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Nucleosynthesis in massive AGB stars with delayed superwinds: implications for the abundance anomalies in globular clusters

D. A. García-Hernández[1,2], A. I. Karakas[3], and M. Lugaro[4]

[1] Instituto de Astrofísica de Canarias, Via Láctea s/n, 38200 La Laguna (Tenerife), Spain
e-mail: agarcia@iac.es
[2] Departamento de Astrofísica, Universidad de La Laguna, 38206 La Laguna (Tenerife), Spain
[3] Research School of Astronomy & Astrophysics, Mount Stromlo Observatory, Weston Creek ACT 2611, Australia, e-mail: akarakas@mso.anu.edu.au
[4] Monash Centre for Astrophysics, Monash University, Clayton VIC 3800, Australia
e-mail: maria.lugaro@monash.edu.au

Abstract. We present nucleosynthesis predictions for massive (5−7 $M_{\odot}$) asymptotic giant branch (AGB) stars of solar metallicity where we delay the onset of the superwind to pulsation periods of P =700−800 days. We found that delaying the superwind in solar metallicity massive AGB stars results in a larger production of s-process elements, something that would be also expected at lower metallicities. These new models and the available observations show that massive C-O core AGB stars in our Galaxy and in the Magellanic Clouds experience considerable third dredge-up (TDU). Thus, if massive AGB stars at the metallicities of the globular clusters (GCs) also experience deep TDU, then these stars would not be good candidates to explain the abundance anomalies observed in most GCs. However, more massive AGB stars (e.g., near the limit of C-O core production) or super-AGB stars with O-Ne cores may not experience very efficient TDU, producing the high He abundances needed to explain the multiple populations observed in some GCs.

Key words. Stars: AGB and post-AGB – Stars: abundances – Stars: atmospheres – Stars: evolution – nuclear reactions, nucleosynthesis, abundances – Galaxy: globular clusters

1. Introduction

García-Hernández et al. (2006, 2007, 2009) identified several Galactic and Magellanic Cloud massive (M > 4−5 $M_{\odot}$) asymptotic giant branch (AGB) stars within a sample of OH/IR stars. The strong enhancements of the neutron-rich element Rb found together with the fact that these stars are O-rich and Li-rich, support the prediction that hot bottom burning (HBB) and an efficient third dredge-up (TDU) have occurred in these stars. Rb is believed to be produced by the s-process in AGB stars. A Rb enrichment over the s-process elements Sr, Y, and Zr is evidence for the efficient operation of the ^{22}Ne(α, n)^{25}Mg neutron source in massive AGB stars (e.g., García-Hernández

Send offprint requests to: D. A. García-Hernández et al. 2006). This is because the production of Rb is sensitive to the high neutron density associated with the ^{22}Ne neutron source. These observational results are particularly important because there is a lack of observational evidence for constraining stellar models of massive AGBs, and especially the TDU and HBB efficiencies. These two last points are much debated in the context of the globular cluster (GC) abundance anomalies (see e.g., Karakas et al. 2006).

van Raai et al. (2012) studied the Rb production in massive AGB stars at different metallicities. The qualitative features of the observations could be reproduced; increasing [Rb/Fe] ratio with increasing stellar mass or decreasing metallicity. However, the models could not reproduce the most Rb-rich AGB stars. Possible solutions are: i) to extend the calculations to include models of masses higher than 6 $M_{\odot}$; ii) to modify the mass-loss rate on the AGB. Here we present the exploration of these two possible solutions by extending calculations to masses of up to 9 $M_{\odot}$ and varying the AGB mass-loss rate. We also briefly discuss the nucleosynthesis results in the context of the abundance anomalies observed in GCs.

2. Delayed superwind massive AGB models

Vassiliadis & Wood (1993) (VW93 hereafter) noted that there are long period variables (LPV) stars with periods of 750 days that are probably stars of ∼5 $M_{\odot}$ and they recommended a delay to the onset of the superwind in stars with M > 2.5 $M_{\odot}$. This suggestion is supported by the optical observations of massive AGBs, which show that the number of dust enshrouded stars dramatically increases for periods longer than 700 days (García-Hernández et al. 2007). Here we explore the effect of delaying the onset of the superwind phase on the AGB nucleosynthesis.

3. Nucleosynthesis results

Stellar evolutionary sequences for massive AGB stars are fed into a post-processing code

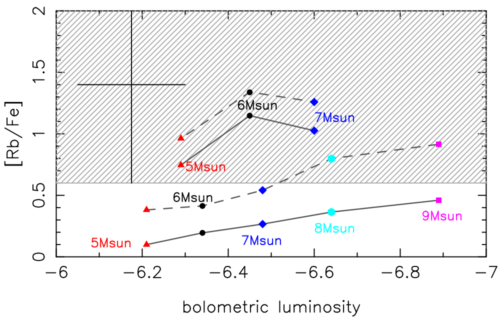

Fig. 1. Bolometric luminosity at the tip of the AGB vs. the [Rb/Fe] abundance from the last TP (connected by the solid lines) and from the synthetic evolution calculations (connected by the dashed lines). Models using the Vassiliadis & Wood (1993) mass-loss prescription are connected by the lower solid and dashed lines, and models calculated using a delayed superwind by the upper solid and dashed lines, respectively. The shaded region indicates the range of observed [Rb/Fe] (average of 1.4 dex and maximun uncertainty of ±0.8 dex).

in order to obtain nucleosynthesis predictions for elements heavier than iron (see Karakas et al. 2012 for more details). In short, we consider stellar masses from 5 to 9 $M_{\odot}$ and we compute one evolutionary sequence using the standard VW93 mass-loss prescription. For M = 5−7 $M_{\odot}$ models, we compute one evolutionary sequence using the modified VW93 mass-loss prescription or "delayed superwind". In all cases convergence difficulties (i.e., model star had left the AGB once the envelope mass drops below ∼1 $M_{\odot}$) end the calculation after the cessation of HBB and the effect of these extra thermal pulses (TPs) on the surface compositions of our model stars is estimated by synthetic evolution (see Karakas et al. 2012 for more details).

In Figure 1 we show the bolometric luminosity at the tip of the AGB versus the [Rb/Fe] ratios for models calculated using the VW93 mass-loss formula and for models with a delayed superwind. From Figure 1 we see that models with a delayed superwind produce higher [Rb/Fe] abundances (shown by the upper solid and dashed lines) and are found within the shaded region of the observations. This is mostly because these models experi-

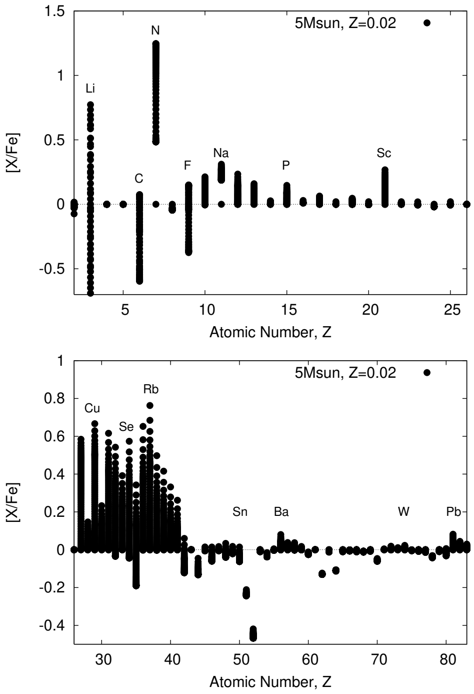

Fig. 2. Evolution of elements [X/Fe] lighter (upper panel) and heavier (lower panel) than Fe as a function of atomic number, Z, for the 5 $M_{\odot}$ model with a delayed superwind and nuclear network using 320 species. Included are the approximate locations of some key elements. Each dot represents the surface composition after a TP.

ence many more TPs and TDU episodes. The evolution of elements [X/Fe] lighter and heavier than Fe for the 5 $M_{\odot}$ model with a delayed superwind is shown in Figure 2, where we see no significant production of elements beyond the first s-process peak.

4. Implications for abundance anomalies in GCs

Delaying the superwind in massive AGB stars results in a far greater production of neutron-capture elements at solar metallicity and we would expect an extension of this effect to the lowest metallicities. The new models and the observations by García-Hernández et al. (2006, 2007, 2009) show that the most massive C-O core AGB stars of solar metallicity (up to 8 $M_{\odot}$) and at the metallicities of the Magellanic Clouds experience considerable TDU. Thus, if massive AGBs at the metallicities of the Galactic GCs (-2.3 < [Fe/H] < -0.7) also experience deep TDU, then these stars would not be good candidates to explain the abundance anomalies observed in every well studied GC (e.g., Gratton et al. 2004). AGB stars of up to 6−7 $M_{\odot}$ might instead be candidates for producing the neutron-capture elements in some GCs, including M4 (e.g., Yong et al. 2008) and M22 (Roederer et al. 2011). Note that the neutron-capture elements observed in GCs do not show any correlation with the light-element abundance patterns, ruling out a relation between the two. However, models of stars with masses near the limit of C-O core production (here the 8 $M_{\odot}$ model) or super-AGB stars with O-Ne cores may not experience very efficient TDU together with very hot HBB and depending upon the model, little pollution from He-intershell material (e.g., Siess 2010; Ventura & D'Antona 2011). Thus, our results and theirs show that super-AGB stars can produce the high He abundances needed to explain the multiple populations observed in the colour-magnitude (C−M) diagrams of some GCs (e.g., Piotto et al. 2005).

It should be noted, however, that Rb abundances in massive AGBs may be largely overestimated as a consequence of our imcomplete understanding of their complex atmospheres (García-Hernández et al. 2009). Model atmospheres of massive AGBs should be improved (see discussion in van Raai et al. 2012) before reaching a final conclusion about the connection of these stars and the abundance anomalies in GCs.

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