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Lithium abundances in high- and low-alpha halo stars

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Abstract. A previous study of F and G main-sequence stars in the solar neighborhood has revealed the existence of two distinct halo populations with a clear separation in [α/Fe] for the metallicity range $-1.4 <$ [Fe/H] < -0.7. The kinematics of the stars and models of galaxy formation suggest that the "high-α" stars were formed *in situ* in the inner parts of the Galaxy, whereas the "low-α" ones have been accreted from satellite galaxies. In order to see if there is any systematic difference in the lithium abundances of high- and low-α stars, equivalent widths of the Li I 6707.8 Å line have been measured from VLT/UVES and NOT/FIES spectra and used to derive Li abundances. Furthermore, stellar masses are determined from evolutionary tracks in the $\log T_{\rm eff}$ - $\log g$ diagram. For stars with masses $0.7 < M/M_{\odot} < 0.9$ and heavy-element fractions $0.001 \lesssim Z < 0.006$, the lithium abundance is well fitted by a relation $A({\rm Li}) = a_0 + a_1\,M + a_2\,Z + a_3\,M\,Z$, where a_0, a_1, a_2, and a_3 are constants. Extrapolating this relation to $Z = 0$ leads to A(Li)= 2.58 ±0.08 close to the primordial Li abundance predicted from standard Big Bang nucleosynthesis calculations and the WMAP baryon density. A(Li) of high- and low-α stars agrees well, which underlines the universality of the origin of lithium. We suggest that these old halo stars were formed with a lithium abundance close to the primordial value, and that lithium in their atmospheres has been depleted in timea with an approximately linear dependence on Z and stellar mass.

Key words. Stars: abundances – Stars: atmospheres – Stars: interior – Galaxy: halo – (Cosmology): early Universe

1. Introduction

Based on the WMAP value of the cosmic baryon density (Komatsu et al. 2011), standard Big Bang nucleosynthesis (BBN) calculations (Cyburt et al. 2008; Coc et al. 2012) predict a primordial lithium abundance, $A(^7{\rm Li}) = 2.72 \pm 0.06$, which is a factor of 3 to 4 higher than the Li abundance in halo stars belonging to the so-called "Spite plateau", first discovered by Spite & Spite (1982) and later confirmed by many investigations. Thus, Asplund et al. (2006) find $A({\rm Li}) = \log(N_{\rm Li}/N_{\rm H}) + 12 = 2.23 \pm 0.03$ for stars with effective temperatures between 5800 and 6400 K and metallicities in the range $-2.5 <$ [Fe/H] < -1.5. Attempts to solve this "lithium problem" include depletion of lithium in the atmospheres of stars by diffusion and mixing (Richard et al. 2005), nuclear burning in massive, zero-metallicity (Population III) stars before low-mass stars on the Spite plateau formed (Piau et al. 2006), and non-standard BBN theories involving decaying supersymmetric particles (see review by Fields 2011), but no convincing solutions have been found.

Recent observational studies of lithium abundances have focused on very metal-poor stars with −4.0 < [Fe/H] < −2.5. In this metallicity range, the average Li abundance of stars with $T_{\rm eff} > 6000$ K is lower than in the case of stars belonging to the Spite plateau (Ryan et al. 1999; Boesgaard et al. 2005; Bonifacio et al. 2007; Aoki et al. 2009; Sbordone et al. 2010; Meléndez et al. 2010), which makes the lithium problem even more puzzling.

As a contribution towards a better understanding of lithium in stars, we have made a study of Li abundances in a sample of 93 halo and thick-disk main-sequence stars with −1.6 < [Fe/H] < −0.4. Previous precise determinations of abundances of elements for this sample (Nissen & Schuster 2010, 2011) have revealed the existence of two distinct halo populations in the solar neighborhood with a clear separation in [α/Fe][1], [Na/Fe], [Ni/Fe], [Cu/Fe], and [Zn/Fe]. The kinematics and ages (Schuster et al. 2012) of the stars suggest that the high-α halo stars were formed rapidly in the inner regions of the Galaxy with only Type II supernovae (SNe) contributing to the chemical evolution, whereas the low-α stars were accreted from satellite galaxies having a slower star formation rate and therefore additional contribution of Fe from Type Ia SNe . Hence, we have a unique possibility to see if lithium abundances of stars formed in different environments are the same. Furthermore, the sample of stars allow us to study trends of A(Li) as a function of stellar mass and heavy-element abundance, which may be used to constrain theories of lithium depletion in stars.

In the following, the main results for lithium abundances in our sample of high-metallicity halo stars are summarized and discussed. Details of the work and a table with parameters and abundances of the stars are being published elsewhere (Nissen & Schuster 2012).

[1] α refers to the average abundance of Mg, Si, Ca, and Ti

2. Determination of A(Li), M, and Z

The abundance of Li is determined from the equivalent width of the Li I 6707.8 Å line measured from high-resolution, high-S/N spectra obtained with UVES at the ESO/VLT and FIES at the Nordic Optical Telescope. The typical error of the equivalent widths is ±1 mÅ.

For each star a model atmosphere has been obtained from the MARCS grid (Gustafsson et al. 2008) by interpolating to the $T_{\rm eff}$, $\log g$, [Fe/H], and [α/Fe] values of the star. The profile and the equivalent width of the Li I 6707.8 Å line are calculated as a function of A(Li) assuming local thermodynamic equilibrium (LTE) and adopting atomic line data as given in Smith et al. (1998). Interpolation to the observed equivalent width then yields A(Li).

Effective temperatures are derived spectroscopically from the excitation balance of weak Fe I lines. The zero point is based on two bright, unreddened "standard" stars, HD 22879 and HD 76932, for which $T_{\rm eff}$ was determined by Nissen & Schuster (2010) from the color indices $(b-y)$ and $(V-K)$ using the calibrations of Ramírez & Meléndez (2005). In view of the recent more accurate calibration by Casagrande et al. (2010) the zero-point of $T_{\rm eff}$ has been increased by +100 K.

Surface gravities are determined by requiring that the same iron abundance is derived from Fe I and Fe II lines. Again, HD 22879 and HD 76932 are used to set the zero point taking advantage of the fact that accurate $\log g$ values can be determined via Hipparcos parallaxes for these two nearby stars.

NLTE – LTE corrections of the derived Li abundances have been adopted from Lind et al. (2009) These corrections depend mainly on the effective temperature and range from about +0.04 dex at $T_{\rm eff}$ = 5400 K to −0.06 dex at $T_{\rm eff}$ = 6100 K.

The largest error of A(Li) arises from the error of $T_{\rm eff}$, for which differential values are determined to a precision of ±30 K. The corresponding error of A(Li) is ±0.025 dex. The systematic error of A(Li) may, however, be larger due to the uncertainty of the zero-point of the $T_{\rm eff}$ scale.

As a check of the precision of the Li abundances, we have compared with data from Meléndez et al. (2010). Their analysis is also based on MARCS models, but $T_{\rm eff}$ is determined by the infrared flux method as implemented by Casagrande et al. (2010), and interstellar Na I D lines are used to estimate the reddening. The agreement between the two sets of Li abundances is very satisfactory; the average difference (this paper – Meléndez) is 0.005 dex with a rms deviation of ±0.051 dex. This confirms that A(Li) in each of the two works is determined to a precision of about ±0.030 dex.

In addition to Li abundances we have determined stellar masses from the Y^2 (Yonsei - Yale) evolutionary tracks (Yi et al. 2003). For a given value of the heavy-element mass fraction Z, the three available [Fe/H] - [α/Fe] combinations lead to practically the same mass tracks. For each star, we have therefore first calculated $Z_{\rm star}$ from the measured [Fe/H] and [α/Fe] values and then determined the stellar mass by interpolating between tracks in the $\log g$ - $\log T_{\rm eff}$ plane. The conversion from [Fe/H] and [α/Fe] to $Z_{\rm star}$ is based on a solar heavy-element abundance $Z_\odot = 0.0181$ as adopted for the Y^2 tracks and isochrones (Kim et al. 2002, Table 2). Furthermore, a small offset in $\log g$ between the Y^2 isochrones and our nearly unevolved ($T_{\rm eff} < 5600$ K) main-sequence stars has been corrected for.

Based on the statistical one-sigma errors given in Nissen & Schuster (2010), $\sigma(T_{\rm eff}) = 30$ K, $\sigma(\log g) = 0.05$ dex, σ([Fe/H]) $=$ 0.03 dex, and σ([α/Fe]) $=$ 0.02 dex, we estimate that the statistical error of the mass is $\sigma(M/M_\odot) = 0.02$. The systematic error may, however, be larger. Meléndez et al. (2010) also derived stellar masses from the Y^2 models using both $\log g$ and absolute magnitudes (determined from Hipparcos parallaxes) in combination with $T_{\rm eff}$. For the 24 stars in common with our study, we find a mean mass difference (this paper – Meléndez) of $-0.014 M_\odot$ and a rms deviation of $0.028 M_\odot$. Given the different methods used to determine $T_{\rm eff}$, this agreement is very satisfactory, and confirms that the statistical error of the mass is on the order of $\pm 0.02 M_\odot$ for both works.

3. Lithium versus mass and Z

In Fig. 1, the Li abundances derived for stars with $Z < 0.006$ [2] are shown as a function of Z for the four mass ranges indicated. A few stars for which the Li line could not be detected are excluded from this figure. For a given mass, A(Li) varies approximately linearly with Z but the slope becomes steeper with decreasing stellar mass. This suggests that A(Li) can be fitted with a function

$$A({\rm Li})_{\rm fit} = a_0 + a_1\, M + a_2\, Z + a_3\, M\, Z \qquad (1)$$

where a_0, a_1, a_2, and a_3 are constants. Taking into account the estimated errors of A(Li), M, and Z, chi-square minimization leads to the expression

$$A({\rm Li})_{\rm fit} = 2.253 + 0.405\, M - 2043\, Z + 2280\, M Z \qquad (2)$$

where M is in units of the solar mass. This fit is obtained for 59 stars; one star, G 16-20, falling within the mass and Z ranges considered, is excluded, because it has a 5.5-sigma deviation in A(Li). It is the most evolved star in the sample, so lithium may have been diluted due to the deepening of the convection zone as the star evolved up along the subgiant branch.

The fit in Eq. (2) is shown as straight lines in Fig. 1 for the mean values of M for the four mass intervals. Part of the dispersion around these lines is due to the range in M for each mass interval. The quality of the fit can be better seen from Fig. 2, where the residuals are shown as a function of Z with individual error bars given. The error of $A({\rm Li}) - A({\rm Li})_{\rm fit}$ increases strongly with increasing Z mainly because $A({\rm Li})_{\rm fit}$ becomes very sensitive to mass at high Z.

As seen from Fig. 2, stars with $0.0015 < Z < 0.003$ tend to have positive residuals,

[2] the limit $Z < 0.006$ corresponds to [Fe/H] $\lesssim -0.7$ for high-α stars and [Fe/H] $\lesssim -0.6$ for low-α stars.

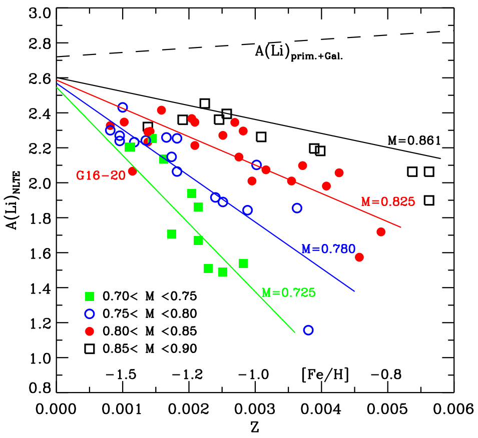

Fig. 1. Li abundances as a function of the heavy-element fraction for stars with $0.70 < M/M_\odot < 0.90$ and $Z < 0.006$. Approximate values of [Fe/H] are shown above the Z-axis. For each of the four mass intervals listed in units of the solar mass, Eq. (2) is shown as a straight line corresponding to the mean mass of the group as indicated at the line. The dashed line shows the sum of the primordial ^{7}Li abundance predicted from standard BBN calculations and ^{7}Li made in the Galaxy due to cosmic ray and stellar nucleosynthesis reactions (Prantzos 2007).

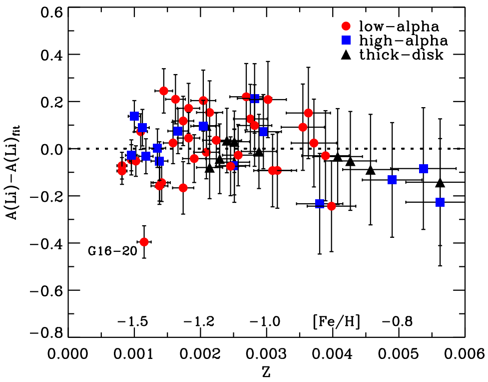

Fig. 2. The residuals of the fit given in Eq. (2) as a function of the heavy-element fraction, Z. One-sigma error bars are shown.

whereas stars with $Z > 0.004$ have negative residuals. This suggests that there is a small curvature in the relation between A(Li) and Z, which is not taken care of in the fit. Nevertheless, the reduced chi-square of the fit given in Eq. (2) has a satisfactorily low value, $\chi^2_{\rm red} = 1.12$. If the deviating star, G 16-20, is included in the fit, the chi-square rises to an unacceptably high value of $\chi^2_{\rm red} = 1.71$.

As discussed in more detail by Nissen & Schuster (2012), a few stars with $Z < 0.006$ deviate strongly from the fit given in Eq. (2) by having A(Li) < 1.0. Some of these stars are blue stragglers or members of binary systems for which lithium depleted gas may have been transferred from the companion, but in other cases there is no obvious explanation of the low Li abundance. For stars with $Z > 0.006$, the frequency of such low-Li stars increases and A(Li) shows a large scatter at a given mass and Z. Obviously, other parameters than M and Z affect the depletion of lithium when the metallicity reaches values typical for the Galactic disk, i.e. [Fe/H] $\gtrsim -0.7$. This is in line with results obtained by Chen et al. (2001) and Lambert & Reddy (2004), who concluded that mass and metallicity are not the only parameters affecting lithium depletion in disk stars and discussed if age and/or initial angular momentum play a role.

4. Discussion and conclusions

A systematic dependence of A(Li) on stellar mass and metallicity for metal-poor stars has previously been observed by Ryan & Deliyannis (1998) and Boesgaard et al. (2005), who used $T_{\rm eff}$ for main-sequence stars as a substitute for mass, and by Meléndez et al. (2010), who investigated A(Li) as a function of mass for selected metallicity groups. The dependence of A(Li) on mass is connected to the increase of the depth of the upper convection zone as the mass decreases, which leads to higher temperatures and hence more destruction of Li by reactions with protons at the bottom of this zone. Models including mixing and diffusion (Pinsonneault et al. 1999; Salaris & Weiss 2001; Richard et al. 2005) predict a mass dependence of A(Li) qualitatively similar to the mass dependence in Eq. (2). It remains, however, to be seen if these models can also reproduce the dependence of A(Li) on Z in Eq. (2).

As seen from Fig. 1, the value of $A(\mathrm{Li})_{Z=0}$, obtained by extrapolating Eq. (2) to $Z = 0$ for a given mass, is nearly independent of mass. For the mean mass of the sample, $M = 0.80\,M_\odot$, we obtain

$$A(\mathrm{Li})_{Z=0} = 2.58 \pm 0.04_{\mathrm{stat.}} \pm 0.07_{\mathrm{syst.}} \tag{3}$$

where the statistical (1-sigma) error is obtained from the chi-square analysis used to derive Eq. (2) and the systematic error corresponds to an uncertainty of ± 100 K in the T_{eff} scale of the stars. Considering the uncertainties, this value of $A(\mathrm{Li})_{Z=0}$ is in reasonable agreement with the primordial ^{7}Li abundance

$$A(^7\mathrm{Li})_{\mathrm{prim}} = 2.72 \pm 0.06 \tag{4}$$

predicted from standard BBN (Cyburt et al. 2008; Coc et al. 2012) and the WMAP baryon density (Komatsu et al. 2011).

The observed Li abundances in stars with $0.7 < M/M_{\mathrm{sun}} < 0.9$ and $0.001 < Z < 0.006$, therefore, seem compatible with a scenario where stars were formed out of interstellar gas with a lithium abundance close to that predicted from standard BBN followed by depletion of the atmospheric lithium content during the stellar lifetime in a way that depends approximately linearly on mass and Z. In this connection it is noted that the Li abundance in the interstellar gas increases with time due to cosmic ray processes and Li production in AGB stars and novae, but as shown in Fig. 1, the Galactic contribution is small compared to the primordial value (Prantzos 2007).

Based on this scenario, one would expect that the difference between the lithium abundance measured for stars on the Spite plateau and that predicted from standard BBN is also due to Li depletion in the stars. The linear relation in Eq. (2) between $A(\mathrm{Li})$, M, and Z derived for stars with $0.001 \lesssim Z < 0.006$ is, however, not valid for more metal-poor stars as seen from Fig. 3, where we have included stars from Meléndez et al. (2010). For $Z \gtrsim 0.001$, the Meléndez et al. stars agree well with our fit, but at lower metallicities, the Li abundances fall below the values expected from Eq. (2). On the Spite plateau ($0.0001 \lesssim Z \lesssim 0.001$), the depletion is stronger than predicted from

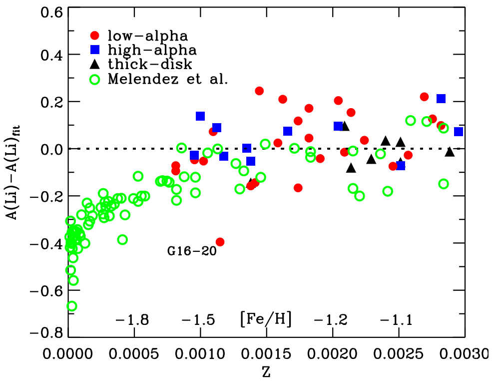

Fig. 3. The residuals in Eq. (2) as a function of Z with stars from Meléndez et al. (2010) included.

an extrapolation of Eq. (2) and is nearly independent of mass and Z. For the lowest metallicities, $Z \lesssim 0.0001$ ([Fe/H] $\lesssim -2.5$), the depletion is even stronger and varies between the stars. Interestingly, the work of Meléndez et al. (2010) suggests that this scatter is related to differences in stellar masses. Hence, although our results suggest that the reason for the difference between the observed Li abundance in halo stars and the primordial value calculated for standard BBN is to be found in terms of stellar depletion, this mechanism is not well understood and has a complicated dependence on mass and metallicity. High-precision homogeneous values of $A(\mathrm{Li})$, M, and Z are needed for large samples of stars spanning the whole metallicity range of the Galactic halo in order to learn more about depletion of lithium.

As seen from Fig. 2, the distribution of the residuals of the fit given in Eq. (2) is nearly the same for high- and low-α halo stars. Given that the high-α stars are likely to have been formed *in situ* in the inner part of the Galaxy, whereas the low-α ones were accreted from satellite galaxies (Purcell et al. 2010; Zolotov et al. 2010), this means that stars belonging to such different systems were formed with the same Li abundance, and later depleted lithium in the same way as a function of mass and Z. This underlines the universality of the origin of lithium in stars.

The similarity of Li abundances in high- and low-α halo stars is in contrast to recent results for beryllium by Tan & Zhao (2011). At a given [α/H], they find the low-α stars to be systematically underabundant in Be relative to the high-α stars by approximately 0.2 dex. Since Be is produced by cosmic ray processes, i.e. CNO nuclei impinging on interstellar H and He, the explanation of the lower Be abundance in low-α stars may be that the cosmic ray nucleosynthesis is less efficient in dwarf galaxies than in the Galaxy (Prantzos 2012). This would also lead to a lower cosmic ray production of lithium, but since the Galactic part of the interstellar abundance of lithium is small compared to the primordial part, it will have only a marginal effect on the measured stellar lithium abundances.

According to Schuster et al. (2012), the high-α halo stars are 2 - 3 Gyr older than the low-α stars, i.e. they have had more time to deplete lithium. As we see no significant difference in the Li abundances of the two populations, this suggests that Li depletion mainly occurs at an early stage of stellar evolution, i.e. either in the pre-main-sequence phase or near the zero-age main sequence before stars evolve up towards the turn-off region.

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