From Lithium to Uranium: Elemental Tracers of Early Cosmic Evolution
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Chemical fingerprints in globular clusters: Searching for the missing stellar link(s)

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Abstract. Globular cluster stars exhibit abundance anomalies which are not shared by their field counterparts. Two global scenarii have been proposed in the past to explain these differences: The primordial enrichment scenario and the evolutionary (or intrinsic) one. Recent observations well below the bump luminosity in globular clusters have raised the weight of the primordial solution. However the stellar sources responsible for these abundance variations have not yet been indubitably identified. In this review we discuss the possible stellar culprits as well as their pros and cons.

Keywords. Nucleosynthesis, stars: interiors, stars: abundances

1. Abundance anomalies in galactic globular clusters

During the last three decades, an incredible amount of data has been collected on the chemical properties of galactic globular clusters (hereafter GCs) thanks to high spectral resolution abundance analysis. We refer to Gratton *et al.* (2004) and to Sneden in these proceedings for recent and extended reviews on the observed abundance trends in GCs. We briefly recall here the main points : (i) Individual GCs appear to be fairly homogeneous as far as the iron peak elements (Ni, Cu) are concerned; (ii) They present very low scatter and the same trends as field stars for the neutron-capture elements (Ba, La, Eu) and the alpha-elements (Si, Ca); (iii) They exhibit however complex patterns and large star-to-star abundance variations for the lighter elements from C to Al which are not shared by their field counterparts.

Among these anomalous patterns, the most striking ones are the so-called universal O-Na anticorrelation (which has been observed in all the GCs where it has been looked for) and the Mg-Al anticorrelation (see e.g. Ramirez & Cohen 2002 and Ivans *et al.* 1999). Both of them were known to exist among the brightest giant stars for a long time (Peterson 1980; see Kraft 1994 for an early review). It was soon recognized that the O-Na anticorrelation occurs thanks to the following coincidence : at a similar temperature ($\sim 2 \times 10^7$ K), proton-captures on ^{16}O and ^{22}Ne lead to the destruction of O and to the production of ^{23}Na (Denissenkov & Denissenkova 1990). The Mg-Al anticorrelation results from a sequence of proton-captures followed by β-decays that transforms ^{24}Mg into ^{25}Mg, ^{26}Mg and finally ^{27}Al (Langer *et al.* 1993; Langer & Hoffman 1995); this chain is only effective at temperatures higher than $\sim 7{\times}10^7$ K due to the larger Coulomb barrier of Mg. The corresponding cycles and chains are shown in Fig. 1.

Although the nuclear mechanisms are clearly identified, the identification of the astrophysical site were they take place has long remained (and is still) a challenge. The anomalies could indeed form in situ; this evolutionary solution calls for some very deep mixing inside the red giant stars that we observe now. The alternative – primordial – scenario is that the abundance differences pre-existed in the protocluster gas.

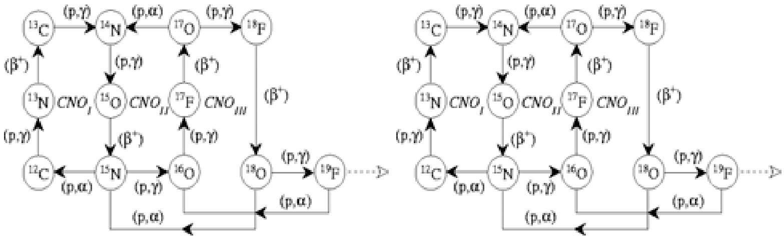

Figure 1. Reactions of the CNO-cycles and NeNa- and MgAl-chains. The dashed lines present the possible leakages out of the cycles. Taken from Arnould *et al.* (1999).

Thanks to the advent of the very large telescopes, both the O-Na and the Mg-Al anticorrelations could recently be observed also in the fainter turnoff and subgiant cluster members (Gratton *et al.* 2001; Grundhal *et al.* 2002; Ramirez & Cohen 2002, 2003; Carretta *et al.* 2003, 2004, 2005). This is a crucial result. Indeed the internal temperatures of the scarcely evolved low-mass stars that we observe today are too low for the NeNa- and MgAl-cycles to operate. The abundance variations cannot thus be intrisic, but must reflect the initial composition. This breakthrough has given a new spin to the primordial enrichment scenario according to which both anticorrelations are due to the pollution of the intracluster gas by a first generation of more massive stars (Cottrell & Da Costa 1981)†. The same "polluters" should also be responsible for the primordial range in [C/Fe] and [N/Fe] observed in individual GCs (see Bellman *et al.* 2001, Cohen *et al.* 2002 and references therein)‡. Importantly, whenever the C and N abundances are available, N is found to be anticorrelated with O, which positively correlates with C, revealing a redistribution of the C, N and O in the CNO-cycle burning. In addition, the total C+N+O is found to be approximately constant in many GCs (Dickens *et al.* 1991; Smith *et al.* 1996; Ivans *et al.* 1999; Smith *et al.* 2005).

To summarize, the emerging scenario is that the GC stars that we observe now must have formed from the mass processed through proton-capture nucleosynthesis via the CNO-cycle and the NeNa- and MgAl-chains and then lost (perhaps mixed with some original material) by a first generation of more massive and faster evolving objects. This first generation consists of the original cluster population and shares the chemical composition of the field stars with similar metallicity. But what type of stars did shape the abundance anomalies?

2. AGB stars: The best candidate polluters, at least qualitatively

Up to now, the best candidate polluters are the low-metallicity, massive TP-AGB stars (thermally pulsing AGBs). These objects indeed present several qualitative advantages that make them very attractive within the primordial scenario: (1) They possibly

† The fact that we see the same patterns in both scarcely and strongly evolved stars, which have respectively very thin and extremely deep convective envelopes, reveals primordial variations instead of pollution on already formed stars.

‡ Note that an anticorrelation between [C/Fe] and the stellar luminosity along the red giant branch is superposed to the primordial range of [C/Fe] in GCs (e.g. Bellman *et al.* 2001). This evolutionary pattern, which is also in field stars (Smith & Martell 2003), together with the decrease of ^{7}Li, C, $^{12}C/^{13}C$ and the increase of N on the upper RGB (Charbonnel *et al.* 1998; Gratton *et al.* 2000; Ramirez & Cohen 2002; Grundahl *et al.* 2002; Shetrone 2003) is the signature of an intrinsic mixing process that occurs after the end of the first dredge-up (see Weiss & Charbonnel 2004 and references therein). Further discussion on the evolutionary aspects is out of the scope of the present paper where we focus on the primordial component.

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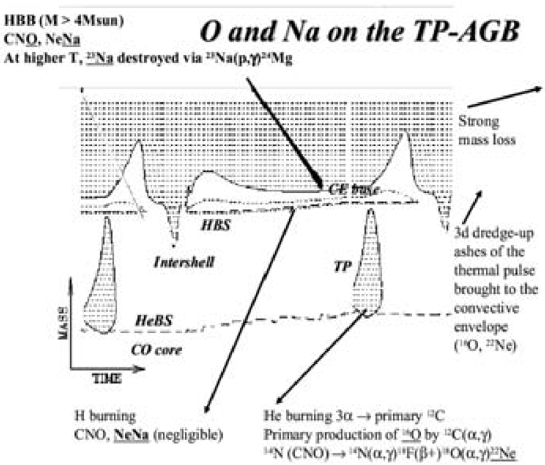

Figure 2. Kippenhahn diagram representing schematically the evolution of the internal structure of an AGB star between two successive thermal pulses (The shaded parts represent the convective regions.). The nucleosynthetic paths and mixing events relevant for the building up of the O-Na anticorrelation are indicated (Adapted from Mowlavi 1998).

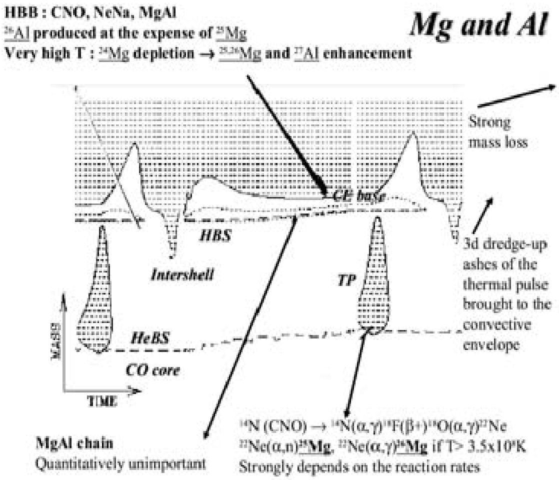

Figure 3. Same as Fig. 2 but for the Mg-Al anticorrelation.

experience the so-called hot bottom burning (hereafter HBB) which processes their large envelopes through the required CNO, NeNa and MgAl nucleosynthesis; (2) They do not produce α- nor Fe-peak elements; (3) They undergo few thermal pulses before the superwind phase so that they should not pollute the intracluster gas with s-process elements; (4) They are expected to undergo strong mass loss that may expel up to 80% of the initial stellar mass; (5) Their low-speed winds may be retained within the cluster; (6) The UV energy produced during the planetary nebulae phase is too low to expel the gas away; (7) Their lifetime (50–100 Myr) is low enough to be compatible with the GC formation.

Figures 2 and 3 summarize qualitatively the nucleosynthetic paths and mixing events which occur in TP-AGB stars and which are relevant for the O-Na and Mg-Al abundance problems (see Mowlavi & Meynet 2000 and Karakas & Lattanzio 2003 for more details on the production of the Mg and Al isotopes).

The competition between the 3d dredge-up events and the HBB is crucial for the final yields. On one hand indeed, the 3d dredge-up is expected to bring to the stellar surface primary ^{16}O (in uncertain quantities), as well as (primary) ^{22}Ne and ^{25,26}Mg produced via successive α-captures on ^{14}N in the convective tongue during the thermal pulses. This production of the neutron heavy Mg isotopes in the He-shell flash via ^{22}Ne(α,n)^{25}Mg and ^{22}Ne(α,γ)^{26}Mg depends on the abundance of the matter left by the H shell at the end of the interpulse phase. It requires temperatures higher than $\sim 3 \times 10^8$K which are reached typically in the He shell for stars initially more massive than ∼3 $M_\odot$ and strongly depends on the reaction rates. The Al isotopes are not produced in the He-shell.

On the other hand, if the bottom envelope temperature is high enough (typically for stars with masses higher than $\sim$ 4 $M_\odot$), HBB further the envelope abundances via the CNO-cycle and the NeNa and MgAl chains. HBB results in the production of ^{14}N, and to the depletion of ^{15}N, ^{18}O, and, if the temperature is high enough, of ^{16}O. When the NeNa- and MgAl-chains operate, ^{23}Na and ^{26}Al are produced at the expense of the dredged-up ^{22}Ne and ^{25}Mg respectively (Note that an important increase of the surface ^{23}Na abundance already occurs as a result of the second dredge-up from the conversion of the initial abundance of ^{22}Ne and some ^{20}Ne by H-shell burning; see Fig. 4). In the case of very high HBB temperatures, proton-captures on ^{23}Na and ^{24}Mg deplete the surface abundances of the elements, and some ^{25,26}Mg and ^{27}Al are produced.

Qualitatively AGB stars are thus very attractive culprits. However some important problems arise when one tries to fit the details quantitatively as we shall see below.

3. AGB stars: Modelling uncertainties and quantitative predictions

During the past ten years, several groups have computed models of metal-poor AGB stars and the associated yields (Forestini & Charbonnel 1997; Marigo *et al.* 1998; Ventura *et al.* 2002; Ventura & D'Antona 2005a,b; Siess *et al.* 2002; Denissenkov & Herwig 2003; Herwig 2004a,b; Karakas & Lattanzio 2003; Decressin *et al.* 2005). The predicted yields are highly uncertain. They depend indeed on the modelling of crucial processes (mass loss, convective transport, transport mechanisms in the radiative regions, ...) which rests on semiempirical calibrations that have to be extrapolated to a range in metallicity where no experimental data are available. In order to illustrate how the prescription uncertainties affect the predictive power of the theory, we will now focus on the most recent low-metallicity AGB models which have been computed in the context of the GC abundance anomalies.

3.1. *Can AGB stars shape the O-Na anticorrelation?*

Soon after the paper by Ventura *et al.* (2002) which showed that O could be efficiently depleted by HBB in low-metallicity AGB stars, Denissenkov & Herwig (2003) discussed the impact of the delicate interplay between 3d dredge-up and HBB on the overall budget of the O, Na and Mg isotopes. According to their high-resolution, full stellar evolution models, massive AGB stars cannot show simultaneously ^{16}O depletion and Na enhancement (as indicated by the anticorrelation observed). On one hand indeed, if no or very little ^{16}O is brought to the surface (in the case of unefficient 3d dredge-up), then this isotope is efficiently destroyed by HBB in the metal-poor massive AGBs; however in this case the ^{22}Ne dredge-up source required to replenishes Na is also cut down, and the O destruction is accompanied by Na depletion. On the contrary, in the case of very efficient 3d dredge-up, O is strongly enhanced after each TP, which undermines the ability of HBB to decrease the surface O abundance. Although Denissenkov & Herwig did not rule out that contamination by AGB stars is at the origin of the O-Na anticorrelation, they

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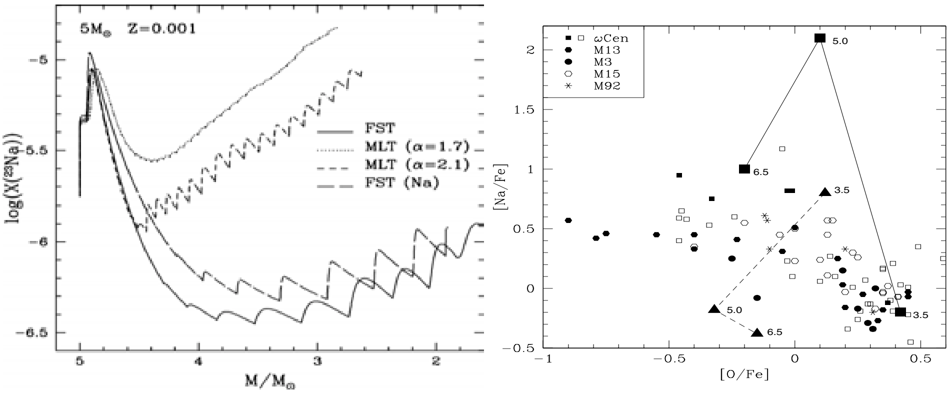

Figure 4. (left) Variation of the surface Na abundance with remaining stellar mass in models computed assuming the FST or the MLT prescriptions for convection (Fig. 12 of Ventura & D'Antona 2005a). (right) Observed data which define the O-Na anticorrelation in the stars of several GCs (see Weiss *et al.* 2000 for references). The yields by Ventura & D'Antona (2005b) and Fenner *et al.* (2004) for 3 stellar masses are indicated by the big black triangles and squares respectively.

underlined the fact that the required fine-tuning of the AGB model parameters casts some doubt on the robustness of this interpretation.

Ventura & D'Antona (2005a) investigated the impact of the treatment of convection on the theoretical yields (see also Renzini & Voli 1981; Sackmann & Boothroyd 1991; Blöcker & Schönberner 1991; D'Antona & Mazzitelli 1996). They showed how different the results can be according to the prescription adopted to determine the temperature gradient within the instability regions, namely the MLT (Mixing Length Theory) or the FST (Full Spectrum of Turbulence; Canuto & Mazzitelli 1991) convective models. In the case of the more efficient FST, the increase of the stellar luminosity and of the mass loss rates is much faster as the evolution proceeds than when MLT is considered. For a given stellar mass the FST model thus lives shorter (by a factor of ~ 3) because of the larger mass loss during the whole AGB evolution, and ejects almost all the envelope mass well before the stage where 3d dredge-up can operate significantly. From the chemical point of view (see Fig. 4) the FST model achieves the largest O depletion, but the Na content also decreases. Conversely in the MLT model which experiences more 3d dredge-up episodes, the depletion of O is modest (only a factor of ~ 2) while the increase of Na is large because of fresh ^{22}Ne carried out during the 3d dredge-up episodes and latter converted into Na.

The right panel of Fig. 4 compares the predictions of Ventura & D'Antona (2005b) with those of Fenner *et al.* (2004) in the plane of O vs Na abundances. These sets of models differ mainly by the convection treatment. Within Fenner's models the extremely large (primary) Na production for the most massive stars is due to the burning of the ^{22}Ne dredged-up from the inner helium layers. In terms of self-enrichment scenario, these models produce too much Na, in great excess with the range observed in GC stars. Ventura & D'Antona models have the opposite problem : They destroy too much Na. In any case, both sets are unable to reproduce the data.

Additional processes may have an important impact on the stellar nucleosynthesis and yields. Rotation for example is known to play a crucial role in many parts of the Herzsprung-Diagram (see Maeder & Meynet 2000 and references therein). We have thus investigated the influence of rotation-induced mixing on the yields of low-metallicity massive AGB stars (see Decressin & Charbonnel, these proceedings). We followed simultaneously the transport of angular momentum and of the chemicals since the zero age main sequence up to the AGB phase using the theory of Zahn (1992) and Maeder & Zahn (1998). It turns out that during central He-burning primary ^{16}O diffuses from the core and is latter carried to the surface in large quantities during the 2d dredge-up. At the end of this phase the surface abundance of ^{16}O is increased by almost 3 dex in a rotating model of initial 7 $M_\odot$ with Z=10^{-5} (see Fig. 1 of Decressin & Charbonnel, these proceedings). Such a huge enhancement can not be erased by HBB latter on the TP-AGB phase. The resulting predicted correlation between O and Na leads us to conclude that massive rotating AGB stars have to be discarded as responsible for the anomalies observed in GC stars.

3.2. *Can AGB stars shape the Mg-Al anticorrelation?*

The recent papers quoted above also considered the shaping of the Mg-Al anticorrelation by AGB stars. Denissenkov & Herwig (2003) discussed in particular the predictions for the magnesium isotopes and showed that at the temperatures that allow strong ^{16}O depletion (i.e., $\sim 10^8$K), ^{24}Mg is depleted even more in favour of (secondary) ^{25}Mg and ^{26}Mg. They claim that this is a robust result in view of the uncertainties on the ratio of the reaction rates of ^{24}Mg(p,γ)^{25}Al and ^{16}O(p,γ)^{17}F given by NACRE (Angulo *et al.* 1999), and also because there is no significant source of ^{24}Mg in AGB stars (^{23}Na(p,γ)^{24}Mg in HBB is insignificant). According to their predictions, the GC turnoff stars with the strongest O depletion should have ^{24}Mg depleted and ^{25}Mg enhanced by more than 1 dex, and their Mg isotopic ratios should be ^{24}Mg:^{25}Mg:^{26}Mg = 13:71:16 (assuming an initial ^{24}Mg:^{25}Mg:^{26}Mg = 90:4.5:5.0).

This is in contradiction with the analysis by Yong *et al.* (2003) in NGC 6752 where the most contaminated (i.e. O-depleted) stars exhibit ^{24}Mg:^{25}Mg:^{26}Mg = 60:10:30, i.e. a ^{24}Mg-dominated isotopic ratio, the second most abundant isotope being ^{26}Mg instead of ^{25}Mg. In this GC the normal stars have ^{24}Mg:^{25}Mg:^{26}Mg = 80:10:10.

This disagreement between the HBB predictions and the observations is shared by all the current low-metallicity AGB models. Ventura & D'Antona (2005a,b)DA05b do encounter the same difficulty for both their MLT and FST models.

Denissenkov & Herwig (2003) proposed two ways to remove this disagreement. The first one rests on a nuclear solution according to which the ratio of the reaction rates of ^{24}Mg(p,γ)^{25}Al and ^{16}O(p,γ)^{17}F at T of the order of 10^8 K would be much lower than the value advocated by Angulo *et al.* (1999), and the reaction ^{25}Mg(p,γ)^{26}Al would be faster. The second one calls for a reduction of the HBB temperature below 10^8 K in the massive metal-poor AGBs. In this case however, both the ^{24}Mg and ^{16}O destruction would be supressed while ^{25}Mg could still be importantly produced. This alternative would require then a modification of the primordial scenario where RGB stars slightly more massive than the present-day turnoff stars might have contributed to the abundance variations (see Denissenkov *et al.* 1999; Denissenkov & Weiss 2001).

Fenner *et al.* (2004) have tested the AGB pollution scenario by constructing a chemical evolution model of the GC NGC 6752 using a two-stage formation schema similar to that proposed by Parmentier *et al.* (1999). Their prediction for the behaviour of Mg and Al is shown in Fig. 5 (left panel). In stark contrast with the observations, the total Mg abundance (full line) increases with increasing Al. This is due to the enhanced abundance of the heaviest Mg isotopes (dashed and dot-dashed lines) which are produced primarily in the He-burning shell of intermediate mass AGB stars. The slight depletion of ^{24}Mg (dotted line) is due to HBB in more massive stars. The discrepancy between data and theory can not be resolved by any choice of the IMF, since none of the yields of individual stars (diamonds) are depleted in total Mg.

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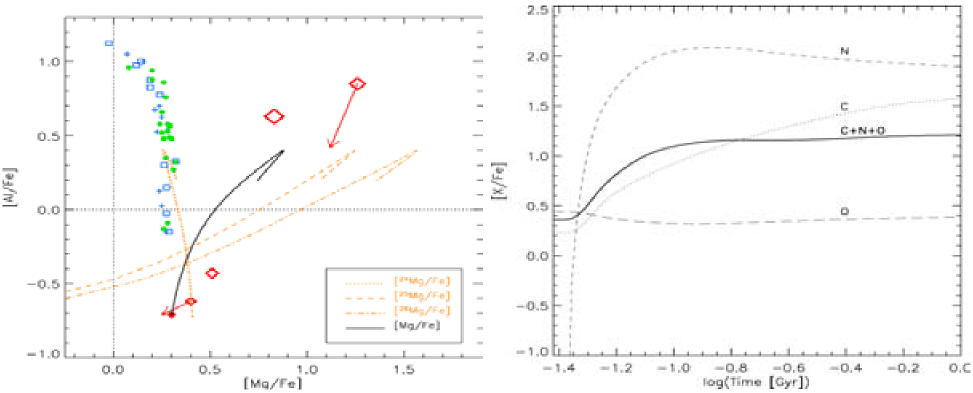

Figure 5. (left) Predicted trend of [Al/Fe] versus [Mg/Fe] (thick curve) in the chemical evolution model of NGC 6752 shown against observational data in this GC. Diamonds correspond to yields of stars with masses between 1.25 and 6.5 $M_\odot$. The evolution of [^{24}Mg/Fe], [^{25}Mg/Fe] and [^{26}Mg/Fe] are shown by dotted, dahed, and dot-dashed lines respectively. (right) Temporal evolution of [C/Fe], [N/Fe], [O/Fe] and [(C+N+O)/Fe] in the same chemical evolution model. Taken from Fenner *et al.* (2004).

3.3. *What about the C+N+O constancy?*

Maybe one of the strongest arguments against AGB stars is the case of the sum of C+N+O. Although there are still very few stars and clusters where this quantity has been determined, the available data show a constant value of C+N+O in the CN-strong and CN-weak stars (Dickens *et al.* 1991; Smith *et al.* 1996; Ivans *et al.* 1999 ; Smith *et al.* 2005). This constancy severely limits the addition of any primary ^{12}C from ^{4}He-burning and

In their self-consistent calculation of NGC 6752, Fenner *et al.* (2004) studied the temporal evolution of [(C+N+O)/Fe], as shown in Fig. 5 (right panel). They find that this quantity increases very rapidly with respect to its initial value (by almost 1 dex within 1Gyr of formation). The slight drop in O is more than compensated by a dramatic increase of N first (from HBB stars) and then from C (from dredge-up in lower mass stars without HBB). Within the MLT framework, Ventura & D'Antona (2005a,b) confirm the findings of Fenner *et al.* (2004). However their FST models in the range 3.5–4.5 $M_\odot$ keep the C+N+O sum almost constant. This is due to the fact that in these models the addition of helium-burning products into the AGB star ejecta by the 3d dredge-up is considerably reduced compared to the MLT-case, as discussed in § 3.1. This confirms the previous indications that a generation of AGB stars which experience HBB but almost no dredge-up would tend to fit some of the data better.

3.4. *Clues from fluorine and lithium abundance variations*

Smith *et al.* (2005; see Smith, these proceedings) presented the first evidence for ^{19}F abundance variations in the GC M4, these variations being correlated with O variations and anti-correlated with the Na and Al variations. This has important implications for the determination of the mass range of the polluting stars because the predicted fluorine yields strongly depend on the stellar mass : Stars with initial masses less than about 3.5 $M_\odot$ are net producers of fluorine during the AGB evolution (Forestini *et al.* 1992; Forestini & Charbonnel 1997) while more massive objects do destroy this element. The stars in the lower mass range can thus be ruled out as significant polluters of a cluster such as M4.

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The Li dispersion among GC stars could in principle bring additional clues in the present context. Until very recently, Li abundances in turnoff stars have been reported only in two GCs, namely NGC 6397 (Pasquini & Molaro 1996; Thévenin *et al.* 2001; Bonifacio *et al.* 2002) and M92 (Boesgaard *et al.* 1998; Bonifacio 2002). In NGC 6397 no intrinsic Li scatter could be detected, and the turnoff stars share the same Li as their halo counterparts (Charbonnel & Primas 2005). Better observations with higher S/N ratios are still awaited to derive definitive conclusions on the intrinsic dispersion in M92. Pasquini *et al.* (2005; see Pasquini, these proceedings) have just discovered that in NGC 6752 turnoff stars the Li abundance anticorrelates with Na and N, and correlates with O. Since Li is a very fragile element which burns at temperatures much lower than those where the CNO-cycle and NeNa-chains are activated, its presence in the most polluted GC turnoff stars implies that some Li has been produced by the polluter stars we are looking for. This is qualitatively in agreement with the predictions of Li production in AGB models by the Cameron & Fowler (1971) mechanism (Sackmann & Boothroyd 1992). Whether this is quantitatively realistic remains to be computed.

3.5. *He enrichment*

There is at least one prediction on which all the current models agree : Intermediate-mass stars should strongly enrich the medium in He, mainly through the 2d dredge-up contribution (the production during the TP-AGB phase being neglibible). D'Antona *et al.* (2002) modelled the stellar evolution of cluster stars by taking into account this possible He enrichment with respect to the primordial value. They showed that the impact on the main sequence, turnoff and RGB would be small and undetectable observationally. Also, the horizontal branch luminosity appears to be only slightly affected. As a consequence the age determination should be affected only in a limited way. However the differences on the morphology of the horizontal branch would be noticeable so that He enrichment could play a role in the formation of blue tails in the GCs which show strong CNO abundance variations.

D'Antona & Caloi (2004) further investigated the implications of the hypothesis that GC stars were born in two separate events, a first generation including the high- and intermediate-mass stars and a fraction of the low-mass stars that we are currently observing, and a second generation in which stars formed from the ejecta of the AGB stars of the first generation. They showed that this scenario provides an interpretation to the dichotomy of the horizontal branch of NGC 2808. It requires however a special and flat IMF up to $\sim$ 4–7 $M_\odot$ (i.e., many more AGB stars than predicted by a classical IMF similar to that inferred from many stellar environments). Such a difficulty could be alleviated by taking into account some dynamical effects (for example, many first generation low-mass stars could have been lost). Supporting evidence for the presence of helium-rich populations in GCs were recently obtained through the detailed analysis of various color-magnitude diagram features (e.g., Lee *et al.* 2005 and references therein). Whether only AGB stars could produce the required He enrichment remains to be discussed.

4. Conclusions

The presence of variations in the abundances of C, N, O, Na, Mg and Al in GC turnoff stars has recently provided compelling evidence for these chemical anomalies already being in place in the intracluster gas from which the present stars formed.

AGB stars have long been suspected as the possible culprits within the so-called primordial scenario. Several custom-made detailed AGB models were recently computed in order to test this attractive hypothesis. Most of these studies have underlined serious

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difficulties encoutered by the AGB pollution scenario: (i) O is not depleted to the extent required by the observations while Na is over-produced; (ii) Mg is produced while it should be destroyed, and the Mg isotopic ratio is in conflict with the (rare) available data; (iii) C+N+O does not remain constant in AGB processed material. On the other hand the models using an alternative treatment for convection can overcome some of the problems related to the dredge-up of the helium-burning products, but they are far from reproducing quantitatively all the observed abundance spreads. One of the most stingent constraint for the models is the Mg isotopic ratio; however its determination is extremely challenging and has thus been obtained only in very rare stars in only one GC. Additional data are thus urgently needed.

As we have tried to underline, the predictive power of the current AGB models is still embedded in considerable difficulties related to the modelling uncertainties of crucial physical mechanisms (HBB, 3d dredge-up, convection, rotation, mass loss, ...) and maybe to nuclear physics. The effect of rotation on the abundance variation of O already during the 2d dredge-up appears to be dramatic and, if confirmed, would certainly kill the AGB pollution scenario.

The most optimistic AGB supporters would however claim that the parameter space has not yet been fully explored, and that it is too early to discard the AGB hypothesis. It is clear that the complexity of the physical phenomena at act certainly requires deeper insight. We might be at a stage where the GC data can severely constrain evolutionary models. It could well be also that we have to think about other possible stellar culprits.

Beside these difficulties, other questions have to be seriously investigated: Why is the material so poorly mixed within the cluster? Why is there a second burst of star formation? Etc. The whole problem certainly requires a complex solution that necessitates a detailed study of the history of star formation, element production, dynamical evolution, and their interactions.

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