LITHIUM AND PROTON-CAPTURE ELEMENTS IN GLOBULAR CLUSTER DWARFS: THE CASE OF 47 TUC

Valentina D’Orazi1, Sara Lucatello1,2, Raffaele Gratton1, Angela Bragaglia3, Eugenio Carretta3, Zhixia Shen4, and Simone Zaggia1

1 INAF-Osservatorio Astronomico di Padova, vicolo dell’Osservatorio 5, I-35122 Padova, Italy; valentina.dorazi@oapd.inaf.it, sara.lucatello@oapd.inaf.it, raffaele.gratton@oapd.inaf.it, simone.zaggia@oapd.inaf.it
2 Excellence Cluster Universe, Technische Universität München, Boltzmann Str. 2, D-85748 Garching, Germany
3 INAF-Osservatorio Astronomico di Bologna, via Ranzani 1, I-40127 Bologna, Italy; angela.bragaglia@oabo.inaf.it, eugenio.carretta@oabo.inaf.it
4 National Astronomical Observatories, Chinese Academy of Science, 20a Datun road, Beijing, China; zshen@bao.ac.cn

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ABSTRACT

Previous surveys in a few metal-poor globular clusters (GCs) showed that the determination of abundances for Li and proton-capture elements offers a key tool to address the intracluster pollution scenario. In this Letter, we present Na, O, and Li abundances in a large sample of dwarf stars in the metal-rich GC 47 Tucanae. We found a clear Na–O anticorrelation, in good agreement with what obtained for giant members by Carretta et al. While lithium and oxygen abundances appear to be positively correlated with each other, there is a large scatter, well exceeding observational errors, and no anticorrelation with sodium. These findings suggest that Li depletion, due to mechanisms internal to the stars (which are cooler and more metal-rich than those on the Spite plateau), combines with the usual pollution scenario responsible for the Na–O anticorrelation.

Key words: globular clusters: individual (NGC 104) – stars: abundances – stars: individual (Population II)

Online-only material: color figures, machine-readable table

1. INTRODUCTION

The traditional paradigm of globular clusters (GCs) as the textbook example of a simple stellar population is now outdated. In the last several years, a wealth of observational studies (both photometric and spectroscopic) have been carried out, revealing the quite complex nature of this old Galactic population.

With the famous exception of ω Cen (Freeman & Rodgers 1975), and of the more recently scrutinized M 54 (Carretta et al. 2010), M22 (Marino et al. 2009), and Terzan 5 (Ferraro et al. 2009), GCs show homogeneous compositions in the iron peak and heavier α elements (e.g., Ca and Ti). Abundance variations in the lighter elements, namely Li, C, N, O, Na, Mg, and Al, have been instead recognized since the 1970s (e.g., Cohen 1978; see Gratton et al. 2004 for a recent review). These peculiarities of GC stars require that some material must have been processed through the complete CNO cycle in hot H burning, through proton-capture reactions (Denisenkov & Denisenkova 1990): element pairs C and N, O and Na, and Mg and Al are anticorrelated, the abundances of C, O, and Mg being depleted while those of N, Na, and Al being enhanced.

A previous generation of stars, which synthesized proton-capture elements in their interiors, is now commonly accepted as responsible for the above-mentioned chemical signatures. Regardless of the debated nature of these element polluters (asymptotic giant branch (AGB) stars experiencing hot bottom burning, e.g., Ventura & D’Antona 2009, or fast rotating massive stars (FRMS), e.g., Decressin et al. 2007), two fundamental observational facts deserve to be emphasized. (1) All the GCs surveyed so far show the Na–O anticorrelation (Carretta et al. 2009b): this indicates the presence of at least two populations (neither coeval nor chemically homogeneous) within each cluster. (2) The primordial nature of such a phenomenon is uniquely indicated by the presence of these chemical signatures also among not evolved turnoff (TO) or scarcely evolved (subgiant, SGB) members (see, e.g., Gratton et al. 2001).

In this context, Li abundances play a fundamental role. In fact, this element can be easily destroyed in stellar interiors (starting at $T_{\text{burn}} \approx 2.5 \times 10^5$ K); and since the CNO and NeNa cycles require much higher temperatures, it is expected that in the site(s) where these cycles occur no Li is left. In particular, the Na-poor, O- and Li-rich stars, that are the first population born in the cluster, share the chemical composition of field stars of the same metallicity, while the Na-rich (Li- and O-poor) stars form from gas progressively enriched by ejecta (which are rich in Na, depleted in O and Li) of the first generation.

As a consequence, if primordial and processed material are mixed in different proportions, then Li and Na (Li and O) are expected to be anticorrelated (correlated) with each other.

Measuring the Li abundances in unevolved stars provides a direct indication of the amount of pristine, and by difference of polluted (CNO-cycle processed), material present in each star. This makes Li a unique tracer of the diffusion process which took place in the GC, supplying also fundamental insights on its early evolutionary stages. Another important point is that Li abundances can provide strong observational constraints on the origin of the polluters; since AGB stars might also produce Li (via the Cameron–Fowler mechanism; Cameron & Fowler 1971), while massive stars can only destroy it, if Li-rich stars are present in GCs, AGB stars would be definitely favored with respect to FRMS.

To date, only three GCs have been surveyed for correlations between Li and proton-capture elements. Pasquini et al. (2005) obtained Li abundances in nine TO members of NGC 6752: they found a depletion reaching down to $\sim$1 dex below the Spite plateau values, clearly anticorrelated with Na abundances. A similar result was obtained by Bonifacio et al. (2007) who found a scatter in Li abundances much larger than observational errors and anticorrelated with Na among (only) four stars in 47 Tuc. Very recently, Lind et al. (2009), targeting about 100 main-sequence (MS) and early subgiant branch (SGB) stars in NGC 6397, detected for the first time a significant
anticorrelation between Li and Na in this GC. This last investigation supersedes an older research by Bonifacio et al. (2002) based on only a few stars, and highlighting the importance of large samples of stars for similar studies.

In this Letter, we present Na, O, and Li abundance determinations in ∼90 unevolved TO stars of the GC 47 Tucanae, providing the largest database of this kind available in the literature so far.

### Table 1

Properties of Target Stars

| StarID  | R.A.  | Decl. | V     | B     | Teff (K) | log g  | log n(O) | log n(Na) | log n(Li) | ERR_1  |
|---------|-------|-------|-------|-------|----------|--------|----------|-----------|----------|--------|
| 001     | 6.15846 | −71.9632 | 17.347 | 17.913 | 5685 | 4.05 | 8.266 | 0.050 | 5.715 | 0.103 | 2.105 | 0.053 |
| 002     | 5.96746 | −71.9607 | 17.301 | 17.853 | 5676 | 4.02 | 8.061 | 0.083 | 5.741 | 0.080 | 1.538 | 0.057 |
| 003     | 6.33533 | −71.9429 | 17.347 | 17.913 | 5685 | 4.05 | 8.445 | 0.050 | 9.999 | 1.998 | 1.30 |
| 005     | 6.24487 | −71.9313 | 17.330 | 17.894 | 5681 | 4.04 | 8.112 | 0.111 | 5.752 | 0.080 | 2.261 | 0.096 |
| 006     | 6.16508 | −71.9222 | 17.372 | 17.941 | 5689 | 4.06 | 8.374 | 0.050 | 5.689 | 0.080 | 2.453 | 0.108 |
| 007     | 6.21133 | −71.9159 | 17.365 | 17.931 | 5688 | 4.05 | 8.493 | 0.050 | 9.999 | 9.999 | 2.381 | 0.087 |
| 008     | 6.27892 | −71.9146 | 17.377 | 17.940 | 5690 | 4.06 | 8.705 | 0.050 | 9.999 | 9.999 | 2.240 | 0.049 |
| 009     | 6.24204 | −71.9106 | 17.360 | 17.926 | 5687 | 4.05 | 8.327 | 0.050 | 9.999 | 9.999 | 2.299 | 0.081 |
| 010     | 6.11050 | −71.9085 | 17.335 | 17.899 | 5682 | 4.04 | 8.514 | 0.050 | 9.999 | 9.999 | 2.294 | 0.112 |
| 011     | 5.80258 | −71.9629 | 17.336 | 17.909 | 5682 | 4.04 | 9.999 | 9.999 | 5.910 | 0.083 | 1.987 | 0.129 |

Notes. We report our ID in Column 1, R.A. and decl. in Columns 2 and 3, while magnitudes V and B are given in Columns 4 and 5. Stellar parameters (Teff and log g) along with abundances and their errors are listed from Columns 6 to 13, respectively.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

3. RESULTS AND DISCUSSION

As shown in Figure 1, the unevolved cluster stars reveal a very clear Na–O anticorrelation, consistently with what has
be obtained for giant members (Carretta et al. 2009b). We detected an oxygen variation of about \(\sim 0.80\) dex and a change in Na of \(\sim 0.77\) dex, to be compared with \(\sim 1\) and 0.82 (O and Na, respectively) for giants in Carretta et al. (2009b). The interquartile ranges IQR[Na/O] are 0.368 ± 0.067 and 0.470 ± 0.041, respectively. These two estimates are consistent at \(1\sigma\) level; however, since the dwarfs are a more homogeneous sample (i.e., very similar atmospheric parameters) and the spectral features used to measure a given element are not the same in dwarfs and giants, the latter being weaker and plagued by higher uncertainties, both the spread (maximum–minimum) and the IQR result slightly higher for giants. It is noteworthy that we found an offset in Na abundances between dwarfs and giants of \(\sim 0.2\) dex for 47 Tuc. A similar offset can be obtained also for NGC 6397, when comparing Na abundances for dwarfs from Lind et al. (2009) and for giants from Carretta et al. (2009b). We investigated the nature of this offset, concluding that it is due to the adopted set of lines, with the doublets 5682–5688 Å and 6154–6160 Å (used in Carretta et al.) yielding always higher abundances than the 8183–8194 Å features (employed for dwarfs). We, in fact, detected the same effect in the Sun (with higher abundances than the 8183–8194 Å features (employed)) and we offset our Na abundances for this effect.

In general, we conclude that there is a very good agreement between the two distributions as can be clearly seen in Figure 2: after applying the derived offset in Na abundances, the cumulative [Na/O] functions look very similar, and a Kolmogorov–Smirnov (KS) test indicates that the two distributions cannot be distinguished (the probability from KS being \(\sim 0.77\) dex, to be compared with 27% ± 5%, 69% ± 8%, and 4% ± 2% from giants (see Carretta et al. 2009b).

On the other hand, there is not a one-to-one correlation between Li and O abundances (the left-hand panel of Figure 3): even if some trend might be present, there is a considerable scatter, much larger than observational errors. The figure shows that, while the stars with low O values have also low Li content, at higher O abundances, Li can assume a large range values, from 1.54 ± 0.06 to 2.51 ± 0.18, with the most extreme star (085) having log\(n(Li) = 2.78 ± 0.08\) (this very Li-rich star, which appears as primordial type according to its O abundances, surely deserves special attention and further high-resolution observations in order to investigate this extreme behavior). In Figure 4 we show, as explicative example, the spectra of three stars with almost the same O abundances; one is star 085 and the two others have intermediate and low Li.

If we then focus on the Li–Na diagram (the middle panel of Figure 3), the scatter is even larger with no evidence for an anticorrelation. As further evidence, the linear correlation coefficient is 0.39 (77 stars) and −0.02 (84 stars), respectively, for the Li–O and Li–Na distributions: in the first case, the significance level is >99.5%, while the second one has no statistical meaning.

\[\text{prob(KS)} = 0.14\]

\[\text{Cumulative [Na/O] distribution for dwarfs (red solid line) and giants (blue dashed line). (A color version of this figure is available in the online journal.)}\]

\[\text{Figure 2.}\]

\[\text{Figure 1. Na–O anticorrelation for 47 Tuc dwarf members; error bars come from uncertainties on EWs. A dilution model (Prantzos & Charbonnel 2006) is also overplotted as a (red) solid line. (A color version of this figure is available in the online journal.)}\]

\[\text{Figure 1.}\]

\[\text{Figure 2. Cumulative [Na/O] distribution for dwarfs (red solid line) and giants (blue dashed line). (A color version of this figure is available in the online journal.)}\]

Thanks to the wide sample available, we confirm that evolutionary effects, acting during the red giant branch (RGB) phase (see, e.g., D’Antona & Ventura 2007 for M 13), cannot contribute to the Na–O distribution (at least for the present cluster), since the extent of anticorrelation in both giants and dwarfs is essentially the same. Furthermore, following the approach by Carretta et al. (2009b) the fractions of primordial (P), intermediate (I), and extreme (E) stars computed from unevolved members are 34% ± 5%, 63% ± 7%, and 3% ± 1%, respectively, to be compared with 27% ± 5%, 69% ± 8%, and 4% ± 2% from giants (see Carretta et al. 2009b).

\[\text{Figure 2. Cumulative [Na/O] distribution for dwarfs (red solid line) and giants (blue dashed line). (A color version of this figure is available in the online journal.)}\]

\[\text{Figure 1. Na–O anticorrelation for 47 Tuc dwarf members; error bars come from uncertainties on EWs. A dilution model (Prantzos & Charbonnel 2006) is also overplotted as a (red) solid line. (A color version of this figure is available in the online journal.)}\]
Figure 3. Run of Li with O and Na for 47 Tuc (left and middle panels). The (blue) open symbols are stars with Li from Bonifacio et al. (2007) and Na, O from Carretta et al. (2004). A dilution model is overplotted as (red) solid lines (see the text). The arrow represents the effect on abundances of a change in $T_{\text{eff}}$ of 145 K, which is the offset between the two different temperature scales employed. In the right-hand panel we show, for comparison, the Li–Na diagram for the GC NGC 6397 from Lind et al. (2009).

(A color version of this figure is available in the online journal.)

Figure 4. Two portions of the spectra, centered on Li (left panel) and O (right panel), are shown for the stars 068, 083, and 085.

(A color version of this figure is available in the online journal.)

Our study increases the sample of Li determination in this cluster, completing the previous studies by Pasquini & Molaro (1997, Li for two stars) and by Bonifacio et al. (2007), who proposed a Li–Na anticorrelation on the basis of only four members.

To get more insight into this issue, we can compare it with a simple model. It is known that the Na–O anticorrelation can be well described by a simple dilution model, like the one proposed by Prantzos & Charbonnel (2006). On the other hand, Li abundances show a wide scatter, with values often well below those expected from a simple dilution model (red solid line in three panels of Figure 3). However, we cannot exclude that this model might represent the upper envelope of the Li distribution. In the case of 47 Tuc, Li is telling us something different from Na and O. Different mechanism(s) have to be invoked in order to explain the observed abundance pattern.

The distribution of Li abundances for 47 Tuc hence looks very different from that found for the metal-poor ([Fe/H] = −1.99; Carretta et al. 2009a) GC NGC 6397. In that case, a handful of Na-rich, Li-poor stars indicates a significant Li–Na anticorrelation (Lind et al. 2009), and a simple dilution model very well reproduces the Li and Na distributions (see the right-hand panel in Figure 3).

It is important to keep in mind that TO stars in 47 Tuc are cooler ($T_{\text{eff}} \sim 5700–5800$ K) than the TO stars of NGC 6397 ($T_{\text{eff}} \sim 6100–6300$ K), and they are well below the limit usually considered for the Spite plateau. The scatter found in Li abundances of 47 Tuc stars is reminiscent (or even better, is the Population II analog) of the large scatter of Li abundances obtained for solar twins in the old open cluster M 67 (Randich et al. 2000) and in general, for old thick disk stars with effective

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The basic equation of this model is $[X] = \log[(1 - \text{dil}) \times 10^{[X_O]+\text{dil}} \times 10^{[X]_p}]$, where $0 < \text{dil} < 1, [X_O]$ and $[X]_p$ are the logarithmic abundances of the element in the original and processed material, respectively.
temperatures close to $\sim5800$ K (Ryan et al. 2001). We note, however, that in this case the Li abundance variation is smaller with respect to typical values detected in Population I stars, probably because the latter ones are significantly more metal-rich.

4. SUMMARY AND CONCLUDING REMARKS

We present in this Letter Li, Na, and O abundances for a large sample ($\sim90$) of TO stars in the metal-rich GC 47 Tuc, providing the largest database of this kind available so far. Our main results can be briefly summarized as follows.

1. We obtained a very clear Na–O anticorrelation, confirming the previous findings from giants derived by Carretta et al. (2009a). This is the first time that the Na–O distributions in dwarfs and giants can be directly compared for a cluster using large samples of comparable sizes for both evolutionary stages. At least for 47 Tuc, evolutionary effects due to the RGB phase can be ruled out as contributors to the extent of Na–O anticorrelation, which in both cases span the same range (within the observational uncertainties).

2. As expected from stellar nucleosynthesis models in conjunction with multiple population scenarios, Li abundances should be positively correlated with O and anticorrelated with Na. At variance of the metal-poor GC NGC 6397, in the case of 47 Tuc the Li content does not show an anticorrelation with Na, and only a weak correlation appears with O, with a quite scatter distribution from both diagrams. Our result disagrees with the previous study by Bonifacio et al. (2007), who found Li–Na anticorrelation from a small sample of only four stars, and once again emphasizes the crucial role of statistics in this kind of analysis. A simple dilution model fails to reproduce the Li–Na–O distributions for this cluster and advocates the presence of some different mechanisms responsible for the observed Li pattern.

3. The scatter we find in Li abundances reminds of what has been detected, and reported in a large body of the literature, in Population I stars of similar parameters ($T_{\text{eff}}, \log g$), the most famous case being the open cluster M 67 (see, e.g., Randich et al. 2000).

We are not presently able to conclude if the trend we discovered in 47 Tuc is peculiar or, on the other hand, other GCs share a similar behavior. In fact, to date, only two GCs have been investigated from this point of view. In this context, we mention that we cannot explain the unlikeness in the Li–Na distributions between NGC 6397 and 47 Tuc; in particular, we cannot discriminate if the differences in $T_{\text{eff}}$’s or metallicity can account for such a discrepancy. To probe this issue, it is crucial to enlarge the sample of simultaneous determinations of Li, Na, O in GC dwarf stars, by including other (nearby) clusters with different structural parameters (e.g., HB morphology, age, metallicity).

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REFERENCES

Alonso, A., Arribas, S., & Martínez-Roger, C. 1996, A&AS, 117, 227
Asplund, M., Carlsson, M., & Botnen, A. V. 2003, A&A, 399, 31
Barklem, P. S., Piskunov, N., & O'Mara, B. J. 2000, A&A, 363, 1091
Bonifacio, P., et al. 2002, A&A, 390, 91
Bonifacio, P., et al. 2007, A&A, 462, 851
Cameron, A. G. W., & Fowler, W. A. 1971, ApJ, 164, 111
Carretta, E., Bragaglia, A., Gratton, R., D'Orazi, V., & Lucatello, S. 2009a, A&A, 508, 695
Carretta, E., Gratton, R., Bragaglia, A., Bonifacio, P., & Pasquini, L. 2004, A&A, 416, 925
Carretta, E., et al. 2007, A&A, 464, 939
Carretta, E., et al. 2009b, A&A, 505, 117
Carretta, E., et al. 2010, ApJL, in press (arXiv:1002.1963)
Cohen, J. G. 1978, ApJ, 223, 487
D'Antona, F., & Ventura, P. 2007, MNRAS, 379, 1431
Decressin, T., Charbonnel, C., Prantzos, N., & Ekstrom, S. 2007, A&A, 464, 1029
Denisenkov, P. A., & Denisenkova, S. N. 1990, SvAL, 16, 275
Ferraro, F. R., et al. 2009, Nature, 462, 483
Freeman, K. C., & Rodgers, A. W. 1975, ApJ, 201, 71
Gratton, R., Carretta, E., Bragaglia, A., Lucatello, S., & D'Orazi, V. 2010, A&A, submitted
Gratton, R., Carretta, E., Claudi, R., Lucatello, S., & Barbieri, M. 2003, A&A, 404, 187
Gratton, R., Carretta, E., Eriksson, K., & Gustafsson, B. 1999, A&A, 350, 955
Gratton, R., Sneden, C., & Carretta, E. 2004, ARA&A, 42, 385
Gratton, R., et al. 2001, A&A, 369, 87
Harris, W. E. 1996, AJ, 112, 1487
Kurucz, R. L. 1993, CD-ROM 13 (Cambridge, MA: Smithsonian Astrophysical Observatory)
Lind, K., Primas, F., Charbonnel, C., Grundahl, F., & Asplund, M. 2009, A&A, 503, 545
Marino, A. F., et al. 2009, A&A, 505, 1099
Momany, Y., et al. 2003, A&A, 407, 303
Pasquini, L., & Molaro, P. 1997, A&A, 322, 109
Pasquini, L., et al. 2005, A&A, 441, 549
Prantzos, N., & Charbonnel, C. 2006, A&A, 458, 135
Randich, S., Pasquini, L., & Pallavicini, R. 2000, A&A, 356, 25
Ryan, S., Kajino, T., & Beers, T. 2001, ApJ, 549, 55
Ventura, P., & D’Antona, F. 2009, A&A, 499, 835