From Lithium to Uranium: Elemental Tracers of Early Cosmic Evolution
Proceedings IAU Symposium No. 228, 2005
V. Hill, P. François & F. Primas, eds.

doi:10.1017/S1743921305005211

Lithium isotopic abundances in metal-poor stars

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Abstract. We report on a survey of ^{7}Li and ^{6}Li isotopic abundances in metal-poor halo stars. The spectra of the 24 stars observed with VLT/UVES are of exceptionally high quality: $S/N > 400$ and resolving power $R \simeq 120000$. The ^{7}Li abundances on our Hα $T_{\rm eff}$-scale show very small intrinsic scatter and a pronounced [Fe/H]-dependence. The resulting estimated primordial ^{7}Li abundance is about 0.5 dex lower than predicted from Big Bang nucleosynthesis and the baryon density inferred by the cosmic microwave background. Nine of the stars yield a positive detection ($>2\sigma$) of ^{6}Li, which suggests the existence of a ^{6}Li plateau for halo stars. The most interesting result is the presence of ^{6}Li in the very metal-poor ([Fe/H] = −2.74) dwarf LP815-43 at the level of ^{6}Li/^{7}Li $\simeq 0.05 \pm 0.02$. According to models for stellar Li depletion due to diffusion or rotationally-induced mixing, a 0.5 dex ^{7}Li depletion would require an unrealistic high initial ^{6}Li abundance (log ^{6}Li $\geqslant 2.0$). Simultaneously, the observed high ^{6}Li abundance at such low [Fe/H] can not be reconciled with existing models for Galactic cosmic ray spallation and α-fusion reactions. This opens up exciting prospects of pre-Galactic ^{6}Li production, possibly due to cosmological cosmic rays or late-decaying massive particles such as the gravitino or neutralino in the Big Bang.

Keywords. Line: formation, line: profiles, radiative transfer, stars: abundances, stars: atmospheres, stars: late-type, stars: Population II, cosmic rays, Galaxy: abundances, Galaxy: halo

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1. Observations and stellar parameters

Spectra of 23 stars were obtained with VLT/UVES during observing runs in July 2000 (three nights, visitor mode), February 2002 (three nights, visitor mode) and August 2004 (5.5 hr, service mode). In addition, we have added the observations of G271-162, which were obtained during the commissioning of UVES (Nissen *et al.* 2000). The spectra have a resolving power of $R \simeq 120000$ around the Li I 670.8 and 610.4 nm lines and cover the wavelength region 600–820 nm (100000 and $500 - 700$ nm in August 2004 due to a different setting). The S/N is in the range $500 - 1000$ for all but two of the stars that have 400 and 470, respectively.

The effective temperatures $T_{\rm eff}$ of the stars were estimated using the Hα line and the most recent H line broadening data (Barklem *et al.* 2002), which is expected to provide a *relative* precision of about 30 K. The *absolute* uncertainty can be significantly higher, however, even if the adopted $T_{\rm eff}$ agree very well with those estimated from $V - K$ and

$b - y$ colours calibrated on measurements from the infrared flux method (Alonso *et al.* 1996). The surface gravities $\log g$ have been estimated from the absolute magnitude as obtained from Hipparcos parallaxes or Strömgren photometry. The metallicity [Fe/H] has been measured from Fe II lines, as reported in Nissen *et al.* (2002).

The spectra have been analysed using 1D MARCS model atmospheres (Asplund *et al.* 1997). The Li abundances have been corrected for non-LTE effects according to the study of Carlsson *et al.* (1994). In addition, the new generation of 3D hydrodynamical model atmospheres for metal-poor stars (e.g. Asplund *et al.* 1999; Asplund & García Pérez 2001; Nissen *et al.* 2002) have been employed for a few stars for comparison purposes; unfortunately 3D models are not yet available for all stellar parameter combinations of our sample. The main advantage with these 3D models is that the traditional free parameters of stellar spectroscopy (mixing length parameters, micro- and macroturbulence) no longer enter the analysis. Furthermore, the intrinsic shape and asymmetry of the lines due to convective motions can be self-consistently predicted (e.g. Asplund *et al.* 2000)

2. Li isotopic abundances

Li isotopic abundances have been derived using the detailed profile of the Li I 670.8 nm resonance line (Fig. 1). The method relies on the isotopic shift for this transition that introduces additional width and asymmetry of the line profile. The intrinsic line broadening due to rotation, micro- and macroturbulence must therefore be measured. For the purpose between three and ten Mg I, K I, Ca I, Fe I and Fe II lines of similar strength as the Li line have been employed, which typically restricted the macroturbulence to within $0.2\,\mathrm{km\,s^{-1}}$; in all cases $v \sin i = 0.5\,\mathrm{km\,s^{-1}}$ were adopted since our observations were unable to disentangle rotational broadening from macroturbulence. Equipped with this line broadening, synthetic spectra for different $^6\mathrm{Li}/^7\mathrm{Li}$ ratios were computed. The comparison between the theoretical and observed profiles was quantified using a χ^2-analysis of typically 26 wavelength points across the Li line. For each $^6\mathrm{Li}/^7\mathrm{Li}$ ratio, the total Li abundance, the wavelength zeropoint of the observed spectrum and the continuum level were allowed to vary in order to optimize the fit and thus minimize χ^2.

The errors in the derived $^6\mathrm{Li}/^7\mathrm{Li}$ ratios have been quantified by taking the uncertainties from the finite S/N as well as line broadening and stellar parameters in quadrature. These have been verified to be realistic by Monte Carlo simulations. The resulting $^6\mathrm{Li}/^7\mathrm{Li}$ ratios are immune to reasonable changes in the stellar parameters as well as to the particular suite of 1D model atmospheres (for example MARCS and Kurucz models). The results obtained with 3D model atmospheres are similar to the corresponding 1D findings.

As seen in Table 1, nine of the 24 stars fulfill our criteria of a $\geqslant 2\sigma$ result to be considered a significant ^{6}Li detection. Together with the previous confirmed detection in HD84937 (Smith *et al.* 1993, 1998; Cayrel *et al.* 1999), this boosts the number of such stars to ten. However, our superior spectrum does not indicate any significant ^{6}Li in HD338529 ($\equiv$ BD +263578), which has previously been claimed as a detection (Smith *et al.* 1998). In addition, a number of our stars are borderline cases of being considered significant ^{6}Li detections. Indeed, there is a tendency for the non-detections to cluster at $^6\mathrm{Li}/^7\mathrm{Li} \approx 0.01$, which could be a signal of unidentified systematic errors in the analysis. Exhaustive tests have not been able to identify such an error. A strong argument in favour of our analysis is the result for the relatively cool main-sequence star HD19445, which was included in our program solely as a consistency check as it should have depleted its ^{6}Li according to standard stellar evolution models. Indeed, our observations for this star imply $^6\mathrm{Li}/^7\mathrm{Li} = 0.002 \pm 0.008$. All our positive detections are very near the turn-off.

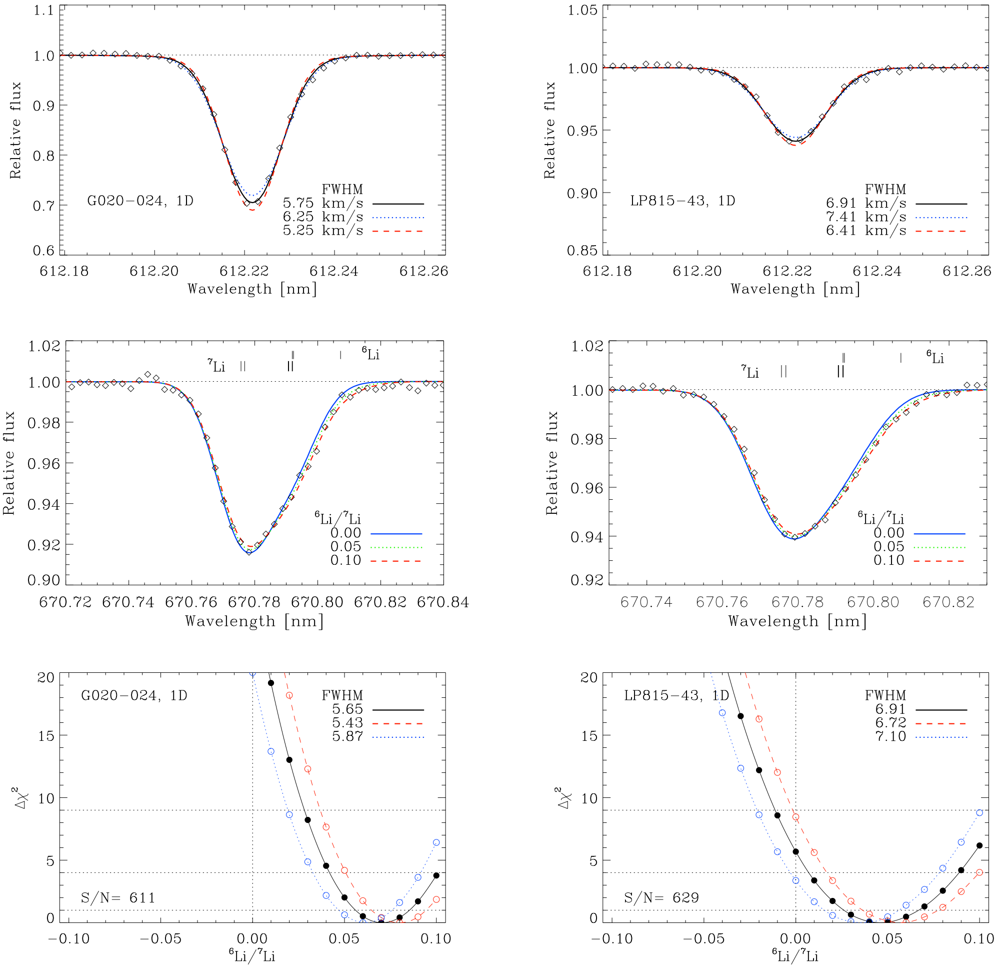

Figure 1. The profile fits for the Ca I 612.2 nm (upper panel) and Li I 670.8 nm lines (middle panel) for G020-024 ([Fe/H] = −1.89) (left panel) and LP815-43 ([Fe/H] = −2.74) (right panel) compared with observations (diamonds). The lower panel shows $\Delta\chi^2$ for the mean macroturbulence from different Ca and Fe lines together with instrumental broadening (FWHM of the combined Gaussian). In both stars ^{6}Li is detected at $> 2\sigma$ significance.

Intriguingly, our ^{6}Li detections together with HD84937 suggest the existence of a ^{6}Li abundance plateau at $\log \epsilon_{^6\mathrm{Li}} \approx 0.8$ (Fig. 2), analogues to the now well-established Spite-plateau for ^{7}Li (Spite & Spite 1982). The scatter in ^{6}Li abundances is appreciable however. The most exciting result of our survey is no doubt the detection of ^{6}Li in the very metal-poor ([Fe/H] = −2.74) turn-off star LP815-43, which has a ^{6}Li abundance typical for the Spite-plateau. Both the spectra obtained in July 2000 ($S/N \approx 540$ at 671 nm) and August 2004 ($S/N \approx 630$) indicate the presence of ^{6}Li: ^{6}Li/^{7}Li = 0.078 ± 0.033 and 0.046 ± 0.022, respectively.

The derived ^{7}Li abundances from the Li I 670.8 nm line in our spectra are similar to most recent studies, in particular those of Ryan *et al.* (1999), who used $S/N \approx 150$ and $R \approx 50000$ spectra of 24 stars. We confirm that the cosmic scatter in ^{7}Li must be very small as the observed scatter ($\sigma = 0.033$ dex) is very similar to the expectations solely

Table 1. The Li isotopic abundances (1D LTE and non-LTE) from the Li I 670.8 and 610.4 nm lines for our sample of 24 stars observed with VLT/UVES. The quoted abundance uncertainties are only those stemming from the finite S/N and the fitting procedure (rounded up to the nearest 0.01 dex) to which the errors from for example stellar parameters should be added. The results given here for LP815-43 correspond to the August 2004 observations.

	Li I 670.8 nm			Li I 610.4 nm	
Star	$\log \epsilon_{^7\mathrm{Li}}$ (LTE)	$\log \epsilon_{^7\mathrm{Li}}$ (non-LTE)	$^6\mathrm{Li}/^7\mathrm{Li}$	$\log \epsilon_{\mathrm{Li}}$ (LTE)	$\log \epsilon_{\mathrm{Li}}$ (non-LTE)
BD −13 3442	2.16 ± 0.01	2.14	0.001 ± 0.028	2.15 ± 0.08	2.19
BD +03 0740	2.12 ± 0.01	2.11	0.015 ± 0.017	< 2.10	< 2.15
BD +09 2190	2.13 ± 0.01	2.10	-0.035 ± 0.022	< 2.20	< 2.25
CD −30 18140	2.25 ± 0.01	2.22	0.042 ± 0.013	2.23 ± 0.03	2.27
CD −35 14849	2.27 ± 0.01	2.24	0.020 ± 0.012	2.26 ± 0.05	2.30
CD −33 1173	2.08 ± 0.01	2.05	0.013 ± 0.041	2.01 ± 0.10	2.04
CD −48 2445	2.22 ± 0.01	2.19	0.032 ± 0.014	2.27 ± 0.03	2.31
CD −33 3337	2.23 ± 0.01	2.24	0.020 ± 0.010	2.27 ± 0.03	2.34
HD 3567	2.32 ± 0.01	2.32	0.017 ± 0.012	2.30 ± 0.04	2.36
HD 19445	2.21 ± 0.01	2.20	0.002 ± 0.008	2.19 ± 0.05	2.24
HD 59392	2.24 ± 0.01	2.24	0.021 ± 0.016	2.16 ± 0.03	2.22
HD 102200	2.25 ± 0.01	2.25	0.047 ± 0.013	2.30 ± 0.03	2.36
HD 106038	2.49 ± 0.01	2.48	0.031 ± 0.006	2.45 ± 0.02	2.52
HD 140283	2.17 ± 0.01	2.20	0.008 ± 0.006	2.11 ± 0.03	2.20
HD 160617	2.28 ± 0.01	2.28	0.036 ± 0.010	2.28 ± 0.03	2.34
HD 213657	2.27 ± 0.01	2.25	0.011 ± 0.011	2.24 ± 0.04	2.29
HD 298986	2.25 ± 0.01	2.24	0.017 ± 0.015	2.24 ± 0.04	2.29
HD 338529	2.25 ± 0.01	2.22	0.010 ± 0.013	2.24 ± 0.05	2.28
G 013-009	2.22 ± 0.01	2.19	0.048 ± 0.019	2.15 ± 0.06	2.20
G 020-024	2.21 ± 0.01	2.18	0.070 ± 0.017	2.14 ± 0.07	2.18
G 075-031	2.30 ± 0.01	2.30	0.015 ± 0.012	2.40 ± 0.03	2.46
G 126-062	2.26 ± 0.01	2.24	0.001 ± 0.015	2.22 ± 0.04	2.27
G 271-162	2.27 ± 0.01	2.25	0.019 ± 0.012	2.14 ± 0.05	2.19
LP 815-43	2.16 ± 0.01	2.13	0.046 ± 0.022	2.17 ± 0.06	2.21

from the finite S/N and the relative uncertainty of 30 K in T_{eff} ($\sigma = 0.026$). A univariate least-square-fit to our results when excluding the unusual Li-rich star HD106038 (Nissen & Schuster 1997) and G271-162 (no Hα-based T_{eff}) implies $\log \epsilon_{^7\mathrm{Li}} = (2.409 \pm 0.020) + (0.103 \pm 0.010) \cdot [\mathrm{Fe/H}]$. The primordial ^{7}Li abundance is estimated to be $^7\mathrm{Li/H} \approx 1.1$–$1.4 \cdot 10^{-10}$, depending on which stars are considered for the extrapolation. We caution, however, that our sample does not extend to extremely low [Fe/H]. We note that even with the as yet unconfirmed very hot T_{eff}-scale of Melendez & Ramirez (2004) this value would only be raised to $^7\mathrm{Li/H} \approx 1.8 \cdot 10^{-10}$.

The quality of our spectra is sufficiently high to enable the very weak Li I 610.4 nm subordinate line to be used to estimate the Li abundances. The line is unambiguously detected in 22 of our 24 stars. The mean difference with the 670.8 nm line is only 0.05 ± 0.05 dex after accounting for 1D non-LTE effects (Table 1). This is in line with the findings of Bonifacio & Molaro (1997) for HD140283 but contradicts the results of Ford *et al.* (2002) who found in general significantly higher abundances for the subordinate line. We believe this discrepancy can be traced to their lower quality spectra.

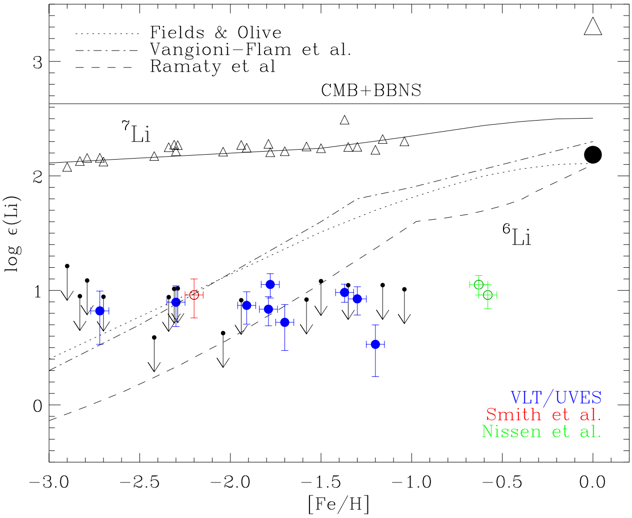

Figure 2. Observed ^{7}Li and ^{6}Li abundances compared with predictions from various models of cosmic ray production of ^{6}Li (dotted line: Fields & Olive 1999, dash-dotted line: Vangioni-Flam *et al.* 1999, dashed line: Ramaty *et al.* 2000). Also shown are the results for HD84937 (Smith *et al.* 1998) and two metal-poor disk stars (Nissen *et al.* 1999).

3. Implications

There are two big questions related to Li in metal-poor stars: why is the observed ^{7}Li abundances a factor of three to four lower than predicted from Big Bang nucleosynthesis with the baryon density measured from the cosmic microwave background anisotropies (e.g. Coc *et al.* 2004) and how can the observed high ^{6}Li abundances at low [Fe/H] be produced? The first one has been recognized for quite some time now while the second is raised by the observations described herein.

The most commonly invoked explanation for the ≈0.5 dex discrepancy between the observed and predicted ^{7}Li abundances is stellar Li depletion, possibly in combination with an erroneous $T_{\rm eff}$-scale. As noted above, even with the very hot $T_{\rm eff}$-scale of Meléndez & Ramírez (2004) the difference amounts to ≈0.4 dex so can only represent a minor part of the solution. Many different types of mechanisms producing Li depletion have been presented with the leading contenders presently being diffusion and rotationally-induced mixing (Richard *et al.* 2005; Pinsonneault *et al.* 2002). It is, however, very difficult to understand the extremely small observed ^{7}Li abundance scatter and the presence of ^{6}Li at $[\rm Fe/H] < -2.5$ if the ^{7}Li content has been diminished by the full ≈0.5 dex. Indeed, this would require the initial ^{6}Li abundance to have been $\log {}^6\rm Li \geqslant 2.0$. Since all ^{6}Li production by cosmic ray spallation and α-fusion results in ≈50% more ^{7}Li, it would require that most of the ^{7}Li in halo stars has a non-Big Bang origin. A ^{7}Li depletion of ≈0.2 dex could perhaps be accommodated by the observations but it would correspond to a simultaneous ^{6}Li destruction of $\geqslant 0.5$ dex during the main sequence for a star like LP815-43.

Even without accounting for any ^{6}Li depletion, the high ^{6}Li abundance in LP815-43 is very difficult to explain from existing models of Galactic cosmic ray production (Fig. 2); the problem is further aggravated by the ≈0.3 dex pre-main sequence depletion plus the destruction accompanying any ^{7}Li depletion. The high ^{6}Li/Be ratio (≈150, Primas *et al.*, in preparation) requires that the dominant production channel is α-fusion rather than spallation. Even the previous detection of ^{6}Li in HD84937 at [Fe/H] $= -2.2$ (Smith *et al.* 1993) required some tweaking of the models to achieve the necessary production rate at such early time (e.g. Fields & Olive 1999; Vangioni-Flam *et al.* 1999), which may require unrealistic energy input to the cosmic ray acceleration (Ramaty *et al.* 2000).

It therefore appears necessary to stipulate a pre-Galactic origin for ^{6}Li. It may be possible to achieve the necessary ^{6}Li synthesis by α-fusion during the formation of the Galaxy within the framework of hierarchical structure formation (Suzuki & Inoue 2002). Such a scenario requires several free parameters to model and it is questionable whether the necessary large dark matter halo could be in place at sufficiently early times.

The final potential site for ^{6}Li synthesis is the Big Bang. In standard Big Bang nucleosynthesis far too little ^{6}Li is produced. However, non-standard particle physics such as supersymmetry could result in substantial ^{6}Li production through proposed late-decaying massive particles such as gravitino, neutralino and axion without interfering too much with the production of D and ^{3,4}He provided their masses and life-times are right (e.g. Jedamzik 2004; Kawasaki *et al.* 2004). Indeed for the right combination of particle properties, a simultaneous increase in the primordial ^{6}Li and reduction of ^{7}Li abundances to the observed values can be achieved, thus solving both of the Li problems (Jedamzik 2004). While this idea is attractive, it rests on as yet unproven and speculative physics.

A full report of this will be published elsewhere (Asplund *et al.* 2005, in preparation).

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