Giants reveal what dwarfs conceal: Li abundance in lower RGB stars as diagnostic of the primordial Li

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ABSTRACT

The discrepancy between cosmological Li abundance inferred from Population II dwarf stars and that derived from Big Bang nucleosynthesis calculations is still far from being satisfactorily solved. We investigated, as an alternative route, the use of Li abundances in Population II lower red giant branch stars as empirical diagnostic of the cosmological Li. Both theory and observations suggest that the surface Li abundance in metal poor red giants after the completion of the first dredge-up and before the red giant branch bump, are significantly less sensitive to the efficiency of atomic diffusio, compared with dwarf stars. The surface Li abundances in these objects – after the dilution caused by the first dredge-up – are predicted to be sensitive to the total Li content left in the star, i.e. they are affected only by the total amount of Li eventually burned during the previous main sequence phase. Standard stellar models computed under different physical assumptions show that the inclusion of the atomic diffusion has an impact of about 0.07 dex in the determination of the primordial Li abundance – much smaller than the case of metal poor main sequence-turn off stars – and it is basically unaffected by reasonable variations to the models, i.e. neglecting Li destruction caused by the process competing with atomic diffusion. We have determined from spectroscopy the surface Li content of 17 Halo lower red giant branch stars, in the metallicity range between $[\text{Fe/H}] \sim -3.4$ and $-1.4$ dex, evolving before the extra-mixing episode that sets in at the red giant branch bump. The initial Li (customarily taken as estimate of the cosmological Li abundance $A(Li)_0$) has then been inferred by accounting for the difference between initial and post-dredge up Li abundances in the appropriate stellar models. It depends mainly on the $T_{\text{eff}}$ scale adopted in the spectroscopic analysis, and is only weakly sensitive to the efficiency of atomic diffusion in the models, so long as one neglects Li destruction caused by the process competing with atomic diffusion. Our final $A(Li)_0$ estimate spans a relatively narrow range, between 2.28 and 2.46 dex, and is $\sim 0.3–0.4$ dex lower than predictions from Big Bang nucleosynthesis calculations.

Key words: stars: abundances – stars: atmospheres – stars: evolution – stars: Population II – (Galaxy:) globular clusters: individual (M4, NGC6397, NGC6752)

1 INTRODUCTION

The discovery by Spite & Spite of a uniform Li abundance in the atmospheres of main sequence (MS) Halo field stars with $T_{\text{eff}}$ above $\sim 5500 – 5900$ K and [Fe/H] below about $-1.5$ dex – the so-called Spite Plateau – has been widely interpreted as a signature of the cosmological abundance of lithium, produced dur-
ing the Big Bang nucleosynthesis (BBN). Adopting the standard notation $A(Li) = \log(n(Li)/n(H))+12$, the Spite Plateau value is between 2.1 and 2.4, depending mostly on the adopted $T_{eff}$ scale (see, e.g., Bonifacio & Molaro 1997; Charbonnel & Primas 2000; Asplund et al. 2006; Bonifacio et al. 2007; Aoki et al. 2009; Sbordone et al. 2010 and references therein).

Estimates of the cosmological baryon density obtained from the power spectrum of the cosmic microwave background fluctuations (Spergel et al. 2003) combined with standard BBN calculations, predict however a cosmological $A(Li)_{0} = 2.72 \pm 0.06$ (Cyburt et al. 2008). Taken at face value, the BBN $A(Li)$ is higher – by at least a factor of 2 – than $A(Li)$ measured in Spite Plateau stars.

The interpretation of Spite Plateau abundances in terms of the initial chemical composition of Halo stars needs however to take into account the possible effect of diffusion on the star surface chemical composition. Stellar models that include only convection as element transport mechanism predict for Spite Plateau stars a negligible pre-MS Li depletion, and no changes of the surface abundances during the whole MS phase. With these assumptions, the observed $A(Li)$ is essentially equal to the primordial value.

On the other hand, detailed stellar evolution calculations need to include additional transport mechanisms that follow from first principles. In low mass stars, atomic diffusion – i.e. the slow transport of chemicals due to temperature, pressure and abundance gradients – is the main process that needs to be included, for taking diffusion into account, the agreement between solar models and constraints from helioseismology is greatly improved (see, i.e. Bahcall et al. 1997). A general prediction of models including atomic diffusion is that Population II MS stars in the Spite Plateau region, with their shallow convective envelopes, are efficiently depleted of Li and metals over the MS lifetime (see, e.g., the seminal paper by Deliyannis et al. 1996). Moreover, the surface Li depletion is a function of the star initial metallicity (and $T_{eff}$), because of the associated variation of the depth of the convective envelopes. These predictions are at odds with the observed constant (both as a function of $[Fe/H]$ and $T_{eff}$) $A(Li)$ along the plateau (but see also Sbordone et al. 2014, for the evidences of a meltdown of the Spite plateau in the very metal-poor regime). Inclusion of radiative levitation (Richard et al. 2003) leaves the overall picture unchanged. For $[Fe/H]$ below $\sim -2.0$ dex radiative levitation moderates the surface depletion of Li due to atomic diffusion but the general picture is not qualitatively modified, whereas at higher metallicities the effect on the surface Li is negligible. Overall, the depletion of Li in Spite Plateau stars due to atomic diffusion (plus radiative levitation) can reach several tenths of a dex at the lowest metallicity and/or higher $T_{eff}$.

For the models with diffusion (and radiative levitation) to display uniform $A(Li)$ abundances along the Spite Plateau, one needs to include some ad-hoc turbulent mixing in the radiative zone below the convective boundary, that limits the settling of Li. Richard et al. 2003 include a specific parametrization of turbulent mixing, treated as a diffusive process, with a free parameter that fixes the values of the turbulent diffusion coefficient. A suitable calibration of this parameter – that enables also the transport of additional lithium down to burning temperatures – produces a flat Li abundance along the plateau, with $A(Li)$ depleted by about 0.4 dex with respect to the initial value (see Fig. 8 in Richard et al. 2003). This depletion, when applied to the range of $A(Li)$ measured by different authors, can potentially bring into agreement the Spite Plateau with BBN predictions.

Richard (2008) includes instead the effect of a rotationally induced tachocline mixing (Spiegel & Zahn 1992) as employed in solar models (Brun et al. 1993) to improve the agreement between theoretical and observed sound speed. Also in this case mixing is treated as a diffusive process, and the author discusses the calibration of the associated free parameters and the dependence on the assumed rotation history. As a result, tachocline mixing – that in plateau stars moderates the efficiency of atomic diffusion – appears to be able to produce a uniform $A(Li)$ along the Spite Plateau, with a depletion of 0.2 dex compared to the initial value. Given the range of measured $A(Li)$, the agreement with the BBN lithium abundance is still marginal at best.

Similar estimates of primordial Li based on spectroscopy of MS stars in globular clusters are complicated by the fact that in many cases the observed $A(Li)$ display spreads related to the presence of second generation stars (see, e.g., Bonifacio et al. 2002; D'Orazi et al. 2010 and references therein). The metal poor cluster NGC6397 is one object with apparently an essentially homogeneous initial Li abundance and Korn et al. (2006a) spectroscopic measurements plus the models by Richard et al. 2003 with a suitably calibrated efficiency of their turbulent mixing parametrization – that turns out to be different from the case of field halo dwarfs – are able to reproduce the observed $A(Li)$ (and $[Fe/H]$) measurements at the MS turn off and the base of the red giant branch (RGB), for an initial $A(Li)=2.54$. The models fail however to match the observed post dredge-up Li abundance on the lower RGB, before the RGB bump. A recent reanalysis by Lind et al. 2004 have revised down this value, to $A(Li)=2.46$. A detailed comparison with the observed post dredge-up Li abundance is not presented. Moreover, Lind et al. 2009 conclude: “We find that some turbulence, in a very limited efficiency-range, is indeed required to explain observations. These models” (including atomic diffusion plus turbulent mixing parametrized as in Richard et al. 2003) “fail to reproduce the behaviour of Li abundance with effective temperature along the plateau, suggesting that a detailed understanding of the physics responsible for depletion is still lacking.” Note also that the assumption of a different temperature scale leads to different results, in terms of match between observations and models, as pointed out by González Hernández et al. 2009.

Another cluster that does not show signatures of a spread in the initial Li abundance is M4. Mucciarelli et al. 2009 shows that models including diffusion plus turbulence with the same efficiency invoked for NGC6397, fail in case of M4. It appears that, in order to reproduce the Li abundances from the turn off to the lower RGB and satisfy at the same time the BBN constraint, for this cluster the turbulence has to reach deeper regions compared to NGC6397, region hot enough for some additional Li burning to occur. The trend of lithium abundance with effective temperature along the

1 One has to notice that in Richard et al. 2003 the term atomic diffusion includes also the process of radiative levitation.
sub-giant branch, found in M4 by [Mucciarelli et al. (2011) is similar to that found by González Hernández et al. (2009) in NGC 6397.

This brief summary of previous investigations shows how problematic, from a theoretical point of view, it is to determine the primordial Li abundance of Spite Plateau stars. In this paper we investigate a complementary avenue to estimate the Halo primordial A(Li). We employ spectroscopy of Halo stars evolving along the lower RGB, defined – following Gratton et al. (2000) – as the portion of the RGB brighter than the luminosity corresponding to the completion of the first dredge-up and fainter than the RGB-bump. We will show that the effect of atomic diffusion on the surface Li abundances of these objects is much smaller than for Spite Plateau stars. As a consequence, the observed A(Li) can be employed to set independent, very strong constraints on any additional physical process (i.e., turbulent mixing, preprocessing of Halo material, modifications to the BBN) eventually needed to reconcile these values with BBN predictions.

The paper is structured as follows. Section 2 analyzes the theoretical advantages of employing A(Li) measured in the atmosphere of lower RGB Halo stars to estimate their primordial Li abundance, while Sect. 3 discusses our selected sample of lower RGB halo objects and the derivation of A(Li) and [Fe/H]. Section 4 presents theoretical predictions for the surface Li abundance in Population II lower RGB stars – from models including atomic diffusion and convection as element transport mechanisms – and the derivation of the initial Li for our selected star sample, that provides an estimate of the Halo primordial Li abundance independent of the Spite Plateau. Section 5 discusses the Li abundance in the lower RGB of the Galactic globulars NGC 6397, NGC 6752 and M4. A summary and conclusions close the paper.

2 WHY LOWER RGB STARS?

The surface Li abundance after the first dredge-up is essentially a consequence of the dilution due to the increased size of the convective envelope after the MS turn off (plus a minor contribution from Li burning in the deep layers of the fully mixed envelope in the most metal rich Halo stars). At the end of the MS phase, when the deepening convective boundary reaches layers where the Li-burning (\(T_{\text{burn}} \sim 2.5 \times 10^6\) K) was efficient during the MS, the surface A(Li) begins to decrease. This depletion essentially ends when the convective envelope attains its maximum depth and the first dredge-up is complete. An important point to notice is that atomic diffusion during the MS produces a local maximum of the Li abundance in the radiative layers right below the convective envelope (see, e.g., Richard et al. 2005), for only a relatively small fraction of the envelope Li is transported deep enough to affect these layers when it is eventually burned. As a consequence, models without and with diffusion – fully efficient or even moderated by levitation or some turbulence that just mixes back material diffused from the envelope – dilute similar amount of Li within the deepening convective region. In addition, the maximum size of the convective envelope is also weakly affected by diffusion – this can also be inferred by the fact that the predicted RGB bump luminosities with and without diffusion are very similar (Cassisi et al. 1997, Michaud et al. 2010) – and the resulting A(Li) abundances on the lower RGB are only slightly changed. This is in contrast with models for upper MS stars, where the effect of diffusion on the surface abundances can reach several tenths of dex (see for example Fig. 3 in [Mucciarelli et al. 2011]). Theoretical models also predict that along the RGB, after the completion of the dredge-up, atomic diffusion and levitation are not able to modify appreciably the surface abundance of Li and all other elements (Michaud et al. 2007, 2010).

The chemical abundance measurements in giant stars by Gratton et al. (2000), Spite et al. (2003) and Lind et al. (2009), suggest that any additional element transport along the RGB is very likely inefficient in this phase. On the other hand, stars evolved beyond the RGB bump display the effect of an additional mixing event, for which the so-called ‘thermohaline mixing’ is nowadays the most popular candidate (see, e.g., Charbonnel & Lagarde 2010, and references therein).

These considerations lead to the conclusion that in general there is a simpler relationship between initial and current surface Li abundances in lower RGB stars compared to Spite Plateau objects. The basic reason is that, for a fixed initial Li abundance, lower RGB surface abundances are sensitive to the total amount of Li left in the star. In fact, after the effect of dilution is accounted for, they are affected only by the total amount of Li burned during the MS phase due to atomic diffusion plus possible additional element transport mechanisms – if they are invoked to solve the discrepancy with BBN results. On the other hand, the observed abundances along the Spite Plateau are determined by the evolution of the rate of Li depletion from the convective envelope due just to diffusion or moderated/enhanced by additional turbulent processes. Combining the information obtained from Li in lower RGB stars with Spite Plateau data, sets much stronger constraints on how these proposed additional mixing processes act between the base of the convective envelope and the deeper Li burning regions.

In this study, we address the issue of the Halo primordial Li abundance by coupling predictions from standard RGB stellar models to the Li abundances measured on a sample of lower RGB Population II field stars. As discussed before, this will provide an independent quantitative estimate of the difference (if any) with the Big Bang value, and set a very robust constraint on the efficiency of additional physical processes invoked to resolve this discrepancy, complementary to the interpretation of the abundances along the Spite Plateau. If the solution of the discrepancy involves pre-processing during the Galaxy formation or modifications to the BBN (see, e.g., Piau et al. 2006; Cyburt et al. 2010), our analysis will provide a solid quantitative estimate of, respectively, the net amount of Li burned during the early Galaxy evolution, or exactly how much Li must be synthesized in the ‘revised’ BBN.

To the best of our knowledge, analyses of the Li abundances measured along the RGB have been so far mainly aimed at testing the agreement between observed and predicted Li depletion after the first dredge-up, assuming a value for the initial A(Li), often equal to what measured along the plateau (García Pérez & Primas 2006).
3 LI ABUNDANCES IN LOWER RGB FIELD HALO STARS

This section presents the observational data employed in our study, and the abundance analysis. Particular care is paid to the issue of the effective temperature scale and its influence on the derived values of A(Li).

3.1 Dataset

We have selected a sample of 17 metal-poor stars (with [Fe/H]<−1 dex), located in the part of the RGB fainter than the RGB bump magnitude level. The selection of this sample was done by cross checking data by Cayrel de Strobel, Soubiran & Ralite (2001), the SIMBAD website, previous works on chemical abundances in metal-poor giant stars (Burris et al. 2000; Gratton et al. 2000; Mucciarelli et al. 2003), and the ESO and ELODIE archives, in order to select suitable high-resolution spectra, covering the Li line at 6708 Å.

Spectra of 11 stars were retrieved from the ESO archive and observed with UVES (Dekker et al. 2000), employing simultaneously different gratings. We used spectra obtained with the CD#3 cross-disperser with a nominal spectral resolution of ~54000 and a spectral coverage between ~4760 and 6820 Å, to measure Li and Fe abundances, and spectra obtained with the grating CD#1 (~3050–3870 Å) or CD#2 (~3760–4980 Å) to measure C abundances and the 12C/13C isotopic ratios. For 6 stars we used spectra from the ELODIE archive (Moutaka et al. 2004), with a spectral resolution of ~42000 and a coverage between ~4000 and 6800 Å.

Table 1 summarizes the main information for these stars (identification number of the corresponding catalog, adopted instrument, atmospheric parameters, abundances and SNR per pixel around the Li doublet).

3.2 Abundance analysis

The abundance analysis was performed by means of the codes SYNTHE (to compute synthetic spectra, Kurucz 1993a, 2003) and WIDTH (that predicts the abundance of a given species by matching the observed and theoretical equivalent widths, Kurucz 1993a, Castelli 2005), coupled to the ATLAS9 model atmospheres (Kurucz 1993a, 2005). We used the Linux version of all the codes (Sbordone et al. 2004; Sbordone 2005). The ATLAS9 models employed in this work were computed with the new set of Opacity Distribution Function (Castelli & Kurucz 2003) and without the inclusion of the approximate overshooting in the calculation of the convective flux.

Iron abundances were obtained from line equivalent widths (EWs) using WIDTH; EWs were measured using the DAOSPEC code (Stetson & Pancino 2008), that performs an automatic measurement of the EWs under the gaussian profile approximation. The adopted linelist includes a hundredth of neutral iron lines whose oscillator strengths are from the recent compilation of accurate laboratory log gf by Fuhr & Wiese (2006) and ~15-20 single ionized iron lines by Raassen & Uylings (1998). For each star we refine iteratively the linelist in order to include only lines predicted to be unblended from the inspection of synthetic spectra computed with the atmospheric parameters and metallicity of each target. The resulted iron abundances were scaled to the solar iron abundance of 7.52 (Caffau et al. 2010). Total uncertainties in the Fe abundances were computed by taking into account the internal error (obtained as the dispersion of the mean normalized to the root mean square of the number of used lines) and the errors related to the atmospheric parameters.

Li abundances were derived with the help of spectral synthesis, in order to take into account the hyperfine structure and the isotopic splitting of the Li resonance doublet at 6707.8 Å. The linelist for the Li transitions is from Yan & Drake (1995). Corrections for departures from LTE are from Carlson et al. (1994). The total error in the A(Li) abundance is computed by taking into account the two main source of uncertainty: (i) the error in the adopted $T_{\text{eff}}$, typically $\delta A(Li) / \delta T_{\text{eff}} \sim$0.09-0.10 dex per 100 K for a giant star (giant stars are slightly more sensitive to $T_{\text{eff}}$ with respect to the dwarf stars, that are sensitive at a level of $\delta A(Li) / \delta T_{\text{eff}} \sim$0.06-0.07 dex per 100 K); (ii) the error in the fitting procedure, obtained by employing MonteCarlo simulations: for each star, we injected Poisson noise into the best-fit synthetic spectrum (in order to reproduce the observed SNR around the Li line) and we repeated the analysis for 1000 MonteCarlo events. We estimated a 1σ level from the resulting abundance distributions; due to the high SNR of the analyzed spectra (>100), the typical errors are lower than 0.03 dex. The errors due to uncertainties on gravity and microturbulent velocity are negligible (of the order of 0.01 dex or less).

We measured also the isotopic ratio $^{12}$C/$^{13}$C in order to robustly assess whether the stars have experienced the additional mixing at/after the RGB bump, and establish their precise evolutionary stage. Being the spectra obtained with different instruments and configurations, we need to use different indicators for the C abundance and its isotopic ratio. For the ELODIE spectra and for those stars observed with the UVES grating CD#2, C abundance and $^{12}$C/$^{13}$C ratio were estimated by spectral synthesis of the $^2\Delta - ^2\Pi$ band of CH (the G band) at ~4310 Å. For the stars for which the grating CD#2 is not available, we used the bluest portion of the spectrum (obtained with the CD#1 grism), covering the spectral region of 3000–3800 Å. For these stars C was obtained from the $^4\Sigma - ^2\Pi$ band of CH at 3143 Å and from other CH transitions in the range between 3088 and 3115 Å. These regions have been used also to measure the $^{12}$C/$^{13}$C ratio. The atomic and molecular linelists were taken from the Kurucz compilation. For the CH transitions, the log gf by the Kurucz database were revised downward by 0.3 dex, in order to well reproduce the solar-flux spectrum by Neckel & Labs (1984) with the C abundance by Caffau et al. (2010); similar corrections were applied also by other authors, see e.g., Bonifacio et al. (1998) and Lucatello et al. (2003). As a first guess we derived C by assuming the solar $^{12}$C/$^{13}$C ratio; then, we computed synthetic spectra varying the $^{12}$C/$^{13}$C ratio, keeping C fixed. The procedure was repeated until...
the convergence within a tolerance of 0.1 dex in the C abundance. Only upper limits can be inferred for several stars in our sample, due to the low intensity of the \(^{13}C/H\) transitions (only for the most metal-poor star in the sample, namely CD \(-30^\circ\)298, we cannot provide a reliable and strict upper limit).

### 3.3 Lithium abundance from excitation temperatures

We performed a fully spectroscopic analysis of the target stars, to derive their atmospheric parameters. They were computed by imposing no trend between neutral iron lines abundances and excitation potential \(\chi\) (to constrain \(T_{\text{eff}}\)), no trend between neutral iron lines abundances and the reduced equivalent width \(\log EW/\lambda\) (to constrain the microturbulent velocity) and the same abundance (within the quoted uncertainties) from neutral and single ionized iron lines (to constrain the gravity).

We noted that the iron lines with \(\chi < \sim 1\) eV exhibit abundances systematically higher than the other lines for stars with metallicity lower than \(-2.5\) dex. Even if the adopted \(T_{\text{eff}}\) provides no dependence between Fe I abundance and \(\chi\) in the range of \(1\sim 5\) eV, the low-\(\chi\) lines give abundances higher by \(\sim 0.3\) dex. We excluded from the analysis the Fe I lines with \(\chi < 1\) eV, because their inclusion can force a too low \(T_{\text{eff}}\) (with a reduction of about 200 K), in order to erase a spurious slope. For more metal-rich stars, this discrepancy is reduced or totally erased. This effect was already noted in other studies of metal-poor stars (Norris, Ryan & Beers 2001; Carretta et al. 2002; Cayrel et al. 2004) and probably ascribable to some inadequacies of the model atmospheres based on the assumptions of 1-dimensional geometry and/or LTE: in fact, the low-\(\chi\) lines are typically formed in the outermost layers of the photosphere, that are exposed to the UV radiation coming from the deep layers (thus, the non-LTE effects are more pronounced in metal-poor stars because of the low opacity and high transparency of the photosphere).

The derived iron abundances range from [Fe/H] = \(-3.40\) dex to [Fe/H] = \(-1.43\) dex. The average Li abundance inferred from these 17 giants turns out to be \(A(\text{Li}) = 0.97\) dex (\(\sigma = 0.06\) dex).

Figure 1 shows the behaviour of the sample stars as a function of [Fe/H] and \(T_{\text{eff}}\) (upper and lower panel, respectively). We checked for the occurrence of slopes in these two planes, performing least-square fits by considering the errors in both variables (following the approach by Press et al. 1992). In the \(A(\text{Li})-\text{[Fe/H]}\) plane we derived a slope of 0.018 dex/dex (with an error of 0.044 dex/dex), while in the \(A(\text{Li})-T_{\text{eff}}\) we find a slope of 0.013 dex/100 K (with an error of 0.028 dex/100 K).

Eight stars in our sample are in common with Gratton et al. (2000). We find a difference in the adopted temperatures of \(T_{\text{eff}}^{\text{Gratton00}} - T_{\text{eff}}\) = \(-107\) K (\(\sigma = 41\) K), probably due to their \(T_{\text{eff}}\) scale, based on the grids of synthetic colors computed by R. L. Kurucz by means of the ATLAS9 model atmospheres with the inclusion of the approximate overshooting and adopting the old set of Opacity Distribution Function (we refer the reader to Castelli & Kurucz 2003, for details about the differences between the two set of ATLAS9 models). The mean \(A(\text{Li})\) difference for the stars in common is \(A(\text{Li})^{\text{Gratton00}} - A(\text{Li}) - 0.19\) dex (\(\sigma = 0.07\) dex), partially due to the different \(T_{\text{eff}}\) scales. The residual discrepancy most likely stems from the adoption of overshooting model atmospheres, that provide higher Li abundances, as pointed out by Molaro, Bonifacio & Primas (1993).

Ten stars are in common with García Pérez & Primas (2006); we find average differences \(T_{\text{eff}}^{\text{Garcia-Perez06}} - T_{\text{eff}}\) = \(-80\) K (\(\sigma = 84\) K) and \(A(\text{Li})^{\text{Garcia-Perez06}} - A(\text{Li}) = -0.11\) dex (\(\sigma = 0.11\) dex).

Figure 2 shows the position of the target stars in the \(T_{\text{eff}} - \log g\) plane, together with theoretical isochrones by Pietrinferni et al. (2003), computed with an age of 12.5 Gyr and metallicities Z=0.0001, 0.0003, 0.0006 and 0.001. These isochrones were computed with the same input physics, code, metal distribution and \(\Delta Y/\Delta Z\) of our calculations. The position of the RGB bump is marked for reference as a grey shaded region. All the stars are located (within the uncertainties in the atmospheric parameters) below the RGB bump level, as confirmed also by the \(^{12}C/^{13}C\) ratio higher than \(\sim 15\) und. \(\Delta Y/\Delta Z\) of our calculations. The occurrence of the extra-mixing episode after the RGB bump decreases dramatically the \(^{12}C/^{13}C\) ratio, reaching values lower than 10 (see for instance Gratton et al. 2004, Spite et al. 2004). This confirms, together with the homogeneous distribution of \(A(\text{Li})\), that all these stars have not yet experienced the extra-mixing episode. The figure also shows that essentially all stars in our sample have attained the final surface \(A(\text{Li})\) values, before the onset of the post RGB bump extra mixing.

### 3.4 Lithium abundance from Infrared Flux Method temperatures

As a sanity check to assess the robustness of the average \(A(\text{Li})\) value we repeated the analysis of the target stars
with other $T_{\text{eff}}$ scales, the temperature being the most crucial parameter in the derivation of $A(\text{Li})$. We infer $T_{\text{eff}}$ in our targets by means of suitable transformations between dereddened broad-band colors and effective temperatures obtained through the classical Infrared Flux Method (IRFM; Blackwell, Petford & Shallis 1980). Several $T_{\text{eff}}$ scales based on this technique are available in literature (e.g., Montegriffo et al. 1999; Alonso, Arribas & Martinez-Roger 1999; Ramirez & Melendez 2005; Mashonkina et al. 2011) of the Drawin formula (Drawin 1968, 1969), different authors provide different non-LTE corrections for iron (see for instance Gratton et al. 2004, providing very different results). For some stars, $E(B-V)$ is larger than 0.4 mag and the interstellar doublet Na I lines (at 5890 and 5896 Å), through the calibration by Munari & Zwitter (1997).

Gravities and microturbulent velocities have been derived spectroscopically, as described in the previous Section. The differences between the photometric and spectroscopic scales are equal to $T_{\text{eff,phot}} - T_{\text{eff,spec}} = +102$ K ($\sigma = 55$ K) and $T_{\text{eff,phot}} - T_{\text{eff,spec}} = +4$ K ($\sigma = 57$ K). This difference is fully consistent with the intrinsic difference between the two scales (see the discussion in G09). Consequently, we derived an average $A(\text{Li})$ of 0.97 dex ($\sigma = 0.07$ dex) and 1.07 dex ($\sigma = 0.07$ dex) when $T_{\text{eff}}$ by A99 and G09 are adopted, respectively.

Thus, the spectroscopic $T_{\text{eff}}$ and those obtained with the A99 calibration can be considered on the same scale, while the scale by G09 is slightly hotter, providing Li abundances ~0.1 dex higher.

Finally, we note that the general agreement between spectroscopic and photometric $T_{\text{eff}}$ (apart from the different zero-points) seems to indicate that no relevant departures from the LTE condition occurs, at least when the low-$\chi$ lines are excluded for the most metal-poor stars.

To date, there is no general consensus about the magnitude of non-LTE corrections for iron, due to the incompleteness of the Fe model atom and the uncertainty about the rate of collision with the hydrogen atoms. Adopting several recipes for the calibration of the $S_H$ parameter, the scaling-factor to correct the H I collision rate provided by the Steenbock & Holweger generalisation (Steenbock & Holweger 1984) of the Drawin formula (Drawin 1968, 1969), different authors provide different non-LTE corrections for iron (see for instance Gratton et al. 1999; Gehren et al. 2004, providing very different results).

Mashonkina et al. (2011) analyzed a metal-poor giant star (slightly colder than those discussed here) by considering the LTE case and the non LTE case with different efficiencies for the collision rate, and found that in case of $S_H=0.1$ (corresponding to a low efficiency of collisions with

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**Table 1.** Identification numbers, adopted instrument, temperatures, gravities, microturbulent velocities, [Fe/H] and $A(\text{Li})$ abundances, $^{12}\text{C}/^{13}\text{C}$ isotopic ratio and SNR around the Li line, for the observed stars.

| ID    | Instrument | $T_{\text{eff}}$ (K) | log g | $v_t$ (km/s) | [Fe/H] | $A(\text{Li})$ | $^{12}\text{C}/^{13}\text{C}$ | SNR |
|-------|------------|----------------------|-------|-------------|--------|--------------|----------------|-----|
| HD 2665 | ELODIE     | 4950                 | 2.20  | 1.80        | -2.18  | 0.95         | 40             | 250 |
| HD 6755 | ELODIE     | 5100                 | 2.30  | 1.50        | -1.57  | 1.01         | >20            | 110 |
| HD 26169 | UVES       | 5050                 | 1.90  | 1.50        | -2.43  | 0.99         | >30            | 320 |
| HD 27928 | UVES       | 5000                 | 2.00  | 1.50        | -2.33  | 1.04         | >30            | 370 |
| HD 45282 | ELODIE     | 5200                 | 2.80  | 1.50        | -1.56  | 1.01         | >30            | 230 |
| HD 87140 | ELODIE     | 5300                 | 2.50  | 1.50        | -1.83  | 0.92         | 35             | 150 |
| HD 111721 | UVES      | 4950                 | 2.30  | 1.30        | -1.43  | 0.98         | 40             | 370 |
| HD 128279 | UVES      | 5300                 | 2.60  | 1.70        | -2.21  | 1.02         | >35            | 280 |
| HD 175305 | ELODIE     | 5050                 | 2.40  | 1.50        | -1.45  | 1.07         | 30             | 180 |
| HD 200654 | UVES      | 5150                 | 2.10  | 1.50        | -2.96  | 0.98         | >35            | 290 |
| HD 211998 | UVES      | 5200                 | 2.90  | 1.20        | -1.59  | 0.97         | 40             | 540 |
| HD 218857 | UVES      | 5000                 | 1.90  | 1.30        | -2.05  | 0.92         | >25            | 330 |
| HD 274939 | UVES      | 5000                 | 2.00  | 1.50        | -1.74  | 0.96         | >20            | 310 |
| BD+01°2582 | UVES     | 5000                 | 1.90  | 1.10        | -2.39  | 0.82         | 40             | 280 |
| BD+23°3130 | ELODIE   | 5200                 | 2.20  | 1.50        | -2.59  | 0.92         | >15            | 170 |
| CD−24°1782 | UVES     | 5000                 | 2.10  | 0.80        | -2.91  | 0.96         | >20            | 280 |
| CD−30°0298 | UVES     | 5100                 | 2.10  | 1.80        | -3.40  | 0.99         | —              | 330 |
equal to \((0.245, 0.00001), (0.245, 0.0001), (0.245, 0.0003), (0.248, 0.002), (0.251, 0.004)\) that correspond to \([\text{Fe}/\text{H}]=-3.62, -2.62, -2.14, -1.31, \) and \(-1.01\), respectively. The adopted \(\Delta Y/\Delta Z=1.4\) is the same as in \(\text{Pietrinferni et al. (2006)}\). For each metallicity we calculated the evolution of one stellar mass whose age along the RGB is equal to \(\sim12.5\) Gyr, and followed its evolution from the pre-MS to luminosities beyond the RGB bump. The range of mass values is comprised between \(\sim0.80\) and \(\sim0.86M_\odot\), increasing with increasing Z. The initial \(A(\text{Li})\) for all metallicities was fixed at the BBN predicted value of 2.72 dex. We have also calculated models with an initial Li abundance increased or decreased by one order of magnitude and found – as expected – that the amount of depletion after the first dredge-up (\(\Delta(\text{Li})\)) is insensitive to the exact value of the initial \(A(\text{Li})\).

Figure 3 displays the evolution of the surface Li abundance of models with initial \([\text{Fe}/\text{H}]=-1.01\). The evolution without diffusion displays a 0.03 dex pre-MS depletion, followed by the MS evolution with unchanged surface \(A(\text{Li})\). Dilution due to the deepening of the convective envelope at the end of the MS starts at \(T_{\text{eff}}\sim5900\) K, and continues until the first dredge-up is completed, at \(T_{\text{eff}}\sim5100\) K, when the model is already evolving along the RGB. As for the evolution with fully efficient atomic diffusion, the surface Li decreases during the MS and reaches a minimum around the turn off. After this point \(A(\text{Li})\) at first increases, due to the deepening convection that returns to the surface part of the Li diffused outside the envelope along the MS. After a local maximum at \(T_{\text{eff}}\sim5850\) K, \(A(\text{Li})\) starts to drop, for the convective envelope reaches regions where Li has been burned (see, e.g. \(\text{Deliyannis et al. (1996)}\), \(\text{Salaris \\& Weiss (2001)}\). The surface Li abundance at the end of the dredge-up is only 0.07 dex lower when diffusion is fully efficient.

Table 2 displays \(\Delta(\text{Li})\) (in dex) for the metallicity range spanned by our calculations, and an age of 12.5 Gyr. An important point to notice is that the \([\text{Fe}/\text{H}]\) values reported in the first column are the initial values. In models without diffusion \([\text{Fe}/\text{H}]\) at the surface stays constant all along the MS and is negligibly affected by the increase of surface He (and associate decrease of H) after the first dredge-up. However, when diffusion is fully efficient, it decreases during the MS, because of the sinking of Fe and increase of H in the envelope. It is only after the first dredge-up that \([\text{Fe}/\text{H}]\) is restored to within \(\sim0.02-0.03\) dex of the initial value. Working with lower RGB stars removes also the ambiguity between initial and actual \([\text{Fe}/\text{H}]\) when diffusion is efficient.

Overall, the total Li depletion from the pre-MS to the RGB shows a mild dependence on the initial metallicity. Metal rich models display a more efficient depletion, due essentially to deeper convective envelopes along the RGB. This is in agreement with previous results by \(\text{Deliyannis et al. (1996)}\) and \(\text{Sackmann \\& Boothroyd (1990)}\). The values of \(\Delta(\text{Li})\) cover a range of \(\sim0.15\) dex over the \([\text{Fe}/\text{H}]\) interval for our models. The variation of \(\Delta(\text{Li})\) is non-linear, with an increase of \(\Delta(\text{Li})/\Delta[\text{Fe}/\text{H}]\) with increasing \([\text{Fe}/\text{H}]\).

We have also calculated models with diffusion but including – starting after the end of the MS – overshooting below the convective envelope. The extension of the overshooting region has been parametrized in terms of the pressure

**4 THEORETICAL ANALYSIS**

Our theoretical analysis is based on a reference grid of stellar evolution models calculated with and without including the effect of atomic diffusion. More details about the code and input physics are in \(\text{Pietrinferni et al. (2006)}\) and \(\text{Mucciarelli et al. (2011)}\). We have considered the \(\alpha\)-enhanced \((\alpha/\text{Fe} \sim 0.4)\) metal mixture of \(\text{Pietrinferni et al. (2006)}\) and pairs of He and metal mass fractions \((Y,Z)\) for all metallicities.

**H I** a satisfactory excitation equilibrium is reached only by decreasing the temperature of \(\sim80\) K.

Recently \(\text{Barklem et al. (2011)}\) have convincingly shown that the Drawin formula lacks the necessary physical ingredients to properly capture the quantum mechanical processes involved in excitation and ionisation, through collisions with hydrogen atoms. In fact in the cases for which such quantum mechanical computations have been performed the results differed by several orders of magnitude with respect to the predictions based on the Drawin formula. This casts some serious doubts on the results of any NLTE computation which depends sensitively on the use of the Drawin formula and a suitable scaling factor.

In our case the good agreement between our photometric and spectroscopic \(T_{\text{eff}}\), regardless of the metallicity, suggests that no significant non-LTE effects on iron are at work, at least for the lines of high excitation.

**Figure 2.** Position of the target stars (grey points) in the \(T_{\text{eff}}\)-\(\log g\) diagram, compared with the \(\alpha\)-enhanced theoretical isochrones from the BaSTI database, for a reference age of 12.5 Gyr and different metallicities (namely Z=0.0001, 0.0003, 0.0006 and 0.001). The isochrones are plotted only up to the tip of the RGB, for sake of clarity. The location of the RGB bump is marked as a grey shaded region. The fainter shaded region marks the boundary beyond which \(A(\text{Li})\) stops decreasing, i.e. attains its final value along the RGB. We also display two lines corresponding to \(A(\text{Li})\) increased by 0.01 dex and 0.10 dex, (short-dashed and long-dashed, respectively).
els without diffusion, with the inclusion of diffusion, and with (solid line) and without diffusion but accounting for overshooting below the envelope con-
Table 2. Li abundance depletion (Δ(Li), in dex) along the RGB for the labelled [Fe/H] values. We report the results for models without diffusion, with the inclusion of diffusion, and without diffusion but accounting for overshooting below the envelope convection, respectively (see text for details).

| [Fe/H] | ∆(Li) (no diff) | ∆(Li) (diff) | ∆(Li) (oversh) |
|--------|-----------------|--------------|---------------|
| −3.62  | 1.28            | 1.35         | 1.29          |
| −2.62  | 1.30            | 1.37         | 1.31          |
| −2.14  | 1.33            | 1.40         | 1.34          |
| −1.31  | 1.40            | 1.46         | 1.41          |
| −1.01  | 1.44            | 1.51         | 1.50          |

Table 3. Estimates of the cosmological Li abundance (A(Li)₀) in our sample of lower RGB Halo stars. We have considered three sets of stellar evolution models with different assumptions about the element transport mechanisms, and three T_eff scales for the A(Li) determinations (see text for details).

| Models   | A(Li)₀ (A99) | A(Li)₀ (G09) | A(Li)₀ (spect) |
|----------|--------------|--------------|----------------|
| Standard | 2.28         | 2.39         | 2.30           |
| Diffusion| 2.35         | 2.46         | 2.37           |
| Overshooting | 2.29       | 2.40         | 2.31           |

Table 2. The effect of overshooting from the convective envelope along the RGB – with our calibration – is negligible (Δ(Li) increases by only 0.01 dex) with the exclusion of the model with [Fe/H]= −1.01 dex for which the difference is of 0.06 dex. We have verified – with calculations for [Fe/H]= −3.32, −1.31 and −1.01 – that the effects of diffusion and overshooting (at least for our choice of the overshooting extension) on Δ(Li) are additive, when we compute models including both effects.

In addition, we have explored the effect of varying age, initial He content and mixing length, by calculating selected models at [Fe/H]= −2.14. We found that increasing the age by 2 Gyr above our reference value of 12.5 Gyr decreases Δ(Li) by 0.02 dex. A decrease of the mixing length by 0.2Hp below our solar calibrated value (2.01Hp) leaves (Δ(Li) unchanged, while an increase of the initial He mass fraction Y by 0.01 increases the depletion by 0.01 dex only.

4.1 Estimate of the primordial Li abundance in Population II stars

As we have discussed in the section on the observational data, the measured values of the 12C/13C ratio and the position in the T_eff−log g diagram place our star sample in the lower RGB phase, after the completion of the first dredge-up and before the onset of the mixing episode at the RGB bump luminosity. We have determined their primordial A(Li) – that we denote as A(Li)₀, to compare with the A(Li)₀ predicted by the BBN nucleosynthesis – for each of the three adopted T_eff scales, making use of a Monte Carlo technique, as detailed below.

For each temperature scale we have first fixed the set of theoretical models. From the chosen set, we have produced a large (500 objects) sample of lower RGB synthetic A(Li) abundances, by drawing random values (flat distribution, consistent with the distribution in the observed sample) of [Fe/H] within the range spanned by our models, and determining the corresponding depletion Δ(Li) by linear interpolation among the values listed in Table 2.

The value of A(Li)₀ has then been determined as follows. To each synthetic Δ(Li) we have added a constant that corresponds to a trial value for the initial Li abundance of the sample. Each element of the resulting ([Fe/H], A(Li)) synthetic sample has been then perturbed by a random Gaussian error. These error values have been calculated taking the mean <σ_obs> spectroscopic error from the observations, perturbed by a Gaussian random distribution with standard deviation equal to the 1σ dispersion of the spectroscopic errors around the value <σ_obs>. The initial Li abundance of the synthetic sample is then varied
Figure 4. Comparison between a synthetic sample of A(Li) values from standard models and A(Li) obtained employing the spectroscopic $T_{\text{eff}}$ scale (see text for details).

until the mean A(Li) of the synthetic sample matches the observed value. The corresponding initial Li-abundance is considered to be the best estimate of A(Li)$_0$. Finally, we have performed a Kolmogorov-Smirnov test to compare the synthetic distribution calculated with the best estimate of A(Li)$_0$ with the observed one, and verified that, for all our choices of models and $T_{\text{eff}}$ scale, the probability $P$ that the two samples are not drawn from the same distribution is well below the 95% threshold. A comparison between synthetic and observed samples for a particular choice of the $T_{\text{eff}}$ scale and stellar models is displayed in Fig. 4.

Our final estimates of A(Li)$_0$ are reported in Table 3. Models that include atomic diffusion without overshooting predict A(Li)$_0$ larger by 0.07 dex with respect to the standard models, while models including only overshooting lead to Li abundance larger by only 0.01 dex when compared with the standard case (at least for the metallicity range covered by our targets). Inclusion of both diffusion and overshooting would increase A(Li)$_0$ of 0.08 dex when compared with the standard models.

5 LI ABUNDANCES IN LOWER RGB GLOBULAR CLUSTER STARS

It is interesting to investigate also the surface A(Li) in lower RGB stars belonging to Galactic globular clusters, in comparison with the values obtained for field stars. A note of caution is however warranted. The estimate and interpretation of the initial Li abundance of Galactic globular clusters in terms of Halo primordial Li should be considered with caution, because of the occurrence of self-enrichment processes during the formation/evolution of the clusters, that are potentially able to affect the measured A(Li). A point to recall is that, in light of the currently accepted self-enrichment scenario for the evolution of the globular clusters, these systems lose a relevant fraction of their first generation stars – whose chemical abundance pattern is expected to be consistent with the field Halo population – during their early evolution. Spectroscopic studies (see e.g. Carretta et al. 2010) show that the large majority of field Halo stars have in fact an abundance pattern consistent with those of first generation stars in globulars, hence both kind of objects are compatible in terms of A(Li). Only a very marginal fraction (less than 2%) of field halo stars is compatible with second generation cluster stars – that show the well known CN and ONa anticorrelation and have Li abundances potentially modified by nuclear processing.

Lithium abundances are available (from the analysis of dwarfs and/or giants) for a few of the closest clusters. To date, NGC 6752 (Shen et al. 2010) and 47 Tuc (D’Orazi et al. 2010) exhibit clear signatures of intrinsic star-to-star dispersion in A(Li), whereas M4 show a very high degree of homogeneity in A(Li) at a given evolutionary phase (Mucciarelli et al. 2011). NGC 6397 shows also similar homogeneous A(Li) abundances, with the detection of only 3 (out of 100) dwarf stars with A(Li)<2 (Lind et al. 2009).

The interpretation of these results is beyond the purpose of this work, and we discuss here only the Li abundance in giants stars of these clusters (namely NGC 6397, NGC 6752 and M4) for which high-resolution spectra of giants are available, to provide a comparison with the Li abundances inferred in field RGB stars.

5.1 NGC 6397

We have analyzed 45 RGB stars (below the RGB bump level) in NGC 6397, retrieved from the dataset of GI-RAFFE/FLAMES spectra discussed by Lind et al. (2009). All the observations are performed with the HR13 and HR15 gratings. Due to the limited number of available iron lines, a full spectroscopic analysis cannot be performed and we discuss only the Li abundances inferred by employing the photometric $T_{\text{eff}}$ scales by A99 and G09. We employed the $(J-K)_0$ color, obtained from 2MASS photometry, corrected for reddening using the value of E(B-V) provided by Ferraro et al. (1999). To reduce the scatter in the derived A(Li) distribution due to the photometric errors, we projected each star along the fiducial line of the RGB sequence in the K–(J-K) plane (note that this technique, obviously applicable to stars members of a stellar cluster and not to field stars, is correct under the assumption that the broadening of the RGB is due to photometric errors only).

In their original work Lind et al. (2009) derive $T_{\text{eff}}$ values by using the synthetic Strömgren $(b-y)$ colors computed by Oncheg et al. (2009), employing MARCS model atmospheres, and find an average A(Li) = 1.13 dex ($\sigma = 0.09$ dex) for the lower RGB sample. We find that the G09 and Lind et al. (2009) $T_{\text{eff}}$ scales well match, with an average difference $T_{\text{eff}}^{\text{G09}} - T_{\text{eff}}^{\text{Lind}09} = -13$ K ($\sigma = 15$ K), while the difference with the temperatures by A99 is $T_{\text{eff}}^{\text{A99}} - T_{\text{eff}}^{\text{Lind}09} = -117$ K ($\sigma = 14$ K). The iron content is [Fe/H]=-2.08 dex ($\sigma=0.09$ dex) with the G09 scale and -2.12 dex ($\sigma=0.08$ dex) with
the A99 scale. We find an average A(Li)=1.00 dex (σ=0.09 dex) with the A99 scale and of A(Li)=1.09 dex (σ=0.10 dex) with the G09 scale.

By interpolating in [Fe/H] among the values of Tab. 2, we derive an estimate for A(Li) of 2.33–2.42 dex with the model without diffusion (A99 and GH09 scales respectively) and 2.40–2.49 dex with the model with diffusion.

5.2 NGC 6752

Twenty-one RGB stars were observed with UVES within the ESO Large Program 65.L-0165 (PI: Grundahl). Concerning the Li abundance, only the qualitative behaviour of the observed EWs as a function of V magnitude was discussed (Grundahl et al. 2002), without the explicit determination of the Li abundance. Here we consider the 12 stars fainter than the RGB bump, for which the Li line is clearly detectable. We analyzed the spectra obtained with the CD#3 cross-disperser, deriving $T_{\text{eff}}$ both spectroscopically and photometrically, adopting the A99 and G09 calibrations for the $(J-K)$ colour. The J and K$_{S}$ magnitudes are from the 2MASS database, corrected for reddening using the E(B-V) value by Ferraro et al. (1999). Also for this cluster, we minimized the scatter in the final A(Li) values by employing $(J-K)$ colours obtained projecting the position of each star along the RGB fiducial line.

Grundahl et al. (2002) derived the $T_{\text{eff}}$ for their targets by means of the A99 calibration for the Strömgren $(b-y)$ index. We find a reasonable consistency with our spectroscopic and photometric $T_{\text{eff}}$ on the A99 scale (as for the case of field stars) with average differences $T_{\text{eff}}^{\text{spect}}-T_{\text{eff}}^{\text{phot}}=-35$ K (σ=45 K) and $T_{\text{eff}}^{\text{phot}}-T_{\text{eff}}^{\text{phot,GRAND}}=-43$ K (σ=25 K), respectively. The offset with the $T_{\text{eff}}$ by G09 is of $T_{\text{eff}}^{\text{GB}}-T_{\text{eff}}^{\text{phot,GRAND}}=+65$ K (σ=26 K).

The average iron content is [Fe/H]=$-1.68$ dex (σ=0.07 dex), when the spectroscopic temperatures are used and different by only a few hundredths dex when the photometric $T_{\text{eff}}$ are adopted. The average A(Li) is 0.83 dex (σ=0.15 dex) with the spectroscopic temperatures (almost the same abundance is obtained with the A99 scale, while the G09 scale provides A(Li)=0.93 dex, σ=0.15 dex). Three stars display A(Li)=0.5-0.6 dex, lower by ~0.3-0.4 dex compared to the other stars in the sample. The remaining 9 stars provide an average Li abundance A(Li)=0.91 dex (σ=0.07 dex). The presence of these three Li-poor stars (already identified by Grundahl et al. 2002) is probably ascribable to the lithium variation in the cluster, as testified by the Li-Na anticorrelation (Pasquini et al. 2002) and Li-O correlation (Shen et al. 2010). These stars could belong to the second generation.

5.3 M4

We summarized briefly the results discussed in Mucciarelli et al. (2011) about the metal-rich cluster M4, from the analysis of a sample of GIRAFFE spectra. The differential reddening that affects the field of view of M4 makes uncertain the abundances derived directly by adopting the photometric $T_{\text{eff}}$, due to the residual of the differential reddening correction. The atmospheric parameters for the RGB stars in the sample were therefore derived by projecting the position of each star along the stellar isochrone the best fit the observed colour-magnitude diagram. This $T_{\text{eff}}$ scale is in nice agreement with the spectroscopic $T_{\text{eff}}$ values inferred by Marino et al. (2008) for the stars in common.

The derived Li abundance in lower RGB stars of M4 is A(Li)=0.92 dex, that leads to A(Li)=2.35 dex (models without diffusion) and 2.40 dex (models with diffusion).

6 SUMMARY AND CONCLUSIONS

We have discussed the use of Li abundances measured in Population II lower RGB stars as an independent, reliable and robust diagnostic of the initial Li abundance in the Galactic Halo. Surface abundances in giant stars fainter than the RGB bump are sensitive to the total Li content left at the end of the MS phase, and are very weakly affected by atomic diffusion during MS. Also, the predicted A(Li) in these objects is basically insensitive to the mixing length calibration, the precise stellar ages, initial He abundances, and realistic estimates of the overshooting extension below the Schwarzschild boundary of the convective envelope. Chemical abundance measurements in giant stars also suggest that any additional element transport along the RGB is very likely inefficient in this phase. Overall, our analysis reveals that the predicted Li depletion $\Delta$(Li) along the lower RGB is robust in terms of theoretical interpretation.

The values of A(Li) inferred from our sample of lower RGB field stars range from 2.28 (obtained with the A99 scale and without the inclusion of atomic diffusion) to 2.46 (when the G09 $T_{\text{eff}}$ scale is used, together with models including atomic diffusion). Inclusion of overshooting from the RGB convective boundary would increase both limits by only 0.01 dex, while variations of age, initial He abundance and mixing length parameter provide changes of a few hundredths of dex or less in terms of $\Delta$(Li). When a $T_{\text{eff}}$ scale is adopted, the effect of fully efficient atomic diffusion on the A(Li) estimate is by at most 0.07 dex.

The discrepancy with A(Li) predicted by BBN calculations thus remains, reconfirmed by the robustness of our estimate. The analysis performed on the lower RGB stars in three Galactic globular clusters confirms similar values for A(Li), although in general the possible occurrence of self-enrichment processes in these objects has to be considered.

There are several discussions in the literature about how to solve this discrepancy with BBN results. Ideas involve a first generation of stars that has processed and efficiently depleted lithium in a substantial fraction of the early Halo baryonic matter (Piau et al. 2006), modifications to the BBN considering the decay of unstable particles (e.g. Cyburt et al. 2010), modifications to the reaction cross sections for the Li production during BBN (e.g. Chakraborty et al. 2011), or ‘deep’ turbulent mixing during the MS that connects the convective envelope to inner, Li-depleted regions (e.g. Richard et al. 2005, Mucciarelli et al. 2011).
Our result for RGB stars provides an additional robust constraint on the efficiency of this turbulent mixing. Independently of its parametrization, during the MS any additional element transport needs to bring into the Li burning region an amount of initial lithium $\Delta_{\text{burn}}(\text{Li}) = 0.3-0.4$ dex, in order to eliminate the discrepancy with BBN calculations (the turbulence model denoted as T6.25 or T6.28 by Richard et al. [2005] appear to burn approximately the right amount of Li in models with $[\text{Fe/H}]=-2.31$). The value by Richard et al. (2005) appear to burn approximately the calculations (the turbulence model denoted as T6.25 or T6.28 0.4 dex, in order to eliminate the discrepancy with BBN calculations (the turbulence model denoted as T6.25 or T6.28 by Richard et al. [2005] appear to burn approximately the right amount of Li in models with $[\text{Fe/H}]=-2.31$). The value by Richard et al. (2005) appear to burn approximately the

The use of lower RGB stars will allow estimates of the Li content in stellar populations more distant than those field and globular cluster stars. The authors warmly thank the anonymous referee for his/her comments and suggestions. PB acknowledges support from the Programme Nationale de Physique Stellaire (PNPS) and the Programme Nationale de Cosmologie et Galaxies (PNCG) of the Institut Nationale de Sciences de l’Univers of CNRS.

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