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ELEMENTAL ABUNDANCE STUDIES OF CP STARS. THE SILICON STARS HD 87240 AND HD 96729

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RESUMEN

En este trabajo se comparan abundancias elementales de estrellas Ap de Si de campo y pertenecientes a cúmulos abiertos. En particular, se presenta un análisis de las estrellas Ap de Si HD 87240 y HD 96729, utilizando modelos de atmósferas de ATLAS9 y material observacional tomado con el espectrógrafo echelle REOSC, adosado al telescopio de 2.15 m *Jorge Sahade* de CASLEO. Estas estrellas químicamente peculiares (CP) pertenecen a los cúmulos abiertos australes NGC 3114 y NGC 3532, respectivamente. Para HD 87240 y HD 96729, C es mayormente solar, Mg y S son ligeramente deficientes, Si y Ca son sobreabundantes por factores entre 1–10. Los elementos más pesados son todos sobreabundantes, TiCrFe por factores de $\sim$ 10, SrYZr por factores entre 100–1000 y tierras raras por factores de $\sim$ 1000 o más.

ABSTRACT

We compared elemental abundances of field and open cluster Ap Si stars. In particular, an analysis of the Ap Si stars HD 87240 and HD 96729 is presented using an ATLAS9 model atmosphere and observational material taken with a REOSC echelle spectrograph attached to the *Jorge Sahade* 2.15 m telescope at CASLEO. These chemically peculiar (CP) stars belong to the southern hemisphere open clusters NGC 3114 and NGC 3532, respectively. For HD 87240 and HD 96729, C is mostly solar, Mg and S are slightly underabundant, Si and Ca are overabundant by factors between 1–10. Heavier elements are all overabundant, TiCrFe by factors of $\sim$ 10, SrYZr by factors between 100–1000 and rare earths by factors of $\sim$ 1000 or more.

Key Words: **STARS: CHEMICALLY PECULIAR — STARS: INDIVIDUAL: HD 87240 — STARS: INDIVIDUAL: HD 96729**

1. INTRODUCTION

This research is part of our current program for deriving elemental abundances among chemically peculiar stars (CP) members of open clusters. Our final purpose is to discuss possible variations of the elemental abundances of critical elements with age. In this paper we report the results for two CP stars of the Silicon class (CP2) (HD 87240 and HD 96729) that belong to two southern open clusters: NGC 3114 and NGC 3532. The clusters included in the program were selected using the WEBDA open clusters database[5] which is maintained by Jean-Claude Mermilliod.

Both stars selected for this paper are CP2 stars in the classification scheme of Preston (1974), and show intensified lines of Si, Cr, Sr or Eu, and probably other elements such as rare-earth. Their spectral types are between late B and A with effective temperatures from 8000 up to 16,000 K. These stars are usually slow rotators and their magnetic fields vary periodically with periods from a few days to years (e.g., Preston 1970; Catalano & Renson 1997, 1998; Renson & Catalano 2001).

The CP2 star HD 87240 (= NGC 3114 025) is a member of the southern open cluster NGC 3114. Its spectrum was classified as an B9p by Frye, Mc Connell, & Humphreys (1970), B8 IVp by Levato &

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[5]http://obswww.unige.ch/webda/

TABLE 1

OBSERVATIONAL DATA FOR THE TWO AP SI STARS[a]

Parameter	HD 87240	HD 96729	References
$B-V$	−0.06	0.01	R1, R4
$U-B$	−0.44	−0.34	R1, R4
V	9.65	9.98	R1, R4
$b-y$	−0.013	−0.009	R2, R3, R5
m_1	0.127	0.166	R2, R3, R5
c_1	0.597	0.591	R2, R3, R5
β	2.716	···	R3
RV [$\mathrm{km\,s^{-1}}$]	2.0	···	R6

[a] References: R1: Lynga (1959), R2: Schneider & Weis (1988), R3: Schmidt (1982), R4: Fernández & Salgado (1980), R5: Schneider (1987), R6: Amieux & Burnage (1981).

TABLE 2

Hγ PROFILES

$\Delta\lambda$(Å)	HD 87240	HD 96729
1	0.378	0.321
2	0.469	0.396
3	0.549	0.470
4	0.618	0.543
5	0.685	0.608
6	0.742	0.664
8	0.816	0.760
10	0.865	0.820
12	0.904	0.871
14	0.926	0.903
16	0.941	0.927
18	0.956	0.947
20	0.963	0.954
22	0.970	0.964
24	0.976	0.973
28	0.988	0.976
32	0.997	0.985
36	0.998	0.989
40	0.999	0.992

Malaroda (1975), ApSi in the Michigan Catalogue (Houk, Cowley, & Smith-Moore 1975), and finally as ApSi by Levato & Malaroda (1975), or CP2 in the classification scheme of Preston (1974). *UBV* photoelectric photometry was published by Jankowitz & McCosh (1962) and Lynga (1959), *ubvy* photoelectric photometry has been provided by Houk et al. (1975) and the Hβ index was measured by Schmidt (1982). A radial valocity of 2.0 km $\mathrm{s^{-1}}$ has been determined by Amieux & Burnage (1981). The membership probability is 0.97 (González & Lapasset 2001). There is no evidence of variability in the photoelectric photometry. HD 87240 is not an extremely slow rotator. The $v \sin i$ value derived from our spectra is $\sim$ 15 km $\mathrm{s^{-1}}$ (Saffe, Levato, & López-García 2004).

HD 96729 belongs to the open cluster NGC 3532, which is located in the η Carina region and contains some hundred stars down to V = 14. This star has been classified as B9 by Cannon & Pickering (1918) and B9III with a Si peculiarity by Hartoog (1976) in their study of MK types in southern open clusters, using classification dispersion spectra. Δa photometry also identifies this object as a peculiar star (Maitzen & Schneider 1987). *UBV* photoelectric observations of the cluster have been done by Wizinowich & Garrison (1982), Fernández & Salgado (1980), and Koelbloed (1959). Stromgren *ubvy* data have been provided by Schneider (1987) and by the Michigan Catalogue (Houk et al. 1975). The properties in the Geneva system have been studied by Hauck & North (1982). The membership probability reported is 0.92 (King 1978). We do not find evidence in the literature of spectral variability, nor magnetic field measures for either star.

The two Ap Si stars were selected to be physically similar, i.e., with similar effective temperature, gravity and chemical peculiarity, but different ages. The star age is assumed to be the average age of the cluster. Table 1 presents some relevant observational data for the stars.

TABLE 3

DETERMINATION OF MICROTURBULENT VELOCITY

Star	Species	n	ξ_1 km s^{-1}	log N/N$_T$	ξ_2 km s^{-1}	log N/N$_T$	gf-values
HD 87240	Fe I	45	1.2	−3.75±0.31	1.4	−3.75±0.31	MF&KX
		42	1.7	−3.96±0.27	1.5	−3.96±0.27	MF
	Fe II	71	1.6	−3.96±0.27	1.8	−3.96±0.27	MF&KX
		28	1.3	−3.96±0.27	1.4	−3.96±0.27	MF
	mean ξ :	1.5 km s^{-1}					
	Ti II	41	1.7	−3.96±0.27	1.0	−3.96±0.27	MF&KX
	Cr II	29	1.3	−3.96±0.27	1.2	−3.96±0.27	MF&KX
HD 96729	Fe I	39	1.9	−3.75±0.31	2.1	−3.75±0.31	MF&KX
		36	1.5	−3.96±0.27	1.5	−3.96±0.27	MF
	Fe II	68	1.7	−3.96±0.27	1.7	−3.96±0.27	MF&KX
		31	1.5	−3.96±0.27	1.5	−3.96±0.27	MF
	mean ξ :	1.7 km s^{-1}					
	Ti II	39	2.1	−3.96±0.27	2.0	−3.96±0.27	MF&KX
	Cr II	32	1.2	−3.96±0.27	1.3	−3.96±0.27	MF&KX

2. OBSERVATIONAL MATERIAL AND LINE IDENTIFICATIONS

The stellar spectra of HD 87240 and HD 96729 were obtained by CS at Complejo Astrónomico El Leoncito (CASLEO). He used the *Jorge Sahade* 2.15 m telescope equipped with a REOSC echelle spectrograph[6] and a TEK 1024x1024 CCD detector. Three spectra of each star were obtained. They covered the visual range $\lambda\lambda$3500–6500. The REOSC spectrograph uses gratings as cross dispersers. We have used one grating with 400 lines mm^{-1}. The S/N ratio of the spectra is around 100 and they have been obtained between April 21 and 23, 2000. The resolving power of the spectra is approximately 12,500.

There is no more than a 20% difference among the equivalent width measurements of the same lines in different spectra. The spectra were reduced by CS using IRAF[7] standard procedures for echelle spectra, and were normalized order by order with the *continuum* task of the same package. The resolution of the spectra is 0.17 Å/px. Extensive description of the characteristics of the observational material, the reduction technique and some results obtained with it, have been published by López-García, Adelman, & Pintado (2001).

The equivalent widths were measured by fitting Gaussian profiles through the stellar metallic lines using the *splot* task.

The stellar lines for HD 87240 were identified by Saffe et al. (2004). For HD 96729 we have used the same procedure for line identification. We used 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, Magnusson, & Zetterberg 1983), Si II (Shenstone 1961), S II (Pettersson 1983), Ti II (Huldt et al. 1982), Gd II (Meggers, Corliss, & Scribner 1961), Mn II (Iglesias & Velasco 1964), Fe II (Johansson 1978), and Eu II (Meggers, Corliss, & Scribner 1975).

For HD 87240 we found H I, C II, Mg I, Mg II, Si II, S II, Cl II, Ca II, Ti II, Cr II, Fe I, Fe II, Fe III, Ni II, Sr II, Y II, Zr II,Eu II, and Hg II. In addition Si I, Mn II, and Gd II may be present, and there are a number of unidentified lines.

3. ATMOSPHERIC PARAMETERS

North & Cramer (1984) have estimated fundamental parameters and magnetic fields of Ap stars using the Geneva photometric system. For HD 87240 they derived two log g values: 4.16 and 3.71. The

[6]On loan from the Institute dAstrophysique de Liege, Belgium.

[7]IRAF is distributed by the National Optical Astronomical Observatories which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the National Science Foundation.

TABLE 4

SENSITIVITY OF THE DERIVED ABUNDANCES OF HD 87240 TO CHANGES IN EFFECTIVE TEMPERATURE AND SURFACE GRAVITY

HD 87240 Elements	log N/H for Adopted Model	log N/H for 500 K Hotter Model	log N/H for 0.5 Dex Greater Model
C II	−3.42	−3.34	−3.22
Mg I	−4.53	−4.31	−4.75
Mg II	−4.56	−4.52	−4.56
Si II	−3.83	−3.76	−3.88
Si III	−4.17	−4.00	−4.22
S II	−4.93	−4.87	−4.72
Ca II	−4.44	−4.26	−4.58
Ti II	−5.41	−5.23	−5.41
Cr II	−4.85	−4.79	−4.75
Mn II	−4.98	−4.93	−4.90
Fe I	−3.33	−3.13	−3.48
Fe II	−3.41	−3.37	−3.29
Fe III	−3.54	−3.49	−3.26
Ni II	−5.05	−5.08	−4.89
Sr II	−7.01	−6.82	−7.19
Y II	−6.63	−6.44	−6.71
Zr II	−6.64	−6.46	−6.67
Ce II	−5.89	−5.72	−5.97
Eu II	−6.96	−6.77	−7.12
Hg II	−7.04	−7.02	−6.92

first value comes from the absolute magnitude of the star and the age of the cluster. For the second, they used directly a calibration (Cramer & Maeder 1979, 1980) with the Geneva photometry. Estimation of the effective temperature was done by Glagolevskij (1994). The author used the Shallis-Blackwell method starting with the total flux emitted by the stars, and found an average temperature of 12,750 K for HD 87240.

To improve these values, we have used the $uvby\beta$ mean colors of Schmidt (1982), Schneider & Weis (1988) and Schneider (1987), with the calibration of Napiwotzki, Shonberner, & Wenske (1993), and then we have corrected these values according to Adelman & Rayle (2000). We have obtained $T_{\rm eff}$ = 12,534 K, $\log g$ = 3.60 for HD 87240, and $T_{\rm eff}$ = 12,543 K, $\log g$ = 3.87 for HD 96729. With the values of effective temperature and $\log g$ chosen we have computed a model atmosphere using Kurucz ATLAS9 (Kurucz 1995) code with [M/H] = +1.0, i.e., ten times the solar abundance, which seems to be adequate for these stars. We compared the observed Hγ profiles with synthetic spectra of the Hγ region calculated with SYNTHE (Kurucz & Avrett 1981), see Table 2. We found in this way $T_{\rm eff}$ = 12,520 K, $\log g$ = 3.55 for HD 87240, and $T_{\rm eff}$ = 12,552 K, $\log g$ = 3.87 for HD 96729. The final values adopted for the effective temperature and gravity are: $T_{\rm eff}$ = 12,530, K, $\log g$ = 3.6 for HD 87240, and $T_{\rm eff}$ = 12,550 K, $\log g$ = 3.9 for HD 96729.

4. ABUNDANCE ANALYSES

Different codes have been applied in the literature to determine elemental abundances from the average equivalent widths in CP stars, such as WIDTH9 (Kurucz 1995) and more recently BLACKWELL (e.g., Saffe & Levato 2004). Both algorithms seem to give very similar results (Saffe & Levato 2004). Particularly, in this work we have used the WIDTH9 program.

The adopted metal line damping constants were the default semi-classical approximations except for those of neutral and singly-ionized Ca-Ni lines, whose values are based on the data of Kurucz &

TABLE 5

COMPARISON OF DERIVED AND SOLAR ABUNDANCES

HD Specie	87240 log N/H	n	96729 log N/H	n	206653 log N/H	192913 log N/H	133029 log N/H	43819 log N/H	170973 log N/H	Sun log N/H
C II	−3.42±0.46	2	−3.59±0.36	2	−4.72	−3.16	−3.08	−3.78	−3.73	−3.45
Mg I	−4.53±0.26	2	···	···	−3.71	−5.10	···	−5.01	−4.90	−4.42
Mg II	−4.56±0.31	4	−5.23±0.24	4	−4.54	−4.70	−4.26	−4.72	−4.52	−4.42
Al I	···	···	−5.58±0.18	2	−4.38	−5.33	···	···	−5.46	−5.53
Si II	−3.83±0.19	5	−4.06±0.21	5	−3.59	−4.06	−3.36	−3.88	−3.82	−4.45
Si III	−4.17±0.49	3	···	···	−4.49	···	···	···	−4.16	−4.45
S II	−4.93±0.39	4	−4.76±0.42	4	−5.52	−4.67	−4.84	−5.46	−4.19	−4.67
Ca II	−4.44±0.00	1	−4.57±0.00	1	−5.83	−5.33	−5.72	−5.12	−4.91	−5.64
Sc II	···	···	−8.77±0.34	···	−6.94	−8.68	···	-9.11	−8.09	−8.83
Ti II	−5.41±0.25	41	−5.40±0.28	39	−5.28	−5.60	−6.02	−5.81	−5.11	−6.98
Cr I	···	···	···	···	···	−3.60	···	−4.69	···	−6.33
Cr II	−4.85±0.24	29	−4.83±0.31	32	−4.95	−4.92	−4.15	−5.02	−4.80	−6.33
Mn II	−4.98±0.32	10	−4.25±0.34	11	−4.95	−4.76	−5.00	−5.55	−5.08	−6.61
Fe I	−3.33±0.18	45	−3.32±0.23	39	···	−3.26	−3.32	−3.48	−3.17	−4.50
Fe II	−3.41±0.22	71	−3.54±0.26	68	−3.47	−3.36	−3.28	−3.66	−3.50	−4.50
Fe III	−3.54±0.32	4	···	···	−4.65	−2.68	−3.18	−3.70	−2.92	−4.50
Ni II	−5.05±0.31	4	−5.49±0.29	4	−5.14	−5.26	−5.70	−6.49	−5.73	−5.75
Sr II	−7.01±0.31	3	−6.71±0.28	4	−5.72	−5.03	−7.01	−5.63	−5.74	−9.03
Y II	−6.63±0.19	4	−7.05±0.21	4	−5.76	−7.59	−7.79	···	−7.48	−9.76
Zr II	−6.64±0.27	5	−7.02±0.32	5	−5.67	−7.22	−7.53	−7.81	−6.98	−9.40
Ba II	···	···	−7.98±0.00	1	−7.37	−8.52	−8.68	···	···	−9.87
Ce II	−5.89±0.18	16	−6.56±0.29	14	−5.79	−6.86	−7.14	−6.86	−6.26	−10.42
Pr II	···	···	···	···	−5.67	−6.66	−6.98	−6.69	−6.04	−11.29
Nd II	−6.90±0.24	5	−7.56±0.19	5	···	−6.81	−6.72	−7.34	···	−10.50
Sm II	···	···	···	···	−5.09	−6.34	···	···	−6.40	−10.99
Eu II	−6.96±0.31	3	−7.48±0.23	3	−6.11	−5.29	−8.44	−8.15	−6.27	−11.49
Gd II	···	···	···	···	···	−7.44	···	−7.18	···	−10.88
Dy II	···	···	−6.51±0.30	3	···	−6.56	···	···	···	−10.86
Hg II	−7.04±0.00	1	−7.03±0.00	1	−6.11	−5.12	−6.57	···	−4.39	−10.83
$T_{\rm eff}$	12530		12550		14385	10900	11200	11300	10750	
$\log g$	3.6		3.9		3.9	3.4	3.8	3.2	3.5	

Bell (1995). For lines of C II, multiplet 6, and Mg II, multiplet 4, adopted values for the Stark broadening were based on data of Sahal-Brechot (1969), and for Si II and Ca II the damping constants are those of Lanz, Dimitrijevic, & Artru (1988) and Chapelle & Sahal-Brechot (1970), respectively. We prefer this choice of gf values to VALD database (Piskunov 1996) to ensure homogeneity with our previous work.

For calculating the microturbulent velocity we have used the standard method. We have computed abundances from Fe II lines for HD 87240 and HD 96729 for a range of possible microturbulent velocities (ξ). For determining the final values (Table 3), we looked for the conditions that the abundances of Fe II were not dependent on the equivalent widths (ξ_1) or that they minimize the rms scatter of the abundances (ξ_2). Values for this species were derived using lines with gf values from Martin, Fuhr, & Wiese (1988) (MF values) and also with gf-values from compatible sources, in this case from Kurucz & Bell (1995) (KX values). From Fe II a mean microturbulence of 1.5 km s^{-1} is found for HD 87240, while for HD 96729 the Fe II lines indicate a microturbulence of 1.7 km s^{-1}. For HD 87240, Cr II and

Ti II indicate a value for the microturbulent velocity similar to that derived from Fe, while for HD 96729, the microturbulent velocity derived from Cr II and Ti II suggest some slightly different values.

In our abundance determination we did not include seriously blended lines. To give an idea of the sensitivity of our results to errors in the effective temperature and surface gravity, we have derived the abundances of HD 87240 for models 500 K hotter and $\log g = 0.5$ dex grater. Table 4 shows the amount of the resultant changes in the abundances.

5. DISCUSSION

Table 5 compares the derived abundances for HD 87240 and HD 96729, both members of open clusters, with a group of field Ap Si stars analyzed with similar spectra: HD 133029 and HD 192913 (López-García & Adelman 1999), HD 206653 (Albacete-Colombo et al. 2002), HD 43819 (López-García & Adelman 1994), and HD 170973 (López-García et al. 2001). We have included the rms of the average abundance for each species, and the number of lines involved in the average. Solar abundances have been taken from Grevesse, Noels, & Sauval (1996).

For both stars, C is mostly solar, Mg and S are slightly underabundant, Si is overabundant by factors between 4–6. All the heavier elements are overabundant. Ti and Cr are overabundant in the two stars studied by a factor of ~ 50, Mn is nearly 50 and 100 times overabundant with respect to the Sun, for HD 87240 and HD 96729, respectively. Mn is also overabundant by a factor 50 and 120, and Fe is 10 times solar in HD 87240 and HD 96729, respectively. The iron peak abundances are similar to the ones calculated for field stars. Sr is a 100 times the solar value and Y and Zr are about 1000 solar in both stars. The rare earths are 1000 times overabundant. Thus, cluster and field Ap Si stars share many of their abundance anomalies (see Table 5).

As we said in the Introduction, our purpose is to discuss the possible trend of the abundances of the critical elements in CP2 stars with age. Membership of the CP2 stars to open clusters makes it possible to derive ages with good precision. The average ages of NGC 3114 and NGC 3532 are estimated to be 150 Myr and 310 Myr, respectively (Carraro & Patat 2001; González & Lapasset 2001; Sagar & Sharples 1991; Fernández & Salgado 1980; Eggen 1981). The two Ap Si stars were selected to be physically similar but with different ages, assumed to be the average ages of the clusters to which the stars belong. Si and Fe are slightly overabundant in HD 96728 with respect to HD 87240. Heavier elements show a similar behavior, but abundance errors are not negligible and, particularly, the number of lines used in some cases is rather small. We will increase the sample in the near future to make a statistically meaningful discussion. Finding a trend or not will be important in the context of the diffusion theory which is the best explanation today for the spectroscopic characteristics of CP2 stars.

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