Spectrum variability of the roAp star HD 60435 in the red region*

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Received: June 20, 1998

Abstract. We present a study of high dispersion CCD spectra of the roAp star HD 60435 taken in the ranges 6123-6175 Å and 6675-6735 Å. Variability of both the equivalent width and radial velocity of the neutral lithium line at 6708 Å was found out. We also noticed a variability of equivalent width of stronger lines of Fe, Ca and Pr, though to a lesser extent. Effective temperature and surface gravity were derived using photometric calibrations. Abundances of identified elements were estimated. Aluminium is deficient by a factor of 20, Si and Sc are only slightly deficient. Fe and Ni are normal, Ca and Ti slightly overabundant. Cr, Mn and Co are overabundant by a factor of 15 to 25. Of rare earths, La, Ce and Gd are overabundant by a factor of 3 to 10, Sm and Nd by factors of 30 and 60 and Eu and Dy by factors of 150 and 300. Lines of Pr III were indentified but many absorptions, mostly in blends, remain unidentified.

Key words: chemically peculiar stars – lithium 6708 Å-blend – spectrum variability – atmosphere parameters – elemental abundances

1. Introduction

HD 60435 (BD $-57°1246$, V 409 Car, A3 SrEu, V=8.898 mag) is a variable, roAp star. Kurtz (1984) discovered its rapid oscillations with a frequency of 123.7 c/d and a peak-to-peak amplitude of 15.7 mmag in B. Matthews et al. (1986) observed broadband light oscillations and slow photometric and spectroscopic variations confirming the oblique pulsator model. Performing magnetic observations, Matthews et al. (1987) resolved, in additon to the above mentioned main frequency, equally spaced frequencies from 12 to 20 min of fundamental spacing 50-55 μHz, matching model predictions for the p-mode spectrum of a slightly evolved A star. They mentioned a possible magnetic field up to 2 kG. Kurtz et al. (1990) determined the period, P=7.6793 d, of the rotational double-waved light curve. Taylor et al. (1993), using the high-speed HST ultraviolet

*Based on observations obtained at the European Southern Observatory, La Silla, Chile photometer, observed a strong amplitude modulation of the frequency and resolved three other close oscillation frequencies. Boyd et al. (1995) observed a variation of the main frequency during observation. Kurtz (1993) derived the effective temperature $T_{\rm eff}$ = 8200 K.

To our present knowledge, no systematic spectroscopic investigation has been published. In this paper we attempt to estimate atmosphere parameters and to explain the observed spectra by means of spectrum synthesis.

2. Observations

This star is included in the project "Lithium in magnetic CP stars" (Hack et al., 1997b). Seven high-dispersion CCD spectra in the region 6675-6735 Å and one (# 22) in 6123-6175 Å were obtained in March 8-14, 1996 with the ESO CAT telescope and reduced by one of us (PN) using the standard IHAP procedures. The resolving power was R = 100 000, and the S/N ratio of an individual spectrogram is better than 100 per resolution element at the 1σ level. The journal of observations is given in Table 1, where phase is calculated for P=7.6793 d and an arbitrarily selected JD_0 = 2450150.224.

Table 1. Journal of the observations, W_λ and RV.

Sp.	HJD	Phase	Σ W_λ[mÅ]				RV [kms^{-1}]		
#	-2450000		Fe I	Ca I	Li I	Pr III	Fe I	Ca I	Li I
03	150.608	0.050	120	62	50	34	20.2	19.7	19.2
13	151.647	0.185	118	77	83	41	20.2	20.5	16.4
21	152.558	0.304	164	91	135	76	19.6	20.7	18.2
22	152.635								
33	153.560	0.434	159	80	128	70	20.0	21.1	21.6
47	154.701	0.583	138	75	68	55	20.6	20.4	23.6
60	155.642	0.706	142	77	52	51	20.0	19.6	16.2
78	156.583	0.828	151	77	72	56	19.7	19.4	18.4

3. Spectrum and RV variability

The seven spectrograms examined are well distributed over the rotational period of the star, which enabled us to demonstrate the spectrum variability. The most remarkable feature of the region observed is the strong Li I 6708 Å blend, showing pronounced equivalent width variability, see Fig. 1. While its equivalent width (W_λ) varies from 50 to 135 mÅ, the equivalent width of the second strongest line, Ca I 6718 Å, changes from 62 to 91 mÅ and the equivalent width of the strongest Fe I line at 6678 Å changes from 44 to 55 mÅ. In Tab. 1, sums of equivalent widths of eight Fe I lines (6677.9, 6692.2, 6705.1, 6713.0, 6713.8, 6715.4, 6716.2 and 6716.8 Å), equivalent widths for Ca I 6717.6 Å and Li I 6708 Å -lines, and sums of two Pr III lines (6706.7 and 6727.6 Å) are given in columns 4, 5, 6 and 7 respectively.

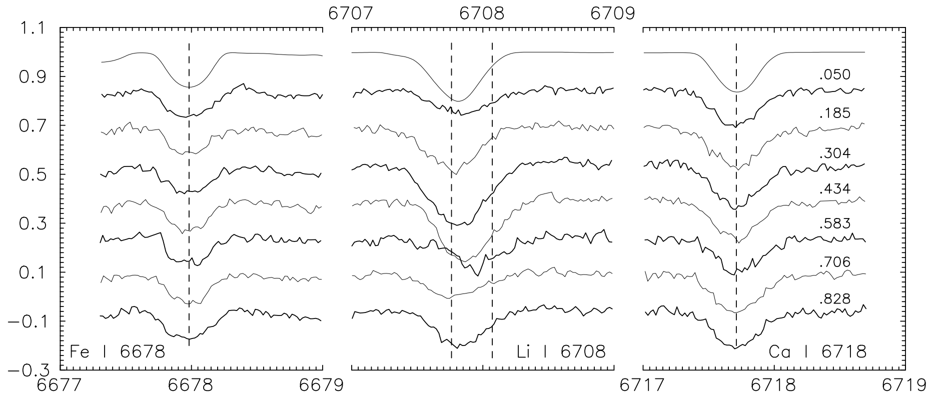

Figure 1. Profile variations of the Li I 6708 Å line with rotational phase (top to bottom, phase indicated to the right). Profiles of Fe I 6678 Å and Ca I 6718 Å as well as the synthetic spectrum (upper smooth line) are shown too as a reference. The dashed lines marks central wavelengths of the Fe I, ^{7}Li, ^{6}Li and Ca I lines respectively.

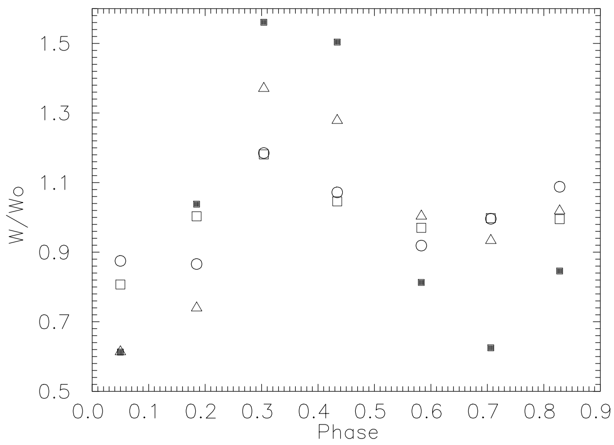

Figure 2. Relative variations of W_λ for Fe I (∘), Ca I (□), Pr III (Δ) and Li I (full squares) lines.

In Fig. 2 the relative changes of equivalent widths are shown, in units of $W_\lambda/\overline{W_\lambda}$. Even though the relative variations of the other elements follow the one for the Li line, their relative amplitudes are significantly smaller. Unlike the equivalent widths, significant radial velocity variations are present only in the

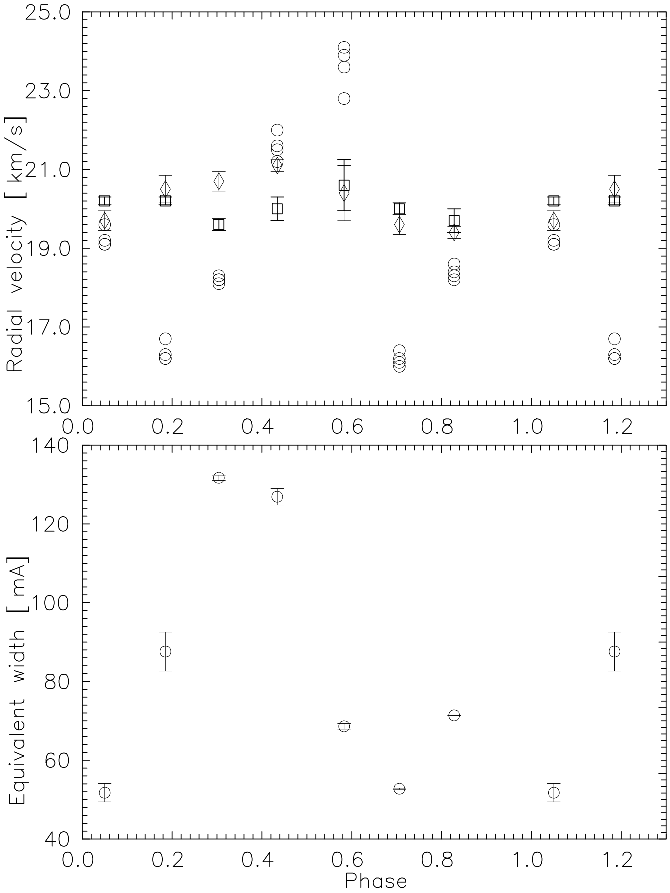

Figure 3. *Upper:* radial velocity curves for ◦: Li I, □: Fe I, ◇: Ca I; error bars show the scatter of the four measurements of the iron and calcium lines. *Bottom:* W_λ curve for the Li I 6708 Å line. Averages of two measurements are shown; error bars are the differences between those two measurement of W_λ.

case of the Li line. In Fig. 3, upper part, the RV changes calculated for ^{7}Li, λ 6707.836 Å, vs. the rotational phase are displayed. The radial velocities were measured four times by means of: polynomial fitting of a line profile, center of mass method, sliding integrations and a reverse profile fitting. While the RV scatter around the average radial velocity within ≤ 0.5 and $\leq 0.7\,\mathrm{km\,s^{-1}}$ for the Fe I 6678 and Ca I 6718 Å lines, respectively, the RV for the Li line varies from 16.2 to 23.6 $\mathrm{km\,s^{-1}}$. Table 1 lists the averages of the four measurements for the three lines on each spectrum. The radial velocity curve of the lithium line is typical of what is expected from a spotted CP star, suggesting that the surface distribution of Li is far from homogeneous, if the line is indeed due to this element.

The possible occurence of a lithium spot or a cloud on the surface is supported by the phase shift of the equivalent widths extrema in comparison with the radial velocity curve, see Fig. 3, bottom part. The peak-to-peak amplitude of the RV curve amounts to about 7 $\mathrm{km\,s^{-1}}$, which is consistent with $v\ \sin i \approx 11\,\mathrm{km\,s^{-1}}$, derived by fitting synthetic profiles of the iron an calcium lines to the observed ones. The $v\ \sin i$ obtained from the Li I line alone changes from 6.5 to 12 $\mathrm{km\,s^{-1}}$, which also agrees with the spot explanation, since the smaller value is for maximum radial velocity and the higher one for the phase corresponding to the subsolar transit of the spot. However, for the spectrum with the minimum RV, we determined as much as $v\ \sin i = 9\,\mathrm{km\,s^{-1}}$, which suggests that the interpretation is not so simple. If one accepts the explanation of the curve in terms of surface spots, then one has to admit the existence of two of them: besides a main spot, which is seen in the spectra between phases 0.185 to 0.583, another spot appears between phases 0.706 to 0.05. The second spot can also be responsible for the asymmetry of the profile on spectra taken at phases 0.185, 0.434 and 0.706. The first and the last spectrum of these three define the beginnings of the individual 'spot' curves, while the asymmetries of the corresponding profiles are of opposite signs. However, no continuation of the 'second spot' curve can be seen in spectra at phases 0.185 and 0.304. This casts doubt on the existence of a spot and suggests an explanation by means of the ^{6}Li isotope in the lithium mixture. Nevertheless, this explanation of the profile variation assumes a rotationally dependent spot visibility too. The ^{6}Li problem is discussed below.

4. Analysis

4.1. Determination of T_{eff} and $\log g$

Besides the above mentioned determination of effective temperature by Kurtz, Renson et al. (1991) give $T_{\mathrm{eff}} = 7716$ K, together with *uvby* indices. Using the '$uvby\beta$' code (Moon & Dworetsky 1985) for A3-F0 stars and Renson's data, we obtained $T_{\mathrm{eff}} = 7770$ K and using the TEFFLOGG code (Smalley & Dworetsky 1995), $T_{\mathrm{eff}} = 7800{\pm}30$ K, $\log g = 4.11{\pm}0.06$. For the same indices we determined $T_{\mathrm{eff}} = 7609$ and 7724 K according to Napiwotzky et al. (1993) and Hauck & Künzli (1996), respectively. Kurtz (1993), using the same data and calibration by Moon & Dworetsky (1985), derived $T_{\mathrm{eff}} = 8200$ K. We obtained $T_{\mathrm{eff}} = 8220 \pm 30$ K and $\log g = 4.40 \pm 0.06$ when processing the indices in the A0-A3 group, with the code of Moon & Dworetsky (1985).

From the Geneva photometry (Rufener, 1980), we derived $T_{\mathrm{eff}} = 7716$ and 7763 K according to Hauck & North (1982) and Hauck & Künzli (1996), respectively. Using the calibration of Künzli et al. (1997) and their CALIB code, we derived $T_{\mathrm{eff}} = 7745 \pm 75$ K, $\log g = 4.52 \pm 0.07$ and $[M/H] = 0.53 \pm 0.07$.

Despite of the fact that the determination from the $uvby\beta$ photometry is based on a calibration devised for 'normal stars', the mean value $T_{\mathrm{eff}}(uvby\beta) =$

7724 K obtained using the code for the A3-F0 group is in excellent agreement with the one derived from the Geneva photometry, $T_{\rm eff} = 7745$ K. A significant difference, however, is in the $\log g$ determination, the value from $uvby\beta$ being smaller by 0.41 dex at the same temperature. On the other hand, there is a good agreement between the surface gravity values resulting from Geneva photometry and from the $uvby\beta$ indices processed within the A0-A3 group.

Unfortunately, all above estimates are sensitive to a possible interstellar reddening, because there is no β-index value available in the literature. In such a case, both $uvby$ and Geneva photometries are unable to disentangle the effects of reddening and $T_{\rm eff}$. In any case, it must be reminded that because of the very distorted energy distributions of Ap stars, photometric surface gravities are generally strongly biased for them, and most often overestimated.

4.2. Synthetic fit, $T_{\rm eff} = 7745$ K, $\log g = 3.0$

We used the SYNSPEC code (Hubený, 1987; Zboril, 1989) for detailed profile computations. The VALD database for atomic line data (Piskunov et al. 1995) was used. First we computed a synthetic spectrum with a model atmosphere from Kurucz' (1993) grid interpolated for $T_{\rm eff} = 7745\,{\rm K}, \log g = 4.52$. To estimate a microturbulent velocity, we fitted profiles of weak Fe I lines at 6705.101, 6713.046 and 6713.791 Å (with 'solar-adjusted' $\log gf$-values, Iliev et al. 1998), and a moderately strong Fe I line at 6677.987 Å. While for normal iron abundance, $\log(N/N_{\rm H}) = -4.37$, a good fit for the weak lines was obtained, the computed line 6677.987 Å was significantly stronger than the observed one even for $\xi_{\rm turb} = 0$, the opposite to anything expected. Likewise, a weak Fe II 6675.305 Å line could not be matched simultaneuously with the weak Fe I lines for one value of abundance because the observed Fe II line is too strong. An acceptable fit could be reached only with a surface gravity significantly lower than the one from photometric calibrations. This was confirmed also in the 6150 Å region, where suitable, moderately strong lines of Fe I (6136.615, 6137.692 Å) and Fe II (6147.741, 6149.258 Å) occur, see Fig. 4. Here we used a model with $T_{\rm eff} = 7745\,{\rm K}, \log g = 3.00$, zero microturbulence and slightly lower abundance of iron, $\log(N/N_{\rm H}) = -4.52$. However, the discrepancy between the weak Fe I lines and the Fe I λ6177.987 line persists. This is even more inconsistent, since the magnetic field should intensify the line and the 'pseudomicroturbulence' corresponds, for its Landé factor (Romanyuk 1984), to 1.9 km s^{-1} (Ryabchikova & Piskunov 1986), a value which increases the equivalent width of the line from 53 to 68 mÅ. We assume that these inconsistencies might arise from the abnormal atmosphere of the roAp star, which is oscillating in a complex way. The Fe I/Fe II discrepancy might also be a manifestation of the element stratification.

Abundances of some elements were estimated by means of synthetic spectrum. As no pronounced radial velocity variations were observed except for the Li-line, the seven spectra were co-added (with the Li-feature prewhitened) to obtain an 'average' spectrum which was then compared with computed ones for two

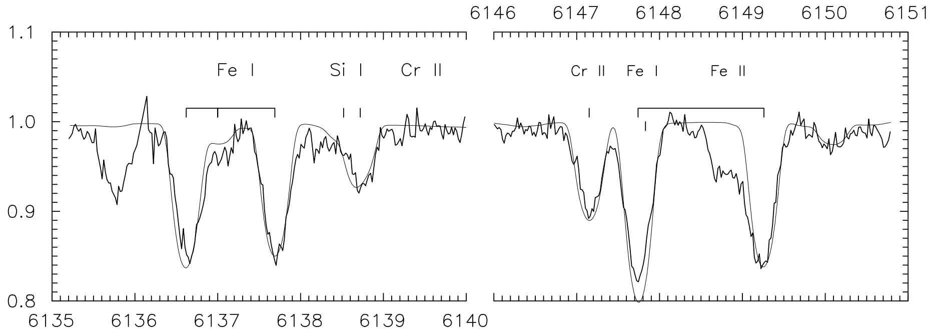

Figure 4. Profiles of the Fe I and Fe II lines in the 6150 Å region. Thick line: observed, thin: computed spectrum for $T_{\rm eff}$ = 7750 K, $\log g$ = 3.0, iron abundance $\log(N/N_{\rm H}) = -4.52$. The computed spectrum is widened with a gaussian instrumental profile of FWHM=0.05 Å, and a rotational one with $v \sin i = 11\,{\rm km\,s^{-1}}$.

atmosphere models, $T_{\rm eff} = 7745\,{\rm K}, \log g = 3.0$ and $T_{\rm eff} = 8250\,{\rm K}, \log g = 4.5$. Although the lines occur mostly in blends and many absorptions remain unidentified, even a 'slight' deficit or overabundance is significant in the sense that it is needed to reach an acceptable fit. Aluminium is deficient by a factor of 20, Si and Sc are only slightly deficient by factors of 0.4 and 0.7 respectively. Fe and Ni are normal, Ca and Ti slightly overabundant by factors of 2 and 3 respectively. Cr and Co are overabundant by a factor of 25 and Mn by a factor of 15. Among rare earths, La is overabundant by a factor of 3, Ce and Gd by a factor of 10. Sm is overabundant by a factor of 30, Nd by a factor of 60, Eu by a factor of 150 and Dy by 300. Ba is only in slight deficit for the cool model and slightly overabundant for the hot one. Lines of Pr III were identified and many absorptions, mostly in blends, remain unidentified.

4.3. Lithium

In the literature, a possible occurence of ^{6}Li on magnetic Ap stars was discussed (Faraggiana et al. 1996, Hack et al. 1997a). A contribution of this isotope could explain the asymmetry in the red wing of the 6708 Å line profile. Even if the asymmetry can be a result of magnetic splitting of the ^{7}Li doublet (Mathys 1990) and as production of the ^{6}Li isotope in Ap stars and its way to the surface are unknown, we tried to fit the observed profile with a synthetic one which originates from a mixture of both isotopes. We considered lines of ^{7}Li at λ 6707.761 and 6707.912 Å and lines of ^{6}Li at 6707.922 and 6708.072 Å (Kurucz,1995). We were able to reach excellent fits of computed profiles to observed ones on all spectra and obtained different values of the ^{6}Li/^{7}Li ratio, which ranges from 0 to 0.6 with one extremum value, 4, for spectrum No. 47, and the abundance of lithium (^{7}Li), $\log(N/N_{\rm H})$, varying from -9.00 to -7.84. At this point a question arises as to the origin of the line and isotopic ratio variability. If it should come from an inhomogeneuous distribution of lithium over the surface of a rotating star, then no contribution of ^{6}Li is needed as ^{7}Li alone in one (two) spot(s) explains the observations, as is shown in paragraph 3. Moreover, no radial velocity shift was taken into account while calculating the combined profiles, while it should certainly be done if the isotopes occurred in spots. A further doubt comes from the fact that no phase dependence of the isotopic ratio is evident. Thus a model with ^{7}Li alone is sufficient, although the presence of the other isotope on the surface of this Ap star might be explained by the effect of ambipolar diffusion of hydrogen, as suggested by Babel (1993).

4.4. Synthetic fit, $T_{\rm eff} = 8250$ K, $\log g = 4.5$

The significant disagreement between the $\log g$ values derived from photometry and from the Fe I/Fe II equilibrium incited us to pay attention to the effective temperature of about 8200 K, which was obtained when the star was processed in the group of A0-A3 stars of the Moon & Dworetsky (1985) code. Here a very good fit to the observed Fe I and Fe II lines in the 6150 Å region can be reached for normal iron abundance as shown in Fig. 5. Also acceptable is a fit for the weak Fe I and Fe II lines in the 6705 Å region.

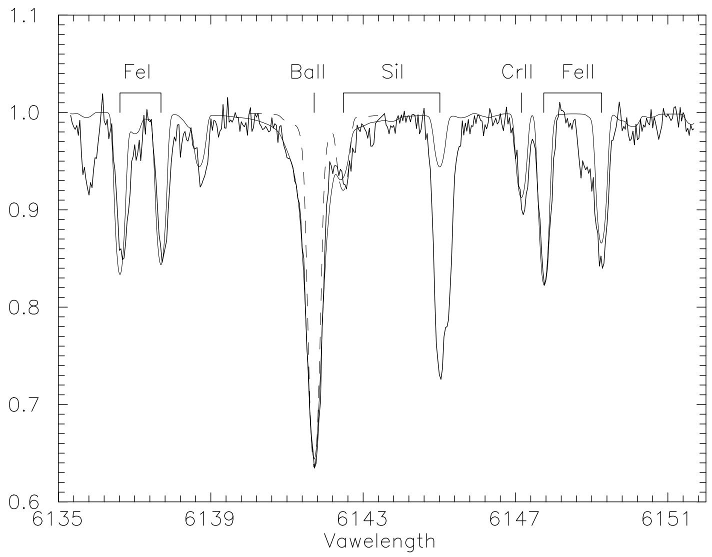

Figure 5. Profiles of the Fe I, Fe II and Ba II lines in the 6150 Å region. Thick line: observed, thin: computed spectrum for $T_{\rm eff} = 8250$ K$, \log g = 4.5$, iron abundance $\log(N/N_{\rm H}) = -4.37$, barium abundance $\log(N/N_{\rm H}) = -9.52$. The dashed line is for the 'normal' $\Gamma_{\rm rad} = 5.9\,10^7$, and to reach the observed central depth of the Ba II line, the barium abundance had to be increased by a factor of 260; in spite of that, the wings remain narrow.

5. Other absorption features

5.1. Ba II 6141.713 Å

The 6150 Å section is dominated by the Ba II 6141.713 Å line. For its relatively small depth, 35%, the line displays unusually wide wings. It was possible to fit them only using an unusually high value of the radiative damping constant, $\Gamma_{\rm rad} = 1.26\ 10^{11}$, while its approximate expected value is $\Gamma_{\rm rad} = 5.9\ 10^{7}$ (Hubený 1987), no matter whether the lower or the higher effective temperature model is used. The only difference is in the value of the barium abundance, which is $\log(N/N_{\rm H}) = -10.05$ for $T_{\rm eff} = 7750$ K, $\log g = 3.0$, thus being in a weak deficit, and $\log(N/N_{\rm H}) = -9.52$ for $T_{\rm eff} = 8200$ K, $\log g = 4.5$, being weakly overabundant relative to the solar value, $\log(N/N_{\rm H}) = 9.91$. The fit is illustrated on Fig. 5. The large $\Gamma_{\rm rad}$ we have to use might result from a neglected hyperfine structure, unless it is simply due to a blend.

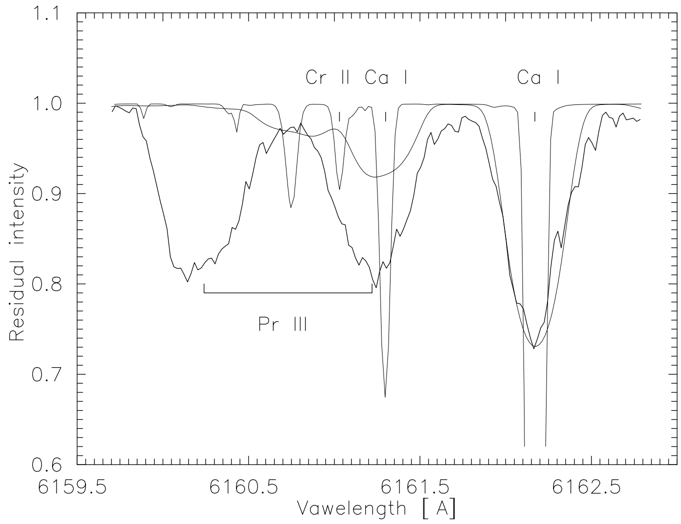

Figure 6. Profiles of the Pr III lines in the 6150 Å region. Thick line: observed, thin: computed spectrum, $T_{\rm eff} = 7750$ K, $\log g = 3.0$. The narrow profiles are unwidened.

5.2. Rare earths elements

Besides well identified lines, there are many lines left unidentified. Fitting the synthetic and observed spectra, we find a few well defined absorptions as well as blends in known lines which cannot be matched using atomic databases available, due to lack of gf data. Good examples are lines of Pr III λ 6160.244, 6161.224, 6706.705 Å (Mathys & Cowley 1992) and 6727.630 Å (Sugar 1974). In spite of checking the catalogue by Reader & Corliss (1980) as well as the sources given in Adelman & Snijders (1974) and Adelman (1978) for rare earth elements data, no other observed features were identified. Among them are λ 6687.7 Å (W_λ 18 mÅ), 6690.8 (28), 6692.2 (10), 6693.3 (10), 6713.0 (11) and blends with Fe I at 6705.1 (16) and Si I at 6721.8 (38). In the 6150 Å region, two other strong Pr III lines occur at λ 6160.244 Å and 6161.224, blending with Ca I 6161.297 Å. Unidentified features are λ 6135.8, 6145.0 in a blend with Si I and 6148.8 in a blend with Fe II 6149.238 Å. It was not possible to reach a better fit of the synthetic to observed spectra, because too many weak absorptions remain unidentified.

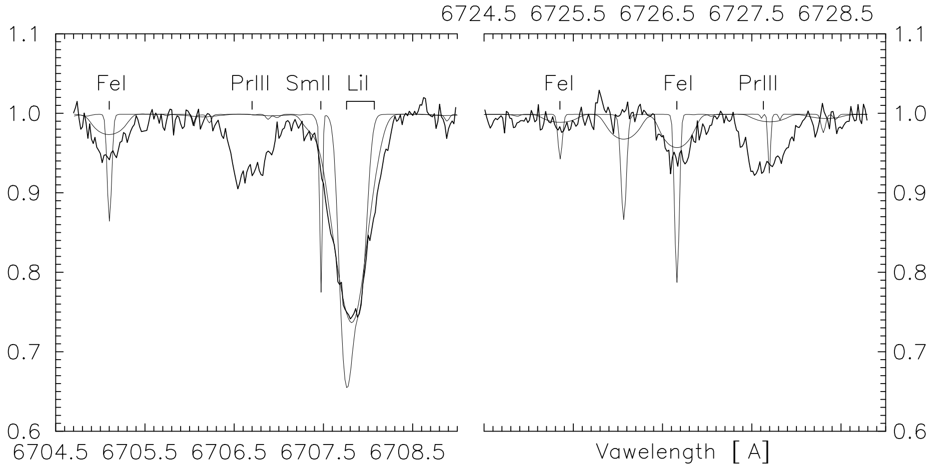

Figure 7. Profiles of the Pr III lines in the 6705 Å region, $T_{\rm eff} = 7750$ K, $\log g = 3.0$.

6. Conclusions

The variability of the lithium line indicates a non-uniform distribution of lithium over the surface of the star. Such a distribution may be explained by diffusion in the presence of a magnetic field. However, the corresponding magnetic intesification was not observed: even though the Landé factor of the Fe I 6678 Å line is relatively significant, the zero microturbulence implies no magnetic intensification and thus no magnetic field. This inconsistency is assumed to arise from the complicated atmospheric structure of a rapidly oscillating magnetic star with time dependent oscillations or, more probably, from the effect of vertical stratification of the iron abundance. We attempted to explain the wavelength shift of the lithium line in terms of possible occurence of the ^{6}Li isotope. As such an interpretation needs the occurence in spots too, we conclude that ^{7}Li in one or two spots is sufficient to explain the observations. The complicated atmospheric structure is further indicated by the dichotomy of atmospheric parameters derived from photometry and stressed by the surface gravity value implied by the Fe I/Fe II equilibrium. Indeed, Matthews et al. (1987) deduced a slightly evolved state from asteroseismology, but the surface gravity $\log g = 3.0$ implies a giant star, which certainly is more than 'slightly evolved'. Interesting features of the red spectrum are the curious Ba II line, the occurence of the four relatively strong Pr III lines, as well as many absorptions which remain unidentified.

Spectra covering a wider spectral range would be useful for the atmosphere analysis, as well as a better phase coverage for a better definition of the radial velocity curve of the lithium line.

Acknowledgements. The VALD atomic database was found very useful. We thank Dr. J. Grygar, Institute of Physics, Academy of Sciences of the Czech Republic, and Mrs. Hammond, Kresge-Physical Science Library at Dartmouth College, Hanover, NH, USA, for their kind assistance in obtaining additional literature with rare earth elements line lists. The authors thanks Dr. Budaj for his valuable comments. JZ is indebted to Prof. Werner W. Weiss, Institute for Astronomy, Vienna, whose financial assistance helped him to participate in the Vienna's meeting in October '97 where the article was presented as a late poster. This work was partly supported by a VEGA grant No. 4175/97.

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