Mem. S.A.It. Vol. 77, 852

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AGB evolution in the early globular clusters

Hints from the observations on the model parameters

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Abstract. Although abundance inhomogeneities in Globular Clusters are commonly believed to derive from self–enrichment from the matter lost by massive Asymptotic Giant Branch stars (AGBs) in the early cluster lifetime, there is still no consensus on the ability of the nucleosynthesis occurring in these stars to reproduce the observed chemical anomalies. We summarize the status of the art scenario, for what concerns the abundances of helium, lithium, CNO and sodium.

Key words. Abundances in Globular Cluster stars – AGB models – self–pollution

1. Introduction

Abundance variations in the light elements susceptible to changes due to proton capture, such as the pp, CN, ON, NeNa and MgAl cycles are known to be present in globular cluster stars since the 1970s. In the years 2000, new spectroscopic observations have confirmed that these variations are present also in unevolved (turnoff) or scarcely evolved (subgiant) stars, where they can not be attributed to in situ mechanisms. Self-enrichment of some kind is required. Asymptotic Giant Branch stars (AGBs) are the most promising candidates. In the 70s two main self-pollution scenarios had been considered: 1) primordial pollution of the gas (Cottrell & Da Costa 1981); 2) accretion of matter on stars (D'Antona, Gratton, & Chieffi 1983). The winning model of the latest years is that there is a second stage of star formation directly from the gas lost by massive AGBs (proposal first published in D'Antona et al. (2002), see also D'Antona (2003)).

The hint suggested in D'Antona et al. (2002) came from understanding that the horizontal branch morphology in Globular Clusters could be influenced by different helium content in the evolving stars. This ruled out the accretion model, as accretion would affect only the external layers of the star. In the cluster model considering a second stellar generation, there is a problem with the mass budget: we need in some clusters half stars belonging to the first stellar generation and half with chemical anomalies: the initial mass function (IMF) must be heavily biased towards the intermediate mass stars (D'Antona & Caloi 2004). The lifetime of intermediate mass AGBs is of $\sim 10^8$ yr, too long for the initial gas to remain in the cluster, and this rules out the primordial pollution of the remaining gas of the first stellar generation.

In this talk we summarize the problem of the helium signature, and the results of our latest models concerning the Carbon, Nitrogen, Oxygen, Sodium and Lithium abundances. The emerging picture is conforting for the self–enrichment model.

2. Helium

It has long been known that helium is enhanced in the matter lost from massive AGBs, due to the action of the second –and also possibly of the third dredge-up. Ventura et al. (2001); Ventura, D'Antona, & Mazzitelli (2002) remarked the concomitance of helium enrichment and the other chemical anomalies. Although it is difficult or impossible to measure small helium content variations spectroscopically (but see Carretta et al. (2006)), a higher helium in the whole star leaves a powerful evolutionary signature in the HR diagrams, as the evolving mass is a function of age, metallicity, *and* Y! For a given age, the evolving M is smaller for larger Y. E.g., the mass is reduced by $\sim 0.05 M_{\odot}$ for an increase in helium by 0.04. This mass difference is important for the $T_{\rm eff}$ distribution on the HB, as first proposed by Norris, Cottrell, Freeman, & Da Costa (1981). In fact, if the same mechanism of mass loss operates on the "standard Y" and on the "enhanced Y" stars along the giant branch and at the helium flash, the final mass in HB will be several hundredths of solar mass smaller, and therefore will have a *bluer* location. This has been remarked by D'Antona et al. (2002), who show that a population of stars having enhanced Y *from the start* (that is, from the main sequence) can explain the existence of extended blue tails in the HB of some clusters, like NGC 6752 or M13, whose red giants show the mentioned huge Oxygen spreads.

We can list a collection of signals of helium enhancement in GCs:

1. Bimodal horizontal branches (e.g. NGC 2808; D'Antona & Caloi 2004);
2. Extreme blue tails (e.g. NGC 6752, D'Antona et al. 2002);
3. Double main sequences (ωCen -see Norris 2004; D'Antona et al. 2005 for NGC2808);
4. Morphology (M3 vs M13 Johnson & Bolte 1998, Caloi & D'Antona (2005))
5. Red giant bump luminosity relative to turnoff luminosity (Caloi & D'Antona 2005)

For sure the best prediction of the model is that we must in many cases expect a bimodality in the HB, and also a "gap in helium content". The reasoning behind this is quite simple: the helium abundance in the AGB ejecta *decreases* with time, as smaller masses evolve, in which the influence of the second dredge up has been smaller (Ventura et al. 2001), it is well possible that the second star formation epoch ends when the helium abundance in the latest forming stars is still higher than the primordial helium from which the first stellar generation formed. E.g., if the star formation ends with the evolution of stars of $3.8 M_{\odot}$, which have a helium content in the ejecta of 0.26–0.27 (according to the metallicity, (e.g. Ventura, D'Antona, & Mazzitelli 2002)), there will be a 'helium gap' of $\sim 0.015 - 0.025$ in mass fraction, if the cluster started with the Big Bang helium (Y=0.245). Thus the "bimodality" of the HB should be normal in all clusters in which there are chemical anomalies, even if they are very evident mainly in the clusters for which the "helium gap" coincides with an evident lack of stars is some regions of the HB, e.g. at the RR Lyr region, like in NGC 2808 (Bedin et al. 2000) and NGC 1851 (Sosin et al. 1997). The helium spread, although not altering in a significant way the absolute luminosity of the RR Lyrae in clusters in which there is a consistent "first generation" population (D'Antona et al. 2002) produces, in the particular case of NGC 2808, the small but noticeable difference in luminosity between the cool side of the blue HB and the hot side of the red HB (Bedin et al. 2000), which, so far, had not been consistently explained. There are other clusters showing a marked bimodality, such as the metal rich ones NGC 6388 and NGC 6441 (Rich et al. 1997). The metallicity of NGC 6441 is quite large ([Fe/H]$\simeq -0.7$, Clementini et al. 2005) and is not consistent with the very long periods of the RRab variables (Pritzl, Smith, Catelan, & Sweigart 2000) in these two clusters. The marked slope of the horizontal part of the HB in both NGC 6388 and NGC 6441 (the bluer stars being more luminous), can be attributed to the same self–enrichment mechanism which we have described here: a fraction of the stars in these clusters belongs to a "second generation" with much larger helium content, and the luminosity increases with $T_{\rm eff}$ because of the larger helium abundance. This may also explain the long pulsation periods.

Thus, if helium is a clue to understand GC chemical anomalies, we derive the following information, on which we should fund a global interpretation:

1) The formation of GCs has two (or more) main stages of star formation independently of Z.

2) The number ratio of the first generation stars (normal helium and no chemical anomalies) to those born from AGB ejecta varies from cluster to cluster and is probably related to the IMF and dynamics.

3) BUT the chemistry of the stars with chemical anomalies MUST be consistent with our AGB modeling at least for some of our intermediate mass star models (NOT necessarily with all).

These are today some key questions on HB morphologies vs AGB models:

1. Is there a helium gap in all HBs? (it gives range of mass of AGB progenitors, if we know Y(Mprog) well);
2. Are there any clusters in which the first generation has disappeared? (M13 vs. M3? see also NGC 6397);
3. Do we have bursts of star formation or some kind of continuous star formation in the 2nd generation? (is the AGB matter collected for a timescale long enough that different AGB masses contribute to the global helium content of the burst?)

A possible controversial hint is the presence of a "Blue Main Sequence" in NGC 2808 which followed the discovery of the double MS in ωCen (Bedin et al. 2004), in which the blue MS can be interpreted as an Y rich sequence (Norris 2004), thanks also to the spectroscopic information (Piotto et al. 2005). The color distribution of the MS in NGC2808 requires 15-20% of stars with Y$\sim$0.40. To explain at the same time the MS and the HB, we need at least three main populations: one with "normal" helium, one with intermediate helium and a last one with Y=0.40. Carretta et al. 2006 find three different classes of objects in O-Na anticorrelation. They find a small spread in [Fe/H] in the subgiants of NGC 2808, with those having higher oxygen having smaller [Fe/H]: they interpret this feature by proposing that the higher oxygen group has smaller helium content.

So there is a first problem: are we able to explain the presence of 15-20% of stars with a helium abundance Y$\sim$0.40? Actually *the AGB models do not predict helium abundances up to 0.4*: there are several possible interpretations:

- Models are wrong: there is more *third* dredge up, and so more helium?
- Models are wrong: there is a higher *second* dredge up?
- the interpretation of the MS is wrong: wrong data or data reduction?
- the relation between MS colors and Y is wrong?
- These 15-20% stars are NOT descendants of AGBs?

Some issues are attacked in D'Antona et al. (2005), but it is important to remark at once that the first possibility is very simply ruled out, if higher Y is related to third dredge up: the almost constant CNO in the GC stars (Ivans et al. 1999; Briley et al. 2002, 2004; Cohen & Meléndez 2005; Cohen et al. 2005), in spite of chemical anomalies, indicates that the third dredge up has not much space to operate.

3. The AGB models for Population II

Let us now go on with the analysis of models and GC chemical anomalies. Certainly, there are still problems in the global quantitative scenario, but a big step forward has been made in these years, so that we suggest that the global dismiss of the AGB self enrichment made on the basis of some model results should be definitely abandoned. We refer, e.g., to the discus-

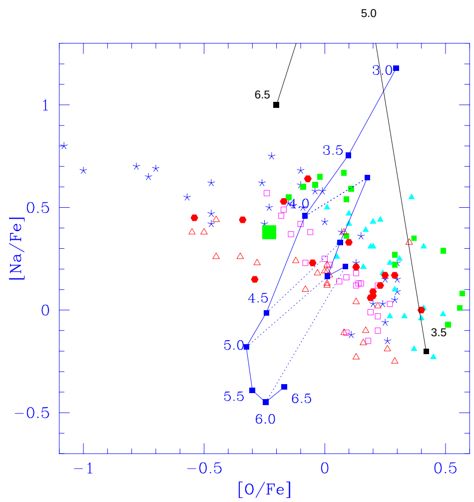

Fig. 1. The Na-O anticorrelation from several data sets is shown with the results of the models by Ventura, D'Antona, & Mazzitelli (2002) for two mass loss rates (lower curves) and by Fenner et al. (2004) (upper line). The big (green) square in the center is the model of $5M_{\odot}$ by Ventura & D'Antona (2005b) with extramixing.

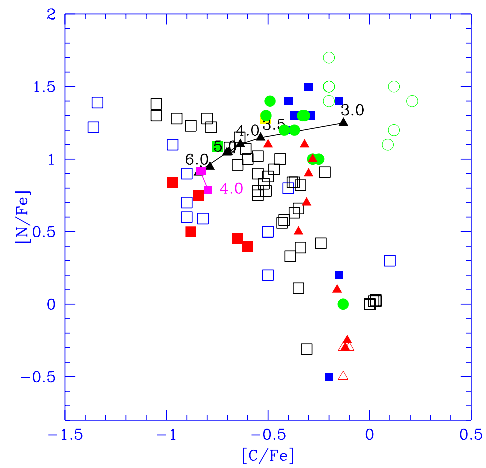

Fig. 2. The C-N anticorrelation is shown by plotting data by Cohen, Briley & Stetson (2002) and Cohen & Meléndez (2005)(open squares); other data are from Carretta et al. (2005) (green dots, red and blue squares), plus the models by Ventura, D'Antona, & Mazzitelli (2002).

sions in Lattanzio (2003); Fenner et al. (2004); Herwig (2004). This latter paper concludes that "the notion that massive AGB stars are the origin of the O–Na abundance anticorrelation in globular cluster giants is not consistent with the model predictions of this study", so he refers to his own studies, but observers may be led to understand that these studies are to be taken seriously. This would be reasonable if we had not repeatedly shown that most problems in the AGB self–enrichment scenario are present only in the computations which rest on MLT standard stellar models of low convective efficiency. In these models, the HBB temperatures are not large enough to allow efficient ON cycling. The recent models by Fenner et al. (2004), who indeed take care of developping an entire chemical evolution model, fail to reproduce the O–Na anticorrelation and most of the other chemical anomalies, due to this choice of convection modelling. This has been shown in detail by Ventura & D'Antona (2005a) and by Ventura in these Proceedings: by tradition, our group adopts the Full Spectrum of Turbulence (FST) model by Canuto, Goldman, & Mazzitelli (1996), whose high efficiency allows strong ON cycling. The modelization of the nuclear yields is enormously dependent on the efficiency of the adopted convection model and, indirectly, on the efficiency of mass loss. Some problems of other modellers, e.g. the high increase in the CNO total abundances, which *is not* found in the observations, is in fact due to the high number of third dredge up episodes, due to the comparatively low lumi-

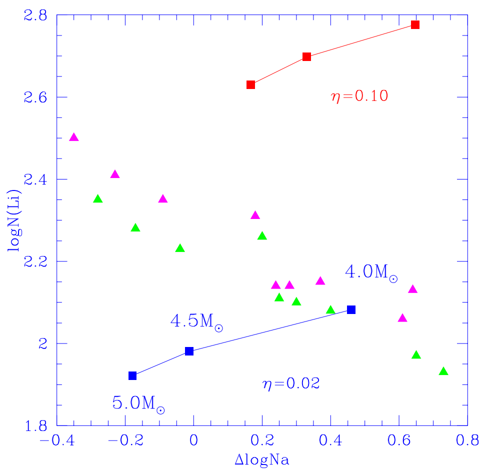

Fig. 3. Na-Li anticorrelation from the data by Pasquini et al. (2005) for the cluster NGC 6752. The models are by Ventura, D'Antona, & Mazzitelli (2002), for standard mass loss (lower curve) and high mass loss (upper curve). The $5M_{\odot}$model by Ventura & D'Antona (2005b) would fall close to the lowest observed data.

nosity of the models with respect to the luminosity of the FST models. So please stop making "full evolutionary" scenarios of chemical evolution based on models which do not predict the correct CNO abundances: we already know that these attempts can not lead anywhere.

In spite of the improvement of using very efficient convection, our most recent models (Ventura, D'Antona, & Mazzitelli 2002; Ventura & D'Antona 2005a) reproduce in a satisfactory way the O–Na anticorrelation only for a limited range of masses (3.5 - $4.5M_{\odot}$, see Figure 1). Only recently Ventura & D'Antona (2005b) have shown that the introduction of *a very small amount of overshooting below the formal convection zone can help in bringing the sodium abundance of the $5M_{\odot}$ model in agreement with the O–Na anticorrelation*. The new sodium vs. oxygen yield of the $5M_{\odot}$ is shown as a big (green) square in Figure 1. There are two dangers with overshooting: 1) we must not dredge up too much Oxygen, and 2) we must not dredge up too much CNO. Notice that there is a big difference between the two "parameters" linked to convection: a *high efficiency of convection* is physically plausible, and it provides straigthforward agreement with many observational data; on the contrary, *extramixing* is a totally arbitrary parameter, as its relation with the physical structure is not known. So we feel we must still investigate about other possibilities to explain all the chemical anomalies. In Figure 2 we show the good agreement of our models with the Carbon – Nitrogen anticorrelation. In Figure 3 we show the Lithium vs. Sodium anticorrelation by Pasquini et al. (2005) for the stars of NGC 6752 and the results by Ventura, D'Antona, & Mazzitelli (2002) for a "standard" mass loss (η = 0.02), and for a mass loss increased by a factor 5 (η = 0.1). Notice that the stars at log N(Li) 2.2-2.4 are the "normal" first generation stars, with low sodium and Big Bang (or close to Big Bang) lithium. The standard $4M_{\odot}$ model reproduces quite well the polluted stars, and the new $5M_{\odot}$ with extramixing now is placed in the same region of the $4M_{\odot}$. From this plot we understand clearly that lithium in the stars with chemical anomalies is a powerful indicator of the mass loss efficiency: in our models, the same calibration which provides constancy of CNO is also able to reproduce the lithium data, giving further consistency to the whole scenario.

Acknowledgements. We thank Inma Dominguez, Carlos Abia and the University of Granada for the organization of this successful meeting.

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