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Elemental abundance studies of CP stars

III. The magnetic CP stars α Scl and HD 170973

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Abstract. Fine analyses of the magnetic CP stars α Scl and HD 170973 are presented using ATLAS9 model atmospheres which have same bulk metallicity as the deduced abundances. The light elements are mostly solar except for silicon, and all the heavier elements except nickel in HD 170973, which is solar, are greatly overabundant. The iron peak elements are typically 10 times overabundant, Sr is of order of 1000 times solar, Y and Zr are of order of 100 times solar. The rare earths are 1000 or more times overabundant.

Key words. stars: chemically peculiar – stars: abundances – stars: individual: α Scl – stars: individual: HD 170973

1. Introduction

Our studies of α Scl and HD 170973, two magnetic chemically peculiar (mCP) stars of the Upper Main Sequence, extend our systematic analyses of the elemental abundances of this class for comparison with those theories which try to explain their substantially non-solar elemental abundances, for example, the various radiative diffusion scenarios of Michaud (1970) and his collaborators. Paper I (Lopez-Garcia & Adelman 1994) concerned the silicon star HD 43819 and HD 147550, which we found to be a very cool HgMn star, while Paper II (Lopez-Garcia & Adelman 1999) the silicon stars HD 133029 and HD 192913.

Shore et al. (1990) discovered magnetically controlled circumstellar matter near the helium-weak star α Scl (HD 5737, HR 280). Breger (1976) made spectrophotometry by Norris (1971) consistent with the Hayes-Latham (1975) calibration of Vega. This star has a rotational period of 21.652 days (Manfroid & Renson 1994). Recently Leone et al. (1997) found its effective temperature, surface gravity, and magnesium abundance.

HD 170973 (HR 6958, MV Ser) is a sharp-lined ($v \sin i = 10$ km s^{-1}) mCP star classified as A0Vp (SiSrEu st, CaMg wk) by Abt & Morrell (1995). Adelman (1997) discovered using differential *uvby* photometry that its photometric period, which is its rotational period, is 18.065 days with amplitudes of variation of 0.03 mag, 0.02 mag, 0.02 mag, and 0.015 mag for u, v, b, and y, respectively. The light curves for b and y are nearly symmetric, but those for u and v are not which indicates a complicated distribution of photospheric abundances. Mathys & Lanz (1992) did not detect magnetically split lines in its spectrum.

2. Observational material and line identifications

Spectra of α Scl were obtained by OIP with the 2.15-m telescope of the Complejo Astronomico El Leoncito (CASLEO) and a REOSC echelle spectrograph, which is on loan from the Institute Astrophysique de Liege, Belgium, and a TEK 1024 CCD. Two spectra covered $\lambda\lambda$4270-4932, two $\lambda\lambda$4942-7829, and three $\lambda\lambda$7945-8141.

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For the second and third groups those regions with substantial telluric contamination were not measured. Hence only one order was studied from the last group. The respective cross dispersers were gratings with 1200, 300, and 300 lines mm^{-1}. The equivalent width scale of these spectrograms for lines whose equivalent widths are $\geq$15 mÅ is marginally greater than those for Kitt Peak National Observatory (KPNO) coudé feed CCD and Dominion Astrophysical Observatory (DAO) Reticon spectrograms (Adelman & Pintado 1997).

For α Scl, the spectra were reduced using IRAF[1]. Each night we subtract the average of many bias frames. An average flat field produced from many such frames was used to divide the spectra to remove the pixel-to-pixel variations. The extraction was done with APALL and the wavelength calibration with ECIDENTIFY and DISPCOR using the ThAr comparison spectra. The spectra were normalized order by order with the interactive computer graphics program REDUCE. Then the radial velocity offsets were found using VCROSS so that the spectra could be coadded with TSTACK. Finally the equivalent widths were measured with VLINE by fitting Gaussian profiles through the stellar metal lines (Hill et al. 1982).

This study used four nitrogen-baked IIa-O 4.3 Å mm^{-1} spectrograms (Ce 23306, Ce 23309, Ce 23317 and Ce 23755) of HD 170973, obtained by SJA with the coudé spectrograph of the 2.5 m telescope of Mount Wilson Observatory. The spectral region is approximately $\lambda\lambda 3760-4650$. These spectra are similar to those used in Papers I and II.

For HD 170973 equivalent widths and Hγ profiles were read directly from the intensity tracings which were made with the PDS microdensitometer of Kitt Peak National Observatory. Those from different spectrograms were averaged to increase the signal-to-noise ratio, but this removes most effects of spectral variability. As the Hγ profiles were assumed to be symmetric about the line core, their wings were averaged (see Table 1).

Table 1. Hγ profile of HD 170973

$\Delta\lambda$(Å)	R
1	0.352
2	0.458
3	0.541
4	0.600
5	0.668
6	0.729
8	0.807
10	0.869
12	0.906
14	0.930
16	0.938
18	0.949
20	0.958
22	0.966
24	0.977
28	0.979
32	0.986
36	0.989
40	0.995

The stellar lines were identified with the general references A Multiplet Table of Astrophysical Interest (Moore 1945) and Wavelengths and Transition Probabilities for Atoms and Atomic Ions, Part 1 (Reader & Corliss 1980) as well as the more specialized references for P II (Svendenius et al. 1983), S II (Pettersson 1983), Ti II (Huldt et al. 1982), Mn II (Iglesias & Velasco 1964), and Fe II (Johansson 1978).

Baschek (1973) discussed the analyses of α Scl independently carried out by Schmitt (1972, 1973) and Vilhu (1972). Lines of H I, He I, C II, N II, O I, Ne I, Na I, Mg II, Si II, Si III, P II, S II, Cl II, Ca II, Sc II, Ti II, Cr II, Mn II, Fe II, and Fe III are definitely present in its spectrum, but Mn II lines are just probably present in our material. There are no published line identifications of HD 170973. We found lines of H I, C II, Mg I, Mg II, Al I, Si II, Si III, S II, Ca II, Sc II, Ti II, Cr II, Mn II, Fe I, Fe II, Fe III, Ni II, Sr II, Y II, Zr II, Ce II, Pr II, Nd II, Sm II, Eu II, and Gd II while those of Ba II and Hg II are probable identifications.

3. Atmospheric parameters

For HD 170973 we adopted the parameters of the 10 times solar metallicty ATLAS9 model of Adelman & Rayle (2000). They compared the predictions of Kurucz's ATLAS9 model atmospheres with the spectrophotometry obtained by Adelman (1983) with their own Dominion Astrophysical Observatory 20 Å mm^{-1} Hγ region spectra with synthesized spectra calculated from models using SYNTHE (Kurucz & Avrett 1981). For a solar composition $T_{\mathrm{eff}} = 11\,000$ K and $\log g = 3.50$ while for models with 10 times solar metals $T_{\mathrm{eff}} = 10\,750$ K and $\log g = 3.50$.

Kroll (1987), from near infrared photometry, assigned $T_{\mathrm{eff}} = 13\,800$ K to α Scl while Theodossiou & Danezis (1991) estimate $T_{\mathrm{eff}} = 11\,500$ K and $\log g = 3$. The catalogue of Cayrel de Strobel et al. (1992) reports $T_{\mathrm{eff}} = 15\,750$ K, $\log g = 3.4$, and a +0.7 dex iron overabundance with respect to the sun. Leone et al. (1997) found $T_{\mathrm{eff}} = 13\,600$ K, $\log g = 3.20$, $Z = [+0.3]$. We used the $uvby\beta$ mean colors of Hauck & Mermilliod (1980) with the calibration of Napiwotzki et al. (1993) to obtain an initial estimate of the atmospheric parameters of α Scl: $T_{\mathrm{eff}} = 14\,296$ K, $\log g = 3.20$. When we compared the predicted fluxes with the spectrophotometry of Norris (1971) using this value of the surface gravity, we found $T_{\mathrm{eff}} = 13\,900$ K.

4. Abundance analyses

We determined the metal abundances from the equivalent widths with Program WIDTH9 (Kurucz 1993). The adopted metal line damping constants were the default

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Table 2. Determination of microturbulent velocity assuming no magnetic field

Star	Species	n	(ξ) (km s^{-1})	log $N/N_{\rm T}$	gf-values
HD 170973	Fe I	52	0.6	-3.20 ± 0.28	MF&KX
		51	0.6	-3.20 ± 0.28	MF
	Fe II	78	0.0	-3.48 ± 0.27	MF&KX
		31	0.0	-3.58 ± 0.25	MF
	mean ξ:	0.3 km s^{-1}			
	Ti II	58	1.0	-5.24 ± 0.28	MF&KX
	Cr II	43	1.4	-4.95 ± 0.29	MF&KX
α Scl	Fe II	229	0.9	-4.01 ± 0.26	MF&KX
		41	0.0	-4.12 ± 0.24	MF
	mean ξ:	0.4 km s^{-1}			
	Ti II	40	0.0	-5.60 ± 0.28	MF&KX
	Cr II	24	0.0	-5.57 ± 0.22	MF&KX

gf-value references: KX = Kurucz & Bell (1995), MF = Martin et al. (1988).

Table 3. Magnetic field determinations

Star	Species	n	H_1 (kG)	log $N/N_{\rm T}$	H_2 (kG)	log $N/N_{\rm T}$	gf-values
HD 170973	Fe I	52	0.8	-3.20 ± 0.28	0.8	-3.20 ± 0.28	MF&KX
		51	0.9	-3.22 ± 0.28	0.9	-3.22 ± 0.28	MF
	Fe II	78	0.2	-3.52 ± 0.29	0.2	-3.52 ± 0.29	MF&KX
		31	0.3	-3.62 ± 0.28	0.3	-3.62 ± 0.28	MF
	mean H:	0.4 kG					
	Ti II	58	1.8	-5.30 ± 0.29	1.0	-5.18 ± 0.28	MF&KX
	Cr II	43	1.5	-4.90 ± 0.32	1.5	-4.90 ± 0.32	MF&KX
α Scl	Fe II	94	0.0	-3.98 ± 0.30	0.0	-3.98 ± 0.30	MF&KX
		38	0.0	-4.09 ± 0.26	0.0	-4.09 ± 0.26	MF
	mean H:	0.0 kG					
	Ti II	40	0.0	-5.60 ± 0.28	0.0	-5.60 ± 0.28	MF&KX
	Cr II	24	0.0	-5.57 ± 0.22	0.0	-5.57 ± 0.22	MF&KX

semi-classical approximations when they were not available from the data of Kurucz & Bell (1995) as supplemented by values from Chapelle & Sahal-Brechot (1970), Lanz et al. (1988), and Sahal-Brechot (1969).

Table 4. Abundances in HD 170973 and α Scl. Table 4 is only available in electronic form at the CDS via anonymous ftp to `cdsarc.u-strasbg.fr (130.79.128.5)` or via `http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/367/859`

We calculated abundances from Fe I and Fe II lines for HD 170973 and from Fe II lines only for α Scl for a range of possible microturbulent velocities (ξ). For the final values in Table 2, the abundances are independent of the equivalent widths (ξ_1) or minimize the rms scatter of the abundances (ξ_2). Values for both species were derived using lines with gf values only from Martin et al. (1988) and also with gf-values from compatible sources, in this case Kurucz & Bell (1995). As the values for both ways to derive the microturbulence are the same, Table 2 does not differentiate between these methods. Here n is the number of lines. From these species a mean microturbulence

Table 5. Comparison of derived and solar abundances

Elements	HD 170973 log N/H	α Scl log N/H	HD 192913 log N/H	HD 133029 log N/H	HD 43819 log N/H	Sun log N/H
C II	−3.73	−3.40	−3.16	−3.08	−3.78	−3.45
N II	...	−3.89	...	...	...	−4.03
O I	...	−3.57	...	...	...	−3.13
Ne I	...	−3.76	...	...	...	−3.92
Mg I	−4.90	...	−5.10	...	−5.01	−4.42
Mg II	−4.52	−4.64	−4.70	−4.26	−4.72	−4.42
Al I	−5.46	...	−5.33	...	...	−5.53
Si II	−3.82	−4.07	−4.06	−3.36	−3.88	−4.45
Si III	−4.16	−4.09	...	...	...	−4.45
P II	...	−6.17	...	...	...	−6.55
S II	−4.19	−5.08	−4.67	−4.84	−5.46	−4.67
Cl II	...	−5.39	...	...	...	−6.5:
Ca II	−4.91	...	−5.33	−5.72	−5.12	−5.64
Sc II	−8.07	−7.51	−8.68	...	−9.11	−8.83
Ti II	−5.11	−5.61	−5.60	−6.02	−5.81	−6.98
Cr I	...	...	−3.60	...	−4.69	−6.33
Cr II	−4.80	−5.58	−4.92	−4.15	−5.02	−6.33
Mn II	−5.08	−4.92	−4.76	−5.00	−5.55:	−6.61
Fe I	−3.17	...	−3.26	−3.32	−3.48	−4.50
Fe II	−3.50	−4.00	−3.36	−3.28	−3.66	−4.50
Fe III	−2.92:	−3.80	−2.68:	−3.18	−3.70	−4.50
Ni II	−5.73	...	−5.26	−5.70	−6.49	−5.75
Sr II	−5.74	...	−5.03	−7.01	−5.63	−9.03
Y II	−7.48	...	−7.59	−7.79	...	−9.76
Zr II	−6.98	...	−7.22	−7.53	−7.81	−9.40
Ba II	...	...	−8.52	−8.68	...	−9.87
Ce II	−6.26	...	−6.86	−7.14	−6.86	−10.42
Pr II	−6.04	...	−6.66	−6.98	−6.69	−11.29
Nd II	−6.48	...	−6.81	−6.72	−7.34	−10.50
Sm II	−6.40	...	−6.34	...	...	−10.99
Eu II	−6.27	...	−5.29	−8.44	−8.15	−11.49
Gd II	−6.69	...	−7.44	...	−7.18:	−10.88
Dy II	−6.41	...	−6.56	...	...	−10.86
Hg II	−4.39	...	−5.12	−6.57	...	−10.83
$T_{\rm eff}$	10 750	13 900	10 900	11 200	11 300	
log g	3.50	3.25	3.40	3.84	3.20	

of 0.30 km s^{-1} is found for HD 170973. The Cr II lines yield 1.4 km s^{-1} while the Ti II lines suggest 1.0 km s^{-1}. For α Scl all the Fe II lines indicate a microturbulence of 0.9 km s^{-1} while Ti II and Cr II lines 0.0 km s^{-1}. A mean value of 0.4 km s^{-1} was finally adopted.

If the mCP stars have quiescent atmospheres as required by various radiative diffusion scenarios, then they lack any classical microturbulence. Their derived values are most likely manifestations of organized weak magnetic fields with each line having its own effective microturbulence due to the width and the distribution of its Zeeman components. Strong lines with wide patterns and many components will be desatured more easily than strong lines with smaller patterns and fewer components. Following Adelman (1973) for each line we equated the mean width of the Zeeman σ components to the Doppler broadening to derive an effective microturbulence which increases with the strength of the magnetic field and the width of the Zeeman pattern. This approximation is adequate for the current data. More refined modeling will be required for observations with somewhat greater signal-to-noise ratios and resolution.

By assuming that there is no microturbulence and requiring that the abundances be independent of the derived magnetic field (H_1) or that the scatter in the derived abundances be a minimum (H_2) we found that the surface magnetic field of HD 170973 (Table 3) is about 0.4 kG from the Fe I and Fe II lines. The Cr II lines yield 1.5 kG and the Ti II lines 1.8 kG. For α Scl we found a surface magnetic field of 0.0 kG for all the elements. As the rms values about the mean are similar if one assume a microturbulence or magnetic field methods, we present the final abundance results for the assumption of a uniform microturbulence of 0.3 km s^{-1} for HD 170973 and 0.4 km s^{-1} for α Scl.

For HD 170973 no He I lines were seen, making it a very He poor star. For α Scl we calculated the He I profiles in LTE from the model atmospheres with the program SYNSPEC (Hubeny et al. 1994). We found He/H = 0.04, 0.05, 0.04, 0.05, 0.05, and 0.06 for λ4388, λ4437, λ4472, λ4713, λ4922, and λ6678, respectively. The mean value $= 0.048 \pm 0.008$, or log He/H $= -1.32$. Thus α Scl has one-half the solar He/H ratio.

Table 4 contains the analyses of the line spectra. For each line we give the multiplet number (Moore 1945), the laboratory wavelength, the gf value and its source, the equivalent width in mÅ, and the derived abundance log N/N_{T}. We omitted seriously blended lines from the analyses.

5. Discussion

Table 5 compares the derived abundances for HD 170973 and α Scl with solar values (Grevesse et al. 1996). Also given are the abundances of HD 43819 (López-García & Adelman 1994), and HD 133029 and HD 192913 (López-García & Adelman 1999). Compared with the sun, the light elements are mostly solar except for Si, which is overabundant in the silicon star HD 170973 by a factor 4 and in the He-weak star α Scl by a factor of 2. All the heavier elements except Ni in HD 170973, which is solar, are greatly overabundant. HD 170973 has underabundant C and overabundant S and Ca while α Scl has O, Mg and S underabundant and overabundant Cl. The iron peak elements are typically 10 times overabundant except Ti and Cr in HD 170973 which are overabundant by factors of 75 and 35 respectively, Cr in HD 133029 which is 100 times solar and Sc in α Scl which is overabundant by a factor of 20, Mn in HD 170973 and α Scl is about 50 times solar and in HD 192913 100 times solar. Sr is of order 1000 solar in HD 170973 and 100 times solar in the other silicon stars and Y and Zr are about 100 solar in all stars. The rare earths are 1000 or more times overabundant. Elements heavier than Fe were not identified in α Scl. Our abundances for α Scl are generally similar to those found by Leone & Manfre (1997). These characteristics are similar to those found by other authors for mCP stars. For a critical comparison with theory, we need to consistently analyze a larger sample.

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