Изв. Крымской Астрофиз. Обс. 109, № 3, 107–113 (2013)

ИЗВЕСТИЯ КРЫМСКОЙ АСТРОФИЗИЧЕСКОЙ ОБСЕРВАТОРИИ

УДК 524.33

Surface lithium abundance distribution and magnetic field for four roAp stars

N. Polosukhina[1], *D. Shulyak*[2], *A. Shavrina*[3], *D. Lyashko*[4], *N.A. Drake*[5,6], *Yu. Glagolevski*[7], *M. Smirnova*[1], *D. Kudryavtsev*[7]

[1] Crimean Astrophysical Observatory of Taras Shevchenko National University of Kiev, Nauchnyi, Ukraine
polo@crao.crimea.ua
[2] Georg-August University, Göttingen, Germany
denis.shulyak@gmail.com
[3] Main Astronomical Observatory of NAS of Ukraine, Kyiv, Ukraine
shavrina@mao.kiev.ua
[4] Tavrical National V.I. Vernadsky University, Simferopol, Crimea, Ukraine
dlyashko@gmail.com
[5] Sobolev Astronomical Institute, St. Petersburg State University, St. Petersburg, Russia
[6] Observatório Nacional/MCTI, Rio de Janeiro, Brazil
drake@on.br
[7] Special Astrophysical Observatory of RAS, Nizhnii Arkhyz, Russia
dkudr@sao.ru

Поступила в редакцию 11 ноября 2013 г.

Abstract. High-resolution spectra obtained with the 6-m BTA telescope, Russia, and with HARPS and VLT/UVES telescopes at ESO, Chile, were used for Doppler Imaging analysis of two roAp stars, HD 12098 and HD 60435, showing strong and variable Li resonance line in their spectra. We found that Li has highly inhomogeneous distribution on the surfaces of these stars. We compared our results with previously obtained Doppler Imaging mapping of two CP2 stars, HD 83368 and HD 3980, and discuss correlation between the position of high Li-abundance spots and magnetic field.

Key words: stars: abundances – stars: chemically peculiar – stars: magnetic field – stars: individual: HD 3980, HD 12098, HD 60435, HD 83368

1 The star HD 12098

Spectral observations of a number of chemically peculiar stars with the echelle–spectrometer NES and the 6-m BTA telescope of SAO RAS allowed us to discover several Ap stars with abnormally high lithium abundance. Among these stars the star HD 12098 — the first rapidly oscillating (roAp) star found in the northern hemisphere (Girish et al., 2001) deserves special interest. The rotational period of this star, P = 5.460 ± 0.001 d, was obtained by Ryabchikova et al. (2005) by determining the mean longitudinal magnetic field (<BZ>). We detected strong and variable Li I 6708 Å̃line in spectra of this star. Despite some gaps in the phase coverage limiting the precision of the Doppler Imaging (DI) method, the existence of lithium spots on its surface can be seen, similar to other roAp stars HD83368, HD 60435 and HD 3980.

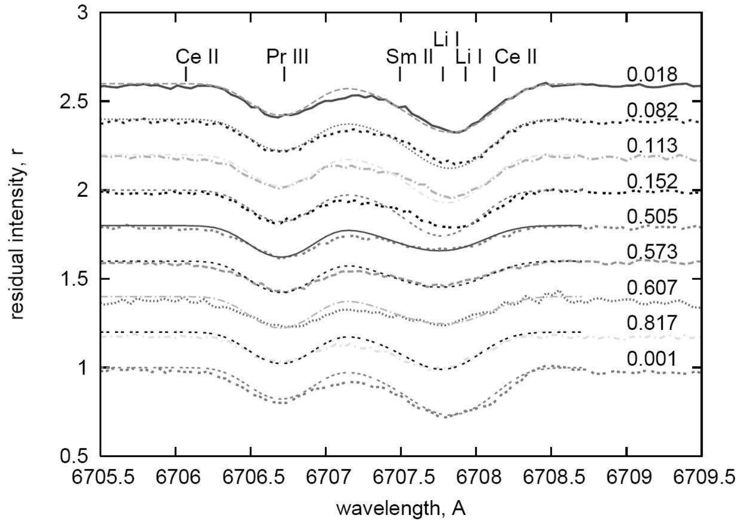


Figure 1. Spectra of HD 12098 in the 6705.5–6708.5 Åspectral region obtained at the phases 0.018, 0.082, 0.113, 0.152, 0.505, 0.573, 0.607, 0.817, and 0.001 and modeled with ROTATE code

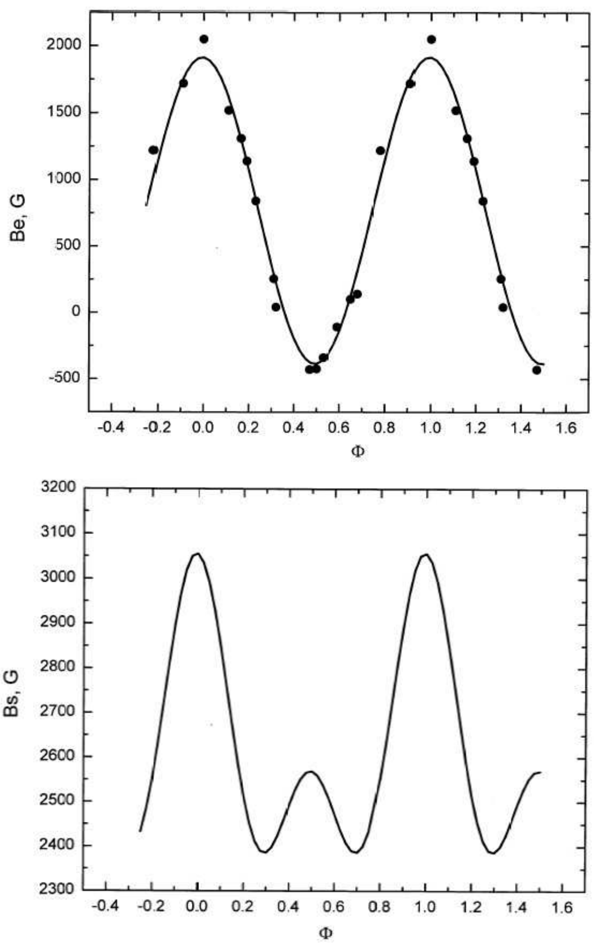


Figure 2. Measurement of the effective magnetic field (Ryabchikova et al., 2005) and central dipole model values Be (top panel) and Bs (bottom panel) for $i = 55°$

1.1 Modeling of the HD 12098 magnetic field and Li spotted stellar surface

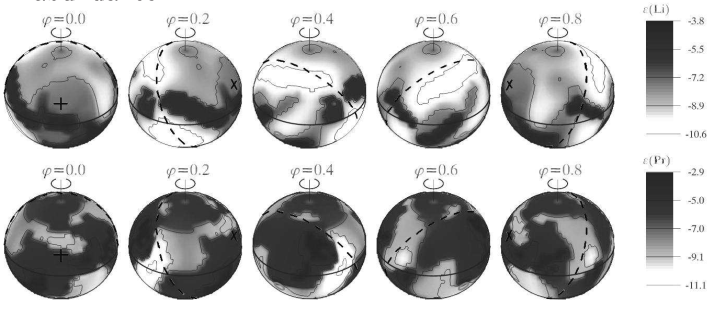
The modeling of magnetic field was based on measurements of longitudinal field made by Ryabchikova et al. (2005). We adopted the model of spatially distributed magnetic charges (Gerth, Glagolevskij, 2000). An assumed central dipole model for surface magnetic field allows us to fit sufficiently well the model values of longitudinal magnetic field Be to measured ones for $i = 55°$ and the inclination angle of dipole axis to rotational axis $\beta = 65°$. The values of magnetic field at the poles ±4050 G and the mean surface magnetic field 2720 G were obtained (Shavrina et al., 2008). The location of poles of the magnetic dipole on the stellar surface was specified: 353° of longitude and 25° of latitude for one pole, 173° of longitude and -25° of latitude for another pole. The location of lithium spots on the surface of HD12098 and lithium abundance in these spots were previously found using Tsymbal's code ROTATE (Tsymbal, 1996) which allows us to calculate synthetic spectra taking into account the spotted surface structure of a star (Shavrina et al., 2009).

1.2 Lithium Doppler Imaging: HD 12098

The DI mapping of HD 12098 was performed with the code INVERS12 (Piskunov, Kochukhov, 2002) based on observations with the echelle spectrometer NES at the 6-m telescope of SAO, RAS.

HD 12098

$T_{\rm eff} = 7800$ K, $\log g = 4.3$,
$v \sin i = 10 \pm 2$ km/s, $P_{rot} = 5.460^d \pm 0.001$,
$B_p = 6.5$ KG, $i \cong 55°$, $\beta = 65°$.
We derived the following positions of "lithium spots":
Spot 1: $l_1 = 30°$, φ = -20°, $R_1 = 40°$, $\log\varepsilon_1$ (Li) = 5.0.
Spot 2: $l_2 = 180°$, φ = 25°, $R_2 = 70°$, $\log\varepsilon_2$ (Li) = 4.2.
Spot 3: $l_3 = 290°$, φ = -20°, $R_3 = 40°$, $\log\varepsilon_3$ (Li) = 4.4.
These atmosphere parameters and spot locations were obtained in the paper of Shavrina et al. (2001). Spot parameters, as for HD12098, have been determined using Tsymbal's code "ROTATE" (Tsymbal, 1996), which assumes round spots of uniform Li abundance.



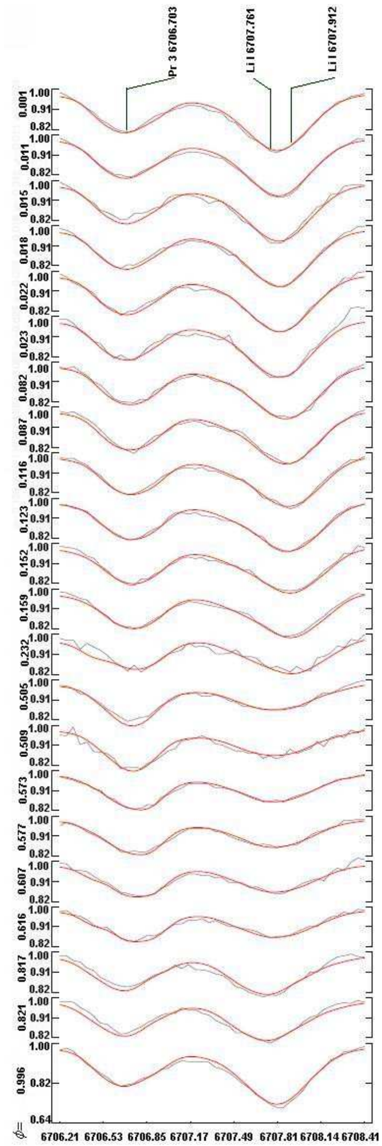


Figure 3. Surface distribution of Li and Pr in HD 12098. Black signs "+" and "○" and black circles show location of magnetic poles and magnetic equator, respectively. The abundance scales are in log N(el)/N(H)(Fig. 3, left panel). Observed and computed profiles of the blend at 6708 Åwith the Li I resonance doublet and the Pr II line vs. rotation phase (Fig. 3, right panel)

2 Variability spectra (dispersograms)

In order to present more clearly the variability of the spectrum, we calculated the spectrum of "variability" Polosukhina et al. (1992) as a value of the dispersion of intensity in each wavelength I_i from the mean intensity value I_{mean},

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

where I_i – intensity of the spectrum in the selected wavelengths (i),
I_{mean} — mean value of the intensity in the corresponding wavelengths,
n – the number of observed spectra.

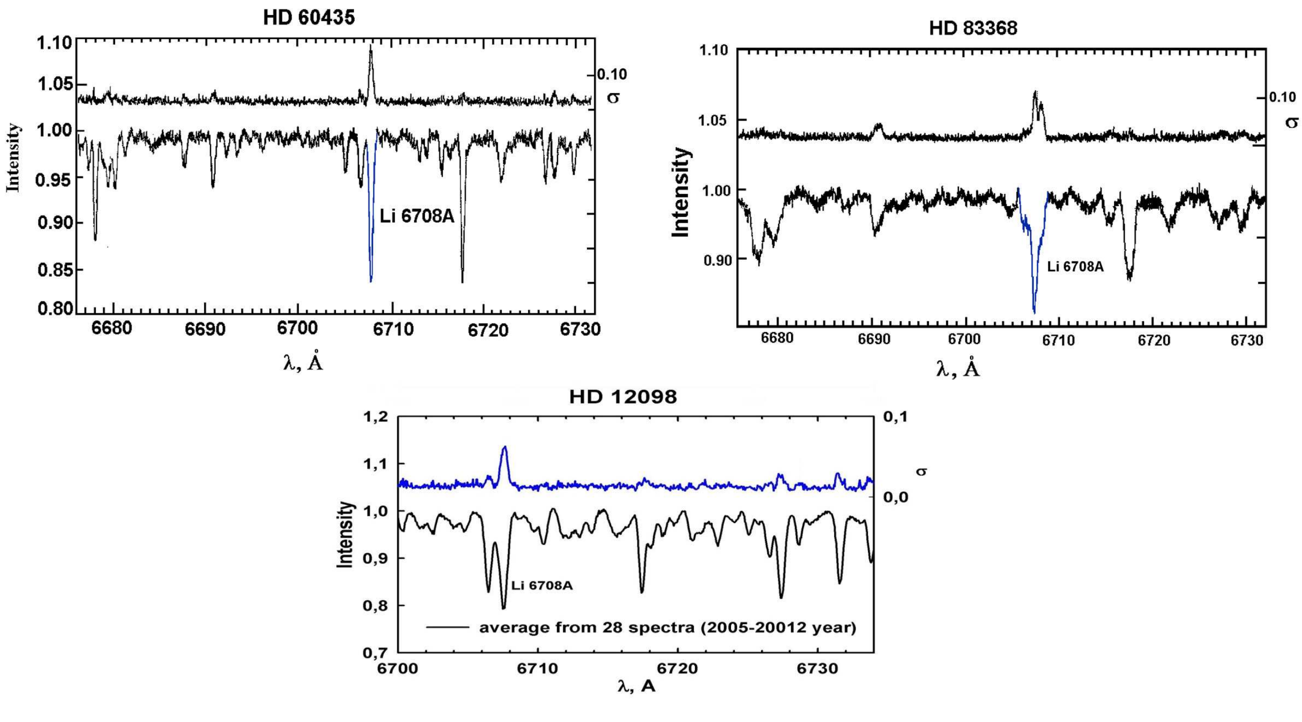


Figure 4. Dispersograms for the stars HD 60435 (Fig. 4, left panel), HD 83368 (Fig. 4, right panel) and HD 12098 (Fig. 4, bottom panel) in the Li I 6708 Å region

Highly important was a discovery of synchronous variations of the Li I 6708 Å line position, magnetic field strength H_{eff}, and stellar luminosity which was explained in terms of the oblique rotator model (Polosukhina et al., 1999). Good correlation between Li regions, magnetic field variations and oscillations indicates the connection between magnetic field configuration and Li local structure of star′s atmosphere.

3 Lithium Doppler mapping of HD 83368 and HD 3980

HD 83368
$T_{\rm eff}$ = 7650 ±150 K, log g = 4.20 ± 0.20,
v sin$i$ = 33.0 ± 0.5 km/s,
$\mathrm{P}_{rot} = 2.851976^d \pm 0.00003^d$,
$i = 68.2° \pm 6.2°$, $\beta = 86.8° \pm 6.2°$,
B_p = 2.49 ± 0.26 kG (Kochukhov et al., 2004).
These atmosphere and spot parameters were obtained in the paper of Shavrina et al. (2009).

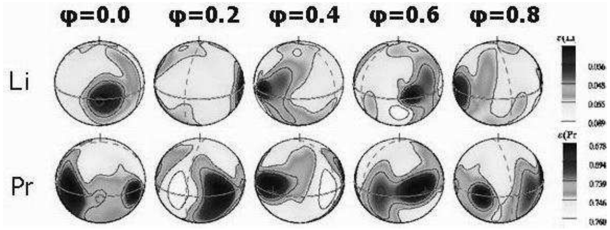


Figure 5. Lithium Doppler mapping of the surface of HD 83368. Li is strongly concentrated at the magnetic poles, with R_{spot} = 15°–20° and very high abundance of log ε(Li) ∼7.0

HD 3980
$T_{\rm eff}$ = 8300° ± 250° K,
log g = 4.0 ± 0.2,
v sin$i$ = 22.5 ± 2 km/s,
$\mathrm{P}_{rot} = 3.9516^d \pm 0.0003^d$,
$i \cong 60°$, $\beta \cong 88°$,
log$\varepsilon(Li)_{spot} \sim 6.0$, B_p = 6.9 kG
(Nesvacil et al., 2012).

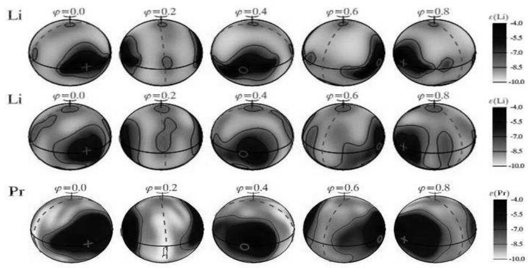
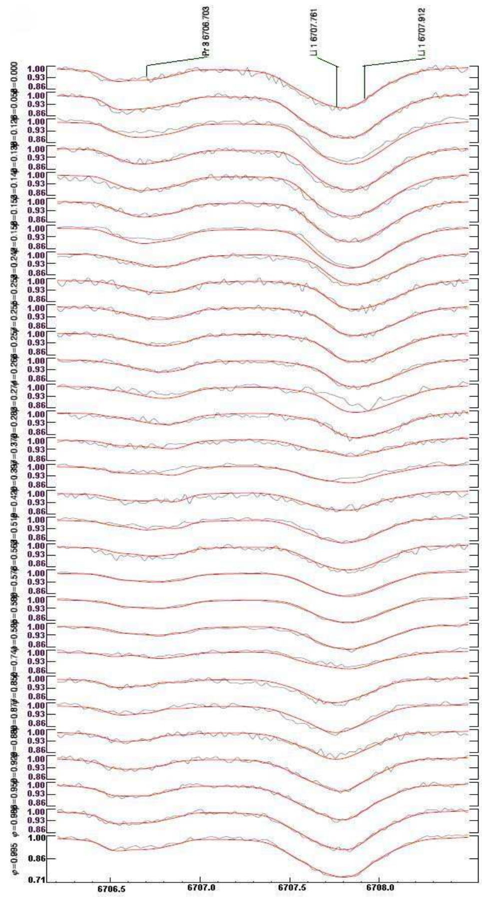


Figure 6. Lithium Doppler mapping of the surface of HD 3980. Two Li maps correspond (from top to bottom) to the cases of simultaneous mapping of the Li I and Pr III blend at 6707 Å, and additional implementation of the Pr III line at 7781.983 Å

5 Conclusion

Magnetic roAp-stars have oscillation periods of 5 – 15 min, highly non-uniform atmospheric chemistry and strong magnetic fields. They are the most interesting objects for applying Doppler Imaging (DI) technique which allows the abundance maps of the stellar surface to be derived. Surface distribution of lithium was investigated earlier applying the multi-element abundance Doppler imaging code INVERS12 (Piskunov, Kochukhov, 2002) to the roAp stars HD 83368 and HD 3980 (Kochukhov et al., 2004; Nesvacil et al., 2012). We found that Li is strongly concentrated at the regions of strong magnetic fields (magnetic poles) pointing to the strong correlation with the magnetic field structure. Recently we have performed the DI mapping of the surface Li abundance for two other roAp stars, HD 12098 and HD 60435, based on high-resolution spectra. We found that on the surface of HD 12098 there are three "Li spots" with R = 40°–70° and Li abundance from 4.2 to 5.0 (in logε(Li) = log(Li/H) + 12.0 scale). For HD 60435 using HIPPARCOS data we derived i = 133. Under these condition, our analysis of profiles of magnetically sensitive FeII lines (6147 Åãnd 6149 Å) leads to the surface field value H_s = 3 kG. From the line profile variations we derived the positions of the lithium spots which are not located strictly at opposite sites of the stellar surface. We suppose that magnetic poles may coincide approximately with lithium spots, however, its characteristics were derived with lower accuracy. Highly inhomogeneous distribution of Li over the surfaces of roAp stars may be explained by a modification of radiative diffusion processes by magnetic fields (Babel, Michaud, 1991). The vertical magnetic field promotes diffusion process, and it is strengthened at poles. It also explains the enhanced abundances of some elements (ions) in polar regions. The ambipolar diffusion has the greatest effect on light elements, and especially on lithium. However, the lack of up-to-date theoretical models doesn't permit a direct comparison of observed lithium abundance distribution on the surfaces of analyzed roAp stars and predictions of diffusion in CP stars. Lithium

4 Lithium Doppler Imaging: HD 60435



We used spectra obtained by P. North (1998) with the ESO Coude Auxiliary Telescope and also HARPS and UVES spectra obtained from the ESO Science Archive Facility.
$T_{\rm eff}$ = 8250 K, log g = 4.5, v sin$i$ = 11 ± 2 km/s,
$P_{rot} = 7.6793^d \pm 0.0006^d$,
H_s = 3 ± 1 kG (Shavrina et al., 2001).
HD 60435: i = 47° (133°), v_e = 15 km/s
We derived the following positions of "lithium spots":
Spot 1: l_1 = 11° ± 6°, φ_1 = −15° ± 6°, R_1 = 44° ± 3°, log$\varepsilon(Li)_1$ = 3.8± 0.2.
Spot 2: l_2 = 205° ± 10°, φ_2= 15° ± 6°, R_2 = 40° ± 7°, log$\varepsilon(Li)_2$ = 2.7 ± 0.2.

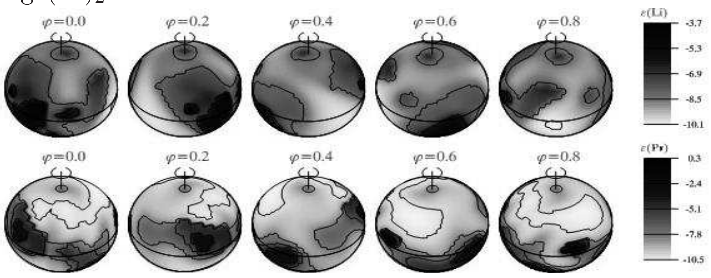


Figure 7. Lithium Doppler mapping of the surface of HD 60435. Observed and computed profiles of the blend 6708 Åw̃ith the resonance doublet Li I 6708 Åãnd Pr vs. rotation phase (Fig. 7, right panel) (Figures are taken from Polosukhina et al., 2013)

might be a key element to improve our understanding of the process of chemical diffusion in the presence of strong magnetic field.

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