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

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Abstract. The lines of lithium at λ 6708Å and λ 6103Å in high-resolution spectra of some sharp-lined rotating roAp stars are analyzed using the three spectral-synthesis codes STARSP, ZEEMAN2, and SYNTHM. The lines from the VALD database were supplemented by lines of rare-earth elements from the DREAM database and new lines calculated using the NIST energy levels. Our synthetic-spectrum calculations take into account magnetic splitting and other line-broadening effects. Lithium overabundances were found in the atmospheres of the stars based on our analysis of both λ 6103 and λ 6708 lithium lines, with high values of the ^{6}Li/^{7}Li isotope ratio (0.2÷0.5). This can be explained if lithium is produced in spallation reactions and the surface ^{6}Li and ^{7}Li is preserved by the strong magnetic fields in the upper layers of the stellar atmospheres, around the poles of the dipole field.

1 INTRODUCTION

In the framework of the project "Lithium in CP stars", a significant series of high resolution (R=100000) spectra was obtained at ESO in 1996 for some rapidly oscillating Ap (roAp) with the strong lithium line 6708Å, which permits us to select 4 groups of these stars on the basis of behaviour of the lithium line 6708Å with rotation phases (Polosukhina et al. 1999, A&A, 351, 283).

The first group of roAp stars shows rotation variations of the lithium line which were explained by inhomogeneous distributions of lithium on the surface of stars (lithium spots). The variations of the Li I 6708Å line profile with rotation phases for two roAp stars (HD 83368 and HD 60435) with a rather high value of $V_e \sin(i)$ were studied in our previous papers (Polosukhina et al., 2000, A&A, 357, 920; Shavrina et al., 2001, A&A, 372, 571; Mashonkina et al., 2002, Astr.Rep., 79, 31).

High lithium abundances in lithium spots near magnetic poles were detected by the direct modelling of synthetic spectra of a rotating star, taking into account blending and magnetic splitting

Table 1: The list of lines used for calculations of spectra in the range 6705.75–6708.75ÅÅ

El	$\lambda, \AA$	E"	$\log gf$	source	el	$\lambda, \AA$	E"	$\log gf$	source
*Dy II	6705.727	2.078	-2.68		*Gd II	6707.462	3.270	-1.98	
Nd II	6705.891	3.269	-2.70		Sm II	6707.473	0.930	-1.48	VALD
Yb II	6705.965	5.856	-3.04	DREAM	Yb II	6707.603	6.651	-1.38	DREAM
Ce II	6706.51	1.840	-0.95	DREAM	*Sm II	6707.648	1.746	-1.27	
Tm II	6706.150	5.322	-1.07	DREAM	Nd II	6707.755	0.170	-3.55	DREAM [Quinet]
Tm II	6706.262	3.955	-2.36	DREAM	^{7} Li I	6707.756	0.000	-0.427	[Smith et al.]
Ce II	6706.307	3.195	-2.40	DREAM	^{7} Li I	6707.768	0.000	-0.206	-"-
Pr III	6706.492	3.104	-1.28		*Sm II	6707.779	2.037	-2.68	
Pr III	6706.705	0.550	-1.64	DREAM	^{7}LI I	6707.907	0.000	-0.932	[Smith et al.]
Nd II	6706.738	2.868	-2.48		^{7}Li I	6707.908	0.000	-1.161	-"-
Sm II	6706.798	1.586	-2.00		^{7}Li I	6707.919	0.000	-0.712	-"-
Sm II	6706.807	1.874	-1.78		^{6}Li I	6707.920	0.000	-0.478	-"-
Tm II	6706.906	4.908	-2.47	DREAM	^{7}Li I	6707.920	0.000	-0.931	-"-
Nd II	6706.922	3.211	-0.88		^{6}Li I	6707.923	0.000	-0.179	-"-
Nd II	6707.015	1.490	-1.88		Nd II	6708.030	1.522	-1.13	DREAM [Quinet]
Nd II	6707.033	2.222	-3.68		^{6}Li I	6708.073	0.000	-0.304	[Smith et al.]
Ce II	6707.121	1.255	-3.76	DREAM	Ce II	6708.077	2.250	-2.57	DREAM
Dy II	6707.153	3.292	-1.27		*Er II	6708.088	3.155	-2.58	
Dy II	6707.266	2.890	-1.28		Ce II	6708.099	0.701	-2.12	DREAM
Sm II	6707.342	0.884	-2.00		*Nd II	6708.400	3.192	-2.48	
Er II	6707.418	3.482	-1.44		*Nd II	6708.458	3.536	-1.08	
Nd II	6707.433	1.499	-2.17		*Nd II	6708.629	0.746	-4.58	
Nd II	6707.453	2.880	-3.18		*Nd II	6708.629	0.746	-4.58	

$^*gf$ - values were estimated by us from best fitting with observed spectrum.

Table 2:

	HD 101065	HD 134214	HD 137949	HD 137949	HD 166473	HD 201601
$T_{eff}/\log g$/[m]	6600/4.2/0	7500/4.0/0	7500/4.5/0	7250/4.5/0	7750/4.0/0	7750/4.0/0
N(Li) 6708Å	3.1	3.9	4.1	3.6	3.6	3.8
N(Li) 6103Å	3.5	4.1	4.4	4.4	4.0	4.0
^{6}Li/^{7}Li 6708Å	0.4:	0.3:	0.2:	0.3:	0.4:	0.5:
$B_r/B_m/B_l$(kG)						
Fe**II** 6149Å	-	-2.9/-1.7/0	4.2/3.3/0	4.2/3.3/0	4.8/4.9/0	3.5/2.6/0.8
Pr **III** I 6706.7Å	0/2.3/0	-2.3/-1.9/0	2.0/5.0/0	1.5/5.0/0	3.0/5.5/0	2.7/3.5/0
CaI 6102Å	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	0.5
$v \sin i$(km s^{-1}),Pr III	3.5	2.0	4.0	4.0	5.0	2.5

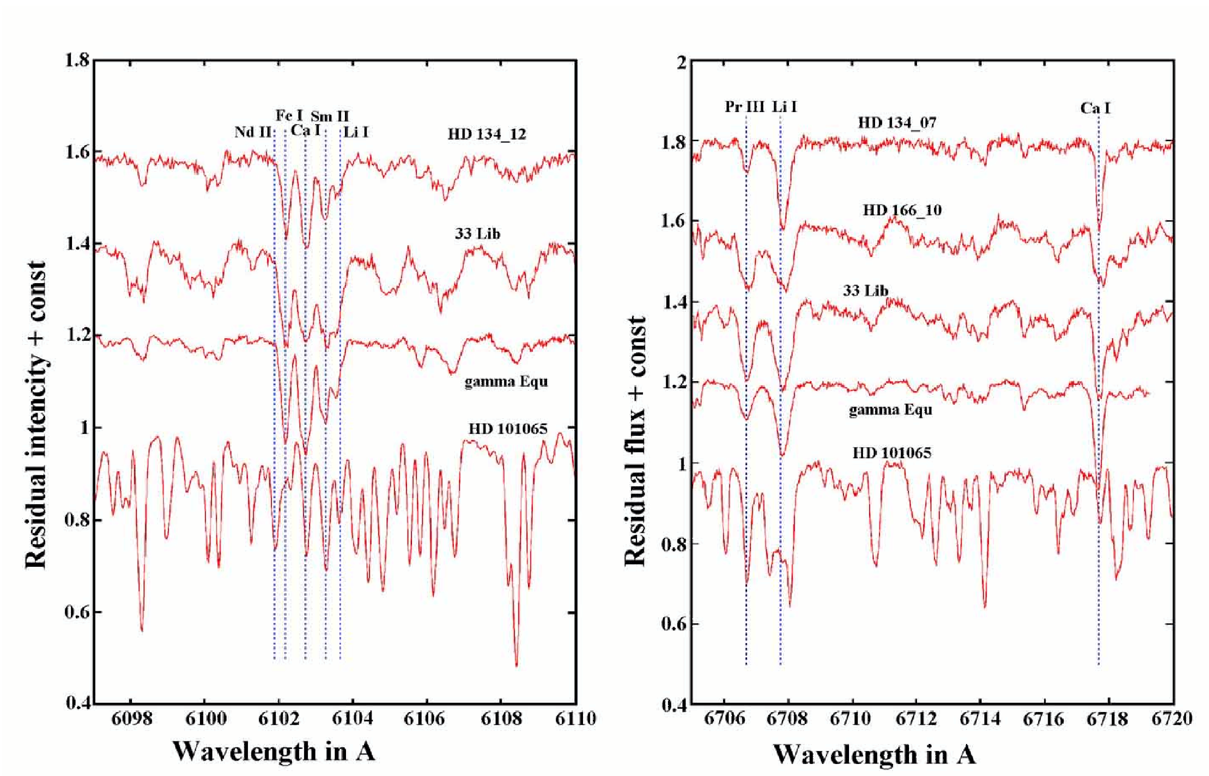

Figure 1: The original spectra of sharp–lined roAP stars: HD 134214, HD 166473, HD 137949 (33 Lib), HD 201601 (γ Equ) and HD 101065 (Przybylski's star) in spectral regions near 6103Å and 6708Å Li lines.

of rare earth element lines.

Another group of roAp stars, sharp-lined stars, show no rotation variability of the lithium line. Analyses of the lithium lines 6708Å and 6103Å in the spectra of 5 sharp-lined roAp stars: 33 Lib (HD 137947), γ Equ (HD 201601), HD 134214, HD 166473, HD 101065 were carried out. All these stars are characterized by sharp lines in their spectra, by strong overabundances of rare earth elements, and by surface magnetic fields from 2 kG to 6.8 kG. The sharp lines in the spectra of these stars result from small $V_e\sin(i)$. For stars with short rotation 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 several years) — γ Equ and 33 Lib — the width of the lines is due to the slow rotation. Some of the stars are therefore observed "pole-on", and an observer always sees one hemisphere of these stars. In this case the spectrum is essentially constant.

2 OBSERVATIONS

The first observational data were obtained at CrAO (ZTSh 2.6 m) and ESO CAT (1995–2001) with spectral resolutions R=50000 and 100000, respectively, for 5 roAP stars: 33 Lib (HD 137947), γ Equ (HD 201601), HD 134214, HD 166473, and HD 101065 in spectral region 6680–6730ÅÅ. The series were supplemented by observations with the 74$''$ telescope (Mount Stromlo Observatory) in October 2001 and FEROS (ESO 2004) and SAO-BTA (6 m) from April 2004 to 2006. The observations with BTA were carried out in Nasmyth focus of the 6 m telescope with the echelle spectrometer "NES" (Panchuk and Klochkova) in spectral region 6000–6800ÅÅ with R=100000 and 40000. The reduction of spectra was performed by D.Kudryavtsev using the reduction package by

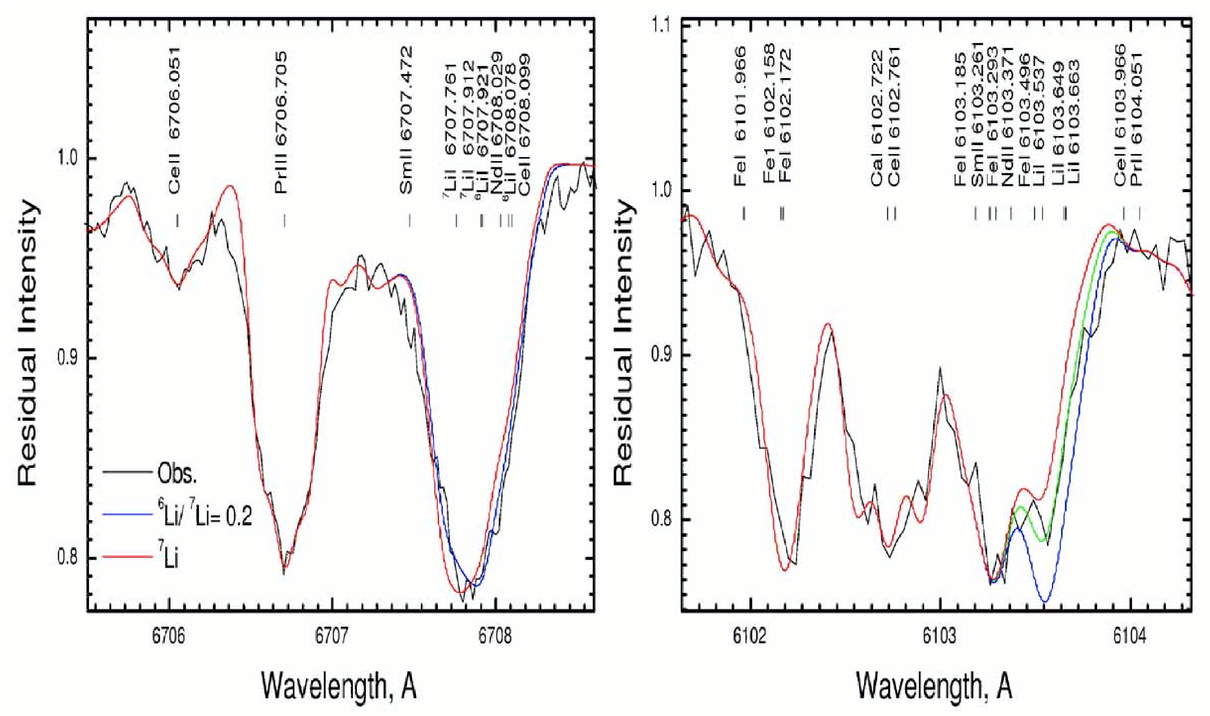

Figure 2: a) The estimation of magnetic field parameters from the lines CeII 6706.051Å and PrIII 6706.705Å for 33 Lib, blue line Br= kG, Bm=5 kG and red line: Br=5 kG, Bm=2 kG, Bl=2 kG; b) FeII 6147Å and 6149Å — Br=2 kG, Bm=5 kG and Bl=0 kG, the same as for PrIII 6706.7Å.

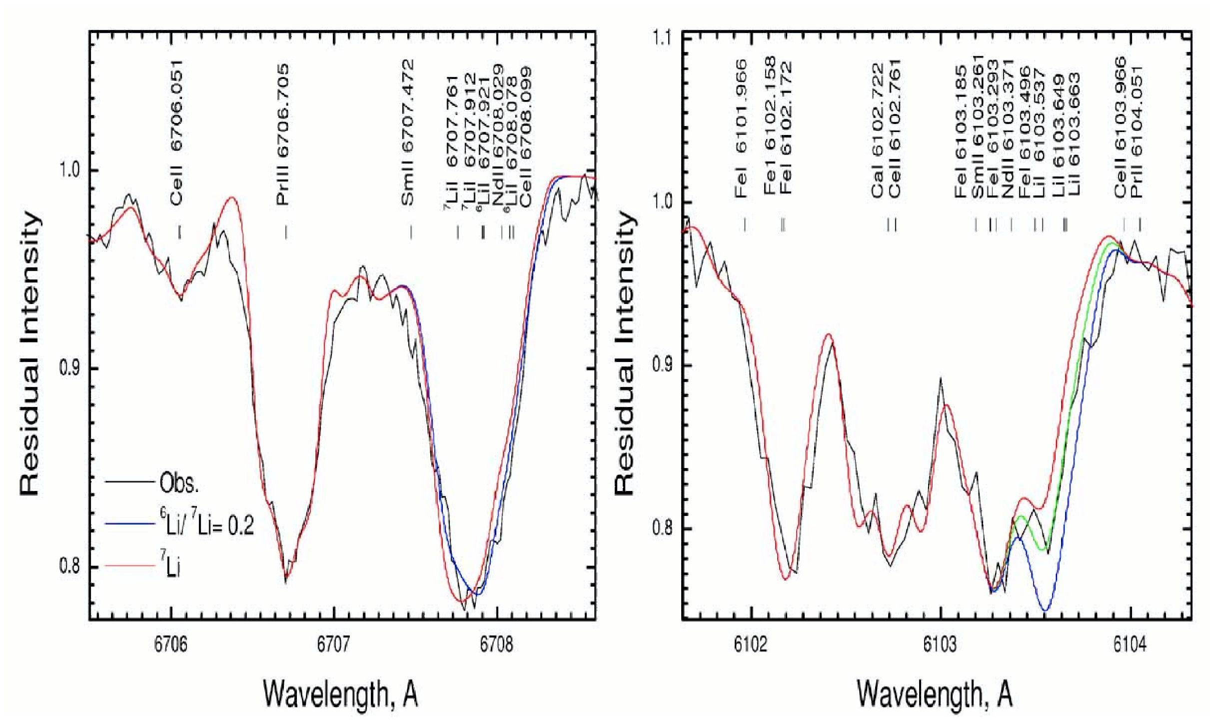

Figure 3: 33 Lib a) LiI 6708Å, blue line $\log N(Li) = -7.95$, $^{6}Li/^{7}Li = 0.2$; red line $\log N(Li) = -7.88$, only ^{7}LiI 6103Å, green line $\log N(Li) = -7.60 \pm 0.3$.

Table 3: The main absorption contributors in the range 6707.60–6708.16ÅÅ

El	λÅ	.60	.62	.64	.66	.68	.70	.72	.74	.76	.78	.80	.82	.84	.86	.88
Sm II	6707.684	6	21	20	20	12	6	2	1							
ND II	6707.755						1	1	2	2	1	1				
^{7}Li I	6707.756	1	2	3	3	4	5	6	7	7	6	6	5	4	2	1
^{7}Li I	6707.768	1	3	4	4	5	7	9	11	11	11	10	9	7	4	3
^{7}Li I	6707.907											1	1	1	1	2
^{7}Li I	6707.908											1	1	1	1	1
^{6}Li I	6707.919										1	1	1	2	2	3
^{7}Li I	6707.920											1	1	1	1	1
^{6}Li I	6707.920											1	1	1	1	1
^{6}Li I	6707.923											1	2	2	2	3
Nd II	6708.029															
^{6}Li I	6708.073															
Ce II	6708.077															
Ce II	6708.099															
El	λÅ	.90	.92	.94	.96	.98	.00	.02	.04	.06	.08	.10	.12	.14	.16	
Sm II	6707.684															
ND II	6707.755															
^{7}Li I	6707.756	1	1													
^{7}Li I	6707.768	2	2	1												
^{7}Li I	6707.907	2	2	2	2	1	1	1								
^{7}Li I	6707.908	1	1	1	1	1	1									
^{6}Li I	6707.919	3	3	3	3	3	2	1	1							
^{7}Li I	6707.920	2	2	2	2	2	1	1								
^{6}Li I	6707.920	2	2	2	2	2	1	1								
^{6}Li I	6707.923	3	3	4	3	3	3	1	1	1						
Nd II	6708.029			2	8	26	62	75	71	55	31	12	3			
^{6}Li I	6708.073			1	1	2	2	2	3	3	4	4	3	2	1	
Ce II	6708.077									1	1	1				
Ce II	6708.099						1	3	8	21	37	46	28	13	5	

(Piskunov N.E. & Valenti J.A., 2002 A&A 385, 1095).

3 ANALYSIS OF OBSERVED AND SYNTHETIC SPECTRA

The stars with strong 6708Å lithium doublets are very poorly studied. We study their spectra in detail in a narrow range near 6708Å and 6103Å, by the method of synthetic spectra, taking into account the Zeeman magnetic splitting and blending by REE lines. The additional broadening, likely pulsation, was described by the parameter $V_e$sin(i). To calculate synthetic spectra, we applied the magnetic spectrum synthesis code SYNTHM (Khan, 2004, JQSRT, 88, N1-3, 71), which is similar to Piskunov's code SYNTHMAG and tested in accordance with the paper by Wade et al., 2001, A&A, 374, 265. For initial calculations we also used the code STARSP of Tsymbal, 1996, ASP Conf. Ser. 108, 198, and in some cases the code ZEEMAN2 (Wade et al., 2001).The simplified model of the magnetic field in the SYNTHM code is characterized by radial (along the radius for each point of the stellar surface), meridional and longitudinal components of the field B_r, B_m, B_l (B_l is always equal to 0, as it is justified for the plane-parallel model atmospheres), which were primarily determined from the Fe II lines 6147Å and 6149Å, Ca I 6102Å, Ce II 6706.05 and Pr III 6706.70Å, (see Table 2).

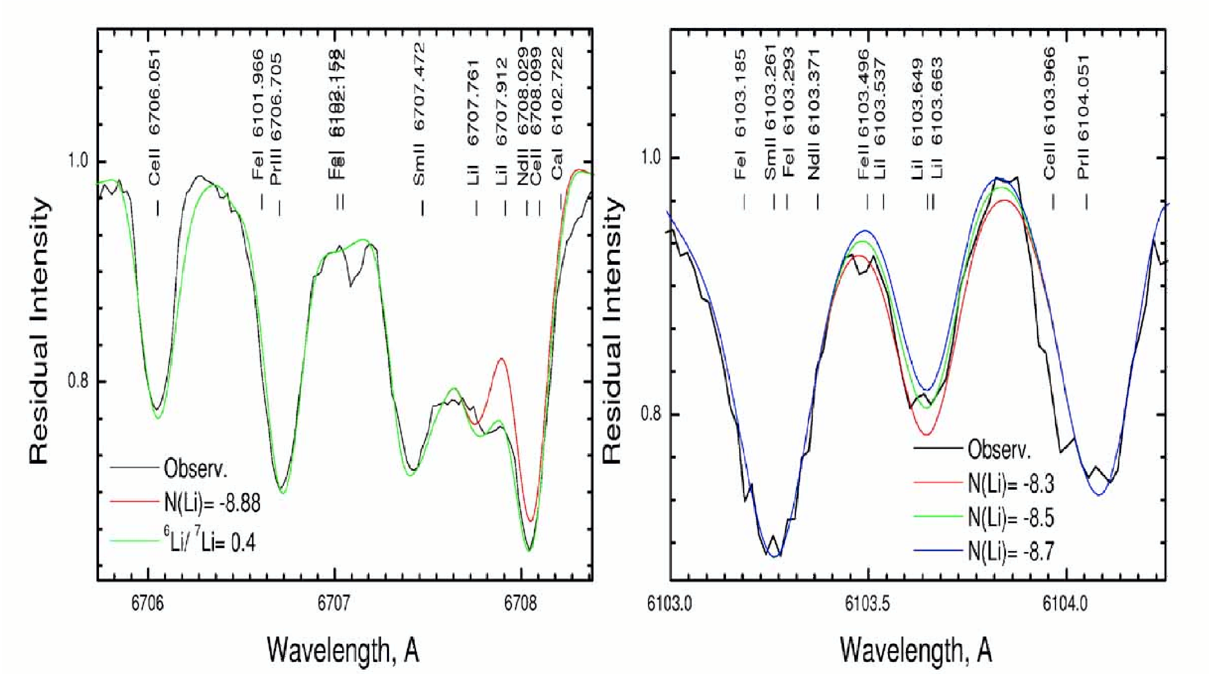

Figure 4: a) HD 101065 fitting of observed and calculated spectra near 6708Å: black — observed spectrum; red line — calculated spectrum taking into account the lines of the main isotope ^{7}Li alone; green line: spectrum with the ratio ^{6}Li/^{7}Li=0.4. The positions of those lines which are the main contributors to absorption are marked at the top of the figure, b) LiI line 6103Å, $N(Li) = -8.50 \pm 0.2$.

4 REE LINES WITH NEW ATOMIC DATA

We used the VALD, (Kupka et al., 1999, A&A, 138, 119) and DREAM (http://www.umh.ac.be/ astro/dream.shtml) databases of atomic spectral line data for calculations of spectra. We also calculated the additional REE II–III lines using NIST energy levels and estimated their "astrophysical" gf-values from the spectra of HD 101065 using elementabundances from Cowley et al. (2000, MNRAS, 317, 299). As well, the theoretical gf-values for important (for the lithium abundance determination) blending lines were especially computed by P.Quinet with Cowan's code (see Shavrina et al., 2003, A&A, 409, 707).

5 RESULTS

Results of the work are presented in Table 2 for all studied sharp-lined stars. The first line gives the HD numbers and the second one gives the parameters of used model atmospheres. The abundances of lithium determined from both 6708Å and 6103Å lines (with an error of 0.1 dex) and the isotopic ratio from the 6708Å line are shown in the table. Parameters of the magnetic field and V*sin(i) found from the fitting of Fe II 6149Å, Pr III 6706.7Å lines are also given. The magnetic field parameters from Ca I 6102.7Å were used in the 6103Å range and those from Pr III 6707.6Å — for the 6708Å range.

HD 101065 is the most unusual and the most peculiar star among roAp-CP stars. The numerous unidentified lines of rare earth elements and strong weakening of the lines of iron group elements complicated the analysis of the atmosphere of HD 101065 during many years and caused discussions concerning the temperature of the star. In the first investigations of the spectrum of HD 101065, Wagner and Petford (PASP 168, 557, 1974) pointed that this star is the coolest Ap-CP star. Fig. 1

with original spectra of CP stars demonstrates that the spectra of HD 101065 differ from those of other CP stars. Using the element abundances from the analysis of spectra of this star of Cowley et al. (MNRAS 317, 299,2000) in the region 3800–6000ÅÅ, we carried out calculations of synthetic spectra for this star in the spectral region 6705.8–6708.7ÅÅ to fit them with the observed spectrum near the lithium line Li I 6708Å. The line lists of VALD and DREAM (for REE lines) databases were used for the analysis. Additional REE lines were calculated on the basis of NIST level energies, and their "astrophysical" gf-values were estimated. The detailed calculations of synthetic spectra taking into account the hyperfine structure of lithium lines, lithium isotopic ratio and blending with rare earth element lines (Ce II, Nd II, Sm II and others) permit estimation of the lithium abundances and lithium isotopic ratio Li^6/Li^7 in the atmosphere of HD 101065.

6 CONCLUSION

The first results of the observations of roAp stars HD 101065, HD 134214 HD 137949, HD 166473,and HD 201601 show:

1. Lithium abundance derived from the Li line 6103Å is more high than that from the line 6708Å;

2. Lithium isotopic ratios slightly differ from one star to another and exceed the isotopic ratio $^6Li/^7Li$ for solar atmosphere and cosmic abundance of this element. Our work on two roAp stars, HD 83368 and HD 60435, 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 high estimates of $^6Li/^7Li$ ratio (0.2–0.5) can be explained by lithium production due to spallation reactions and preservation of both ^6Li and ^7Li by the strong magnetic fields of these stars. The values of the $^6Li/^7Li$ ratio expected from GCR production are about 0.5–0.8 (Knauth, Federman, and Lambert, 2003, ApJ, 586, 268; Webber et al., 2002, ApJ, 568, 1, 210).