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The origin of heavy elements in globular clusters

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Abstract. Recent observations of heavy elements in GC stars reveal intriguing deviations from the standard paradigm of the early nucleosynthesis of the Milky Way. We report first results of a theoretical investigation devoted to understand this peculiar chemical evolution pattern.

Key words. Stars: abundances – Stars: nucleosynthesis – Galaxy: globular clusters – Galaxy: abundances

1. Introduction

All the elements heavier than iron are produced by neutron captures. There exist two different nucleosynthesis processes of this type, the slow (s) process and the rapid (r) process. In the first case, when an unstable isotope is produced, the timescale of the n capture is smaller than that of the β decay (on the average), while in the latter neutron captures are faster than the decays. In principle, the production of a given element may be due to both these process, although there exist isotopes produced by either the s or the r process only.

Significantly different physical conditions are implied by these two processes. First of all, the neutron density is more than 10 orders of magnitude smaller in the s than in the r process. Such a diversity implies very different astrophysical environments.

The r process is commonly associated to massive stars. The most popular scenarios are: core-collapse supernovae (type II or Ib, Ic) and Neutron-Star mergers. Nevertheless, none of the proposed astrophysical sites has yet been confirmed by direct observations. Some evidence exists concerning the possible occurrence of multiple components (i.e. multiple sources) of the r process (see Sneden et al. 2008).

On the contrary, our knowledge of the s-process sites has been greatly improved in the last 20 years (see, e.g., **?**Straniero et al. 2006). Three different components have been identified:

1) The WEAK component, which includes nuclei with $29 < Z < 40$, is due to massive stars. A marginal contribution comes from the core-He burning phase, but the main production occurs in the C-burning shell. In both cases, neutrons are provided by the ^{22}Ne$(\alpha, n)^{25}$Mg reaction. Due to the lack of ^{22}Ne, the weak component is inhibited at low Z[1]. Such a difficulty

[1] During the H burning, the original amount of C+N+O is converted into ^{14}N. Later on, two α captures on ^{14}N allow the production of ^{22}Ne. Therefore, the amount of ^{22}Ne within the He core or in the C shell depends on the original amount of C+N+O.

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could be overcome in the case of fast rotating massive stars (Pignatari et al. 2008).
2) The MAIN and the STRONG components, which include nuclei with $37 < Z < 84$, are due to thermal-pulsing low-mass AGB stars ($1.5 < M/M_\odot < 2.5$). In this case, the s process takes place in the He-rich layer. The main neutron source is the $^{13}C(\alpha,n)^{16}O$, while the $^{22}Ne(\alpha,n)^{25}Mg$ provides a second neutron burst (Gallino et al. 1998; Cristallo et al. 2009, 2011). Due to the primary nature of ^{13}C, this s process works at any Z[2]. Note, for example, that the main sources of the solar Pb were low-mass low-metallicity AGB stars. This is the standard paradigm of the s process, confirmed by many observations, since the first detection of Tc lines in a S-type AGB star (**?**).

In practice, due to the long lifetime of low-mass stars, at least 1 Gyr, only r process yields are expected in fossil records of the early Galaxy. Spectroscopic studies confirm such a scenario. In general halo stars are r-process enriched, but s-process poor. Exceptions are CH and CEMP-s (Carbon-Enhanced-Metal-Poor, the "s" stay for s enriched) stars, but in this case the s, as well as the C, enrichment is probably the consequence of mass transfer or wind accretion in binary systems (see Bisterzo et al. 2012, and references therein),

However, recent spectroscopic studies of GC stars revealed a rather different scenario. While the r process yields generally appear similar to those observed in halo field stars, some GCs show a clear signature of the s-process main component pollution. More intriguing, some spectroscopic indexes, which depend on the metallicity of the polluters, does not match the low Z theoretical expectations. In particular, the ratio between heavy-s elements (Ba, La or Nd) and light-s elements (Sr, Y or Zr) are found in solar proportions, while an excess of heavy s is expected at low Z. In a few cases, lead measures are available, which also appear in solar proportion with respect either heavy or light s, while a large Pb excess is expected. The clusters for which this s process enrichment has been discovered are: M4 (Yong et al. 2008), all observed stars; *ω-Cen* (**?**Jonson et al. 2010; D'Orazi et al. 2011), stars with [Fe/H]>-1.5 only; and M22 (Roederer et al. 2011), all stars belonging to the most-metal-rich population. On the contrary, other clusters, like M5, present a "normal-halo" distribution of the heavy elements (Ivans etal. 2001), as well as the metal-poor stellar populations of *ω-Cen* and M22. Is it a further puzzling feature of the multiple population scenario?

2. The polluters

The first constraint for the mass of the stars responsible of the s process patchwork observed in GCs can be derived from theoretical considerations. Actually, massive TP-AGB have an extremely small He-rich layer compared to the one of a low-mass AGB stars. At the epoch of the first thermal pulse, the extension of the He-rich layer is about 10^{-2} $M_\odot$ for a 2 $M_\odot$ star, but only 10^{-4} $M_\odot$ for a 6 $M_\odot$. For this reason, in spite of various uncertainties affecting the AGB models, massive AGB as well as super-AGB stars should suffer a negligible, if any, dredge up of material processed in the deep interior. Basing on our theoretical investigation, we may put a conservative upper limit for the mass of s-process polluters at about 5 $M_\odot$. The lower mass limit can be also constrained by measuring the age spread within the GC system. By comparing the turn-off luminosity of M4 and M5, two clusters with similar [Fe/H], but very different heavy-element pattern, one may derive a maximum (conservative) age spread of about 500 Myr. An even smaller age difference (300 Myr) has been estimated by Marino et al. (2012) between the r rich and the r+s rich stellar populations of M22. Therefore, if the s-process enhancement is the result of a delayed pollution, such age estimation implies a lower-mass-limit for the s process polluters of about 2.7 $M_\odot$ (see, e.g., Z=0.0001 models in Dominguez et al. 1999).

In summary, the most probable s-process polluters should have had 3 or 4 $M_\odot$.

In order to test such an hypothesis, we have computed a 3 $M_\odot$ evolutionary sequence

[2] Within the He-rich mantel of a thermal-pulsing AGB star, the ^{13}C is produced through proton captures on (primary) ^{12}C nuclei. ^{12}C is the main He-burning yield.

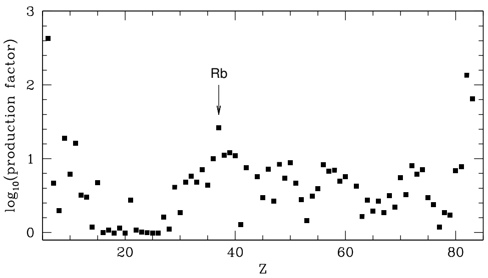

Fig. 1. Production factors,X_f/X_i, of the 3 $M_\odot$ models with [Fe/H]=-2.16, [α/Fe]=0.5 and Y=0.245. X_i is the initial mass fraction, while X_f refers to the last computed model (AGB tip).

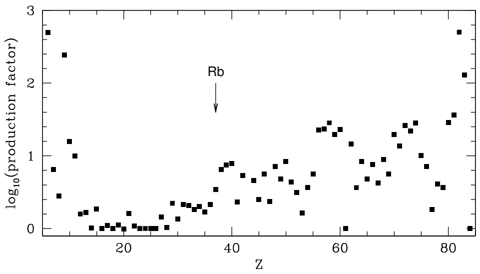

Fig. 2. As in Figure 1, but for M=1.5 $M_\odot$.

with our latest version of the full-network stellar evolution code described in Straniero et al. (2006). It includes 500 isotopes, from H to U, and a full set of 800 reactions among p, α and n captures, β decays and electron captures. The initial composition, namely that of the first pre-main-sequence model in hydrostatic equilibrium, is: [Fe/H]=-2.16, [α/Fe]=0.5 and Y=0.245. We have computed the evolution up to the AGB tip, when the mass of the H-rich envelope is reduced down to the limit for the occurrence of the third dredge up (about 0.3 $M_\odot$ at that metallicity, see Straniero et al. (2003)). The resulting production factors, i.e. X_f/X_i, where X_f and X_i are the final and the initial mass fractions, respectively, are reported in Figure 1. For comparison, the same plot, but for the 1.5 $M_\odot$, is reported in Figure 2.

The expected excess of heavy s with respect to the light s elements is clearly shown in the latter plot. In the case of the 3 $M_\odot$ model, however, we found a nearly flat distribution of the production factors, between $Z = 38$ and 81. Such a difference is due to the major contribution of the second neutron burst, powered by the ^{22}Ne$(\alpha,n)^{25}$Mg. This reaction is activated when the peak temperature is attained at the bottom of the convective zone generated by the thermal pulse. This peak temperature is relatively small in the low-mass model (never exceeds 300 MK), so that the second neutron burst provide a marginal contribution only to the overall s-process nucleosynthesis. In the 3 $M_\odot$, on the contrary, larger temperatures are attained in the same zone ($T > 350$ MK) and the second neutron burst substantially modify the compositions resulting from the first s-process episode. Noteworthy is the excess of Rb we find in the 3 $M_\odot$ model. This is the signature of the activation of the ^{22}Ne$(\alpha,n)^{25}$Mg. Actually, the ^{13}C$(\alpha,n)^{16}$O, which burns at low temperature during the relatively long inter-pulse period, produces a very low neutron density (a few 10^6 neutrons/cm^3) compared to the ^{22}Ne$(\alpha,n)^{25}$Mg (up to 10^{11} neutrons/cm^3). This occurrence provides us the opportunity to distinguish between the two s-process contributions. In the first case (low neutron density) the branching at ^{85}Kr is closed, so that ^{85}Rb is produced after the ^{85}Kr β decay. However, in the latter case (large neutron density), the branching is open, and ^{85}Kr may capture a further neutron producing ^{86}Kr, a stable nucleus. Then, after one further n capture and one β decay, ^{87}Rb is obtained. Due to its particularly small n-capture cross-section, ^{87}Rb (a so-called magic nucleus) is accumulated, so that a Rb excess is displayed. Another feature we want to stress concerns the Pb overproduction which is smaller in the 3 $M_\odot$ model compared to the 1.5 $M_\odot$ case.

3. Conclusions

In Figure 3 we compare the surface abundances of the last computed model of the 3 $M_\odot$ evolutionary sequence to the s process abundance pattern observed in M22.

A similar plot can be obtained by using the heavy elements data available for M4. The match between theory and observations is definitely encouraging. A direct Rb detection may

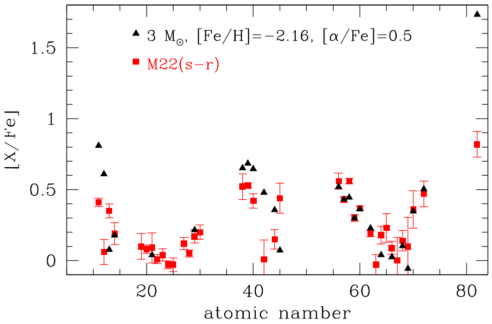

Fig. 3. Final surface abundances of the M=3 M$_\odot$ model compared to the observed s-process pattern of M22. Model abundances has been scaled to the observed La.

(or may not) confirm the proposed theoretical scenario here discussed. The predicted Pb abundance is probably too high. Likely, a more massive model (4 M$_\odot$) or a moderate rotation could provide a better reproduction of the few Pb observations (see the Cristallo et al contribution). Let us finally mention that there are some evidences (see, e.g., D'Orazi et al. 2011) that the s process enhancement in GC stars coincides with a certain C+N+O enhancement. It would be a proof of the role played by the third dredge up. Also in agreement with the theoretical expectations is the recent discovery of a correlation between s and fluorine enrichments in M22 stars (D'Orazi et al. 2013).

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