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

Valentina D'Orazi[1], Sara Lucatello[1,2], Raffaele Gratton[1], Angela Bragaglia[3], Eugenio Carretta[3], Zhixia Shen[4], and Simone Zaggia[1]

Draft version February 26, 2010

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 intra-cluster 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. (2009a). 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.

Subject headings: Stars: abundances -Stars: Individual: Population II- (Galaxy:) globular clusters: individual: NGC 104

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The traditional paradigm of Globular Clusters (GCs) as the textbook example of a Simple Stellar Population is now outdated.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, Ti). Abundance variations in the lighter elements, namely Li, C, N, O, Na, Mg and Al, have been instead recognized since the 70's (e.g. Cohen 1978; see Gratton, Sneden & Carretta 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 enhanced.

A previous generation of stars, which synthesized in their interiors proton-capture elements, 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: (*i*) all the

GCs surveyed so far show the Na-O anticorrelation (Carretta et al. 2009a): this indicates the presence of at least two populations (neither coeval, nor chemically homogeneous) within each cluster. (*ii*) The primordial nature of such a phenomenon is uniquely indicated by the presence of these chemical signatures also among not evolved Turn-Off (TO) or scarcely evolved (subgiant, SGB) members (see e.g. Gratton et al. 2001).

In this context, Li abundances play a fundamental rôle. In fact, this element can be easily destroyed in stellar interiors (starting at $T_{burn}\approx2.5\times10^6$ 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-, 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 un-evolved 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 dilution 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 favoured 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

Electronic address: valentina.dorazi@oapd.inaf.it

[1] INAF–Osservatorio Astronomico di Padova, vicolo dell'Osservatorio 5 , I-35122, Padova, Italy

[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

[4] National Astronomical Observatories, Chinese Academy of Science, 20a Datun road, Beijing, China

to $\sim$1 dex below the Spite plateau values, clearly anti-correlated 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 sub-giant 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 $\sim$90 un-evolved turn-off (TO) stars of the GC 47 Tucanae, providing the *largest* database of this kind available in literature so far.

2. SAMPLE AND ANALYSIS

We retrieved from the ESO Archive FLAMES-Giraffe spectra (MEDUSA configuration) of 109 un-evolved members of the metal-rich GC 47 Tuc (Programme 081.D-0287, PI Z. Shen). The observations were carried out in Service mode on August–September 2008; gratings HR15n (R$\sim$17000), HR18 (R$\sim$18400) and HR20A (R$\sim$16000) were used to cover Li I (6707 Å), O I (7771, 7773, 7774 Å), and Na I (8183, 8194 Å) features, respectively.

The data reduction was performed with the ESO Giraffe pipeline[5] using GASGANO and following the standard procedure: bias subtraction, flat-field correction, wavelength calibration and optimal spectrum extraction. A careful sky subtraction has been done using the IRAF[6] task *skytweak* in order to take into account wavelength shifts and possible differences in emission line strengths between stellar and sky spectra. It is noteworthy that the presence of the moon at more than 90% illumination along with diffuse clouds caused some of the observed frames to be severely contaminated and were thus discarded (the night of August 17th). Different exposures were then co-added to improve S/N ratios, obtaining typical values of $\sim$50–100 per pixel (near the Li I region at $\sim$6708 Å).

The abundance analysis was carried out using the *ROSA* code (developed by R. Gratton) and Kurucz (1993) model atmospheres; for Na and O, we derived abundances from the equivalent widths (EWs), applying corrections due to NLTE effects (Gratton et al. 1999). LTE Li abundances were instead obtained through spectral synthesis. Stellar parameters were derived as follows: (i) we obtained initial effective temperatures (T_{eff}) from the de-reddened (E(B−V)=0.04, Harris 1996) B-V colours[7] and the calibration by Alonso et al. (1996). The adopted values were derived from a relation between V magnitude and colour-based T_{eff}. This reduces errors for individual stars. (ii) The surface gravities were estimated from the fundamental relation between M, L, and T_{eff} (log g=4.44+log(M/M$_\odot$) − log(L/L$_\odot$) +
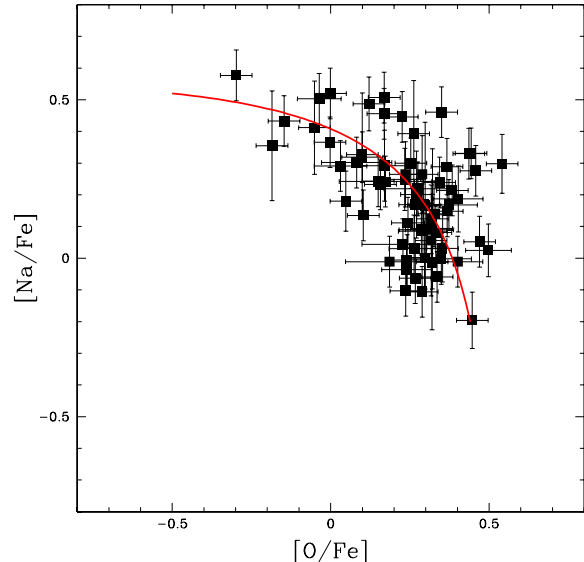

FIG. 1.— Na-O anticorrelation for 47 Tuc dwarf members; error-bars come from uncertainties on EWs. A dilution model (Prantzos & Charbonnel 2006) is also over-plotted as a a (red) solid line.

$4\log T_{eff} - 15.0447$), by adopting the bolometric corrections by Alonso et al. along with a distance modulus of 13.34 (Harris 1996), while M_{TO} was calculated in the same fashion described in Gratton et al. (2010, submitted).

Finally we assumed for all our sample stars microturbulence ξ=1.00 kms^{-1} (note that none of the elements under scrutiny is strongly affected by ξ values).

The [X/Fe] ratios were calculated assuming as solar references $\log n(Na)_\odot$=6.21 and $\log n(O)_\odot$=8.79, values obtained in a fully consistent fashion from the analysis of the solar spectrum by Gratton et al. (2003), and [Fe/H]=−0.76 (Carretta et al. 2009b) as cluster metallicity.

Both internal (random) errors and external (systematic) errors may affect our analysis. A discussion of the first kind of uncertainty, which is predominant for investigating star-to-star variations, can be found in Carretta et al. (2007); here we just mention that errors in EWs are dominant, while the internal uncertainties on stellar parameters (T_{eff}) can be neglected (note that the distance of a star on the color-magnitude diagram from the MS main loci represents the major error source in the adopted temperature values). Systematic errors due to the adopted set of model atmospheres and/or to reddening and T_{eff} scale can not be larger than $\sim$0.1 dex (see Bonifacio et al. 2002, 2007 and Gratton et al. 2001); in particular, for Li, the combination of 3D and NLTE effects yields negligible corrections (see e.g. Asplund et al. 2003).

All the abundance values with the corresponding uncertainties, along with magnitudes and coordinates are available only in electronic version.

3. RESULTS AND DISCUSSION

As shown in Fig. 1, the un-evolved cluster stars reveal a very clear Na-O anticorrelation, consistently with what has been obtained for giant members (Carretta et al. 2009a). We detected an oxygen variation of about

~0.80 dex and a change in Na of ~0.77 dex, to be compared with ~1 and 0.82 (O and Na respectively) for giants in Carretta et al. (2009a). The interquartile ranges IQR[Na/O] are 0.368±0.067 and 0.470±0.041, respectively. These two estimates are consistent at 1σ 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 ~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. (2009a). 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 the same $\Delta(\text{Na}) \sim 0.2$ dex). We propose that the way damping wings are treated is responsible of the observed difference. The present analysis uses values consistent with the Barklem et al. (2000) values; however, EWs are extracted using Gaussian profiles, which may result in systematic underestimates of the EWs for very strong lines, like the 8183-8194 Å ones. We then consider abundances from the weaker doublets as more reliable, 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 Fig. 2: after applying the derived offset in Na abundances, the cumulative [Na/O] functions look very similar, and a Kolmogorov-Smirnov test indicates that the two distributions cannot be distinguished (the probability from KS being ~14%).

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), can not 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. (2009a) the fractions of Primordial (P)[8] , 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. 2009a).

On the other hand, there is not a one-to-one correlation between Li and O abundances (left-hand panel of Fig. 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 (# 85) having $\log n(\text{Li}) = 2.78 \pm 0.08$ (this very Li-rich star, which appears as primordial type according to its O abundances,
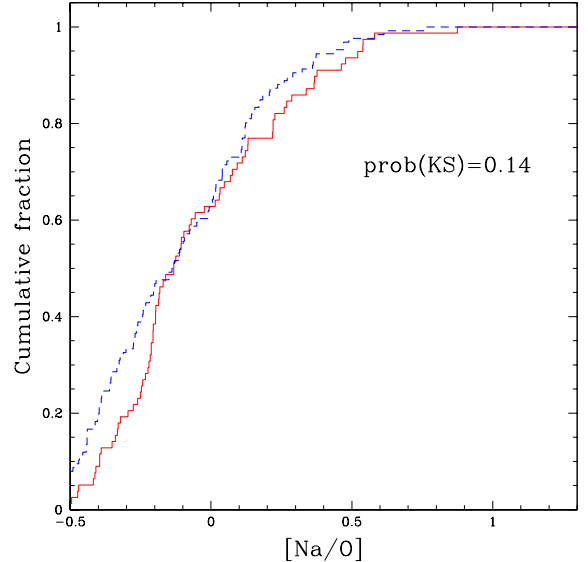

Fig. 2.— Cumulative [Na/O] distribution for dwarfs (red solid line) and giants (blue dashed line).

surely deserves special attention and further high resolution observations, in order to investigate this extreme behaviour). In Fig. 4 we show, as explicative example, the spectra of three stars with almost the same O abundances; one is star #85 and the two others have intermediate and low Li.

If we then focus on the Li-Na diagram (middle panel of Fig. 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 more than >99.5%, while the second one has no statistical meaning.

Our study increases the sample of Li determination in this cluster, completing the previous studies by Pasquini & Molaro (1997, Li for 2 stars) and by Bonifacio et al. (2007), who proposed a Li-Na anticorrelation on the basis of only 4 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[9], 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 three panels of in Fig. 3). However, we can not 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. 2009b) GC NGC 6397. In that case, a handful of Na-rich, Li-poor stars indicates

---

[8] The P stars must have $[\text{Na/Fe}] \leq [\text{Na/Fe}]_{\min} + 0.3$, then the remainig stars are divided in I and E according to [O/Na] larger and smaller than −0.9 dex, respectively.

[9] The basic equation of this model is: $[\text{X}] = \log[(1-\text{dil}) \times 10^{[\text{X}_{\text{O}}]} + \text{dil} \times 10^{[\text{X}_{\text{P}}]}]$, where $0 < \text{dil} < 1$, $[\text{X}_{\text{O}}]$ and $[\text{X}_{\text{P}}]$ are the logarithmic abundances of the element in the original and processed material.

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 Fig. 3).

It is important to keep in mind that TO stars in 47 Tuc are cooler ($T_{eff} \sim$5700-5800 K) than the TO stars of NGC 6397 ($T_{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 Pop 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 temperatures close to $\sim$5800 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 Pop. 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 ($\approx$90) 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:

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).

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 4 stars, and once again emphasizes the crucial rôle 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.

The scatter we find in Li abundances reminds of what has been detected, and reported in a large body of literature, in Pop. I stars of similar parameters (T_{eff}, $\log g$), the most famous case being the old 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 behaviour. In fact, to date, only two GCs have been investigated from this point of view. In this context, we mention that we can not neither explain the unlikeness in the Li-Na distributions between NGC 6397 and 47 Tuc; in particular, we can not discriminate if the differences in T_{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).

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, 109
Bonifacio, P., Pasquini, L., Spite, F., et al. 2002, A&A, 390, 91
Bonifacio, P., Pasquini, L., Molaro, P., et al. 2007, A&A, 462, 851
Cameron, A.G.W., Fowler, W.A. 1971, ApJ, 164, 111
Carretta, E., Gratton, R., Bragaglia, A., Bonifacio, P., Pasquini, L. 2004, A&A, 416, 925
Carretta, E., Bragaglia A., Gratton, R., et al. 2007, A&A, 464, 939
Carretta, E., Bragaglia, A., Gratton, R., et al. 2009a, A&A, 505, 117
Carretta, E., Bragaglia, A., Gratton, R. , D'Orazi, V., Lucatello, S. 2009b, A&A, 508, 695
Carretta, E., et al. 2010, in prep
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., Dalessandro, E., Mucciarelli, A., et al. 2009, Nature, 462, 483-486
Freeman, K.C., Rodgers, A.W. 1975, ApJ, 201, 71

Gratton, R., Carretta, E., Eriksson, K., Gustafsson, B. 1999, A&A, 350, 955
Gratton, R., Bonifacio, P., Bragaglia, A., et al. 2001, A&A, 369, 87
Gratton, R., Sneden, C., Carretta, E. 2004, ARA&A, 42, 385
Gratton, R., Carretta, E., Bragaglia, A., Lucatello, S., D'Orazi, V. 2010, A&A, *submitted*
Harris, W.E. 1996, AJ, 112, 1487
Kurucz, R.L. 1993, CD-ROM 13, Cambridge, Mass., Smithsonian Astrophysical Observatory
Lind, K., Primas, F., Charbonnel, C., Grundahl, F., Asplund, M. 2009, A&A, 503, 545
Marino, A.F., Milone, A., Piotto, G., et al. 2009, A&A, 505, 1099
Momany, Y., Cassisi, S., Piotto, G., et al. 2003, A&A, 407, 303
Pasquini, L., Molaro, P. 1997, A&A, 322, 109
Pasquini, L., Bonifacio, P., Molaro, P., 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
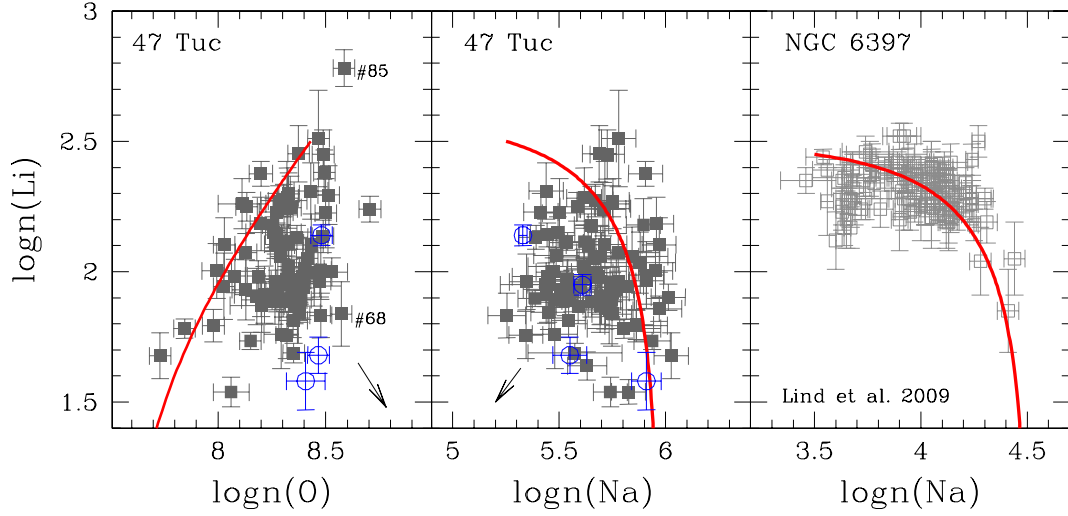Ventura, P., D'Antona, F. 2009, A&A, 499, 835

FIG. 3.— Run of Li with O and Na for 47 Tuc (left-hand 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 text). The arrow represents the effect on abundances of a change in T_{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).
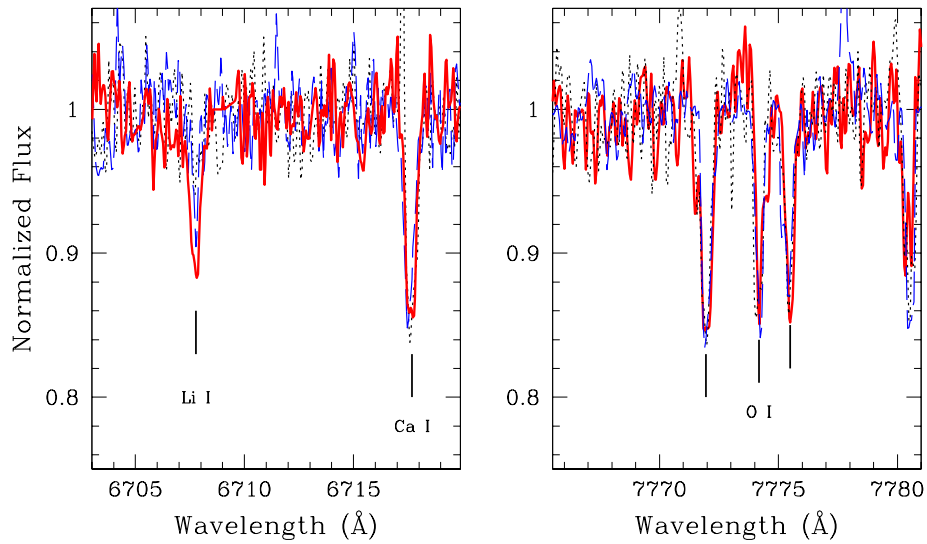

FIG. 4.— Two portions of the spectra, centered on Li (left panel) and O (right panel) are shown for the stars #068, #083, and #085.

V. D'Orazi et al.

TABLE 1
PROPERTIES OF TARGET STARS. WE REPORT OUR ID IN COL. (1), RA AND DEC IN COLS. (2) AND (3), WHILE MAGNITUDES V AND B ARE GIVEN IN COLS (4) AND (5). STELLAR PARAMETERS (T$_{\text{eff}}$ AND LOGg) ALONG WITH ABUNDANCES AND THEIR ERRORS ARE LISTED FROM COL.(6) TO (13), RESPECTIVELY. COMPLETE TABLE IS AVAILABLE ONLY IN ELECTRONIC FORM.

star$_{\text{ID}}$	RA (deg)	Dec (deg)	V (mag)	B (mag)	T$_{\text{eff}}$ (K)	log$g$ (dex)	logn(O) (dex)	err$_O$ (dex)	logn(Na) (dex)	err$_{Na}$ (dex)	logn(Li) (dex)	err$_{Li}$
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	9.999	1.998	0.130
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