LITHIUM AND ITS ISOTOPIC RATIO ^{6}Li/^{7}Li IN THE ATMOSPHERES OF SHARP-LINED roAp STARS γ EQUULEI and HD 166473

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The lithium lines at 6708 Å for two sharp-lined roAp stars γ Equ and HD 166473 and at 6103 Å for γ Equ were analyzed in high resolution spectra. 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 and high estimates of ^{6}Li/^{7}Li ratio ($0.2 \div 0.5$) can be explained by the Galactic Cosmic Ray (GCR) production due to spallation reactions and the preservation of original ^{6}Li and ^{7}Li by strong magnetic fields.

INTRODUCTION

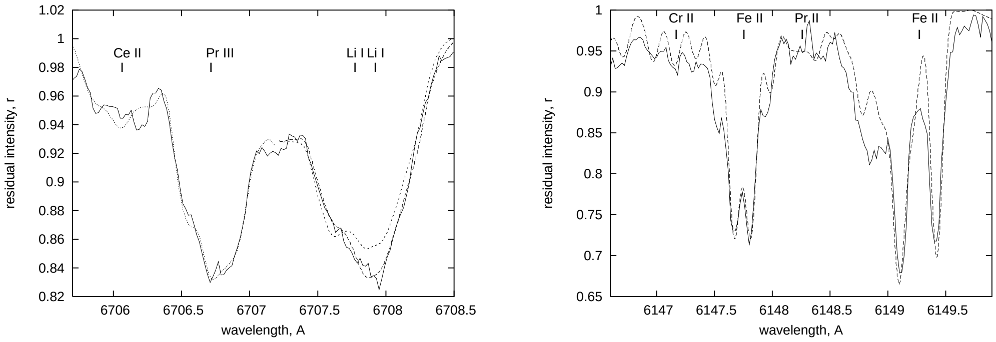
This research was carried out in the framework of the project "Lithium in CP stars" [8]. HD 201601 (γ Equ) and HD 166473, both roAp stars, are characterized by sharp lines in their spectra, by the strong overabundance of the rare-earth elements, and by strong magnetic fields (about 4.1 kG and 8.6 kG, respectively). The sharp lines in the spectra of both stars result from their slow rotation: their periods are approximately 4 years for HD 166473 and 77 years for γ Equ.

OBSERVED SPECTRA

The spectra of HD 166473 were obtained by P. North on March 8–14, 1996 with the 1.4-m Coude Auxiliary Telescope (CAT) and Coude Echelle Spectrometer (CES) at La Silla. The detector was the ESO CCD N 34 with 2048 pixels along the dispersion direction (pixel size are 15 μm $\times$ 15 μm), which provides the resolving power $R = 100\,000$ and the wavelength range of 58.2 Å for the central wavelengths 6705, 6645, and 6150 Å. In Table 1, we give the epoch, exposure time, and wavelength coverage of used spectra.

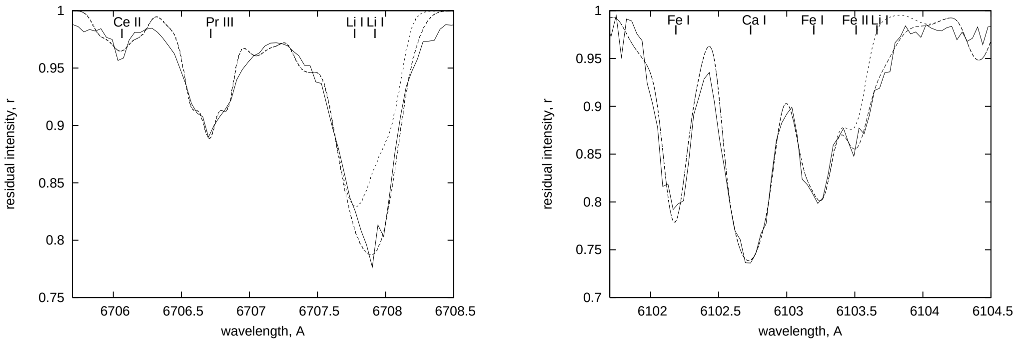
Table 1. The list of observations for HD 166473

N	Date, d m yr	T, UT hr min	Exp., min	HJD, 2450000+	Range
10	08.3.1996	8 23	80	150.876	6675–6735 Å
20	09.3.1996	8 48	50	151.883	6675–6735 Å
31	10.3.1996	8 45	60	152.884	6675–6735 Å
45	11.3.1996	8 48	60	153.886	6675–6735 Å
54	12.3.1996	8 38	60	154.880	6675–6735 Å
73	13.3.1996	8 52	50	155.886	6120–6180 Å
87	14.3.1996	8 36	60	156.878	6615–6675 Å



a) HD 166473, Li I 6708 Å　　b) HD 166473, Li I 6708 Å, Fe II 6149 Å

Figure 1. For HD 166473 (a) Li I 6708 Å, black: observed spectrum; red line: a calculated spectrum by taking into account lines of only the main isotope ^{7}Li, $\log N(\mathrm{Li})/N(\mathrm{H}) = -8.2$; green line: spectrum with the ratio $^6\mathrm{Li}/^7\mathrm{Li} = 0.4$, $\log N(\mathrm{Li})/N(\mathrm{H}) = -8.3$. The positions of those lines, which are the main contributors to the absorption, are marked at the top of the figure. Note that the Pr III line model profile fits to the observed one for magnetic field parameters B_r, B_m, $B_l = 3000$, 5500, 0 G, respectively, while for the Li I line profile these parameters are 4000, 9000, 0 G, respectively. (b) Fe II 6147 Å and 6149 Å lines, $B_r = 4.8$ kG, $B_m = 4.9$ kG, $B_l = 0$ kG.



a) γ Equ, Li I 6708 Å　　b) γ Equ, Li I 6103 Å

Figure 2. For γ Equ (a) Li I 6708 Å, blue line: $\log N(\mathrm{Li}) = -7.95$, $^6\mathrm{Li}/^7\mathrm{Li} = 0.5$; red line: $\log N(\mathrm{Li}) = -7.80$, only ^{7}Li. (b) Li I 6103 Å, 6103 Å, $\log N(\mathrm{Li})/N(\mathrm{H}) = -8.0$ and $\log N(\mathrm{Li})/N(\mathrm{H}) = -8.3$.

The observations of γ Equ were obtained on March 9–10, 2004 by D. Kudryavtsev with the 6-m BTA telescope and Nasmyth Echelle Spectrometer (NES, Panchuk *et al.* [9]) of the Russian Special Astrophysical Observatory. They consist of the continuous sequences of 25 and 16 spectra for March 9 and 10, respectively, with exposure times of about 3 min that allows one to analyze the pulsational variability of spectral lines. The spectra with signal-to-noise ratio of above 80 (15 and 4 spectra for March 9 and 10, respectively) did not show any significant variability of the 6708 Å lithium line profiles and were selected for the analysis. In Fig. 2, we show an averaged spectrum for March 9, which almost coincides with the similar one for March 10.

Table 2. Results of the determination of the Li abundances, $^6Li/^7Li$ ratio, magnetic field parameters as well as the $v \sin i$ determination

	HD 166473	HD 201601
$T_{\rm eff}$/log g/[min]	7750/4.0/0	7750/4.0/0
N(Fe I) 6103 Å	–	7.80
N(Fe II) 6149 Å	7.60	7.50
N(Li) 6708 Å	3.7	3.8
N(Li) 6103 Å	–	4.0
^{6}Li/^{7}Li, 6708 Å	0.4:	0.5:
$B_r/B_m/B_l$/ (kG)		
Fe II 6149 Å	4.8/4.9/0	3.5/2.6/0.8
Pr III 6706.7 Å	3.0/5.5/0	2.7/3.5/0
Ca I 6102.7 Å	–	0/4.0/0
$v \sin i$ (km s^{-1}) (Fe II)	3.0	0.5
$v \sin i$ (km s^{-1}) (Pr III)	5.0	2.5

SYNTHETIC SPECTRA

These stars, HD 166473 and γ Equ, with the strong 6708 Å lithium doublets are not well studied. We analyzed their spectra in detail in a narrow range near 6708 Å by the method of synthetic spectra, taking into account the Zeeman magnetic splitting and blending by REE lines. The additional broadening, likely pulsational, was described by the parameter $v \sin i$. Spectral calculations for both stars were carried out using the model atmospheres of [7] with parameters from [3, 10, 11]. For synthetic spectra calculations, we applied the magnetic spectrum synthesis code SYNTHM [4], which is similar to the Piskunov code SYNTHMAG and was tested in accordance with [15]. For initial calculations, we also used the code STARSP of [14] and in some cases the code ZEEMAN2 [15]. We used the VALD [6] and DREAM[1] databases for atomic spectral lines. These data do not in fact allow us to fit synthetic spectra to the observed ones for all stars investigated. Therefore, we calculated additional REE II-III lines using the NIST energy levels and estimated their "astrophysical" gf-values from the spectra of HD 101065 using the elements abundance from [2]. The theoretical gf-values for important (by the lithium abundance determination) blending lines were especially computed by P. Quinet with the Cowan's code as well (see [13]).

RESULTS

Results of the research are presented in Table 2. In the second line, parameters of the model atmospheres used are given. In Table 2, we give for each star the abundance of Fe I and Fe II in the scale of $\log N(\mathrm{H}) = 12.0$, derived from a group of the Fe I (6102–6103 Å) and Fe II (6149 Å) lines (3rd, 4th lines in the table). The lithium abundances determined from both 6708 Å and 6103 Å lines and isotopic ratio derived from the 6708 Å line are shown in 5th–7th lines of the table. Under the solid line, we present the parameters of magnetic field and $v \sin i$ found from the fitting of the Fe II 6149 Å, Pr III 6706.7 Å, and Ca I 6102.7 Å lines. The last value of $v \sin i$ was used for spectra calculations in both lithium lines ranges. The magnetic field parameters from Ca I 6102.7 Å were used for the 6103 Å range and the ones from Pr III 6707.6 Å – for the 6708 Å range.

CONCLUSIONS

- Our research of two roAp stars, HD 83368 and HD 60435 [12], provides an evidence for the enhanced lithium abundance near the magnetic field poles. We can expect similar effects in sharp-lined roAp stars. The high lithium abundance for these stars and the estimates of ^{6}Li/^{7}Li ratio ($0.4 \div 0.5$) can be explained by the Galactic Cosmic Ray (GCR) production due to spallation reactions with ISM in star-forming regions and the preservation of the original ^{6}Li and ^{7}Li by strong magnetic fields of these stars. The values of ^{6}Li/^{7}Li ratio expected from the GCR production are about $0.5 \div 0.8$ [5, 16].
- New laboratory and theoretical gf-values for the REE lines are necessary in order to refine our estimates of the lithium abundance and of the isotopic ratio.

[1] [http://www.umh.ac.be/~astro/dream.shtml]

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[1] *Bi'emont E., Palmeri P., Quinet P.* D.R.E.A.M. Database on Rare Earths at Mons University // [http://www.umh.ac.be/~astro/dream.shtml].

[2] *Cowley C. R., Ryabchikova T., Kupka F., et al.* Abundances in Przybylski's star // Mon. Notic. Roy. Astron. Soc.–**317**, N 1.–P. 299–309.

[3] *Gelbman M., Ryabchikova T., Weiss W., et al.* Abundance analysis of roAp stars. V. HD 166473 // Astron. and Astrophys.–2000.–**356**, N 1.–P. 200–208.

[4] *Khan S.* The code of spectrum synthesis in atmospheres of Ap stars // J. Quant. Spectrosc. and Radiat. Transfer.–2004.–**88**, N 1–3.–P. 71–81.

[5] *Knauth D. C., Federman S. R., Lambert D. L.* An ultra-high-resolution survey of the interstellar $^7Li/^6$Li isotope ratio in the solar neighborhood // Astrophys. J.–2003.–**586**, N 1.–P. 268–285.

[6] *Kupka F., Piskunov N. E., Ryabchikova T. A., et al.* VALD-2: Progress of the Vienna Atomic Line Data Base // Astron. and Astrophys. Suppl. Ser.–1999.–**138**, N 1.–P. 119–133.

[7] *Kurucz R.* Atomic and Molecular Lines Database–1994.–CDROM (1–23).

[8] *Polosukhina N., Kurtz D., Hack M., et al.* Lithium on the surface of cool magnetic CP stars. I. Summary of spectroscopic observations with three telescopes // Astron. and Astrophys.–1999.–**351**, N 1.–P. 283–291.

[9] *Panchuk V. E., Klochkova V. G., Najdenov I. D.* Nasmyth Echelle Spectrometer for BTA // Preprint of the Special Astrophys. Obs.–1999.–N 135.

[10] *Ryabchikova T. A., Landstreet J. D., Gelbmann M. J., et al.* Abundance analysis of roAp stars. III. γ Equulei // Astron. and Astrophys.–1997.–**322**, N 1.–P. 234–241.

[11] *Ryabchikova T., Piskunov N., Savanov I., et al.* EU III identification and EU abundance in CP stars // Astron. and Astrophys.–1999.–**343**, N 1.–P. 229–236.

[12] *Shavrina A. V., Polosukhina N. S., Zverko J., et al.* Lithium on the surface of cool magnetic CP stars. II. Spectrum analysis of HD 83368 and HD 60435 with lithium spots // Astron. and Astrophys.–2001.–**372**, N 2.–P. 571–578.

[13] *Shavrina A. V., Polosukhina N. S., Pavlenko Ya. V., et al.* The spectrum of the roAp star HD 101065 (Przybylski's star) in the Li I 670.8 nm spectral region // Astron. and Astrophys.–2003.–**409**, N 2.–P. 707–717.

[14] *Tsymbal V.* A Software System For the Analysis of the Spectra of Normal Stars // Odessa Astron. Publ.–1994.–**7**, N 1–P. 146.

[15] *Wade G. A., Bagnulo S., Kochukov O., et al.* LTE spectrum synthesis in magnetic stellar atmospheres. The interagreement of three independent polarised radiative transfer codes // Astron. and Astrophys.–2001.-**374**, N 1.–P. 265–279.

[16] *Webber W. R., Lukasiak A., McDonald F. B.* VOYAGER measurements of the charge and isotopic composition of cosmic ray Li, Be, and B nuclei and implications for their production in the Galaxy // Astrophys. J.–2002.–**568**, N 1.–P. 210–215.