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The Paschen-Back effect in the Li I 6708 Å line and the presence of lithium in cool magnetic Ap stars⋆

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ABSTRACT

Context. A number of cool magnetic Ap stars show a prominent feature at λ 6708 Å. Its identification with Li I remains controversial due to the lack of knowledge of the spectra of rare-earth elements that are strongly enhanced in peculiar stars so they can potentially provide an alternative identification.

Aims. We suggest investigating the 6708 Å line in Ap stars with strong magnetic fields. In these objects, the magnetic broadening and splitting provides an additional, powerful criterium for line identification, allowing the whole line profile to be used instead of depending on a mere coincidence in the observed and predicted wavelengths.

Methods. The small separation of the Li I doublet components means that their magnetic splitting pattern deviates from the one expected for the Zeeman effect, even in relatively weak fields. We carried out detailed calculations of the transition between the Zeeman and Paschen-Back regimes in the magnetic splitting of the Li I line and computed polarised synthetic spectra for the range of field strength expected in Ap stars. Theoretical spectral synthesis is compared with the high-resolution observations of cool Ap stars HD 116114, HD 166473, and HD 154708, which have a mean field strength of 6.4, 8.6, and 24.5 kG, respectively, and show a strong 6708 Å line.

Results. High-resolution spectra for the 6708 Å region were analysed for 17 magnetic Ap stars. The presence of the 6708 Å line is confirmed for 9 stars and reported for the first time for 6 stars. The strength of the Li I doublet does not correlate with the absorption features of any other element. The stars HD 75445 and HD 201601 provide an extreme example of the two objects, which are dissimilar with respect to the 6708 Å line, but very close in the atmospheric parameters and abundances of other elements. We demonstrate that the observed profiles of the 6708 Å line in the strong field stars HD 116114, HD 166473, and HD 154708 correspond fairly well to the theoretical calculations when assuming the Li I identification. Including the Paschen-Back effect improves the agreement with observations, especially for HD 154708.

Conclusions. Results of our study confirm the Li I identification proposed for the 6708 Å line in cool Ap stars.

Key words. line: formation – stars: abundances – stars: atmospheres – stars: chemically peculiar – stars: magnetic fields

1. Introduction

Chemically peculiar A and B stars (also known as Ap/Bp stars) represent unique astrophysical laboratories for investigating the hydrodynamic processes, rotation, and magnetism in the upper main sequence stars. Cool magnetic Ap stars ($T_{\rm eff} \lesssim 8000$ K) are especially interesting for their slow rotation, the presence of non-radial oscillations, strong global magnetic fields, and the remarkable richness of the optical spectra. Abnormal strengths of spectral lines in these stars reveal large deviations in the stellar surface chemistry from the scaled solar abundance pattern. Modern abundance analyses (see a summary by Ryabchikova 2005) typically find that the light elements are underabundant and that the iron-peak elements are mildly enhanced or close to solar, whereas huge overabundances are reported for the heavy elements, especially rare earths. Adding complexity to this observational picture, chemical elements are distributed inhomogeneously in many Ap stars, showing both a non-uniform horizontal structure (chemical spots) and different distribution with height (stratification) in the stellar atmosphere. Combined with a prominent Zeeman broadening and splitting of spectral lines, these unusual properties make the appearance of Ap-star spectra dramatically different from the normal stars of similar spectral classes. In particular, the line density is greatly increased, with the spectral regions accessible to typical modern CCD spectroscopy populated by thousands of unidentified lines of the rare-earth elements (REEs). This obviously creates significant problems for identifying and measuring the lines of astrophysically interesting ions.

The history of the identification and analysis of lithium in Ap stars is characteristic of the difficulties encountered in the studies of elements with a small number of absorption lines. The feature at the position of the resonance Li I doublet at λ 6707.76 and 6707.91 Å (hereafter referred to as Li I 6708 Å) was originally reported for several Ap stars based on low-resolution, low S/N observations (e.g., Wallerstein & Merchant 1965). Modern observations with electronic detectors (Faraggiana et al. 1996; Polosukhina et al. 1999) have suggested the presence of the resonance Li line in about a dozen stars and also uncovered a conspicuous variation in this line with the rotational phase in a few objects. The lithium abundance exceeding the solar concentration of this element by 2–3 orders of magnitude is required to reproduce the observed equivalent width of the 6708 Å line (Shavrina et al. 2001a; Polosukhina & Shavrina 2007). Moreover, up to a 6 dex lithium overabundance in the

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areas around magnetic poles is deduced in the spatially-resolved Doppler imaging investigations of the Li spots in HD 83368 (Kochukhov et al. 2004b) and in HD 3980 (Drake et al. 2005). Such unusual behaviour that combines an extreme lateral inhomogeneity and a large overabundance is often found for the REEs in Ap stars, but is uncharacteristic of the light elements. Consequently, the Li I identification of the 6708 Å feature has often been questioned (e.g. Nesvacil et al. 2004), citing the incompleteness of the currently available REE line lists. Indeed, an element identification hinging on a single line can be incorrect, and the resulting abundance can be significantly overestimated if an unknown REE line by chance overlaps the expected position of the resonance lithium line. Interestingly, recent extension of the Ce II line list has solved a similar "Li problem" for the s-process-enriched, low-mass post-AGB stars, where the absorption previously attributed to the redshifted Li I line has turned out to be caused by Ce II 6708.099 Å (Reyniers et al. 2002).

The inconclusive situation with the identification of Li in cool Ap stars warrants a new look at this problem. The previous studies were largely concerned with measuring Li abundance and interpreting the line strength variations, but have not fully explored the line profile information available in the high-resolution observations of the slowly rotating Ap stars. Here we propose that an additional interesting constraint and, possibly, an ultimate confirmation of the Li identification, can be obtained through studying the 6708 Å line shape in stars with strong magnetic fields. As pointed out by Mathys & Lanz (1995), line identification in the Ap stars with resolved Zeeman split lines can be strengthened by comparing the observed and expected magnetic splitting patterns. In stars with strong fields, both the central line position and the whole line profile shape, as determined by the number and relative strengths of the π and σ components, can serve as a consistency check in the cases where line identification is doubtful. The first practical application of this strategy was presented by Ryabchikova et al. (2006). These authors used observations of the resolved Zeeman-split lines in the strongly magnetic Ap star HD 144897 for a major reclassification of the Nd III spectrum, thereby substantially increasing the number of Nd III lines with precise wavelengths and atomic parameters.

The aim of the present paper is to study the formation of the Li I resonance doublet in the slowly rotating cool Ap stars, taking its special behaviour in a strong magnetic field into account. It is well known that, for the kG-strength magnetic fields typically found in Ap stars, the splitting of the Li line exhibits substantial deviation from the normal linear separation of the Zeeman components due to the partial Paschen-Back effect (e.g. Maltby 1971; Mathys 1991). The importance of the Paschen-Back effect for the profiles of the individual multiplets of iron-peak elements has been demonstrated by Mathys (1990), Landolfi et al. (2001), and Stift & Leone (presentation at the Vienna CP#Ap Workshop, September 2007); however, no study has previously incorporated the Paschen-Back splitting into the Li I line formation calculations for magnetic A-type stars.

In Sect. 2 we address the problem of the departure of magnetic splitting in the Li I 6708 Å line from the simple Zeeman pattern. We present calculations of the partial Paschen-Back effect in the Li doublet and demonstrate how transition from the weak-field Zeeman to the strong-field Paschen-Back regimes manifests itself in the theoretical profiles of the Li line computed for the conditions typical of the cool Ap-star atmospheres. Section 3 gives an overview of the available observations of the Li line in Ap stars with strong magnetic fields and presents a spectral synthesis modelling of the 6708 Å feature in Ap stars HD 116114, HD 166473, and HD 154708, which turn out to be the most suitable objects for our investigation. Finally, conclusions of this study are summarised in Sect. 4.

2. The Paschen-Back effect for the ^{2}S–^{2}P transition

In the usual situation of the Zeeman effect, the splitting produced by the magnetic field is less than the energy separation between different J-levels of a multiplet. In this case the influence of the magnetic field can be considered as a small perturbation of the fine-structure Hamiltonian describing the system in the absence of the field. However, when the magnetic splitting becomes comparable to the fine-structure separation, the perturbation theory of the Zeeman effect is no longer valid. In this so-called Paschen-Back regime the Hamiltonians corresponding to the spin-orbit interaction and to the magnetic field effects should be diagonalised simultaneously. A comprehensive derivation of the theory of the Paschen-Back effect in atomic systems is given by Landi Degl'Innocenti & Landolfi (2004, Sect. 3.4) so will not be repeated here. It suffices to say that the expressions for the splitting and strengths of the π and σ components can be derived under the assumption of L-S coupling, but evaluation of these expressions has to be performed numerically for all but the simplest terms.

The Li I doublet is formed by the transition between the ^{2}S and ^{2}P levels. The upper level exhibits the fine-structure splitting into the levels with $J = 1/2$ and $3/2$, separated by $\Delta E_J = 0.337$ cm^{-1}. The behaviour of the energy levels as a function of the magnetic field strength can be characterised by the quantity

$$\omega = \frac{ehB}{4\pi m_e c\beta}, \quad (1)$$

where B is the magnetic field strength, β the multiplet separation constant ($\beta = \Delta E_J/3 = 0.112$ cm^{-1} for the ^{2}P term in Li I), and other constants have their usual meaning. In the regime of the Zeeman effect ($\omega \ll 1$), the magnetic splitting increases linearly with the field strength. For $\omega \sim 1$, which for the Li I 6708 Å doublet corresponds to $B \sim 1$ kG, the eigenvalues start to perturb each other, and linearity of the splitting pattern is lost. This regime is often called the incomplete or partial Paschen-Back effect. Finally, for $\omega \gg 1$ (the complete Paschen-Back effect), the spin-orbit interaction can be treated as a small perturbation in comparison with the magnetic splitting. For the Li I 6708 Å line, the complete Paschen-Back triplet splitting pattern will emerge for $B \gtrsim 12$ kG. Each component of this normal Zeeman pattern is split according to the multiplicity of the electronic levels.

These considerations show that substantial deviations from the linear magnetic splitting characteristic of the simple Zeeman effect are expected to occur in the Li I 6708 Å line for the magnetic field strengths of a few kG. Such fields are common at the surfaces of magnetic Ap stars and in the magnetic regions on the Sun and active late-type stars. Thus, an investigation of the Li I resonance doublet requires detailed Paschen-Back treatment of the magnetic splitting for essentially all types of magnetic stars. However, since the experimental work of Paschen and Back (Back 1912), little attention has been paid in astrophysical studies to the unusual response of the Li line to a strong magnetic field. Based on the quantum mechanical calculations, Darwin (1927) and Darwin (1928) presented rules for forming chains of non-linear equations from which the parameters of the line splitting in the partial Paschen-Back regime could be derived. In a series of papers, published between 1930 and 1941

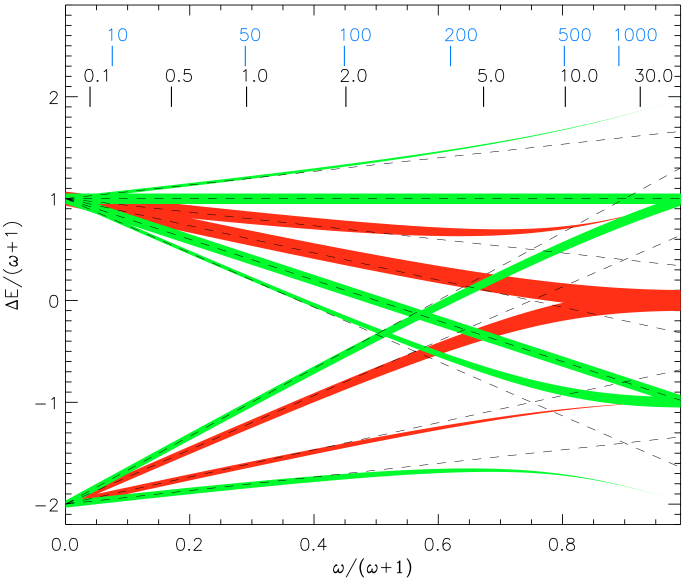

Fig. 1. The strength and separation of the magnetic components of the ^{2}S–^{2}P multiplet as a function of the magnetic field strength. The relative energy ΔE (vertical axis) is given in units of the multiplet splitting constant β. Both axes are divided by $\omega + 1$. Dashed lines show splitting for the linear Zeeman effect. Shaded curves correspond to the magnetic splitting calculated taking the Paschen-Back effect into account. The width of the curves is proportional to the strength of the respective π (darker curves) and σ (lighter curves) components. The vertical bars show the magnetic field strength (in kG) corresponding to the fine-structure splitting in the Na D lines (upper row) and the Li I resonance doublet (lower row).

(Green 1930, 1941), Green and collaborators applied the Darwin formalism to interpreting the laboratory measurements of the emission spectra of various ions in strong magnetic fields. The third paper in the series (Green & Loring 1936) examined the strong field behaviour of the ^{2}S–^{2}P multiplet of Li I. Using the results of Darwin's calculations, Traub (1968), Engvold et al. (1970) and Maltby (1971) studied the formation of the resonance Li I line in sunspots. They have carried out the line profile computations for the Li I doublet under the assumption of the Milne-Eddington atmosphere. Polosukhina (1974) investigated the influence of the Paschen-Back effect on the centroid position of the Li I line. Mathys (1991) presented another theoretical calculation of the Paschen-Back splitting in the lithium doublet. Mathys (1990) and Nesvacil et al. (2004) stressed the importance of taking this effect into account in analyses of the Li feature in Ap stars. However, several recent studies of the Li I line in magnetic stars, even those supposedly presenting refined modelling of the Li transition in the magnetic fields exceeding 3–5 kG (e.g. Polosukhina & Shavrina 2007; Leone 2007), have failed to include the Paschen-Back effect.

The goal of our study is to carry out accurate line profile calculations for the Li I doublet in strong magnetic fields. Two approaches were used to evaluate the separation and relative strengths of the π and σ components of the Li line formed in the Paschen-Back regime. First, we solved the system of equations for the ^{2}S–^{2}P multiplet following the formalism developed by Darwin (1927). Then, we performed equivalent calculations with the help of a computer program provided by Landi Degl'Innocenti, who implemented more advanced mathematical methods of the Racah algebra described in Landi Degl'Innocenti & Landolfi (2004). Results of the two alternative computations are in excellent agreement. In Fig. 1 we illustrate the separation and strength of the ^{2}S–^{2}P multiplet components as a function of $\omega/(\omega + 1)$. In this scaled format, the figure characterises the behaviour of all astrophysically important ^{2}S–^{2}P transitions (the Li I resonance doublet, Na D, Ca H and K, Mg II resonance lines). The vertical bars in Fig. 1 indicate the magnetic field strength corresponding to a given splitting pattern for the Na D lines and the Li I doublet. It is clear that deviations from the linear Zeeman splitting for the latter feature can no longer be neglected for $B \gtrsim 2$ kG, while significant asymmetry in the intensity of the red and blue π components already appears at $B \gtrsim 1$ kG.

We have incorporated results of the Paschen-Back effect modelling in the polarised radiative transfer calculations of the Li I 6708 Å line profile. The total oscillator strength of the Li multiplet is adopted from Yan et al. (1998). The presence of a non-zero nuclear spin implies that the lithium line exhibits hyperfine splitting. This effect should be treated simultaneously with the magnetic splitting only for the magnetic fields below 1 kG (Traub 1968). In this study we investigate the Li line in stars with much stronger fields, therefore a self-consistent treatment of the hyperfine and magnetic splitting is unnecessary. In fact, the separation of the hyperfine components is so small that it can be neglected for all calculations presented here. The wavelengths and relative strengths of the ^{6}Li and ^{7}Li line components are taken from Smith et al. (1998). Their line list is consistent with the very accurate theoretical calculations (Sansonetti et al. 1995) and experimental results (Volz & Schmoranzera 1996).

2.1. Local profiles

To avoid complications due to integrating the spectra over unresolved stellar surface with a complex magnetic geometry, we first study the Li I line profile for a solar-like case. The local disk-centre theoretical Stokes I and V spectra of the Li doublet are shown in Fig. 2. These calculations, based on the polarised radiative transfer code `SYNTHMAG` (Kochukhov 2007a), employ the `ATLAS9` model atmosphere (Kurucz 1993) with $T_{\rm eff} = 8000$ K, $\log g = 4.0$, and Li abundance $\log (N_{\rm Li}/N_{\rm tot}) = -8.00$. This 3 dex enhancement of the Li concentration relative to the solar photospheric Li abundance ($\log (N_{\rm Li}/N_{\rm tot}) = -10.99$, Asplund et al. 2005) is representative of the abundance of this element inferred for the Li-rich Ap stars. The ^{6}Li/^{7}Li isotopic ratio is fixed at the solar system value of 0.07 (Anders & Grevesse 1989). For the purpose of comparison with the standard treatment of the Li I line used in all previous studies of this feature in Ap stars, Fig. 2 also shows line profile calculations neglecting the Paschen-Back effect. Polarised line profile synthesis shows that, in the magnetic fields stronger than ≈3 kG, an accurate modelling of the Li I doublet is impossible without considering the Paschen-Back effect. For those magnetic fields stronger than about 10 kG, the line profile shape predicted by the Zeeman regime calculations is entirely different from the correct Paschen-Back treatment.

2.2. Disk-integrated profiles

A wide variety of the global magnetic field geometries can be considered for Ap stars. An assumption of the low-order multipolar topology is often used to fit the curves of the magnetic observables (e.g. Landstreet & Mathys 2000). However, these models cannot reproduce high-resolution observations of Ap stars in all four Stokes parameters (Bagnulo et al. 2001; Kochukhov et al. 2004a) and typically fail to achieve a good fit to the Zeeman split lines (Bagnulo et al. 2003). Furthermore, for the slowly rotating cool Ap stars considered here no phase-resolved

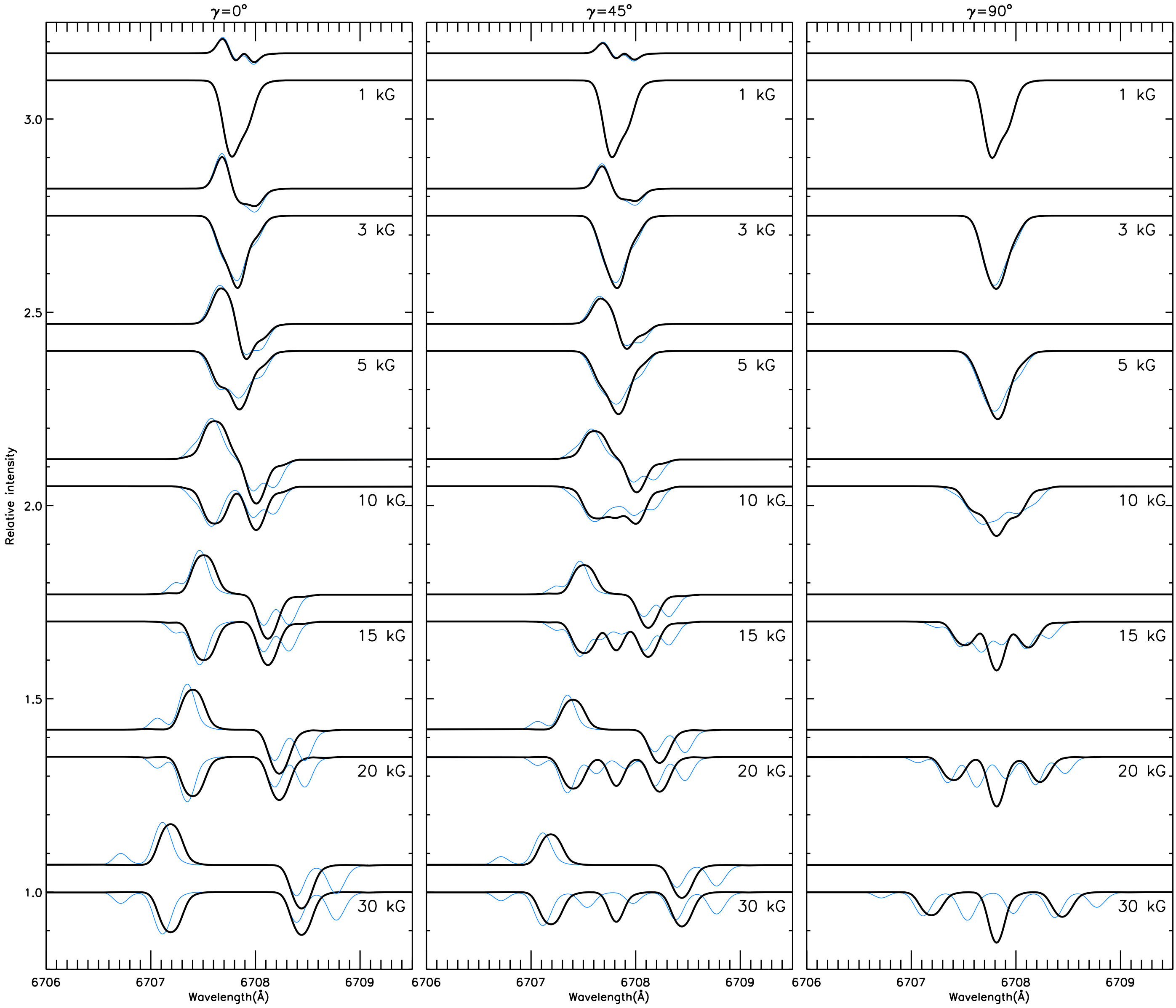

Fig. 2. Theoretical disk-centre Stokes I and V profiles of the Li I 6708 Å doublet computed with the SYNTHMAG code. The three panels show the spectra for different angles γ between the magnetic field vector and the line of sight. Calculations for different field strengths ($B = 1$, 3, 5, 10, 15, 20, and 30 kG) are shifted upward for display purposes. The Stokes V profiles are also shifted upward by 1.07 relative to the corresponding Stokes I spectra. The two sets of calculations are shown: synthetic spectra including the Paschen-Back effect (thick curves) and the calculations treating the Li line splitting in the Zeeman regime (thin curves).

high-resolution observations in the Stokes I or other Stokes parameters are available. In this situation multipolar models are severely underconstrained.

An alternative to using purely theoretical and often inadequate multipolar geometries is to minimise the number of free parameters describing the magnetic field structure and consider only those quantities which can be *directly constrained* by the available observational data. From the splitting of the Zeeman resolved lines one can determine the mean magnetic field strength, while the relative intensities of the π and σ components contain information about the field orientation. Thus, it is convenient to represent the field structure with a homogeneous distribution over the stellar surface for the purpose of calculating the disk-integrated Stokes I spectra. This simple magnetic topology is characterised by a single value of the field strength and a single inclination with respect to the stellar surface. Here we parameterise the field with a combination of the radial and azimuthal field components. Note that the latter is tangential to the stellar surface and is always perpendicular to the observer's line of sight. The line of sight symmetry of such homogeneous magnetic field geometry allows one to obtain disk-integrated intensity spectra by combining the local SYNTHMAG profiles, evaluated at 7 positions between the disk-centre and the stellar limb (Kochukhov 2007a). This simplified treatment of the magnetic field topology of slowly rotating Ap stars is usually adequate for the purpose of abundance analysis and the line profile fitting (e.g. Kochukhov et al. 2002a; Nielsen & Wahlgren 2002; Kochukhov 2003; Leone et al. 2003; Shavrina et al. 2006; Ryabchikova et al. 2004, 2006). In fact, a recent study (Kochukhov 2007b) of the triplet lines in the spectra of strongly magnetic Ap stars revealed that the narrow σ components in a few such objects indicate a much smaller surface scatter of the field strength compared to the predictions of low-order multipolar magnetic models. This provides an additional justification for the simplified single field

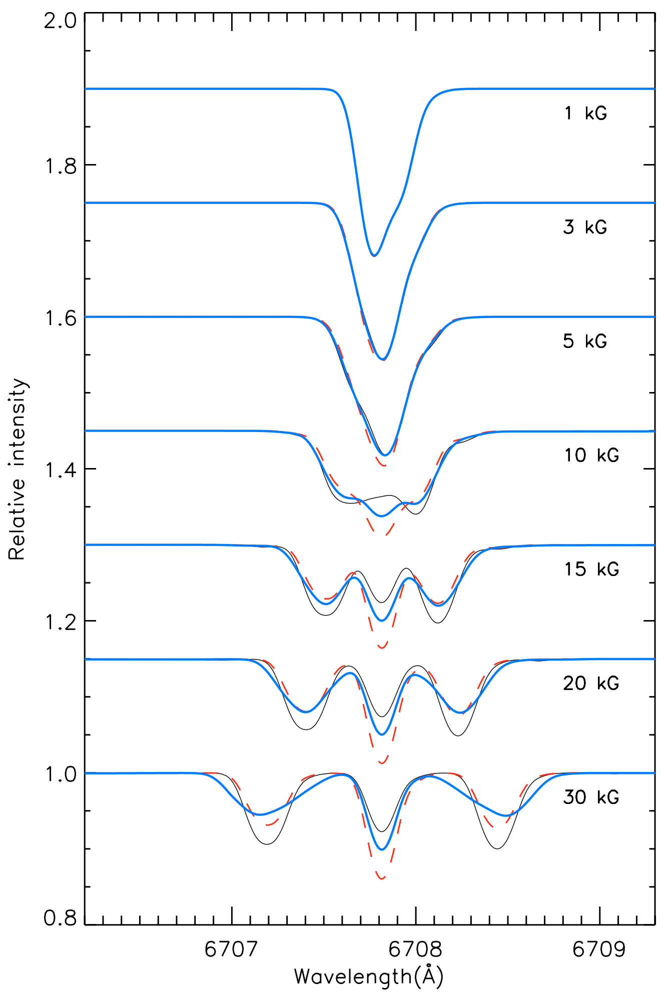

Fig. 3. Theoretical disk-integrated Stokes I profiles of the Li I 6708 Å doublet. Calculations for different field strengths ($\langle B\rangle = 1, 3, 5, 10, 15, 20$, and 30 kG) are shifted upward for display purposes. The spectra computed for different magnetic field geometries are shown with the thin solid line (homogeneous radial field), dashed line (homogeneous azimuthal field), and the thick solid line (centred dipole field aligned with the line of sight).

strength value approach to synthesising the Stokes I spectra of magnetic A stars.

Eventually, the homogeneous field assumption should fail when a wide range of the magnetic field strength variation over the visible stellar surface is present, inducing a broadening of the σ components. The only known observational example of this situation in a cool Ap star is found for HD 154708 – a star with an extremely strong magnetic field (Hubrig et al. 2005). Kochukhov (2007a) has shown that a major improvement in the fit to the triplet profile of the Y II 5087 Å line in this star can be achieved with a dipolar field aligned with the line of sight. The Stokes I spectra corresponding to this magnetic geometry can be modelled with the help of a simple modification of the disk integration procedure applied to the local profiles produced with SYNTHMAG. Instead of a constant field strength and field inclination values in 7 concentric rings, we can adopt parameters appropriate for the aligned dipole.

In this section we present calculation of the Li I line intensity for 7 values of the mean field modulus, $\langle B\rangle$, ranging from 1 to 30 kG. The model atmosphere, atomic parameters and abundances are identical to those adopted previously. Calculations are carried out for the extreme cases of the homogeneous field structure (radial field and azimuthal field) and for the dipolar geometry aligned with the line of sight. In the latter case the polar field strength of the dipole is adjusted to yield a given value of $\langle B\rangle$. The stellar rotation and the instrumental broadening are neglected.

The resulting profiles of the Li line are illustrated in Fig. 3 (only magnetic synthesis accounting for the partial Paschen-Back effect is shown). It is evident that the morphology of the lithium line profile is not very different from the local case considered in Sect. 2.1, although the variation of the field inclination with respect to the line of sight and the surface changes in the field strength for the dipolar geometry introduce some smoothing of the calculated spectra.

One can notice that the surface variation of the magnetic field strength in the dipolar model also leads to additional differential broadening of the σ components when those become resolved. But for all the three field structures considered, the characteristic simple triplet splitting pattern emerges in the 6708 Å line for the mean field modulus above ≈12 kG. This behaviour can be a key factor in supporting or refuting the Li line identification, provided that an absorption in the 6708 Å region can be detected for an Ap star with a strong enough magnetic field.

3. The Li line in magnetic Ap stars

To clarify the question of the presence of Li in magnetic Ap stars and to choose the best objects for application of the theoretical framework outlined in Sect. 2, we examined the high-resolution spectra of 17 slowly rotating, late A magnetic peculiar stars. All observations analysed in the present study were obtained with the UVES spectrograph at the ESO VLT, using either the dichroic setup (390+580 nm) with a 0.5″ slit or the 600 nm red arm setting with an image slicer. The resolving power reaches 80 000 for the slit spectra and 115 000 for the observations obtained with the image slicer, respectively. Detailed description of the reduction procedures employed for both types of the UVES data can be found in Kochukhov et al. (2006, 2007a). All observations in the 600 nm red-arm mode were acquired in the context of the programmes devoted to the time-resolved monitoring of pulsations in rapidly oscillating Ap (roAp) stars. These spectral time series, containing typically 60–150 individual exposures, were combined to yield $S/N \geq 300$ for most of the targets. Comparable noise levels were also achieved for the UVES slit spectra. One-dimensional extracted and merged spectra were rectified in the 6680–6730 and 6130–6170 Å regions using low-order polynomials. The first spectral interval is employed in the analysis of the Li I doublet, and the second segment is useful for determining the average magnetic field strength from the separation of the resolved Zeeman components of the magnetically-sensitive Fe II line at λ 6149 Å (Mathys et al. 1997).

The sample of 17 objects studied here includes 9 sharp-lined Ap stars in which the presence of the 6708 Å feature was previously reported in the literature (Faraggiana et al. 1996; Polosukhina et al. 1999; Kochukhov 2003). The three broad-lined stars with a strong variable 6708 Å line (HD 3980, HD 60435, and HD 83368) are not considered in our study because their relatively high projected rotational velocities and the prominent horizontal inhomogeneities prohibit accurate investigation of the subtle magnetic broadening and splitting effects.

A collection of the 16 spectra of cool Ap stars in the Li region is presented in Fig. 4. The stars are arranged according to the mean magnetic field strength, which is taken from the

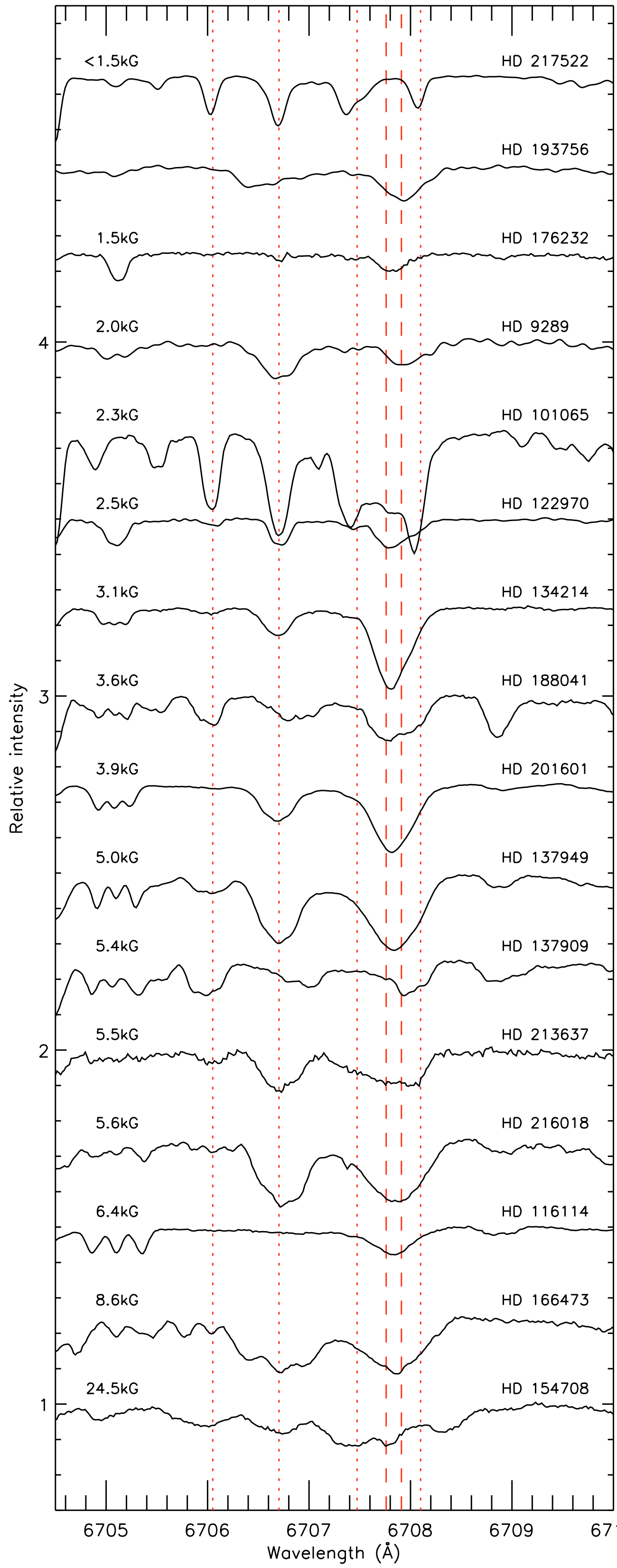

Fig. 4. Spectra of magnetic Ap stars in the 6708 Å region. Stars are arranged from top to bottom in the order of increasing magnetic field strength. The vertical lines show the position of the Li I doublet (dashed lines), as well as positions of some prominent rare-earth lines, Ce II 6706.051, Pr III 6706.703, Sm II 6707.473, and Ce II 6708.099 Å (dotted lines).

literature or determined using the Fe II 6149 Å line. The spectra are shifted to the laboratory frame using 3–5 lines of the iron-peak and rare-earth elements in the 6690–6720 Å region. All stars except HD 217522 clearly show an absorption at the expected position of the Li I 6708 Å line. The presence of this feature in the spectra of HD 9289, HD 116114, HD 122970, HD 154708, HD 193756, and HD 216018 is reported here for the first time.

From the comparison of the 6708 Å line with the strength of the nearby lines of Nd III, Pr III, Ce II, Gd II, and Sm II one can conclude that the former line does not exhibit an obvious correlation with the absorption due to any known REE features, thus making an alternative REE identification of the 6708 Å line unlikely. The cases of HD 217522 and HD 75445, in which no Li line is detected, provide a particularly convincing illustration of the deviating behaviour of the 6708 Å line. The former star is one of the coolest magnetic Ap stars known. It shows strong lines of the REEs in several ionisation stages. All four rare-earth lines in the vicinity of the Li I feature are prominent in the spectrum of HD 217522, yet no absorption at the position of the lithium resonance doublet is observed.

The Ap star HD 75445 appears to be very similar to the bright roAp star HD 201601 (γ Equ). Comparison of the stellar spectra in the 6140–6162 Å region (Fig. 5, upper panel) shows little difference, apart from the marginal effect caused by a slightly stronger magnetic field in γ Equ. The abundance analyses by Ryabchikova et al. (2002, 2004) show that the two stars closely resemble each other in the atmospheric parameters and chemical composition. Nevertheless, the two stars exhibit remarkable discrepancy in the Li I region: γ Equ shows a strong line at λ 6708 Å, while this line is entirely absent in HD 75445 (Fig. 5, lower panel). This finding again supports the view that the 6708 Å feature cannot be produced by an unidentified line of a common REE ion.

The sequence of spectra presented in Fig. 4 highlights the difficulty of a quantitative analysis of the Li region. The Li line is often blended by Sm II 6707.473 and Ce II 6708.099 Å, most prominently in HD 101065. In stars with stronger fields, the wings of the Li I line and the resolved Zeeman components of Pr III 6706.703 Å start to overlap, further complicating the analysis.

It is not the intention of this paper to perform detailed modelling of the 6708 Å region and to present accurate Li abundance determination for every star in Fig. 4. Instead we wish to answer the question of whether theoretically predicted Paschen-Back splitting signature of the Li line can be observed, thus providing a strong argument in favour of identifying the 6708 Å feature with the resonance Li I line. Previous studies of the Li region in Ap stars (Shavrina et al. 2001b, 2006; Polosukhina & Shavrina 2007) have succeeded in obtaining reasonable fits to the Li blend neglecting the Paschen-Back effect for the stars with fields ≤6 kG. This was achieved by introducing a number of additional fitting parameters, where different types of broadening, field strength, and field inclination were adjusted on a line-by-line basis, and additional low-quality predicted REE line lists were used. This means that, although the Paschen-Back effect could be important for these stars, its observational signature is ambiguous. Therefore, in the context of our investigation, we will study in detail only a few strong-field stars, showing a particularly distinct Li line profile shape or exhibiting resolved components of the Li blend.

Magnetic splitting of the resonance Li line is not observed in any star except, possibly, in HD 154708 ($\langle B \rangle = 24.5$ kG). This

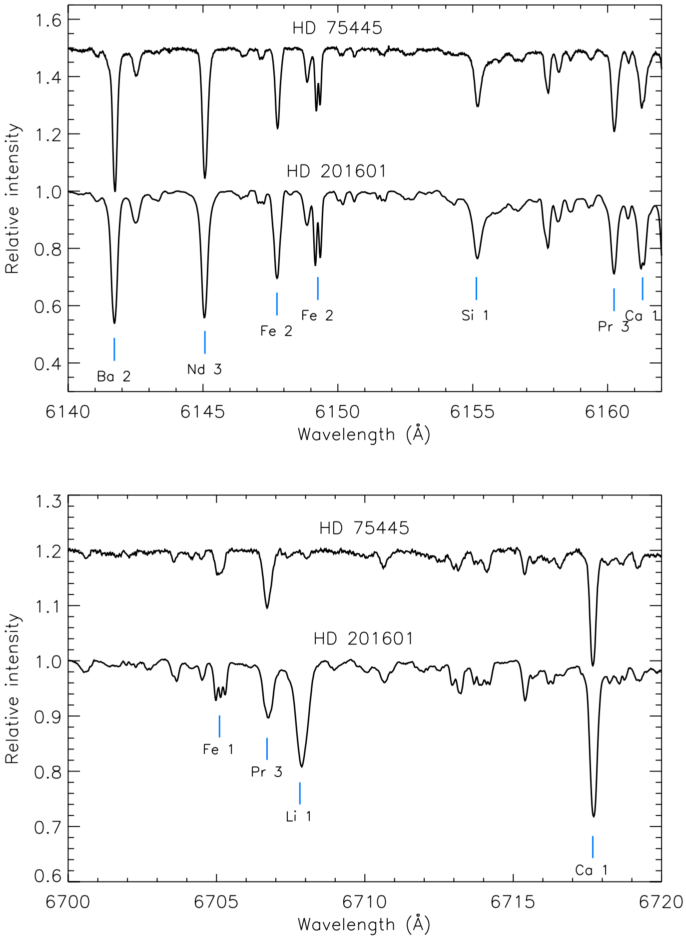

Fig. 5. Comparison of the spectra of HD 75445 and HD 201601 in the 6140–6162 Å (*upper panel*) and 6700–6720 Å (*lower panel*) regions. The two stars have very similar abundances and the line absorption, except for the 6708 Å line, which is strong in HD 201601 but absent in HD 75445.

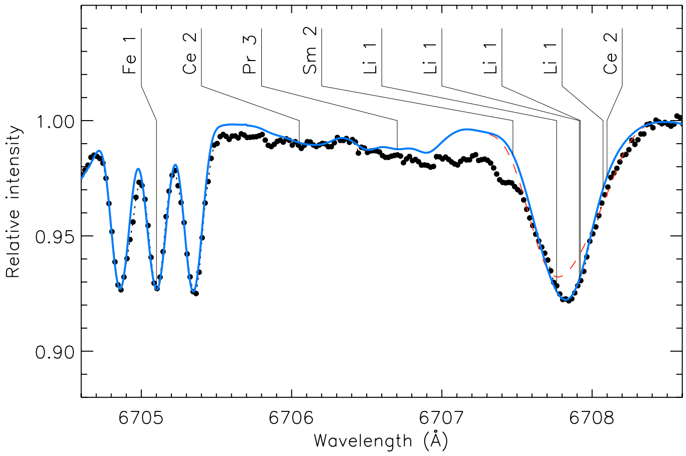

Fig. 6. Comparison of the observed (symbols) and computed (curves) spectra of the cool Ap star HD 116114. The solid curve shows calculations accounting for the partial Paschen-Back effect in the Li I 6708 Å line, while the dashed curve illustrates the synthetic spectrum computed for the Zeeman treatment of the Li I line splitting.

qualitatively agrees with the theoretical predictions of the Li line behaviour in magnetic field. In Sect. 2 we found that even in the most favourable cases of negligible rotation, resolved components of the Li I doublet should appear only for those fields exceeding ≈12 kG. The other two stars, distinguished by the strong magnetic fields and by the appearance of their spectra in the Li region, are HD 116114 and HD 166473. These objects have the third and the second strongest fields, respectively, among the Ap stars analysed here, and at the same time, they show a moderately strong Li I feature. Furthermore, in HD 116114 this line is free of interfering absorption by the REEs. Thus, we chose HD 116114, HD 166473, and HD 154708 for the detailed spectrum synthesis analysis based on the Paschen-Back calculations of the magnetic splitting in the Li I 6708 Å line.

Our magnetic spectrum synthesis was carried out for the two types of magnetic-field geometries discussed above (homogeneous and pole-on dipolar). The relevant magnetic-field parameters and $v_e \sin i$ are adjusted with the help of lines with a simple and distinct Zeeman patterns (triplets). We did not attempt to tune these parameters any further to improve the Li line description. Instead, the observed spectra were fitted by varying only the element abundances and macroturbulent broadening. The latter is required to account for the broad line profiles of some ions in cool Ap stars (Kochukhov 2003; Ryabchikova et al. 2007). The reality of turbulent broadening is also supported by the analysis of line profile variations in roAp stars (Kochukhov et al. 2007a). On the other hand, the lack of diagnostic lines and the absence of time-resolved spectra did not allow us to consider chemical stratification and spotted distribution of Li. For these reasons, and because we adopt a simplified description of the magnetic field structure, our theoretical calculations will not give an ideal fit to observations. However, we believe that the basic qualitative agreement between the observed and synthesised spectra is close enough to verify the behaviour of the 6708 Å line in strong magnetic fields.

3.1. HD 116114

The cool Ap star HD 116114 shows resolved Zeeman split lines, indicating a mean field modulus, $\langle B \rangle$, of 5.9–6.0 kG and a long rotation period (Mathys et al. 1997). In a later investigation Landstreet & Mathys (2000) adopted a 27.6 d rotation period and fitted the phase curves of magnetic observables with a global dipolar-like field, forming a small angle with the rotational axis of the star. At the same time, the rotational modulation of all magnetic observables is marginal and could still be consistent with a much longer rotation period.

The atmospheric properties of HD 116114 were investigated by Ryabchikova et al. (2004). They determined $T_{\rm eff} = 8000$ K, $\log g = 4.1$, $\langle B \rangle = 6.2$ kG and found a moderately large overabundance of the iron-peak elements for this star. Compared to many other Ap stars in this temperature range, HD 116114 does not exhibit any enhanced absorption due to the Nd III and Pr III features. Consequently, the contribution of the Pr III 6706.703 Å line to the Li region is small, which facilitates accurate analysis of the Li I line. For the field strength of HD 116114, we expect to see no splitting of the Li I line (see Figs. 2 and 3), but the partial Paschen-Back effect is already quite pronounced: the Li blend is deeper, narrower, and more symmetric; the red wing is less extended; and the central structure is absent.

We performed a spectrum synthesis modelling of the Li region of HD 116114 with the help of the SYNTHMAG code, using the element abundances and model atmosphere of Ryabchikova et al. (2004). The resonance lithium doublet was treated in the same way as in Sect. 2. The atomic parameters of other lines in the Li region were extracted from the VALD database (Kupka et al. 1999), which includes the DREAM data for rare-earth

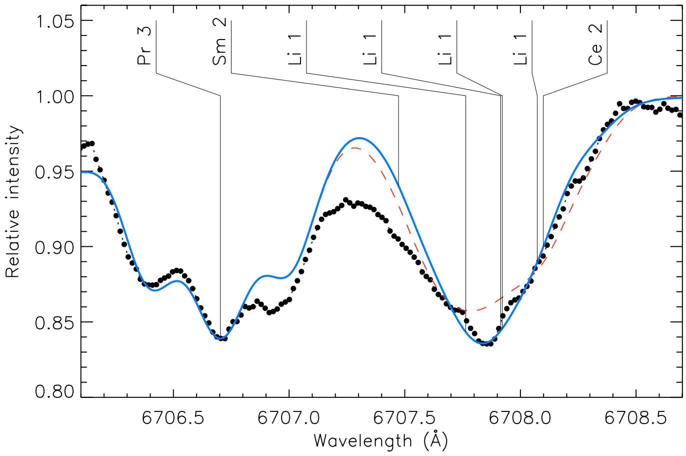

Fig. 7. The same as Fig. 6 for HD 166473.

elements (Biémont et al. 1999). The resulting line list has been used throughout the present paper. The average field strength and the field orientation in HD 116114 were determined by fitting the resolved Zeeman components of the Fe I 6705.101 Å line. A good description of the observed profile of this feature in HD 116114 (Fig. 6) was achieved for $\langle B \rangle = 6.4$ kG, a 40° inclination of the field vector relative to the surface normal and the projected rotational velocity $v_e \sin i = 3.5$ km s^{-1}. Theoretical calculations for the Li I line using these magnetic field parameters and $v_e \sin i$ are presented in Fig. 6. A good agreement between observations and spectrum synthesis is found for $\log (N_{\rm Li}/N_{\rm tot}) = -8.35$ and for a contribution of the light lithium isotope similar to the solar system value ^{6}Li/^{7}Li = 0.07 (Anders & Grevesse 1989). A macroturbulent broadening of $V_{\rm mac} = 7$ km s^{-1} is applied to the Li I line, while the Fe I 6705.101 Å line indicates $V_{\rm mac} \lesssim 2$ km s^{-1}. This range of $V_{\rm mac}$ inferred from the lines of different elements agrees with the results obtained by Ryabchikova et al. (2007).

A comparison of the spectral synthesis for the Zeeman and partial Paschen-Back treatment of the Li I line splitting shows that the latter approach is more successful in reproducing the 6708 Å feature in the spectrum of HD 116114. In particular, the Paschen-Back calculations predict a narrow line core, which agrees better with the observed profile shape. At the same time, the Paschen-Back calculations lead to a deterioration of the fit in the red wing. This problem may be related to an unexplained blending or to a spotted distribution of Li. Despite this uncertainty, it can be concluded that observations of HD 116114 are consistent with the Li I identification and that they confirm theoretically expected partial Paschen-Back behaviour of the magnetic splitting in the lithium resonance doublet.

3.2. HD 166473

The cool Ap star HD 166473 shows an unusually large amplitude of the field modulus variation with a period of about 10 yr (Mathys et al. 1997). Our observations of this star were obtained close to the maximum of $\langle B \rangle$ and, thus, are best-suited for investigating the Paschen-Back effect in the Li I line. The lithium feature in HD 166473 has been modelled previously by Polosukhina & Shavrina (2007), but they have neglected the Paschen-Back effect and used observations corresponding to the rotational phase of smaller $\langle B \rangle$.

Gelbmann et al. (2000) analysed the atmospheric properties of HD 166473 in detail. They have determined the stellar parameters, $T_{\rm eff} = 7700$ K and $\log g = 4.2$, and inferred a large overabundance of the REEs along with a moderate enhancement of the iron-peak elements. The effective temperature obtained by Gelbmann et al. (2000) has subsequently been confirmed on the basis of detailed analysis of the hydrogen Balmer line profiles (Kochukhov et al. 2002b).

Our theoretical calculations of the Li I line (Sect. 2) show that, for the field strength of HD 166473 and an insignificant line broadening, one should expect to find a strong influence of the partial Paschen-Back effect. In particular, for the fields inclined significantly with respect to the line of sight, the Li line profile acquires a distinct triangular shape, similar to the one observed in the stellar spectrum.

Here we have modelled the Li I resonance doublet in HD 166473 using the model atmosphere parameters and abundances from Gelbmann et al. (2000). The model atmosphere of HD 166473 was calculated with the `LLModels` code (Shulyak et al. 2004), taking individual stellar chemical composition into account and including the approximate treatment of the Zeeman effect in the line opacity (Kochukhov et al. 2005).

Comparison of observations and the spectrum synthesis of the Pr III 6706.703 Å + Li I blend (Fig. 7) suggests that the mean magnetic field vector should be inclined by ≈70° with respect to the stellar surface normal for the field $\langle B \rangle = 8.6$ kG to match the deep central component of the Pr III line. At the same time, a large macroturbulent broadening, $V_{\rm mac} = 9$ km s^{-1}, is needed to fit the line width. Due to the long rotation period of HD 166473, the rotational Doppler broadening can be neglected. The fit illustrated in Fig. 7 was produced using $\log (N_{\rm Pr}/N_{\rm tot}) = -7.20$, $\log (N_{\rm Li}/N_{\rm tot}) = -8.05$ and adopting Gelbmann et al. (2000) abundances for other elements. The oscillator strength of the Pr III line, $\log gf = -1.64$, is from Biémont et al. (1999). The inferred Pr III abundance is consistent with the Gelbmann et al. (2000) estimate of $\log (N_{\rm Pr\,III}/N_{\rm tot}) = -7.60 \pm 0.38$.

Theoretical calculations including the Paschen-Back effect lead to a somewhat better description of the observations compared to the synthesis based on the linear Zeeman splitting of the Li blend components. The latter calculation is unable to match the narrow triangular core of the Li I line even for highly inclined fields. However, significant missing opacity in the 6706.9–6707.5 Å interval and the large broadening complicates the assessment of the partial Paschen-Back effect signature in HD 166473.

3.3. HD 154708

A very strong magnetic field, $\langle B \rangle = 24.5 \pm 1.0$ kG, was detected in Ap star HD 154708 by Hubrig et al. (2005). Their $T_{\rm eff}$ determination led to contradictory results, with the $B2 - G$ temperature calibration of Geneva photometry (Hauck & North 1993) giving $T_{\rm eff} = 6800$ K, while Strömgren photometry (Napiwotzki et al. 1993) pointing to $T_{\rm eff} = 7500$ K. We find that the hydrogen Balmer lines in HD 154708 are reproduced better with the latter $T_{\rm eff}$ value. On the other hand, Geneva photometric indices are known to be susceptible to anomalous line blanketing (Kochukhov et al. 2005). Hence, here we adopt $T_{\rm eff} = 7500$ K for the spectrum synthesis analysis of HD 154708. The model atmosphere for this very peculiar star is calculated with the `LLModels` code, assuming $\log g = 4.0$. This model takes into account preliminary abundance estimates derived from fitting metal lines in the two studied spectral regions and includes the effect of magnetic field on the metal line opacity.

Comparison of the theoretical spectra for a single value of magnetic field strength with the observed profiles of triplet lines shows that a homogeneous magnetic topology, similar to the one used for HD 116114 and HD 166473, is inadequate for HD 154708. While the π components in the spectrum of this star are rather narrow and can be fitted with $v_e \sin i \approx 5$ km s^{-1}, the σ components show an excessive broadening, indicating substantial spread of the field modulus over the visible part of the stellar surface. To account for this property of the field structure in HD 154708, we have modified the disk integration procedure applied to the local profiles produced with SYNTHMAG in such a way that the resulting flux spectra would correspond to a dipolar field aligned with the line of sight (see Sect. 2.2). With this modification, a major improvement in the fit to triplet lines can be achieved for a dipole field with the polar strength of $B_p = 30$ kG (see Kochukhov 2007a). For this geometry the disk-averaged field strength is $\langle B \rangle = 24$ kG, which agrees with the direct measurements.

Inspection of the Li region shows that the feature that could possibly be identified with the split Li I line is blended by the strong line of Pr III at λ 6706.703 Å (Fig. 8). In the 6705.5–6709.0 Å interval, the spectrum of HD 154708 shows 5 line components with the central wavelengths 6706.0, 6706.7, 6707.4, 6707.8, and 6708.4 Å. The first two features can be attributed to the groups of the blueshifted σ and π components of the Pr III line. The other components contain a significant contribution by the absorption due to the Li I line, which exhibits nearly complete Paschen-Back splitting for the field strength of HD 154708. Adopting the magnetic field geometry described above, we are able to identify the feature at λ 6707.4 Å with the blend of the redshifted Pr III σ components and the blueshifted σ component of the Li I triplet. The remaining two features belong to the π and to the redshifted σ components of the Li line.

The spectrum synthesis results presented in Fig. 8 demonstrate the reasonable agreement of the observed profile of the Pr III and Li I blend with the theoretical calculations including the Paschen-Back effect for Li I 6708 Å. These spectra were obtained by adopting the solar system ratio of the Li isotopes and using an enhanced total abundance of this element, $\log (N_{\rm Li}/N_{\rm tot}) = -8.20$. The REE abundances, $\log (N_{\rm Pr}/N_{\rm tot}) = -7.70$, $\log (N_{\rm Ce}/N_{\rm tot}) = -8.20$, $\log (N_{\rm Sm}/N_{\rm tot}) = -8.50$, were used. The relevant REE line parameters (Biémont et al. 1999) were extracted from VALD. The optimal description of the observed spectrum is achieved for $V_{\rm mac} = 7$ km s^{-1}.

As expected, computation for the Zeeman splitting pattern of the lithium doublet produces an unrealistic spectrum with no resemblance to the actual observations. However, even calculations with the detailed Paschen-Back treatment of the Li I line do not reproduce some of the details, in particular the narrow 6707.8 Å component, in the HD 154708 spectrum. We attribute this problem to the simplistic magnetic field topology adopted in our polarised radiative transfer calculations. In reality the field structure probably deviates from a pure dipole, and spectra may be influenced by the horizontal and vertical chemical inhomogeneities. Additional constraints on the magnetic and abundance distributions in HD 154708 require spectroscopic phase-resolved monitoring of this star. Nevertheless, even with the limited data available in the present study, it is remarkable to find that the absorption features observed in the 6708 Å region of HD 154708 coincide with the theoretically predicted positions of the magnetically-split components of the Li I doublet. The latter behaves unusually in the strong magnetic field of this star, and it is very unlikely that such a coincidence (both in the central wavelength and in the splitting pattern) could be due to an unrecognised blending. Thus, observations of HD 154708 lend strong support to the suggestion that the line at 6708 Å in the spectra of cool Ap stars is due to lithium, which is strongly overabundant in the line-forming atmospheric region.

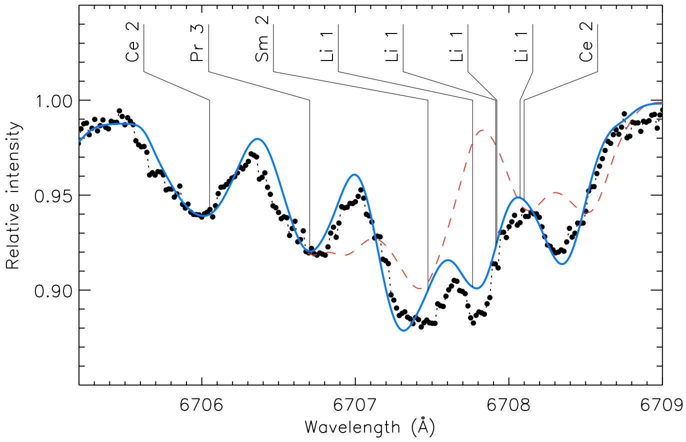

Fig. 8. The same as Fig. 6 for HD 154708.

4. Conclusions

In this study we addressed the question of the unusual behaviour of the Li I resonance doublet in a strong magnetic field. Because of the small separation of the Li doublet components, its magnetic splitting occurs in the partial Paschen-Back regime for the field strengths typically found on the surfaces of magnetic stars. We model in detail the Paschen-Back splitting in the Li transition and present the first polarised radiative transfer spectrum synthesis calculations that take into account the partial Paschen-Back effect for this line. Comparing these calculations with the high-quality spectra of cool magnetic Ap stars, we are able to shed new light on the long-standing problem of the Li I 6708 Å line identification in Ap stars.

The main findings of our investigation can be summarised as follows:

- The presence of significant departures of the Li line splitting pattern from the one expected for the linear Zeeman effect in a moderately strong field is hereby confirmed. The local line profile calculations show that the Paschen-Back effect becomes noticeable in the Stokes V for $B \gtrsim 1$ kG and in the Stokes I for $B \gtrsim 3$ kG, while a major modification of the Li I line profile shape is found for $B \geq 5$ kG. Since the magnetic fields of the Li-rich Ap stars are often stronger than this limit, these results question the validity of the previous attempts (e.g., Polosukhina & Shavrina 2007) to model the Li I line ignoring the Paschen-Back effect.
- Calculations of the disk-integrated Stokes I spectra show that the triplet splitting pattern emerges in the Li I line for $\langle B \rangle \gtrsim 12$ kG, offering a unique opportunity to verify the 6708 Å line identification in Ap stars with a very strong magnetic field.
- A survey of the available high-resolution UVES spectra of cool Ap stars reveals the presence of significant 6708 Å absorption in 15 stars, out of which 6 objects are identified as potentially Li-rich stars for the first time.
- The intensity of the 6708 Å line does not correlate with the overabundance of the REEs, thus invalidating the hypothesis that this line is produced by an unidentified feature of one of the common REE ions. The cases of HD 75445 and HD 217522, which do not show the Li I absorption but are very similar in their REE abundances to known Li-rich

Ap stars, emphasise the difficulty of attributing the 6708 Å line to anything but Li.

- We undertook spectrum synthesis modelling of the Li I line in Ap stars HD 116114, HD 166473, and HD 154708. The last object has the strongest magnetic field among all cool Ap stars, thus representing a unique natural laboratory for studying the Paschen-Back effect in the resonance lithium line. We find that the synthetic spectral calculations, which properly account for the Paschen-Back splitting, improve the fit to the Li I line in the spectra of HD 116114 and HD 166473. For HD 154708, theoretically expected Paschen-Back triplet splitting of the Li I line is detected in the observed spectrum. Given the difficulty of treating the unusually strong magnetic field of this star and the lack of observational constraints for the field geometry, the agreement between the predicted and observed positions and the relative strengths of the resolved magnetic components of the blend containing the Li I line is deemed satisfactory. For all three stars, we need roughly 2.6–2.9 dex overabundance of Li relative to the chemical composition of the solar photosphere to fit the observed line profiles.

In short, we confirm the Li I identification of the 6708 Å line in cool Ap stars. The puzzling diversity of the strength of the Li absorption in stars with similar atmospheric parameters suggests that this element is sensitive to the time-dependent diffusion effects (Alecian 1998) or is possibly influenced by the chemical weather recently discovered in the non-magnetic, chemically peculiar stars (Kochukhov et al. 2007b). The interesting and diverse behaviour of Li in cool Ap stars challenges modern atomic diffusion theories (e.g., Alecian & Stift 2006) to find a satisfactory explanation for the accumulation of this element in the line-forming atmospheric layers.

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Note added in proof. In a publication, which appeared after submission of the present paper, Stift et al. (2008) presented a theoretical study of the partial Paschen-Back effect for a number of Fe and Cr lines observed in Ap stars. They have also calculated the Paschen-Back splitting for the Li I line, illustrating their results with a figure similar to Fig. 1 of the present paper.

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