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Heavy elements in planetary nebulae: A theorist's gold mine

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Abstract. Observations of planetary nebulae have revealed a wealth of information about the composition of heavy elements synthesized by the *slow* neutron capture process (the s process). In some of these nebulae the abundances of neutron-capture elements are enriched by factors of 10 to 30 times the solar value, indicating that these elements were produced in the progenitor star while it was on the asymptotic giant branch (AGB). In this proceedings we summarize results of our recent full *s*-process network predictions covering a wide range of progenitor masses and metallicities. We compare our model predictions to observations and show how this can provide important insights into nucleosynthesis processes occurring deep within AGB stars.

Keywords. Nuclear reactions, nucleosynthesis, abundances, stars: AGB and post-AGB, stars: abundances, planetary nebulae: general

1. Introduction

After the thermally-pulsing AGB (TP-AGB) phase is terminated, low to intermediate-mass stars (~ 0.8 to $8 M_{\odot}$) evolve at near constant luminosity to become post-AGB objects. If the ejected envelope has sufficient time to become ionized by the hot central star before dissipating, then the object will be observed as a planetary nebula (PN). For recent reviews of TP-AGB and post-AGB stars, see Herwig (2005) and van Winckel (2003), respectively. The ionised nebula is comprised of material from the convective envelope that once surrounded the core, hence, nebular abundances may reveal information about the efficiency of mixing events and chemical processing that took place during previous evolutionary phases, in addition to the initial composition of the parent star.

Briefly, a TP-AGB star is characterised by two nuclear burning shells above a degenerate C-O core, surrounded by a deep convective envelope. During the TP-AGB phase the He-burning shell becomes thermally unstable every $\sim 10^5$ years, which may be followed by the inward motion of the convective envelope into the He-intershell region. This inward movement of the convective envelope is known as the third dredge-up (TDU), and is responsible for enriching the surface in ^{12}C and other products of He-burning, as well as heavy elements produced by the s process. Hot bottom burning (HBB) occurs in intermediate-mass AGB stars ($M \gtrsim 4$ M$_{\odot}$, depending on Z) when the base of the convective envelope becomes hot enough to sustain proton-capture nucleosynthesis. Note that AGB stars that experience HBB have H-exhausted cores $\gtrsim$0.8 M$_{\odot}$, and will have very short post-AGB lifetimes and may not form PNe. Owing to initial mass function considerations these stars will also be relatively rare.

Abundances derived from PN spectra provide a complimentary data set to the abundances derived from the spectra of cool evolved stars. For example, the elemental abundances of He, Ne, and Ar can be obtained, along with the abundances of C, N, O, S, and Cl, e.g., Henry *et al.* (2010), Shaw *et al.* (2010). It has also been shown that some PNe are enriched in heavy elements that can be produced by the s-process including Ge, Se, Kr, Xe, and Ba, e.g., Pequignot & Baluteau (1994), Dinerstein & Geballe (2001), Sharpee *et al.* (2007), Sterling & Dinerstein (2008), Otsuka *et al.* (2010). Sterling & Dinerstein (2008) obtained Se and Kr abundances for 120 Galactic PNe, and investigated trends between s-process enrichment and PN morphology and other nebular and stellar characteristics.

Here we show examples of full s-process nucleosynthesis predictions that can be compared to the available observations. We aim to be able to constrain the neutron sources operating in AGB stars of different mass, using observational abundance constraints from planetary nebulae. Likewise, we would like to be able to constrain PNe progenitor masses using the information from neutron-capture element abundances. One current limitation is the number of available observations for comparison, along with the large uncertainties in the derived abundances.

2. AGB nucleosynthesis predictions

AGB nucleosynthesis can be divided into that operating in lower mass AGB stars ($M \lesssim 3$ M$_\odot$) and that operating in stars with HBB. Lower mass AGB stars may become carbon and s-process rich through the repeated action of TDU episodes. Observations and theoretical models have confirmed that the main neutron source in low-mass AGB stars is the ^{13}C$(\alpha, \mathrm{n})^{16}$O reaction (Gallino *et al.* 1998; Abia *et al.* 2002). To operate efficiently, this reaction requires more ^{13}C than is left over from CN cycling in the H-shell; hence some mechanism to mix protons from the H-rich envelope into the intershell is needed to produce the extra ^{13}C. In our models, protons are artificially mixed into the top $\sim$1/10$^{\mathrm{th}}$ of the He-intershell at the deepest extent of each TDU, producing a region rich in ^{13}C (^{13}C pockets; see Karakas 2010 for more details). Note that the details of how the ^{13}C pocket forms and its extent in mass in the He-intershell are still unknown.

In AGB stars over $M \gtrsim 3$ M$_\odot$, the ^{22}Ne$(\alpha, \mathrm{n})^{25}$Mg reaction is likely to be the dominate neutron source. This reaction operates at higher temperatures and produces much higher neutron densities ($> 10^{10}$ neutrons cm^{-3}) compared to the ^{13}C neutron source (see discussion in Karakas *et al.* 2009). Observations of the brightest Galactic AGB stars (García-Hernández *et al.* 2006) have found large enrichments of the element Rb, consistent with the operation of the ^{22}Ne$(\alpha, \mathrm{n})^{25}$Mg neutron source operating in these stars e.g., van Raai *et al.* (2012).

At $Z = 0.01$ ([Fe/H] $= -0.15$†) we have full s-process predictions for model stars with masses $M = 1.25, 1.8, 3$ and 6 M$_\odot$. Little s-process element production takes place in the 1.25 and 6 M$_\odot$ models. In contrast, copious Sr, Ba, and some Pb production occurs in the 1.8 and 3 M$_\odot$ models, see Fig. 1. These models are based on calculations from Karakas *et al.* (2010) and will be published in Karakas *et al.* (2011, in preparation). We note that with the new $Z = 0.01$ models we can produce [Sr/O] = 1.0 and [Kr/O] = 1.3 depending on the extent of the mixing required to produce ^{13}C pockets. These new predictions are within the uncertainties of the observationally-derived abundances of the most Se and Kr-enriched PNe, unlike the models in Karakas & Lugaro (2010).

A decrease in the initial metallicity will result in more s-process elements produced at the second peak (around Ba, La) and at the third peak (Pb) (Busso *et al.* 2001). At a

† We adopt the standard spectroscopic notation of $\log \epsilon(\mathrm{X}) = \log_{10}(\mathrm{X/H}) + 12$, and $[\mathrm{X/Y}] = \log_{10}(\mathrm{X/Y})_{\mathrm{star}} - \log_{10}(\mathrm{X/Y})_\odot$, where X and Y are abundances by number.

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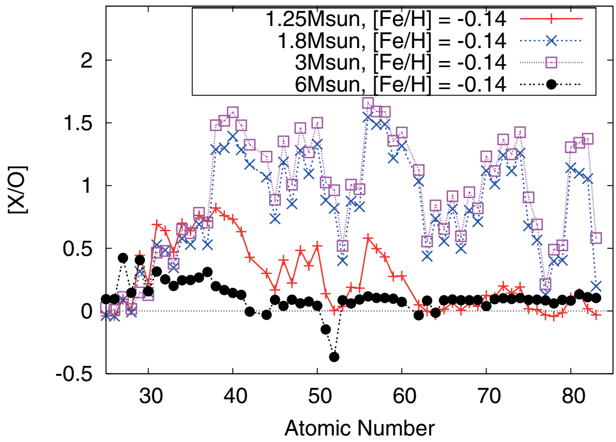

Figure 1. Heavy element nucleosynthesis predictions (in [X/O]) for various masses at $Z = 0.01$ ([Fe/H] $= -0.15$).

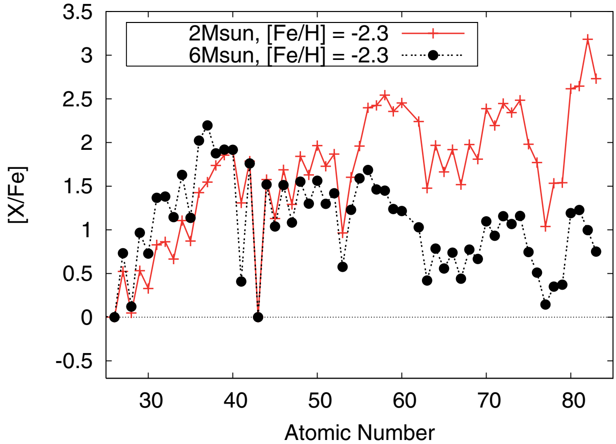

Figure 2. Heavy element nucleosynthesis predictions (in [X/Fe]) for models of $M = 2$ and 6 $M_\odot$, at $Z = 0.0001$ ([Fe/H] $= -2.2$).

metallicity of [Fe/H] $= -2.3$, the s-process in low-mass stars produces large quantities of Pb. In intermediate-mass stars of low-metallicity, the ^{22}Ne$(\alpha, n)^{25}$Mg reaction along with many TDU episodes results in a dramatic increase in the Rb content of the envelope. In Fig. 2 we show that the [Rb/Fe] $= 2.2$ in a 6 $M_\odot$ model of $Z = 0.0001$. In **?** we present s-process predictions for stars with masses between 0.9 to 6 $M_\odot$ at Fe/H] $= -2.3$. These represent the first s-process element predictions for masses higher than 2 $M_\odot$ and below 1.3 $M_\odot$ at this metallicity.

3. Comparison to observations: Low-metallicity PNe

The new s-process predictions can be compared to the composition of the metal-poor PN BoBn 1 studied by Otsuka *et al.* (2010). For the comparison we use a model of 1.5 $M_\odot$ with [Fe/H] -2.3, and note that the model is initially enriched in α-elements (e.g., O, Ne, Mg, Si), and the r-process component of each heavy element isotope is enhanced such that $[r/\text{Fe}] = +0.4$ (e.g., [Ba/Fe] $= 0.21$, [Eu/Fe] $= 0.4$). The final surface abundance predictions from the AGB star model are: $\log \epsilon(\text{O}) = 7.76$ (initial 6.82), [Kr/H] $= -0.68$

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([Kr/Fe] = 1.56), [Xe/H] = −0.71 ([Xe/Fe] = 1.46), and [Ba/H] = 0.12 ([Ba/Fe] = 2.29). The predicted Kr, Xe, and Ba abundances are consistent with the abundances derived for BoBn 1: [Kr/H] $\leqslant -0.48$, [Xe/H] $\leqslant -0.27$, and [Ba/H] = 0.12, Otsuka *et al.* (2010). Furthermore, the high fluorine abundance of this PN ([F/H] = +1.39 compared to the predicted [F/H] = +0.86) is also consistent with the present day PN being the product of a star that has accreted material from a previous AGB companion of $\sim$1.5 $M_\odot$ of low metallicity (see discussion in Otsuka *et al.* 2010).

We finish with a comment about the O abundances predicted from the AGB models of [Fe/H] = −2.3. For masses of $M = 0.9$ or $\geqslant 1.25 M_\odot$ from **?** we find substantial O production (see discussion in Lugaro *et al.* 2012 for the reasons for this). For example, starting at an initial (scaled solar) O abundance of $\log \epsilon(\mathrm{O}) = 6.54$, the final surface abundance in the 0.9 $M_\odot$ model was ≈ 7.5. However, at 1 $M_\odot$ we find $\log \epsilon(\mathrm{O}) = 6.93$, with $\log \epsilon(\mathrm{C}) = 8.16$ and $\log \epsilon(\mathrm{N}) = 6.55$. Our predicted O abundance is consistent with the O abundance of the halo PN TS 01, which has the very low O abundance of $1/70^{\mathrm{th}}$ of the solar value ($\log \epsilon(\mathrm{O}) \approx 6.9$, Stasińska *et al.* 2010). However, the C abundance is near the derived upper limit for TS 01 and our predicted N is too lower. Note that Stasińska *et al.* (2010) find that rapid rotation greatly improves the agreement between the predicted and observed abundances, and in particular enhances the N abundance.

References

Abia, C., Domnguez, I., Gallino, R., *et al.* 2002, *ApJ*, 579, 817

Busso, M., Gallino, R., Lambert, D. L., Travaglio, C., & Smith, V. V. 2001, *ApJ*, 557, 802

Dinerstein, H. L. & Geballe, T. R. 2001, *ApJ*, 562, 515

Gallino, R., Arlandini, C., Busso, M., *et al.* 1998, *ApJ*, 497, 388

García-Hernández, D. A., Garca-Lario, P., Plez, B., D'Antona, F., Manchado, A., & Trigo-Rodríguez, J. M. 2006, *Science*, 314, 1751

Henry, R. B. C., Kwitter, K. B., Jaskot, A. E., Balick, B., Morrison, M. A., & Milingo, J. B. 2010, *ApJ*, 724, 748

Herwig, F. 2005, *ARA&A*, 43, 435

Karakas, A. I. 2010, *MNRAS*, 403, 1413

Karakas, A. I., *et al.* 2009, *ApJ*, 690, 1130

Karakas, A. I. & Lugaro, M. 2010, *PASA*, 27, 227

Karakas, A. I., Campbell, S. W., & Stancliffe, R. J. 2010, *ApJ*, 713, 374

Lugaro, M., Karakas, A. I., Stancliffe, R. J., & Rijs, C. 2012, *ApJ*, 747, 2

Otsuka, M., Tajitsu, A., Hyung, S., & Izumiura, H. 2010, *ApJ*, 723, 658

Pequignot, D. & Baluteau, J. P. 1994, *A&A*, 283, 593

Sharpee, B., Zhang, Y., Williams, R., Pellegrini, E., Cavagnolo, K., Baldwin, J., Phillips, M., & Liu, X.-W. 2007, *ApJ*, 659, 1265

Shaw, R. A., Lee, T. H., Stanghellini, L., Davies, J. E., García-Hernández, D. A., García-Lario, P., Perea-Calderón, J. V., Villaver, E., Manchado, A., Palen, S., & Balick, B. 2010, *ApJ*, 717, 562

Stasińska, G., Morisset, C., Tovmassian, G., Rauch, T., *et al.* 2010, *A&A*, 511, A44

Sterling, N. C. & Dinerstein, H. L. 2008, *ApJS*, 174, 158

van Raai, M. A., Lugaro, M., Karakas, A. I., García-Hernández, D. A., & Yong, D. 2012, *A&A*, 540, A44

van Winckel, H. 2003, *ARA&A*, 41, 391