The enigma of lithium: from CP stars to K giants. First results of CP star observations obtained at Mount Stromlo Observatory

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Abstract.
We present the results of the observations of some roAp stars made at Mount Stromlo Observatory during 17 nights in 2001 September-October. This long observing run permitted us to obtain a good phase-rotation coverage. In chemically peculiar magnetic stars, the Li\textsubscript{i} 6708 Å spectral line presents very anomalous behaviour: in some stars it is a strong feature, in others, with similar atmospheric parameters, it is invisible. Interesting results were obtained for the roAp star HD 3980 which presents variations of the profile and position of the Li\textsubscript{i} line with the rotation period. These new observational results should serve as a base for the development of atmospheric models of “Li-spotted” roAp stars.

1. Introduction

The “Li puzzle” is the great spread in lithium abundance for stars with similar physical parameters ($T_{\text{eff}}$, $\log g$, $M$). Its main cause is related to unknown physical processes. The strongest Li feature in a star’s spectrum – the lithium resonance doublet at 6708 Å – is very sensitive to evoludional changes, to the temperature regime and to conditions of mixing. Usually, lithium is depleted with stellar age. The presence of the Li\textsubscript{i} line 6708 Å in a stellar spectrum is an
The enigma of lithium: from CP stars to K giants

indication of youth of a star, or of a breaking of mixing between internal (hot) and external (cool) layers of a star, or an indication of active processes with an eventual lithium synthesis.

The presence of a magnetic field is one of the conditions for Li synthesis (for example, by spallation reactions on the stellar surface). A magnetic field also inhibits mixing of stellar material and, hence, lithium depletion.

An influence of surface activity connected with magnetic field structure on Li line profiles is a problem under discussion for the late type chromospherically active Li-rich giants too. Attempts to detect spots and rotational modulation with photometric variations gave contradictory results (Randich et al. 1993). Since the discovery of the first Li-rich K giant, the existence of oxygen giant stars with high Li abundance became a puzzle, although different mechanisms were proposed to explain the high Li abundance on the surface of these stars (Brown et al. 1989; de la Reza et al. 1996, 1997). It is important to mention that in the past Lambert & Sawyer (1984) suggested that Li-rich giants may be the “descendants” of one or more classes of magnetically peculiar CP stars, i.e. there is an evolutional connection between magnetic CP stars with high Li abundance and Li-rich red giants.

A comprehensive investigation of the correlation of lithium line profiles with chemically peculiar (CP) stars’ rotation (Polosukhina et al. 1999) permits us to separate the observed Ap-CP stars into four groups with different behaviour of the Li I line 6708 Å. The behaviour of this line can be explained by the existence of Li-rich spots on the star’s surface, using the oblique rotator model with different parameters for each star. Recently, a preliminary spectroscopic analysis of the chemically peculiar Ap star HD 83368 was carried out in the Li I 6708 Å spectral region (Polosukhina et al. 2000). This analysis revealed a very strong Li line 6708 Å with significant variations in the intensity and position with rotational phases. The Li line was attributed to two lithium spots (with log $\epsilon$(Li) equal to 3.6 and 3.5, respectively). The Li spottedness on the surface of HD 83368 was first indicated by North et al. (1998).

The lack of recent advances in the interpretation of the Li behavior in peculiar Ap stars could be ascribed to the scanty number of available observations. The recent very important and interesting observations of CP stars at ESO gave a new impulse for the organization of a new monitoring campaign of CP stars in the Li spectral region.

2. Observations

High resolution ($R = 47\,000$) spectra of HD 83368 were obtained with FEROS at 1.52m telescope in ESO, Chile. Observations were carried out on December 5 to 12, 2000. Due to the short rotational period of the HD 83368 ($P = 2^h 8^m 52^s$), two phases were observed every night. Spectral coverage is 3900 Å – 9000 Å without gaps. At the present time the spectral regions of the Li I line at 6708 Å and O I triplet at 7770 Å have been analyzed (see Kochukhov, Drake, de la Reza in this Proceedings).

High-resolution spectra ($R = 88\,000$) of eleven CP stars were obtained during the observing run in September – October 2001 with the 74-inch telescope
The enigma of lithium: from CP stars to K giants

and echelle spectrograph of the Mount Stromlo Observatory. Now we present the first part of the research concentrated on the $\text{Li}^\dagger 6708 \text{ Å}$ feature.

The reduction of the observed spectra from bias subtraction and flat-field corrections through spectra extraction and wavelength calibration was done using standard NOAO IRAF procedures.

3. Results

Analysis of the observational results permits us to separate our sample into two groups: stars with a clearly detectable $\text{Li}^\dagger 6708 \text{ Å}$ line and stars having no or a very weak feature at 6708 Å. Some stars from our program, such as HD 3980, HD 83368, HD 208217, and $\gamma$ Equ, show a clearly detectable feature at the predicted position of the $\text{Li}^\dagger$ doublet. However, the spectra of some stars have not yet been reduced.

In order to identify the nature of the 6708 Å feature, we overlapped the observed spectra and synthetic ones calculated with the atmospheric parameters of a given star (previously determined by us or taken from the literature). Atmospheric models, atomic data, and synthetic spectra computing code are those as in Polosukhina et al. (2000). For many lines present in the spectra of CP stars, we do not know atomic parameters or even their identifications. So, some spectral lines were not included in the calculations of the synthetic spectra. The lines of the rare earth elements (REE) are very strong in the spectra of CP stars, and they were included in our line list. For example, the strong Ca $\text{i}$ line at 6717.681 Å is blended with Gd $\text{ii}$ 6718.13 Å. This line is very strong in the spectra of Ap – CP stars, such as HD 3980, HD 15144, and HD 208217, while in the spectra of normal A - F stars the line at 6718 Å is due to the Ca $\text{i}$ 6717.681 Å line blended with a weak Ti $\text{i}$ 6717.794 Å line.

The line of Pr $\text{iii}$ 6706.705 Å near the $\text{Li}$ feature is clearly visible in the spectra of some roAp – CP stars and is a strong indicator of roAp stars. Some stars, such as $\gamma$ Equ and HD 24712, were observed by us for testing and comparison with the results of other observers.

Here we present only some part of observations and preliminary results of the spectral reduction. The final analysis of all obtained results will be presented elsewhere.

Now we present only the spectra of the $\text{Li}^\dagger 6708 \text{ Å}$ line region. In the future we plan to study other spectral regions containing lines of some alkaline elements having excitation conditions similar to those of the $\text{Li}$ line. An analysis of temperature sensitive lines may permit us to separate the effects of the temperature and abundance inhomogeneities on the line profiles of the studied elements.

In Figures 1 – 7 we present original spectra of some CP stars in the $\text{Li}^\dagger 6708 \text{ Å}$ spectral region.

4. Comments on Individual Stars

The most important result was obtained for the star HD 3980. The monitoring of this star, as can be seen on Figures 1 and 2, shows strong variations of the spectra, especially in the $\text{Li}^\dagger 6708 \text{ Å}$ line. A large Doppler shift of the $\text{Li}$ line
Figure 1. Spectra of the star HD 3980 in the Li I 6708 Å region. The rotational phases are given on the right. The Li I line shows strong variability both in position and in intensity. In our interpretation, the Li line originated in a first “Li spot” (spot 1) moves to the red from phase 0.07 to 0.37. A second “Li spot” (spot 2) has appeared by phase 0.58 (see Fig. 2) and the Li line position moves to the red also. Note the striking similarity of behaviour of Li line 6708 Å profiles of HD 3980 with Li-spotted star HD 83368.
Figure 2. Continuation of the spectra in Figure 1.
Figure 3. The spectrum of the well known Li CP star \( \gamma \) Equ. We present this star for comparison reasons.
Figure 4. Spectra of the star HD 15144 in the Li i 6708 Å region. No Li line is observed.
Figure 5. Three spectra of the star HD 24712. \( \text{Li}\,\text{i} \) line is not observed in this star, its position is marked by short vertical line. A feature at \( \sim 6707\,\text{Å} \) is the \( \text{Pr}\,\text{iii} \) line 6706.705 Å.
Figure 6. Two spectra of the star HD 42659 obtained with time difference of three days. No Li I line is observed.
Figure 7.  HD 208217. The strong Li I line is observed in the spectrum of this star obtained on September 27.
position is observed, as it was for HD 83368. This gives us an opportunity to join these two stars in one group of CP stars with lithium spots.

**HD 3980 = ξ Phe** is a late type Ap star with strong photometric variations in V-band. On this curve there are two minima (primary minimum amounts to 0.13 mag, the secondary minimum shows half of this value). The two maxima are equal, and all extrema are separated by 0.25 phases. We have not completed spectral studies concerning this star, but in the similar star, HD 98088, the lines of REE (for example, Eu II lines) vary exactly in antiphase with the light curve: primary and secondary minima of light variations correspond to primary and secondary maxima in the line variations. Both stars belong to A3 spectral type. In the paper of Maitzen et al. (1980) there are magnetic measurements of $H_{\text{eff}}$ (for HD 3980) with a great scattering. A reversal of polarity was noted every second day, while $H_{\text{eff}}$ is variable with a 4 day period and amplitude of 2 kG. Unfortunately, magnetic field measurements are not reliable enough to make a $H_{\text{eff}}$ magnetic field curve.

We used for phase calculations the rotational period of $P = 3.95200$ days (Catalano & Renson 1998). The radial velocity of this star, $V_{\text{rad}} = 9.8$ km s$^{-1}$, was taken from the catalog of Barbier-Brossat & Figon (2000).

**HD 83368 = IM Vel** is a bright, southern, rapidly oscillating (roAp), cool, magnetic, chemically peculiar star. In addition to the short-term pulsational changes, the star shows variations of spectral line profiles, mean longitudinal magnetic field and brightness with a rotational period of 2.851976 days.

**HD 208217 = BD Ind** is a variable star of α$^2$ CVn type having $P = 8.44500$ days and $v \sin i = 55.0$ km s$^{-1}$ (Catalano & Renson 1998). At first, we detected a strong Li I line in the spectrum of this star obtained on September 27, 2001. We have a second spectrum of this star obtained two days before, but, unfortunately, it is of very poor quality due to bad weather conditions. However, there are indications of strong variability of its spectrum. More observations are clearly needed.

**HD 201601 = γ Equ** is the well known CP star of spectral type F0p. We present this star for comparison reasons.

In the second group of CP stars, those with an absent Li line, are the stars: HD 15144, HD 42659, and HD 24712. Position of the Li I line is marked by a short vertical line in the figures displaying their spectra.

5. Discussion

- During our observations with the 74-inch telescope of the Mount Stromlo observatory using the echelle spectrograph, we discovered that HD 208217 is a CP star with strong Li I line 6708 Å.

- Reduction of all 74-inch spectra is unfinished, but the most important result of this set is a monitoring of HD 3980 which is shown in Figures 1 and 2.

- The behaviour of the Li I 6708 Å line in this star is very similar to that of HD 83368. It is a new evidence of Li spottedness on CP star surfaces. We have finished only preliminary reduction of HD 3980 data and obtained only an estimation of Li abundance $\log \epsilon(\text{Li}) \sim 4.0$. 


- There are some stars with similar physical atmospheric parameters ($T_{\text{eff}}$, $\log g$) but without the Li I line at 6708 Å: HD 15144, HD 24712, and HD 42659. For these stars we carried out a monitoring too.

- Our knowledge of some peculiarities and magnetic field structure of these stars is very poor. But there are some indications that HD 3980 has a dipole magnetic field like HD 83368.

- At the present time we have some CP stars with high Li abundance ($3.1 \leq \log \epsilon(\text{Li}) \leq 4.0$): $\beta$ CrB, $\gamma$ Equ, HD 188041, HD 83368, HD 60435, HD 134214, HD 137949, HD 166413, HD 101065, HD 3980. Some of these stars were studied by Faraggiana, Gerbaldi, & Delmas (1996). Our results for the Li abundance of HD 188041, HD 137949, and HD 3980 are in good agreement with the results of these authors.

6. Conclusions

The discovery of Li spots in HD 83368 and HD 3980 is the first indication of spottedness in the lithium distribution in some cool magnetic CP stars. A good correlation between positions of the spots, magnetic field, brightness and oscillation phenomena indicates possible connection between the magnetic field configuration, the local structure of the atmosphere and the local distribution of the chemical anomalies, such as Li abundance. However, the present state of our knowledge does not allow us to make any more detailed conclusions about the structure and physical conditions in the atmosphere within or outside the magnetic spots. Model atmospheres which take into account magnetic fields, radiative and convective energy transport, opacity due to overabundances, etc., are needed. Also, the occurrence of lithium on the surface needs to be studied. A theoretical possibility has been suggested by Babel (1994): ambipolar diffusion of hydrogen may result in a significant overabundance of Li I in the vicinity of the magnetic poles of CP2 stars.

The investigation of the physical conditions in Li spots should be the next step in the study of the cool magnetic CP stars' anomalies. Lithium might be the “key” element to improve our understanding of the atmospheric structure and other anomalies in these stars.

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