Mem. S.A.It. Vol. 75, 274
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Memorie della

Abundances in scarcely evolved stars in globular clusters

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Abstract. Abundances for stars on the main sequence and early subgiant branch (i.e. less evolved than the Red Giant Branch Bump) in globular clusters are reviewed. Emphasis is given to those elements that are involved in the Na-O and Mg-Al anticorrelations. Results obtained in the last few years clarified that very deep mixing (if any) cannot be the only cause of the abundance anomalies found in globular cluster stars. The new scenarios, calling for pollution by material processed in an earlier generation of stars, are briefly presented; the issues related to the lithium abundances are briefly commented.

Key words. Globular clusters: general – Stars: abundances – Stars: evolution

1. Introduction

Star-to-star inhomogeneities in globular clusters have challanged astronomers for over thirty years, since their very first discovery in the early '70s (Osborne 1971). Leaving aside the peculiar case of ω Cen, they generally concern only a few (mostly light) elements, while clusters turned out to be very homogeneous insofar e.g. Fe-peak elements are concerned. Since these early epochs, a quite large bulk of observations has accumulated, suggesting links between the presence and extent of these inhomogeneities with other basic properties of globular clusters (eccentricity, luminosity, colour of the horizontal branch, etc.), although most of these correlations are still controversial. Early studies concentrated on the strong bands of CH and CN in the violet and blue spectra of giant stars, observable at low dispersion, and even photometrically if suitable band systems were used (e.g. the DDO system). Once the different temperature and luminosity of the stars were properly taken into account, the strengths of these bands were found to be anticorrelated by several authors. One of the most important achievement concerned the discovery that the distribution of band strengths is often bimodal (e.g. in the case of NGC6752: Norris et al. 1981). Furthermore, a general trend for decreasing C and increasing N abundances with luminosity emerged, albeit with a rather large scatter (Carbon et al. 1982; Langer et al. 1986). A review of these early results was given by Smith (1987).

The advent of high spectral resolution in the late '70s brought the possibility to observe more elements, shedding new light.

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Star-to-star variations of the strengths of the lines of O, Na, Mg, and Al were noticed quite soon (Peterson 1980). However, a more clear picture, clarifying that star-to-star variations were indeed present in the vast majority of the clusters, and that they were quantitatively much larger than systematic average cluster-to-cluster variations in the abundance ratios, was only possible with the basic extensive systematic surveys made mainly by the Lick-Texas group in the late '80s and '90s (for a review of early results of this group, see Kraft 1994). The most important observation concerned the discovery of a well defined anticorrelation between the abundances of O and Na; a similar anticorrelation was found between the abundances of Mg and Al.

2. Proton captures, deep mixing and AGB stars

A basic progress in our understanding of this phenomenon was the recognition that the first of these anticorrelations actually occurs due to a coincidence: at a similar temperature (typically $\sim 20\,10^6$ K), proton captures on both ^{16}O and ^{22}Ne cause the depletion of O and the cumulation of freshly produced ^{23}Na (Denisenkov & Denisenkova 1990). The Mg-Al anticorrelation is due to a sequence of proton captures (followed by β decays) that progressively transforms ^{24}Mg into ^{25}Mg, ^{26}Mg, and finally ^{27}Al (Langer & Hoffman 1995); given the larger Coulomb-barrier of Mg, this chain is only effective at rather high temperatures ($> 70\,10^6$ K).

Although the basic physical mechanism was now known, the astrophysical site for it was still not unambiguously established. Most astronomers in the field favoured some sort of very deep mixing, bringing up to the surface material processed through CNO cycle at high temperatures from the H-burning shell of red giants. The arguments favouring this interpretation were mainly based on the general decrease/increase of C/N abundances with luminosity on the red giant branch, which was not predicted by standard non-rotating models. Alternative hypotheses of external pollution or of a second generation of stars, formed from material processed in now defunct intermediate mass stars during their AGB phase, however, could not be ruled out. Massive AGB stars are promising candidate for pollution because they experience hot bottom burning, precisely the physical mechanism apt to produce the observed abundance pattern; and have strong, low velocity winds, likely not enough energetic to escape the cluster potential well. However, it was soon acknowledged that a strong limitations to the mass range for these intermediate mass stars was posed by the observation that the abundances of the n-capture elements (usually produced in thermally pulsing AGB stars) were not correlated with that of Na (Armosky et al. 1994; James et al. 2003).

However, only in the most recent years, with the spectacular instrument progresses represented by the availability of efficient high resolution spectrographs on 8-10 m class telescopes, the overall scenario of these inhomogeneities is slowly becoming more clear. In fact, these new instruments allowed for the first time a systematic spectroscopic exploration of faint stars in globular clusters.

Faint, scarcely evolved stars, hereinafter small mass stars that have not yet reached the red-giant branch bump, play in fact a basic rôle in our understandings of the physical pocesses that lead to inhomogeneities in globular clusters. For brighter stars there is no fundamental physical obstacle to very deep mixing episodes. For this reason, interpretation of the observed star-to-star inhomogeneities remain ambiguous: they can be either due to nuclear processing within the same star where anomalous abundances are observed, or to some form of pollution from material coming from stars other than those observed. On the other side, for less evolved stars the molecular weight barrier created by the maximum inward penetration of the outer convective region (when the stars was at the base of the red giant branch) forbids any deep mixing. In these conditions, abundances for only a few elements (Li, ^{12}C, ^{13}C, N) can be significantly altered by mixing mechanisms (Sweigart & Mengel 1979; Charbonnel 1994).

3. Field stars

While the observational scenario of mid '90s for cluster stars was still confused, these theoretical predictions were beautifully confirmed by observations of field stars in a reference paper by Gratton et al. (2000). In order to provide a guide in the then somewhat confused scenario, these authors considered observations of a selected sample of metal-poor stars in a restricted abundance range (ensuring that they roughly had the same mass, age, and chemical composition), with well determined absolute magnitude either from parallaxes or from Strömgren photometry (ensuring they had both accurately determined atmospheric parameters and reliable evolutionary phase), over the whole evolutionary path from main sequence to the asymptotic giant branch. Care was taken to observe significant samples of stars in all crucial evolutionary phases. High quality observations were obtained for the most relevant elements (Li, C, N, O, and Na), as well as the ^{12}C/^{13}C isotopic ratio. While the results obtained did not contrast with previous observations, they represented a clear progress on the observational side.

The main results of this paper are shown in Fig. 1. They are in amazing qualitative and quantitative agreement with theoretical predictions, and unequivocally show that along the evolution of field small mass stars (roughly, increasing luminosities), surface abundances are modified only in two main episodes: the earliest one is the first dredge-up, first identified by Iben (1965). This occurs at the base of the red giant branch, when the outer convective envelope penetrates inward, into regions where some nuclear burning has occurred during the previous main sequence phase. The effects of the first dredge-up are a small decrease of the abundance of ^{12}C, and an increase of ^{13}C and ^{14}N. The expansion of the outer convective envelope also causes a dilution of the Li survived only in the outer (cool) regions of the main sequence progenitor. The second mixing phase occurs after the red giant branch bump. It is worth noting that the abundances of O and Na are not modified over all these phases.

4. The triumph of the primordial hypothesis

The obvious next step was to repeat a similar study for globular clusters. This was now possible thanks to the availability of UVES at VLT2. Observations of scarcely evolved stars in globular cluster was the subject of an ESO Large Program by Gratton et al. (2001). Two groups of stars, one at the turn-off, and the other at the base of the red giant branch, were selected for observations in the three closest clusters (NGC6397, NGC6752, and 47 Tuc; M4 was excluded due to its differential reddening). Gratton et al. observations of stars in NGC 6752 showed that the O-Na anticorrelation is present among stars of all evolutionary phases, including those near the main sequence turn-off (see Fig. 2). As noticed by these authors, the temperature at even the very center of these stars is not hot enough for any significant proton capture on ^{16}O or ^{22}Ne. A similar result was later obtained for other clusters too, in part by the same group (47 Tuc: Carretta et al. 2003a; NGC 6397 and M55: Carretta et al. 2003b), and in part by others (M71: Ramirez & Cohen 2002; M5: Ramirez & Cohen 2003). Practically, the O-Na anticorrelation (that is completely absent among field stars) has been found among turn-off and early subgiants in all globular clusters surveyed insofar. Gratton et al. (2001) also found hints for a Mg-Al anticorrelation in early subgiants of NGC 6752. These observations clearly tell us that the proton captures responsible for the O-Na anticorrela-

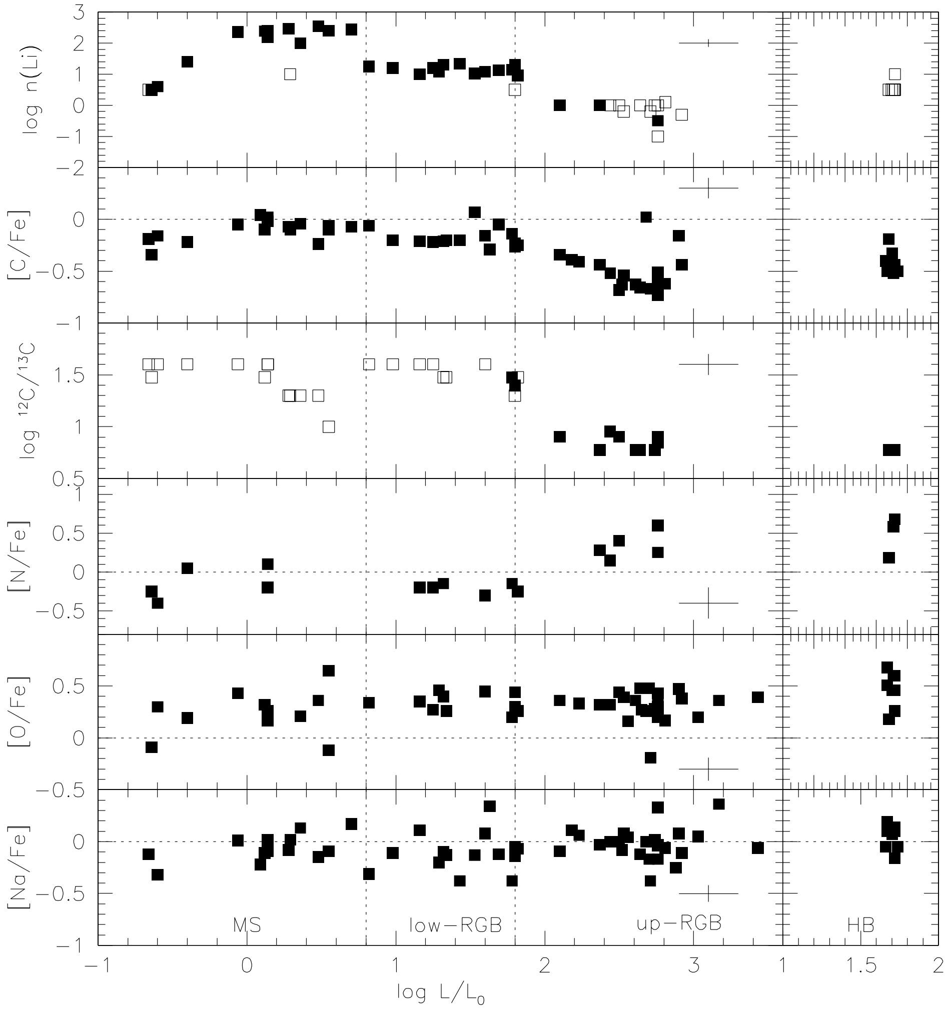

Fig. 1. Runs of the abundance of Li, of the abundance ratios [C/Fe], [N/Fe], [O/Fe], and [Na/Fe], and of the isotopic ratio ^{12}C/^{13}C with luminosity for stars with $-2 <$[Fe/H]< -1. Filled symbols are actual measures; arrows are upper (for Li) or lower (for ^{12}C/^{13}C) limits. Typical error bars for the various quantities are shown. Dashed lines separate various evolutionary phases (Main Sequence and Turn-Off stars; red giant branch stars below the bump; red giant branch stars above the bump). Results for red horizontal branch stars are plotted separately for clarity (from Gratton et al. 2000)

tion did not occur in the stars where it was observed.

Using the new powerful instrumentation, observations of the strong CH and CN bands can now be extended to even fainter stars, well below the turn off point: various authors showed that a strong anticorrelation between CH and CN band strengths (that can be interpreted as evidence of an anticorrelation between C and N abundances) can be traced up to at least two magnitudes below the turn-off point in 47 Tuc (Briley et al. 1994; Cannon et al. 1998; Herbeck et al. 2003). These stars, with a

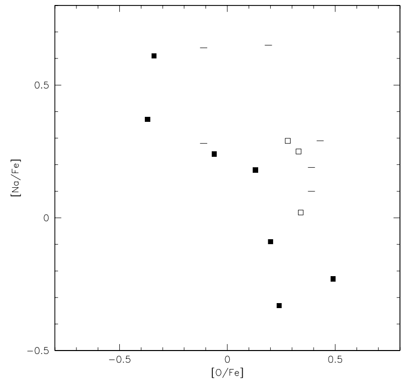

Fig. 2. Run of the abundances of Na and of O for stars in NGC 6752. Filled squares are turn-off stars, opens squares are subgiants, and lines represent upper limits (for O) (from Gratton et al. 2001)

mass of only 0.64 solar masses, are certainly too small for an efficient CN burning.

5. Deep Mixing but not Very Deep Mixing

There are two important things to be noticed. First, observations of stars in various evolutionary phases in NGC6752 (Gratton et al. 2001; Yong et al. 2003) show that the extent of the O-Na anticorrelation seems independent of the evolutionary phases. Second, the various mixing episodes found from observations of the field stars can be clearly traced also among globular cluster stars. Gratton et al. (2001) found clear indication for dilution of Li at the base of the red giant branch of various clusters, confirming the early result for NGC6397 by Castilho et al. (2000). Furthermore, various observations (Li in M71 and NGC6752 by Ramirez & Cohen 2002, and Grundahl et al. 2002 respectively; ^{12}C/^{13}C ratio in various clusters by Shetrone 2003) clearly indicate that the same deep mixing mechanism observed in field stars brighter than the red giant branch bump is also active in globular cluster stars.

On the other side, there is not any strong indication that the distribution of O and Na abundances change significantly at the red giant branch bump, indicating that they are involved in this deep mixing event. The definition of these distributions requires extensive observations, and has been insofar obtained for only a few clusters: the only two for which data are adequate are M13 (Pilachowski et al. 1996), and NGC2808 (Carretta et al. 2003c). Both clusters display an extended O-Na anticorrelation: in both cases some trend of abundances with luminosity seem to exist, but they are of opposite sign, so that this evidence cannot be considered as conclusive (see Fig.3). On the other side, data gathered for other clusters (M15 and M92: Sneden et al. 2000) are based on smaller samples: anyhow, they do not show any clear trend.

Summarizing, it is possible to conclude that the O-Na (and related) anticorrelation(s) is a phenomenon limited to globular clusters. The proton captures responsible for it did not occur on the stars that we currently observe. It is overposed to the normal (though not entirely canonical) mixing episodes typical of small mass stars: first dredge up, and further deep mixing after the red giant branch bump.

6. Primordial variations, not pollution on already formed stars

The stars enriched in Na (and depleted in O) are homogenous. This is indicated by two facts: (i) if the Na- and N-rich material would have been added to a preexisting star, we would expect different degrees of dilution of the enriched material when the outer convective envelope penetrates inward at the base of the subgiant branch (depending on the amount of polluting material), roughly canceling the clear anticorrelations existing e.g. between C and N. As noticed by Cohen et al. (2002), this is not the case. (ii) Since the outer convective envelope is much thinner for main sequence

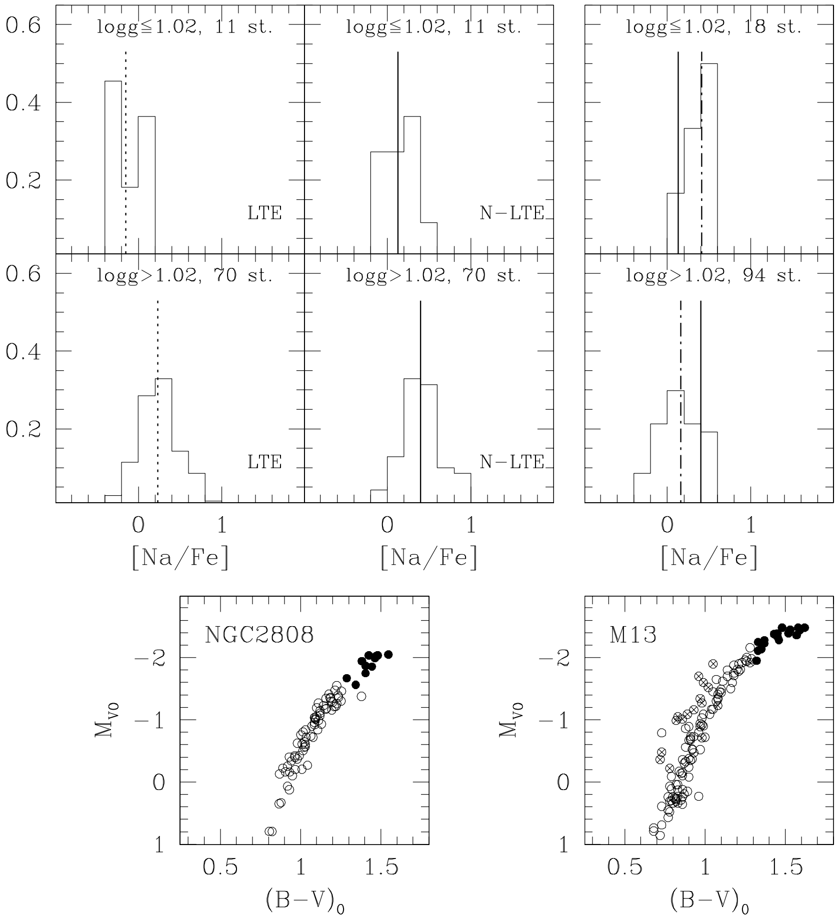

Fig. 3. Bottom panels: CMD's for the RGB stars studied in NGC 2808 and M13; filled and open circles represent stars with log $g \leq$ and > 1.02, respectively; crosses indicate objects not considered in the histograms because they are possible AGB stars. Upper panels: histograms for the [Na/Fe] values, for log $g \leq$ and > 1.02 respectively, normalized to the total number of stars used in the adopted range (labelled in the box). For NGC 2808 we plot both the LTE and NLTE cases. The vertical lines (dotted: NGC 2808 LTE; solid: NGC 2808 NLTE; dashed-dotted: M 13) indicate the median values for each considered range and case; the value for the NLTE distributions in NGC 2808 are shown also in the M13 panels for comparison (from Carretta et al. 2003c)

stars, we would expect a much larger incidence of polluted stars among main sequence stars than among red giant branch stars, However, the ratio of N-rich/N-poor stars appear similar in various evolutionary phases, at least in 47 Tuc (Norris & Freeman 1979; Cannon et al. 1998; Herbeck et al. 2003), and the width of the distribution is roughly constant, at least in NGC6752 (Yong et al. 2003).

7. Second generation of stars: perspectives and problems

The emerging scenario considers the presence of two generation of stars in a typical globular clusters. The first generation consists of the original cluster population, and shares the chemical composition of field stars of similar metallicity. The second generation formed from the ejecta of the most massive intermediate mass stars; most of the mass was lost by these stars during its late phases of evolution, while these stars were on the AGB and experienced hot bottom burning. The formation of this second population was likely inconspicuous, since stars might have formed over a rather long period of time, starting when the cluster was about 10^8 yr old, and lasting for a few 10^8 yr.

A few features of this scenario have been explored by Ventura et al. (2001) and D'Antona et al. (2002). The age difference between the two stellar generations is so small that it can easily go undetected; however, the second population is expected to be richer in He than the first one. This feature will be further discussed in the contribution by D'Antona: here, it is interesting to note that it is possible to link the distribution of O and Na abundances to some features of the distribution of stars along the cluster horizontal branch: this is a promising observational field since extensive observations of cluster stars in reasonably short observational time are now possible thanks to FLAMES at VLT2.

The formation of stars of this second hypothetical generation occurs in a quite different environment from those of the first one. The initial mass function can be quite different, possibly not favourable to the formation of massive stars. This aspect has still to be explored.

The second generation scenario has some difficulties to be overcome. The first concerns the already mentioned lack of any variation in the abundances on the n-capture elements. While this observation may reveal fatal for this scenario, it may perhaps indicate a restricted mass range of the AGB stars over which the mechanism was efficient. Adequate modelling of the evolution of metal-poor, massive AGB stars should explore this.

The abundances of Li may pose some problem; on the whole, we expect significant star-to-star variations in the Li abundances, since Li should be first destroyed, then built, and finally destroyed again during the evolution of the massive intermediate mass stars (Ventura et al. 2001). If the results by Bonifacio et al. (2002) for NGC 6397 - where a very small star-to-star scatter in the Li abudances, around a value close to the Spite plateau's one was found - should reveal to be the rule among globular clusters, then this may be a serious concern.

Models of massive AGB stars have difficulties in producing just the right amounts of C, N, O, and Na needed to explain the observations. While these models are likely not definitive, this may be a serious concern in this scenario.

Most of these features, as well as others not mentioned here, will be discussed in the remaining contributions of this Joint Discussion.

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