From Lithium to Uranium: Elemental Tracers of Early Cosmic Evolution
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Lithium abundances in extremely metal-poor unevolved stars†

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Abstract. We have studied the lithium abundance in 18 extremely metal-poor main-sequence turnoff stars as a function of [Fe/H] and $T_{\rm eff}$, using high-quality VLT/UVES spectra. The sample covers the range $-3.3 \leqslant$ [Fe/H] $\leqslant -2.5$, with half of the stars below [Fe/H] $= -3.0$. $T_{\rm eff}$ is determined from Hα line profiles as well as from B-V, V-K, J-H and J-K colours. The behaviour of A(Li) as a function of metallicity is markedly different when different temperature scales are adopted. However, even when applying standard depletion corrections, it is a robust result that the Li abundance in extremely metal poor dwarfs is far below the prediction of standard big bang nucleosynthesis using a baryonic density consistent with the WMAP data.

Keywords. Nuclear reactions, nucleosynthesis, abundances, Galaxy: halo, Galaxy: abundances, cosmology: observations

1. Introduction

Almost forty years ago Wagoner *et al.* (1967) demonstrated that under the conditions prevailing in the early stages of an homogeneous, isotropic, expanding universe, nuclear reactions would lead to the formation of significant amounts of ^{7}Li in addition to ^{2}H, ^{3}He and ^{4}He. The abundances of these nuclei depend on the *a priori* unknown baryon density. However, the then available measurements of Li in stars did not provide any strong constraints on the value of this "primordial" Li abundance.

It took 15 more years before Spite & Spite (1982a) showed that the primordial abundance of lithium can be measured in the photospheres of warm metal-poor stars. Specifically, they argued (Spite & Spite 1982a,b) that the remarkable constancy of the Li abundance in these stars as a function of both temperature and metallicity (the *Spite plateau*) proved that the Li had to be produced before the formation of any star or galaxy.

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Thus, the Li abundance measured in metal-poor stars may, in principle, provide a direct measure of a cosmological parameter: the baryonic density.

However, for this to be possible, two conditions must be satisfied: 1) the photospheric Li abundance in these stars must not have been altered, unlike the Sun for which the photospheric Li abundance is almost two orders of magnitude below the meteoritic value; and 2) there must have been no significant Li production in the early Galaxy to raise the observed Li above the primordial value. Although both issues are reasons for concern, the greatest problem confronting us today in the use of Li as a baryometer is the inconsistency with the baryonic density derived from the fluctuations in the cosmic microwave background as measured by the WMAP satellite (Spergel *et al.* 2003). As we shall show, that value is a factor of 1.4 to 1.7 *larger* than derived from the stellar Li data; because of the small formal errors of the WMAP data, the two values are only marginally consistent within the 3σ errors of all ingredients, including the Standard Big Bang Nucleosynthesis (SBBN) predictions. The conflict between these two results needs to be understood.

Here we report on our Li measurements in a sample of the lowest-metallicity Galactic stars and investigate the effects of adopting different temperature scales.

2. Observations and data reduction

19 of the most metal-poor main-sequence turnoff stars from the HK surveys (Beers *et al.* 1985, 1992) were selected from medium-resolution spectra. Known binaries, horizontal-branch stars, halo blue stragglers, and carbon-rich stars were eliminated.

An homogeneous set of spectra with high S/N and wide spectral coverage was obtained for our stars with the Kueyen 8.2-m VLT telescope and UVES spectrograph (Dekker *et al.* 2000) in 2000-2001. All the observations used dichroic mirror #1 in either of two settings (396+573) or (396+850), providing almost complete spectral coverage from 330nm to 1040nm at a resolution of $R \sim 43000$. The Li line was included in both red-arm settings, yielding a final S/N ratio >100 per pixel around this crucial line. The integration times were adjusted to obtain comparable S/N ratios for all stars.

The spectra were reduced using the UVES context within MIDAS. The equivalent widths (EWs) of the Li doublet were measured by fitting a synthetic profile as described by Bonifacio *et al.* (2002).

3. Li abundances

Equivalent widths of iron lines were measured using the genetic algorithm described in François *et al.* (2003). $\log g$ was determined from the iron ionization equilibrium, and the microturbulence by requiring that strong and weak Fe lines yield the same abundance. The derived [Fe/H] are within a few hundredths of a dex of our preliminary values (Bonifacio *et al.* 2003).

Measuring Li abundances may be simple in principle, but requires accurate knowledge of the effective temperatures. We have determined the $T_{\rm eff}$ of each star from the spectrum by fitting the Hα profile with synthetic spectra, computed with an updated version of *Turbospectrum* (Alvarez & Plez 1998), based on OSMARCS model atmospheres (Plez *et al.* 1992; Gustafsson *et al.* 2003, and references therein), and our preliminary metallicities (Bonifacio *et al.* 2003). The most important improvement was the use of the Barklem *et al.* (2000) Balmer line broadening theory rather than Vidal *et al.* (1973) as used previously (Bonifacio *et al.* 2003). A sample fit is shown in Fig.1.

With the atmospheric parameters fixed, we determined the Li abundances by fitting synthetic spectra to match the observed EW of the Li doublet. As in Bonifacio & Molaro

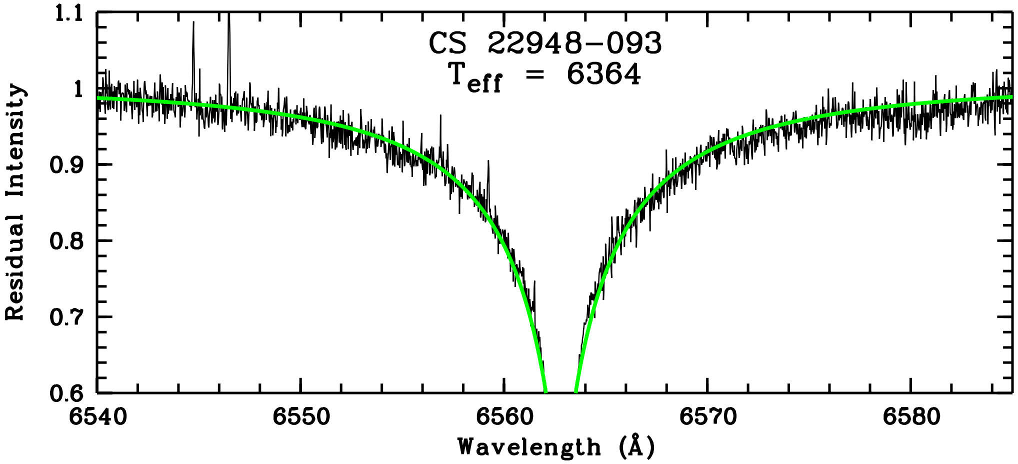

Figure 1. Synthetic spectrum fit to the Hα line profile of CS 22948-093.

(1997), the Li abundances were corrected for NLTE effects as described by Carlsson *et al.* (1994) (very small), and also for Li depletion as predicted by standard models (Deliyannis *et al.* 1990) (below 0.03 dex except for BS 16076-006, see below).

Of our 19 initial stars, BS 16076-006 was found to be a cool subgiant. CS 29527-015 is a double-lined binary with a strongly varying EW of the Li line, explaining why it was detected by Spite *et al.* (2000), but not by Thorburn (1994) or Norris *et al.* (1997). These stars will be kept separate from the rest of the sample.

4. Results and Discussion

Our results are summarised in Fig. 2, where the Li abundances are plotted versus [Fe/H]. Excluding BS 16076-006 and CS 29527-015, the mean log A(Li) of the sample is 2.20 with a standard deviation of 0.090 dex. The error of our Li abundances is dominated by the error of $T_{\rm eff}$, which we estimate to be 100 K, corresponding to an average error in A(Li) of ∼0.06 dex for our sample. This suggests that some intrinsic dispersion in A(Li) exists, above the measurement error. However, if we assume that the error of $T_{\rm eff}$ is 150 K, the computed error of A(Li) becomes totally consistent with the observed dispersion, leaving no room for intrinsic scatter.

The errors in our EWs have been estimated using Monte Carlo simulations and are all well below 0.1 pm. However, these simulations just add Poisson noise to a synthetic spectrum and do not include the effects of residual fringing, which is present in our data at the level of a few percent and seriously limits the accuracy of the EW measurements. Assuming an EW error of 0.1 pm for all stars increases the mean error of A(Li) to 0.08 dex (assuming 100 K errors in $T_{\rm eff}$), again leaving little room for extra scatter. Overall, the evidence for extra scatter is thus marginal, at best.

Leaving BS 16076-006 and CS 29527-015 aside, Fig. 2 shows a tight clump of 14 stars, plus another three stars having lower A(Li). For the group of 14 we find $< A(Li) > = 2.23$ and $\sigma = 0.05$ (st.d.), while the three outliers have $< A(Li) > = 2.04$ and $\sigma = 0.06$. Thus, each group shows a constant A(Li), with a dispersion completely consistent with all error estimates. While one can speculate that light from a binary companion might partly fill in the Li line in the three stars, we have at the moment no evidence to support such a conjecture and retain them in the sample for now.

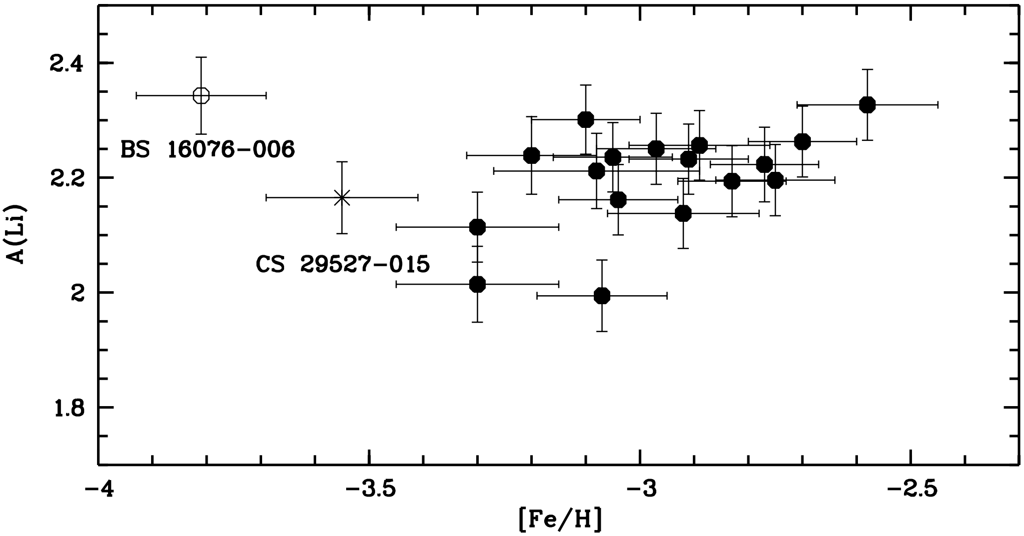

Figure 2. Li abundances as a function of [Fe/H] for our sample. The binary CS 29527-015 is shown by an asterisk. The cool subgiant BS 16076-006 (open circle) is strongly Li-depleted, but the depletion correction (1.19 dex) brings it to the same level as the other stars.

4.1. *Slope of the Spite plateau*

Our sample is not ideally suited to verify the existence of a slope in the Spite plateau (Thorburn 1994; Ryan, Norris, & Beers 1999), since all the stars are extremely metal-poor and define only a short baseline in [Fe/H]. Accordingly, a variety of parametric and non-parametric tests have failed to detect such a slope. In order to obtain a longer baseline in [Fe/H] we must combine our results with other existing data sets.

In doing so, the crucial issue is to make sure that the temperature scales of the different samples are consistent. In order to investigate these effects, we have derived effective temperatures from J-H, J-K, B-V, and V-K colours, using the Alonso, Arribas, & Martínez-Roger (1996) calibration (we refer to these as IRFM temperatures in the following), and from B-V using the theoretical colours of VandenBerg & Clem (2003). When deriving $T_{\rm eff}$ from colours, we have corrected for interstellar reddening using the maps of Schlegel *et al.* (1998) as corrected by Bonifacio *et al.* (2000a). We have also used the intrinsic color calibration of Bonifacio *et al.* (2000b), which is not entirely justified since all of our stars are outside the range of metallicity for which the calibration is valid. However, for investigating the plausible range in $T_{\rm eff}$ covered by our stars, these two reddening estimates should provide adequate information.

The colour data provide a total of 10 $T_{\rm eff}$ estimates for each star. In some cases, they are in good agreement with $T_{\rm eff}$ as derived from the Hα fits; this is the case both for $T_{\rm eff}$ from V-K using E(B-V) from the maps, and for $T_{\rm eff}$ from the VandenBerg & Clem (2003) colours, using E(B-V) from the calibration. However, in other cases significant offsets exist between the different $T_{\rm eff}$ scales – up to 400 K for the most extreme cases. We conclude that the temperature scale for metal-poor stars still leaves much to be desired, with systematic errors of the order of 200K still possible. A preliminary comparison with the recent data by Charbonnel & Primas (2005) suggests that our Hα-based $T_{\rm eff}$ is consistent with their *(b-y)*-IRFM scale, but a more detailed check is in progress.

Fig. 3 shows our data together with three other samples drawn from the literature: *(i)* EWs from the literature and A(Li) computed with our IRFM temperatures (similar to the sample of Meléndez & Ramírez 2004); *(ii)* the A(Li) results of Ryan, Norris, &

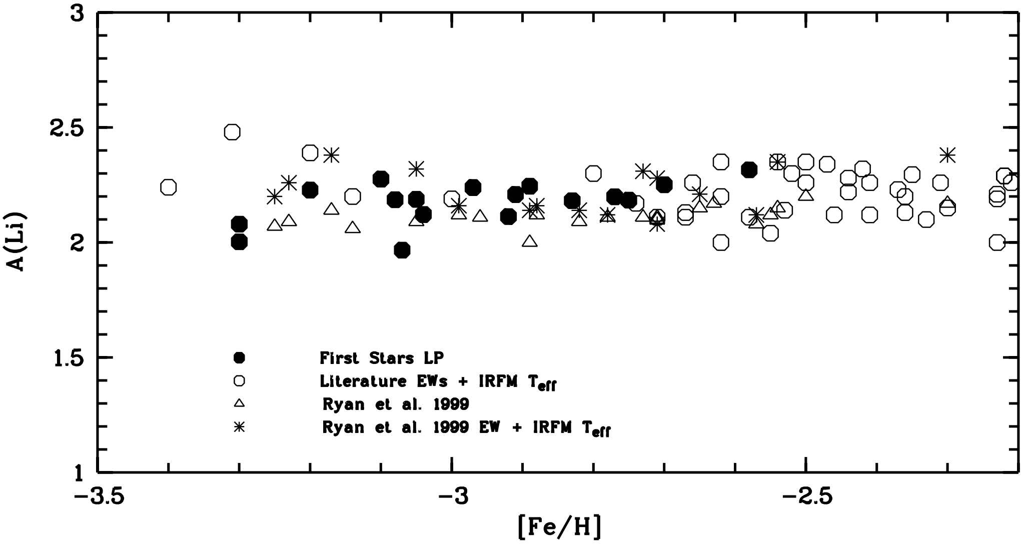

Figure 3. Comparison of our Li abundances (filled circles) with values derived: *(i)* from EWs from the literature and our IRFM temperatures (open circles); *(ii)* by Ryan, Norris, & Beers (1999) (triangles); and *(iii)* using EWs and [Fe/H] from Ryan, Norris, & Beers (1999) but our IRFM effective temperatures.

Beers (1999); and *(iii)* A(Li) computed from the Ryan, Norris, & Beers (1999) EWs and our IRFM temperatures. As is immediately evident, the Li abundances based on IRFM temperatures show no variation with [Fe/H], while the original Ryan, Norris, & Beers (1999) data do. It thus appears that the existence of a slope depends more on the temperature scale chosen than on the observed Li line strengths. The mean level of the plateau ranges from 2.1 to 2.4.

4.2. *The primordial Li abundance*

Adopting the highest reasonable $T_{\rm eff}$ scale and ignoring any possible slope, A(Li)= 2.4 is the highest possible value for the Spite plateau that is consistent with the data. This implies a baryon/photon ratio $\eta = 4.64 \times 10^{-10}$, completely inconsistent with the WMAP value $\eta = (6.14 \pm 0.25) \times 10^{-10}$ which in turn would imply A(Li)= 2.63. Agreement can only be achieved by adding the full 3σ error on the SBBN calculations to the 3σ observational errors.

Uniform depletion of Li in metal-poor stars from a high primordial value might offer a solution, but the (at best) tiny observed dispersion poses serious difficulties for any mechanism proposed so far, with the possible exception of models including diffusion and turbulent mixing (Richard *et al.* 2005). Non-standard BBN might be another alternative; e.g., (Jedamzik 2004a,b) suggested that a decaying massive particle (gravitino, neutralino etc.) could alter SBBN, producing less ^{7}Li and appreciable amounts of ^{6}Li. However, Ellis *et al.* (2005) have shown that, for suitable ranges of the lifetime and abundance of this unstable particle, unacceptably low D abundances or large ^{3}He/D ratios result.

It may seem depressing that after twenty years of effort to understand the Li abundance in halo dwarfs and its cosmological implications, we have progressed very little from the classic paper of Spite & Spite (1982a). On the other hand, the inconsistency between the Li data and the WMAP result may eventually lead us to new discoveries on stellar structure, on cosmology, or perhaps “Both, if necessary”! (Wilde 1895).

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