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Published in:
Astronomy & Astrophysics

DOI:
10.1051/0004-6361:20020264

2002

A&A 385, L14–L17 (2002)
DOI: 10.1051/0004-6361:20020264

Astronomy & Astrophysics

Abundances of RGB stars in NGC 6752[⋆,⋆⋆]

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Received 29 January 2002 / Accepted 17 February 2002

Abstract. Abundances of O, Fe, Al, Mg, Na and Li determined from high-resolution and high signal–to–noise spectra of 21 red giant branch (RGB) stars in the globular cluster NGC 6752 are presented. We demonstrate that the Strömgren c_1 index correlates extremely well with the measured NH, CH and CN indices and that variations in c_1 are due to differences in UV NH band strengths. As shown by Grundahl et al. (2002), the RGB stars in *all* 20 globular clusters surveyed possess large star-to-star variations in their c_1 index, which we interpret as significant inhomogeneities in N abundances. The well known relations among O and Na and Mg and Al as well as with CN, CH, and NH are also present in these stars, some of which are fainter than the RGB bump. We find that the Li (6708 Å) equivalent width becomes too small to be measured as the luminosity of the stars increase above the luminosity of the RGB bump. Taken together, these data enforce the results of Gratton et al. (2001) for turnoff and sub–giant branch stars, and suggest that in this cluster the abundance correlations observed among the brighter giants are in place prior to appreciable RGB ascent and likely due to previous generation(s) of stars, rather than due to mixing in the observed stars.

Key words. globular clusters – individual: NGC 6752 – stars: abundances – mixing

1. Introduction

For the past three decades, the origin of the star-to-star variations in the abundances of light elements (C, N, O, Na, Mg, Al, etc.) observed in *every* Galactic globular cluster has defied a comprehensive explanation. Proposed theories divide into two fundamental scenarios, each with supporting evidence. Observations of decreasing C abundances during RGB ascent in metal-poor clusters, low $^{12}C/^{13}C$ ratios among bright giants, and differing Al abundances between pre- and post-RGB bump stars suggest an origin lying within the stars themselves, i.e., the mixing of material freshly exposed to nucleosynthesis to the surface via some yet to be understood transport mechanism. In contradistinction, other observations of C, N, Na, and O abundance variations among considerably less evolved (main-sequence turn-off and subgiant) cluster stars in a handful of clusters (47 Tuc, NGC 6752, and M 71) require a significant component of the inhomogeneities to be in place before RGB ascent and the operation of mixing mechanisms (i.e., a "primordial" scenario). Exactly how the star-to-star differences could be imprinted on the present giants during the early epoch of cluster formation is uncertain. These ideas and the supporting evidence are elaborated on more fully in the review by Kraft (1994) and the discussion by Cannon et al. (1998).

Related to this question is the demonstration by Grundahl et al. (1998) that the globular cluster M 13 (NGC 6205) exhibits large star–to–star variations in the Strömgren c_1 index for stars on the RGB. This has since been observed in 20 other clusters (Grundahl et al. 2002). who argue that the most likely cause for the c_1 variations is large star–to–star variations in the abundance of nitrogen revealed through the varying strength of the 3360 Å NH feature which is included in the Strömgren u filter.

If the identification of c_1 scatter with abundance variations is correct, the implication is that all clusters show significant abundance variations in stars fainter than the RGB bump level. Below this luminosity, theory (Sweigart & Mengel 1979; Charbonnel et al. 1998) does not predict significant mixing to occur – thus such abundance variations would favour a "primordial" origin for the bulk of the globular cluster abundance variations.

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⋆ Based on observations obtained with the ESO Very Large Telescope UVES spectrograph for programme 65.L-0165(A).

⋆⋆ Based on observations obtained with the Danish 1.5 m telescope at the European Southern Observatory, La Silla, Chile.

To identify the source of the c_1 variations and to clarify their relation to inhomogeneities of other light elements, we obtained high-resolution, high signal-to-noise spectra of RGB stars in the globular cluster NGC 6752 with the ESO VLT telescope Kueyen and its spectrograph UVES. Here we report on the first results of this study.

2. Observations and abundance analysis

All observations were carried out in service mode with UVES by the ESO staff (programme 65L-0165(A)), with the width of the spectrograph slit set to 1$''$.0 for the UV channel and 0$''$.7 for the red, giving spectral resolutions of approximately 40 000 and 60 000, respectively. Exposure times were chosen to give a signal-to-noise ratio of ∼100 per pixel (∼4 pixels per spatial resolution element) at 6700 Å. In total 21 stars were observed, under generally excellent seeing conditions. The spectrograph slit orientation was chosen such that no other visible stars would enter it. We used the ESO pipeline reduced spectra for the abundance analysis, since an independent reduction of one representative star showed only negligible differences compared to the pipeline result. For the determination of oxygen abundances using the [OI] line at 6300.31 Å we used spectra of rapidly rotating B stars to remove the signatures of the telluric lines.

Equivalent widths were measured using our own software developed in IDL, allowing automatic measurements for many lines. MARCS LTE atmospheres kindly calculated by M. Asplund and programs from the Uppsala group were used for the abundance analysis. The details of these steps will be given elsewhere. We derived the stellar temperatures using our own observed Strömgren $(b-y)$ index and the calibrations of Alonso et al. (1999). Other indices generally led to variations less than 100 K in $T_{\rm eff}$. An error of 0.01 mag in $(b-y)$ gives rise to a temperature error of ∼40 K.

Surface gravities were estimated using the stellar luminosities, derived temperatures, and assumed masses of 0.84 $M_\odot$. To estimate the luminosity we assumed a cluster distance modulus of $(m-M)_V = 13.30$, a reddening of $E(B-V) = 0.04$, and bolometric corrections from a 14 Gyr isochrone with [Fe/H]$= -1.61$ from VandenBerg et al. (2000).

Microturbulent velocities were derived by requiring no trends with equivalent width for 99 iron lines with EQWs less than 100 mÅ. The derived velocities show a linear trend with $\log g$, with a slope of -0.337 (very similar to that found by Carretta & Gratton 1997). The effective temperatures and gravities for our stars span the range 4700–4950 K and 1.83–2.40 in $\log g$. The lines used for the abundance analysis were adopted from the papers of the Lick/Texas group (e.g., Kraft et al. 1997)

We have not (yet) derived the abundances of C and N from a spectroscopic analysis, but we have measured the strength of the NH (3360 Å) and CN (3590 Å) bands using the indices defined in Briley & Smith (1993). The CH strength was measured by integrating the spectrum over the interval 3664.75 Å to 3665.10 Å relative to the region from 3666.0 Å to 3667.0 Å.

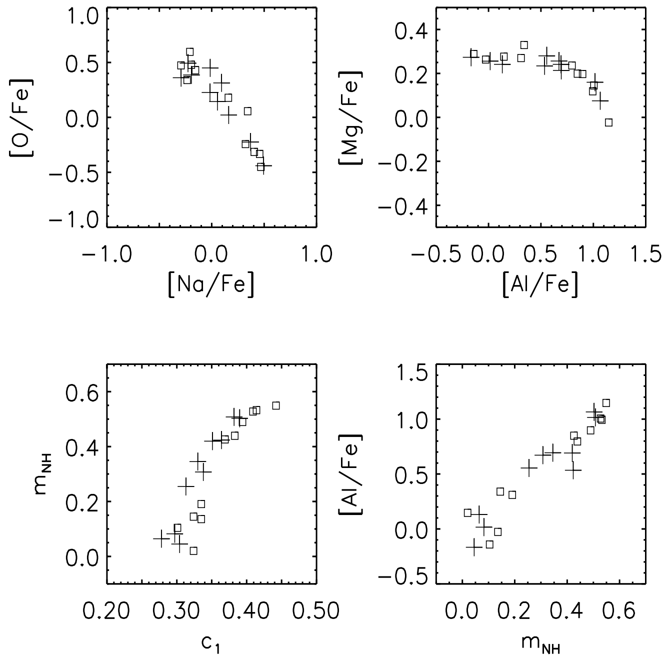

Fig. 1. Observed anti-correlations between O and Na (*upper left panel*) and Mg and Al (*upper right*). Plus signs and squares denote stars which are fainter and brighter than the RGB bump, respectively. The anti-correlations hold for stars irrespective of their luminosity. The lower left panel show how the Strömgren c_1 index correlates with NH magnitude.

Equivalent widths for Li were measured, but abundances were not derived. For the brightest 1/3 of the sample these are essentially upper limits, as there does not seem to be any measurable Li in these.

3. Observed abundances and their correlations

We now turn our attention to an investigation of the correlations among the light elements in our sample of 21 stars, the photometric index $c_1 = (u-v)-(v-b)$, and the spectroscopic indices of CH, CN and NH. The discussion and interpretation of these results will be given in Sect. 5.

Investigations in several clusters have already revealed clear anti-correlations between the abundance of O and Na on one hand and Mg and Al on the other (most notably through the work of the Lick-Texas group, see e.g. Kraft et al. 1997). In Fig. 1 we show our observations for these elements. Obviously these correlations also exist among the NGC 6752 stars studied here, some of which (+ signs) are fainter than the RGB bump. None of the O, Al, Mg and Na abundances show any correlation with luminosity. In Fig. 2 (left-hand panel) we show the CH index versus the NH index. These two show a clear anti-correlation suggesting a strong anti-correlation between [N/Fe] and [C/Fe] among our program stars. This correlation does not depend on luminosity. The right-hand panel of Fig. 2 shows that there is a positive correlation between CN and NH strength, and since there is a negative correlation

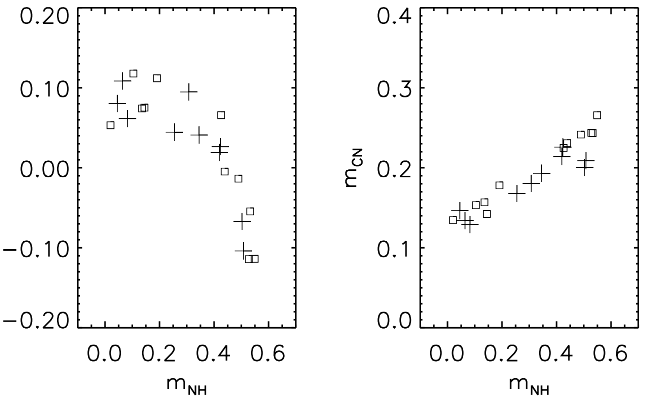

Fig. 2. Correlations among the CH, CN and NH indices derived from our spectra. Symbols have the same meaning as in Fig. 1.

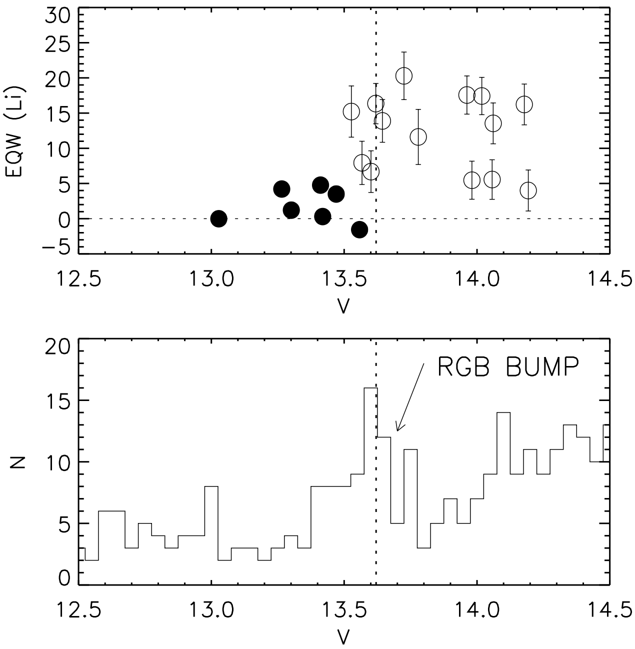

Fig. 3. The change in Li abundance as a function of luminosity. The RGB bump is marked by the vertical line. The filled circles denote upper limits.

between CH and NH, we conclude it is the abundance of N which controls the strength of CN.

4. The case of Li

In Fig. 3 the measured equivalent width of the 6707.8 Å line is plotted as a function of the V magnitude. We see that once the luminosity exceeds that of the RGB bump, the equivalent width drops dramatically. We interpret this decrease to be the result of mixing, with Li being destroyed during the circulation of envelope material down into the shell-burning region. This result is in excellent accord with the measurements of Charbonnel et al. (1998) and Gratton et al. (2000) as well as the theoretical works of Sweigart & Mengel (1979) and others which suggest that mixing is inhibited prior to the bump. Furthermore, this observation rules out the operation of such a process in stars which are intrinsically fainter than the RGB bump. Thus the abundance inhomogeneities/correlations seen among the "pre-bump" stars *are likely not the result of mixing.*

5. Discussion

The correlation of c_1 with NH band strength confirms our suspected relation between c_1 and [N/Fe]. Indeed, among our stars with the highest c_1 index, the NH bands are completely saturated, indicating substantial enhancements of this element. This result and the large scatter in c_1 indices observed in every globular studied by Grundahl et al. (2002) implies that large abundance variations of the light elements (or at least N) in GCs is a very common phenomenon – perhaps even "universal".

In addition, the data presented in Grundahl et al. (2002) and in this paper provide us with the following facts which must be explained:

• All GCs have c_1 scatter (Grundahl et al. 2002).
• The NH variations correlate very well with CN (3590 Å) and CH band strengths *and* the abundances of O, Na, Mg and Al in NGC 6752.
• O-Na and Al-Mg anti-correlations exist among our observed stars both before and after the RGB bump.
• Lithium is not detected in stars brighter than the RGB bump, whereas it is detected in the stars at and below the bump luminosity.
• The patterns of abundance variations found here agree very well with those found in Gratton et al. (2001) for stars at the turnoff and lower SGB stars.
• The scatter of iron-peak element abundances among our stars is consistent with the measuring errors. The star–to–star scatter in the [Ca/Fe] and [Ni/Fe] ratios is 0.025 dex.

These observations can be interpreted as follows:
The fact that Li disappears above the RGB bump (as also found for PopII field stars by Gratton et al. 2000) implies that the "physics" of cluster and field stars may be very similar, in the sense that a post-first dredge-up mixing episode *does* take place which brings CN-cycle exposed material to the surface. This is consistent with the low $^{12}C/^{13}C$ ratios and decreasing C abundances observed among the NGC 6752 bright giants by Suntzeff & Smith (1991). This "extra mixing" may be more extreme in at least some clusters (e.g., the lower O and high Na abundances reported for stars in M 13 by Kraft et al. 1997).

Yet we also observe variations and correlations among O, Na, Mg and Al, as also found by Gratton et al. (2001), and correlations with NH, CN, and CH as well. It is well known that the Pop II field giants do not exhibit the same extreme variations in these elements. We therefore assume that some aspect of the cluster environment is responsible for these observed variations. That the patterns of inhomogeneities are present among NGC 6752 stars before the bump (this paper and Gratton et al. 2001), which our Li widths point to as the onset of deep-mixing, implies that the bulk of the light-element inhomogeneities are the result of a process other than mixing, i.e., that the present abundance variations are of "primordial" origin.

The primordial scenario, and variations on it, has been proposed and discussed several times before in the literature (see for example Cottrell & Da Costa 1981, and Cannon et al. 1998). The small star–to–star scatter in the iron peak elements (as observed in this work) indicates that the contribution to the inhomogeneities from type II supernovae is likely very small – their ejecta were well mixed or completely escaped the cluster (as pointed out by numerous authors). A more promising source is pollution from intermediate mass (3–6 $M_\odot$) stars via low speed winds during the AGB phase of their evolution. This idea was explored by Ventura et al. (2001), who demonstrate that the very CNO-cycle/proton-capture reactions considered to be the source of the C, N, O, Na, Al, Mg abundance changes during RGB ascent could also take place in low metallicity 5–6 $M_\odot$ AGB stars. Clearly the incorporation of such material into the present day cluster stars could give rise to our observed abundance patterns, although the specifics of this process are still quite uncertain. Yet our results and those of Gratton et al. (2001) bring up a number of questions which remain open:

Since all clusters observed by Grundahl et al. (2002) show c_1 scatter, do our NGC 6752 results then imply that all clusters have pre-bump O, Mg, Na and Al variations which correlate with c_1? We note that for other clusters the available spectroscopic material for Mg, Na, O and Al in stars fainter than the RGB bump is still very limited. Briley et al. (1996) found significant Na variations, correlated with CN-band strength in 47 Tuc ([Fe/H] = –0.8) turn-off stars. Gratton et al. (2001) also studied NGC 6397 ([Fe/H] = –2.0) for which Grundahl et al. (2002) also detect c_1 scatter. Gratton et al. found that the inhomogeneities in this cluster were significantly smaller than for NGC 6752, indicating that the observed correlations with c_1 for NGC 6752 may not hold in NGC 6397. Perhaps even more significant, theory predicts that the abundance spread becomes larger with decreasing metallicity (due to greater temperatures at the base of the convective envelopes in more metal-poor AGB stars and to proportionally lower "pre-pollution" abundances). Certainly, the distribution of the c_1 variations observed by Grundahl et al. (2002) suggest that the distribution of N abundances may vary from cluster to cluster. Thus, the extent of AGB pollution may have varied from cluster to cluster (a result which may be consistent with NGC 6397's relatively lower mass compared to NGC 6752 and 47 Tuc).

Finally we note that any primordial scenario must necessarily involve a significant fraction of the mass of the present stars, and cannot simply be a surface contamination. If pollution occurred while the stars were still on the main sequence, their then very thin convective envelopes only contained of order 2% of the total stellar mass. For RGB stars this is closer to 30%, implying that if it was only a surface contamination while the stars were on the main sequence, a dramatic "dilution" of the variations and absolute abundance values should occur during RGB ascent. Thus a significant fraction of the AGB-processed material must have been returned to the present cluster stars. This naturally leads to two questions: do the initial mass functions of the clusters support a sufficient number of high mass stars to produce the necessary contaminants, and would such a process result in a more steep mass function for the low mass cluster stars?

6. Conclusions

The UVES data presented here show un-ambiguously that the c_1 variations seen among RGB stars in NGC 6752 are caused by large star–to-star variations in the strength of their NH bands and thus their nitrogen abundance. We have further shown that the NH (c_1) strength correlates extremely well with the abundance of O, Mg, Na, Al and the strength of the CH and CN indices both before and after the RGB bump – a result difficult to explain in the context of a mixing scenario.

Acknowledgements. Martin Asplund is thanked for generating the MARCS atmosphere models used here. MMB acknowledges support from the National Science Foundation (under grant AST-0098489).

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