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The *s* process in massive AGB stars: a new tool to study abundances in globular clusters

Focusing on NGC 6121 (M4)

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Abstract. With a few exceptions (e.g., Omega Centauri), globular clusters show no evidence of internal variations in the abundances of the elements heavier than Fe such as Y, Sr, Rb, Zr, and Ba. On the other hand they exhibit significant variations in the abundances of the light elements, such as Li, C, N, O, and Na. For example, in the GC M4 variations of O and Na by factors larger than 2 and 3, respectively, are not accompanied by variations in the elements from Y to Pb produced by *slow* neutron captures (the *s* process). We present models of the *s* process in intermediate-mass (IM, >4 $M_\odot$) asymptotic giant branch (AGB) stars, which have been proposed as possible candidates to explain the observed variations. We show that AGB stellar models with stronger mass loss rates produce lower *s*-process yields, because of a shorter AGB life time. These models are compatible with the observations of M4. The light elements abundances are also affected by the value of the mixing-length parameter α_{MLT}, where a larger value results in higher temperatures at the base of the convective envelope during hot bottom burning. This solution is opposite of what is required to match direct observations of the *s*-process abundances in IM-AGB stars in the Galaxy and in the Magellanic Clouds. However, this cannot be used as a strong constraint while serious problems are still present in current model atmospheres of luminous AGB stars.

Key words. Stars: abundances – Stars: AGB and post-AGB – Galaxy: globular clusters

1. Introduction

The *slow* neutron-capture process (*s* process) is responsible for the production of roughly

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half of the cosmic abundances of the elements heavier than Fe, such as Y, Zr, Ba, and Pb. Plenty of observational evidence indicates that the *s* process occurs in asymptotic giant branch (AGB) stars (e.g. Busso et al. 2001, and references therein). In this paper we focus on comparing the *s*-process abundances observed in the globular cluster (GC) M4 to models of intermediate-mass (IM, > 4 $M_\odot$) AGB stars, which are candidates to have polluted the material from which subsequent stellar generations formed in GCs (Ventura et al. 2002; Renzini 2008). The AGB *s*-process predictions and the methodology presented here can potentially be applied to any GC. Overall, the elements heavier than Fe produced by neutron captures can provide important constraints on the nature of the stars that contributed to the gas from which GC multiple populations formed.

M4 represents an excellent example of an archetypal globular cluster: it presents two stellar generations defined by substantial changes only in elements affected by proton captures, with a Na-poor/O-rich first generation (FG) and a Na-rich/O-poor second generation (SG) (see Table 1; Marino et al. 2008; Carretta et al. 2009b,a; Villanova & Geisler 2011). We derived Y abundances for 103 RGB stars in M4 and found no variations with Na and O (D'Orazi et al. 2012). The same result is obtained using Zr, Rb, Ba, and Pb (Ivans et al. 1999; Marino et al. 2008; D'Orazi et al. 2010; Villanova & Geisler 2011) and any observed scatter, particularly for Ba, is probably due to observational uncertainties. Taking into account the constraints coming from the elements heavier than Fe, we address the question if the SG stars could have formed from material expelled by IM-AGB stars.

2. Nucleosynthesis and models of IM-AGB stars

The occurrence of proton captures at the base of their convective envelope (hot bottom burning, HBB, see e.g. Ventura & D'Antona 2005) makes IM-AGB stars good candidates to have polluted the the gas from which the SG in M4 formed. During HBB the temperature at the base of the envelope can reach above 100 MK and proton captures are activated within the CNO, NeNa, and MgAl cycles, potentially producing N, Na, and Al and destroying C, O, and Mg. Li can be produced via the Cameron-Fowler mechanism (Cameron & Fowler 1971). In these stars the ^{22}Ne(α,n)^{25}Mg neutron source is also efficiently activated at the base of the convective zones triggered by the recurrent episodes of shell He burning (thermal pulses, TPs) when the temperature reaches above 300 MK. The free neutrons drive the production of *s*-process elements and the mixing episodes that may follow each TP (the third dredge-up, TDU) carry these newly synthesised elements into the convective envelope. The envelope is eroded via strong stellar winds, which inject IM-AGB material in the surrounding interstellar medium from which SG stars can form.

We computed IM-AGB models of initial mass 5 $M_\odot$ and 6 $M_\odot$ and the initial composition observed in the FG stars of M4. We explored the impact of three main stellar model uncertainties: (i) the mixing length parameter α_{MLT}, (ii) the mass-loss rate, and (iii) the nuclear reactions that produce and destroy Na. For α_{MLT} we used 1.75, set by reproducing a model of the Sun, and 2.2, which results in more efficient HBB, similar to the models that use a full spectrum of turbulence description of convection (Ventura & D'Antona 2005), and is closer to the value required by observations of IM-AGB stars (McSaveney et al. 2007). The higher α_{MLT} mainly results in a higher temperature at the base of the convective envelope and a slightly shortened stellar lifetime.

For the mass-loss rate, we used the empirical rate based on observations of AGB stars in the Galaxy and in the Magellanic Clouds recommended by Vassiliadis & Wood (1993) (hereafter VW93) and the theoretical rate based on dynamical calculations of the atmospheres of Mira-like stars proposed by Blöcker (1995) (hereafter B95) with the free parameter η=0.02 as used, e.g., by (Ventura et al. 2011). The latter results in a faster mass loss and a shortened stellar lifetime: the 6 $M_\odot$ model experienced 32 TPs when computed with α_{MLT}=2.2 and the B95 mass-loss rate,

Table 1. Comparison between the observations and three selected 6 $M_\odot$ models.

Elements showing variations	observed variation	α_{MLT}=1.75 & VW93	α_{MLT}=2.2 & B95	α_{MLT}=2.2 & B95 & Na rates
ΔHe	+0.04	+0.09	+0.09	
Δ[O/Fe]	−0.35[a], −0.43[b], −0.60[c]	−0.50	−0.50	
Δ[Na/Fe]	+0.58[a], +0.46[b], +0.86[c]	+0.2	+0.15	+0.3
Δ[Al/Fe]	+0.4[a,d]	+0.45	+0.25	
Elements showing no variations				
A(Li)		−2.3	−0.7	
[C+N+O/Fe]		+0.7	+0.3	
[Mg/Fe]		+0.2	+0.05	
[Y/Fe]		+1.	+0.1	
[Rb/Fe]		+1.	+0.2	
[Ba/Fe]		+0.5	0.	

[a] Marino et al. (2008). [b] Villanova & Geisler (2011). [c] Carretta et al. (2009a). [d] No variations according to Villanova & Geisler (2011).

with respect to 76 TPs when computed with α_{MLT}=1.75 and the VW93 mass-loss rate.

For the nuclear reactions that produce and destroy Na we tested the "high" ^{22}Ne(p,γ)^{23}Na and the "low" ^{23}Na(p,α)^{24}Mg values recommended by Iliadis et al. (2010). The main effect is to enhance the production of Na. These choices are rather conservative because they represent 1σ deviations in the probability distributions computed by Iliadis et al. (2010). Furthermore, these distributions are based on the available experimental data, which may change as future experiments provide more accurate and detailed information at the low energies corresponding to those of stellar interiors.

The main nucleosynthetic results are that in the models computed with the B95 mass-loss rate and α_{MLT}=2.2 a larger fraction of the whole stellar lifetime is Li-rich and the surface abundances of O and Na are depleted more quickly by HBB than in the models computed with VW93 mass-loss rate and α_{MLT}=1.75. Most importantly, the surface abundances of the elements affected by the occurrence of the TDU is lower in the B95 models, since there are fewer TDU episodes. These abundances include the sum of C+N+O and the *s*-process elements, in particular those belonging to the first *s*-process peak associated with the magic number of neutrons N=50, i.e., Sr, Y, Zr, and Rb. These elements reach final surface abundances [X/Fe] > 1 dex, in the models computed with the VW93 mass-loss rate, while they stay below [X/Fe] < 0.5 in the models computed with the B95 mass-loss rate.

3. Comparison with M4

In Table 1 we present a comparison between the observations, in terms of variations between the SG and FG stars, and three selected 6 $M_\odot$ models, in terms of the difference between the final integrated yields, i.e., the abundances ejected over the whole life of the star, and the initial composition. Overall, the model computed with the B95 mass-loss rate better reproduce the observations mostly due to the much reduced predicted variations in the elements heavier than Fe, as well as to the production of Li during the AGB phase.

4. Comparison with direct observational constraints

Garcia-Hernandez et al. (2006); García-Hernández et al. (2009) observed [Rb/Fe] up to 2.5 and 5. dex in IM-AGB stars belonging to the Galaxy and to the Magellanic Clouds, respectively, with [Zr/Fe] <0.5 dex (Garcia-Hernandez et al. 2007). These data represent the first observational evidence of the operation of the ^{22}Ne(α,n)^{25}Mg neutron surce in IM-AGB stars, but they cannot be quantitatively matched by standard IM-AGB models (van Raai et al. 2012). Models where the stellar lifetime is extended by lowering the mass-loss rate can present a better match (Karakas et al. 2012, 2013). This solution is opposite of what we have shown is required to match the abundance pattern in M4, where a shorter stellar lifetime is needed instead. However, serious problems are still present in current model atmospheres of luminous AGB stars: the atmospheres are dynamic, pulsating, and should be modelled in 3D, while the used models are in 1D. Also the current models do not include the presence of a circumstellar dust envelope and dust formation (García-Hernández et al. 2009). Furthermore, direct observations of IM-AGB stars are available only for the Galaxy, and Magellanic Clouds, i.e., at metallicities typically higher than GCs. In any case the question remains of what could be the physical mechanism driving a possible stronger mass loss in IM-AGB stars in GCs than what is observed in the Galaxy and in the Magellanic Clouds (Vassiliadis & Wood 1993). Dust formation and/or binary interaction may be candidate mechanisms to be investigated. More AGB *s*-process models need to be computed, also to investigate the evolution of GCs showing multiple populations with *s*-process variations, such as M22 and Omega Centauri.

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