Lithium Abundance of Halo Dwarfs Revised
Paolo Molaro1, Francesca Primas2, Piercarlo Bonifacio3
1 Osservatorio Astronomico di Trieste, Via G.B. Tiepolo 11, I-34131, Trieste, Italy
2 Dipartimento di Astronomia, Università degli Studi di Trieste, I-34131, Trieste, Italy

Accepted: January 1995

Abstract. Lithium abundances in a sample of halo dwarfs have been redetermined by using the new $T_{\text{eff}}$ derived by Fuhrmann et al (1994) from modelling of the Balmer lines. These $T_{\text{eff}}$ are reddening independent, homogeneous and of higher quality than those based on broad band photometry. Abundances have been derived by generating new atmospheric models by using the ATLAS-9 code by Kurucz (1993) with enhanced $\alpha$-elements and without the overshooting option. The revised abundances show a remarkably flat plateau in the Li-$T_{\text{eff}}$ plane for $T_{\text{eff}} \geq 5700$ K with no evidence of trend with $T_{\text{eff}}$ or falloff at the hottest edge. Li abundances are not correlated with metallicity for [Fe/H] $\leq -1.4$ in contrast with Thorburn (1994). All the determinations are consistent with the same pristine lithium abundance and the errors estimated for individual stars fully account for the observed dispersion. The weighted average Li value for the 24 stars of the plateau with $T_{\text{eff}} > 5700$ K and $\text{[Fe/H]} \leq -1.4$, is $\text{[Li]} = 2.210 \pm 0.013$, or 2.224 when non-LTE corrections by Carlsson et al (1994) are considered.

Key words: Stars: abundances – Stars: Population II – Stars: fundamental parameters – Galaxy: halo – Cosmology: observations

1. Introduction

The lithium observed in the atmospheres of unevolved halo stars is generally believed to be an essentially unprocessed element which reflects the primordial yields. In the framework of the standard BBN it provides a sensitive measure of $\eta = n_0/n_e$, at the epoch of the primordial nucleosynthesis and thus of the present baryon density $\Omega_b$. The primordial nature of the lithium of the halo dwarfs is inferred from the presence of a constant lithium abundance for all the halo dwarfs where convection is not effective ($T_{\text{eff}} \geq 5600$ K). Such an uniformity is taken as evidence for the absence of any stellar depletion during the formation and the long life of the halo stars and also as evidence for the absence of any production mechanism acting either before or at the same time of the formation of the halo population.

Send offprint requests to: P. Molaro, Osservatorio Astronomico di Trieste, Via G.B. Tiepolo 11, Trieste, Italy

2. Lithium Abundances

2.1. The role of $T_{\text{eff}}$ and of atmospheric models

In the atmospheres of G dwarfs lithium is mainly ionized and the abundance determination is particularly sensitive to the effective temperature and to the $T(\tau)$ behaviour inside the photosphere since it requires large ionization corrections. Conversely, lithium abundance is not particularly sensitive to the stellar surface gravity and to the metallicity of the star. Also the Li I 6707 Å line is not generally saturated due to the intrinsically low lithium abundance of the halo stars, and therefore it is insensitive to the value of the microturbulent velocity. The effective temperature is by far the most important parameter and its accuracy determines the ultimate lithium abundance accuracy. Unfortunately, the determination of the effective temperature for cool stars and in particular for metal poor stars is rather poor, as discussed in detail in Fuhrmann et al (1994). Fuhrmann et al pointed out the severe limitations of the methods based on broad band photometry, which they considered inadequate to provide accurate effective temperatures for
individual stars. The main arguments rely on the dependence of colour-based temperatures on the reddening corrections and on the particular color used.

Table 1

| Star     | Teff ± σTeff | log g | EW ± σEW | [Li] ± σLi |
|----------|--------------|-------|----------|-----------|
| HD 3567  | 5750±200     | 4.0   | 45±5.8   | 2.22±0.197|
| HD 19445 | 6040±52      | 4.2   | 33.6±0.5 | 2.25±0.039|
| HD 64090 | 5499±56      | 4.1   | 12.1±0.7 | 1.33±0.062|
| HD 74000 | 6211±44      | 4.5   | 25.3±2.2 | 2.21±0.073|
| HD 108177| 6090±77      | 4.3   | 30.1±1.3 | 2.29±0.063|
| HD 116064| 5822±72      | 3.6   | 30.2±2.5 | 2.01±0.073|
| HD 140283| 5814±44      | 3.6   | 46.5±0.6 | 2.26±0.036|
| HD 166171| 5664±84      | 3.5   | 42.3±3.8 | 2.10±0.087|
| HD 166913| 5955±109     | 3.3   | 40.3±3.8 | 2.29±0.100|
| HD 188510| 5500±220     | 4.0   | 18.3±3.4 | 1.56±0.222|
| HD 189558| 5534±32      | 4.0   | 42.1±1.6 | 2.02±0.086|
| HD 193901| 5700±109     | 4.0   | 30.3±3.3 | 1.96±0.111|
| HD 194598| 5950±100     | 4.0   | 27.0±0.7 | 2.09±0.076|
| HD 200654| 5522±119     | 3.2   | 8.1±1.7  | 1.12±0.143|
| HD 201889| 5645±61      | 4.1   | 5.4±3.3  | 1.06±0.230|
| HD 201891| 5797±57      | 4.4   | 24.3±0.8 | 1.92±0.048|
| HD 211988| 5388±65      | 3.5   | 13.4±3.4 | 1.21±0.150|
| HD 219617| 5815±76      | 4.2   | 40.2±0.8 | 2.19±0.062|
| BD 2° 3375| 6034±60     | 4.0   | 31.5±2.1 | 2.19±0.058|
| BD 3° 740 | 6264±73      | 3.5   | 17.3±1.3 | 2.06±0.065|
| BD 9° 352 | 6285±77      | 4.5   | 34.6±7.6 | 2.42±0.130|
| BD 9° 2190| 6452±60      | 4.0   | 18.3±3.4 | 2.00±0.107|
| BD 17° 4708| 6100±110   | 4.1   | 25.1±1.7 | 2.13±0.084|
| BD 21° 607 | 6135±70     | 4.0   | 25.2±2.6 | 2.19±0.074|
| BD 23° 3130| 5190±84     | 2.7   | 13.1±1.3 | 1.06±0.095|
| BD 24° 1676| 6278±76     | 3.9   | 27.1±6.6 | 2.29±0.062|
| BD 26° 2606| 6161±64     | 4.1   | 30.1±1.2 | 2.25±0.050|
| BD 29° 366 | 5760±64      | 3.8   | 14.4±2.9 | 1.61±0.105|
| BD 37° 1458| 5451±59     | 3.5   | 11.2±1.1 | 1.22±0.107|
| BD 38° 4955| 5337±73     | 4.5   | 8±3.3    | 1.06±0.250|
| BD 42° 3607| 5836±66     | 4.4   | 47.4±5.5 | 2.29±0.083|
| BD 66° 268 | 5511±91      | 4.0   | 10±7.8   | 1.23±0.476|
| G 64-12   | 6356±75      | 3.9   | 25.8±2.4 | 2.31±0.074|
| G 64-37   | 6364±75      | 4.1   | 14.1±2.2 | 2.09±0.066|
| G 66-9    | 5885±83      | 4.6   | 29.2±6.0 | 2.04±0.081|
| G 206-34  | 6258±50      | 4.3   | 27±2.5   | 2.26±0.060|
| G 239-12  | 6260±70      | 4.1   | 24.2±3.1 | 2.21±0.084|
| G 255-32  | 5962±53      | 4.0   | 30±2.9   | 2.11±0.064|
| LP 608 62 | 6435±52      | 4.1   | 21.5±2.3 | 2.28±0.063|

Fuhrmann et al (1994) derived T_{eff} from the full spectral synthesis of the Balmer lines for a large sample of stars. These T_{eff} are reddening independent and they show a high degree of internal consistency when the various members of the series are used. Being obtained from absorption line, they are particularly suitable for line abundance applications. Fuhrmann et al are also able to provide errors in the T_{eff} for individual stars and in most cases they are as good as ±50 K, which is a factor 2 smaller than the grossly estimated errors for photometric-based T_{eff}.

Out of the Fuhrmann et al’ sample, 39 have already been studied for lithium. They represent a significant fraction of the presently available lithium determinations, and form an unique sample with a good and homogeneous T_{eff}.

Fig. 1. T_{eff} from Fuhrmann et al (1994) versus T_{eff} from Li literature.

Fig. 2. Curves of Growth for different models. Dash: Bell; solid line: ATLAS8; dot: ATLAS9; Long dash: ATLAS9 without overshooting; dot - long dash: Kurucz 1991 adopted by Thorburn 1994.

On average, the Fuhrmann et al temperatures are 125±120 K higher than those previously used in literature on lithium (cfr Fig. 1). The presence of considerable scatter together with a systematic offset suggest that there are intrinsic differences in the individual temperatures derived by various methods. The Li equivalent widths have been taken from the literature and the theoretically derived random errors from Deliyannis et al (1993) or computed following their prescriptions. In the case of multiple measurements of the lithium line of the same star we adopted the weighted average to minimize the errors. Atmospheric models may be important for the lithium abundance. The role played by different atmospheric models is illustrated in Fig. 2 where several curves of growth obtained with different atmospheric models are shown. The COGs are for T_{eff} = 6000 K, log g = 3.5, microturbulence $\xi = 2$ km s$^{-1}$ and [Fe/H] = −3.0,
but a similar behaviour is shown by other temperatures relevant for Li. The curves of growth for lithium obtained by using ATLAS-9 and ATLAS-8 are notably different. In Fig. 2 are also shown the COG used by Thorburn (1994) referred to unpublished models of Kurucz (1991) and to those of Bell and Gustafsson. For a given EW the abundances of the most recent Kurucz codes are $\approx 0.1$ dex higher than all the other curves. We have computed a grid of atmospheric models where the convection is treated with the mixing length theory but without the overshooting option. The corresponding COG, also shown in Fig. 2, is very close to the COG of the old Kurucz or Bell and Gustafsson models. This shows that the implementation of the approximate treatment for overshooting in the ATLAS-9 code is likely to be responsible for the difference among the versions of the ATLAS code. The center of the convective bubbles stops at the top of the convective zone so that convective flux extends one bubble radius above the end of the convection zone. Overshooting rises the temperature in correspondence of the depths relevant for the formation of the lithium line, thus resulting in higher abundance for the same equivalent width. The effect is almost negligible at solar metallicities but it increases towards lower metallicities where the fraction of the total flux transported via convection increases.

The presence of abundances derived with different atmospheric models is also responsible for the systematic differences in the lithium abundances for common stars among different authors. This factor has been essentially overlooked and has introduced a spurious scatter in a straightforward compilation of the literature data. The comparison of the measurements of Thorburn (1994) with those of the literature shows that the equivalent widths are almost the same but the Thorburn abundances derived using Kurucz (1991) are systematically higher than those by other authors. The finding by Norris et al. (1994) showing that Li abundances in stars with $\mathrm{[Fe/H]}<-3.0$ are on average about 0.15 dex lower than the higher metallicity halo stars from Thorburn (1994) can be also understood as a model effect. Norris computed the Li abundances by using Bell and Gustafsson atmospheric models which give abundances lower than those by Thorburn (1994). The comparison between the stars studied by both Norris et al. (1994) and Thorburn (1994) shows nearly identical EWs for both, but lower abundances in the former authors.

Implementation of overshooting improves the reproduction of the solar spectrum, but the effects on metal poor stars have not been yet fully tested and it should be considered with caution until a deeper analysis of possible secondary effects on metal poor objects is carried out. Here we have not used this option and the new lithium abundances have been determined by computing Kurucz (1993) atmospheric models without overshooting. For all the stars the models have been computed with the temperatures available from Fuhrmann et al. (1994). The gravities used are taken from the literature according to the compilation of Deliyannis et al. (1993) or computed from $T_{\text{eff}}$ colors, and are reported in Table 1. Convection is treated with the mixing length theory with a scale height over pressure scale of 1.25. The choice of this parameter is not critical and a change from 0.5 to 2 produces almost negligible effects on the lithium abundance. If we use the Kurucz 1993 grid which includes overshooting the lithium abundance is increased by $\approx 0.09$ dex, but all other conclusions are still valid, since they are not dependent on this assumption. In view of the important implications related to the primordial abundances, it is desirable that a deeper discussion may follow shortly.

![Fig. 3. $[\text{Li}]$ versus $T_{\text{eff}}$. Open squares are for stars with metallicities in the range -1.4<$\mathrm{[Fe/H]}$<-1.0.](image)

### 3. Results

The Li abundances in the Li-$T_{\text{eff}}$ plane with associate 1 $\sigma$ errors are shown in Fig. 3. Following Rebolo et al. (1988) and Deliyannis et al. (1990), stars with $-1.4<\mathrm{[Fe/H]}<-1.0$ (open squares in Fig. 3) are taken off from sample of genuine halo stars since they may show some depletion. The errors shown in Fig. 3 are those given in the last column of Table 1. They have been estimated by summing under quadrature the errors in the lithium abundance produced by the uncertainties in $T_{\text{eff}}$ and in EW, also given in Table 1, namely $\sigma_{\text{Li}}^2 = \sigma_{\text{ew}}^2 + \sigma_{\text{eff}}^2(T_{\text{eff}})$. We have considered negligible the effects produced by uncertainties in gravity, microturbulence and metallicity. The lithium abundances show a plateau extending up to nearly 6500 K, with no evidence of falloff at the hottest edge as expected by microscopic diffusion models, and with the depletion region bending at $T_{\text{eff}} \approx 5700$ in good agreement with what observed in the Hyades.

The existence of a tilt of the plateau has received considerable attention (Molaro 1987, Rebolo et al. 1988, Thorburn 1994, Norris et al. 1994) since the presence of a moderate stellar depletion in the cool edge plateau implies that only the highest values are close to the pristine value. Norris et al. (1994) and Thorburn (1994) found a slope of 0.03 and 0.024 for 100 K, respectively. Thorburn (1994) claimed also that when this underlying trend with $T_{\text{eff}}$ is taken into account the increase of N(Li) with the metallicity becomes notable already at $\mathrm{[Fe/H]} \approx -2.0$. Considering only stars with $T_{\text{eff}} > 5700$ K and $\mathrm{[Fe/H]} \leq -1.4$ the weighted linear fit is $[\text{Li}] = 0.58(\pm 0.88)(T_{\text{eff}}/10^4)$. The slope we found is one order of magnitude lower than those of Norris et al. (1994) or Thorburn (1994), and is consistent with a real plateau in the undepleted region of the Li-$T_{\text{eff}}$ plane. Non-LTE effects have been studied by Carlsson et al. (1994), who provide corrections of 0.020, 0.015 and 0.010 at 5500, 6000 and 6500 K respectively, and for $\mathrm{[Fe/H]}$ between -1.0 and -3.0. Once we correct our abundances for nonLTE effects the slope of the fit becomes even smaller: 0.20(± 0.93).

The lithium abundances versus the stellar metallicity are shown in Fig. 4 and do not show any clear trend with iron.
over two orders of magnitude of increase in the stellar metallicity. Strictly speaking we observe a decrease in the lithium abundance with the increasing of the metallicity. The weighted regression analysis gives a negative slope with lithium decreasing by 0.008 dex for ∆[Fe/H]=1. By contrast Thorburn (1994) found an increase in Li by 0.4 dex from the [Li]=2.20 at [Fe/H]=−3.5 up to 2.60 at [Fe/H]=−1.0. Our interception at [Fe/H]=−3.5 is of [Li]=2.215, fully consistent with the value of [Li]=2.221 obtained from the hottest halo dwarfs (T_{eff}=6400 K). In our data sample both the lowest metallicity stars, i.e. the oldest, and the hottest subdwarf, i.e. the less depleted, share the same Li abundance.

Fig. 5 shows a zoom of the plateau region with the errors in the Li abundances at the 3 σ level plotted for each star. On the plateau all the Li abundances are consistent with a unique pristine Li abundance. In 10 out of 24 cases the consistency is achieved already at 1 σ confidence level. For three stars (G 64-13, BD 3° 740, HD 116064) the full 3σ error box is required to achieve the consistency, and they might show a real dispersion if errors can be further reduced. With the present estimated errors our analysis does not support the presence of real dispersion on the plateau region, and it seems likely that the dispersion claimed by Thorburn (1994), or the correlations of Li with metallicity or temperature, are artifacts caused by errors in the effective temperatures. We stress that both the absence of a tilt and dispersion in the plateau region are independent of the assumption we made on overshooting, since its inclusion would increase the Li abundance by about the same amount for all the stars. The weighted mean on the plateau of the 24 stars with T_{eff} ≥ 5700 and [Fe/H] ≤ -1.4, where each abundance is weighted inversely by its own variance in the sum, is [Li]=2.210 ± 0.013. When the non-LTE corrections of Carlsson et al (1994) are considered, the mean rises to 2.224 ± 0.013. This value is somewhat higher than the 2.08±0.1 previously estimated by Spite and Spite (1982), Hobbs and Duncan (1988), Rebolco et al (1988), and Molaro (1991). The increase in the value of the plateau results from the increase of the Fuhrmann et al effective temperatures compared to those previously used in the lithium literature.

The present analysis shows that when very precise effective temperatures and individual errors are considered, the Li abundances on the plateau show no trends either with T_{eff} in a range of 600 K or with the stellar metallicity over two orders of magnitude. The lithium abundances are all closely gathered and are consistent with the same initial abundance, thus confirming that the lithium observed in these stars is essentially undepleted and very close to the primordial value as already put forward by Spite and Spite (1982).

Acknowledgements. It is a pleasure to thank Fiorella Castelli and Bob Kurucz for many useful discussions in particular on the role played by atmospheric models on the lithium abundance. Partial support from a bilateral CNR grant is acknowledged.

References

Carlsson M., Rutten, R.J., Bruls, J.H.M.J., Shchukina N.G. 1994 AA 288, 860
Fuhrmann, K., Axer, M., Gehren T., 1994 AA 285, 585
Deliyannis C. P., Demarque, P., and Kawaler, S.D., 1990 ApJS 73, 21.

Fig. 4. Li-[Fe/H].

Fig. 5. Zoom on the plateau, with the [Li] abundances corrected for non-LTE effects. The errors are at 3 σ. The dash line shows the weighted mean at [Li]=2.224.

Deliyannis C. P., Pinsonneault M. H., Duncan D. K., 1993 ApJ 414, 740
Hobbs, L.M., and Duncan D.K., 1988 ApJ 317, 796.
Kurucz, R.L., 1993, CD-ROM No 11, 13, 18
Kurucz, R.L., 1991, private communnication in Thorburn (1994)
Molaro, P., 1991 Mem. Soc. Astron. Ital., 62, 17
Molaro, P., 1987 phd Thesis I.S.A.S. Trieste, Italy.
Molaro, P., Bonifacio, P., Primas, F. 1995 proc. IAU JCM on Stellar and Interstellar Lithium and Primordial Nucleosynthesis memorie SAIIt in press.
Norris, J. E., Ryan, S. G., Stringfellow G. S., 1994 ApJ 423, 386
Rebolco, R., Molaro, P., Beckman, J., 1988 AA 192, 192.
Spite, F., Spite, M., 1982 AA 163, 140.
Thorburn, J., 1994, ApJ 421, 318.

This article was processed by the author using Springer-Verlag LaTeX A&A style file 1990.