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

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Abstract. The lines of lithium at $\lambda\lambda$ 6708 and $\lambda$ 6103 are analyzed in high resolution spectra of some sharp-lined and slowly rotating roAp stars. 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 studied are obtained for both lithium lines. High estimates of $^{6}\text{Li}/^{7}\text{Li}$ ratio ($0.2 \div 0.5$) for the studied stars can be explained by Galactic Cosmic Ray (GCR) production by spallation reactions and the preservation of the original $^{6}\text{Li}$ and $^{7}\text{Li}$ by the strong magnetic fields.

Keywords. Stars: chemically peculiar, stars: magnetic fields, stars: individual: (HD 137947, HD 201601, HD 134214, HD 166473, HD 101065)

1. Introduction

In the framework of the project “Lithium in CP stars”, a significant series of observations was obtained at ESO and CrAO ($R = 100000$ and $50000$, respectively, 1996–2001) for 5 rapidly oscillating Ap (roAp) stars: 33 Lib (HD 137947), $\gamma$ Equ (HD 201601), HD 134214, HD 166473, HD 101065, in the spectral region $\lambda\lambda$ 6680–6730. These series were supplemented by ESO (March 2004) and SAO-BTA (April 2004) spectra with $R = 100000$ and 60000, respectively. The observations show a very strong and nonvariable resonance doublet Li i $\lambda$ 6708. The spectra of these roAp stars are group II in the classification...
of lithium roAp stars in accordance with Li $\lambda$6708 appearance over the phases (Polosukhina et al. 1999).

All these stars are characterized by sharp lines in their spectra, by the strong overabundance of Rare Earth Elements, and by magnetic fields from 2 kG to 6.8 kG. The sharp lines (2 ± 3 km s$^{-1}$) in the spectra of these stars result from small $v \sin i$ values. For the stars with short rotational periods the sharp lines appear to be due to the combination of equatorial velocity $v$ and a significant inclination angle $i$. For the stars with longer periods (of some years), $\gamma$ Equ and 33 Lib, the width of the lines is attributed to slow rotation. (Note that the broadening of spectral lines due to rotation is not distinguished from the broadening due to the rapid oscillations). Some of the stars are, therefore, observed “pole-on”, and an observer always sees only one hemisphere of these star. In this case the spectrum is essentially constant.

2. Synthetic spectra

These stars with strong $\lambda$6708 lithium doublets are very poorly studied. We study their spectra in detail in a narrow range near $\lambda$6708 by the method of synthetic spectra, taking into account Zeeman magnetic splitting and blending by REE lines. Any additional broadening, likely pulsational, was described by the parameter $v \sin i$.

Spectral calculations for HD 166473, $\gamma$ Equ and 33 Lib were carried out using the model atmospheres of Kurucz (1994) with parameters from Gelbman et al. (2000), Ryabchikova et al. (1997), and Ryabchikova et al. (1999). For HD 101065 Pavlenko’s model was used, as in the work of Shavrina et al. (2003). For synthetic spectra calculations we applied the magnetic spectrum synthesis code SYNTHM (Khan 2004), which is similar to Piskunov’s code SYNTHMAG and was tested in accordance with Wade et al. (2001). For initial calculations we used the code STARSP of Tsymbal (1996) and in some cases the code ZEEMAN2 (Wade et al. 2001).

A simplified model of the magnetic field is characterized by radial (along line of sight), meridional, and longitudinal components of field $B_r$, $B_m$, $B_l$ ($B_l = 0$ always, as it is justified for the plane-parallel model atmospheres), which were primarily determined from Fe $\Pi$ $\lambda$6147, $\lambda$6149, Ce $\Pi$ $\lambda$6706.05 and Pr $\Piii$ $\lambda$6706.70 (see Table 1).
Figure 2. Fitting of the observed and the calculated spectra of HD 101065 near λ6708 with \(^6\text{Li}/\ ^7\text{Li}=0.4\). Left: The spectrum calculated when taking into account only the main isotope \(^7\text{Li}\) does not fit the observed one at λ6707.9. The primary contributing lines are marked at the top of each panel.

Figure 3. Fe \(^{II}\) λ6147 and λ6149 for 33 Lib with magnetic field components. Left: \(B_r = 4.2\) kG, \(B_m = 3.3\) kG, \(B_l = 0\) kG; Right: \(B_r = 2\) kG, \(B_m = 5\) kG and \(B_l = 0\) kG like for Pr \(^{III}\) λ6708 (see Fig. 1, Right).

3. REE lines with new atomic data

We used the VALD (Kupka et al. 1999) and the DREAM[†] databases for atomic spectral lines. These data do not in fact allow us to fit synthetic spectra to the observed ones for all stars studied. We, therefore, calculated additional REE \(^{II-III}\) lines using the NIST energy levels and estimated their “astrophysical” gf-values from the spectra of HD 101065 using elemental abundances from Cowley et al. (2000). Theoretical gf-values for other important (for the lithium abundance determination) blending lines were computed by P. Quinet with Cowan’s code (Shavrina et al. 2003).

4. HD 101065

We present a new spectral analysis of the star HD 101065 in the lithium spectral ranges λ6708 and λ6103 using the new atomic data for REE lines and the new magnetic synthesis code SYNTHM (Khan 2004). The lithium abundance estimates from λ6708 and λ6103

Table 1. Results of abundance, $^6\text{Li}/^7\text{Li}$ - ratio, magnetic fied, and $v\sin i$ determination.

<table>
<thead>
<tr>
<th>HD 101065</th>
<th>HD 134214</th>
<th>HD 137949</th>
<th>HD 137949</th>
<th>HD 166473</th>
<th>HD 201601</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{eff}}/\log g/[\text{M/H}]$</td>
<td>6600/4.2/0</td>
<td>7500/4.0/0</td>
<td>7750/4.5/0</td>
<td>7250/4.5/0</td>
<td>7750/4.0/0</td>
</tr>
<tr>
<td>N(Fe i) $\lambda 6103$</td>
<td>6.95 (Fe ii)</td>
<td>7.60</td>
<td>8.00</td>
<td>7.80</td>
<td>-</td>
</tr>
<tr>
<td>N(Fe ii) $\lambda 6149$</td>
<td>-</td>
<td>7.25</td>
<td>7.70</td>
<td>7.80</td>
<td>7.35</td>
</tr>
<tr>
<td>N(Li) $\lambda 6708$</td>
<td>3.1</td>
<td>3.9</td>
<td>4.1</td>
<td>3.6</td>
<td>3.7</td>
</tr>
<tr>
<td>N(Li) $\lambda 6103$</td>
<td>3.5</td>
<td>4.1</td>
<td>4.4</td>
<td>4.4</td>
<td>-</td>
</tr>
<tr>
<td>$^6\text{Li}/^7\text{Li}$ $\lambda 6708$</td>
<td>0.4:</td>
<td>0.3:</td>
<td>0.2:</td>
<td>0.3:</td>
<td>0.2:</td>
</tr>
</tbody>
</table>

$B_r/B_m/B_l$ (kG)

| $\text{Fe} \, ii \, \lambda 6149$ | - | -2.9/-1.7/0 | 4.1/4.1/0 | 4.2/3.3/0 | 2.0/6.0/0 | 3.5/2.6/0.8 |
| $\text{Pr} \, iii \, \lambda 6706.7$ | 0/2.3/0 | -2.3/-1.9/0 | 2.0/5.0/0 | 1.5/5.0/0 | 2.0/6.5/0 | 2.7/3.5/0 |
| $\text{Ca} \, i \, \lambda 6102.7$ | 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$^{-1}$)

| $\text{Fe} \, ii$ | - | 3.0 | 2.5 | 2.5 | 3.0 | 2.5 |
| $\text{Pr} \, iii$ | 3.5 | 2.0 | 4.0 | 4.0 | 5.5 | 2.5 |

Figure 4. Fitting the observed with the computed spectra for 33 Lib. Left: Li i $\lambda 6708$, log $N$(Li) = $-$7.95 and $^6\text{Li}/^7\text{Li}$ =0.2; when only $^7\text{Li}$ is taken int account then log $N$(Li) = $-$7.88. Right: the best fit was reached for log $N$(Li) = $-$7.60 $\pm$ 0.3, $^6\text{Li}/^7\text{Li}$ =0.2.

are 3.1 dex and 3.4 dex, respectively, in the scale of log $N(H)$=12.0 dex, and its isotopic ratio $^6\text{Li}/^7\text{Li}$ is about 0.4 ($\lambda 6708$) and 0.3 ($\lambda 6103$).

5. Results

The results are presented in Table 1. In the second line parameters of model atmospheres $T_{\text{eff}}/\log g/[\text{M/H}]$ are given. The calculations for HD 137949 were carried out for two model atmospheres 7750/4.5/0 and 7250/4.5/0 in the possible effective temperature range. The abundances derived from the lines of Fe i, Fe ii and Li i on the scale log $N(H)$ = 12.0 are given in lines 3 - 6, and the isotopic ratio estimated from Li i $\lambda 6708$ in line 7. To take into account the Fe ii line $\lambda 6103.496$ near the Li i line at $\lambda 6103.6$, we used for HD 101065 the abundance of Fe ii according to Cowley et al. (2000). The bottom part of the table summarizes the parameters of magnetic field and $v\sin i$ values derived by fitting of the lines Fe ii $\lambda 6149$, Pr iii $\lambda 6706.7$, and Ca i $\lambda 6102.7$. 
6. Conclusions

- The lithium abundances for all stars determined from the \( \text{Li} \, \lambda 6103 \) line are greater than the abundances determined from \( \text{Li} \, \lambda 6708 \). This may be evidence of a vertical lithium stratification, an abnormal temperature distribution, or consistent unidentified blending with the \( \lambda 6103 \) line.

- Our work on two roAp stars, HD 83368 and HD 60435 (Shavrina et al. 2001) 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 \( \text{Li} \) lines and the estimates of \( ^6\text{Li}/^7\text{Li} \) ratio (0.2 ÷ 0.5) can be explained by the Galactic Cosmic Ray (GCR) production due to spallation reactions with the ISM near where these stars formed and the preservation of original both \( ^6\text{Li} \) and \( ^7\text{Li} \) by their strong magnetic fields. The values of the \( ^6\text{Li}/^7\text{Li} \) ratio expected from GCR production are about 0.5 ÷ 0.8 (Knauth et al. 2003, Webber et al. 2002).

- The new laboratory and theoretical gf-values for REE lines are necessary to refine our estimates of lithium abundances and the isotopic ratio.

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