From Lithium to Uranium: Elemental Tracers of Early Cosmic Evolution
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Li and Be in turnoff stars of globular clusters

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Abstract. Lithium abundance in Turnoff stars of Globular Clusters (GC) provide precious information about primordial nucleosynthesis and Globular Cluster formation. Out of the three GC so far observed in some detail, the metal poor NGC6397 shows a constant Li abundance, at the same level of the Spite' plateau; while the more metal rich NGC6752 and 47 Tuc show a beautiful Li-Na anticorrelation (the first of this kind observed in PoP II stars), suggesting the presence of gas processed by a previous generation of stars. These observations are quite puzzling: while they are qualitatively compatible with the scenario of contamination from intermediate mass AGB stars, no progenitor can quantitatively reproduce the observations. Beryllium has also been detected in NGC6397 Turnoff stars, indicating that the gas which formed the stars was exposed for about 200 Myr to the Galactic Cosmic Rays. The emerging picture seems to require that in the early Galaxy both local (SNae, AGB stars) and global (Galactic Cosmic Rays) enrichment processes were acting simultaneously in the star formation phase of the halo.

Keywords. Stars:abundances, globular clusters: general, globular clusters: individual (NGC6397, NGC6752, 47Tuc, M92)

1. Introduction

First observations of Li in main sequence stars (stars at the Turnoff (TO) or close to) of Globular Clusters (GC) are only about 11 years old (Molaro & Pasquini (1994)). The reason is quite simple: GC are fairly far away, and unevolved stars are therefore at the limit of 4m. class telescopes capabilities even in the nearest GC, such as NGC6397, where TO stars have a visual magnitude V∼16. These observations concentrated mostly on the problem if the *plateau* represents the signature of the primordial nucleosynthesis (Spite & Spite (1982)), and if the Li level of the GC stars was the same of the field stars' *plateau.*

In the southern hemisphere the NTT at ESO, La Silla was used to observe TO stars in NGC6397 ([Fe/H=-2]) and 47 Tuc ([Fe/H=-0.66]) (Pasquini & Molaro (1996),Pasquini & Molaro (1997)), while in the Northern hemisphere A. Boesgaard and collaborators used the Keck telescope to observe the metal poor M92 ([Fe/H=-2.3]) (Deliyannis *et al.* (1995),Boesgaard *et al.* (1998)).

These early observations could give spectra only for a few stars per cluster; Molaro & Pasquini (1994) and Pasquini & Molaro (1996) derived for 3 TO stars of NGC6397 a Li abundance A(Li)= 2.28 ± 0.1, and for 47 Tuc A(Li)=2.37 ± 0.13, and concluded that the two values were well compatible with the field stars' *plateau.* In addition, no evidence for spread was found, but the signal to noise ratio of the observations was admittedly rather low. One interesting point was that they observed in 47 Tuc one CN-rich and one CN-poor star, and no clear difference in Li abundance was found among the two stars; this result is similar to what is observed in N rich stars in the field, which have the same Li as the other Pop II stars (Spite & Spite (1986)), a quite puzzling result (cfr. the presentation by F. Spite at this conference).

The Keck observations of M92 TO stars were instead more intriguing: Deliyannis *et al.* (1995) and Boesgaard *et al.* (1998) claimed the evidence for a large spread of Li abundance among the M92 stars, and argued that this was the long sought evidence that the *plateau* did not represent the primordial Li abundance. The study of the Keck observations was revised by Bonifacio (2002), who, performing a different analysis with a careful treatment of the errors, showed as the data are compatible with the absence of Li spread and as the M92 Li level derived (A(Li) = 2.36 ± 0.19) is well compatible with the other clusters' estimates and with the field *plateau*.

Although the quest for comparing the Li level of GC with the *plateau* and for using the GC to infer the primordial Li is legitimate, the evolution of Li in GC might be quite complex, and not so simple as it could appear at first glance. In fact GC stars show signatures of CNO processing and contamination even among the main sequence stars (Gratton *et al.* (2001)). Li and Be therefore may be key elements to study the formation and chemical evolution of GC; they are destroyed at temperatures of a few million K, which are 20-30 times cooler than the temperatures at which the typical reactions responsible for GC anomalies occur (cfr. Sneden, these proceedings). King *et al.* (1998) found that the same stars which indicated the Li abundance spread in M92 also showed anomalous Na and Mg abundances, as if the gas on their surface had been processed through the Mg-Al and Ne-Na cycles. They noticed on the other hand that, if this was true, the Li abundance observed was too high (or the spread too small) because no Li could have survived at the high temperatures at which these cycles take place.

2. Li in GC in the VLT era

The advent of the VLT has produced a quantum step in this field, since the 8m class aperture, coupled to state of the art spectrographs and to the visibility of the nearest GC, has allowed the detailed study of a considerable number of stars, and even more will do in the future, once the multi-objects FLAMES spectra will become available.

2.1. *NGC6397*

NGC 6397 became one of the best studied clusters, and two studies addressed Li in the TO stars: Thevenin *et al.* (2001) and Bonifacio *et al.* (2002) have used UVES at the VLT to obtain high resolution, high S/N ratio observations for a total sample of 12 TO objects. The results, summarized in the careful analysis of Bonifacio *et al.* (2002) which includes all the stars, are very clean: in NGC6397 the Li abundance is constant among the observed stars, with A(Li)=2.36 ± 0.056. Two further points must be emphasized: a) when considering the intrinsic errors expected by the limited S/N of the observations and the uncertainties in effective temperature, the small scatter observed leaves room for an intrinsic scatter of the Li abundance of less than σA(Li)<0.035; b) when the same temperature scale is used, the field stats *plateau* abundance is of A(Li)=2.32, in perfect agreement with that derived in the cluster' stars.

The interpretation of these results would have been straightforward if the same spectra had not revealed strong variations of Oxygen among these stars (Pasquini *et al.* (2004), Carretta *et al.* (2005)); we will come back to this point during the discussion.

2.2. *NGC 6752*

Starting from the experience of previous observations and of NGC6397, it has been an exciting surprise to find that in the more metal rich NGC6752 ([Fe/H]=-1.4), not only Li clearly varies among the TO stars, as shown in Figure 1, which shows the spectra of two very similar stars in the Li region, but also that the Li abundance strongly correlates with

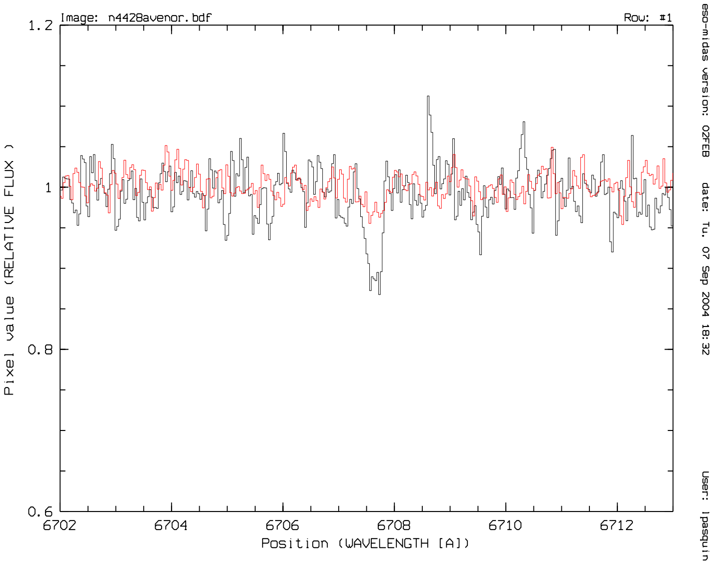

Figure 1. The spectra of two NGC6752 TO stars in the Li region. Note the difference in Li line strength. The stars have virtually the same temperature and gravity

Oxygen and anticorrelates with Na, as shown in Figure 2(from Pasquini *et al.* (2005)). This is to our knowledge the first time that a clear departure from the *plateau* has been detected in hot Pop II stars.

In addition, it is relevant to notice that the stars with the highest Li have an abundance level comparable to what observed in NGC6397 and in the field (when the same temperature scale is adopted). This suggests that the Li-rich, O-rich and Na poor stars are those with a composition as close as possible to the 'pristine' one. The second relevant point is that Li is detected even in the most Na-rich stars. This has important consequences, as we shall see in the following.

2.3. *47 Tuc*

47 Tuc TO stars are more than one magnitude fainter than TO stars in NGC6397, and the cluster is substantially more metal rich ([Fe/H]=-0.66). Bonifacio *et al.* (2005) have observed 4 TO stars in this cluster, and Carretta *et al.* (2005) have analyzed them for other elements, in a similar fashion than the previous two clusters. Also for 47 Tuc the results show, in spite of the limited number of stars, a clear Li-Na anticorrelation, as shown in Figure 3. As for NGC6752, also in 47 Tuc Li is detected in the most Na-rich stars. Finally, the Li content of the most Na-rich star in 47 Tuc is lower than in the Na-rich stars of NGC6752. This abundance might be used to constrain the composition of the ejecta of the cluster contaminants.

2.4. *Li in GC TO stars: discussion*

Introducing the discussion on GC chemical anomalies and contamination it is important to recall that the observations show as the processed material does not pollute only the stellar surface, rather it pollutes the whole star. The strongest indication comes from the fact that the same chemical anticorrelations are seen everywhere along the cluster C-M diagram. This shows that deep mixing phenomena such as the first dredge up do not modify substantially the surface composition of Na and CNO material, and therefore the interior of the star has the same composition as the external layers, as far as these

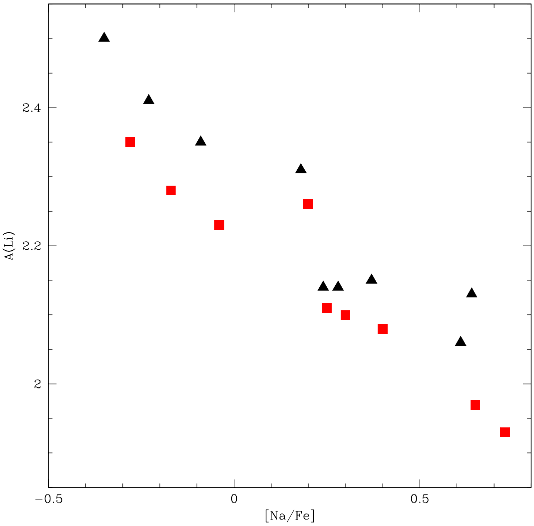

Figure 2. Li-Na anticorrelation in the TO stars of NGC6752. The 2 different symbols refer to the use of different temperature scales used. The anticorrelation is independent of the temperature scale adopted; see Pasquini *et al.* (2005) for details.

elements are concerned. We are therefore facing a substantial contamination of the stellar gas, which might involve a considerable fraction of the total mass of the cluster. Another background information to be kept in mind is that (cfr. Sneden in these proceedings) only some elements show chemical anomalies in GC, while the majority shows an impressive homogeinity across all stars observed.

As far as Li is concerned, the clusters observed do not present the same behaviour, and we do not know if the same pollution mechanism was acting in all of them. The two most metal poor clusters, NGC6397 and M92 show at the same time evidence for CNO processing and Li abundance at the *plateau* level, without any evidence for Li spread, in particular in NGC6397. This represents a paradox, very difficult to be explained.

NGC6752 and 47Tuc, instead show clear Li variations and Li-Na anticorrelation.

One solution could be to invoke the presence of polluters just injecting CNO processed material in a medium with the typical composition of the halo. The problem with this solution is that such polluting stars will always contribute some oxygen and they cannot create an oxygen-Na anticorrelation, nor O-poor stars.

The alternative is that Li has been first destroyed and later created. This could happen during the AGB phase, where Li could be produced and brought to the stellar surface by the Cameron-Fowler mechanism, and then dispersed in the ISM by stellar winds. This idea has been explored by Ventura *et al.* (2001), Ventura *et al.* (2002) in a series of papers dedicated to self enrichment of GC from AGB stars.

These models have some positive predictions: the range of abundances they predict is in fairly good agreeement with the observations (with exception of Na, see e.g. Charbonnel in this proceedings), and in particular they can produce an amount of Li close to the *plateau*. The similarity of the Li observed in NGC6397 with the *plateau* would, on the other hand, require a very high fine tuning between AGB and Big Bang production. In addition, when the comparison extends to the detailed quantitative predictions of all elements, no AGB model at present is able to reproduce all the observed abundance

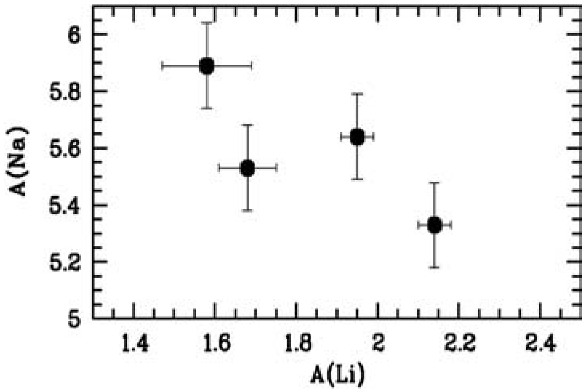

Figure 3. Na-Li anticorrelation for the 4 TO stars observed in 47 Tuc. From Bonifacio *et al.* (2005).

ratios. On the other hand the uncertainties present in the models of these AGB stars are quite large, henceforth it might be that in this phase are the observations which drive stellar evolution theory rather than the opposite.

3. Beryllium

If Li observations of TO stars of GC are challenging, observations of Beryllium, which has the only two useful lines in the far UV (313 nm), are almost prohibitive. The only observations obtained so far are those by Pasquini *et al.* (2004), who observed two TO stars of the nearby NGC6397. The two stars have *plateau* Li abundance. By using the VLT and UVES, Be has been detected in both stars and an abundance of Log(Be/H)= -12.35 ± 0.15 derived. The same observations revealed that the two stars have different Oxygen abundance and that they are both very rich in Nitrogen, as if CNO processing occurred.

Be is produced via spallation of CNO and heavier nuclei (Reeves *et al.* (1970)) and the observations show that Be in the early Galaxy is mostly of primary origin. If this is the case, Be atoms are immediately spread all over the Galaxy. In a first approximation, Be abundance is uniform in the Galaxy, and it increases with time. It can be henceforth used as a very good clock.

By applying Galactic chemical evolution models to the Be abundance observed in NGC6397, Pasquini *et al.* (2004) demonstrated that the "Be age" of NGC6397 is very similar to the age derived from stellar evolution and main sequence fitting and that the cluster was born within 500 million years after the onset of star formation in the Galaxy.

In the context of GC formation, it is important to recall that Be is similar to Li, because it is destroyed at temperatures of a few (3.5) MK; on the other hand, at odds with Li, Be cannot be produced by stellar processes; it can only be produced via Galactic Cosmic Ray spallation and destroyed in stars. The detection of Be in the atmosphere of these stars implies therefore that the gas which formed them was exposed for a few hundred million years to the Galactic Cosmic Rays after (or while) being contaminated by the previous generation of stars. The presence of Be indicate that, if AGB stars were causing the contamination, this early phase of the GC saw the simultaneous presence of local (AGB stars) and global (GCR) enrichment processes.

Table 1. Element abundance of the ejecta which polluted the cluster, from Bonifacio *et al.* (2005)

Element	M92	NGC6397	C NGC6752	47 Tuc
Li/H	∼2.35	∼2.36	∼1.9	∼1.6
O/H		<6.7	<7.0	< 7.8
Na/H	4.4	4.5	> 5.4	> 5.9
N/H		7.3	7.9	8.3

4. Some Conclusions

Observations of Li and Be in TO stars of GC have a great potentiality, because, thanks to their fragility and formation mechanisms, these elements put strong constraints to the previous generation of (polluting) cluster stars. The presence of Li and be in the stellar atmosphere proves, for instance, that the nuclear processes responsible for the chemical anomalies have not occourred in the stars themselves.

We could not identify any single candidate for pollution which can explain quantitatively all the abundances observed in GC; although AGB stars still remain the most likely candidates, other sources cannot be excluded. In this phase accurate observations of many stars may drive stellar evolution theory. Table 1 contains an attempt to summarize for some elements the composition that the ejecta from an hypothetical 'polluter' should have had, based on the most recent observations (adapted from Bonifacio *et al.* (2005)). The observations so far collected suggest that the Li created and ejected decreases with the cluster iron abundance, while Na (and pssibly N) increases, and the [Na/Fe] of the ejecta remain almost constant.

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