Mem. S.A.It. Suppl. Vol. 22, 129
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Memorie della
Supplementi

Lithium in roAp stars with strong magnetic fields

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Abstract. We discuss lithium abundance and ^{6}Li/^{7}Li isotopic ratio in atmospheres of some magnetic roAp stars. Overabundances of the lithium were found in atmospheres of some roAp stars based on the analysis of both lithium lines at 6104 Å and 6708 Å as well as the high values of the ^{6}Li/^{7}Li isotopic ratio (0.2 – 0.5). These facts can be explained by lithium production in spallation reactions on stellar surface and by preserving ^{7}Li and ^{6}Li isotopes to be destroyed in the inner layers of stellar atmospheres by strong magnetic fields near magnetic poles. Our synthetic spectrum calculations take into account magnetic line broadening effects.

Key words. Stars: abundances — stars: chemicaly peculiar — stars: magnetic fields — stars: individual (HD 3980, HD 83368)

1. Introduction

The main cause of Li puzzle is unknown physical process which is responsible for a great spread in lithium abundance for stars with similar physical parameters ($T_{\rm eff}$, $\log g$, M). The strongest Li feature in stellar spectrum, the lithium resonance doublet at 6708 Å (χ=5.39 eV), is very sensitive to evolutional changes, to temperature regime and conditions of mixing. Usually, lithium is depleted with stellar age. The presence of the Li I line at 6708 Å in stellar spectrum is an indication of youth of a star, or a breaking of mixing between external (cool) and internal (hot) layers of stellar atmosphere, or an indication of active processes with eventual lithium synthesis (Herbig 1964, 1965).

The presence of magnetic field can be one of the conditions for Li synthesis. An influence of the surface activity connected with magnetic field structure on the Li lines profiles is a problem under discussion for the late type chromospherically active Li-rich giants. Attempts to detect spots and rotational modulation with photometric variations gave contradictory results (Pallavicini et al. 1993).

Since the discovery of the first Li-rich K giant (Wallerstein & Sneden 1982) the stars with high Li abundance became a puzzle, since efficient Li dilution is expected to occur during the first dredge-up. Different mechanisms were proposed to explain the high Li abundance on the surface of K giant stars, however the detailed discussion of the mechanisms is out of scope of this paper (see, e.g., Kumar et al. 2011, Monaco et al. 2011 and references therein).

Lambert & Sawyer (1984) suggested that Li-rich giants may be the "descendants" of one or more classes of chemically peculiar magnetic stars, i.e. there is an evolutional connection between magnetic A-type (Ap) stars with high Li abundance and Li-rich red giants.

The correlation between rapid rotation, mass loss, as measured by the far-IR excess and an asymmetric Hα line, and a high Li abundance was discussed in Drake et al. (2002). It was found that among rapidly rotating ($v \sin i \geq 8$ km s^{-1}) K giants, a very large proportion ($\sim 50\%$) are Li-rich giants. This proportion is in contrast with a very low proportion ($\sim 2\%$) of Li-rich stars among the much more common slowly rotating K giants.

The first surface magnetic field in a rapidly rotating active Li-rich giant was detected by Lèbre et al. (2009). These authors showed that the G8 II giant HD 232862 has high Li abundance ($A_{\rm Li} = 2.45$) and variable $B_{\rm l}$ value.

1.1. Lithium in CP-Ap stars

Chemically peculiar (CP2) stars are the stars of the spectral type A having anomalous chemical abundances and strong magnetic fields with a large-scale structure. The lithium problem in Ap-CP2 stars has been, for a long time, a subject of debate. Individual characteristics of CP2 stars, such as a high abundance of the rare-earth elements (REE), presence of strong magnetic fields, complicated surface distribution of chemical elements, rapid oscillations of some CP stars, make a task to detect the lithium lines and to determine the lithium abundance very difficult.

Rapidly oscillating Ap (roAp) stars are a subgroup of magnetic Ap stars that oscillate with non-radial, low-order acoustic p-modes with the axis oscillation aligned with the axis of the magnetic field (Kurtz 1982). The amplitudes and phases of oscillations in roAp stars change with stellar rotation. These changes are interpreted in the framework of oblique pulsator model (Shibahashi & Takata 1993).

The study of radial velocity behavior in roAp stars leads to understanding that individual lines of different elements show different behavior, and these variations of radial velocity (RV) are individual for each roAp star. In various papers it has been shown that the lines of REE Pr III and Nd III have large amplitudes of RV variations as compared to the lines of the iron group (having very small variations) (Kochukhov & Ryabchikova 2001, Kochukhov et al. 2002). Ryabchikova et al. (2002) showed that pulsation amplitudes change as a function of the line formation depth.

2. Rapidly-rotating Ap-CP2 stars ($v \sin i > 10$ km s^{-1})

The most important result of the spectral observations of roAp stars was the discovery of a variability of the profile of the Li I 6708 Å line with the rotation phase in the spectra of two roAp stars HD 83368 and HD 3980 (Polosukhina et al. 1999, 2003, Drake et al. 2004).

The Doppler shift of the Li I line in the spectra of HD 83368 ($v \sin i = 27.6 \pm 2.1$ km s^{-1}) and HD 3980 ($v \sin i = 22.5 \pm 2.0$ km s^{-1}) is the result of the rotation modulation of the spotted stellar surface. We have also shown that Li spots are situated near the magnetic poles of the stellar magnetic field.

Highly important was also a discovery of synchronous variations of the Li I 6708 Å line position, magnetic field strength $H_{\rm eff}$, and stellar luminosity (see Figs. 1 - 3 in Polosukhina et al. 2000 and Fig. 4 in Drake et al. 2004, respectively). This was explained in terms of the oblique rotator model (Polosukhina et al. 2000). Good correlation between Li regions, magnetic field variations and oscillations (HD 83368) point to connection between magnetic field configuration and Li local structure of star's atmosphere.

The relative contributions of Li, Ce, Nd, and Sm to the absorption feature at 6708 Å in the spectrum of HD 3980 and a few other Ap stars with different effective temperatures and different strengths of the magnetic field was estimated in Drake et al. (2005). We have shown that the spectral feature at 6708 Å in the spectrum of HD 3980 is due to the Li I doublet with only a minor contribution of the Ce II line at 6708.099 Å.

2.1. Lithium Doppler imaging of HD 83368 and HD 3980

Very inhomogeneous distribution of the Li abundance on the surfaces of HD 83368 and HD 3980 was confirmed using the Doppler Imaging code INVERS12. The surface distribution of lithium for HD 83368 was reconstructed by Kochukhov et al. (2004) using 21 rotation phases of the FEROS (at 1.52 m ESO telescope) and CAT/CES (at 3.6 m ESO telescope) spectra. The results of Doppler mapping generally confirm the Li map inferred by Polosukhina et al. (2000). Kochukhov et al. (2004) found also that Li is strongly concentrated at the magnetic poles, with $R_{\rm spot}$ = 15 – 20°, and has very high abundance, $\log(N_{\rm Li}/N_{\rm tot}) = -5.0$ (Fig. 3).

Nesvacil et al. (2012) using forty-six phases have reconstruct the abundance variations of Li on the surface of HD 3980. It was shown that lithium is concentrated in the areas of the magnetic poles and depleted in the regions around the magnetic equator. The enhancements of Li at the magnetic poles have an overabundance of about 3 dex relative to the initial cosmic abundance (Fig. 4).

3. Sharp-lined roAp-CP stars ($v \sin i < 10$ km s^{-1})

The stars HD 101065, HD 134214, HD 166473 are low-velocity rotators ($v \sin i < 10$ km s^{-1}). They have spectra rich in REE lines and strong magnetic fields (1500 – 5000 G). The recently obtained spectra of these stars confirmed the results obtained earlier and did not show any rotational variability of the strong Li I 6708 Å line. Lithium abundance and ^{6}Li/^{7}Li ratio for these stars were estimated by Shavrina et al. (2006).

3.1. HD 101065 (an example of the most peculiar roAp star)

The presence of the lithium in the spectrum of this unique star was for the first time mentioned by Przybylski (1961), and this remark was noticed by Warner (1966) who made additional observations of this star at the Radcliffe Observatory, using the 74” reflector, in the spectral range 3770 – 6880 Å (dispersion 6 Å/mm). He found very strong lines of singly ionized REE in the region 5500 – 6880 Å, the relative intensities of which were similar to the laboratory intensities from the tables of Meggers et al. (1961).

However, as mentioned by Przybylski (1966), the line of Sm II at 6707.45 Å can be considered only as a part of the lithium blend, and the main contribution to this blend remains to be the resonant lithium doublet at 6708 Å. The first estimation of the lithium abundance relative to the solar value was made by Warner (1966): [Li/H]=2.4 dex. This author also mentioned the probable presence of the ^{6}Li.

We have carried out detailed calculations of the blend at 6708 Å (6705.75 – 6708.75 Å) using the atomic data of the REE from the DREAM and VALD databases (Shavrina et al. 2003). The evidence for the presence of lithium in the spectrum of HD 101065 is very strong, as shown by the excellent fit of observed and synthetic spectra which include the Li lines, while the synthetic spectra without lithium (only REE lines, Sm II 6707.799 Å) clearly fail to achieve a good fit. All possible transitions between REE low energy levels of NIST were included in the line list for synthetic spectra calculations.

3.2. HD 50635

We calculated synthetic spectra for HD 50635, the young F0p star (Trilling et al. 2007), with Kurucz atmosphere model 7250/4.0, $v \sin i$ = 8.0 km s^{-1} and $V_{\rm macro}$ = 3 km s^{-1} (atmospheric parameters were taken from Trilling et al. 2007). We have determined preliminary value of the lithium abundance $\log N({\rm Li})$=2.60 (in the scale $\log N({\rm H})$=12) and the isotopic ratio ^{6}Li/^{7}Li=0.8 (see Fig. 6). However, Trilling et

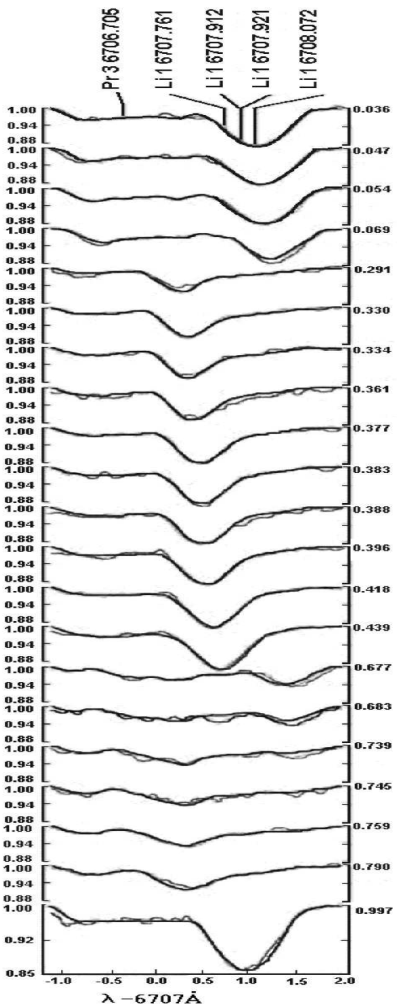

Fig. 1. Observed and computed profiles of the blend at 6708 Å with the resonance Li i doublet vs rotation phases for HD 83368 (Kochukhov et al. 2004).

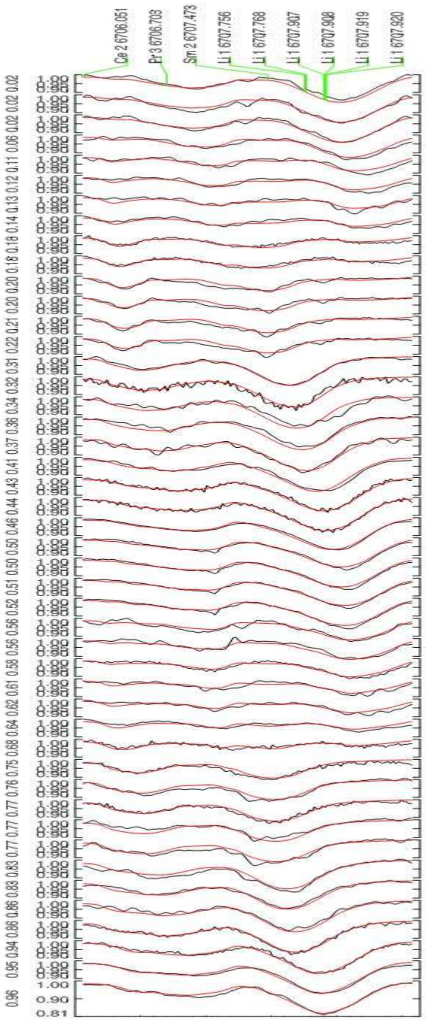

Fig. 2. Observed and computed profiles of the blend at 6708Å with the resonance Li i doublet vs rotation phases for HD 3980 (Nesvacil et al. 2012).

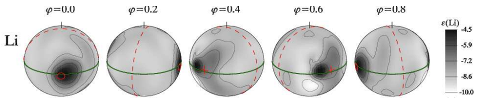

Fig. 3. Abundance distribution of Li at the surface of HD 83368. $T_{\rm eff}$ = 7650 ± 150 K, log g = 4.20 ± 0.20, $v \sin i$ = 27.6 ± 2.1 km s^{-1}, $P_{\rm rot}$ = 2.8520$^{\rm d}$ ± 0.0005, i = 68°, β = 87°, $B_{\rm p}$ = 2.5 kG (Kochukhov et al. 2004).

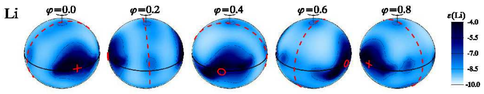

Fig. 4. Abundance distribution of Li at the surface of HD 3980. $T_{\rm eff}$ = 8300±250 K, log g =4.0 ± 0.20, $v \sin i$ = 22.5±2.0 km s^{-1}, $P_{\rm rot}$ = 3.9516$^{\rm d}$±0.0003, i = 60°, β = 88°, $B_{\rm p}$ = 6.9 kG (Nesvacil et al. 2012).

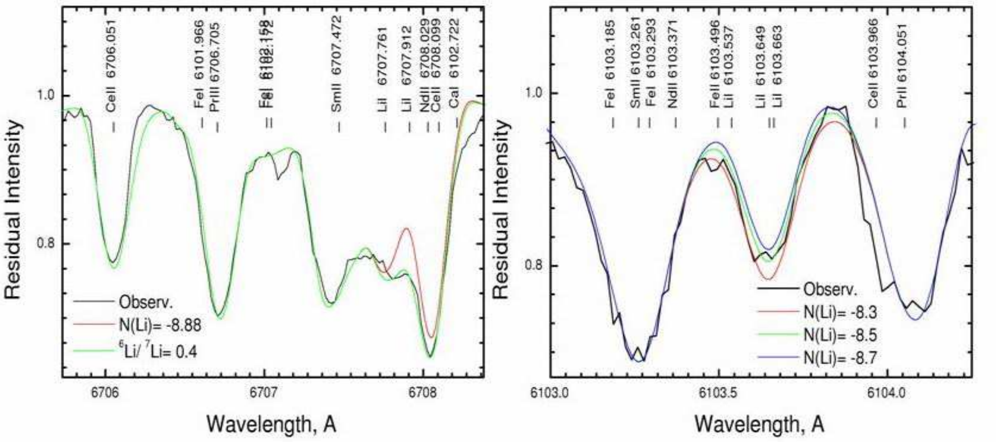

Fig. 5. HD 101065. a) Fitting of observed and calculated spectra near the Li I 6708 Å line: *black line* - observed spectrum; *red line*: spectrum calculated taking into account only the main ^{7}Li isotope; *green line*: spectrum calculated with the isotopic ratio ^{6}Li/^{7}Li=0.4. The positions of those lines which are the main contributors in absorption are marked at the top of the figure. b) The same but for Li I line at 6104 Å.

Table 1. Li abundance, ^{6}Li/^{7}Li isotopic ratio and surface magnetic field. We could suppose a correlation between the value of the surface magnetic field B_s and the ^{6}Li/^{7}Li isotopic ratio

	HD 101065	HD 134214	HD 137949	HD 137949	HD 166473	HD 201601
$T_{\rm eff}$/log g	6600/4.2	7500/4.0	7750/4.5	7250/4.5	7750/4.0	7750/4.0
N(Li) 6708 Å	3.1	3.9	4.1	3.6	3.6	3.8
N(Li) 6104 Å	3.5	4.1	4.4	4.4	4.0	4.0
^{6}Li/^{7}Li 6708 Å	0.4 :	0.3 :	0.2 :	0.3 :	0.4 :	0.5 :
B_s, kG (Pr III)	2.3	3.0	5.4	5.2	6.8	4.4
B_s, kG (Li I 6708 Å)					9.8	
$v \sin i$ (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

al. (2007) analyzing chromospheric activity of this star concluded that the spectral type F0 V may be too early for chromospheric activity, so a likely scenario is the presence of an active late-type dwarf companion. The detailed analysis of HD 50635 taking into account eventual composite nature of its spectrum is needed to derive a reliable value of the ^{6}Li/^{7}Li isotopic ratio.

3.3. ^{6}Li/^{7}Li isotopic ratio in cosmic rays

Aguilar et al. (2011) present measurements of the isotopic ratios ^{3}He/^{4}He, ^{6}Li/^{7}Li, ^{7}Be/(^{9}Be+^{10}Be) and ^{10}Be/^{11}Be in the range 0.2 - 1.4 GeV of kinetic energy per nucleon. The measurements are based on the data collected by the Alpha Magnetic Spectrometer,

Table 2. Main absorption contributors in the range 6707.60 – 6708.16 Å.

El	λ,Å	.60	.62	.64	.66	.68	.70	.72	.74	.76	.78	.80	.82	.84	.86	.88	.90	.92	.94	.96	.98	.00	.02	.04	.06	.08	.10	.12	.14	.16
Sm II	6707.648	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	1	1												
^{7}Li I	6707.768	1	3	4	4	5	7	9	11	11	11	10	9	7	4	3	2	2	1											
^{7}Li I	6707.907											1	1	1	1	2	2	2	2	2	1	1	1							
^{7}Li I	6707.908											1	1	1	1	1	1	1	1	1	1	1								
^{6}Li I	6707.919										1	1	1	2	2	3	3	3	3	3	3	2	1	1						
^{7}Li I	6707.920											1	1	1	1	1	2	2	2	2	2	1	1							
^{6}Li I	6707.920											1	1	1	1	2	2	2	2	2	2	1	1							
^{6}Li I	6707.923											1	2	2	2	3	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

AMS-01, during the STS-91 flight in June, 1998, a period of relatively quiet solar activity, at an altitude of ~380 km, free from atmospheric induced background. The high value of the ^{6}Li/^{7}Li isotopic ratio was obtained: ^{6}Li/^{7}Li = 0.951 ± 0.086.

4. Conclusions

Two main explanations of chemical peculiarities of Ap stars were proposed: nucleosynthesis and gravitational and ambipolar diffusion (Babel & Michaud 1991).

The vertical magnetic field could affect diffusion process, and it is strengthened on the magnetic poles. It also explains the enhanced abundances of some elements (ions) in polar regions. The ambipolar diffusion will render the greatest effect on light elements, and especially on lithium.

The most important result of International collaboration was the discovery of the profile variability of the Li I 6708 Å line with the rotation phase in the spectra of two roAp stars HD 83368 and HD 3980.

The Doppler shift of the Li I line in the spectra of HD 83368 ($v \sin i$ = 27.6±2.1 km s^{-1}) and HD 3980 ($v \sin i$ = 22.5±2.0 km s^{-1}) is the result of rotational modulation of the lithium spotted stellar surface. It was shown also that Li spots are situated near the magnetic poles of the dipole magnetic field (Polosukhina et al. 1999, 2000; Kochukhov et al. 2004; Drake et al. 2004, Nesvacil et al. 2012).

The high lithium abundance can be explained by physical processes which prevent the mixing in the stellar atmosphere and maintain its high initial abundance due to suppression of convective motions by strong magnetic fields and an action of the ambipolar diffusion.

The place where a nuclear synthesis could occur is a stellar surface near polar regions of magnetic field. High lithium abundance may be produced in CP2 stars with strong magnetic fields by spallation reactions in the regions of the magnetic poles, where accelerated protons and α-particles destroy CNO nucleus and produce lithium (Goriely 2007). However, the Li problem in Ap and K giant stars remains still unresolved. The stars with similar physical parameters show a great spread in a Li abundance, posing many interesting questions for the theoretical studies of diffusion mecha-

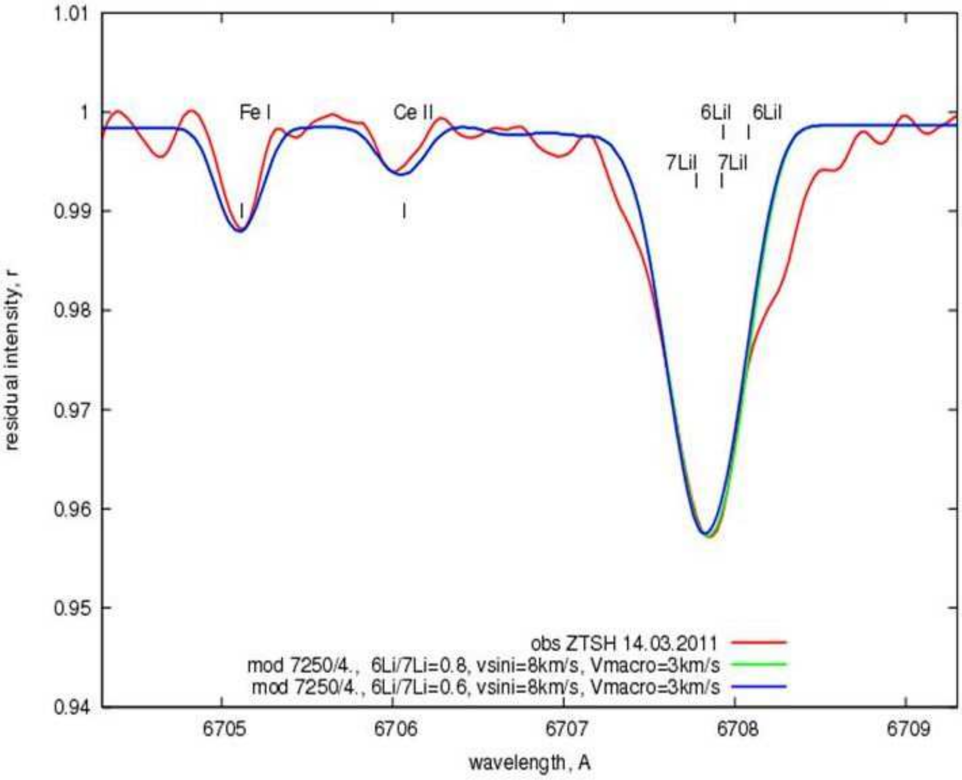

Fig. 6. HD 50635. We show the fit of the observed spectrum obtained with the ZTSh 2.6 m telescope at CrAO (March 14, 2011) and calculated spectra for two values of the lithium isotopic ratio: ^{6}Li/^{7}Li=0.8 (adopted, green line) and 0.6 (blue line).

nisms and spallation reactions in the presence of magnetic fields.

Acknowledgements. N.A.D. thanks support of the Saint Petersburg State University, Russia, under the Project 6.38.73.2011. We acknowledge the use of electronic databases (NIST, VALD, SIMBAD, NASA/ADS).

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