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

A. Shavrina$^1$, N. Polosukhina$^2$, S. Khan$^3$, Ya. Pavlenko$^1$, V. Khalack$^1$, G.A. Wade$^4$, P. Quinet$^5$, N. Mikhailitska$^1$, A. Yushchenko$^{6,8}$, V. Gopka$^6$, A. Hatzes$^7$, D. Mkrtichian$^{6,8}$ and A. Veles$^1$

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, Universite de Mons-Hainaut, Belgium
email: Pascal.Quinet@umh.ac.be

6 Observatory of Odesa University, Ukraine
email: yua@odessa.net, gopka@arktur.tenet.odessa.ua

7 Thüringer Landessternwarte, 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@arcsec.sejong.ac.kr

Abstract. The lines of lithium at 6708 Å and 6103 Å 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 the 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 to 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 6680–6730 Å. These series were supplemented by ESO (March 2004) and SAO-BTA (April 2004) spectra with R=100000 and 60000. The observations show very strong and non-variable resonance doublets of Li i at 6708Å. The spectra of these roAp stars are group II in the classification of lithium roAp
stars in accordance with the Li I line 6708 Å appearance over the phases (Polosukhina, Kurtz, Hack, et al. 1999)).

All these stars are characterized by sharp lines in their spectra, by the strong over-abundance of rare earth elements, and by magnetic fields from 2 kG up to 6.8 kG. The sharp lines (2 ÷ 3 km s\(^{-1}\)) in the spectra of these stars result from small \(v\_e\sin i\). For the stars with short rotational periods the sharp lines appear to be due to the combination of equatorial velocity \(v\_e\) 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 by 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 6708 Å lithium doublets are very poorly studied. We study their spectra in detail in a narrow range near 6708 Å by the method of synthetic spectra, taking into account Zeeman magnetic splitting and blending by REE lines. The 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 the papers of Gelbman, et al. (2000), Ryabchikova, Landstreet, Gelbmann, et al. (1997), Ryabchikova, et al. (1999). For HD 101065 Pavlenko’s model was used, as in the work of Shavrina, Polosukhina, Pavlenko, et al. (2003). For synthetic spectra calculations we applied the magnetic spectrum synthesis code SYNTHM (Khan 2004), which is similar to Piskunov code SYNTHMAG and was tested in accordance with the paper of Wade et al. (2001). Also for initial calculations we used the code STARSP of Tsymbal (1996) and in some cases the code ZEEMAN2 of Wade et al. (2001).

The 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 lines 6147 Å, 6149 Å Ce II 6706.05 and Pr III 6706.70 Å (see Table I).
3. REE lines with new atomic data

We used the VALD (Kupka F., et al. 1999) and 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 NIST energy levels and estimated their "astrophysical" gf-values from the spectra of HD 101065 using elemental abundances from Cowley, Ryabchikova, Kupka, et al. (2000). As well, the theoretical gf-values for important (under the lithium abundance determination) blending lines were especially computed by P. Quinet with Cowan’s code (Shavrina, Polosukhina, Pavlenko, et al. 2003).

† [http://www.unh.ac.be/~astro/dream.shtml]
Table 1.

| $T_{\text{eff}}/\log g/[\text{m}]$ | HD 101065 | HD 134214 | HD 137949 | HD 137949 | HD 166473 | HD 201601 |
|---------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| N(FeI) 6103Å                    | 6.95      | 7.60      | 8.00      | 7.80      | -         | 7.80      |
| N(FeII) 6149Å                   | -         | 7.25      | 7.70      | 7.80      | 7.35      | 7.50      |
| N(Li) 6708Å                     | 3.1       | 3.9       | 4.1       | 3.6       | 3.7       | 3.8       |
| N(LiI) 6103Å                    | 3.5       | 4.1       | 4.4       | 4.4       | -         | 4.0       |
| $^{6}\text{Li}/^{7}\text{Li}$ 6708Å | 0.4:      | 0.3:      | 0.2:      | 0.3:      | 0.5:      | 0.3:      |
| $B_{\nu}/B_{\text{m}}/B_{l}$ (kG) |           |           |           |           |           |           |
| FeII 6149Å                      | -         | -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 6706.7Å                  | 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 |
| CaI 6102.7Å                     | 0/2.4/0   | -1.7/-2.8/0 | 3.0/4.0/0 | 3.5/4.0/0 | -         | 0/4.0/0   |
| $\nu \sin i$ (km s$^{-1}$)      | -         | 3.0       | 2.5       | 2.5       | 3.0       | 2.5       |
| FeII                            |           |           |           |           |           |           |
| $\nu \sin i$ (km s$^{-1}$)      | 3.5       | 2.0       | 4.0       | 4.0       | 5.5       | 2.5       |

$B_{\nu}/B_{\text{m}}/B_{l}$ (kG)

Figure 4. For 33 Lib a) Li I 6708 Å, blue line: log N(Li) =-7.95, $^{6}\text{Li}/^{7}\text{Li}=0.2$; red line: log N(Li)= -7.88, only $^7\text{Li}$. b) Li I 6103 Å, green line: log N(Li)= -7.60 ±0.3, $^{6}\text{Li}/^{7}\text{Li} =0.2$

4. HD101065

We present a new version of the spectra analysis of the star HD 101065 in the lithium spectral ranges 6708Å and 6103Å using the new atomic data for REE lines and the new magnetic synthesis code SYNTHM (Khan 2004). The lithium abundance estimates from 6708Å and 6103Å are 3.1 dex and 3.4 dex respectively, in the scale of log $N(\text{H})=12.0$ dex, and its isotopic ratio $^{6}\text{Li}/^{7}\text{Li}$ is about 0.4 (6708Å) and 0.3 (6103Å).

5. Results

Results of the work are presented in the Table. I the first line, the HD numbers and in the second one - the parameters of used model atmospheres are given. The calculations for star HD 137949 were carried out for two model atmospheres in a possible effective temperature range - 7750/4.5/0 and 7250/4.5/0. In six column for each star(model) we give the abundances of Fe I and Fe II in the scale of log $N(\text{H})=12.0$, derived from a group of the Fe I lines (6102-6103 Å) and Fe II 6149 Å(3.4 lines in the table). For HD 101065 with weak Fe lines we use the abundance of Fe II from the paper of Cowley et al. (2000)
The abundances of lithium determined from both 6708 Å and 6103 Å lines and isotopic ratio from 6708 Å line are shown in 5-7 lines of table. Under the solid line we give the parameters of magnetic field and vsini found from the fitting of Fe II 6149 Å, Pr III 6706.7 and Ca I 6102.7 lines. Last value of vsini was used for spectra calculations in both lithium lines ranges. Magnetic field parameters from Ca I 6102.7 were used in the 6103 Å range and ones from Pr III 6707.6 Å for 6708 Å range.

6. Conclusions

- The lithium abundance for all stars determined from the Li I 6103 Å line is higher than the abundance determined from Li I 6708 Å. This may be evidence of vertical lithium stratification, an abnormal temperature distribution, or consistent unidentified blending with the 6103 Å line.
- Our work on two roAp stars, HD 83368 and HD 60435 (Shavrina, Polosukhina, Zverko, 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 ÷ 0.5) can be explained by the Galactic Cosmic Ray (GCR) production due to spallation reactions with ISM in the areas of these stars formation and preservation of original both $^6\text{Li}$ and $^7\text{Li}$ by the strong magnetic fields of these stars. The values of the $^6\text{Li}/^7\text{Li}$ ratio expected from GCR production are about 0.5 ÷ 0.8 (Knauth et al. 2003, Webber, Lukasiak, McDonald, 2002).
- The new laboratory and theoretical gf-values for REE lines are necessary in order to refine our estimates of lithium abundances and the isotopic ratio.

Acknowledgements

The authors are grateful to Dr. J. Zverko and Dr. J. Žižňovský for their useful comments. A. Shavrina, N. Polosukhina, V. Khalack and V. Gopka would like also to express gratitude to the Local Organizing Committee and IAU for financial support.

References

Biémont E., Palmeri P. and Quinet P., D.R.E.A.M. Database on Rare Earth at Mons.Univ., http://www.umh.ac.be/~astro/dream.shtml
Cowley, C. R., Ryabchikova, T., Kupka, F., Bord J.D., Mathys G., Bidelman W.P. 2000, MNRAS 317, 299
Gelbman M., Ryabchikova T., Weiss W., Piskunov N., Kupka F., and Mathys G., 2000, A&A 356, 200
Khan, S. 2004, JQSRT, 88, N1-3, 71
Knauth David C.,Federman S. R., Lambert David L. 2003, ApJ 586, 268
Kupka F., Piskunov N.E., Ryabchikova T.A., Stempels H.C., Weiss W.W. 1999, A&A 138, 119
Kurucz, R. 1994, CDR(1-23)
Polosukhina, N., Kurtz, D., Hack, M., North, P., Zverko, J., Shachovskoy, D. 1999, A&A 351, 283
Ryabchikova, T.A., Landstreet, J.D., Gelbmann, M.J., et al.} 1997, A&A 327, 1137
Ryabchikova T.,Piskunov N., Savanov L., Kupka F., Malamushenko, V. 1999, A&A 343, 229
Shavrina, A.V., Polosukhina, N.S., Zverko, J., Mashonkina, L.I., Khalack V., Ziznovski, J., Hack, M., Tsymbal, V., North, P., Vygonec, V.V. 2001, A&A 372, 571
Shavrina, A.V., Polosukhina, N.S., Pavlenko, Ya.V., Yushchenko, A.V., Quinet, P., Hack, M., North, P., Gopka, V.F., Zverko, J., Žižňovský, J., Veles, A. 2003, A&A 409, 707
Tsymbal, V. 1996, ASP Conf. Ser. 108, 198
Wade G.A., Bagnulo S., Kochukov O., Landstreet J.D., Piskunov N., Stift M.J. 2001, A&A 374, 265
Webber, W. R., Lukasiak, A., McDonald, F. B. 2002, ApJ, 568, 1, 210