The lithium isotope ratio in the metal-poor halo star G271-162 from VLT/UVES observations *

P.E. Nissen1, M. Asplund2, V. Hill3, and S. D’Odorico3

1 Institute of Physics and Astronomy, University of Aarhus, DK–8000 Aarhus C, Denmark (pen@ifa.au.dk)
2 Uppsala Astronomical Observatory, Box 515, SE–751 20, Sweden (martin@astro.uu.se)
3 European Southern Observatory, Karl-Schwarzschild Str. 2, D–85748 Garching b. München, Germany (vhill@eso.org, sdodoric@eso.org)

Received March 15 2000/ Accepted April 12 2000

Abstract. A high resolution (λ/Δλ ∼ 110 000), very high S/N (≥ 600) spectrum of the metal-poor turnoff star G 271-162 has been obtained in connection with the commissioning of UVES at VLT/Kueyen. Using both 1D hydrostatic and 3D hydrodynamical model atmospheres, the lithium isotope ratio has been estimated from the LiI 670.8 nm line by means of spectral synthesis. The necessary stellar line broadening (1D: macroturbulence + rotation, 3D: rotation) has been determined from unblended K I, Ca I, and Fe I lines. The 3D line profiles agree very well with the observed profiles, including the characteristic line asymmetries. Both the 1D and 3D analyses reveal a possible detection of 6Li in G 271-162, 6Li/7Li = 0.02 ± 0.01 (1σ). It is discussed if the smaller amount of 6Li in G 271-162 than in the similar halo star HD 84937 could be due to differences in stellar mass and/or metallicity or whether it may reflect an intrinsic scatter of 6Li/7Li in the ISM at a given metallicity.

Key words: Stars: abundances – Stars: atmospheres – Stars: fundamental parameters – Stars: individual: G271-162 – cosmic rays

1. Introduction

Due to the special status of 6Li for astrophysics and cosmology, much work has been devoted to the search for this isotope in metal-poor stars ever since the first detection in HD 84937 by Smith et al. [1993]. The reason for this interest is threefold: i) The presence of 6Li in the envelope of halo stars severely limits the possible depletion of 7Li, and thus allows a more accurate determination of the primordial 7Li abundance (Ryan et al. 1993; Asplund & Carlsson 2000); ii) 6Li abundances provide an additional test of theories for the production of the light elements (Li, Be, and B) by cosmic ray processes; iii) Since 6Li is an even more fragile nuclei than 7Li it is a sensitive probe of possible mixing events during the stellar life.

To date 6Li is claimed to have been detected in two metal-poor disk stars, HD 68284 and HD 130551 (Smith et al. 1998; Hobbs & Thorburn 1997; Cayrel et al. 1994; Nissen et al. 1999). Clearly, an observational test of models for the formation and evolution of 6Li and for the depletion of 6Li in stellar envelopes requires a much larger set of 6Li data spanning a large metallicity range. With the advent of high-resolution spectrographs on 8m-class telescopes this is now becoming feasible.

The determinations of 6Li abundances are based on the increased width and asymmetry of the LiI 670.8 nm doublet introduced by the isotope shift (0.16 Å = 7.1 km s−1) of 6Li. Since the line is not resolved, the derived 6Li abundance depends on the adopted stellar line broadening as estimated from other spectral lines. Until now all such analyses have relied on 1D hydrostatic model atmospheres which cannot predict the inherent line asymmetries introduced by the convective motions in the atmosphere and thus is a potential source of uncertainty. An attractive alternative is provided by the new generation of 3D hydrodynamical model atmospheres (e.g. Stein & Nordlund 1998; Asplund et al. 1999, 2000) which self-consistently compute the time-dependent convective velocity fields and thus are able to predict the convective line asymmetries.

In the present Letter we analyze a high resolution, very high S/N spectrum of the metal-poor halo star G271-162 obtained during the commissioning of UVES on VLT/Kueyen using both 1D and 3D model atmospheres. Thereby we also investigate the ability of UVES to provide high quality spectra as needed in many astrophysical studies.

2. Observations and reductions of UVES spectra

The metal-poor star G271-162 (BD = −10 388) was chosen as one of the targets for the first commissioning of UVES, the UV-Visual Echelle Spectrograph (D’Odorico & Kaper, 2000) on the ESO VLT UT2 (Kueyen) telescope. The aim was to test if UVES can supply high quality spectra suitable for a determination of the lithium isotope ratio in stars – one of the most demanding problems in observational stellar astrophysics. Being situated at the turnoff point for halo stars in the HR diagram, G271-162 is very similar to HD 84937; hence, one would expect the Li isotope ratio to be about the same, i.e.
Fig. 1. UVES spectrum of G 271-162 in the regions of the Li $\lambda$ 670.8 and K $\lambda$ 769.9 nm lines with nearby thorium emission lines inserted

$^{6}\text{Li}/^{7}\text{Li} \approx 0.06$. Furthermore, G 271-162 represents a group of about 50 halo turnoff stars with $10 \leq V \leq 11.5$ that are too faint to be searched for $^{6}\text{Li}$ using high resolution spectrographs at 4m class telescopes. With UVES it should be possible to reach these stars and hence to increase the sample of stars with $^{6}\text{Li}$ determinations by an order of magnitude.

Four spectra of G 271-162 were obtained on October 11 - 13, 1999, with exposure times ranging from 30 to 60 min. The width of the entrance slit was set at 0.3 arcsec to get a resolution close to 120000. An image slicer is foreseen for this high resolution mode of UVES, but was not available during the first commissioning run. Instead, the star was continuously moved along the slit within $\pm5$ arcsec corresponding to approximately 50 pixels on the CCDs. This widening of the echelle orders is essential in obtaining very high S/N. The lack of the image slicer made the efficiency of UVES critically dependent on the seeing, but it is noted that on one night with excellent seeing on Paranal (0.35 arcsec) the efficiency of UVES was as high as 20%. In addition, the Th lines can be used to check the resolution; the instrument profile is well approximated with a Gaussian and no asymmetry is seen. The resolution as measured from the FWHM of the Th lines varies, however, along a given spectral order from about 100 000 to 120 000. Thanks to the large number of Th lines available, the variation could be mapped and the actual instrumental resolution for a given stellar line determined and applied in connection with the spectrum synthesis. It is noted that this problem of resolution variations has been fixed during the second commissioning run of UVES.

3. Analysis

The analysis of the Li I feature (equivalent width 29.0 mÅ) has been carried out using both 1D hydrostatic (Asplund et al. 1997) and 3D hydrodynamical LTE model atmospheres (Asplund et al. 1999). According to Strömgren photometry the stellar parameters of G 271-162 are $T_{\text{eff}} = 6295 \pm 70$ K and [Fe/H] $= -2.15 \pm 0.2$ while the uncertain Hipparcos parallax suggests $\log g = 3.7^{+0.5}_{-0.5}$. G 271-162 closely resembles HD 84937 for which the IR flux method (IRFM), the Hipparcos parallax and stellar spectroscopy imply $T_{\text{eff}} = 6330 \pm 80$ K, $\log g = 4.0 \pm 0.1$ and [Fe/H] $= -2.25 \pm 0.2$, which we therefore also adopt for G 271-162. It should be emphasized though that the exact choice of parameters does not influence significantly the lithium isotope ratio determinations although it does of course affect the absolute abundances.

When applying 1D model atmospheres to spectral synthesis additional line broadening besides the instrumental broadening is required. This broadening, which is mainly due to macroturbulence, was approximated by a Gaussian function and determined from a $\chi^2$ fit of five unblended lines (Ca I 6162.2, Ca I 6166.2, Fe I 6230.0, Ca I 6439.9, and K I 769.9 nm), all of similar strength as the Li I 670.8 nm line. In the case of the K I 769.9 nm resonance line the hyperfine structure and isotopic shift between $^{39}\text{K}$ and $^{41}\text{K}$ were taken into account although the effect turned out to be rather negligible. A more sophisticated broadening like a radial-tangential profile did not improve the agreement with the observed profiles. In contrast, in hydrodynamical model atmospheres the self-consistent convective motions account for all of the line broadening except for the unknown rotational velocity $v_{\text{rot}} \sin i$ of the star. This parameter was determined by fitting a disk-integration of the angle-dependent theoretical 3D line profiles to the observed profiles of the K I, Ca I and Fe I lines.

The comparison between theoretical and observed profiles was quantified using a $\chi^2$ analysis in an analogous way to previous investigations (Nissen et al. 1995). The $\chi^2$ was computed through

$$\chi^2 = \sum (O_i - S_i)^2 / \sigma^2,$$

where $O_i$ is the observed spectral point, $S_i$ the synthesis and $\sigma = (S/N)^{-1}$ as estimated in two adjacent continuum windows to the lines. When estimat-
Fig. 2. The predicted (solid line) and observed (diamonds) Ca I 616.2 nm line together with the residual fluxes based on the 1D analysis. The Gaussian broadening with which the theoretical spectrum has been convolved include the combined effects of macroturbulence, rotation and instrumental resolution. Note the remaining systematic signal in the residuals.

Fig. 3. The predicted (solid line) and observed (diamonds) Ca I 616.2 nm line together with the residual fluxes for the best fit with $6\text{Li}/7\text{Li} = 0.02$ in the 3D analysis. The Gaussian broadening with which the theoretical spectrum has been convolved include only the instrumental resolution while the rotational broadening has been applied following a full disk-integration of the 3D profiles.

The temperature inhomogeneities and velocity fields in the 3D hydrodynamical model atmospheres introduce characteristic line asymmetries, which for the Sun perfectly describe the observed asymmetries even on an absolute wavelength scale (Asplund et al. 2000). The existence of the predicted line asymmetries in the 3D analysis vastly improves the agreement with the observed profiles for G 271-162 (Fig. 3); other lines show similarly encouraging correspondence. This provides additional support for the realism of the 3D model when describing the real stellar photosphere, as well as giving a higher degree of confidence in the estimate of the lithium isotope ratio. The stellar rotation was determined to be $v_{\text{rot}} \sin i = 2.9 \pm 0.1 \text{ km s}^{-1}$, which in turn implies $6\text{Li}/7\text{Li} = 0.02 \pm 0.01 (1\sigma)$ according to Fig 3. Again, the minimum $\chi^2_{\text{red}}$ is close to 1 as it should.

4. Discussion and conclusions

Both the 1D and 3D analyses suggest a possible detection of $6\text{Li}$ in G 271-162 at the level of $6\text{Li}/7\text{Li} = 0.02 \pm 0.01$. Given the remaining uncertainties in the determination of the stellar
Evidently, the convective line asymmetries are rather negligible on 1D investigations (e.g. Smith et al. 1998; Nissen et al. 1999). Compared to the isotopic shift of the 6Li/7Li ratio appears in any case to be smaller than in HD 84937 for which a weighted average of the results of Schuster & Nissen (1989) and the supernovae-driven chemical evolution model for the Galactic halo by Suzuki et al. (1999). It is clear that the ability of UVES on VLT/Kueyen to gather high quality, high resolution and very high S/N spectra of even 6Li/7Li in the ISM at a given metallicity. In this connection we note that some models for the formation of the light elements by cosmic ray processes in the early Galaxy predict a scatter of one order of magnitude in the abundance of 6Li, Be and B relative to Fe, e.g. the bimodal superbubble model of Parizot & Drury (1999) and the supernovae-driven chemical evolution model for the Galactic halo by Suzuki et al. (1999).

Regardless of whether 6Li has been detected in G 271-162 or not, the 6Li/7Li ratio appears in any case to be smaller than in HD 84937 for which a weighted average of the results of Hobbs & Thorburn (1997), Smith et al. (1998) and Cayrel et al. (1999). Evidently, the convective line asymmetries are rather negligible compared to the isotopic shift of the 6Li doublet.

Table 1. Strömgren photometry from Schuster & Nissen (1988)

| ID          | V   | (b − y)₀ | m₀   | c₀   | β    |
|-------------|-----|----------|------|------|------|
| HD 84937    | 8.33| 0.303    | 0.056| 0.354| 2.613|
| G 271-162   | 10.35| 0.306    | 0.055| 0.355| 2.602|
| BD +26 3578 | 9.37| 0.308    | 0.045| 0.366| 2.600|

Table 2. Stellar parameters and Li isotope ratios

| ID          | T eff | [Fe/H] | M V   | 6Li/7Li |
|-------------|-------|--------|-------|---------|
| HD 84937    | 6315 K| −2.14  | 3.58  | 0.059 ± 0.016 |
| G 271-162   | 6295 K| −2.15  | 3.53  | 0.020 ± 0.010 |
| BD +26 3578 | 6280 K| −2.60  | 3.08  | 0.050 ± 0.030 |

Fig. 5. The variation of ∆χ² in the 3D analysis of the 6Li 670.8 nm line as a function of the relative abundance of 6Li for different adopted ν rot sin i: 2.7 (dotted), 2.9 (solid) and 3.1 km s⁻¹ (dashed). The corresponding estimates of 6Li/7Li are 0.027 ± 0.009, 0.023 ± 0.009 and 0.017 ± 0.010, respectively. The widths of K I, Ca I and Fe I lines imply ν rot sin i = 2.9 ± 0.1 km s⁻¹. The horizontal lines represent the formal 1σ, 2σ and 3σ confidence limits.

HD 84937, BD +26 3578 and G 271-162 in the M V-log T eff diagram compared to evolutionary tracks from Vandenberg et al. (2000) with masses and metallicities indicated.

Fig. 6. The position of HD 84937, BD +26 3578 and G 271-162 in the M V-log T eff diagram. Clearly, HD 84937 and G 271-162 have nearly the same mass. This makes it difficult to explain the lower 6Li abundance in G 271-162 as a depletion effect and raises the interesting question of a possible intrinsic scatter of 6Li/7Li in the ISM at a given metallicity. In this connection we note that some models for the formation of the light elements by cosmic ray processes in the early Galaxy predict a scatter of one order of magnitude in the abundance of 6Li, Be and B relative to Fe, e.g. the bimodal superbubble model of Parizot & Drury (1999) and the supernovae-driven chemical evolution model for the Galactic halo by Suzuki et al. (1999).

It is clear that the ability of UVES on VLT/Kueyen to gather high quality, high resolution and very high S/N spectra of even 6Li/7Li in the ISM at a given metallicity. In this connection we note that some models for the formation of the light elements by cosmic ray processes in the early Galaxy predict a scatter of one order of magnitude in the abundance of 6Li, Be and B relative to Fe, e.g. the bimodal superbubble model of Parizot & Drury (1999) and the supernovae-driven chemical evolution model for the Galactic halo by Suzuki et al. (1999).

It is clear that the ability of UVES on VLT/Kueyen to gather high quality, high resolution and very high S/N spectra of even 6Li/7Li in the ISM at a given metallicity. In this connection we note that some models for the formation of the light elements by cosmic ray processes in the early Galaxy predict a scatter of one order of magnitude in the abundance of 6Li, Be and B relative to Fe, e.g. the bimodal superbubble model of Parizot & Drury (1999) and the supernovae-driven chemical evolution model for the Galactic halo by Suzuki et al. (1999).
expected to be of great importance both for an improved understanding of Big Bang nucleosynthesis, cosmic chemical evolution of the light elements and stellar mixing events.

Acknowledgements. We are greatly indebted to all the people involved in the conception, construction and commissioning of the UVES instrument, without whom this project would have been impossible.

References

Alonso A., Arribas S., Martínez-Roger C., 1996a, A&A 313, 873
Alonso A., Arribas S., Martínez-Roger C., 1996b, A&AS 117, 227
Asplund M., Gustafsson B., Kiselman D., Eriksson K., 1997, A&A 318, 521
Asplund M., Nordlund À., Trampedach R., Stein R.F., 1999, A&A 346, L17
Asplund M., Carlsson M., 2000, submitted to A&A
Asplund M., Nordlund À., Trampedach R., Allende Prieto C., Stein R.F., 2000, submitted to A&A
Cayrel R., Spite M., Spite F., et al., 1999, A&A 343, 923
D’Odorico S., Kaper L., 2000, UVES User Manual, ESO Doc. no VLT-MAN-ESO-13200-1825
ESA, 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200
Hobbs L.M., Thorburn J.A., 1997, ApJ 491, 772
Nissen P.E., Lambert D.L., Primas F., Smith V.V., 1999, A&A 348, 211
Nissen P.E., Schuster W.J., 1991, A&A 251, 457
Parizot E., Drury L., 1999, A&A 349, 673
Ryan S.G., Norris J.E., Beers T.C., 1999, ApJ 523, 654
Schuster W.J., Nissen P.E., 1988, A&AS 73, 225
Schuster W.J., Nissen P.E., 1989, A&A 221, 65
Smith V.V., Lambert D.L., Nissen P.E., 1993, ApJ 408, 262
Smith V.V., Lambert D.L., Nissen P.E., 1998, ApJ 506, 405
Stein R.F., Nordlund À., 1998, ApJ 499, 914
Suzuki T.K., Yoshii Y., Kajino T., 1999, ApJ 522, L125
VandenBerg D.A., Swenson F.J., Rogers F.J., Iglesias C.A., Alexander D.R., 2000, ApJ 532, 430