Trends and Scatter of Abundance Ratios for Metal-poor Turnoff Stars

P. E. Nissen  
Department of Physics and Astronomy, University of Aarhus, DK-8000 Aarhus C, Denmark

M. Asplund  
Research School of Astronomy and Astrophysics, Mt. Stromlo Observatory, Cotter Road, Weston, ACT 2611, Australia

D.L. Lambert  
Department of Astronomy, University of Texas, Austin, TX 78712-1083, USA

F. Primas  
European Southern Observatory, Karl-Schwarzschild Str. 2, D-85748 Garching b. München, Germany

V.V. Smith  
Department of Physics, University of Texas, El Paso, TX 79968-0515, USA

Abstract. Trends and scatter of abundances of Li, O, Ca and Fe in metal-poor stars are discussed with particular emphasis on new results obtained by analyzing high resolution ESO VLT/UVES spectra of 23 turnoff stars using effective temperatures derived from the Hα line. Evidence of a significant cosmic scatter in O/Fe and Ca/Fe at a given metallicity is found, whereas the scatter in Li/H is very small, i.e. less than 0.03 dex. The results are compared to previous data for halo, thick and thin disk stars, and to the prediction of the primordial Li abundance from WMAP.

1. Introduction

The ratios between the cosmic abundances of certain elements provide important information about nucleosynthesis in stars and chemical evolution of galaxies. Well known examples are Li/H in metal-poor turnoff stars as a test of Big Bang nucleosynthesis and the ratio between α-capture elements and iron, [α/Fe], as an indicator of the relative importance of Type Ia and Type II supernovae in producing the elements and hence of the time scale for chemical evolution.

Much effort has been put into studies of the trends of element ratios as a function of metallicity, but often without conclusive results. For example, it is still an open question whether [O/Fe] rises quasi-linearly to very high values (~1.0 dex), when we go to more and more metal-poor stars, or whether [O/Fe]
levels off to a plateau of $\sim 0.4$ dex for $[\text{Fe/H}] < -1.0$. The quasi-linear behavior is derived from the infrared oxygen triplet, while a plateau is suggested from the forbidden oxygen line at 6300 Å (see e.g. Nissen et al. 2002). This difference may be related to errors in the effective temperature scale or to non-LTE and 3D effects in the model atmosphere analysis of the observed lines. Another example of a controversial problem is the Li abundance in metal-poor turnoff stars, which depends critically on the adopted $T_{\text{eff}}$ scale (see e.g. Ryan, Norris & Beers 1999). This problem is particularly interesting in view of the high primordial Li abundance predicted from the WMAP observations (Spergel et al. 2003, Coc et al. 2004).

In addition to the metallicity trend of various abundance ratios, it is also interesting to study the scatter of these ratios at a given $[\text{Fe/H}]$, especially if one finds variations that are correlated with position or kinematics of the stars. If the selected sample of stars has a narrow range in $T_{\text{eff}}$ and gravity then we can expect that possible errors due to non-LTE and 3D effects will cancel when comparing abundances at a given metallicity. Hence, it becomes possible to derive differential abundance ratios to a very high precision.

In this paper, we discuss some new results on abundance ratios derived from high resolution spectra observed with the ESO VLT/UVES spectrograph with the primary purpose of studying the lithium isotope ratio in turnoff stars. This aspect is discussed in detail by Asplund et al. (2005), who also derive precise abundances of Li, O, K, Ca and Fe taking advantage of the very high quality of the UVES spectra. Here we will briefly review the methods used by Asplund et al. to derive the abundances and then focus on a discussion of the scatter of the abundance ratios Li/H, O/Fe and Ca/Fe in comparison with other recent studies of these elements.

2. Abundances in metal-poor turnoff stars from UVES spectra

2.1. Observations

The stars in the lithium isotope program were selected from the $uvby$-$\beta$ catalogue of Schuster & Nissen (1988) and from the Li abundance survey of very metal-poor stars by Ryan et al. (1999). UVES spectra for 23 stars were obtained during two observing runs in July 2000 and February 2002. As seen from Table 1, the stars cover the metallicity range $-3.0 < [\text{Fe/H}] < -1.0$, and are confined to quite narrow ranges in effective temperature ($5750 \, K < T_{\text{eff}} < 6400 \, K$) and gravity ($3.7 < \log g < 4.5$).

The spectra were taken in the red arm of UVES and cover the spectral region 6000 - 8200 Å. A narrow entrance slit, 0.3 arcsec wide, was applied in combination with an image slicer, which for an entrance aperture of $1.5 \times 2$ arcsec produces five spectra with a resolution of about $R \approx 110,000$. In addition to increasing the efficiency, the image slicer in UVES serves to broaden the spectrum over a larger area of the CCD. This helps to minimize problems in the flat-fielding, e.g. to reduce the amplitude of any residual fringing existing after the flat-fielding.

Further details about the observations and a description of the IRAF reduction procedure can be found in Asplund et al. (2005). Here we just note that the spectra obtained have a very high $S/N$ - from about 400 in the fainter, very
metal-poor stars to about 800 in the brightest stars such as HD 140283. Three representative spectra for the Li 6708 Å region are shown in Fig. 1.

### 2.2. Effective temperature

The most important parameter when studying the scatter of abundance ratios is the effective temperature. As discussed by Nissen et al. (2002), the determination of $T_{\text{eff}}$ from color indices such as $b - y$ and $V - K$ is limited to a 1σ precision of about ±70 K due to the uncertainty in the interstellar reddening. In order to obtain more precise values of $T_{\text{eff}}$, Asplund et al. (2005) therefore derived the effective temperature from the profile of the Hα line, which is very sensitive to temperature and practically independent of interstellar reddening.

The Hα line is well centered in one of the echelle orders of the UVES spectra. The main problem in getting an accurate profile is to determine the echelle blaze function of this order. The method of fitting cubic spline functions to the continuum, which works well for narrow, well isolated lines, cannot be applied to a broad line like Hα. Hence, a special reduction of the Hα echelle order was made taking advantage of the fact that the blaze function varies smoothly and slowly with echelle order. This allows us to determine the blaze function of the Hα order by interpolating in the blaze functions of the two adjacent orders. The same technique has been successfully applied by Barklem et al. (2002) and Korn (2002) for various echelle spectrographs including UVES.

The Hα profile is affected by a few metallic lines and several telluric H$_2$O lines, but due to the high resolution of the spectra these narrow absorption lines can easily be removed by interpolating the Hα profile over the disturbing lines. Examples of the resulting profiles are shown in Fig. 2. The symmetric and smooth appearance of the profiles indicates that the reduction procedure has worked well.
The observed Hα profiles have been compared to theoretical profiles computed for MARCS model atmospheres using an LTE spectrum synthesis code, kindly supplied by P. Barklem. Stark broadening is based on calculations of Stehle (1994) with the so-called Model Microfield Method, and self-broadening of hydrogen from Barklem, Piskunov, & O’Mara (2000a) is included. The profiles are computed for models having the same gravity and metallicity as the star but with a range of effective temperatures embracing the value estimated from the color of the star. Hence, an improved $T_{\text{eff}}$ may be determined from chi-square fitting to the observed profile (see Fig. 2). The region within ±6 Å from the center is not included in the fit because the core of Hα is quite strongly affected by deviations from LTE (Przybilla & Butler 2004). Note also that the continuum setting is considered as a free parameter in the fit as the true continuum is ill-defined due to the limited width of the Hα echelle order.

![Figure 2](image-url)  
*Figure 2. Left: Observed Hα profiles for three stars; with increasing line strength the profiles refer to HD 140283 ($T_{\text{eff}} = 5750$ K), HD 3567 ($T_{\text{eff}} = 6025$ K) and BD +09°2190 ($T_{\text{eff}} = 6390$ K). Right: Observed Hα profile for BD +03 740 (dots) compared to theoretical profiles calculated for atmospheric models with the gravity and metallicity of the star ($\log g = 4.04$, [Fe/H] = −2.65) and three values of the effective temperature: $T_{\text{eff}} = 6170$ K, 6270 K (best fit), and 6370 K.*

The $T_{\text{eff}}$ derived for a given star from spectra observed on different nights is extremely stable; variations are less than ±15 K. Furthermore, the calculated Hα profile is relatively insensitive to errors in the gravity and the metallicity of the models. Altogether, we estimate that relative temperatures for turnoff stars at a given metallicity have been determined with a one-sigma precision of about ±30 K. The absolute temperature scale is, however, more uncertain, because it depends on the theory of hydrogen line broadening, and possible non-LTE and 3D effects. In this connection, it should be noted that our effective temperatures for the most metal-poor stars are about 100 K lower than the $T_{\text{eff}}$ values calculated from the $V - K$ color index using the IRFM calibration of Alonso, Arribas, & Martínez-Roger (1996).

### 2.3. Surface gravity

The surface gravity is determined from the fundamental relation $g \propto \mathcal{M} T_{\text{eff}}^4 / L$ where $\mathcal{M}$ is the mass of the star. The luminosity $L$ is obtained via the absolute visual magnitude $M_V$ as derived from the Strömgren indices using a new calibration by Schuster et al. (2004), and also directly from the Hipparcos parallax (ESA 1997) if available with an accuracy $\sigma(\pi) / \pi < 0.3$. The bolometric cor-
Trends and Scatter of Abundance Ratios

Correction is taken from Alonso, Arribas, & Martínez-Roger (1995), and the mass of the star is derived by interpolating in the $M_V - \log T_{\text{eff}}$ diagram between the α-element enhanced evolutionary tracks of VandenBerg et al. (2000).

The derived values of $\log g$ are given in Table 1. The internal error of $\log g$ is dominated by the error of $M_V$, which we have estimated to be $\sigma(M_V) \simeq 0.20$. This corresponds to $\sigma(\log g) \simeq 0.08$ dex.

Table 1. Effective temperatures, gravities and abundance ratios for 23 turnoff stars

<table>
<thead>
<tr>
<th>Star</th>
<th>$T_{\text{eff}}$</th>
<th>$\log g$</th>
<th>[Fe/H]</th>
<th>[O/Fe]</th>
<th>[Ca/Fe]</th>
<th>$\log \epsilon(\text{7Li})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD 3567</td>
<td>6026</td>
<td>4.08</td>
<td>-1.14</td>
<td>0.35</td>
<td>0.13</td>
<td>2.32</td>
</tr>
<tr>
<td>HD 19445</td>
<td>5980</td>
<td>4.42</td>
<td>-2.02</td>
<td>0.64</td>
<td>0.24</td>
<td>2.20</td>
</tr>
<tr>
<td>HD 59392</td>
<td>5936</td>
<td>3.99</td>
<td>-1.61</td>
<td>0.57</td>
<td>0.23</td>
<td>2.25</td>
</tr>
<tr>
<td>HD 102200</td>
<td>6062</td>
<td>4.15</td>
<td>-1.25</td>
<td>0.40</td>
<td>0.20</td>
<td>2.20</td>
</tr>
<tr>
<td>HD 106038</td>
<td>5905</td>
<td>4.30</td>
<td>-1.35</td>
<td>0.59</td>
<td>0.16</td>
<td>2.48</td>
</tr>
<tr>
<td>HD 140283</td>
<td>5753</td>
<td>3.70</td>
<td>-2.40</td>
<td>0.66</td>
<td>0.11</td>
<td>2.20</td>
</tr>
<tr>
<td>HD 160617</td>
<td>5990</td>
<td>3.79</td>
<td>-1.76</td>
<td>0.33</td>
<td>0.26</td>
<td>2.28</td>
</tr>
<tr>
<td>HD 213657</td>
<td>6180</td>
<td>3.92</td>
<td>-1.90</td>
<td>0.56</td>
<td>0.28</td>
<td>2.25</td>
</tr>
<tr>
<td>HD 298986</td>
<td>6103</td>
<td>4.22</td>
<td>-1.33</td>
<td>0.35</td>
<td>0.16</td>
<td>2.24</td>
</tr>
<tr>
<td>HD 338529</td>
<td>6335</td>
<td>4.04</td>
<td>-2.26</td>
<td>0.58</td>
<td>0.38</td>
<td>2.22</td>
</tr>
<tr>
<td>G 013-009</td>
<td>6298</td>
<td>3.99</td>
<td>-2.30</td>
<td>0.59</td>
<td>0.38</td>
<td>2.19</td>
</tr>
<tr>
<td>G 020-024</td>
<td>6247</td>
<td>3.98</td>
<td>-1.89</td>
<td>0.54</td>
<td>0.32</td>
<td>2.18</td>
</tr>
<tr>
<td>G 075-031</td>
<td>6000</td>
<td>4.08</td>
<td>-1.02</td>
<td>0.34</td>
<td>0.12</td>
<td>2.00</td>
</tr>
<tr>
<td>G 126-062</td>
<td>6183</td>
<td>4.11</td>
<td>-1.51</td>
<td>0.46</td>
<td>0.34</td>
<td>2.24</td>
</tr>
<tr>
<td>BD +09 2190</td>
<td>6392</td>
<td>4.09</td>
<td>-2.66</td>
<td>0.44</td>
<td>0.24</td>
<td>2.10</td>
</tr>
<tr>
<td>BD +03 0740</td>
<td>6266</td>
<td>4.04</td>
<td>-2.65</td>
<td>0.59</td>
<td>0.28</td>
<td>2.11</td>
</tr>
<tr>
<td>BD −13 3442</td>
<td>6311</td>
<td>3.86</td>
<td>-2.71</td>
<td>0.62</td>
<td>0.35</td>
<td>2.14</td>
</tr>
<tr>
<td>CD −30 18140</td>
<td>6222</td>
<td>4.11</td>
<td>-1.90</td>
<td>0.62</td>
<td>0.32</td>
<td>2.22</td>
</tr>
<tr>
<td>CD −33 1173</td>
<td>6390</td>
<td>4.28</td>
<td>-2.95</td>
<td>0.62</td>
<td>0.38</td>
<td>2.05</td>
</tr>
<tr>
<td>CD −33 3337</td>
<td>5897</td>
<td>4.01</td>
<td>-1.31</td>
<td>0.55</td>
<td>0.08</td>
<td>2.24</td>
</tr>
<tr>
<td>CD −35 14849</td>
<td>6244</td>
<td>4.30</td>
<td>-2.27</td>
<td>0.57</td>
<td>0.24</td>
<td>2.24</td>
</tr>
<tr>
<td>CD −48 2445</td>
<td>6222</td>
<td>4.25</td>
<td>-1.93</td>
<td>0.53</td>
<td>0.25</td>
<td>2.19</td>
</tr>
<tr>
<td>LP 815-43</td>
<td>6400</td>
<td>4.17</td>
<td>-2.74</td>
<td>0.54</td>
<td>0.32</td>
<td>2.11</td>
</tr>
</tbody>
</table>

2.4. The derivation of Li, O, Ca and Fe abundances

Element abundances are derived from an analysis of spectral lines based on hydrostatic stellar model atmospheres in LTE and with convection treated by the mixing length theory. The models have parameters $T_{\text{eff}}$, $\log g$ and [Fe/H] as given in Table 1 and an overabundance, $[\alpha/\text{Fe}] = +0.4$, of the α-capture elements. The models have been generated with the MARCS code (Gustafsson et al. 1975; Asplund et al. 1997), which includes realistic continuous and line opacities for a wide range of atomic and molecular species. The radiative transfer in the construction of the model atmospheres is treated by opacity sampling.

For the majority of stars the microturbulence parameter, $\xi_{\text{micro}}$, could be determined by requesting that the derived Fe abundance should be independent of line strength. In the more metal-poor stars, [Fe/H] < −2.0, all lines are, however, so weak that $\xi_{\text{micro}}$ is not affecting the line strength significantly. For these stars we assumed $\xi_{\text{micro}} = 1.5 \text{ km s}^{-1}$. Furthermore, line broadening due to
collisions with hydrogen and helium atoms was included using either data from Barklem et al. (2000b) or, in the case of Fe\textsc{ii} lines, adopting the Unsöld (1955) theory of Van der Waals broadening with the interaction constant enhanced by a factor of two. Since all Fe\textsc{ii} lines used are quite weak ($EW < 50 \text{ mÅ}$) the Fe abundances derived are not sensitive to the value of the enhancement factor.

**Lithium.** Isotopic abundances of lithium were determined from chi-square fitting to the profile of the $\lambda$6708 Li\textsc{i} line. In addition to the abundances of $^{6}$Li and $^{7}$Li, the wavelength of the Li line is considered as a free parameter in the fit, whereas the intrinsic line broadening due to macroturbulence and rotation is determined from Ca\textsc{i} and Fe\textsc{i} lines of similar strength as the Li\textsc{i} line. A more detailed description of the method is given in Asplund et al. (2005). The main result of their paper is a probable ($> 2\sigma$) detection of $^{6}$Li in eight stars with values of the isotopic ratio $^{6}$Li/$^{7}$Li ranging from 0.03 to 0.08. In addition, $^{7}$Li abundances were determined. The values are given in Table 1 and include a small non-LTE correction determined from the computations of Carlsson et al. (1994) by interpolating in their data to the stellar parameters of our sample. Due to the high quality of our spectra and the insensitivity of the $\lambda$6708 Li\textsc{i} line to variations in log $g$ and [Fe/H] the internal error of the $^{7}$Li abundance is totally dominated by the error of the effective temperature; the estimated precision of $T_{\text{eff}}$ of $\pm 30 \text{ K}$ corresponds to an error of $\sigma (\log^{7}\text{Li}/\text{H}) = 0.022 \text{ dex}$.

**Oxygen.** Oxygen abundances were derived from the equivalent widths of the O\textsc{i} $\lambda$7774 triplet lines using $gf$-values from Wiese, Fuhr, & Deters (1996) and applying non-LTE corrections as described in Nissen et al. (2002). The corrections range from about $-0.10 \text{ dex}$ to $-0.25 \text{ dex}$ in the most metal-poor stars. Furthermore, we note that a solar oxygen abundance of $\log \epsilon(O) = 8.74$ was adopted in calculating [O/H].

**Calcium.** Equivalent widths of up to 11 Ca\textsc{i} lines in the spectral region 6100 - 6500 Å were used to determine LTE abundances of calcium. $gf$-values from Smith & Raggett (1981) were adopted. The line-to-line scatter of the derived Ca abundance for a given star is very small, $\sigma \log \epsilon(Ca) \approx 0.04 \text{ dex}$, which testify to the high precision of both the $gf$-values and the measured equivalent widths.

**Iron.** Iron abundances were determined from 13 Fe\textsc{ii} lines as described in detail by Nissen et al. (2002). These lines were also measured in the solar flux spectrum (Kurucz et. al. 1984) and analyzed with the MARCS model of the solar atmosphere. Hence, differential iron abundances, [Fe/H], could be determined without knowledge of the oscillator strengths of the lines. We note, however, that for a solar iron abundance, $\log \epsilon(Fe) = 7.50$, the $gf$-values derived from the solar spectrum agree well with those of Biémont et al. (1991).

Equivalent widths of up to 11 weak Fe\textsc{i} lines could also be accurately measured in our spectra. $gf$-values of these lines were taken from O’Brian et al. (1991) and used to derive [Fe/H] assuming LTE. As seen from Fig. 3, the agreement with the iron abundances from Fe\textsc{ii} lines is quite good; the average difference, [Fe/H]$_{\text{II}}$ - [Fe/H]$_{\text{I}}$, is 0.08 dex with an rms scatter of 0.041 dex only. The expected scatter arising from the adopted errors, $\sigma(T_{\text{eff}}) = 30 \text{ K}$ and $\sigma \log g = 0.08 \text{ dex}$, is 0.046 dex, i.e. in fact a bit larger than the observed scatter. This suggests, that the estimated precision of $T_{\text{eff}}$ and $\log g$ is realistic.

The systematic difference in the derived Fe abundances from Fe\textsc{i} and Fe\textsc{ii} lines could reflect departures from LTE for Fe\textsc{i}, erroneous stellar parameters or simply incorrect $gf$-values. The lack of any apparent trend in [Fe/H]$_{\text{II}}$ - [Fe/H]$_{\text{I}}$
with either $T_{\text{eff}}$ or $[\text{Fe/H}]$ is a strong argument against pronounced departures from LTE. In particular, it should be noted that the difference between $[\text{Fe/H}]_{\text{II}}$ and $[\text{Fe/H}]_{\text{I}}$ is much smaller than predicted by Thevenin & Idiart (1999). These authors neglected the thermalizing effect of inelastic H collisions with Fe atoms. Hence our data support the conclusion of Korn, Shi & Gehren (2003) that hydrogen collisions are important and tend to bring the population of the Fe I energy levels close to LTE.

3. Discussion

This section contains a brief discussion of our new results from the UVES program (see Table 1) in comparison to other recent studies of Li, O, Ca and Fe abundances.

3.1. Lithium

As we have determined precise abundances of both lithium and oxygen, we have the possibility to plot $^7\text{Li}$ vs. O. Oxygen has the advantage of being a better tracer of Type II SNe than iron. Fig. 4 shows two such plots, the left one with the logarithmic abundances and the right one on linear scales. In both figures the error bars equal the estimated internal 1σ precision of the data.

As seen from Fig. 4, the star HD 106038 has a very high Li abundance. Nissen & Schuster (1997) found this star to have unusual high s-process abundances (Y and Ba) with respect to Fe. Hence, it is likely that the high Li abundance is due to mass transfer from an AGB star, although there is apparently no indication of radial velocity variations for HD 106038 (Latham et al. 2002). Excluding HD 106038 and the other four stars with $[\text{O/H}] > -0.9$, a parabolic fit has been made to the data. The rms deviation from the fit is remarkable small, i.e. $\sigma \log (^7\text{Li}/\text{H}) = 0.029$ dex. This is of the same order of size as the expected scatter of 0.025 dex calculated from the estimated errors of $\log (^7\text{Li}/\text{H})$ and $[\text{O/H}]$. Hence, we conclude that there is very little room for a cosmic scatter in the Li abundance of metal-poor turnoff stars. The same conclusion was reached by Ryan et al. (1999), who observed $\log (^7\text{Li}/\text{H})$ as a function of $[\text{Fe/H}]$ and obtained a spread of 0.031 dex for 21 turnoff stars with $-3.6 < [\text{Fe/H}] < -2.3$. The
Figure 4. Logarithmic and linear plots of the $^7$Li abundance vs. the oxygen abundance for 23 turnoff stars. The full drawn lines show parabolic fits to stars with [O/H] < −0.9. The dashed line in the right figure is a linear fit to the nine stars with the lowest oxygen abundance.

slightly higher scatter of their Li abundances may be due to the fact that their spectra have lower $S/N$ and resolution than our UVES spectra. In particular, we note that one star, BD+09 2190, which is considered as an outlier by Ryan et al., falls nicely on our log ($^7$Li/H) - [O/H] trend.

The data in Fig. 4 suggests that the slope, $\Delta \log (^{7}\text{Li}/\text{H})/\Delta [\text{O}/\text{H}]$ decreases as [O/H] increases. For the nine stars with the lowest [O/H] the slope is $\sim 0.2$. For comparison, Ryan et al. (1999) found a slope of $\sim 0.12$, when considering the Li abundance as a function of [Fe/H] for their sample of 21 very metal-poor stars. Our slope of $\Delta \log (^{7}\text{Li}/\text{H})/\Delta [\text{O}/\text{H}]$ is surprisingly high when compared to predictions from Galactic models for the evolution of the light elements (Ramaty et al. 2000), but note that these models also have difficulties in producing sufficient $^6$Li to explain our detections. Nevertheless, there is good reason to undertake a closer investigation of the effective temperatures of metal-poor stars as a function of [Fe/H].

Assuming that lithium in metal-poor turnoff stars is not depleted, one may find the primordial $^7$Li abundance by extrapolating the relation between $^7$Li/H and O/O$_{\odot}$ in Fig. 4 to O/O$_{\odot} = 0$. Depending on whether we adopt a linear or parabolic fit, we get values between 1.0 and 1.3 × $10^{-10}$ for the primordial $^7$Li/H ratio. Similar values (0.9 - 1.2 × $10^{-10}$) were obtained by Ryan et al. (2000). This is far below the primordial $^7$Li/H ratio of $(4.15 \pm 0.5) \times 10^{-10}$ predicted by Big Bang nucleosynthesis calculations (see e.g. Coc et al. 2004) for the baryon-to-photon ratio of $\eta = (6.5 \pm 0.4) \times 10^{-10}$ determined from WMAP observations (Spergel et al. 2003). The difference is unlikely to be explained by systematic errors in our Li abundance determinations. Even if our $T_{\text{eff}}$ scale for the most metal-poor stars is systematically too low by as much as 200 K that would only raise the estimated primordial $^7$Li/H ratio to about $1.8 \times 10^{-10}$ — still far below the prediction from the WMAP observations. Furthermore, Asplund, Carlsson & Botnen (2003) have shown that Li abundances derived for metal-poor turnoff stars by 3D, non-LTE calculations agree with the 1D, LTE results to within 0.05 dex.

The canonical explanation of the discrepancy between the Li abundance predicted from the WMAP observations and the value measured for metal-poor turnoff stars, is that the atmospheric composition of the stars has been de-
pleted by processes that mix the upper convection zone with deeper layers, where lithium has been burned by proton reactions. Detailed models have, however, difficulties in explaining the large depletion (~ 0.5 dex) required, together with the observed small dispersion and the dependence of 7Li abundance on [O/H]. Thus, Pinsonneault et al. (2002) conclude that their models of rotational induced mixing allows a mild depletion of ~ 0.2 dex only, if the Li abundance distribution of the Ryan et al. (1999) stars is to be explained. In a more recent work, Richard, Michaud & Richer (2005) find that atomic and turbulent diffusion may reduce the primordial Li abundance sufficiently to explain the discrepancy with the WMAP observations. They predict, however, that the 7Li abundance should be independent of metallicity in disagreement with the gradient found in this work and by Ryan et al. (1999). Furthermore, Richard et al. predict that 6Li should be totally destroyed, which disagree with our probable detection of 6Li in some turnoff stars.

A more straightforward explanation of the small dispersion and rise of 7Li shown in Fig. 4 is that the primordial 7Li/H ratio is around 1.2 × 10⁻¹⁰ and that 7Li is produced by cosmic ray α + α reactions along with the Galactic evolution of [O/H] caused by oxygen production in Type II SNe. Such α + α reactions would also produce 6Li. If this explanation is correct, then either the WMAP value of the baryon-to-photon ratio is wrong or the Big Bang nucleosynthesis calculations for 7Li are in error. The last possibility is explored by Coc et al. (2004), who point out that in the production of 7Li via the unstable isotope 7Be, the cross section for the 7Be destruction reaction, 7Be(d, p)24He, is not well known. Increasing the standard adopted cross section by a factor of ~ 100 would bring agreement between 7Li from WMAP and the value measured in metal-poor turnoff stars. Clearly, attempts to measure this cross section are of high interest.

3.2. Oxygen and Calcium

Fig. 5 shows [O/Fe] and [Ca/Fe] vs. [Fe/H]. As mentioned in Sect. 2.4, the oxygen abundances were derived from a non-LTE analysis of the λ7774 O i triplet. The Fe abundances applied when calculating [O/Fe] are from Fe ii lines. This makes the ratio relatively insensitive to possible errors in Teff and log g, because the main ionization stages are O i for oxygen and Fe ii for iron. In calculating [Ca/Fe], on the other hand, the Ca and Fe abundances are derived from neutral lines. This makes the ratio practically independent of Teff and log g.

As seen from Fig. 5, both [O/Fe] and [Ca/Fe] show an increasing trend with decreasing [Fe/H]. One should, however, not put too much weight on these trends. Oxygen abundances of dwarf stars derived from the λ6300 O i line lead to a lower and more flat trend of [O/Fe] (Nissen et al. 2002). Puzzling differences between oxygen abundances derived from permitted and forbidden oxygen lines have also been encountered for a large sample of subgiant and giant stars by Fulbright & Johnsson (2003). Furthermore, Israelian et al. (2004) have recently found a large discrepancy of oxygen abundances derived from the triplet and the forbidden line, respectively, for two very metal-poor giants. In the case of [Ca/Fe], the increasing trend may be more reliable, but there could be small non-LTE effects affecting the trend, which are not taken into account.

More interesting than the trends seen in Fig. 5 is the scatter. In contrast to Li/H, there appears to be a significant cosmic scatter in both [O/Fe] and [Ca/Fe] at a given metallicity. In the case of [O/Fe], the rms deviation around
the linear fit is $\sigma_{\text{obs}} = 0.086$ dex, whereas the expected scatter from the errors in $T_{\text{eff}}$, $\log g$ and equivalent widths of the lines is $\sigma_{\text{exp}} = 0.038$ dex. The same numbers for [Ca/Fe] are $\sigma_{\text{obs}} = 0.063$ dex and $\sigma_{\text{exp}} = 0.020$ dex. In the case of [O/Fe], HD 160617 shows the largest deviation as seen from Fig. 5. This star is known to be very rich in nitrogen (Bessell & Norris 1982) relative to iron ($[\text{N}/\text{Fe}] \sim 2$), and it is therefore possible that its atmosphere has been polluted with material where some O has been converted to N via the CNO cycle. But even if HD 160617 is excluded, the observed scatter, $\sigma_{\text{obs}} = 0.079$ dex, remains significantly higher than the expected scatter. For [Ca/Fe] the well known star HD 140283 shows the largest deviation from the fit, but other stars deviate with 3 to 4$\sigma$.

There are several possible explanations of the cosmic scatter in abundance ratios among halo turnoff stars: i) contribution to Fe from Type Ia SNe for some stars thereby decreasing [O/Fe] and [Ca/Fe]; ii) variations in the Initial Mass Function, and iii) statistical variations in the number of the high-mass SNe that have been involved in producing the elements of the gas out of which a star has been formed. As discussed in detail by Nissen et al. (1994) on the basis of yields taken from Thielemann et al. (1992), cosmic dispersions at the same level as observed in this paper, $\sigma[\text{O/Fe}] = 0.07$ and $\sigma[\text{Ca/Fe}] = 0.05$, can be expected if the number of Type II SNe involved is on the order of 30 to 50. When integrating the standard Salpeter IMF towards lower masses, this would suggest that our turnoff stars were formed in regions containing a few times $10^4$ stars. Hence, star formation and self-enrichment in regions with typically globular cluster masses are suggested if small number statistics of Type II SNe is the explanation of the scatter in [O/Fe] and [Ca/Fe].

Figure 5. Plots of [O/Fe] and [Ca/Fe] vs. [Fe/H]. Linear fits to the data are shown.

Recently, Cayrel et al. (2004) have used UVES spectra for a precise study of various abundance ratios, including O/Fe and Ca/Fe, for 35 giant stars with metallicities in the range $-4.2 < [\text{Fe/H}] < -2.5$. The scatter in [O/Fe] and [Ca/Fe] is surprisingly small even for this low metallicity range, although there is room for a cosmic scatter of the same order of size as detected in our sample. In addition, there is one outlier, CS 22949-37 with a very high $[\text{O/Fe}] \simeq +1.6$ at $[\text{Fe/H}] = -4.0$. Another interesting case is the “Christlieb” star, HE 0107-5240, which at $[\text{Fe/H}] = -5.3$ has $[\text{O/Fe}] = +2.3$ (Bessell, Christlieb & Gustafsson 2004). Obviously, these anomalous stars have been formed from gas enriched by a special supernovae.
In the case of more metal-rich halo stars as well as thick and thin disk stars with metallicities around $[\text{Fe/H}] \simeq -1$ and above, we see quite pronounced variations in abundance ratios that may be correlated with the kinematics of the stars. Thus, Nissen & Schuster (1997) found a group of six halo stars in the metallicity range $-1.0 < [\text{Fe/H}] < -0.7$ with solar-like abundance ratios between the $\alpha$-capture elements (O, Mg, Si, Ca and Ti) and iron, i.e. $[\alpha/\text{Fe}] \sim 0$, in contrast to thick disk stars in the same metallicity range which have $[\alpha/\text{Fe}] \sim +0.3$. As seen from Fig. 6, these $\alpha$-poor halo stars have low Na and Ni abundances and fall on a well defined $[\text{Ni/Fe}] - [\text{Na/Fe}]$ relation. Furthermore, dwarf spheroidal galaxies and the globular cluster Palomar 12, which probably belongs to the extended stream of the Sagittarius dSph galaxy, fit the relation quite well. The $\alpha$-poor halo stars also tend to be on larger Galactic orbits than halo stars with a high $\alpha/\text{Fe}$ ratio. All of this suggests that the $\alpha$-poor stars are captured from satellite galaxies with a slower chemical evolution than the inner part of the Galactic halo. However, a recent investigation of abundances and kinematics of a large sample of Galactic stars by Venn et al. (2004) did not confirm this. They find that most dSph stars are distinct from Galactic stars in abundance ratios like Ba/Y, and argue that the Galaxy has not been formed by continuous merging of low-mass galaxies similar to dSph satellites.

Concerning the Galactic disk there is increasing evidence for a chemical separation between thick and thin disk stars in the metallicity range $-0.8 < [\text{Fe/H}] < -0.3$. Gratton et al. (1996) and Fuhrmann (1998) were the first to discover a separation in $[\text{O/Fe}]$ and $[\text{Mg/Fe}]$. Later this has been nicely confirmed by Bensby, Feltzing & Lundström (2003) and Reddy et al. (2003). Furthermore, the ratio between $r$ and $s$ process elements, i.e. $[\text{Eu/Ba}]$, seems to differ between thick and thin disk stars (Mashonkina et al. 2003). A detailed discussion of these results is given in Nissen (2004), who points out that to some degree it is also possible to interpret the abundance differences in terms of gradients in the Galactic disk as advocated by Edvardsson et al. (1993).

Figure 6. $[\text{Ni/Fe}]$ vs. $[\text{Na/Fe}]$. Filled circles refer to thick disk stars and asterisks to halo stars with abundance ratios from Nissen & Schuster (1997). The dashed line is a fit to these data, excluding the peculiar star HD 106038. The squares are red giant stars in dwarf spheroidal galaxies with abundances determined by Shetrone et al. (2003) and with metallicities in the range $-1.4 < [\text{Fe/H}] < -0.6$. The open circle shows the abundance ratios of the Galactic globular cluster Palomar 12 as determined by Cohen (2004).
4. Concluding remarks

We have seen that the scatter in Li/H among metal-poor turnoff stars is extremely small, which poses severe problems when one is trying to explain the large difference in the primordial Li abundance predicted from WMAP data and the Li abundance found in the atmospheres of metal-poor turnoff stars. The abundance ratios O/Fe and Ca/Fe, on the other hand, have a significant scatter at a given metallicity.

These results were obtained from high resolution spectra with very high signal-to-noise ratios of 400 to 800, but for a rather small number of 23 stars covering the metallicity range $-3.0 < [\text{Fe/H}] < -1.0$. Clearly, the results need to be confirmed for a larger sample. In particular, it would be interesting to look for distinct abundance patterns as a function of the kinematics of the stars. For this purpose one would need very precise high resolution spectra of say $> 1000$ of stars covering all metallicities.

References

ESA 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200
5. Questions and Comments

_N. Grevesse_: You have to wait until 2007 when ESA will launch the Planck Satellite which has a better resolution than WMAP to see if the observations of the primordial \(^7\)Li abundance really disagree with the predictions from the observations of the very early universe!

_T. Beers_: Have you checked that your slope of \(^7\)Li/H vs. [O/H] is consistent with the slope of the Ryan, Norris & Beers (1999) \(^7\)Li vs. Fe results? Also, new data on Li will be forthcoming from the Cayrel et al. group shortly (≈ 35 stars with [Fe/H] < −2.5)
P.-E. Nissen: The slope of $^7\text{Li}/\text{H}$ vs. $[\text{O}/\text{H}]$ is somewhat higher than the slope of the Ryan, Norris & Beers ($\sim 0.2$ against 0.12). Part of this may be related to a negative gradient in $[\text{O}/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$.

J. Cohen: You don’t have to wait for the not yet written paper of Cayrel et al. (i.e. previous comment by Tim Beers). Instead Cohen et al. (ApJ, 612, 1107) present an analysis of extremely metal poor turnoff stars, with results that agree well with those of Cayrel et al. for giants. There is little or no sign of abnormal abundance ratios or scatter beyond that expected from the observations except in the C-rich stars.

P.-E. Nissen: Yes, but your new paper does not contain any data on lithium.

K. Venn: In reinterpreting our dSph abundances, we believe the Na-Ni correlation is related to the neutron density during core burning. Na is formed through neutron capture and Ni through decay of a neutron rich isotope of Fe. Thus, the Na-Ni relation seen in some halo stars does not necessarily connect them to the dSph stars and remnants of merged galaxies.