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The origin of the heavy elements in stars in the Globular Clusters M4 and M5

A. I. Karakas[1], S. W. Campbell[2,3,4], M. Lugaro[4], D. Yong[1], and A. Chieffi[4,5]

[1] Research School of Astronomy & Astrophysics, Mount Stromlo Observatory, Weston Creek ACT 2611, Australia, e-mail: `akarakas@mso.anu.edu.au`
[2] Departament de Física i Enginyeria Nuclear, EUETIB, Universitat Politécnica de Catalunya, C./Comte d'Urgell 187, E-08036 Barcelona, Spain
[3] Institut de Ciéncies de l'Espai (CSIC), Campus UAB, Facultat de Ciéncies, Torre C5-parell, 2 planta, E-08193 Bellaterra (Barcelona), Spain
[4] Centre for Stellar & Planetary Astrophysics, Monash University, Clayton VIC 3800, Australia
[5] Istituto Nazionale di Astrofisica, Istituto di Astrofisica Spaziale e Fisica Cosmica, Rome, Italy

Abstract. We investigate the origin of the abundance patterns of neutron-capture elements observed in the globular clusters M4 and M5. These clusters have a similar metallicity but exhibit very different heavy element abundance patterns. We assume that a generation of very low-metallicity supernovae pre-polluted the forming clusters with iron-group and *r*-process elements. On top of this, a population of asymptotic giant branch (AGB) stars polluted the clusters with elements synthesized by the slow-neutron capture process (the *s*-process). Using a set of α- and *r*-enhanced AGB models tailor-made for globular clusters (with a metallicity [Fe/H] = -1.4), we compute the *s*-process abundance pattern of elements from iron to lead. We compare our predicted abundance patterns to the observed distribution, discuss the effect of the two neutron sources (^{13}C versus ^{22}Ne) and comment on formation scenarios for M4 and M5.

Key words. Stars: AGB and Post-AGB – Stars: abundances – Stars: Population II – Galaxy: globular clusters

1. Introduction

Globular clusters (GCs) are excellent laboratories to test our theories of stellar evolution and nucleosynthesis. Star-to-star abundance variations of the light elements, C, N, O, Na, Mg and Al, have been observed in every well studied globular cluster (GC) to date (Kraft 1994; Gratton et al. 2004, and references therein) but are not found in field stars of the same metallicity (Gratton et al. 2000). The abundances of iron-peak, *s*- and *r*-process elements do not show the same star-to-star scatter nor do they vary *with* the light elements (Gratton et al. 2004; James et al. 2004; Yong et al. 2006). The origin of the light element abundance anomalies must be a product of the cluster environment, although the sequence of events that led to the present day abundances

Send offprint requests to: A. Karakas

along with the mass distribution of the polluting stars is unknown. Because the [Fe/H] abundance is roughly constant in stars in a given GC it has been assumed that polluters were intermediate-mass AGB stars with initial masses between about 3 and 8 $M_\odot$ rather than supernovae, which produce Fe. The hot bottom burning experienced by these stars provides the hydrogen burning environment that can (at least qualitatively) alter the abundances of the light elements. Rapidly rotating massive single stars (Decressin et al. 2007), as well as massive binaries (de Mink et al. 2009), have also been suggested as candidates.

Abundance measurements of neutron-capture elements of stars in GCs allow us to gain insight into stellar nucleosynthesis processes occurring at the earliest Galactic epochs. With some notable exceptions (e.g. ω Centauri, M22) stars in a given GCs show the same star-to-star abundances of these elements. The mean abundances, however, have been shown to vary greatly from cluster to cluster. The GCs M4 and M5 are particularly well studied in this regard, owing to the two clusters having a nearly identical mean metallicity, where [Fe/H] ≈ -1.2 (Ivans et al. 1999, 2001). The similarity in abundances between M4 and M5 extends to the α-elements (e.g. Si and Ca), Fe-peak elements (e.g. Mn, Co and Ni but not Cu and Zn) as well as the *r*-process element Eu (Ivans et al. 2001; Yong et al. 2008a). Detailed abundance studies have, however, revealed striking differences in the abundances of *s*-process elements (e.g. Rb, Y, Ba, La and Pb, Ivans et al. 2001; Yong et al. 2008a,b). In summary, M4 shows a higher level of *s*-process abundances compared to M5. The ratios [Rb/X] where X is Y, Zr or La, are similar. These results suggest that the nature of the *s*-process site was the same in both clusters but that M4 received a higher concentration of *s*-process enriched gas than M5.

In these proceedings, we discuss our hypothesis for the origin of the heavy elements in M4 and M5 and present new *s*-process abundance predictions from low-metallicity AGB models.

2. Hypothesis

Following on from the discussions in Yong et al. (2008a), we postulate that the abundance differences in the *s*-process elements was present before the present-day stars formed. Further, we assume that AGB stars are responsible for producing the *s*-process elements. This idea is supported by the high mean [Pb/Fe] abundance of M4 (+0.3 dex) compared to M5 (−0.3 dex). While some Pb is produced by the *r*-process via the decay of radioactive heavy elements. The largest Pb enrichments come from low-metallicity AGB stars (Travaglio et al. 2001). The AGB stars that produced the *s*-process elements cannot be too low in mass, owing to timescale considerations. Because there is no star-to-star scatter present, the *s*-process elements must have been produced and well mixed into the proto-GC before the formation of the present-day stars. This sets a generous lower limit on the mass at about 2.5 $M_\odot$ (lifetime of about 500 Myr) but a more realistic lower limit is likely to be around 4 $M_\odot$. The early evolution of M4 and M5 likely started with the pre-enrichment of α and Fe-peak elements from very low-metallicity Type II supernovae; this was followed by the enrichment of C, N and *s*-process elements from intermediate-mass AGB stars. The relative proportion of *s*-process enriched gas that was retained appears to have been higher in M4 than M5. The gas from these sources was well mixed (possibly with some primordial gas) before the stars we observe today formed. Yong et al. (2008b) noted that the Rb and Pb abundances in M4 and M5 do not correlate with the abundances of O or Na, so that whatever process produced these neutron-capture elements was *not* responsible for the light-element abundance anomalies.

To test if AGB stars can produce the abundances measured in M4 and M5, we use a set of α and *r*-process enhanced AGB models of M = 1.25, 2.5, 3.5, 5.0 and 6.5 $M_\odot$, tailor-made for globular clusters (with a metallicity [Fe/H] = −1.4). These models were previously discussed by Fenner et al. (2004) and Karakas et al. (2006) in the context of the self-pollution scenario. The initial abundances were chosen

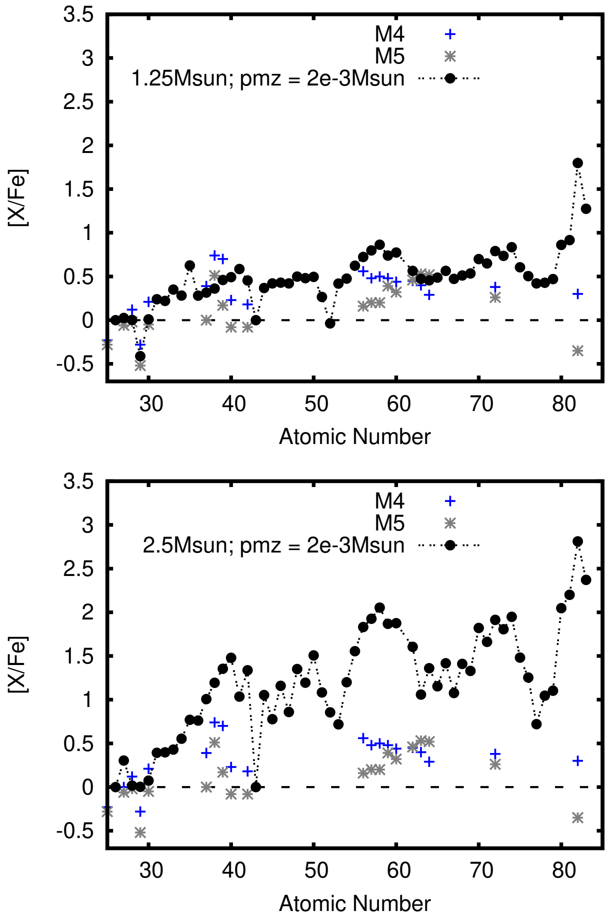


Fig. 1. Predicted abundance ratios (black solid circles) versus atomic number from the 1.25 $M_\odot$ and 2.5 $M_\odot$ [Fe/H] = −1.4 models. Each model has a PMZ of 0.002 $M_\odot$. Models without PMZs produce very little *s* elements. Also shown are the mean abundances for stars in M4 (crosses) and M5 (stars) from Yong et al. (2008a). Errors are not shown but reflect the dispersion in the sample, which are about 0.1 dex or less for most elements heavier than Fe.

such that the α elements are enhanced at the level of about0.4 dex For the neutron-capture elements, we enhanced the *r*-process component of each isotope by [*r*/Fe] = +0.4, based on the Eu abundance of M4 and M5 and noted that Eu is an almost pure *r*-process element. We set the *s*-process component of each isotope to be scaled solar, [*s*/Fe] = 0.0. The Pb abundance of M5 is [Pb/Fe] = −0.3; perhaps this is a more suitable starting point for the *s*-process contribution to each isotope or, at least, the Pb isotopes. We plan to investigate the influence of initial abundances in a future study.

To compute the abundances of the *s*-process elements, we utilize a post-processing algorithm with a network of 291 species and the JINA Reaclib database. The details of this procedure and the codes used to compute the models have been previously described in detail (e.g. Karakas et al. 2009, and references therein). In AGB stars there are two main neutron producing reactions: The $^{13}C(\alpha, n)^{16}O$ and

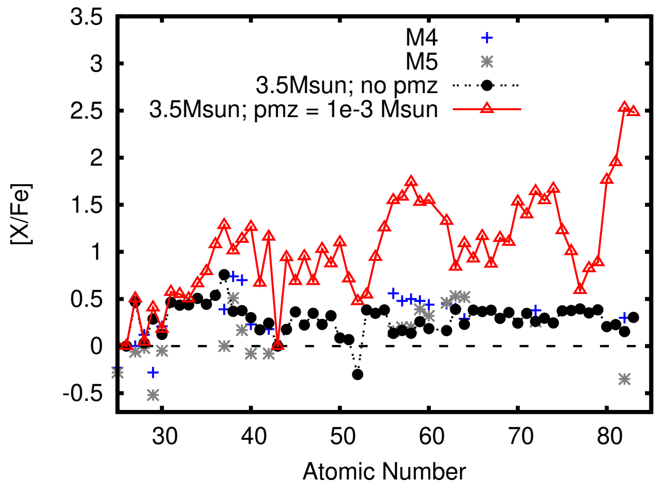


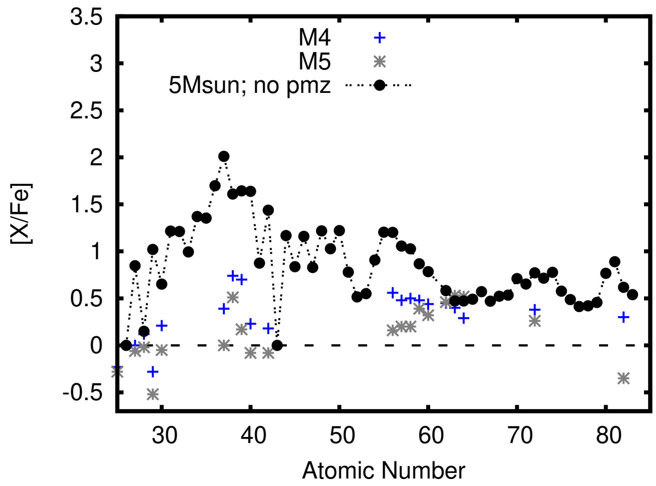
Fig. 2. Predicted abundance ratios versus atomic number from the 3.5 $M_\odot$, [Fe/H] = −1.4 model with a PMZ of 0.001 $M_\odot$ (black solid circles) and without a PMZ (solid triangles). M4 and M5 data as in Fig. 1.

^{22}Ne$(\alpha,n)^{25}$Mg reactions. Observational and theoretical evidence (e.g. Busso, Gallino, & Wasserburg 1999) suggests that the dominant neutron source in lower mass AGB stars is the ^{13}C source, whereas the higher temperatures required for efficient activation of the ^{22}Ne are found in intermediate-mass AGB stars ($M \gtrsim 3.5\,M_\odot$, depending on Z). In the models of lower-mass stars (1.25, 2.5, and 3.5 $M_\odot$) we artificially include a ^{13}C pocket by adding in a partially mixed zone (PMZ) of protons into the top of the He-intershell at the deepest extent of each TDU. These protons are quickly captured by the abundant ^{12}C to form ^{13}C and ^{14}N pockets in the top $1/10^{\rm th}$ or so of the He-intershell. A ^{13}C pocket is required because the amount of ^{13}C left over from CN cycling is not enough to activate the ^{13}C$(\alpha,n)^{16}$O reaction and synthesize heavy elements (Busso et al. 1999).

The technique we use to include a ^{13}C pocket has been described elsewhere (Lugaro et al. 2004). Here we note that we include a PMZ of constant mass of 0.002 $M_\odot$ in the 1.25 and 2.5 $M_\odot$ models, and 0.001 $M_\odot$ in the 3.5 $M_\odot$ model. The resultant ^{13}C pocket is smaller (in mass) than the mass of the PMZ (see discussion in Karakas 2010). In the 5 and 6.5 $M_\odot$ models neutrons are only produced by the ^{22}Ne$(\alpha,n)^{25}$Mg reaction during convective thermal pulses. For the models of lower-mass stars, we perform one calculation with a ^{13}C pocket and one calculation without a ^{13}C pocket.

3. Abundance predictions

In Figs 1 to 3 we show the predicted abundance pattern from the stellar models. In each model we are showing the surface abundance after the final computed thermal pulse because this is when most of the mass is lost. Fig. 1 illustrates the predictions from the lowest mass AGB models of 1.25 $M_\odot$ and 2.5 $M_\odot$. In these models the s-process abundance distribution is dominated by the ^{13}C$(\alpha,n)^{16}$O reaction. This produces elements at this metallicity at the second and third s-process peaks (corresponding to the elements Ba and Pb, e.g. Gallino et al. 1998). Hence the final [Ba/Sr] and [Pb/Sr] ratios are greater than 0, in contrast to the intermediate-mass models. In Fig. 2 we show the predicted abundance distribution for the 3.5 $M_\odot$ model with and without ^{13}C pocket. The effect of the PMZ on the production of neutron-capture elements is easily seen. The model without a PMZ produces a moderate amount of elements at the



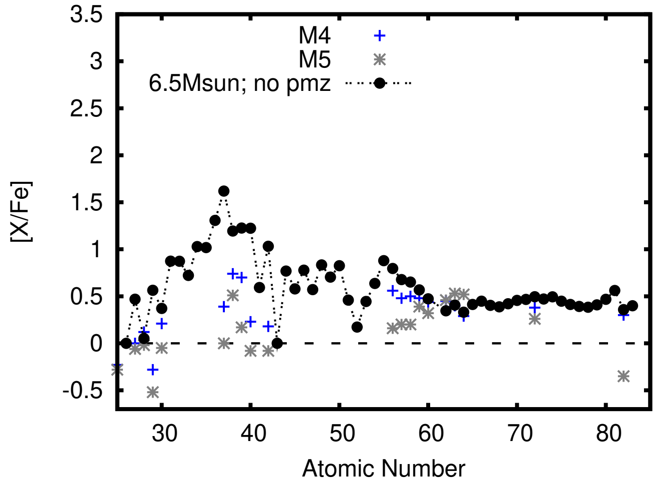


Fig. 3. Predicted abundance ratios (black solid circles) versus atomic number from the 5 $M_{\odot}$ and 6.5 $M_{\odot}$ [Fe/H] = −1.4 models. M4 and M5 data as in Fig. 1.

first *s*-process peak (Rb, Sr) as a consequence of neutrons released by the ^{22}Ne source. Note that in this model the [Rb/Sr] ratio is 0.39, typical of an intermediate-mass AGB star (in comparison, [Rb/Sr] < 0 in low-mass AGB stars). Little Ba and Pb are produced, with final abundances only marginally greater than the initial.

In Fig. 3 we show the predicted abundance distribution for the 5 $M_{\odot}$ and 6.5 $M_{\odot}$ models. In these models neutrons are released exclusively by the $^{22}\mathrm{Ne}(\alpha, n)^{25}\mathrm{Mg}$ reaction and this is shown by the overproduction of elements at the first *s* peak (notably Rb). Of interest here is that these models still produce a moderate amount of elements at the second and third peaks. For example, the [Ba/Fe] and [Pb/Fe] ratios are 1.2 and 0.62 dex for the 5 $M_{\odot}$ model and 0.8 and 0.36 dex for the 6.5 $M_{\odot}$ model. A comparison by eye suggests the 6.5 $M_{\odot}$ model is the best although still far from perfect because it has a positive [Rb/Sr] ratio while the observations have a negative [Rb/Sr] ratio.

Certainly the abundance pattern of M4 does not appear to be characteristic of a low-mass AGB *s*-process abundance distribution, which produce more Pb than observed in M4.

4. Discussion

If intermediate-mass AGB stars were responsible for producing the *s*-process elements in M4 then an enhancement of the Mg isotopes is also to be expected. Yong et al. (2008a) tentatively determined the Mg isotope ratios for a number of stars in M4, with the result that stars in this cluster show a roughly solar isotopic mix (^{24}Mg:^{25}Mg:^{26}Mg = 80:10:10) with no variation from star to star (as seen in other clusters). Field stars of the same metallicity show a mixture heavily weighted toward ^{24}Mg (typically 94:3:3). Hence there has been some enhancement in the neutron-rich isotopes in M4. However, if we contrast these numbers with the predictions from the 6.5 $M_\odot$ model (^{24}Mg:^{25}Mg:^{26}Mg = 0.4:46.8:52.8) we see that most of the elemental Mg is in the form of ^{25}Mg and ^{26}Mg, with little ^{24}Mg. The winds from these stars are presumably diluted and mixed with ejecta from SNII (in which the Mg content is mostly ^{24}Mg) and primordial gas. We conclude that a detailed chemical evolution model of the sort performed by Fenner et al. (2004), but with the inclusion of *s* elements, would be useful to check this abundance feature as well as the origin of the heavy elements in M4 and M5 in general. In summary, the moderate [Pb/Fe] overabundance of M4 seems to indicate a contribution from AGB stars. However, comparing individual AGB models of one mass and *Z* to the observed distribution shows that intermediate-mass AGB stars produce too much Rb, while low-mass AGB stars produce too much Pb. These issues may be resolved by considering the mixing of gas from an entire population of AGB stars, depending on the shape of the initial mass function, and the dilution of AGB material with primordial gas. Furthermore, it is worth noting that there are considerable uncertainties involved in the modelling of AGB stars including mass loss and convection. An investigation of how these uncertainties affect the *s*-process abundances is vital in order to determine the chemical enrichment history of M4 and M5.

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