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Observations of ^{6}Li in metal poor stars

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Abstract.
Methods and accuracies of determining the lithium isotope ratio in stellar atmospheres from high resolution observations of the profile of the λ6708 Li I doublet are discussed, and recent results for metal-poor disk stars and halo stars are reviewed. The data are compared to models for the Galactic evolution of the ^{6}Li abundance. It is concluded that a much larger data set is needed to understand properly the formation of ^{6}Li in the interstellar medium as well as the depletion in stars.

1. Introduction

Measurements of the abundance of the ^{6}Li isotope in stellar atmospheres are of considerable interest and have attracted much attention since the first probable detection of ^{6}Li in the metal-poor turnoff star HD 84937 by Smith, Lambert, & Nissen (1993). The reason for this interest is threefold:

i) Detection of ^{6}Li in halo turnoff stars puts strong limits on the possible depletion of ^{7}Li, and thus allows better determination of the primordial ^{7}Li abundance from the observed Li abundance of stars on the 'Spite plateau'.

ii) ^{6}Li abundances as a function of [Fe/H] provide an additional test of theories for the production of the light elements Li, Be and B by interactions between cosmic ray nuclei and ambient ones.

iii) Information on depletion of ^{6}Li as a function of stellar mass and metallicity puts new constraints on stellar models in addition to those set by ^{7}Li depletion. This is so because the proton capture cross section of ^{6}Li is much larger than that of ^{7}Li. Hence, at a given metallicity there will be a mass interval, where ^{6}Li but not ^{7}Li is being destroyed according to standard stellar models.

Altogether, ^{6}Li abundances may contribute to the study of such different fields as Big Bang nucleosynthesis, cosmic ray physics and stellar structure. It will, however, require a rather large data set of ^{6}Li abundances to get information in all these areas. The most metal-poor stars around the turnoff are of particular interest in connection with the determination of the primordial ^{7}Li abundance, whereas more metal-rich halo stars and disk stars are of interest for the study of the formation and astration of the light elements.

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2. Methods to determine the Li isotope ratio

The ^{6}Li/^{7}Li ratio in stars can be determined by two methods: From the center-of-gravity (*cog*) of the Li I 6708 Å line or from a detailed model atmosphere synthesis of the profile. The isotopic shift of the ^{6}Li doublet is +0.158 Å relative to the ^{7}Li doublet. Addition of ^{6}Li therefore shifts the Li I line to longer wavelengths and increases the width. The *cog*-method relies in principle on a very simple and straightforward measurement, but its accuracy is limited by possible errors in the laboratory wavelengths of the lithium line and the reference lines needed to correct for the radial velocity shift of the star. Furthermore, differences in convective blueshifts of the lines may be a problem. Hence, the profile method is superior to the *cog*-method and the exact wavelength of the Li I line should be considered as a free parameter in the comparison between synthetic and observed profiles.

In order to determine the Li isotopic ratio with good accuracy, the profile of the Li I 6708Å line should be observed at high resolution and very high S/N. Experience shows that $R \simeq 100\,000$ and $S/N > 400$ are required to obtain errors less than ± 0.02 in ^{6}Li/^{7}Li.

The synthesis of the Li I line has to be based on a model atmosphere with the same effective temperature, surface gravity and composition as the star. As discussed by e.g. Smith et al. (1993) the errors of these parameters do not add significantly to the error of the ^{6}Li/^{7}Li determination. Furthermore, data for the fine structure and hyper-fine structure splitting of the Li line as well as the isotopic shift between the ^{6}Li and ^{7}Li components is known with superior accuracy; see e.g. Table 3 of Smith, Lambert, & Nissen (1998).

Due to the weakness of the lithium line in the solar spectrum one has a good possibility to see if it is blended by other lines. As discussed by Nissen et al. (1999), the blue wing of the Li line is contaminated by a weak Fe I line (λ6707.43) and a few very weak CN lines. In the red wing there are two unidentified lines with equivalent widths of 0.6 and 1.1 mÅ. For more metal rich stars these blends are a problem and limits the obtainable accuracy of the ^{6}Li/^{7}Li determination. For metal-poor disk stars with $-0.8 <$ [Fe/H] < -0.5 only the Fe I line in the blue wing plays a role, and for halo stars with [Fe/H] below say -1.5 this line has also disappeared.

The basic problem in the synthesis is to determine the broadening of the lithium line due to rotation and turbulent motions in the stellar atmosphere. In the studies performed so far a homogenous, plane parallel model has been adopted and a symmetric velocity broadening profile has been determined from other lines in the spectrum with about the same strength as the lithium line. Due to convective motions in the atmosphere a slight asymmetry is expected, but as discussed by Smith et al. (1998) the asymmetry is probably too small to affect the derived ^{6}Li/^{7}Li ratio significantly. This has recently been confirmed by Asplund (2000) from an analysis of the Li line in HD 84937 based on inhomogeneous 3D hydrodynamical model atmospheres (Asplund et al. 1999) for which the only free parameter is the rotation velocity of the star.

As an example of the method of determining ^{6}Li/^{7}Li, Figs. 1 and 2 show the synthesis of the lithium line for two metal-poor disk stars, HR 8181 and HD 130551, as performed by Nissen et al. (1999). The atmospheric velocity

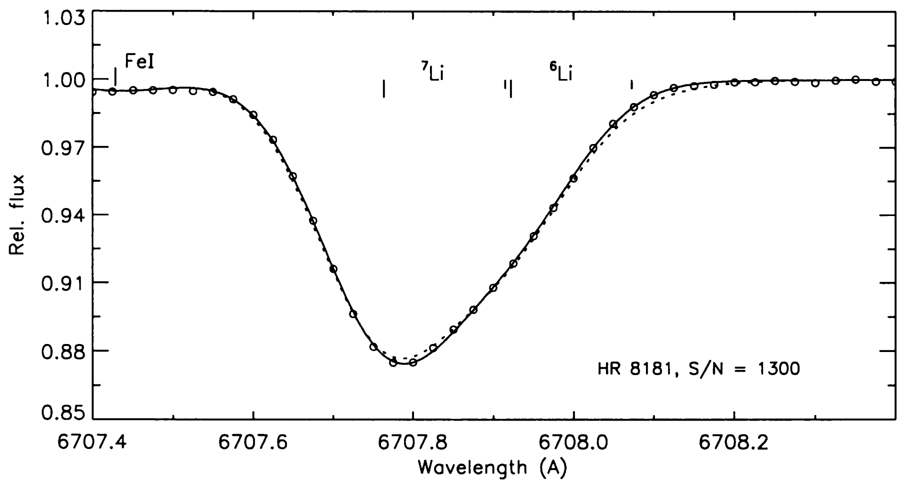

Figure 1. The model atmosphere synthesis of the the Li I 6707.8 Å line in the spectrum of HR 8181. The datapoints are shown with open circles. The full drawn line corresponds to ^{6}Li/^{7}Li = 0.0 (the best fit) and the dotted line to ^{6}Li/^{7}Li = 0.05. Note, that when ^{6}Li/^{7}Li is varied the other free parameters in the fit, the wavelength and the equivalent width of the line, are optimized to get the best possible fit

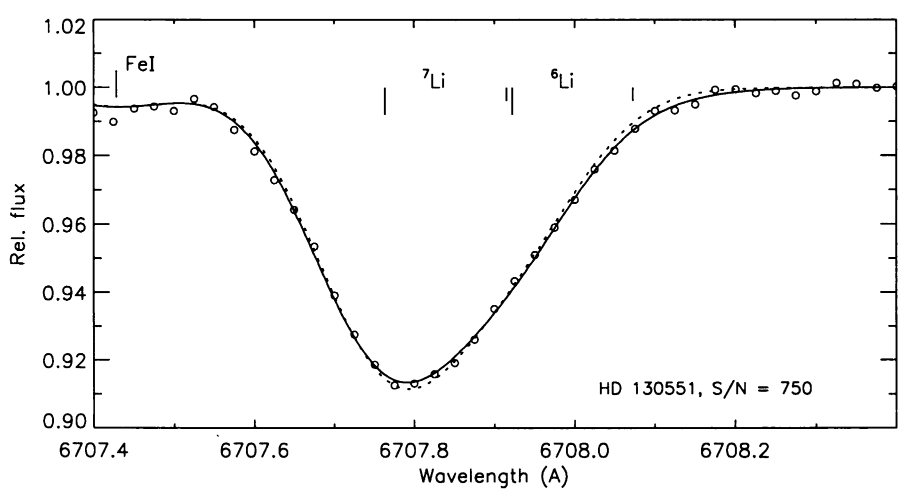

Figure 2. Same as Fig. 2 for HD 130551. Here the full drawn line corresponds to ^{6}Li/^{7}Li = 0.06 (the best fit) and the dotted line to ^{6}Li/^{7}Li = 0.0

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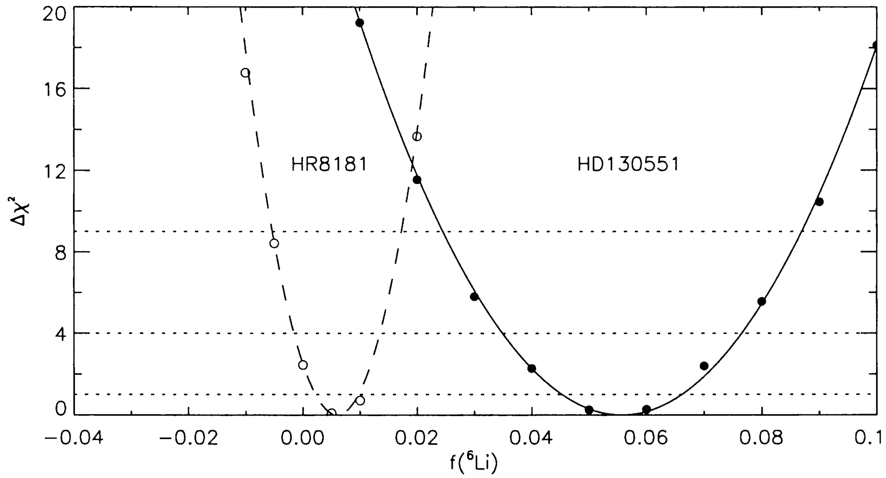

Figure 3. Variation of the χ^2 of the fit to the Li I 6707.8 Å line as a function of the relative abundance of ^{6}Li for two stars, HR 8181 and HD 130551

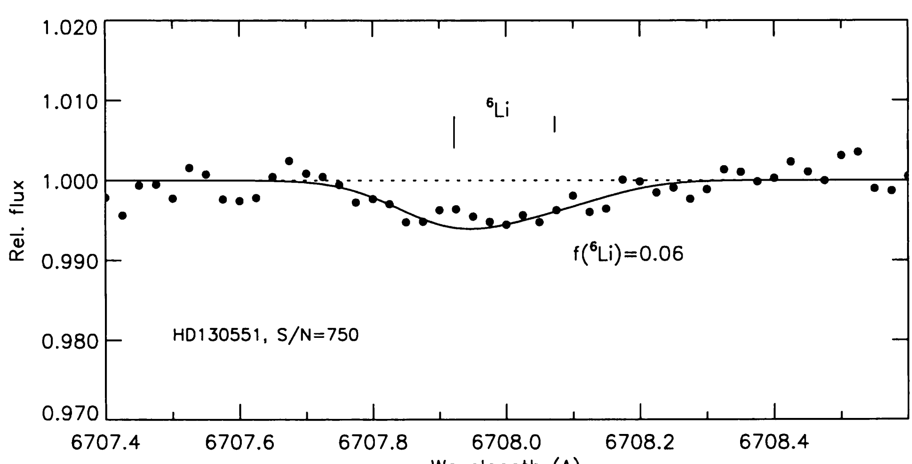

Figure 4. The residuals of the observations of HD 130551 after subtraction of the ^{7}Li and Fe I 6707.43 Å part of the synthesis of the Li I line. For comparison the synthesis of the ^{6}Li doublet is shown with a full drawn line

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broadening was determined from two nearby Fe I lines (λ6703.6 and λ6705.1) of about the same strength as the Li line. A good fit ($\chi^2_{red} \simeq 1$) to these lines was obtained for a Gaussian broadening profile with FWHM parameters of 5.5 and 6.6 km s^{-1} for HR 8181 and HD 130551, respectively. These parameters have then been applied in a χ^2 fit of the Li line using the relative abundance of ^{6}Li, the total Li abundance and the wavelength of the line as free parameters. The χ^2 variation as a function of $f(^6\text{Li}) = {}^6\text{Li}/({}^6\text{Li}+{}^7\text{Li})$ is shown in Fig. 3. Note, that the steeper variation of χ^2 for HR 8181 is due to the higher S/N (1300) of the observations than in the case of HD 130551 ($S/N = 750$). It should also be stressed that for each value of $f(^6\text{Li})$, the other free parameters are optimized to get the lowest possible value of χ^2. $\Delta\chi^2 = 1$, 4 and 9 then correspond to the 1, 2, and 3σ confidence limits of $f(^6\text{Li})$ (Bevington & Robinson 1992). The setting of the continuum may also be considered as a free parameter in the fit, but normally it will be well constrained by the continuum on each side of the Li line.

As seen from Fig. 3, ^{6}Li is not present in HR 8181 but is detected in HD 130551 at about the 3σ confidence level. The presence of ^{6}Li can be seen from Fig. 2, and more clearly from Fig. 4, which shows a plot of the residuals in the observations after subtracting the ^{7}Li and Fe I part of the synthesis. A residual absorption at the wavelength of the ^{6}Li doublet is present.

3. Metal-poor disk stars

Nissen et al. (1999) have studied the Li isotope ratio in 5 metal-poor disk stars in the turnoff region of the HR diagram. The observations were carried out with the ESO 1.4m CAT and 3.6m telescopes using the CES instrument to obtain $R \simeq 110\,000$ spectra in the lithium line region. The derived ^{6}Li/^{7}Li ratio is given in Table 1 together with T_{eff} and [Fe/H] as well as the absolute magnitude derived from the Hipparcos parallax and the mass derived from comparing the position of the star in the T_{eff}-M_V diagram with evolutionary tracks from VandenBerg et al. (2000) based on stellar models with enhanced abundances of the α-elements, $[\alpha/\text{Fe}] = 0.3$. In estimating the error of the mass, both the error of T_{eff} ($\pm$70 K) and the error of M_V have been taken into account.

Table 1. Effective temperatures, absolute magnitudes, metallicities, masses and Li isotope ratios for 5 metal-poor disk stars. The quoted errors and upper limits are one sigma values.

ID	T_{eff}	M_V	[Fe/H]	$\mathcal{M}/\mathcal{M}_\odot$	^{6}Li/^{7}Li
HR 2883	5980 K	$3.55 \pm .06$	-0.75	$1.02 \pm .02$	< 0.02
HR 3578	5970	$4.16 \pm .04$	-0.82	$0.88 \pm .02$	< 0.01
HR 8181	6140	$4.41 \pm .01$	-0.67	$0.96 \pm .02$	< 0.01
HD 68284	5880	$3.41 \pm .19$	-0.59	$1.07 \pm .04$	$0.04 \pm .01$
HD 130551	6240	$3.77 \pm .09$	-0.62	$1.06 \pm .02$	$0.06 \pm .01$

As seen from Table 1, the two stars with ^{6}Li present have significantly higher masses than the three with non-detections. This makes sense, because

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the depth of the convection zone in a star on the main sequence decreases rapidly as a function of increasing mass. Hence, according to standard stellar models without mixing, the depletion of ^{6}Li is less severe in the more massive stars. In this connection we note that although HD 68284 is the coolest of the stars, it is a subgiant that has spent most of its life as a main sequence star at $T_{\rm eff} \simeq 6300$ K.

Hobbs & Thorburn (1997) have also studied a few metal-poor disk stars based on observations with the 2.7m reflector and coudé spectrograph at McDonald Observatory. No detections of ^{6}Li was obtained. The tightest upper limit, $^6\mathrm{Li}/^7\mathrm{Li} < 0.02$, was found for HD134169 a subgiant with $T_{\rm eff} \simeq 5800$ K, [Fe/H] $\simeq -1.0$ and $M_V = 3.82 \pm 0.14$. From the evolutionary tracks of VandenBerg et al. (2000) we derive a mass $\mathcal{M}/\mathcal{M}_\odot = 0.90 \pm 0.03$, again significantly lower than the mass of the two stars with ^{6}Li detections.

4. Halo stars

The primary candidate in the search for ^{6}Li has been HD 84937 – the brightest metal-poor halo star near the turnoff. A probable detection of ^{6}Li was obtained by Smith et al. (1993) based on observations with the coudé spectrograph at McDonald Observatory. A later refinement of the analysis of these observations (Smith et al. 1998) resulted in $^6\mathrm{Li}/^7\mathrm{Li} = 0.06 \pm 0.03$. Independent observations and analysis by Hobbs & Thorburn (1994, 1997) led to $^6\mathrm{Li}/^7\mathrm{Li} = 0.08 \pm 0.04$. Recently, Cayrel et al. (1999) have observed HD 84937 with the GECKO spectrograph at the CFHT at a resolution of 10^5 and a S/N as high as 650 yielding $^6\mathrm{Li}/^7\mathrm{Li} = 0.052 \pm 0.019$. The weighted mean of these values is $^6\mathrm{Li}/^7\mathrm{Li} = 0.059 \pm 0.016$, where all errors quoted are one sigma values.

The paper of Cayrel et al. (1999) is particular interesting. Due to the very high S/N obtained, the χ^2 fitting of the Li line was carried out by including the FWHM of the Gaussian broadening function as a free parameter in addition to $^6\mathrm{Li}/^7\mathrm{Li}$, the wavelength zero-point, the total abundance of Li, and the continuum setting. This is possible, because the slope of the blue wing of the Li line primarily depends on the FWHM of the broadening function, whereas the red wing depends both on the FWHM and $^6\mathrm{Li}/^7\mathrm{Li}$. After having determined the FWHM parameter from the Li line it was checked if the Ca I line at 6162 Å could be fit with the same value, which is indeed the case. Cayrel et al. also show that the extra absorption seen in HD 84937 at the position of the ^{6}Li doublet is very unlikely to be due to a binary component. Furthermore, there is no sign of radial velocity variations of the star based on 30 years CORAVEL and ELODIE observations although such variations have been suspected by Carney et al. (1994).

Apart from HD 84937, ^{6}Li seems to have been detected in BD +26 3578 by Smith et al. (1998) based on a spectrum with $S/N \simeq 400$. Hobbs & Thorburn (1994, 1997) also studied this star, but due do a lower S/N they were only able to place an upper (3σ) limit, $^6\mathrm{Li}/^7\mathrm{Li} < 0.09$. Another 15 halo stars have been searched for ^{6}Li by Smith et al. (1998), Cayrel et al. (1999), and Hobbs, Thorburn & Rebull (1999) but without detections. Table 2 lists the results for a group of [Fe/H] $\simeq -2.0$ halo stars with detections or tight upper limits of $^6\mathrm{Li}/^7\mathrm{Li}$. The absolute magnitudes are based on Hipparcos parallaxes or (for the more distant stars) on the Strömgren c_1 index, and masses are derived from a comparison with the α-enhanced evolutionary tracks of VandenBerg et al. (2000). As in the case of the metal-poor disk stars, the two stars for which ^{6}Li is detected are among those having the highest masses. It is, however, puzzling that several other stars (HD 74000, HD 160617 and BD +20 2603) have equally high masses within the errors. Hence, it cannot be excluded that there is a real dispersion in the ^{6}Li abundance at a given mass and metallicity.

Table 2. Same as Table 1 for 7 halo turnoff stars with metallicities [Fe/H] $\simeq -2$

ID	$T_{\rm eff}$	M_V	[Fe/H]	$\mathcal{M}/\mathcal{M}_\odot$	^{6}Li/^{7}Li
HD 19445	5870 K	$5.12 \pm .10$	-2.00	$0.65 \pm .03$	< 0.03
HR 74000	6190	$4.47 \pm .25$	-1.80	$0.70 \pm .04$	< 0.03
HR 84937	6310	$3.81 \pm .19$	-2.20	$0.75 \pm .03$	0.059 ± 0.016
HD 160617	5960	$3.49 \pm .25$	-1.90	$0.79 \pm .06$	< 0.03
HD 218502	6000	$4.03 \pm .18$	-2.00	$0.69 \pm .04$	< 0.02
BD +20 2603	6210	$3.90 \pm .25$	-2.20	$0.73 \pm .04$	< 0.02
BD +26 3578	6310	$3.08 \pm .25$	-2.40	$0.85 \pm .07$	$0.05 \pm .03$

5. Discussion and conclusions

Fig. 5 shows a comparison of the ^{6}Li data from Smith et al. (1998) and Nissen et al. (1999) with three recent Galactic evolutionary models. In the model of Fields & Olive (1999) the 'standard' picture of Galactic cosmic ray nucleosynthesis of Li by spallation of C,N,O nuclei and $\alpha + \alpha$ fusion is adopted. The cosmic rays are assumed to have the composition of the average ISM at a given epoch, and the energy spectrum is that of present days cosmic rays in the solar neighborhood i.e. relativistic energies are dominant. A novel ingredient in the model of Fields & Olive is the incorporation of recent measurements of the oxygen abundance in halo stars indicating that [O/Fe] increases steply with decreasing [Fe/H] (Israelian et al. 1998, Boesgaard et al. 1999). Furthermore, the time integrated Li,Be,B outputs are normalized to the ^{6}Li, Be and ^{10}B abundances in meteorites. Vangioni-Flam et al. (1999) invoke an additional low energy cosmic ray component (LECR) which they associate with the acceleration of supernovae ejecta in superbubbles created collectively by winds from massive stars in OB associations. A key point about this component is that the He, C, and O abundances of the ejecta are considered to be much higher than in the halo interstellar medium and, then, the dominant spallation process is between O in the ejecta and protons in the interstellar gas, whereas in the standard picture the leading process is between protons in the cosmic rays and O in the interstellar gas.

As seen from Fig. 5, the models of Fields & Olive (1999) and Vangioni-Flam et al. (1999) reproduce the observed ^{6}Li abundances of the two halo stars very well. Ramaty et al. (2000) have, however, criticized these models for requiring an unrealistic high energy input of the supernovae into cosmic ray acceleration. Another problem with the two models is the high ^{6}Li abundance predicted in the

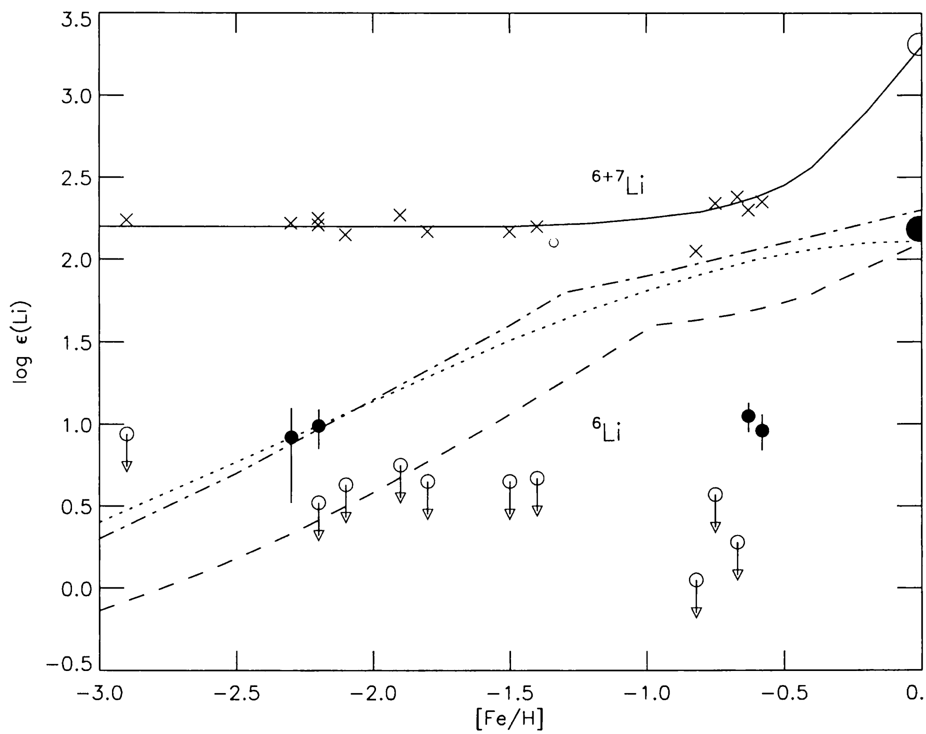

Figure 5. Abundances of the lithium isotopes as a function of [Fe/H] for 9 halo stars from Smith et al. (1998) and 5 disk stars from Nissen et al. (1999). Crosses indicate the total Li abundance, filled circles ^{6}Li abundances with one-sigma error bars, and open circles one-sigma upper limits of the ^{6}Li abundance. The big symbols indicate meteoritic abundances from Anders & Grevesse (1989). The upper full drawn line is a fit to the 'Spite plateau' of lithium abundances for [Fe/H] < -1.5 and to the upper envelope of the Li abundance distribution for disk stars according to Lambert et al. (1991). The dotted line represents the evolution of ^{6}Li in the model of Fields & Olive (1999), the dashed-dotted line the model of Vangioni-Flam et al. (1999), and the dashed line the model of Ramaty et al. (2000)

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metallicity range $-1.0 < [\mathrm{Fe/H}] < -0.5$ corresponding to ^{6}Li/^{7}Li of the order of 0.3 to 0.4. The measured ^{6}Li abundances in HD 68284 and HD 130551 are about a factor of 10 lower than predicted requiring a very large ^{6}Li depletion factor for the stars. Furthermore, the ^{6}Li production is accompanied by a ^{7}Li production in the ratio $(^7\mathrm{Li}/^6\mathrm{Li})_{CR} \simeq 1.5$ according to the well known cross sections for cosmic ray production of the two isotopes. Added to the primordial ^{7}Li value this gives an expected ^{7}Li abundance in HD 68284 and HD 130551 of about $\log \epsilon\,(^7\mathrm{Li}) = 2.50$, considerably higher than the observed value of 2.30. Hence, a substantial ^{7}Li depletion in the stars is also required, if the two models are correct.

Ramaty et al. (2000) have studied the evolution of ^{6}Li in two models, the CRI model in which the cosmic ray composition is similar to that of the ISM at all epochs, and the CRS model in which the cosmic rays are accelerated out of the supernovae ejecta in superbubbles and hence always have a composition similar to that of present days cosmic rays. The energy spectrum is given by an expression appropriate for shock acceleration implying a spectrum extending to ultrarelativistic energies. The evolution of Li, Be and B is computed together with the evolution of O and Fe, and it is shown that the CRI model cannot reproduce the observed Be abundances as a function of O or Fe, whereas the CRS model is doing well. Both models fails, however, to account for the observed ^{6}Li abundance of the two halo stars. As seen from Fig. 5, the CRS model underpredicts ^{6}Li with about a factor of 4, and the CRI model fails with a still larger margin. The models require, on the other hand, only a moderate depletion of ^{6}Li in HD 68284 and HD 130551 and no depletion of ^{7}Li to fit the observations.

The discrepancy between the model predictions of Ramaty et al. (2000) and the observed values of ^{6}Li in HD 84937 and BD +26 3578 raises the interesting question, if there are other (pregalactic?) sources of ^{6}Li. Before answering this question a much larger data set ^{6}Li abundances must be obtained. We need detections of ^{6}Li in several additional metal-poor halo turnoff stars, before we can be confident that the abundance found in HD 84937 and BD +26 3578 represents the interstellar value at $[\mathrm{Fe/H}] \simeq -2.3$, especially because other stars with about the same mass and metallicity do not have measurable abundances of ^{6}Li in their atmospheres. Furthermore, ^{6}Li data for more metal rich stars are needed to be able to study the evolution and astration of lithium in the Galaxy.

Up to now the search for ^{6}Li has been carried out with high resolution ($R \simeq 100\,000$) coudé spectrographs attached to 3-4 meter class telescopes. The limiting magnitude has been around $V \simeq 9.5$ meaning that only a few halo turnoff stars could be reached. With the advent of 8 meter class telescopes and new more efficient high resolution echelle spectrographs like UVES at the ESO VLT, HRS at the Hobby Eberly Telescope, and HDS at Subaru, the limit can be extended to $V \simeq 12$. This opens the possibility for a large ^{6}Li survey of halo turnoff stars with hopefully new rewarding results.

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