Lithium Isotopic Abundances in Metal-Poor Stars: A Problem for Standard Big Bang Nucleosynthesis?

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Spectra obtained with VLT/UVES suggest the existence of the ^{6}Li isotope in several metal-poor stars at a level that challenges ideas about its synthesis. The ^{7}Li abundance is, on the other hand, a factor of three lower than predicted by standard Big Bang nucleosynthesis theory. Both problems may be explained if decaying supersymmetric particles affect the synthesis of light elements in the Big Bang.

Ever since the discovery of a plateau for lithium abundances in warm, metal-poor halo stars by Spite & Spite (1982), the Big Bang has been identified as the initial and major origin of the ^{7}Li isotope, with the plateau abundance being used to test theories of Big Bang nucleosynthesis. According to the standard Big Bang model, the relative abundances of the light elements (hydrogen, deuterium, helium and lithium) depend on only one parameter: the baryon-to-photon ratio η. Using the recent precise determination of η from cosmic microwave background fluctuations, the lithium-to-hydrogen ratio is predicted to be $N_{^7\mathrm{Li}}/N_\mathrm{H} = (4.15 \pm 0.5) \times 10^{-10}$ (Coc et al. 2004). This corresponds to a logarithmic abundance $\log\varepsilon(^7\mathrm{Li}) \equiv \log(N_{^7\mathrm{Li}}/N_\mathrm{H}) + 12.0 = 2.62 \pm 0.05$ on the traditional astronomical scale, where the logarithmic hydrogen abundance is normalised to 12. The predicted ^{7}Li abundance is about a factor three higher than Li abundances found in very metal-poor stars on the Spite plateau. Thus, a key question has become – How does one bridge the gap between ^{7}Li observation and prediction?

A second question has arisen from the detection of ^{6}Li in the metal-poor star HD 84937 (Smith et al. 1993; Hobbs & Thorburn 1994; Cayrel et al. 1999) with an abundance that is orders of magnitudes higher than predicted from standard Big Bang nucleosynthesis. How does one explain this unexpected high ^{6}Li abundance?

In order to study these two lithium problems in more detail, we have conducted a survey of isotopic lithium abundances in a sample of 24 dwarf stars ranging in metal abundance, $[\mathrm{Fe/H}] \equiv \log(N_\mathrm{Fe}/N_\mathrm{H})_\mathrm{Star} - \log(N_\mathrm{Fe}/N_\mathrm{H})_\mathrm{Sun}$, from –1 to –3, i.e. with metal-to-hydrogen ratios that are a factor of 10 to 1000 smaller than the ratio in the Sun. Hence, the stars are likely to have been formed from interstellar gas relatively little affected by element production in stars.

VLT/UVES high-resolution spectra

The isotopic shift of the 670.8 nm resonance line of ^{6}Li relative to the corresponding ^{7}Li line is only 0.016 nm. This is comparable to the width of the lithium line due to fine structure splitting and line broadening caused by turbulence in the stellar atmosphere. In addition, it turns out that the $^6\mathrm{Li}/^7\mathrm{Li}$ ratio does not exceed 10 %. Hence, the presence of ^{6}Li is revealed by a slight additional asymmetry of the 670.8 nm line. Consequently, both very high spectral resolution and signal-to-noise are needed to detect ^{6}Li. With 4-m-class telescopes, only a few fairly bright ($V < 9$ mag) stars, such as HD 84937, could be studied, but beginning in 1999 the VLT and its high-resolution spectrograph UVES opened up the possibility to conduct a systematic search for ^{6}Li in fainter and more metal-poor stars.

The spectra used in the present study were obtained in July 2000, February 2002 and August 2004. In order to obtain the highest possible spectral resolution ($\lambda/\Delta\lambda = 120\,000$) we used an image slicer, which transforms the seeing disc of the star to a rectangular image matching the narrow (0.3 arcsec) entrance slit of the UVES spectrograph. In addition to improving the efficiency of the observations, the image slicer also serves to broaden the spectrum, and hence to minimise problems of flatfielding the spectra to a smooth continuum.

A detailed description of the observations and data reduction is given in Asplund et al. (2005). The spectra cover the spectral region 600–820 nm, except for the August 2004 observations, when the very metal-poor star LP815-43 was re-observed with a different UVES setting corresponding to the 500–700 nm region in order to test a tentative detection of ^{6}Li based on the July 2000 spectrum.

Figure 1 shows the spectra of three stars in the wavelength region around the Li 670.8 nm line. The signal-to-noise (S/N) per spectral bin (0.0027 nm) is 600, which is typical for the sample. Note the differences in metallicity between the three stars as reflected in the strength of the calcium line at 671.8 nm.

Stellar parameters

In order to derive isotopic lithium abundances we must know the basic physical parameters that characterise the atmosphere of a given star. These parameters

Figure 1: Sample spectra around the Li I 670.8 nm line with CD −48°2445 and CD −33°3337 shifted 0.10 and 0.20, respectively. Note, that the region between the Li I and the Ca I lines in the spectrum of CD −33°3337 is affected by several faint lines not identified on the figure.

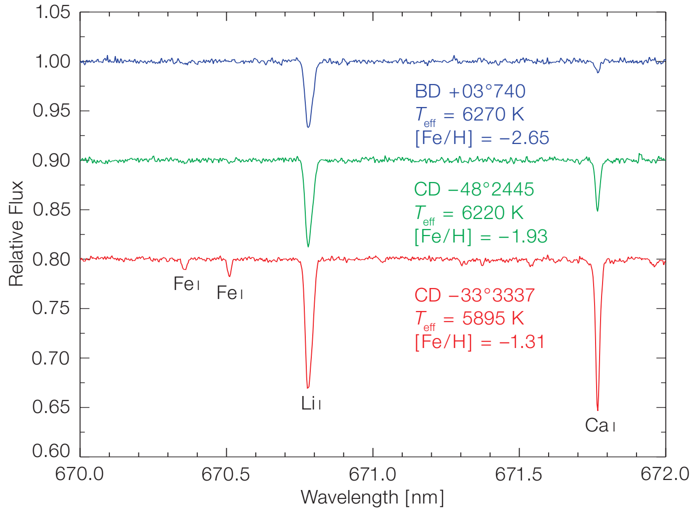
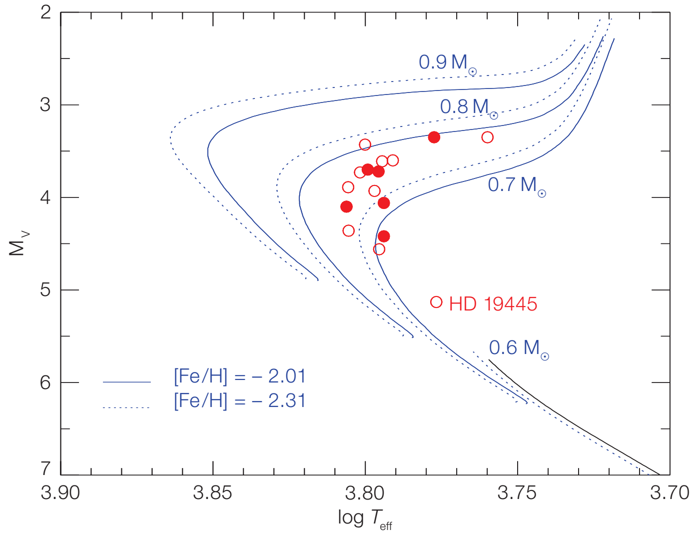


Figure 2: HR-diagram for stars with [Fe/H] < −1.7. Filled circles are stars with a ≥ 2σ detection of ^{6}Li, and open circles refer to stars with no clear detection of ^{6}Li. Evolutionary tracks corresponding to a range of masses are from VandenBerg et al. (2000).



are: the effective temperature T_{eff}, the surface gravity g, and the metallicity [Fe/H].

Precise values of T_{eff} are particularly important. Often this characteristic surface temperature is derived from the stellar colour, but as the observed colour may be affected by interstellar reddening the value obtained can be wrong. Instead, we have obtained T_{eff} by comparing the observed Hα line in the UVES spectra with synthetic profiles calculated for model atmospheres having a range of effective temperatures. As discussed in Asplund et al. (2005), relative values of T_{eff} are determined to a precision of about ± 30 K; the absolute T_{eff} scale is, however, more uncertain.

The surface gravity of a star was estimated via its absolute magnitude M_V as determined from Strömgren photometry and Hipparcos parallaxes. The metallicity is based on Fe II lines. The values of these parameters are not critical for the derived isotopic Li abundances, but they are important when discussing the interpretation of our results. Thus, the M_V-logT_{eff} diagram in Figure 2 shows that our most metal-poor stars (except HD 19445) lie close to the turnoff region of halo stars. From a comparison with evolutionary tracks from VandenBerg et al. (2000) we derive ages of about 12–14 Gyr confirming that the sample is indeed representative of the oldest stellar population in our galaxy.

Deriving ^{6}Li/^{7}Li

The lithium isotopic ratio was derived by comparing synthetic profiles of the Li I 670.8 nm line with the observed profile. Traditional plane-parallel model atmospheres were applied, but it has been checked that 3D hydrodynamical models give similar or even higher ^{6}Li/^{7}Li ratios than 1D models.

The method is illustrated in Figure 3. First, the width of spectral lines due to macroturbulence in the stellar atmosphere and instrumental broadening is determined as shown in the upper panel for the Ca I 612.2 nm line. Several such lines were applied to determine the macroturbulence velocity and a minor variation of the instrumental broadening with wavelength as determined from the width of thorium comparison lines was taken into account.

In the next step (middle panel) the average macroturbulence velocity plus instrumental broadening are applied in a synthesis of the observed Li I 670.8 nm line. The comparison between the theoretical and observed profiles is quantified by calculating the chi-square function $\chi^2 \equiv \Sigma(O_i - S_i)^2/\sigma^2$, where O_i and S_i denote the observed and synthetic flux at wavelength point i, respectively, and σ = (S/N)$^{-1}$ is estimated in three nearby continuum windows. For each ^{6}Li/^{7}Li, the total Li abundance, the wavelength zero-point of the observed spectrum and the continuum level are allowed to vary in order to optimise the fit and thus minimise χ^2.

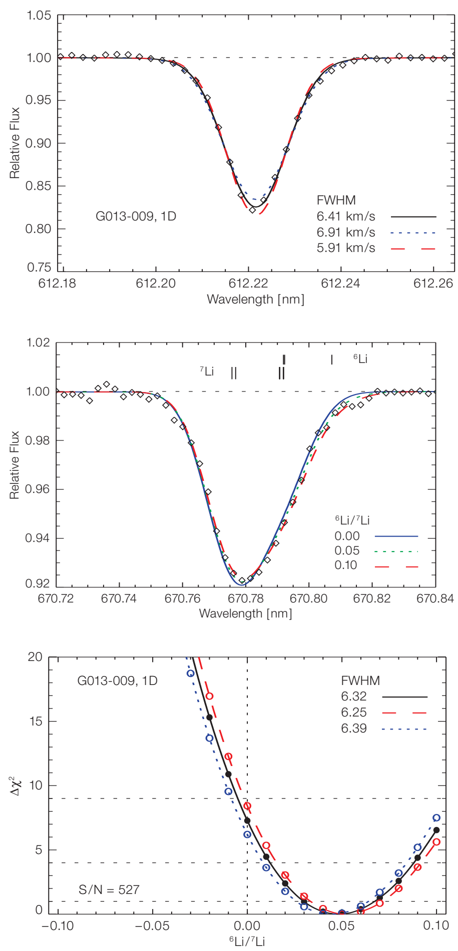


Figure 3: Illustration of the method applied to determine ^{6}Li/^{7}Li in G 013-009. See text for a description of the three panels.

The most probable value for ^{6}Li/^{7}Li corresponds to the minimum of χ^2.

In the case of G 013-009 the derived value of ^{6}Li/^{7}Li is close to 0.05 as seen from the lower panel of Figure 3. This value is quite insensitive to the estimated error in the macroturbulence velocity. The 1σ, 2σ and 3σ confidence limits of the determination correspond to $\Delta\chi^2 = \chi^2 - \chi^2_{min}$ = 1, 4 and 9, respectively. As seen, ^{6}Li is detected in G 013-009 with a confidence limit of about 2.5σ, i.e. with a probability of 99 %.

The derived ^{6}Li/^{7}Li ratios are plotted as a function of [Fe/H] in Figure 4. As seen, there are nine stars with a $\geq 2\sigma$ detection of ^{6}Li. Many of the other stars may also have a small amount of ^{6}Li; the average of ^{6}Li/^{7}Li for the whole sample is close to 2 %. In this connection, it is natural to ask if there could be a systematic error in the ^{6}Li/^{7}Li determinations of this small amount. If so, there would be very few significant detections of ^{6}Li. The fact that the main-sequence star HD 19445 has a ^{6}Li/^{7}Li ratio close to zero (see Figure 4) is, however, an argument against this possibility. As shown in Figure 2, HD 19445 is an unevolved main-sequence star. With its mass of about 0.65 solar masses, it has a rather deep upper convection zone, and according to models of stellar structure, ^{6}Li cannot survive proton destruction in such a star. Hence the star can be considered as a reliable check of the zero point of the ^{6}Li determinations.

Except for HD 19445, the stars in Figure 4 are all turnoff stars or slightly evolved beyond the turnoff. Particularly interesting is the very metal-poor star LP 815-43 (T_{eff} = 6 400 K, log$g$ = 4.2 and [Fe/H] = −2.7). From the July 2000 spectrum, we obtained ^{6}Li/^{7}Li = 0.078 ± 0.033. Given the rather large error bar, it was decided to re-observe the star in August 2004 with a different setting of UVES to get an independent determination of ^{6}Li/^{7}Li. The new result is ^{6}Li/^{7}Li = 0.046 ± 0.022. Within the error bars the two results agree fairly well, and the weighted average value is ^{6}Li/^{7}Li = 0.056 ± 0.018, i.e. formally a 3σ detection of ^{6}Li.

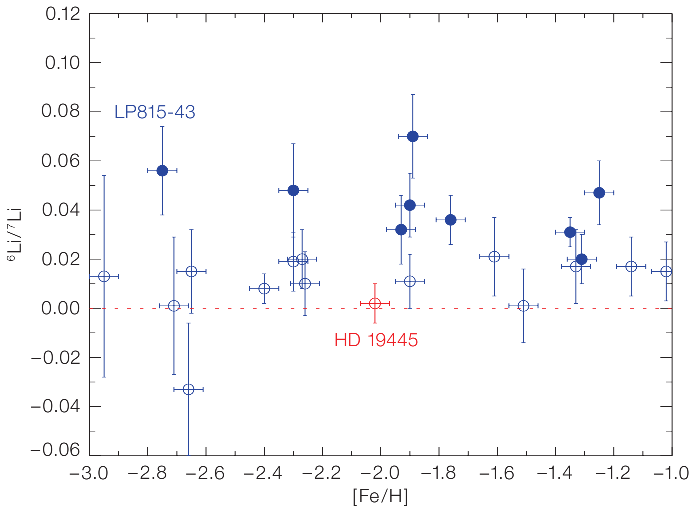


Figure 4: The derived ^{6}Li/^{7}Li ratio as a function of [Fe/H]. Stars considered to have a significant detection ($\geq 2\sigma$) of ^{6}Li are shown with filled circles.

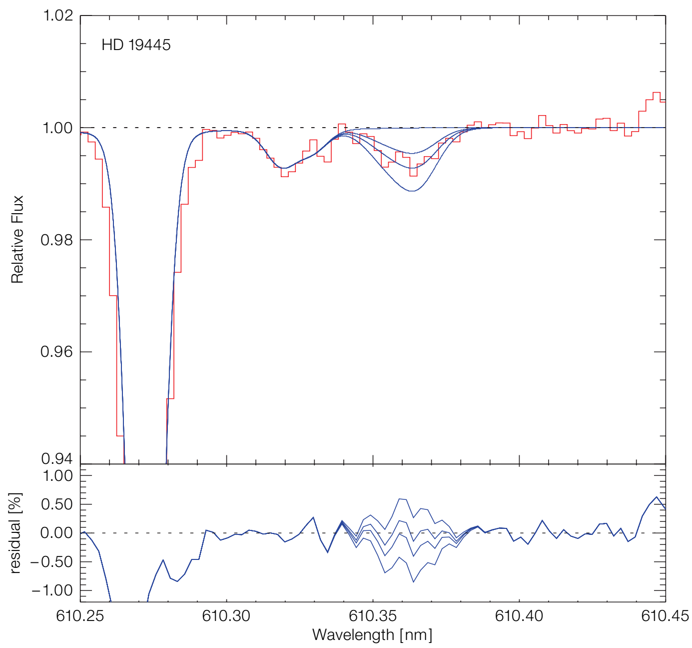


Figure 5: Observed (red) and theoretical (blue) Li I 610.4 nm profiles for HD 19445. The four synthetic profiles are computed with no Li and logε(Li) = 2.0, 2.2 and 2.4, respectively.

The two lithium problems

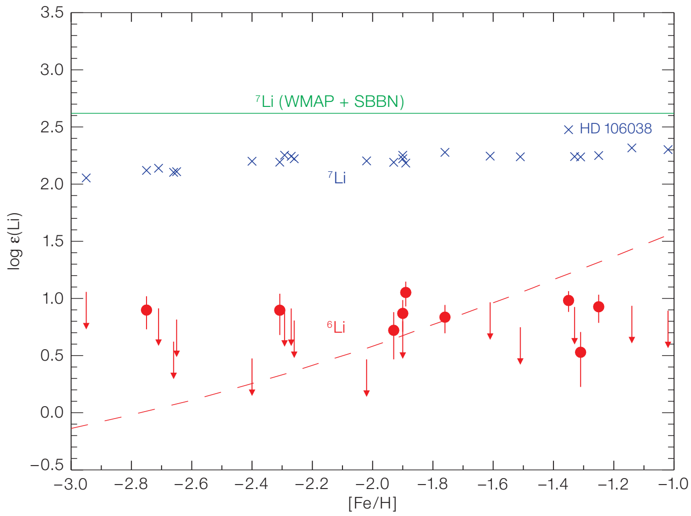
In addition to ^{6}Li/^{7}Li, we derive precise values for the total lithium abundance from the fits to the 670.8 nm line. Furthermore, the exceptionally high quality of our UVES spectra allows Li abundances to be derived from the subordinate Li I line at 610.36 nm. Figure 5 shows this line in HD 19445 together with synthetic spectra calculated for various Li abundances. The best fit is obtained for logε(Li) = 2.19 ± 0.05, close to the value obtained from the 670.8 nm line. The subordinate line is detected in 22 of the 24 stars, and the mean difference of Li abundances derived from the subordinate line and the resonance line is + 0.05 ± 0.05 dex. This is an encouraging confirmation of the reliability of our Li abundance scale.

In Figure 6, ^{6}Li and ^{7}Li abundances are plotted as a function of [Fe/H]. Except for one star, HD 106038 (known to have peculiar high s-process abundances), the scatter in ^{7}Li is remarkably small, i.e.

~ 0.03 dex at a given metallicity. The ^{7}Li abundance appears to increase slightly with increasing metallicity, which may be due to Galactic cosmic-ray production of ^{7}Li. The trend implies an apparent "primordial" ^{7}Li abundance of about 2.1 dex, i.e. a factor of three below the value of 2.6 dex predicted from standard Big Bang nucleosynthesis and the WMAP-based value of the baryon-to-photon ratio. People studying stellar structure and evolution have tried to explain this difference as due to depletion of ^{7}Li by processes that mix the gas in the stellar atmosphere with hotter layers, where Li is destroyed by reactions with fast protons. Turbulent diffusion seems to be the most promising mechanism; for the right choice of free parameters it can provide both a factor of three depletion and retain a very small dispersion of ^{7}Li among the plateau stars (Richard et al. 2005).

The turbulent diffusion models, which deplete ^{7}Li with a factor of three, predict, however, a depletion of ^{6}Li by more than a factor of 30. This would mean that the observed ^{6}Li values in Figure 6 should be corrected upwards by at least 1.5 dex to correspond to the original ^{6}Li abundance at the time of star formation. Such high ^{6}Li abundances seem impossible to be explained by production of ^{6}Li through Galactic cosmic-ray processes involving $\alpha + \alpha$ fusion and spallation of CNO nuclei. The production in a realistic model by Ramaty et al. (2000), involving cosmic rays accelerated out of supernova ejecta-enriched superbubbles, is shown as a dashed line in Figure 6; as seen the model has already difficulties in explaining the uncorrected ^{6}Li abundances in the most metal-poor stars. More speculative models of pregalactic synthesis of ^{6}Li have been suggested. Thus, Suzuki and Inoue (2002) suggest that α-particles are accelerated by gravitational shocks induced by infalling matter during hierarchical structure formation, and Rollinde et al. (2005) suggest an early burst of cosmological cosmic rays perhaps caused by population III stars. The energetics of such a scenario were, however, not considered.

Figure 6: Observed logarithmic abundances of ^{6}Li (red circles) and ^{7}Li (blue crosses) as a function of metal abundance. Stars with a $\geq 2\sigma$ detection of ^{6}Li are shown with filled circles; 2σ upper limits are shown for the other stars. The predicted evolution of ^{6}Li due to Galactic cosmic-ray processes (dashed line) is taken from Ramaty et al. (2000), and the predicted ^{7}Li abundance due to standard Big Bang nucleosynthesis is shown as a green horizontal line.



Big Bang nucleosynthesis of lithium

The most interesting feature of Figure 6 is perhaps that the observed ^{6}Li abundances appear to form a plateau in contrast to the rise of ^{6}Li predicted by Galactic cosmic-ray processes. A plateau in ^{6}Li could be an indication that ^{6}Li has a primordial Big Bang origin like ^{7}Li. Standard Big Bang nucleosynthesis predicts, however, ^{6}Li/^{7}Li ~ 10^{-5}, i.e. orders of magnitudes below the ^{6}Li observations.

Extensions of standard particle physics to supersymmetry predict the existence of various exotic particles, including the gravitino. The decay of such relic particles during the era of Big Bang nucleosynthesis can alter the resulting light element abundances, provided the masses and lifetimes of these putative particles are right. As shown by Jedamzik (2004), the injection of energetic nucleons through hadronic decay about 10^3 s after Big Bang can lead to substantial ^{6}Li production without spoiling the agreement with observed values of the primordial abundance of D and He. Furthermore, simultaneous destruction of ^{7}Li with a factor 2 to 3 is possible. This would explain both the observed ^{6}Li plateau and the low ^{7}Li abundances in metal-poor stars. Thus, both of the Li problems can conceivably be solved at the same time.

While this idea is attractive, it rests on as yet unproven physics. Furthermore, it should be noted that the ^{6}Li results we have obtained are at the borderline of being clear detections. Hence, more work is needed in order to obtain additional data especially for the most metal-poor stars and also to verify the zero-point of the ^{6}Li/^{7}Li determinations.

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