Magnetic Stars, 2011, pp. 374 – 381

New Results of Spectral Observations of CP Stars in the Li I 6708 Å Spectral Region with the 6–m BTA Telescope

Polosukhina N.[1], **Shavrina A.**[2], **Drake N.**[3], **Kudryavtsev D.**[4], **Smirnova M.**[1]

[1] Crimean Astrophysical Observatory, Ukraine
[2] Main Astronomical Observatory of NAS of Ukraine, Kyiv, Ukraine
[3] Soboles Astronomical Institute, St. Petersburg State University, Russia
[4] Special Astrophysical Observatory, Nizhny Arkhyz, Russia

Abstract. The lithium problem in Ap–CP stars has for a long time been a subject of debates. Individual characteristics of CP stars, such as a high abundance of rare–earth elements, the presence of magnetic fields, complex structures of the surface distribution of chemical elements, rapid oscillations of some CP stars, make the detection of lithium lines, and determination of lithium abundance a challenging task. The lithium problem in Ap–CP stars was discussed during the meeting in Slovakia in 1996. The results of the Li study, carried out in CrAO (Polosukhina, 1973 – 1976), the works of Faraggiana & Hack (1963), Wallerstein & Hack (1964), Faraggiana et al. (1992 – 1996) formed the basis of the international project, called Lithium in the Cool CP Stars with Magnetic Fields. The main goal of the project was, using systematical observations of Ap–CP stars with phase rotation in the spectral regions of the resonance doublet Li I 6708 Å and subordinate 6104 Å lithium lines with different telescopes, to create a database, which will permit to explain the physical origin of the anomalous Li abundance in the atmospheres of these stars.

Key words: spectra – lithium – magnetic stars

1 The First Results of Observations in the Framework of International Project Lithium in Cool CP Stars with Magnetic Fields

- The first observations of Ap–CP stars in the framework of the International Project showed abnormally high Li abundances for some of these stars, as well as a different behavior of the Li doublet with stellar rotation.
- The most important result of the observations was the discovery of the profile variability of the Li I 6708 Å line with rotation phase in the spectra of two southern roAp stars HD 83368 and HD 60435 (North et al., 1998).
- The Doppler shift of the Li I line in the spectrum of HD 83368 is about 0.7 Å ($v \sin i = \pm 27.6$ km/s) and is a result of rotation — the modulation of the spotted stellar surface. We have also shown that Li spots are situated near the magnetic poles of the stellar magnetic field (Polosukhina et al., 1999)

2 BTA Program for Lithium Observations and Data Treatment

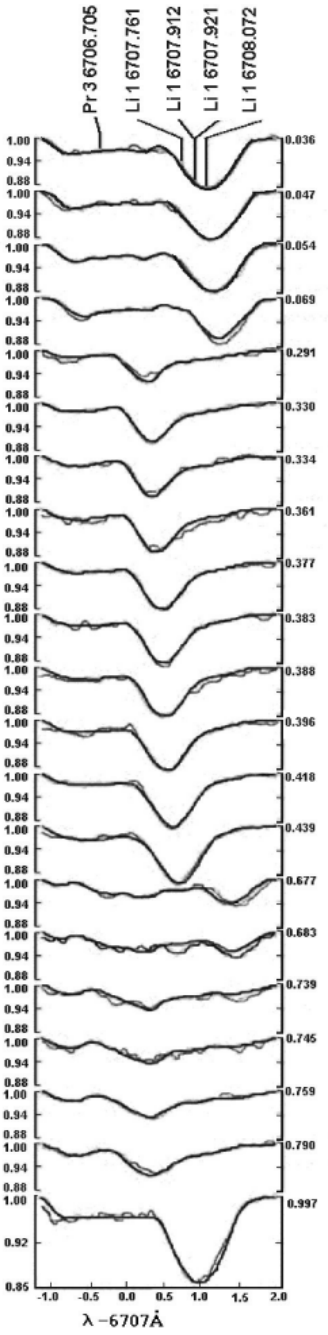

Figure 1: Observed and computed profiles of Li I 6708 Å with rotational phases for HD 83368

We continue our Lithium research using the BTA observations. The program of Li observations, which was set up on the 6–m BTA telescope of the Special Astrophysical Observatory, Russia, had the following objectives:

1. Pilot observations in the search of the Li I 6708 Å line in the spectra of selected CP stars;
2. Observations of slowly–rotating roAp stars (with sharp lines, $v \sin i \leq 10$ km/s);
3. Monitoring of rapidly rotating roAp stars ($v \sin i \geq 10$ km/s) in order to study the Li I 6708 Å line behavior with the rotation phase, and look for the CP stars with "Li spots";
4. Identification of weak REE lines in the region of the Li I 6708 Å line in the spectra of slowly–rotating CP stars;
5. Determination of the Li abundance using resonance Li I 6708 Å and subordinate Li I 6104 Å lines, accounting for the magnetic field effects;
6. Determination of the isotope ratio ^{6}Li/^{7}Li using the Li I 6708 Å line.

3 Observations and Data Treatment

For the reduction of the obtained spectra we used the REDUCE package (Piskunov & Valenti, 2002).

1. Test observations permitted us to discover some new stars with the detectable Li I 6708 Å line: HD 62140, HD 65339, HD 176232, HD 107612, HD 149822, HD 169842. Some of these stars have short rotational periods, and we are planing to carry out spectral monitoring of these objects in order to study the behavior of the Li I line with stellar rotation.
2. roAp–CP stars with sharp lines. The stars 33 Lib, HD 134214, HD 166473 are low rotors ($v \sin i \leq 10$ km/s). They have spectra, rich in REE lines, and strong magnetic fields (1500 – 5000 G). The spectra of these stars confirmed the earlier obtained results and did not show any rotational variability of the strong Li I 6708 Å line.
3. Rapidly–rotating Ap–CP stars ($v \sin i > 10$ km/s): HD 65339, HD 169842, HD 12098. Among these stars, HD 12098 deserves a special attention. In the spectrum of this star we detected a strong and variable Li I 6708 Å, indicating that Li spots must exist on the surface of this star, which is the first roAp star, discovered on the northern hemisphere. The quantitative analysis of this star is presented in (Shavrina et al., 2008) (see also Polosukhina et al., 2010).

4 Variability Spectra (Dispersograms)

We used the method of dispersograms for the detection of variable details in the stellar spectra. In order to present more clearly the variability of the spectrum, we calculated the spectrum of "variability" (Malanushenco et al, 1992) as a value of the dispersion of intensity in each wavelength I_i from the mean intensity value I_{mean},

$$\sigma_{obs} = \frac{1}{I_{mean}} \sqrt{\frac{\sum (I_i - I_{mean})^2}{n-1}} \tag{1}$$

where I_i is intensity of the spectrum at selected wavelengths (i), I_{mean} is the mean value of the intensity at the corresponding wavelengths, n — the number of observed spectra. In Fig. 6 we present examples of the dispersograms for the slowly–rotating stars with an invariable Li I 6708 Å line: HD 134214, HD 166473, and 33 Lib.

5 Analysis of the Observed and Synthetic Spectra

The stars with strong 6708 Å lithium doublets are very poorly studied. We study their spectra in detail in a narrow range near 6708 Å and 6103 Å, using the method of synthetic spectra, taking into account the Zeeman magnetic splitting and blending by REE lines. To calculate the synthetic spectra we applied the magnetic spectrum synthesis code SYNTHM (Khan, 2004), which is similar to Piskunov's SYNTHMAG code. We also used the STARSP code by Tsymbal (1996).

– Analyses of the lithium 6708 Å and 6103 Å lines in the spectra of these sharp–lined roAp stars were carried out. All the stars are characterized by a strong overabundance of REE and by the surface magnetic fields from 2 kG to 6.8 kG (Shavrina et al., 2004)

– For the stars with long periods (some years), for example 33 Lib. Some stars are observed "pole–on", where one hemisphere is visible (the spectrum is constant).

– Results of modeling, observed and calculated 6708 Å Li I line profiles for stars HD 83368, HD 60435 and HD 12098 (Shavrina et al., 2007, 2001):

HD 83368 for $i = 90°$, $v_e = 35$ km/s, and lithium abundance in the photosphere $\log \varepsilon(\mathrm{Li}) = 1.8$

Spots 1: $l_1 = 173° \pm 6°$, $\varphi_1 = 0° \pm 6°$, $R_1 = 33° \pm 6°$, $\log \varepsilon_1(\mathrm{Li}) = 3.6 \pm 0.2$

Spots 2: $l_2 = 337° \pm 6°$, $\varphi_2 = 0° \pm 6°$, $R_2 = 35° \pm 6°$, $\log \varepsilon_2(\mathrm{Li}) = 3.5 \pm 0.2$

HD 60435 for $i = 47°$ (133°), $v_e = 15$ km/s, and lithium abundance in the photosphere $\log \varepsilon(\mathrm{Li}) = 1.8$

Spots 1: $l_1 = 11° \pm 6°$, $\varphi_1 = -15° \pm 6°$, $R_1 = 44° \pm 3°$, $\log \varepsilon_1(\mathrm{Li}) = 3.8 \pm 0.2$

Spots 2: $l_2 = 205° \pm 10°$, $\varphi_2 = 15° \pm 6°$, $R_2 = 40° \pm 7°$, $\log \varepsilon_2(\mathrm{Li}) = 2.7 \pm 0.2$

HD 12098

Spot 1: $l_1 = 30°$, $\varphi_1 = -20°$, $R_1 = 40°$, $\log \varepsilon_1(\mathrm{Li}) = 5.0$

Spot 2: $l_2 = 180°$, $\varphi_2 = 25°$, $R_2 = 70°$, $\log \varepsilon_2(\mathrm{Li}) = 4.2$

Spot 3: $l_3 = 290°$, $\varphi_3 = -20°$, $R_3 = 40°$, $\log \varepsilon_3(\mathrm{Li}) = 4.4$

Table 1: Lithium abundance in sharp–lined roAp–CP stars

	HD 101065	HD 134214	HD 137949	HD 137949	HD 166473	HD 201601
$T_{eff}/\log g$	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	3.3	3.8
N(Li) 6103 Å	3.5	4.1	4.4	4.4	4.0	4.0
^{6}Li/^{7}Li	0.4	0.3	0.2	0.3	0.4	0.5

6 Conclusions

The analysis of the spectra of roAp–CP stars in the 6708 Å region shows that Li doublet is the main contributor.

– The dispersograms clearly show a different behavior of the lithium line in the spectra of slowly and rapidly rotating roAp–Cp stars.

– The dispersograms obtained for HD 12098 and the "Li–spotted" stars HD 83368 and HD 60435 clearly show the variability of their spectra in the region of the Li I line 6708 Å. The dispersograms also show that the amplitude of intensity variations of the Li line is sufficiently higher than that of the lines of the rare–earth elements Nd III, Pr III, Ce II etc. This fact is an additional evidence that the blend at 6708 Å belongs to the lithium.

– The observations of CP stars with the 6–m BTA telescope confirmed a non–variability of the Li I 6708 Å line in the spectra of slowly rotating stars in comparison to the spectra, observed at ESO in 1996. Analysis of the observed and synthetic spectra for the sharp–lined stars HD 134214, 33 Lib, HD 166473 is shown in Table 1.

– The lithium abundance, derived from the secondary Li I 6104 Å line is slightly higher than that derived from the resonance Li I 6708 Å line for all stars of this group.

– The lithium isotopic ratio (^{6}Li/^{7}Li) differs slightly from one star to another, and is higher than ^{6}Li/^{7}Li ratio in the solar atmosphere and in the interstellar medium.

– The observations of HD 12098 with the 6–m BTA telescope in the Li I 6708 Å region revealed strong variations of this line, testifying that one more Ap–Cp star with Li spots was discovered. Figure 5 clearly demonstrates an identical behavior of the spectra of HD 12098 and HD 60435 (HD 60435 is a classical roAp star with Li spots on magnetic poles).

– The creation of a database of observational data in the region of Li lines is very important for the studies of CP stars, and our new results on lithium abundances in Ap–CP stars, as well as their interpretation, open new perspectives in the research of the physical nature of these stars.

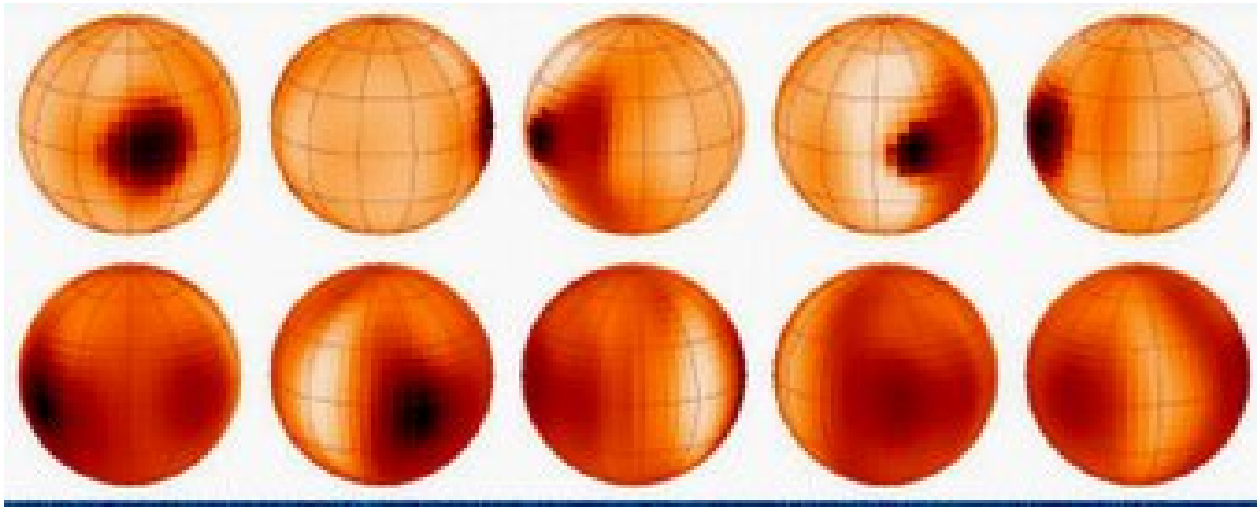

Figure 2: The test D.I. of Li 6708 Å blend (using observations of the CAT and FEROS telescopes) was made assuming that it consists only of Li I and Pr III (Kochukhov et al., 2004)

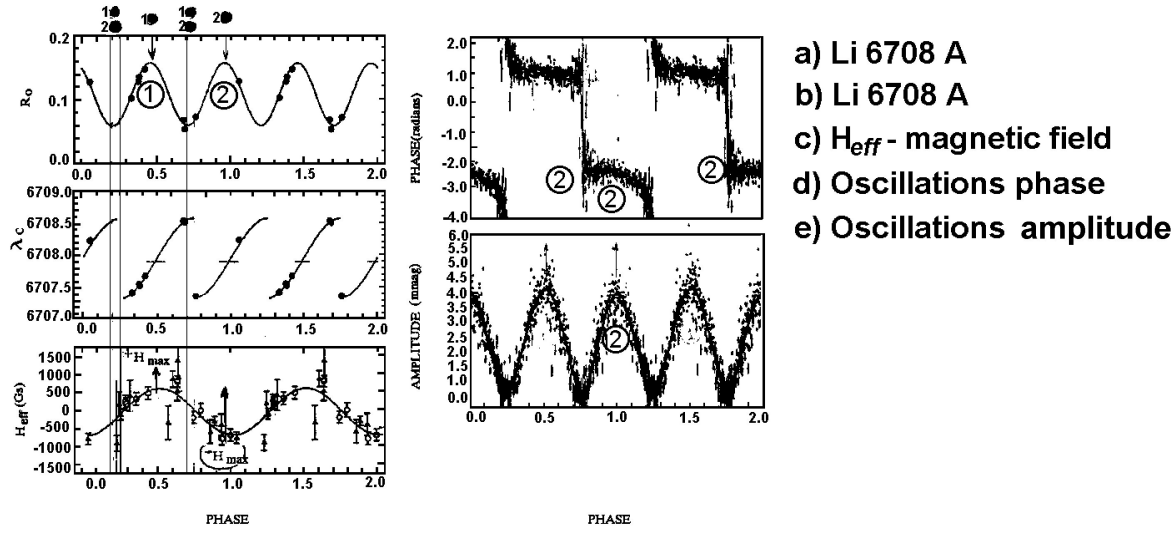

Figure 3: Observations of HD 83368 obtained in the ESO

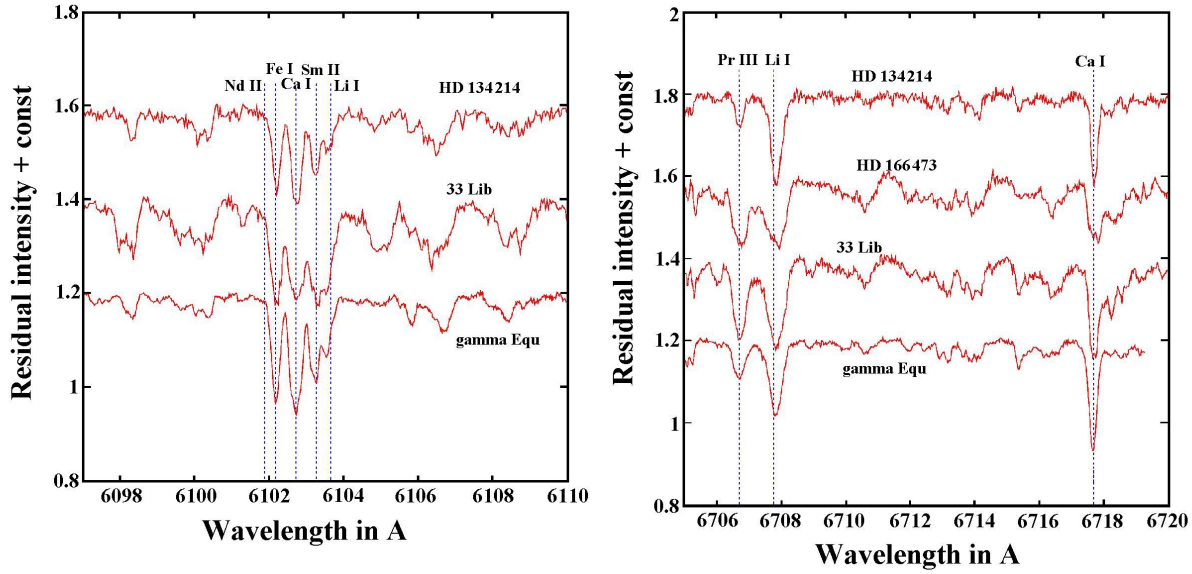

Figure 4: Spectra of sharp–lined stars having high lithium abundances, obtained using both lithium lines: Li I 6708 Å and Li I 6104 Å. It is important to note that the higher Li abundance was obtained using the Li I 6104 Å line.

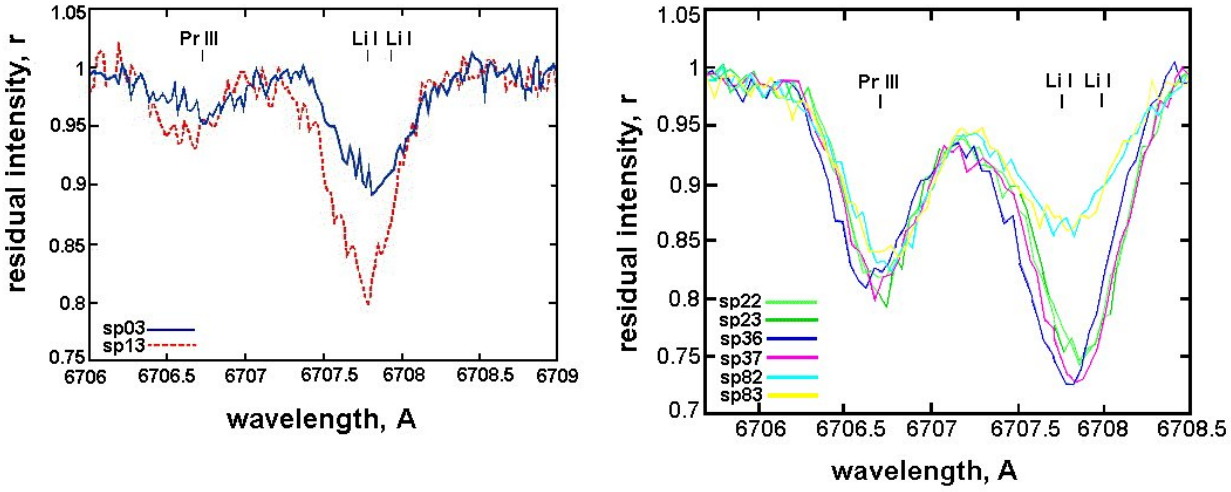

Figure 5: Spectra of HD 12098 and HD 60435 (a classical roAp–CP star with lithium spots)

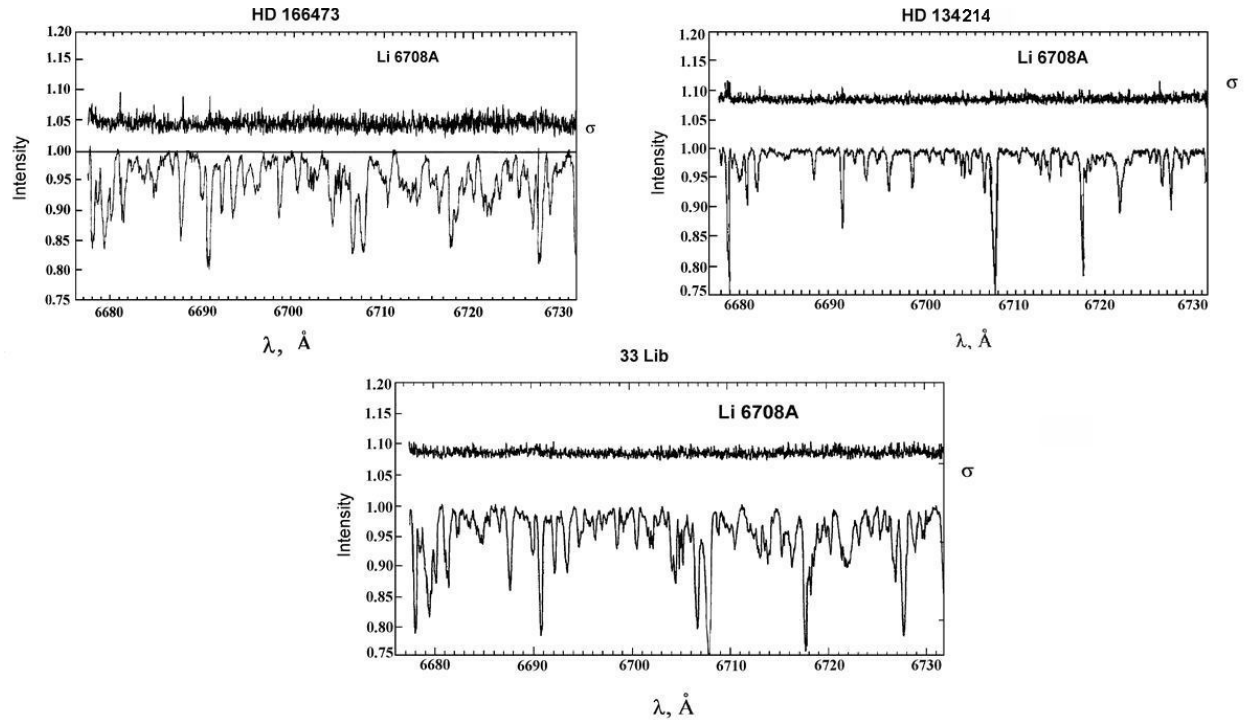

Figure 6: Examples of the dispersograms for the sharp–lined stars with invariable Li I 6708 Å line: HD 134214, HD 166473, and 33 Lib

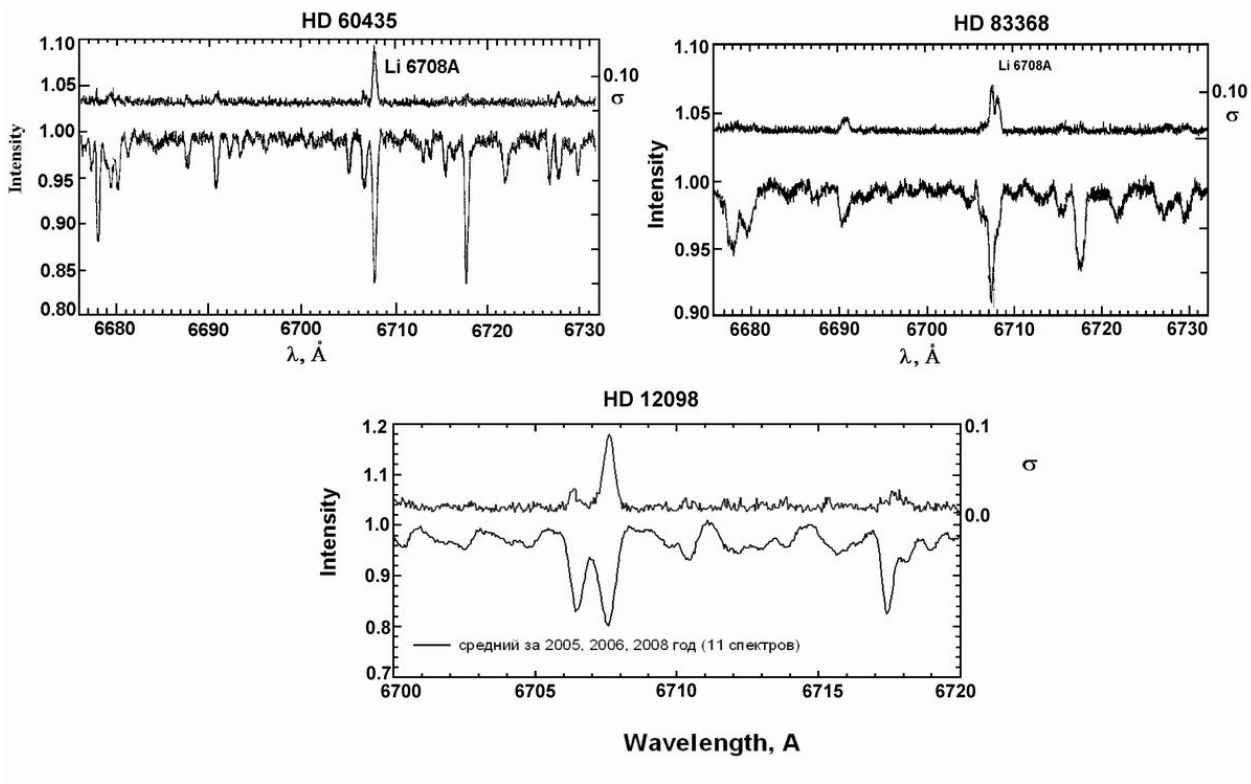

Figure 7: Dispersograms for the stars HD 60435, HD 83368 and HD 12098 in Li I 6708 Å region

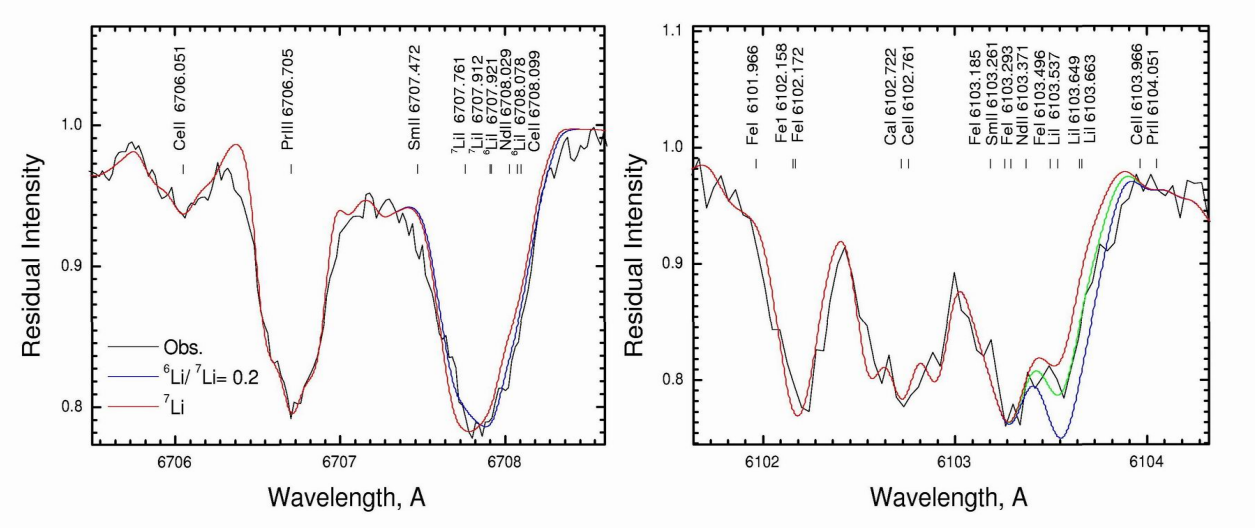

Figure 8: 33 Lib 6708 Å, blue line: $\log N(\mathrm{Li}) = -7.95$, $^6\mathrm{Li}/^7\mathrm{Li} = 0.2$; red line: $\log N(\mathrm{Li}) = -7.88$, only ^{7}Li I 6103 Å; green line: $\log N(\mathrm{Li}) = -7.60 \pm 0.3$

References

Faraggiana R. et al., 1992 – 1996, Memorie della Società Astronomia Italiana

Faraggina R., Hack M., 1963, PASP, 75, 367

Khan S., 2004, Journal of Quantitative Spectroscopy and Radiative Transfer, 88, 71

Kochukhov O., Drake N. A., Piskunov N., de la Reza R., 2004, A&A, 424, 935

Malanushenko V. P., Polosukhina N. S., Weiss W. W., 1992, A&A, 259, 567

North P., Polosukhina N., Malanushenko V., Hack M., 1998, A&A, 333, 644

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

Polosukhina N., 1973 – 1976, Izvestiya CrAO

Polosukhina N., Kurtz D., Hack M., North P., Ilyin I., Zverko J., Shakhovskoy D., 1999, A&A, 351, 283

Polosukhina N. S., Shavrina A. V., Drake N. A., Kudryavtsev D. O., Smirnova M. A., 2010, IAUS, 268, 351

Shavrina A. V., Polosukhina N. S., Drake N. A., Kudryavtsev D. O., 2008, Astrophysics, 51, 517

Shavrina A., Polosukhina N., Khan S., Pavlenko Ya., Khalack V., Wade G. A., Quinet P., Mikhailitska N., Yushchenko A., Gopka V., Hatzes A., Mkrtichian D., Veles A., 2004, IAUS, 224, 711

Shavrina A., Polosukhina N., Khan S., Pavlenko Ya., Kudryavtsev D., Khalak V., Wade G. A., Quinet P., Mikhailitska N., Lyubchik Yu., Yushchenko A., Hatzes A., Mkrtichian D., Ilyin I., 2007, in: Romanyuk I. I., Kudryavtsev D.O. (eds), Proc. Int. Conf., "Physics of Magnetic Stars", 341

Shavrina A. V., Polosukhina N. S., Zverko J., Mashonkina L. I., Khalack V., Žižňovský J., Hack M., Tsymbal V., North P., Vygonec V. V., 2001, 2009, A&A, 372, 571

Tsymbal V., 1996, ASP Conf. Ser., 108, 198

Wallerstein R., Hack M., 1964, The Observatory, 84, 160