Zone

The inclusion of a partial mixing zone (PMZ) at the deepest extent of dredge-up will mix protons from the envelope into the He–intershell, producing a ^{13}C pocket. In the PMZ neutrons are liberated during the interpulse period by the reaction $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$, and they are captured by iron-seed nuclei to produce heavy elements. Observational and theoretical evidence suggests this is the dominant neutron source in low-mass AGB stars (Gallino et al. 1998); however, the details of how the pocket forms and its extent in mass in the He–intershell are still unknown.

As done in previous nucleosynthesis studies (Gallino et al. 1998; Goriely & Mowlavi 2000; Lugaro et al. 2004) we artificially include a PMZ of constant mass. The masses were estimated to be between $\sim 10\%$ and 20% of the mass of the He-rich intershell, noting that the mass of the intershell decreases with time. We chose a proton profile in which the number of protons decreases exponentially with the mass depth below the base of the convective envelope in the same way as described in Lugaro et al. (2004).

4. Results

For all cases, the [Ga/Fe] and [Ge/Fe] ratios at the surface after the last computed TP were ≤ 0.67 (or a factor of $\lesssim 4.7$), where the Ga enhancements were slightly larger than those of Ge for most models. We note that the Ga detection in one PN was tentative, so we do not put much weight on results for this element. Models with no ^{13}C pocket produced little *s* process material. Results are presented in tabulated form in Karakas et al. (2007), including a compari-

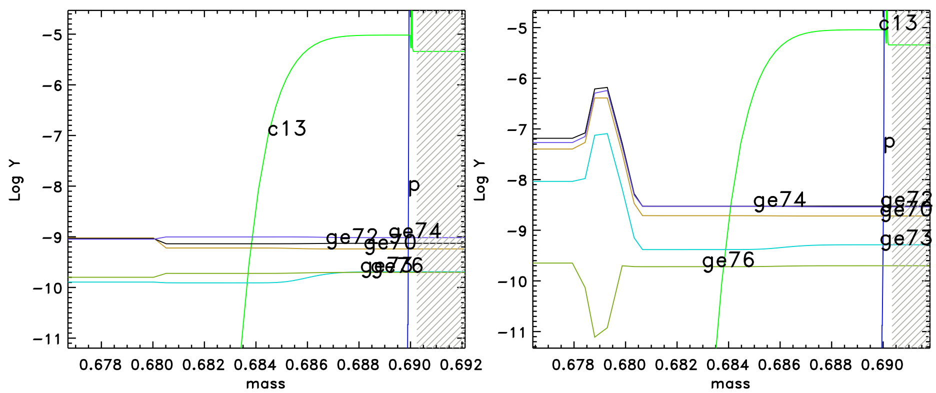

Figure 2. Composition profile showing the intershell abundances (in $\log Y$, where mass fraction $X = YA$) just before the final thermal pulse for the $3\,M_{\odot}$, $Z = 0.012$ model with (*left*) no pocket and (*right*) a PMZ of 0.002 $M_{\odot}$. The shaded region is the inner edge of the convective envelope. Note that the intershell abundances are typically diluted by one order of magnitude at the surface by the last TDU episode.

son to the *Torino* *s*-process models (Gallino et al. 1998). In Figure 2 we can see that the inclusion of a PMZ facilitates the formation of heavy elements like Ge, whereas the model with no pocket (*left*) produced little *s*-process material during the interpulse period.

The exception to this is the $6.5\,M_{\odot}$ model where neutrons are released by efficient activation of the ^{22}Ne neutron source during TPs. For this model, the increase of heavy elements was less than about a factor of 2. In comparison the $5\,M_{\odot}$, $Z = 0.02$ model produced very little Ge (or Ga), either with ([Ge/Fe] = 0.112) or without (0.04) a PMZ. Massive AGB stars are the favored progenitors of Type I bipolar PNe because of their high He and N/O abundances (Stanghellini et al. 2006). Sterling (2006) finds a correlation between PNe morphology and *s*-process abundances, where elliptical PNe are more enriched than bipolar PNe, which show little or no enhancement.

5. Discussion

In Karakas et al. (2007) we conclude that in light of the considerable observational uncertainties (Sterling 2006) that arise from the choice of the level of dust depletion, and the many uncertainties inherent in the stellar models, the AGB models presented here provide a reasonable match to the *s* process composition of most PNe.

The composition of the most *s*-enriched objects (for example SwSt 1 and BD +30°3639, both of them surrounding a H-deficient [W–C] central star), might be accounted for by noting that most models had some remaining envelope mass when the computations ended. These models could, in principle, experience further TPs and TDU episodes. In Karakas et al. (2007) we estimate that 2 more

TPs could occur for the $3\,M_{\odot}$, $Z = 0.012$ model, and speculatively assuming that the TDU efficiency does not change, we estimate that the final [Ge/Fe] ratio is ~ 0.9, close to the maximum value required to match the composition of the most Ge-enriched objects. This value is likely to be an over-estimate, given the evidence for decreasing TDU efficiency with decreasing envelope mass (Straniero et al. 1997, but see Stancliffe & Jeffery (2007)). Variations in the mass-loss rate will also influence our results.

The relation between PNe with H-deficient central stars and those with the largest Ge abundances (Sterling & Dinerstein 2006) might be explained if a late TP was responsible for both. Such a scenario would also produce enhancements of the other *s*-process elements, but this is not seen (Sterling 2006). However, evidence for a late TP might come from BD +30°3639, with enhanced Ge and an Fe-deficient central star (Werner & Herwig 2006), possibly indicating a high level of mixing of *s*-processed material. Further study of the stellar model uncertainties together with more accurate observations are needed, and these will be the subject of future work.

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