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A contribution of ^{26}Al to the O-Al anticorrelation in globular cluster red giants

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ABSTRACT

We modify our combined ("deep mixing" plus "primordial") scenario explaining the star-to-star abundance variations in globular cluster red giants in such a way that it confirms with new experimental data: *(i)* the new and better constrained (NACRE) thermonuclear reaction rates and *(ii)* a discovery of the O-Na anticorrelation in stars below the main-sequence turn-off in the cluster NGC6752. For the latter we propose that some main-sequence dwarfs in globular clusters accrete material lost by red giant primary components of close binaries during a common envelope event. As a consequence of the new reaction rates, we are drawn to the conclusion that the anomalies in [Al/Fe] in globular cluster red giants are in fact manifestations of ^{26}Al$^{\rm g}$ (instead of the stable isotope ^{27}Al) abundance variations produced by deep mixing.

Subject headings: stars: evolution – stars: interiors – galaxy: globular clusters: general – nuclear reactions, nucleosynthesis, abundances

1. Introduction

Several years ago we proposed (Denissenkov et al. 1998) a combined scenario which explained self-consistently the star-to-star abundance variations of C, N, O, Na, Al and Mg in globular cluster red giants (GCRGs). This scenario has two components: a "deep mixing" (or "evolutionary") and a "primordial" one. The deep mixing component demonstrates that the overabundances of N, Na and Al correlating with the deficiencies of C and O can be produced inside the GCRGs themselves via the hydrogen-shell burning in the concurrent CNO-, NeNa-, and MgAl-cycles. It requires that some extra-mixing bridges the outer wing of the H-burning shell (HBS) with the base of the convective envelope (BCE). The decline of [C/Fe] with decreasing $M_{\rm V}$ in M92 red giants reported for the first time by Langer et al. (1986) and confirmed recently by Bellman et al. (2001) is convincing evidence of deep mixing in GCRGs. Moreover, Gratton et al. (2000) have shown that extra-mixing

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resulting in considerable changes of the surface C, N and Li abundances in low-metallicity field red giants is rather the rule than the exception.

However, in order to reproduce the large ($> 1\,$dex) variations of [Al/Fe][3] and the O-Al anticorrelation in ω Cen red giants found by Norris & Da Costa (1995) we assumed *(i)* that the initial abundance of ^{25}Mg had been increased up to $[^{25}\mathrm{Mg/Fe}] = 1.1$ primordially, and *(ii)* that the rate of the reaction $^{26}\mathrm{Al^g(p,\gamma)^{27}Si}$, which leads to ^{27}Al via $^{27}\mathrm{Si}(\beta^+\nu)^{27}\mathrm{Al}$, was 10^3 times faster than that given by Coughlan & Fowler (1988). The first assumption – being the primordial component of our combined scenario – was supported by our accepted model of globular clusters' self-enrichment. In this model (based on the earlier ones of Cayrel (1986) and Brown et al. (1995)) type II supernovae are considered to enrich globular clusters with Fe and α-elements (e.g. ^{16}O and ^{24}Mg), and intermediate-mass ($M = 3$-$8\,M_\odot$) asymptotic giant branch stars (hereafter, IM AGB stars) with ^{25,26}Mg and, to a lesser extent, with Na and Al. The second assumption concerning the $^{26}\mathrm{Al^g(p,\gamma)^{27}Si}$ reaction was permissible because the uncertainty factor in this rate was as large as $\sim 10^3$ (Arnould et al. 1995) at that time, at least for typical H-shell burning temperatures.

Since the publication of Paper I the following important results related to the problem of the origin of the O-Na and O-Al anticorrelations in GCRGs have been obtained: *(i)* the globular cluster self-enrichment model has received new observational support (Jehin et al. 1999; Smith et al. 2000) and has been developed further by Parmentier et al. (1999); *(ii)* detailed calculations of nucleosynthesis in IM AGB stars of low metallicities have confirmed our earlier conclusion about their ability to produce considerable amounts of ^{25}Mg and ^{26}Mg (Lattanzio et al. 2000; Messenger 2000); *(iii)* a compilation of new thermonuclear reaction rates (NACRE) has been published (Angulo et al. 1999); the new rate for the $^{26}\mathrm{Al^g(p,\gamma)^{27}Si}$ reaction is constrained much tighter, with an upper limit of only ~ 50 times that of Coughlan & Fowler (1988) at the temperatures relevant to the outer wing of the HBS in GCRGs ($T = 40$-$50{\cdot}10^6$ K); *(iv)* in addition to ω Cen the observations by Ivans et al. (1999) provided a second cluster – M4 – for which four abundance correlations (the O-Na, O-Al, C-O and C-N ones) have been observed simultaneously for a number of red giants, and also in this cluster Al is found to be strongly overabundant; *(v)* quite recently the O-Na anticorrelation (and, possibly, also the O-Al one, both seen before only in GCRGs) has been detected in stars below the main-sequence turn-off (MSTO) in the cluster NGC 6752 (Gratton et al. 2001). Ventura et al. (2001) have proposed an interpretation for these latter observations: they have taken advantage of the globular clusters' self-enrichment model and their finding that at very low metallicity the so-called hot bottom burning, i.e. thermonuclear processing at the BCE, in IM AGB models occurs at $T \geq 10^8$ K; Ventura et al. (2001) emphasize that at such high temperatures O should be depleted and Na enhanced, therefore they infer that the O-Na anticorrelation in GCRGs most likely is a consequence of accretion of material lost by IM AGB stars of a previous generation by low-mass MS stars (i.e. a pure primordial effect). Work is in preparation (Denissenkov & Weiss 2001, in preparation) to examine this hypothesis with detailed models and within the framework

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[3] $[\mathrm{A/B}] \equiv \log_{10}(N(\mathrm{A})/N(\mathrm{B}))_{\mathrm{star}} - \log_{10}(N(\mathrm{A})/N(\mathrm{B}))_\odot$, where $N(\mathrm{A})$ is the number density of species A

of our own approach for solving the abundance anomalies.

While the first two new results support the ideas of Paper I, fact *(iii)* is in clear contradiction to our original combined scenario which required that the critical reaction rate for $^{26}\mathrm{Al^g}(\mathrm{p},\gamma)^{27}\mathrm{Si}$ was set to the highest possible value. Therefore, we modify our scenario in the present *Letter* in such a way that it agrees with the new experimental results listed above, for example that it can explain the observations concerning M4 as well. To anticipate our main result, we find that the Al-anomalies observed cannot be understood in terms of the stable isotope $^{27}\mathrm{Al}$, but can be explained self-consistently and naturally within the deep mixing scenario if they are due to $^{26}\mathrm{Al}$ (in ground state).

2. Aluminium nucleosynthesis in the hydrogen shell of red giants

In this section we will present new models concerning the abundance anomalies in ω Cen and M4. The method and details of the calculations (both of the evolutionary models and of the nucleosynthesis) have been described elsewhere (e.g. in Paper I) and will not be repeated here. We just recall the important fact that the deep mixing and nucleosynthesis calculations are done on background models obtained from interpolation of the envelope and H-shell structure of several selected sequences of full stellar evolution models. The models have mass ($M/M_\odot = 0.80$) and initial chemical composition appropriate for the two clusters ($Z = 0.0005$ for ω Cen and 0.001 for M4). The deep mixing is assumed to be of diffusive nature and is characterized by two parameters: mixing depth and speed (expressed as a diffusion constant). The difference to our earlier work is the use of the new NACRE (Angulo et al. 1999) rates. Concerning the Al-nucleosynthesis, we fully take into account the two states of $^{26}\mathrm{Al}$ (ground and metastable state indicated by additional superscripts “g” resp. “m”) and treat them as two independent species in our network.

The new NACRE-rate of the reaction $^{26}\mathrm{Al^g}(\mathrm{p},\gamma)^{27}\mathrm{Si}$ is not fast enough for producing $^{27}\mathrm{Al}$ (the β^+-decay product of $^{27}\mathrm{Si}$) in GCRGs even if its upper limit (approximately a factor 50 above the given rate) was used. Almost all initial $^{25}\mathrm{Mg}$, whose abundance is assumed to be increased primordially, is transformed into $^{26}\mathrm{Al^g}$ which in turn decays to $^{26}\mathrm{Mg}$ rather than captures protons to produce $^{27}\mathrm{Al}$. This implies that our combined scenario presented in Paper I is no longer feasible, since it worked only due to the fact that it was possible at that time to increase the proton capture rate by a factor of 1000.

Figure 1 illustrates the abundance profiles due to proton-capture nucleosynthesis within a red giant model typical for ω Cen. We point out to the reader that the abundance of $^{26}\mathrm{Al^g}$ rises steeply in layers farther outside the shell than does $^{27}\mathrm{Al}$, with a peak abundance almost half a magnitude larger. It is important to emphasize that we used all NACRE reaction rates as published without changing them within the possible error limits.

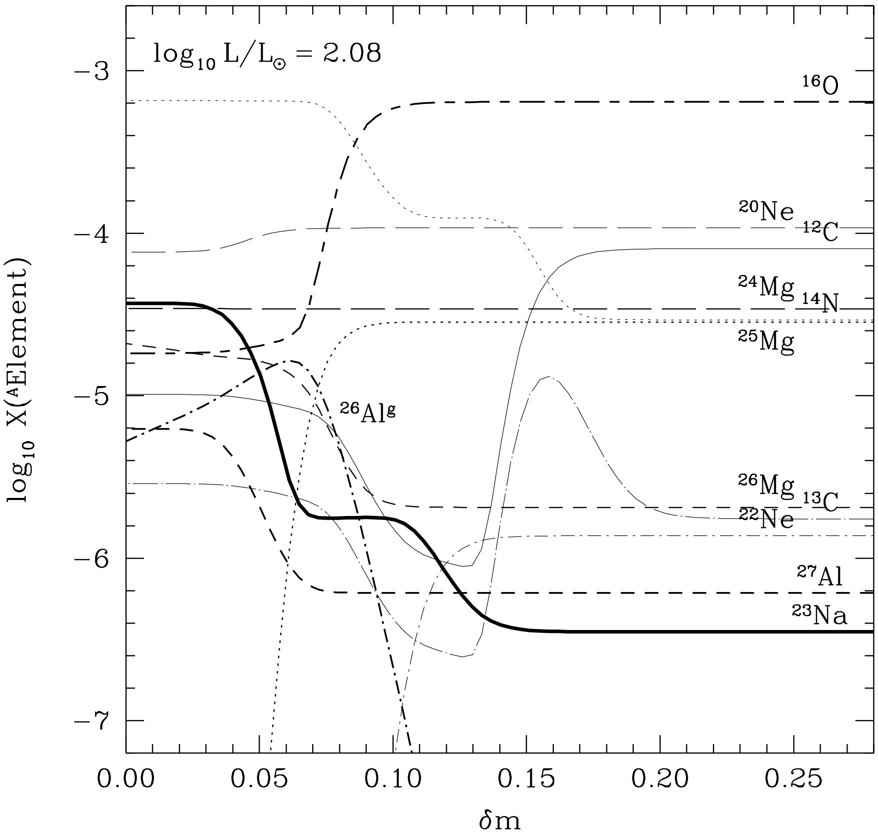

Fig. 1.— Abundance profiles (logarithms of mass fractions) within the hydrogen shell of an $0.8\,M_\odot$ model of luminosity $\log L/L_\odot = 2.08$ and metallicity $Z = 0.0005$ (or [Fe/H] $= -1.58$), which corresponds to the mean metallicity of red giants in ω Cen. For this model, [Mg/Fe]=1.2 was assumed (primordial enrichment) and the standard NACRE-rates were used. The abscissa is in our standard relative mass coordinate δm, which is 0 at the bottom of the H-shell and 1 at the bottom of the convective envelope.

This offers the attractive possibility to explain the O-Al anticorrelation in GCRGs by assuming that the observed variations of [Al/Fe] are in fact manifestations of the surface $^{26}\mathrm{Al^g}$ abundance variations produced by deep mixing! In Figs. 2 and 3 we illustrate that *all known abundance variations and correlations* can be explained simultaneously both for ω Cen and M4, with parameters for the deep mixing which are similar but not identical for the two clusters. It is also shown that the prediction for ^{27}Al clearly fails to reproduce the observations. Given this, the question arises why the obvious possibility that the observed Al is actually the isotope ^{26}Al has not been tried before? One reason might be that ^{26}Al is unstable against β-decay to ^{26}Mg (emitting the famous 1.8 MeV γ-line) with a life-time of $\approx 10^6$ yrs; therefore the survival of this isotope at the surface over the much longer lifetime of a red giant might appear unlikely. However, within the deep mixing scenario this argument does not hold necessarily. Indeed, the following simple estimate supports our hypothesis:

The typical size of the radiative zone between the HBS and the BCE in GCRGs is $\Delta r =$1-2 $R_\odot$. For a deep mixing rate (a diffusion constant) of $D_{\rm mix} = 4-5\cdot 10^8$ cm^2·s^{-1}, with which the four abundance correlations in the globular clusters ω Cen and M4 are reproduced simultaneously (Figs. 2 and 3), the extra-mixing turnover time is $\tau_{\rm mix} \approx (\Delta r)^2/D_{\rm mix} = 0.3-1.5\cdot 10^6$ years. This is comparable with the life-time ($1.07\cdot 10^6$ years) of $^{26}\mathrm{Al^g}$. Hence, part of the freshly synthesized $^{26}\mathrm{Al^g}$ can survive the transport from the HBS to the BCE. Our detailed deep mixing calculations confirm this simple estimate (Figs. 2b and 3b). It should be noted that in spite of the rather long life-time of stars on the RGB ($\sim 10^7$ years for GCRGs) the surface $^{26}\mathrm{Al^g}$ abundance may be growing steadily (its absolute value reaching $X(^{26}\mathrm{Al^g}) = 9.4\cdot 10^{-6}$ in Fig. 2b, solid line) because during all this time we have an active source of $^{26}\mathrm{Al^g}$ at the bottom of the deep mixing zone and assume continuing deep mixing. Some increase of the ^{27}Al abundance occurs only later on (Fig. 2b, dashed line).

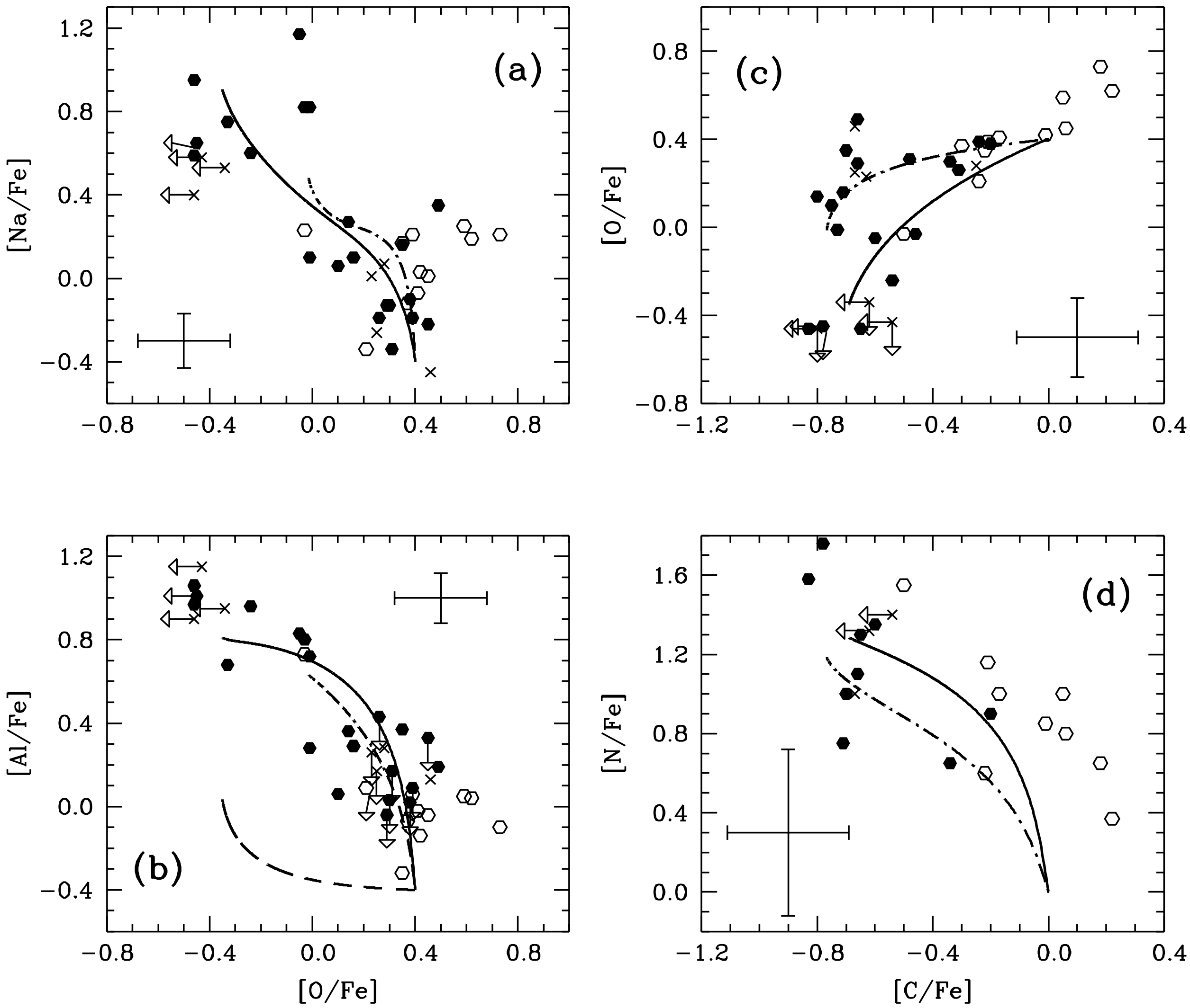

Fig. 2.— The abundance trends seen in ω Cen red giants (symbols; from Norris & Da Costa 1995) compared with the results of our deep mixing calculations. Two sets of mixing depth δm (see text) and rate (diffusion constant expressed in $cm^2{\cdot}s^{-1}$) are used: $(\delta m_{\rm mix};D_{\rm mix}) = (0.05; 5\,10^8)$ – solid and dashed lines – and $(0.065; 5\,10^8)$ – dot-dashed lines. The initial ^{25}Mg abundance was assumed to be $[^{25}{\rm Mg/Fe}] = 1.2$. In panel b the solid and dot-dashed lines show the pure $^{26}{\rm Al^g}$, whereas the dashed line the pure ^{27}Al abundance. Large crosses indicate observational error bars. Open and filled symbols refer to CO-strong and CO-weak stars, and crosses denote stars with unidentified CO status, following Norris & Da Costa (1995).

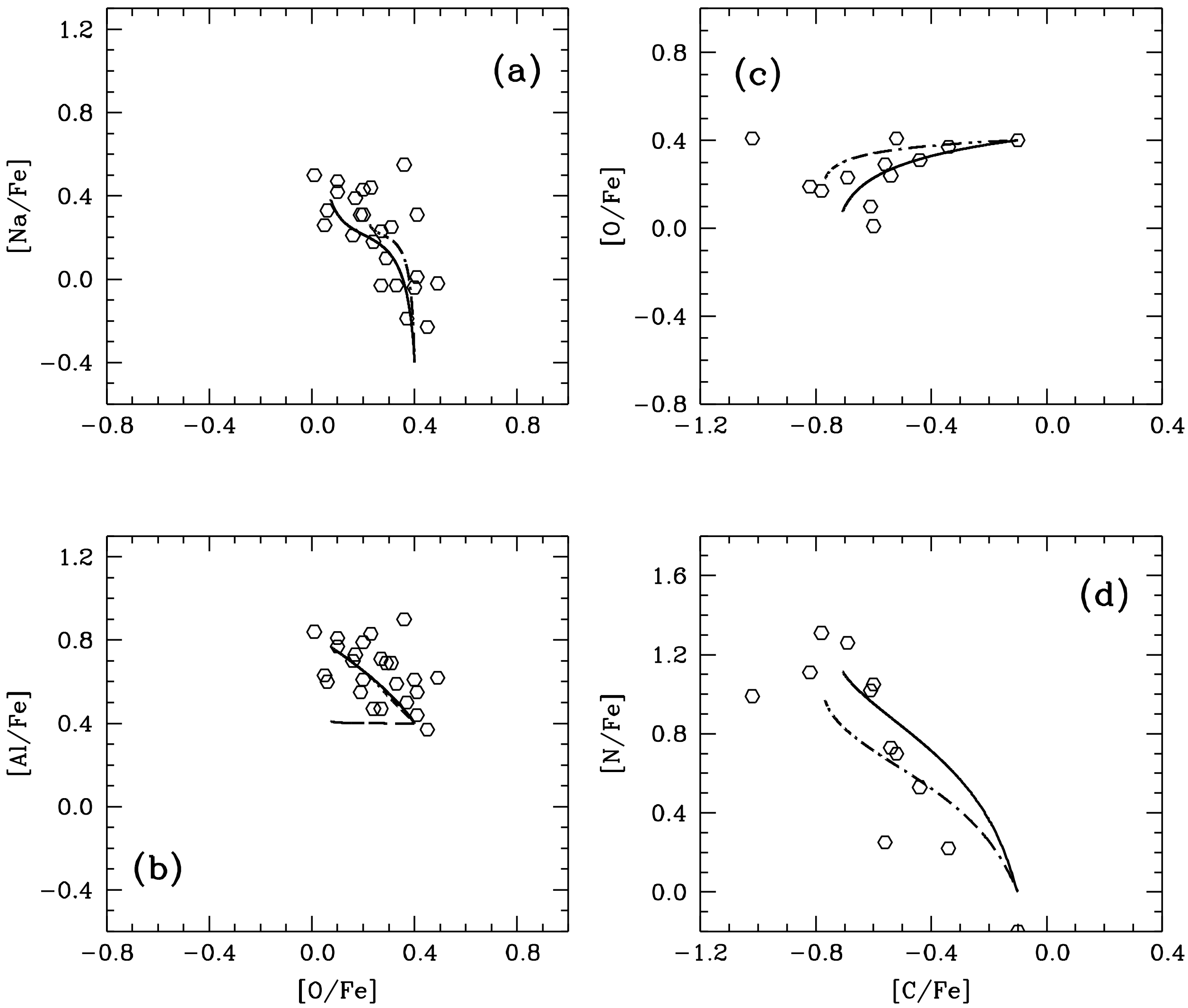

Fig. 3.— Abundance trends seen in M4 red giants (symbols; from Ivans et al. 1999) compared with deep mixing results for two sets of mixing depth and rate ($\delta m_{\rm mix}$;$D_{\rm mix}$) = (0.065; $4\,10^8$) – solid and dashed lines – and (0.075; $4\,10^8$) – dot-dashed lines. The initial ^{12}C, ^{25}Mg and ^{27}Al abundances were assumed to be [C/Fe] = −0.1, [^{25}Mg/Fe] = 1.2 and [Al/Fe] = +0.4, respectively. Panel b, solid line: pure ^{26}Al$^{\rm g}$ yield; dashed line: pure ^{27}Al. Calculations for this and Fig. 2 were done with the NACRE reaction rates (Angulo et al. 1999). We emphasize the fact that the mixing parameters used in Figs. 2 and 3 have very similar, but not identical values.

3. The oxygen component of the O-Al anticorrelation

The presence of s-process elements in ω Cen and M4 red giants (Smith et al. 2000; Ivans et al. 1999) implies that AGB stars did contribute to the abundance anomalies seen in GCRGs. We have used this to argue for a primordial enhancement of ^{25}Mg in the models presented in the previous section. Similarily, the correlating C, N, Na and O abundance variations in stars below or around the MSTO in some globular clusters (Briley et al. 1996; Gratton et al. 2001) are apparent signs of primordial pollution or accretion and not the result of deep mixing, which we assume to happen only in evolved red giants.

Ventura et al. (2001) have suggested that these anomalies are the result of nucleosynthesis in and pollution by an earlier generation of IM AGB stars. We will investigate this idea elsewhere (Denissenkov & Weiss 2001, in prepartion). Here we propose an alternative interpretation of the O-Na (and O-Al) anticorrelation in stars below the MSTO in NGC6752 which does not preclude deep mixing in GCRGs but instead takes advantage of it: We assume that some MS dwarfs in globular clusters might accrete material lost by red giant primary components of close binary systems during the so-called common envelope event (Iben & Livio 1991). If these red giants had experienced deep mixing before they filled their Roche-lobes then their ejected envelopes could be enriched in Na and Al and be deficient in O. Potentially any primary with $0.8<M/M_\odot<2.5$ can play a rôle in this scenario because in such stars the HBS erases the molecular weight discontinuity left behind by the BCE (which is thought to prevent deep mixing from operating) before these stars will reach the RGB tip.

4. Conclusions

Forced by new and better constrained proton-nucleosynthesis reaction rates we modified our combined (primordial plus deep-mixing) scenario (Denissenkov et al. 1998, Paper I) and reinvestigated the results of deep mixing between the convective envelope and the hydrogen-burning shell in GCRGs. We found that quite naturally, *all* (anti-)correlations in ω Cen and M4 can be explained simultaneously if the observed Al-isotope is in fact the unstable ^{26}Al$^{\rm g}$ one. This is possible only within the deep mixing scenario and in fact necessitates ongoing exchange of matter between the ^{26}Al$^{\rm g}$-source in the shell and the convective envelope. As the primordial component we have (as before) to assume an enrichment in ^{25}Mg by pollution with IM AGB debris. Anomalies found around the MSTO clearly cannot be explained within our scenario and require additional (primordial) sources for which we tentatively suggest common-envelope effects in close binaries, where the donor star has experienced deep mixing.

To verify our explanation for the Al-anomalies in GCRGs one could either try to identify the isotope ratios of Al or make use of the γ-line emitted during the decay of ^{26}Al$^{\rm g}$ (^{26}Al$^{\rm m}$ is present only in vanishing amounts). Estimates have shown that the γ-flux from ω Cen is expected to be of order 10^{-7} photons/cm$^2\cdot$sec and therefore 2 orders of magnitude below the COMPTEL detection limit, but might be within reach of the planned "Advanced Comptel Telescope". However, we hope that the ingenuity of observers might lead to the identification of the Al-isotope to clarify this question.

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