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Abundance analyses of roAp stars

VI. 10 Aql and HD 122970*

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Abstract. In this sixth paper in a sequence on abundance analyses of roAp stars we present the results for two further members of this group, which are fairly similar and have only a small magnetic field. The analysis of 10 Aql and HD 122970 did not require, for the first time in this long term project, the development of tools and hence was rather straight-forward. We reanalyzed Sm, Eu and Gd in HD 203932, because better atomic parameters have become available with VALD-2; and for Eu we also took hyperfine-structure effects into account.

Similar to the five roAp stars analysed so far (α Cir: Kupka et al. 1996, HD 203932: Gelbmann et al. 1997, γ Equ: Ryabchikova et al. 1997a, HD 24712: Ryabchikova et al. 1997b, and HD 166473: Gelbmann et al. 2000) we find nearly solar abundances of Fe and Ni, and a definite overabundance of Cr and especially Co, with large overabundances of rare earth elements. This pattern seems to be a common property of chemically peculiar (CP2, Ap) stars. HD 101065 (Przybylski's star), another roAp star, has a similar peculiarity pattern, except of iron (Cowley et al. 2000) which is underabundant.

10 Aql and HD 122970 provide another example for the anomalous line strengths of the second ions of rare earth elements resulting in an abundance increase of up to 2 dex (!) compared to values obtained from lines of the first ions. As we mentioned in an earlier paper, this anomaly yet is not found in non-roAp and "normal" stars.

Key words: stars: abundances – stars: chemically peculiar – stars: individual: 10 Aql, HD 122970 – stars: magnetic fields – stars: oscillations

1. Introduction

The present paper is part of a project on abundance analyses of rapidly oscillating (roAp) stars with the goal of providing accurate fundamental parameters for this group of pulsating stars (Paper I to V), especially $T_{\rm eff}$, $\log\ g$ and abundances of as many chemical elements as possible. In a previous paper of this series we found for the atmosphere of HD 166473 (Gelbmann et al. 2000 - Paper V) an anomalous behaviour in different ionization stages for some of the rare-earth elements (REE). Anomalous intensities of Pr III and Nd III lines relative to the lines of the first ions of the same elements in spectra of roAp and non-roAp stars were studied by Ryabchikova et al. (2000) who found this anomaly to be typical for roAp stars, because it cannot be found in spectra of non-roAp stars. Furthermore, it was shown for the roAp star γ Equ that pulsations cause the largest radial velocity amplitudes in Pr III and Nd III lines (Malanushenko et al. 1998). In this paper we perform detailed abundance analyses for two sharp-lined roAp stars: 10 Aql and HD 122970.

10 Aql (HD 176232, HR 7167, mag(V) = 5.89) was discovered as roAp star by Heller & Kramer (1988) with a pulsation period of about 11.9 min and an amplitude, ΔB, well below 1 mmag. The similarity of this star to γ Equ was already mentioned by Wolff (1983) and except for light and intermediate REE (Magazzu & Cowley 1986) no systematic abundance analysis was published.

HD 122970 (mag(V) = 8.30) is a roAp star recently discovered in the northern hemisphere (Handler & Paunzen 1999) with a pulsation amplitude of 2.0 mmag and a period of 11.1 min. $uvby\beta$ photometry (Hauck & Mermillod 1998) indicates that HD 122970 is one of the coolest roAp stars. Except for a spectral classification (F0) no further spectroscopic information is published for HD 122970 according to a SIMBAD based survey.

Observations are described in Sect. 2, and data reduction in Sect. 3 and Sect. 4, which mainly are concerned with the choice of atmospheric parameters, rotation period and magnetic field

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[*] Based on observations obtained at Crimea and McDonald Observatories

parameters, while abundance results are given in Sect. 5. Possible abundance stratification scenarios are briefly discussed in Sect. 6.

2. Observation and reduction of the spectra

CCD spectra of 10 Aql were obtained at different observatories using different spectrographs. Spectra in the $\lambda\lambda$6110–6177 region were obtained by IS during 8 nights in the period from Sept. 1998 to Sept. 1999 at the coudé focus of the 2.6 m Shajn reflector of the Crimean Astrophysical Observatory as a part of a RV-variability programme on roAp stars. A total of 160 spectra with a resolution of 27000 was obtained and averaged for the abundance analysis. The reduction procedure was the same as is described in Ryabchikova et al. (1999a). High resolution echelle spectra of 10 Aql and HD 122970 were obtained by AH on July 26, 1997, and on Jan. 30, 1998, with the 2dcoudé spectrograph (Tull et al. 1995) of the 2.7 m telescope at McDonald Observatory. The instrument provides a nominal wavelength coverage of 4000–10000 Å per exposure when using a Tektronix 2 k^2 CCD detector. The observations were taken as part of a programme to study the radial velocity behaviour of the stellar pulsations, hence only a subframe of the CCD was readout in order to minimize the readout time. Consequently, only the 4700–7070 Å region was recorded. The measured full width at half maximum of thorium calibration lines was 2.2 pixel, yielding an effective resolving power of R = 56000. Bias subtraction, flat fielding, and scattered light subtraction was done with IRAF. The wavelength calibration is based on a Th-Ar comparison spectrum and low-order cubic spline fits provided the continuum estimate. As this procedure is unreliable in the wings of hydrogen lines we did not use these spectral regions to determine atmospheric parameters.

Heliocentric radial velocities were obtained for 10 Aql (+19.1 $\pm$ 0.1 km s^{-1}) and for HD 122970 (-31.8 ± 0.5 km s^{-1}). For 10 Aql we found RV measurements ranging from +13 km s^{-1} to +15.9 km s^{-1} in the SIMBAD data base, and Mathys et al. (1996) gave +17.9 $\pm$ 0.4 km s^{-1}. The scatter of radial velocity values obviously exceeds the quoted errors which makes 10 Aql a good candidate for a long period binary system. No published radial velocity value for HD 122970 could be found in SIMBAD.

Equivalent widths were measured using the MULTIPROFILE code (Smirnov & Ryabchikova 1995) which approximates an observed spectrum by Gaussian profiles. A lower limit for the equivalent width measurements is estimated to be 1.0–1.5 mÅ. No systematic differences were found between spectra obtained at Crimean and McDonald observatories.

The Vienna Atomic Line Database (VALD-2: Kupka et al. 1999, Ryabchikova et al. 1999b) was extensively used for line identifications and synthetic spectrum calculations. In addition we used line lists for Ce II (Corliss 1973) and P III (Sugar 1974), and a line identification list of HD 101065 (Przybylski's star) for other REE elements whose lines are not included in VALD-2 (see Cowley et al. 2000, and www.astro.lsa.umich.edu/users/cowley/prznew2.html).

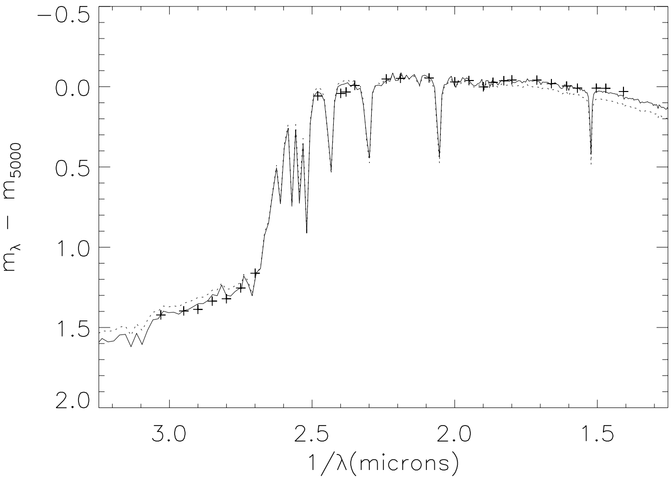

Fig. 1. A comparison between observed (crosses) and computed spectrophotometry for two models of 10 Aql: 7550g40p00 (full line) and 7760g41p00 (dotted line).

Due to the sharpness of the spectral lines, the high S/N ratio and spectral resolution we were able to produce the hitherto most complete line identification list for cool Ap stars for the 4730–7070 Å spectral region. (http://ams.astro.univie.ac.at)

3. Effective temperature and surface gravity

Strömgren photometry taken from the catalogue of Hauck & Mermillod (1998) and the calibration from Moon & Dworetsky (1985) indicate a $T_{\rm eff}$ = 7760 K and $\log g$ = 4.10 for 10 Aql and a $T_{\rm eff}$ = 6956 K and $\log g$ = 4.36 for HD 122970. The problem of deducing fundamental parameters for CP stars from Strömgren indices calibrated with normal stars is well known and for HD 122970 was also discussed by Handler & Paunzen (1999).

For HD 122970 we tried an alternative approach via the Hipparcos parallax (Perryman et al. 1997). To estimate the maximum reddening we followed Matthews et al. (1998) and found it to be negligible. The bolometric correction $BC = 0.06$ mag was obtained by interpolation between data for twelve roAp stars (Matthews et al. 1998) and we obtained $M_{\rm V} = 2.69 \pm 0.28$ mag. The calibration of Crawford (1975) for β and $M_{\rm V}$ resulted in "corrected" $c_1 = 0.617 \pm 0.030$, which gives the atmospheric parameters $T_{\rm eff}$ = 6930±100 K and $\log g$ = 4.11±0.1 using the calibration of Villa (1998). The effective temperatures obtained by the two different methods are identical whereas the second method gives a lower surface gravity which would be consistent with the concept of roAp stars being evolved from the ZAMS. It has to be stressed that this low effective temperature locates the star outside the empirically determined cool border of the δ Scuti instability strip.

Spectrophotometry of 10 Aql (Adelman 1981) could be best fitted with $T_{\rm eff}$ = 7550 K, $\log g$ = 4.0, $\xi_{\rm t}$ = 2 km s^{-1}, assuming solar metallicity. The effective temperature of 7760 K derived with the Moon & Dworetsky (1985) calibration does not fit the Paschen continuum (Fig. 1). Similar to HD 122970 it is possible to derive an estimate for the surface gravity from the Hipparcos luminosity. This latter value, $L/L_\odot$ = 21.4, was taken from Matthews et al. (1998). Using the Warsaw-New Jersey stellar evolution and pulsation code (Pamyatnykh et al. 1998) we derive $M = 2.0 \pm 0.2\,M_\odot$ and two values for the stellar radius, depending on the chosen $T_{\rm eff}$: $R = 2.50 \pm 0.2\,R_\odot$ ($T_{\rm eff}$=7550 K), and $R = 2.38 \pm 0.2\,R_\odot$ ($T_{\rm eff}$=7760 K), respectively. This leads to $\log\,g$ = 3.95±0.25 and $\log\,g$ = 3.99±0.25, respectively, with both values being in agreement with spectrophotometry, but being smaller than what was derived from the Strömgren photometry. We decided to choose the 7550g40 model for our further analysis as it reproduces all the observations best.

4. Magnetic field and rotational velocity

Already a quick inspection of the HD 122970 spectrum reveals that some spectral lines, mainly those of the rare-earth elements, are systematically wider than others, which suggests the presence of a magnetic field. These lines were synthesized with the SYNTHMAG code (Piskunov 1999) taking a magnetic field in the transfer equations into account. A simplified model with a uniform radial magnetic field was used for the same reasons as are explained in Paper V. Our calculations showed that a magnetic field with a mean field modulus $B_{\rm s}$ = 2.3 kG is needed to fit the REE lines while the Fe lines call for only $\sim$2.0 kG. The corresponding Zeeman patterns would be resolvable with a spectral resolution twice as high as that of our data.

Modelling spectral lines of different elements requires slightly different rotational velocities. We obtained $v \cdot \sin i$ = 5.5±0.5 km s^{-1} for iron-peak elements and $v \cdot \sin i$ = 4.5±0.5 km s^{-1} for REE. The difference is within the error limits, but nevertheless systematic and it may indicate an inhomogenous abundance distribution similar to what we observe for another cool roAp star, HD 24712.

A comparison between observed and synthetic spectra, based on different rotational velocities and magnetic field moduli is shown in Fig. 2 for Fe I lines and in Fig. 3 for REE lines.

A similar investigation was performed for 10 Aql. Magnetically sensitive REE lines are much weaker in the spectrum of this star than for HD 122970 and are not well suited for a magnetic synthesis. The procedure applied to the same pair of Fe I lines allows only to estimate the magnetic field modulus crudely to be $\sim$1 kG with $v \cdot \sin i$ = 5 km s^{-1} as an upper limit. Preston (1970) measured an effective magnetic field of $+500 \pm 100$ G and a $v \cdot \sin i \leq$ 5km s^{-1}.

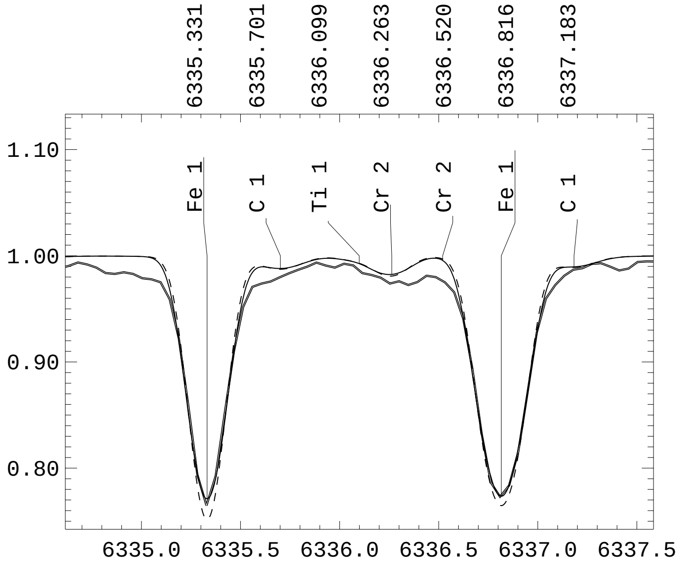

Fig. 2. A comparison of observed (thick line) and synthetic spectra for HD 122970 in the region of Fe I lines at λ 6335.33 Å ($g_{\rm eff}$ = 1.15) and at λ 6336.82 Å ($g_{\rm eff}$ = 2.01). Calculations are shown for the magnetic field modulus of $B_{\rm s}$ = 2.0 kG and two different rotational velocities: $v \cdot \sin i$ = 5 km s^{-1} (dashed line) and $v \cdot \sin i$ = 6 km s^{-1} (full line).

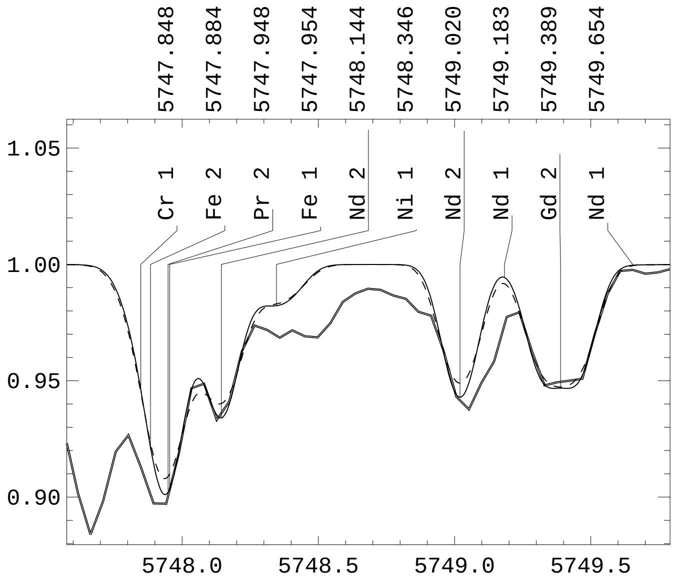

Fig. 3. A comparison of observed (thick line) and synthetic spectra for HD 122970 in the region of the Gd II line at λ 5749.39 Å ($g_{\rm eff}$=2.09). Calculations are shown for the magnetic field modulus of $B_{\rm s}$ = 2.3 kG and two different rotational velocities: $v \cdot \sin i$ = 5 km s^{-1} (dashed line) and $v \cdot \sin i$ = 4 km s^{-1} (full line).

5. Abundance analysis

All abundance calculations were made with Kurucz's WIDTH9 code modified by V. Tsymbal to accept the VALD input file format. VALD-2 provides the most recent collection of oscillator strength data and will be commented later on in the corresponding sections. The microturbulent velocities were determined for HD 122970 to be $\xi_{\rm t}$ = 0.85 km s^{-1}, and for 10 Aql to be $\xi_{\rm t}$ = 0 km s^{-1}. These small values are consistent with the weak magnetic fields detected in both stars and it confirms our experience expressed in Papers I to V that from a physical point of view: $\xi_{\rm t}$ of (all ?) magnetic stars in this region of the HR-diagram is close to zero. If a spectroscopic analysis infers a larger $\xi_{\rm t}$ it is probably caused by magnetic intensification.

Elemental abundances are summarized in Table 1. For comparison we also list abundances for another cool roAp star with a negligible magnetic field, HD 203932 (Gelbmann et al.1997, Gelbmann 1998). Because new and better oscillator strength data have become available with VALD-2, we decided to redetermine the abundances of Sm II, Eu II, and Gd II. Furthermore, we included hyperfine-structure for Eu II lines and for the other two elements we included more lines in the red spectral region to improve the comparison with HD 122970 and 10 Aql. REE abundances for the second ions are taken from Ryabchikova et al. (2000) and are marked with an asterisk in Table 1. The most recent solar photospheric abundances are given in the last column (Grevesse et al. 1996).

A complete table of line abundances and atomic parameters used can be found at (http://ams.astro.univie.ac.at)

5.1. *Light Elements*

Oscillator strengths for CNO elements from the recent NIST compilation (Wiese et al. 1996) are now included in VALD-2. Elements C and O are deficient in both stars and less abundant in the hotter star 10 Aql, a trend which is corroborated by HD 203932 and α Cir (Kupka et al. 1996).

The other light elements Na, Mg, Al, Si, and S are nearly solar abundant within the quoted errors, which is also typical for roAp stars. Abundances obtained from resonance as well as weak Na I lines agree, which is not the case for the very peculiar roAp star HD 166473 with a 8.6 kG magnetic field (Gelbmann et al. 2000) for which the Na I resonance doublet abundance is an order of magnitude lower than the abundance obtained from weak lines. The same phenomenon is observed for Mg I lines. While the strong Mg I triplet at λ 5167–83 Å provides a significantly lower abundance for HD 166473 than the weaker lines, the abundances obtained for 10 Aql and HD 122970 from *all* lines agree well. Such an anomaly for Na and Mg may indicate stratification in very peculiar atmospheres of Ap stars with a strong magnetic field, while in the atmospheres of less peculiar stars with a small magnetic field stratification seems to be negligible. On the other hand, as will be discussed in Sect. 6, we find evidence for stratification of REE even for the weakly magnetic stars discussed in this paper.

5.2. *Iron Peak Elements*

New experimental oscillator strength data for Fe I were taken from O'Brian et al. 1991, Bard et al. 1991, Bard & Kock 1994, and for Ni I from Blackwell et al. 1989, and Wickliffe & Lawler 1997a. Due to the sharpness of the spectral lines we could measure more than 150 neutral iron lines in the atmosphere of each star, which allowed us to determine the microturbulence well. We also checked for any trend of line abundances with the lower level excitation potential, which is an indicator for the correct choice of the effective temperature, and with $g_{\rm eff}$, which is sensitive to a magnetic field.

We could measure 16 Fe II lines for 10 Aql with the lower excitation energy level higher than 10 eV. Abundances obtained from these lines are typically larger by 0.4 dex than from other lines. Unfortunately, oscillator strengths for these lines are known only from calculations. However, more accurate oscillator strengths recently calculated with the orthogonal operator technique (Raassen & Uylings 1998) do not change our result. High excitation Fe II lines have to be studied also in other roAp and non-roAp stars in order to investigate this yet unexplained effect.

In general, abundances of the iron peak elements in 10 Aql and HD 122970 follow the same pattern as in other roAp stars: normal or slightly increased abundance of Ca, Ti, V, Cr, Mn, Fe, normal or underabundant Sc and Ni, while Co is overabundant by more than 1.0 dex. Within the error limits the ionization balance is fulfilled for all iron peak elements for which lines of two ions could be measured.

We also mention here that Cu and Zn are slightly underabundant in both stars as well as in HD 203932.

5.3. *Sr, Y, Zr, Ba, and rare-earth elements (REE)*

Strontium is overabundant by 2.0 dex in 10 Aql and by 1.4 dex in HD 122970. We found such a strontium anomaly also in other roAp stars with similar effective temperatures. Y and Zr seem to have an opposite correlation with temperature, but this claim has to be corroborated by further investigations. Ba is solar abundant in 10 Aql and overabundant in HD 122970.

The excellent quality of the available spectra (spectral resolution and sharpness of the lines) allowed us to measure weak REE lines which could not be used in our previous analyses of Ap stars. Abundances of all stable REE (all based on first ions) agree well in both stars and, with the exception of Tm, no violation of the odd-even effect is found. New oscillator strength data, now included in VALD-2, were used for Dy II (Biémont & Lowe 1993), Tm II (Wickliffe & Lawler 1997b), and Lu II (Bord et al. 1998, Den Hartog et al. 1998). Abundances of Ce, Nd, Sm, Eu, and Gd in 10 Aql agree reasonably well with the values obtained by Magazzu & Cowley (1986) who used blue photographic spectra, although our abundances are systematically higher. Part of the disagreement may be due to the adopted atmospheric parameters, microturbulence, and/or oscillator strengths. The most discordant result is obtained for La: for this element our mean abundance is about 1.0 dex higher. We cannot yet offer a plausible explanation for this discrepancy, however, our La abundance matches a scaled solar REE pattern better.

We also identified and measured for the first time lines of Pr III, Nd III, Tb III, and Er III. Our identification of Pr III was based on the line lists from Sugar (1974), of Nd III on Cowley & Bord (1997), on the line identification list for Przybylski's star for Tb III and of Er III on Wyart et al. (1997). For Nd III and Er III oscillator strength calculations were available in the cited papers, while for Pr III we used oscillator strengths from Bord (priv. comm.). Only for Tb III no such data exist and our crude abundance estimate is based on an assumed $\log gf = 0$. For Nd III only those lines for which the laboratory and predicted wavelengths coincided were used for the abundance determination (see Cowley & Bord 1997, Bord 1999).

In both stars abundances derived from the second ions exceed those derived from the first ions by more than 1.0 dex. This anomaly of Nd III was first mentioned by Cowley & Bord (1997)

Table 1. Abundances of the roAp stars HD 122970 and 10 Aql based on n lines with formal error estimates in units of the last digit given in parentheses. HD 203932 values are taken from Gelbmann et al. (1997), except for those marked by *.

Ion	HD 122970		10 Aql		HD 203932	$\odot$
	$\log(N/N_{tot})$	n	$\log(N/N_{tot})$	n	$\log(N/N_{tot})$	$\log(N/N_{tot})$
C I	-3.51(25)	15	-4.21(17)	15	-4.09	-3.49
O I	-3.34(15)	6	-3.72(08)	4	-3.73	-3.17
Na I	-5.87(02)	3	-6.05(10)	6	-5.72	-5.71
Mg I	-4.50(14)	4	-4.32(30)	5	-4.28	-4.46
Mg II			-4.46:	1	-4.14	-4.46
Al I	-5.73:	1	-5.83(06)	2	-5.34	-5.57
Si I	-4.45(21)	25	-4.19(24)	34	-4.45	-4.49
Si II	-4.24(17)	3	-4.11(35)	3	-3.96	-4.49
S I	-4.83(12)	8	-5.34(17)	8	-5.05	-4.71
Ca I	-5.48(24)	21	-5.28(19)	20	-5.20	-5.68
Ca II	-5.43(16)	2	-5.50(43)	5	-4.92	-5.68
Sc I	-8.33:	1				-8.87
Sc II	-8.66(14)	10	-9.55(25)	6	-9.77	-8.87
Ti I	-6.91(21)	27	-7.12(16)	16	-7.21	-7.02
Ti II	-6.88(17)	19	-7.09(15)	23	-6.94	-7.02
V I	-7.84(15)	6	-7.94(10)	4	-7.49	-8.04
V II	-7.73(11)	3	-7.78(25)	6		-8.04
Cr I	-5.99(20)	17	-5.13(17)	70	-5.62	-6.37
Cr II	-6.06(21)	20	-5.08(23)	64	-5.70	-6.37
Mn I	-6.40(17)	11	-6.13(24)	16	-6.39	-6.65
Mn II	-6.31(02)	2	-6.13(16)	8		-6.65
Fe I	-4.48(18)	160	-4.28(21)	181	-4.42	-4.54
Fe II	-4.46(19)	27	-4.08(25)	66	-4.42	-4.54
Co I	-6.06(26)	64	-5.66(25)	89	-5.97	-7.12
Co II	-5.84(05)	2	-5.59(02)	4		-7.12
Ni I	-5.89(19)	48	-6.37(22)	35	-6.34	-5.79
Cu I	-8.13(08)	2	-8.59(07)	2	-7.89	-7.83
Zn I	-7.80(26)	2	-8.89:	1	-7.88	-7.44
Sr I	-7.70(22)	5	-6.93(14)	14	-6.96	-9.07
Sr II	-7.31:	1			-7.60	-9.07
Y I	-8.67:	1				-9.80
Y II	-9.09(17)	14	-8.72(16)	15	-8.29	-9.80
Zr I	-8.41(29)	4	-8.73:	1		-9.44
Zr II	-8.48(17)	7	-8.97(28)	5	-9.27	-9.44
Ba I	-8.12(41)	2				-9.91
Ba II	-8.99(05)	2	-9.78(32)	2	-9.33	-9.91
La II	-9.34(25)	27	-9.73(23)	21	-10.10	-10.87
Ce II	-8.82(28)	34	-9.05(22)	23	-9.27	-10.46
Pr II	-10.04(21)	22	-10.17(27)	16	-10.09	-11.33
Pr III	-8.63(30)	15	-9.21(30)	15	-8.80*	-11.33
Nd II	-9.23(27)	64	-9.77(29)	41	-9.50	-10.54
Nd III	-8.03(26)	8	-7.22(54)	8	-7.58*	-10.54
Sm II	-9.33(22)	45	-9.24(22)	47	-9.28*	-11.03
Eu II	-9.66(13)	6	-9.64(13)	5	-9.47*	-11.53
Gd II	-8.67(19)	44	-8.69(23)	45	-9.16*	-10.92
Tb II	-10.00(12)	4	-10.51:	1		-12.14 (-11.69†)
Tb III	-9.49(22)	10	-9.78(39)	9		-12.14
Dy II	-9.07(17)	8	-9.23(27)	10	-9.38	-10.90
Er II	-9.63(37)	5	-9.17(27)	4	-9.73	-11.11
Er III	-7.60(43)	4	-7.59(29)	2	-7.83:	-11.11
Tm II	-9.04(23)	12	-9.15(25)	9		-12.04 (-11.89†)
Yb II	-9.83(39)	6	-10.05(34)	5		-11.02
Lu II	-9.75(10)	4	-10.52(47)	6	-10.40	-11.28
Hf II	-8.66(06)	2	-9.26(26)	6		-11.16

Table 1. (continued)

Ion	HD 122970 $\log(N/N_{tot})$	n	10 Aql $\log(N/N_{tot})$	n	HD 203932 $\log(N/N_{tot})$	$\odot$ $\log(N/N_{tot})$
Th II	-9.91(44)	4	-9.71(23)	26	-10.85	-11.91†
U II			-9.86(20)	2		-12.54†
$T_{\rm eff}$	6930 ± 100		7550 ± 150		7450	
$\log\, g$	4.11 ± 0.1		4.00 ± 0.1		4.30	
B_s (kG)	2.3		1.0		<1.0	

† abundances determined from meteorites.

for γ Equ. It was later confirmed by Ryabchikova et al. (2000) for a larger sample of roAp stars, including 10 Aql. This strange discrepancy observed for *all four* REE can not be explained by systematic errors of the oscillator strengths, because practically no abundance differences are observed for the first and second REE ions for several non-roAp stars, like β CrB and HR 7575, as well as for the Am stars 15 Vul and 32 Aqr (Ryabchikova et al. 2000). Model atmospheres with different $T_{\rm eff}$ $(\pm 500^\circ)$ and $\log\, g$ $(\pm 0.5\, dex)$ cannot remove the mentioned abundance anomaly - a temperature increase by 1 000° would be required!

5.4. *Heavy elements*

A search for lines of heavy elements resulted in a definite identification of Hf II and Th II in both stars, and of U II in 10 Aql. Whith a few exceptions these lines are very weak, 1.3–3.5 mÅ, which is just above the accuracy limit of our equivalent width determinations. Anyway, the coincidence with laboratory wavelengths lends credence to our identification but we consider the derived abundances of heavy elements only as upper limits.

6. Discussion

The abundance pattern found for 10 Aql and HD 122970 is very similar to what we have previously found for the other 6 roAp stars investigated so far: nearly solar abundance for Fe and Ni, a definite overabundance of Cr and especially Co, with significant overabundances of REE. Furthermore, we corroborate the characteristics of roAp stars that second ions of REE are overabundant by a factor of up to 100 (!) compared to values derived from singly ionized species.

The high spectral resolution and excellent signal-to-noise ratio of the spectra, together with the sharpness of the lines in both stars allowed us to use many more REE lines for abundance determinations. These lines were unsuitable for previous analyses. Unfortunately, the availability of reliable atomic parameters becomes more of a problem as we are leaving the beaten track of classical spectroscopy.

The abundances derived from second REE ions is significantly higher than that derived from the first ions. Ionization equilibrium calculations across the stellar atmosphere show two regions where the second ions are dominant: close to the continuum forming region, where the temperature is high, and in the upper photospheric layers, where the column density drops below $\leq 10^{-4}$ (mass variable in ATLAS9 models). Qualitively we may explain the anomalous intensities of Pr III and Nd III lines in the spectrum of HD 122970 with a layer in the upper atmosphere which is overabundant by up to +4.0 dex relative to deeper layers. This simplified abundance stratification model explains Pr III line intensities also for 10 Aql, while a few Nd III lines would require an even larger abundance gradient in this star. Diffusion theory (Michaud 1970) predicts that heavy elements with a large number of absorption lines suffer radiation acceleration which may exceed gravity. In principle, heavy elements are even blown off the star, if there is no process which decreases radiation acceleration in the upper atmospheric layers below gravity. A temperature inversion (chromosphere) which changes the ionization balance could be such a feature and would be also necessary for explaining the existence of a cut-off frequency in the pulsation spectrum of roAp stars (Audard et al. 1998, Gautschy et al. 1999).

The increased iron abundance obtained from high excitation Fe II lines in 10 Aql may serve as an additional indication for stratification in cool CP-star atmospheres. Similar evidence for Cr was found by Savanov & Kochukhov (1998) in 10 Aql, γ Equ β CrB and HR 7575. For the latter star Kato & Sadakane (1999) confirmed this evidence. In any case, detailed NLTE diffusion calculations are needed to understand the peculiar abundance features observed for roAp stars better.

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