

Lithium and its isotopic ratio ${}^6\text{Li}/{}^7\text{Li}$ in the atmospheres of some sharp-lined roAp stars

A. Shavrina¹, N. Polosukhina², S. Khan³, Ya. Pavlenko¹, V. Khalack¹,
G.A. Wade⁴, P. Quinet⁵, N. Mikhailitska¹, A. Yushchenko^{6,8},
V. Gopka⁶, A. Hatzes⁷, D. Mkrtichian^{6,8} and A. Veles¹

¹ Main Astronomical Observatory of NASU 27 Zabolotnogo Str., 03680, Kyiv, Ukraine
email: shavrina@mao.kiev.ua, yp@mao.kiev.ua, khalack@mao.kiev.ua,
veles@mao.kiev.ua

² Crimean Observatory, Ukraine
email: polo@crao.crimea.ua

³ Simpheropol University, Ukraine
email: serg@starsp.org

⁴ Physics Department, Royal Military College of Canada
email: gregg.wade@rmc.ca

⁵ Astrophysique et Spectroscopie, Université de Mons-Hainaut, Belgium
email: Pascal.Quinet@umh.ac.be

⁶ Observatory of Odesa University, Ukraine
email: ayushchenko@hotmail.com, gopka@arktur.tenet.odessa.ua

⁷ Thüringer Landersternwarte, Tautenburg, Germany
email: artie@tls-tautenburg.de

⁸ Astrophysical Research Center of the Structure and Evolution of the Cosmos (ARCSEC),
Sejong University, Seoul 143-747, Korea
email: david@arsec.sejong.ac.kr

Abstract. The lines of lithium at $\lambda 6708$ and $\lambda 6103$ are analyzed in high resolution spectra of some sharp-lined and slowly rotating roAp stars. Three spectral synthesis codes, STARSP, ZEEMAN2 and SYNTHM were used. New lines of the Rare Earth Elements from the DREAM database, and lines calculated on the basis of the NIST energy levels were included. Magnetic splitting and other line broadening processes were taken into account. Enhanced abundances of lithium in the atmospheres of the stars studied are obtained for both lithium lines. High estimates of ${}^6\text{Li}/{}^7\text{Li}$ ratio ($0.2 \div 0.5$) for the studied stars can be explained by Galactic Cosmic Ray (GCR) production by spallation reactions and the preservation of the original ${}^6\text{Li}$ and ${}^7\text{Li}$ by the strong magnetic fields.

Keywords. Stars: chemically peculiar, stars: magnetic fields, stars: individual: (HD 137947, HD 201601, HD 134214, HD 166473, HD 101065)

1. Introduction

In the framework of the project “Lithium in CP stars”, a significant series of observations was obtained at ESO and CrAO ($R = 100000$ and 50000 , respectively, 1996–2001) for 5 rapidly oscillating Ap (roAp) stars: 33 Lib (HD 137947), γ Equ (HD 201601), HD 134214, HD 166473, HD 101065, in the spectral region $\lambda\lambda 6680$ – 6730 . These series were supplemented by ESO (March 2004) and SAO-BTA (April 2004) spectra with $R = 100000$ and 60000 , respectively. The observations show a very strong and nonvariable resonance doublet Li I $\lambda 6708$. The spectra of these roAp stars are group II in the classification

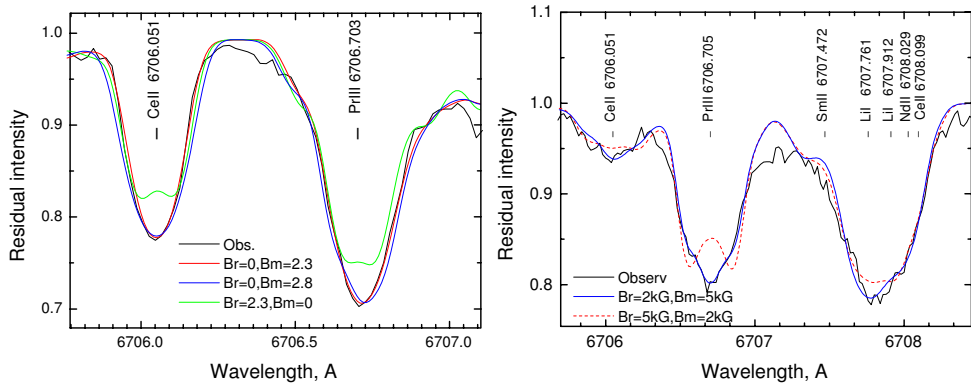


Figure 1. Estimates of the magnetic field parameters from Ce II $\lambda 6706.051$ and Pr III $\lambda 6706.705$ for HD 101065 (left) and 33 Lib (right).

of lithium roAp stars in accordance with Li I $\lambda 6708$ appearance over the phases (Polosukhina *et al.* 1999).

All these stars are characterized by sharp lines in their spectra, by the strong overabundance of Rare Earth Elements, and by magnetic fields from 2 kG to 6.8 kG. The sharp lines ($2 \div 3 \text{ km s}^{-1}$) in the spectra of these stars result from small $v \sin i$ values. For the stars with short rotational periods the sharp lines appear to be due to the combination of equatorial velocity v and a significant inclination angle i . For the stars with longer periods (of some years), γ Equ and 33 Lib, the width of the lines is attributed to slow rotation. (Note that the broadening of spectral lines due to rotation is not distinguished from the broadening due to the rapid oscillations). Some of the stars are, therefore, observed “pole-on”, and an observer always sees only one hemisphere of these star. In this case the spectrum is essentially constant.

2. Synthetic spectra

These stars with strong $\lambda 6708$ lithium doublets are very poorly studied. We study their spectra in detail in a narrow range near $\lambda 6708$ by the method of synthetic spectra, taking into account Zeeman magnetic splitting and blending by REE lines. Any additional broadening, likely pulsational, was described by the parameter $v \sin i$.

Spectral calculations for HD 166473, γ Equ and 33 Lib were carried out using the model atmospheres of Kurucz (1994) with parameters from Gelbman *et al.* (2000), Ryabchikova *et al.* (1997), and Ryabchikova *et al.* (1999). For HD 101065 Pavlenko’s model was used, as in the work of Shavrina *et al.* (2003). For synthetic spectra calculations we applied the magnetic spectrum synthesis code SYNTHM (Khan 2004), which is similar to Piskunov’s code SYNTHMAG and was tested in accordance with Wade *et al.* (2001). For initial calculations we used the code STARSP of Tsymbal (1996) and in some cases the code ZEEMAN2 (Wade *et al.* 2001).

A simplified model of the magnetic field is characterized by radial (along line of sight), meridional, and longitudinal components of field B_r, B_m, B_l ($B_l = 0$ always, as it is justified for the plane-parallel model atmospheres), which were primarily determined from Fe II $\lambda 6147, \lambda 6149$, Ce II $\lambda 6706.05$ and Pr III $\lambda 6706.70$ (see Table 1).

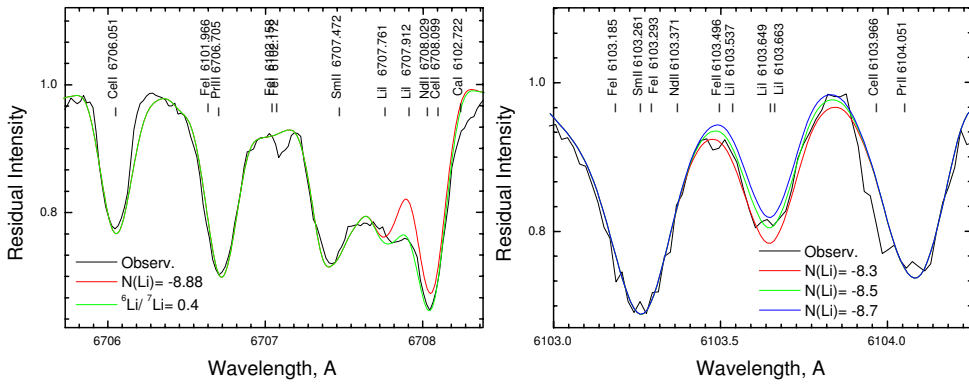


Figure 2. Fitting of the observed and the calculated spectra of HD 101065 near $\lambda 6708$ with ${}^6\text{Li}/{}^7\text{Li}=0.4$. Left: The spectrum calculated when taking into account only the main isotope ${}^7\text{Li}$ does not fit the observed one at $\lambda 6707.9$. The primary contributing lines are marked at the top of each panel.

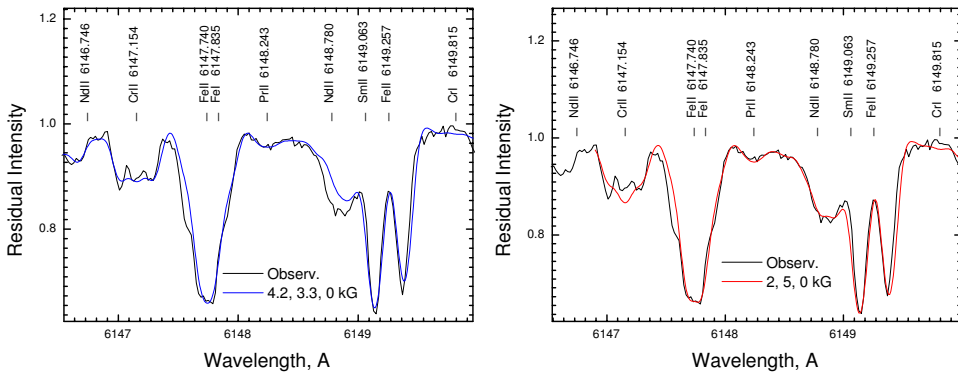


Figure 3. Fe II $\lambda 6147$ and $\lambda 6149$ for 33 Lib with magnetic field components. Left: $B_r = 4.2$ kG, $B_m = 3.3$ kG, $B_l = 0$ kG; Right: $B_r = 2$ kG, $B_m = 5$ kG and $B_l = 0$ kG like for Pr III $\lambda 6708$ (see Fig. 1, Right).

3. REE lines with new atomic data

We used the VALD (Kupka *et al.* 1999) and the DREAM† databases for atomic spectral lines. These data do not in fact allow us to fit synthetic spectra to the observed ones for all stars studied. We, therefore, calculated additional REE II-III lines using the NIST energy levels and estimated their "astrophysical" gf-values from the spectra of HD 101065 using elemental abundances from Cowley *et al.* (2000). Theoretical gf-values for other important (for the lithium abundance determination) blending lines were computed by P. Quinet with Cowan's code (Shavrina *et al.* 2003).

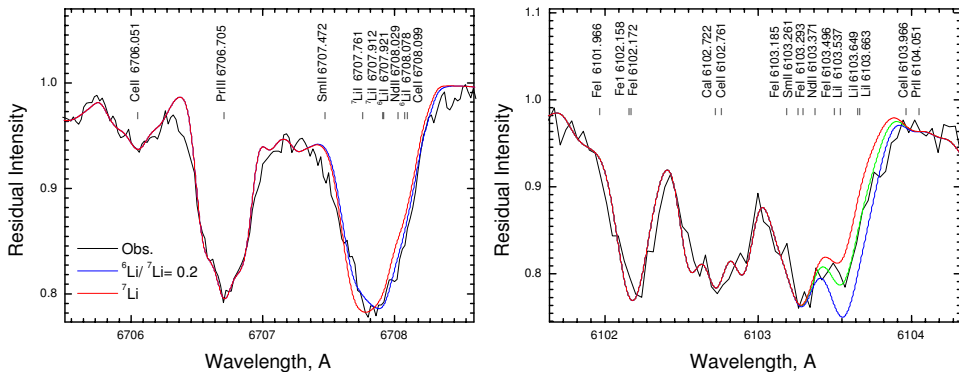
4. HD 101065

We present a new spectral analysis of the star HD 101065 in the lithium spectral ranges $\lambda 6708$ and $\lambda 6103$ using the new atomic data for REE lines and the new magnetic synthesis code SYNTHM (Khan 2004). The lithium abundance estimates from $\lambda 6708$ and $\lambda 6103$

† [<http://www.umh.ac.be/~astro/dream.shtml>]

Table 1. Results of abundance, ${}^6\text{Li}/{}^7\text{Li}$ - ratio, magnetic field, and $v \sin i$ determination.

	HD 101065	HD 134214	HD 137949	HD 137949	HD 166473	HD 201601
$T_{\text{eff}}/\log g/[M/H]$	6600/4.2/0	7500/4.0/0	7750/4.5/0	7250/4.5/0	7750/4.0/0	7750/4.0/0
N(Fe I) $\lambda 6103$	6.95 (Fe II)	7.60	8.00	7.80	-	7.80
N(Fe II) $\lambda 6149$	-	7.25	7.70	7.80	7.35	7.50
N(Li) $\lambda 6708$	3.1	3.9	4.1	3.6	3.7	3.8
N(Li) $\lambda 6103$	3.5	4.1	4.4	4.4	-	4.0
${}^6\text{Li}/{}^7\text{Li}$ $\lambda 6708$	0.4:	0.3:	0.2:	0.3:	0.5:	0.3:
$B_r/B_m/B_l$ (kG)						
Fe II $\lambda 6149$	-	-2.9/-1.7/0	4.1/4.1/0	4.2/3.3/0	2.0/6.0/0	3.5/2.6/0.8
Pr III $\lambda 6706.7$	0/2.3/0	-2.3/-1.9/0	2.0/5.0/0	1.5/5.0/0	2.0/6.5/0	2.7/3.5/0
Ca I $\lambda 6102.7$	0/2.4/0	-1.7/-2.8/0	3.0/4.0/0	3.5/4.0/0	-	0/4.0/0
$v \sin i$ (km s^{-1})						
Fe II	-	3.0	2.5	2.5	3.0	2.5
Pr III	3.5	2.0	4.0	4.0	5.5	2.5

**Figure 4.** Fitting the observed with the computed spectra for 33 Lib. Left: Li I $\lambda 6708$, $\log N(\text{Li}) = -7.95$ and ${}^6\text{Li}/{}^7\text{Li} = 0.2$; when only ${}^7\text{Li}$ is taken into account then $\log N(\text{Li}) = -7.88$. Right: the best fit was reached for $\log N(\text{Li}) = -7.60 \pm 0.3$, ${}^6\text{Li}/{}^7\text{Li} = 0.2$.

are 3.1 dex and 3.4 dex, respectively, in the scale of $\log N(H) = 12.0$ dex, and its isotopic ratio ${}^6\text{Li}/{}^7\text{Li}$ is about 0.4 ($\lambda 6708$) and 0.3 ($\lambda 6103$).

5. Results

The results are presented in Table 1. In the second line parameters of model atmospheres $T_{\text{eff}}/\log g/[M/H]$ are given. The calculations for HD 137949 were carried out for two model atmospheres 7750/4.5/0 and 7250/4.5/0 in the possible effective temperature range. The abundances derived from the lines of Fe I, Fe II and Li I on the scale $\log N(H) = 12.0$ are given in lines 3 - 6, and the isotopic ratio estimated from Li I $\lambda 6708$ in line 7. To take into account the Fe II line $\lambda 6103.496$ near the Li I line at $\lambda 6103.6$, we used for HD 101065 the abundance of Fe II according to Cowley *et al.* (2000). The bottom part of the table summarizes the parameters of magnetic field and $v \sin i$ values derived by fitting of the lines Fe II $\lambda 6149$, Pr III $\lambda 6706.7$, and Ca I $\lambda 6102.7$.

6. Conclusions

- The lithium abundances for all stars determined from the Li I $\lambda 6103$ line are greater than the abundances determined from Li I $\lambda 6708$. This may be evidence of a vertical lithium stratification, an abnormal temperature distribution, or consistent unidentified blending with the $\lambda 6103$ line.

- Our work on two roAp stars, HD 83368 and HD 60435 (Shavrina *et al.* 2001) provides evidence of an enhanced lithium abundance near the magnetic field poles. We can expect similar effects in sharp-lined roAp stars. The high lithium abundance for all stars determined from the Li I lines and the estimates of ${}^6\text{Li}/{}^7\text{Li}$ ratio ($0.2 \div 0.5$) can be explained by the Galactic Cosmic Ray (GCR) production due to spallation reactions with the ISM near where these stars formed and the preservation of original both ${}^6\text{Li}$ and ${}^7\text{Li}$ by their strong magnetic fields. The values of the ${}^6\text{Li}/{}^7\text{Li}$ ratio expected from GCR production are about $0.5 \div 0.8$ (Knauth *et al.* 2003, Webber *et al.* 2002).

- The new laboratory and theoretical gf-values for REE lines are necessary to refine our estimates of lithium abundances and the isotopic ratio.

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