6Li in metal-poor halo stars: real or spurious?

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Abstract. The presence of convective motions in the atmospheres of metal-poor halo stars leads to systematic asymmetries of the emergent spectral line profiles. Since such line asymmetries are very small, they can be safely ignored for standard spectroscopic abundance analysis. However, when it comes to the determination of the ⁶Li/⁷Li isotopic ratio, \( q(\text{Li}) = n(\text{⁶Li})/n(\text{⁷Li}) \), the intrinsic asymmetry of the ⁷Li line must be taken into account, because its signature is essentially indistinguishable from the presence of a weak ⁶Li blend in the red wing of the ⁷Li line. In this contribution we quantify the error of the inferred ⁶Li/⁷Li isotopic ratio that arises if the convective line asymmetry is ignored in the fitting of the \( \lambda 6707 \text{ Å} \) lithium blend. Our conclusion is that ⁶Li/⁷Li ratios derived by Asplund et al. (2006), using symmetric line profiles, must be reduced by typically \( \Delta q(\text{Li}) \approx 0.015 \). This diminishes the number of certain ⁶Li detections from 9 to 4 stars or less, casting some doubt on the existence of a ⁶Li plateau.

Keywords. hydrodynamics, convection, radiative transfer, line: profiles, stars: atmospheres, stars: abundances, stars: individual (G020-024, G271-162, HD 74000, HD 84937)

1. Introduction

The spectroscopic signature of the presence of ⁶Li in the atmospheres of metal-poor halo stars is a subtle extra depression in the red wing of the ⁷Li doublet, which can only be detected in spectra of the highest quality. Based on high-resolution, high signal-to-noise VLT/UVES spectra of 24 bright metal-poor stars, Asplund et al. (2006) report the detection of ⁶Li in nine of these objects. The average ⁶Li/⁷Li isotopic ratio in the nine stars in which ⁶Li has been detected is \( q(\text{Li}) \approx 0.04 \) and is very similar in each of these stars, defining a ⁶Li plateau at approximately \( \log n(\text{⁶Li}) = 8.5 \) (on the scale \( \log n(\text{H}) = 12 \)). A convincing theoretical explanation of this new ⁶Li plateau turned out to be problematic. Even when the depletion of the ⁶Li isotope during the pre-main-sequence phase would be ignored, the high abundances of ⁶Li at the lowest metallicities cannot be explained by current models of galactic cosmic-ray production (for a concise review see e.g. Christlieb 2008, and references therein).

A possible solution of the so-called ‘second Lithium problem’ was suggested by Cayrel et al. (2007), who point out that the intrinsic line asymmetry caused by convection in the photospheres of cool stars is almost indistinguishable from the asymmetry produced by a weak ⁶Li blend on a presumed symmetric ⁷Li profile. As a consequence, the derived ⁶Li abundance should be significantly reduced when the intrinsic line asymmetry in properly taken into account. Using 3D non-LTE line formation calculations based on 3D hydrodynamical model atmospheres computed with the CO⁵BOLD code (Freytag et al. 2002, Wedemeyer et al. 2004, see also http://www.astro.uu.se/~bf/co5bold_main.html), we quantify the theoretical effect of the convection-induced line asymmetry on the resulting ⁶Li abundance as a function of effective temperature, gravity, and metallicity, for a parameter range that covers the stars of the Asplund et al. (2006) sample.
2. 3D hydrodynamical simulations and spectrum synthesis

The hydrodynamical atmospheres used in the present study are part of the CIFIST 3D model atmosphere grid, as described by Ludwig et al. (2009). They have been obtained from realistic numerical simulations with the CO5BOLD code which solves the time-dependent equations of compressible hydrodynamics in a constant gravity field together with the equations of non-local, frequency-dependent radiative transfer in a Cartesian box representative of a volume located at the stellar surface. The computational domain is periodic in $x$ and $y$ direction, has open top and bottom boundaries, and is resolved by typically $140 \times 140 \times 150$ grid points. The vertical optical depth of the box varies from $\log \tau_{\text{Ross}} \approx -8$ (top) to $\log \tau_{\text{Ross}} \approx +8$ (bottom). The selected models cover the stellar parameter range $5900 \, \text{K} < T_{\text{eff}} < 6500 \, \text{K}$, $3.5 < \log g < 4.5$, $-3.0 < [\text{Fe/H}] < -1.0$.

Each of the selected models is represented by about 20 snapshots chosen from the full time sequence of the corresponding simulation. All these representative snapshots are processed by the non-LTE code NLTE3D that solves the statistical equilibrium equations for a 17 level lithium atom with 34 line transitions, fully taking into account the 3D thermal structure of the respective model atmosphere. The photo-ionizing radiation field is computed at 704 frequency points between $\lambda 925$ and $32407 \, \text{Å}$, using the opacity distribution functions of Castelli & Kurucz (2004) to allow for metallicity-dependent line-blanketing, including the HI–H$^+$ and H1–H1 quasi-molecular absorption near $\lambda 1400$ and $1600 \, \text{Å}$, respectively. Collisional ionization by neutral hydrogen via the charge transfer reaction $H(1s) + Li(n\ell) \leftrightarrow Li^+(1s^2) + H^-$ is treated according to Barklem, Belyaev & Asplund (2003). More details are given in Sbordone et al. (2009).

Finally, 3D non-LTE synthetic line profiles of the Li I $\lambda 6707 \, \text{Å}$ feature are computed with the line formation code Linfor3D (http://www.aip.de/~mst/linfor3D.main.html), using the departure coefficients $b_i = n_i(\text{NLTE})/n_i(\text{LTE})$ provided by NLTE3D for each level $i$ of the lithium model atom as a function of geometrical position within the 3D model atmospheres. As demonstrated in Fig. 1, 3D non-LTE effects are very important for the metal-poor dwarfs considered here: not only is the 3D LTE equivalent width too large by more than a factor 2, but also is the half-width of the 3D LTE line profile too narrow by about 10%. Moreover, the lithium lines are significantly less asymmetric if the non-LTE effects are taken into account.

3. Method and Results

As outlined above, the $^6\text{Li}$ abundance is necessarily overestimated if one ignores the intrinsic asymmetry of the $^7\text{Li}$ line profile. To quantify this error theoretically, we rely only on synthetic spectra. The idea is to represent the observation by the synthetic 3D non-LTE line profile of the $^7\text{Li}$ line blend. This 3D flux profile is computed with zero $^6\text{Li}$ content. Except for an optional rotational broadening, the only source of non-thermal line broadening is the 3D hydrodynamical velocity field, which also gives rise to a convective blue-shift and an intrinsic line asymmetry. Next we compute a small grid of 1D LTE synthetic line profiles of the full $^6\text{Li}/^7\text{Li}$ blend from a so-called 1D LHD model, a 1D mixing-length model atmosphere that has the same stellar parameters and uses the same microphysics and radiative transfer scheme as the corresponding 3D model. The parameters of the grid are the total $^6\text{Li}+^7\text{Li}$ abundance, $A(\text{Li})$, and the $^6\text{Li}/^7\text{Li}$ isotopic ratio, $q(\text{Li})$. Microturbulence is fixed at $\xi_{\text{mic}} = 1.5 \, \text{km/s}$, $v \sin i$ is identical to the value used in the 3D spectrum synthesis (we tried 0 and 2 km/s). Now the 1D line profiles from the grid are used to fit the 3D profile. Four parameters are varied independently to find the best fit (minimum $\chi^2$): in addition to $A(\text{Li})$ and $q(\text{Li})$, which control line strength and line asymmetry, respectively, we also allow for an extra line broadening characterized...
Figure 1. Comparison of 3D LTE (dashed) and 3D non-LTE (solid) line profile (left) and line bisector (right) of a single $^7$Li component, computed for a typical metal-poor turn-off halo star ($T_{\text{eff}} = 6300 \text{ K}$, log $g = 4.0$, [Fe/H] = $-2$). Non-LTE effects strongly reduce the equivalent width of the line ($W: 35.5 \rightarrow 15.6 \text{ mA}$) while they increase the half width of the line profile ($FWHM: 7.7 \rightarrow 8.5 \text{ km/s}$); the line asymmetry is diminished in non-LTE (velocity span of bisector $\delta v: 0.31 \rightarrow 0.19 \text{ km/s}$).

by FWHM of the Gaussian kernel, and a global line shift, $\Delta v$. The value $q^*(\text{Li})$ of the best fit is then identified with the correction $\Delta q(\text{Li})$ that has to be subtracted from the $^6\text{Li}/^7\text{Li}$ isotopic ratio determined from the 1D LTE analysis in order to correct for the bias introduced by the intrinsic line asymmetry: $\Delta q(\text{Li}) = q^*(\text{Li})$, and $q^{(3D)}(\text{Li}) = q^{(1D)}(\text{Li}) - \Delta q(\text{Li})$. The procedure takes saturation effects properly into account.

We have determined $\Delta q(\text{Li})$ in the relevant range of stellar parameters according to the method outlined above. The results are displayed in Fig. 2 for $[\text{Fe/H}]=-1$ and $-2$. At given metallicity, the corrections are largest for low gravity and high effective temperature, increasing towards higher metallicity. We note that $\Delta q(\text{Li})$ is essentially insensitive to the choice of $v \sin i$. The downward correction of the $^6\text{Li}/^7\text{Li}$ isotopic ratio determined from the 1D LTE analysis is typically in the range $0.01 < \Delta q(\text{Li}) < 0.02$ for the stars of the Asplund et al. (2006) sample (see Fig. 2). After subtracting for each of these stars the individual $\Delta q(\text{Li})$, according to $T_{\text{eff}}$, log $g$, and [Fe/H], the mean $^6\text{Li}/^7\text{Li}$ isotopic ratio of the sample is reduced from 0.0212 to 0.0059, as illustrated in Fig. 3. If we keep the error bars given by Asplund et al. (2006), the number of stars with a $^6\text{Li}$ detection above the $2\sigma$ level decreases from 9 to 4. One of them, HD 106038, survives only because of its particularly small error bar of $\pm 0.006$, another one, CD-30 18140, just barely fulfills the $2\sigma$ criterion. The remaining two stars are G020-024, which shows the clearest evidence for the presence of $^6\text{Li}$ ($q(\text{Li}) = 0.052 \pm 0.017$), and HD 102200 with a somewhat weaker $^6\text{Li}$ signal ($q(\text{Li}) = 0.033 \pm 0.013$). The spectra of these stars should be reanalyzed with 3D non-LTE line profiles.

Figure 2. Contours of $\Delta q(\text{Li})$ in the $T_{\text{eff}} - \log g$ plane for metallicities $[\text{Fe/H}]=-2$ (left) and $[\text{Fe/H}]=-1$ (right). White symbols mark the positions of the stars from the Asplund et al. (2006) sample with $-2.5 < [\text{Fe/H}] < -1.5$ (left), and $-1.5 < [\text{Fe/H}] < -0.5$ (right).
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Figure 3. $^6$Li/$^7$Li isotopic ratio, and ±1σ error bars, as a function of effective temperature as derived by Asplund et al. (2006) before (left) and after (right) subtraction of ∆q(Li) to correct for the bias due to the intrinsic line asymmetry. Filled circles denote $^6$Li detections above the 2σ level, open circles denote non-detections.

Table 1. Fitting three observed Li I $\lambda$6707 Å spectra with 1D LTE and 3D non-LTE synthetic line profiles, respectively. Columns (7)–(10) show the results for $v$ sin $i$ = 0.0/2.0 km/s.

<table>
<thead>
<tr>
<th>Star</th>
<th>$T_{\text{eff}}$</th>
<th>log $g$</th>
<th>[Fe/H]</th>
<th>S/N</th>
<th>Model</th>
<th>$A$(Li)</th>
<th>$q$(Li)</th>
<th>FWHM</th>
<th>$\Delta v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD 74000</td>
<td>6203</td>
<td>4.03</td>
<td>−2.05</td>
<td>600</td>
<td>3D LTE</td>
<td>2.25/2.25</td>
<td>−1.1/−1.1</td>
<td>3.1/2.1</td>
<td>0.64/0.64</td>
</tr>
<tr>
<td>G271−162</td>
<td>6230</td>
<td>3.93</td>
<td>−2.30</td>
<td>550</td>
<td>3D LTE</td>
<td>2.30/2.30</td>
<td>0.6/0.6</td>
<td>5.9/5.4</td>
<td>0.42/0.42</td>
</tr>
<tr>
<td>HD 84937</td>
<td>6310</td>
<td>4.10</td>
<td>−2.40</td>
<td>630</td>
<td>3D LTE</td>
<td>2.21/2.20</td>
<td>4.0/4.2</td>
<td>3.7/2.7</td>
<td>0.08/0.07</td>
</tr>
</tbody>
</table>

Notes: 1) $T_{\text{eff}}$/log $g$/[Fe/H] = 6280K/4.0/-2; 2) log $[n(^6\text{Li}) + n(^7\text{Li})] - log n(\text{H}) + 12$; 3) Gaussian kernel

As a consistency check, we have also fitted a few observed Li I $\lambda$6707 Å spectra with 1D LTE and 3D non-LTE synthetic line profiles, respectively. The fitting parameters are again $A$(Li), $q$(Li), FWHM, and $\Delta v$. As expected, the 3D analysis yields lower $q$(Li) by roughly −0.02. Details are compiled in Table 1. HD 74000 and G271−162 are considered non-detections, while HD 84937 remains a clear $^6$Li detection with $q^{(3D)}$(Li) ≈ 0.04.

4. Conclusions

The present study indicates that only 2 or at most 4 out of the 24 stars of the Asplund et al. (2006) sample remain significant $^6$Li detections when subjected to a 3D non-LTE analysis, suggesting that the presence of $^6$Li in the atmospheres of galactic halo stars is rather the exception than the rule. This would imply that it is no longer necessary to look for a global mechanism accounting for a $^6$Li enrichment of the galactic halo, but that it is sufficient to explain only a few exceptional cases, which is probably much easier.

References

Freytag, B., Steffen, M., & Dorch, B. 2002, AN, 323, 213