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Today's AGB stars and the role of binaries

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Abstract. Recent observations of the star-to-star abundance variations well below the bump luminosity in globular clusters have raised the weight of the primordial scenario. So far, intermediate-mass AGB stars have been considered as the most likely primordial sources of these abundance variations. I present some arguments against this idea and propose alternative sources. These are RGB and/or AGB stars a little bit more massive than the present-day MSTO stars that had experienced enhanced extra mixing in the past. In this case the more preferable way of polluting the lower mass MS stars by nuclearly processed material would be mass transfer in binaries rather than stellar winds from single stars.

Key words. stars: AGB — stars: abundances — globular clusters: general

1. Introduction

Today, we know exactly that

(i) MS and subgiant stars in globular clusters (GCs) are contaminated by material partially processed in H-burning;
(ii) the majority of upper RGB stars in GCs, like their field counterparts, experience "canonical" extra mixing that dredges up products of CN-processing.

The first statement is supported by observations of star-to-star abundance variations of C, N, O, Na, Mg and Al slightly above and below the MSTOs in some GCs (Gratton et al. 2001; Ramírez & Cohen 2002; Cohen et al. 2002; Briley et al. 2002; Grundahl et al. 2002; Harbeck et al. 2003). The anti-correlations of C–N, O–Na and Mg–Al (the abundances of C, O and Mg are depleted and those of N, Na and Al are enhanced) point to simultaneous operation of the CNO-, NeNa-, and MgAl-cycles of H-burning.

From the other hand, the evolutionary decrease of the C abundance and that of the $^{12}C/^{13}C$ ratio seen above the bump luminosity, both in the field and in GCs (Gratton et al. 2001; Bellman et al. 2001; Keller et al. 2001; Shetrone 2003), are reproduced very well by the diffusion model of (canonical) extra mixing with nearly the same parameters of depth and rate (Figs. 1 and 2). This confirms the second statement.

However, we don't know yet what objects have contaminated MS stars in GCs. I will briefly discuss the *pros* and *cons* for 2 types of potential contaminators:

- intermediate-mass AGB (IM-AGB) stars (proposed by D'Antona et al. 1983),
- low-mass upper RGB stars slightly more massive ($0.8 \lesssim \mathcal{M}/\mathcal{M}_\odot \lesssim 2$) than the present-day MSTO stars in GCs that

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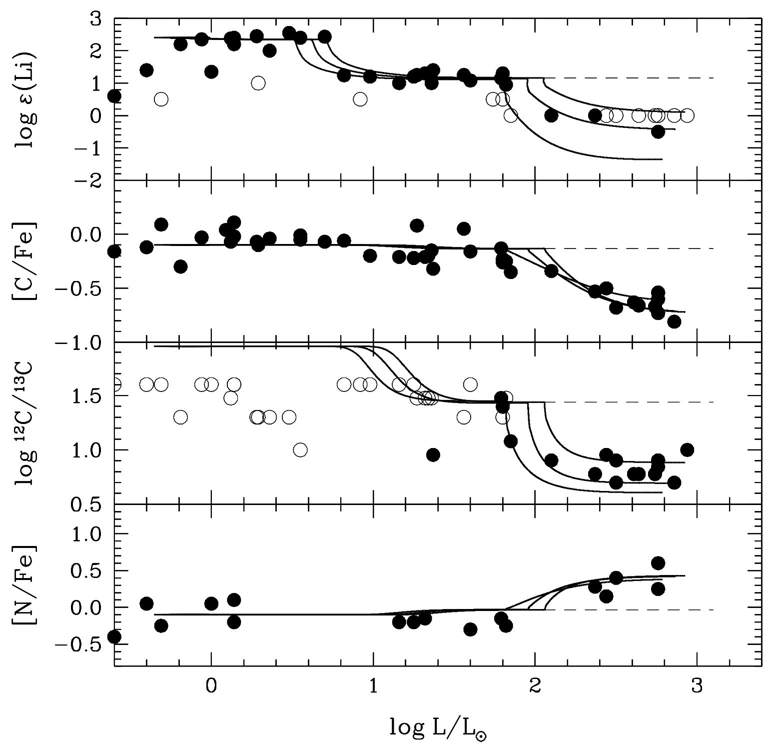

Fig. 1. Comparison of the observational data of Gratton et al. (2000) for MS, subgiant and RGB stars (*circles*) with the calculations of Denissenkov & VandenBerg (2003) (*solid curves*) for the variations of the surface chemical composition in the model star with $\mathcal{M} = 0.85\,\mathcal{M}_\odot$ due to the first dredge-up and extra mixing on the upper RGB. Extra mixing is modelled by diffusion. Its depth and rate parameters are the same ($\Delta \log T = 0.19$ and $D_{\rm mix} = 4 \times 10^8\,{\rm cm}^2\,{\rm s}^{-1}$) for $Z = 0.002$, 0.001 and 0.0005 (from left to right). Here, $\Delta \log T$ is a difference between the logarithms of temperature at the base of the H-burning shell and at the maximum depth of extra mixing, and $D_{\rm mix}$ is a constant diffusion coefficient. Note that all the composition parameters except [N/Fe] have observational errors ~ 0.1 dex, that of [N/Fe] being twice as large. *Open circles* for Li are upper observational limits, those for $^{12}C/^{13}C$ are lower limits. *Dashed lines* indicate predictions from the standard theory.

had experienced "enhanced" extra mixing in the past (Denissenkov & VandenBerg 2003).

The both types of stars have already completed their lives.

2. Intermediate-mass AGB stars

PROS:

- H-burning at very high temperatures (up to $\sim 10^8$ K; e.g. Ventura et al. 2001) in massive convective envelopes (hot-bottom burning, HBB); hence, a possibility of ^{24}Mg destruction, as required by some spectroscopic observations (e.g. Shetrone 1996), and nuclear processing of large amounts of stellar material;
- high ejected masses (e.g. Ventura et al. 2002);
- short life-times ($\sim 10^8$ years) compared to GCs' orbital periods; hence, a reservoir of

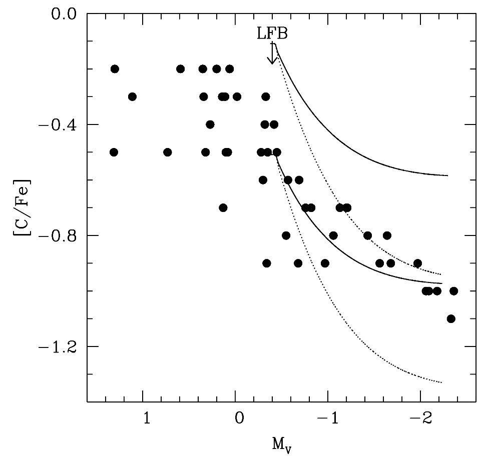

Fig. 2. Comparison of the observational data of Bellman et al. (2001) for RGB stars in the globular cluster M 92 with our calculations of extra mixing on the upper RGB for the model star with $\mathcal{M} = 0.8\,\mathcal{M}_\odot$ and $Z = 0.0001$. Diffusion parameters are from the same set — $\Delta \log T = 0.19$ and $D_{\rm mix} = 4 \times 10^8\,{\rm cm^2\,s^{-1}}$; $\Delta \log T = 0.22$ and $D_{\rm mix} = 8 \times 10^8\,{\rm cm^2\,s^{-1}}$ (*solid* and *dotted curve*, respectively) — which have been used for the field low-mass red giants. The upper and lower sets of curves have been calculated, in turn, with the initial abundances [C/Fe] = –0.1 and [C/Fe] = –0.5. An arrow shows the location of the bump luminosity where extra mixing presumably begins to penetrate much closer to the hydrogen-burning shell ("LFB" means luminosity function bump).

gas from IM-AGB stars can be pumped up in a GC before it will cross the galactic disk and the disk ram pressure will sweep the gas out (Thoul et al. 2002).

CONS:

- H-burning in IM-AGB stars is accompanied by recurrent He-shell flashes that produce plenty of ^{12}C and some ^{16}O (this must be especially noticeable at low metallicities); the 3rd dredge-up brings fresh ^{12}C and ^{16}O to the convective envelope where they can be transformed into ^{14}N by HBB and from where they are blown out to the inter-stellar medium (ISM); since the efficiency of these processes varies with the stellar mass and time, it would be very difficult to explain the approximate constancy of the sum C+N+O in GC red giants, reported by some observers (e.g. Pilachowski 1988; Smith et al. 1996), if IM-AGB stars are considered as the only or predominant contaminators;
- theoretical models of HBB in metal-poor IM-AGB stars seem to have problems with simultaneous reproduction of the O-Na anticorrelation and Mg isotopic composition in GC stars (Fig. 3).

3. Low-mass upper RGB stars experiencing "enhanced" extra mixing

In the majority of upper RGB stars, both in the field and in GCs, depth and rate of extra mixing do not seem to vary greatly from star to star: according to Denissenkov & VandenBerg (2003), these quantities can be parametrized by any pair of correlated values within the limits specified by $\Delta \log T \approx 0.19$ and $D_{\rm mix} \approx 4{\times}10^8\,{\rm cm^2\,s^{-1}}$, and $\Delta \log T \approx 0.22$ and $D_{\rm mix} \approx 8 \times 10^8\,{\rm cm^2\,s^{-1}}$. Therefore, we call this universal non-convective mixing process "canonical extra mixing". As I have mentioned above, it can dredge up only the products of CN-processing.

Once it has been established that some extra mixing operates in upper RGB stars, it is natural to ask whether it is possible for this process to produce a depletion in the surface O abundance, accompanied by enhancements in Na and Al, and if so, what extra mixing depth and rate are required. To answer this question, we have calculated the evolution of a star with $\mathcal{M} = 0.8\,\mathcal{M}_\odot$ and $Z = 0.0005$ (this is close to metallicity of the GC M 13, which exhibits the most extreme abundance anomalies of O, Na, Mg, and Al). The resultant abundance profiles for a model star just slightly above the bump luminosity are plotted in Fig. 4. We see that, if extra mixing could reach the depths indicated by the left-hand pair of arrows, then it would indeed bring to the stellar surface material that is deficient in O and enriched in Na and the

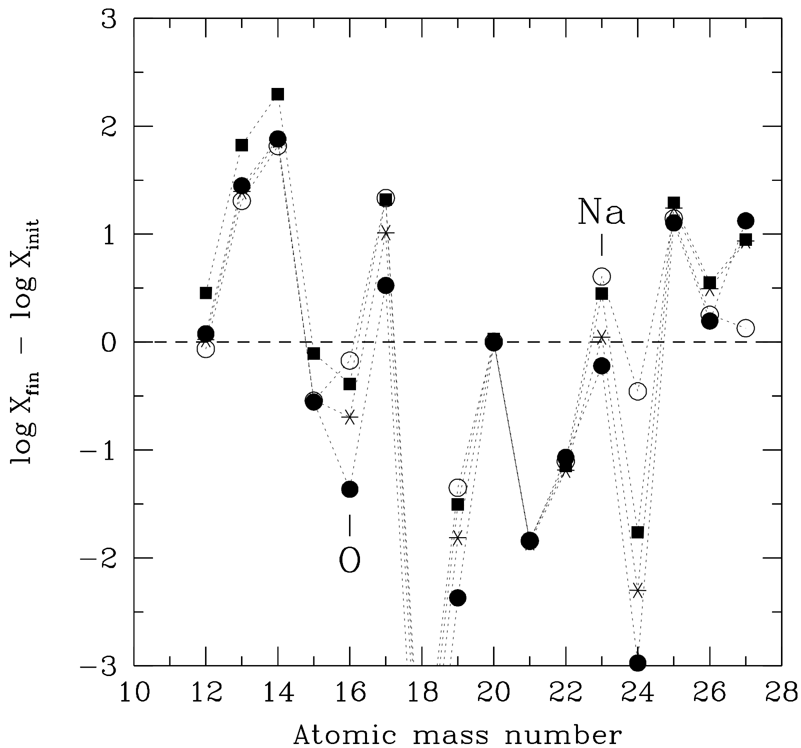

Fig. 3. Final envelope abundances (mass fractions, $X_{\rm fin}$) with respect to the initial ones ($X_{\rm init}$) after 8 thermal pulses calculated with the parametric AGB model for $\mathcal{M} = 5\,\mathcal{M}_\odot$ and $Z = 0.0005$: $(\lambda,\ T_{\rm HBB}) = (1, 10^8$ K) (*filled squares*), $(0.3, 9\times10^7$ K) (*open circles*), $(0.3, 10^8$ K) (*asterisks*), and $(0.3, 1.1\times10^8$ K) (*filled circles*). Here, λ is a parameter that determines the efficiency of the 3rd dredge-up (for details see Denissenkov & Herwig 2003). The most important and robust result is the considerable ^{24}Mg depletion exceeding that of ^{16}O. This should result in a $^{25}{\rm Mg} + {}^{26}$Mg dominated Mg isotopic mixture, which is not observed (Shetrone 1996; Yong et al. 2003).

$^{26}{\rm Al}^{\rm g}$ isotope[1]. If extra mixing in upper RGB stars is driven by rotation, then the depth required to produce the O, Na, and Al abundance anomalies that are observed in GCs can be reached in a star which is rotating ~10 times as fast as the "normal" stars experiencing canonical extra mixing (Denissenkov & VandenBerg 2003).

[1] If the rates of the reactions $^{26}{\rm Al}^{\rm g}(p,\gamma)^{27}$Si and $^{26}{\rm Mg}(p,\gamma)^{27}$Al are underestimated in the NACRE compilation (Angulo et al. 1999) used by us, then ^{27}Al could be brought to the stellar surface instead of $^{26}{\rm Al}^{\rm g}$ (for details see Denissenkov & Weiss 2001).

The required factor of 10 increase in rotational velocities over the average rotation rate will produce not only deeper, but also ~100 times faster extra mixing than in the canonical case, as e.g. for the rotation-driven turbulent diffusion $D_{\rm mix}\propto\Omega^2$ (Maeder & Meynet 1996). We call this hypothetical case "enhanced extra mixing". Instead of having $D_{\rm mix} = 4\times10^8\ {\rm cm^2\,s^{-1}}$ or $D_{\rm mix} = 8\times10^8\ {\rm cm^2\,s^{-1}}$, enhanced extra mixing would imply $D_{\rm mix}\approx10^{11}\ {\rm cm^2\,s^{-1}}$.

In the case of canonical extra mixing, the observationally constrained values of $D_{\rm mix}$ have an uncertainty of a factor of ~4 at most (Denissenkov & VandenBerg 2003). This transforms into an uncertainty of a factor of ~2 in the rotational velocity. A factor of ~10 in-

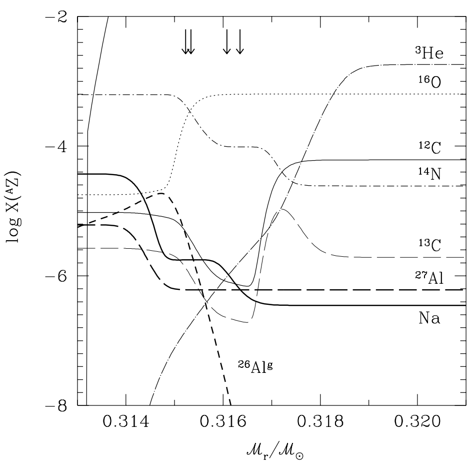

Fig. 4. Abundance profiles in the radiative zone of a model star with $\mathcal{M} = 0.8\,\mathcal{M}_\odot$ and $Z = 0.0005$ located just slightly above the bump luminosity. It has been assumed that initially $[^{25}\mathrm{Mg/Fe}] = 1.2$ (the motivation for this choice is given in Denissenkov et al. 1998). The right-hand pair of arrows indicate the extra mixing depths specified by parameters $\Delta \log T = 0.19$ and 0.22, while the left-hand pair indicate the depths that could be reached by turbulent diffusion if rotation was nearly 10 times as fast as that required to explain the abundance anomalies seen on the upper RGB in most low-mass stars.

crease in the rotational velocity should therefore be considered the exception. Hence, to distinguish this exceptional case, we introduce the special term "enhanced extra mixing". Of course, this does not exclude the possibility that there is a continuum of mixing rates and depths between canonical and enhanced extra mixing. Neither does this mean that there is some basic difference in the underlying physics of these mixing processes. However, the spin-up of an RGB star to a rotation rate that exceeds the average rate by a factor of ~ 10 may be a stochastic process insofar as it may depend on the environmental stellar density in GCs. It is most likely that such the spin-up is caused by some external sources of angular momentum available in GCs.

I conjecture that dynamical processes in GCs, such as hardening of binary systems as a result of binary-single-star scattering encounters (e.g. Hut et al. 2003), followed by the tidal synchronization of the spin and orbital rotation of an RGB binary component (Fig. 5), or collisions between red giants and free-floating planets (e.g. Soker et al. 2001), may result in a larger proportion of the spun-up red giants in GCs than in the halo field, which would favour enhanced extra mixing. Indeed, in GCs, there is a large variation, both between individual stars and from cluster to cluster, of the projected rotational velocity $v \sin i$ of horizontal branch (HB) stars (Peterson et al. 1995; Recio-Blanco et al. 2002), which are immediate descendants of upper RGB stars. This can be considered as indirect observational evidence of the existence of sub-populations of stars with different rotation rates on the RGB.

According to observations, there are about 15%–38% of binaries in the inner core of NGC 6752 (Rubenstein & Bailyn 1997), 14% in 47 Tucanae (Albrow et al. 2001) and 8%–38% in the inner region of NGC 288 (Bellazzini et al. 2002).

Enhanced extra mixing can produce correlations between the C, N, O, Na, Mg and Al abundance variations at any location on the upper RGB (above the bump luminosity). Alternatively, these correlations as well as those observed in the unevolved stars in GCs may be of the primordial origin, in the sense that they could have been produced in low-mass upper RGB stars slightly more massive than the present-day MSTO stars that had experienced enhanced extra mixing in the past and that had contaminated the lower-mass stars.

In Pop I field red giants, enhanced extra mixing may be responsible for the phenomenon of Li-rich giants. Indeed, for single K giants, Drake et al. (2002) find that "among rapid ($v \sin i \geq 8\,\mathrm{km\,s^{-1}}$) rotators, a very large proportion (~ 50%) are Li-rich giants" and that "this proportion is in contrast with a very low proportion (~ 2%) of Li-rich stars among the much more common slowly rotating K giants." Spinning up of a field red giant, which is required for the internal Li-synthesis by enhanced extra mixing (via the Cameron-Fowler

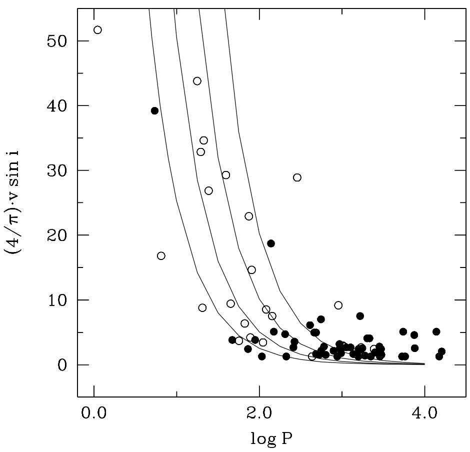

Fig. 5. Distribution of the projected rotational velocity (multiplied by the factor $4/\pi$ for taking into account a random orientation of the axis of rotation) as a function of the orbital period, for G and K giant components of field binaries with available orbital parameters (De Medeiros et al. 2002). Binary systems with a circular or nearly circular orbit ($e \leq 0.10$) are represented by *open circles*, whereas the systems with eccentric orbits ($e > 0.10$) are represented by *filled circles*. Theoretical curves are constructed under the assumption that $\Omega_{\rm spin} = \Omega_{\rm orb}$ for 4 values of the red giant's radius: $R/R_\odot = 5$, 10, 20 and 40 (from left to right). The tidal circularization time is shorter than the synchronization time (e.g. Hurley et al. 2002), therefore the giants represented by open circles are most likely to have the synchronized rotation.

mechanism), may be caused by the tidal synchronization in a close binary (Fig. 5) or by the swallowing of an orbiting giant planet (Siess & Livio 1999; Denissenkov & Weiss 2000; Costa et al. 2002; Carney et al. 2003).

If we assume that

(i) only IM-AGB stars with initial masses $4 \lesssim \mathcal{M}/\mathcal{M}_\odot \lesssim 6$ contributed to the contamination of low-mass stars in GCs;
(ii) $(\mathcal{M} - 1\mathcal{M}_\odot)$ is the mass ejected by each of them into ISM;
(iii) every upper RGB star, independently of its initial mass, has lost $0.2\,\mathcal{M}_\odot$ before the core He-flash;
(iv) the initial mass function was that of Salpeter;

then the ratio of the total masses lost by IM-AGB stars and by upper RGB stars is 1.3, i.e. these masses are comparable. The spun-up red giants may lose even more mass, which could potentially explain the different HB morphologies of the second parameter pairs of GCs (Soker et al. 2001).

PROS:

- pure H-burning; hence, C+N+O would be constant;
- binaries in GCs tend to concentrate at the cluster core; hence, the mass lost by upper RGB stars, the former members of close binaries, could also be centrally concentrated;
- pretty high masses may be accreted by low-mass stars in close binaries with red giant companions via the common envelope event;
- a potential possibility to explain the HB morphology (extended blue tails) and the extremely fast rotation of HB stars in GCs (Peterson et al. 1995; Sills & Pinsonneault 2000; Behr et al. 2000a,b; Recio-Blanco et al. 2002); e.g., ~ 69% of extreme HB stars are known to be members of the short period binaries (Maxted et al. 2001);
- if it would be shown that GCs with higher ellipticities contain on average larger fractions of binaries (or free-floating planets) then the puzzling correlation between the ratio of CN-strong to CN-weak stars and the GC ellipticity could be understood (Norris 1987; Smith 2002);

CONS:

- temperatures are not high enough to destroy ^{24}Mg;
- long evolutionary time-scales ($\sim 10^{10}$ years).

I will elaborate upon the outlined ideas in the nearest future.

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