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ELEMENTAL ABUNDANCE STUDIES OF CP STARS. THE SILICON STARS HD 87405 AND HD 146555

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RESUMEN

Presentamos un análisis de las estrellas Ap(Si) HD 87405 y HD 146555 usando modelos de atmósferas de ATLAS9. Estas estrellas químicamente peculiares (CP) pertenecen a los cúmulos abiertos australes NGC 3114 y NGC 6087, respectivamente. Para ambas estrellas el C y el Ca (sólo una línea) son $\sim$ solares, el Mg, y el S se encuentran levemente por debajo del valor solar y el Si es sobreabundante por factores entre $\sim 4-6$. Los elementos más pesados son todos sobreabundantes, el Ti, y el Cr por factores de ~ 50, mientras que el Mn es sobreabundante por factores de ~ 50 y ~ 120, para HD 87405 y HD 146555, respectivamente. El Fe es ~ 10 veces solar, el Sr, el Y, y el Zr son sobreabundantes por factores entre $\sim 100-1000$ y las tierras raras por factores de ~ 1000 o más. Este trabajo es parte de un estudio para verificar la posible existencia de una tendencia entre las abundancias con la edad de estrellas CP en cúmulos abiertos.

ABSTRACT

In this paper we present an analysis of the Ap(Si) stars HD 87405 and HD 146555 using an ATLAS9 model atmospheres. These Chemically Peculiar (CP) stars belong to the southern hemisphere open clusters NGC 3114 and NGC 6087, respectively. For HD 87405 and HD 146555, C and Ca (only one line) are mostly solar, Mg and S are slightly underabundant, while Si is overabundant by factors between $\sim 4-6$. Heavier elements are all overabundant, Ti, Cr by factors of ~ 50, while Mn is nearly ~ 50 and ~ 120 times overabundant for HD 87405 and HD 146555, respectively. Fe is ~ 10 times solar, Sr, Y, Zr are overabundant by factors between $\sim 100-1000$ and rare earth by factors of ~ 1000 or more. This work is part of our current study for verifying a possible tendence of abundances with the age of CP stars in open clusters.

Key Words: stars: chemically peculiar — stars: individual (HD 87405, HD 146555)

1. INTRODUCTION

Chemically Peculiar (CP) stars present strong and/or weak intensities in the spectral lines of certain chemical species. In particular, the group called CP2 in the classification scheme of Preston (1974), shows 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 K up to 16000 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).

Recent works in the literature studied evolutionary effects of CP2 stars, with special attention to the magnetic field of the stars. For example, Landstreet et al. (2008) found that the time scale for the magnetic field decay varies with the mass of the star (250 Myr and 15 Myr, for stars with masses $2-3\ M_{\odot}$ and $4-5\ M_{\odot}$, respectively). Kochukhov & Bagnulo (2006) found that magnetic CP stars with masses $< 3\ M_{\odot}$ present an inhomogeneous age distribution. Pöhnl, Paunzen, & Maitzen (2005) show that CP2 stars could exist even close to the ZAMS (Zero Age Main Sequence). These works showed that age could be an important parameter. This research in particular is part of our current program for deriving elemental abundances among CP stars for members of open clusters. Our final goal 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 (i.e. CP2): HD 87405 and HD 146555 that belong to the open clusters NGC 3114 and NGC 6087, respectively. The average ages of NGC 3114 and NGC 6087 are estimated to be 173 Myr and 85 Myr, respectively (Kharchenko et al. 2005). The clusters included in the program were selected using the WEBDA open clusters database[1] which is maintained by Ernst Paunzen and Jean-Claude Mermilliod.

The star HD 87405 (= NGC 3114 # 108) is a member of the southern open cluster NGC 3114. This star has been classified as B9p-Si as a result of an objective-prism survey carried out by Frye, MacConnell, & Humphreys (1970). They detected Si II $\lambda\lambda$4128-30 in 108 Å/mm dispersion spectra. Levato & Malaroda (1975) studied the MK types of 22 stars in NGC 3114 and classified HD 87405 as B8.5 IIIp. They noted that this is a Si star, with Si II $\lambda\lambda$3955 clearly seen in 125 Å/mm dispersion spectra. The star is listed as B9 Si in different catalogs of peculiar stars (Renson 1988, 1992; Niedzielski & Muciek 1988). The Δa photometry also identifies this object as a CP2 star (Maitzen, Weiss, & Schneider 1988). UBV photoelectric photometry was published by Jankowitz & McCosh (1963). Geneva and $uvby$Hβ photometry have been provided by Hauck & North (1982), Rufener (1988) and Schmidt (1982), respectively. There is no evidence of variability in the photometry or in the spectra of this star in the literature. Radial velocities by Amieux & Burnage (1981) and Muciek (1988) are in agreement with the cluster membership of this object (86%). Schneider & Weiss (1988) also present a positive membership. However González & Lapasset (2001) found a lower membership probability of $\sim$70%. Then, this object should be taken with caution. HD 87405 is not an extremely slow rotator. The $v \sin i$ value derived from our spectra is $\sim$ 25 km s^{-1}.

The CP2 star HD 146555 (= NGC 6087 # 05) is a member of the southern open cluster NGC 6087. Its spectrum was classified as an Ap(Si) by Houk & Cowley (1975) and Bidelman, MacConnell, & Frye (1973). The object has been listed as B9p Si by Renson (1992) and as A0IIIp by Niedzielski & Muciek (1988). Maitzen (1985) measured the star in the Δa photometric system and identifies the object as peculiar. UBV photoelectric photometry was published by Landolt (1964). The properties in the Geneva photometric system have been studied by Rufener (1988). There is no evidence of variability in the photometry or in the spectra of this star. Using a radial velocity study, King (1982) found a probability membership of 94%.

Bagnulo et al. (2006) measured relatively low magnetic fields for HD 87405 and HD 146555 ($\sim$100 G and $\sim$500 G, respectively). They found a magnetic field in only 41/97 Ap stars (i.e. 58%), explaining that the probable reason is that the error (or threshold) in their measurement was $\sim$250 G. Observations based on high resolution spectropolarimetry have shown that a number of Ap stars exhibit an small longitudinal field (e.g. Auriere et al. 2004). However, Bagnulo et al. (2006) cautioned that some peculiar objects may have been observed at rotation phases at which the longitudinal field is small. The line-of-sight component of the magnetic field varies roughly sinusoidally with time (e.g. Mestel & Landstreet 2005). For example, for HD 74619 the authors detected a field in only one of two measurements.

The age of the two Ap(Si) stars is assumed to be the average age of the cluster. Table 1 presents some relevant observational data for both stars.

2. OBSERVATIONAL MATERIAL AND LINE IDENTIFICATIONS

The stellar spectra of the two Ap(Si) stars were obtained at Complejo Astrónomico El Leoncito (CASLEO) between April 21 and 23, 2004. We used the *Jorge Sahade* 2.15 m telescope equipped with a REOSC echelle spectrograph[2] and a TEK 1024 × 1024 CCD detector. The REOSC spectrograph uses gratings as cross dispersers. We have used one grating with 400 lines mm^{-1}. Three spectra of each star were obtained, covering the visual range $\lambda\lambda$3500–6500. The S/N ratio of the spectra is around 150 and the resolving power of the spectra is approximately 12500.

The spectra were reduced using IRAF[3] standard procedures for echelle spectra. We applied bias and flat corrections and then normalized order by order with the *continuum* task, using 7–9 order Chebyshev polynomials. We also corrected the scattered light in the spectrograph (*apscatter* task). We fitted the background with a linear function on both

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

[2] On loan from the Institute d'Astrophysique de Liege, Belgium.

[3] 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 1

OBSERVATIONAL DATA FOR HD 87405 AND HD 146555

Parameter	HD 87405	HD 146555	References
B-V	−0.09	−0.02	R1,R2,R8
U-B	−0.43	−0.35	R1,R2,R8
V	8.50	10.26	R1,R2,R8
b-y	−0.029		R3
m_1	0.117		R3,R4
c_1	0.603		R3,R4
β	2.690		R3,R4
B_1-B	0.828	0.846	R11
B_2-B	1.550	1.529	R11
V_1-B	1.756	1.661	R11
G-B	2.251	2.120	R11
Sp. Type	B9p-Si,B8.5 IIIp	Ap(Si), B9pSi	R5,R6,R9,R10
Cluster	NGC 3114	NGC 6087	
Age	173 Myr	85 Myr	R7

References: R1: Lynga (1960); R2: Jankowitz & McCosh (1963); R3: Hauck & Mermilliod (1998); R4: Schmidt (1982); R5: Frye et al. (1970); R6: Levato & Malaroda (1975); R7: Kharchenko et al. (2005); R8: Breger (1966); R9: Houk & Cowley (1975); R10: Renson (1992); R11: Rufener (1988).

sides of the echelle apertures, using the task *apall*. 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 in the literature (Saffe, Levato, & López-García 2004, 2005; Saffe et al. 2008). The equivalent widths were measured by fitting Gaussian profiles through the stellar metallic lines using the *splot* task. There is no more than a 15% difference among the equivalent width measurements of the same lines in different spectra.

The stellar lines of HD 87405 and HD 146555 were identified using the same procedure of previous papers (Saffe et al. 2004, 2005). 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 et al. 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).

3. ATMOSPHERIC PARAMETERS

Estimation of the effective temperature was done by Glagolevskij (1994), who used the Shallis-Blackwell method starting with the total flux emitted by the stars. In particular, he derived two temperatures from the parameters Q and X (reddening-free index and multicolor photometry parameter).

For HD 87405, Glagolevskij (1994) obtained 12650 K and 12200 K, while for HD 146555 he derived 12500 K and 12900 K, using the parameters Q and X, respectively. So the average temperatures for HD 87405 and HD 146555 are 12420 K and 12700 K, respectively.

To improve these values, we have used the $uvby\beta$ mean colors of Schmidt (1982) with the calibration of Napiwotzki, Shonberner, & Wenske (1993), and then we have corrected these values according to Adelman & Rayle (2000). We have obtained $T_{\rm eff}$ = 12962 K, log g = 3.46 for HD 87405. There is a good agreement with the $T_{\rm eff}$ and log g parameters (within 50 K and 0.1 dex) derived using the Geneva colors from Rufener (1988), together with the calibration of Kunzli et al. (1997) and corrected according to Hauck & North (1993). For the star HD 146555, we have used the Geneva photometry ($uvby\beta$ colors are not measured) from Rufener (1988) with the calibration of Kunzli et al. (1997) and corrected according to Hauck & North (1993). We have obtained $T_{\rm eff}$ = 12653 K, log g = 3.56 for HD 146555. We also compared the observed Hγ profiles with synthetic

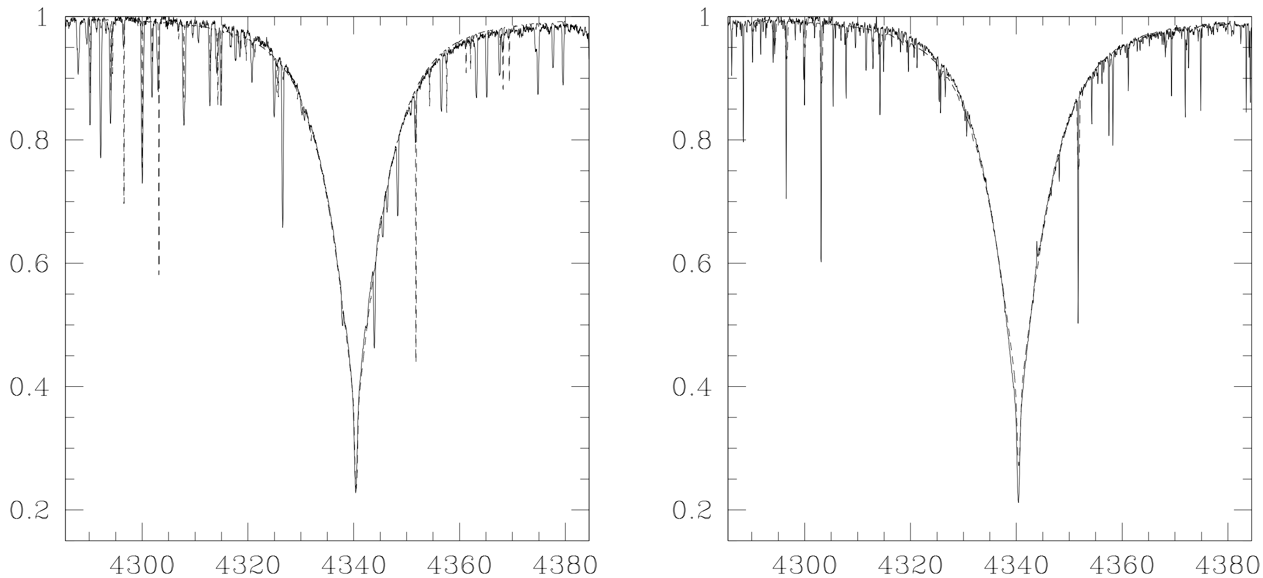

Fig. 1. Observed Hγ profiles (solid line) and synthetic spectra (dashed line) calculated with SYNTHE (Kurucz & Avrett 1981). Left and right panels correspond to HD 87405 and HD 146555, respectively.

TABLE 2

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 87405	Fe I	47	1.4	-3.43 ± 0.14	1.4	-3.46 ± 0.14	MF&KX
		41	1.2	-3.46 ± 0.17	1.2	-3.49 ± 0.18	MF
	Fe II	68	1.3	-3.45 ± 0.26	1.5	-3.41 ± 0.27	MF&KX
		29	1.4	-3.43 ± 0.27	1.1	-3.40 ± 0.28	MF
	mean ξ :	1.3 km s^{-1}					
	Ti II	43	1.5	-5.52 ± 0.23	1.0	-5.42 ± 0.24	MF&KX
	Cr II	28	1.3	-4.98 ± 0.21	1.2	-4.96 ± 0.23	MF&KX
HD 146555	Fe I	40	1.8	-3.32 ± 0.19	2.0	-3.36 ± 0.21	MF&KX
		37	1.4	-3.36 ± 0.22	1.4	-3.41 ± 0.23	MF
	Fe II	71	1.6	-3.54 ± 0.29	1.6	-3.56 ± 0.28	MF&KX
		30	1.4	-3.49 ± 0.27	1.4	-3.43 ± 0.26	MF
	mean ξ :	1.6 km s^{-1}					
	Ti II	38	2.0	-5.40 ± 0.25	1.9	-5.28 ± 0.26	MF&KX
	Cr II	33	1.1	-5.10 ± 0.27	1.3	-5.37 ± 0.27	MF&KX

spectra of the Hγ region calculated with SYNTHE (Kurucz & Avrett 1981) and used Kurucz ATLAS9 (Kurucz 1995, private communication) model atmospheres with [M/H]=+1.0, i.e. ten times the solar abundance, which seems to be adequate for these stars. Observed and computed profiles are presented in Figure 1. We found in this way $T_{\rm eff}$ = 12850 K, log g = 3.45 for HD 87405, and $T_{\rm eff}$ = 12650 K, log g = 3.50 for HD 146555.

The final values adopted for the effective temperature and gravity are: $T_{\rm eff}$ = 12850 K, log g = 3.45 for HD 87405, and $T_{\rm eff}$ = 12650 K, log g = 3.50 for HD 146555.

TABLE 3

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

HD 87405 Element	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	−3.44	−3.36	−3.24
Mg I	−4.95	−4.73	−5.17
Mg II	−4.66	−4.62	−4.66
Si II	−3.87	−3.80	−3.92
Si III	−3.97	−3.90	−4.01
S II	−4.74	−4.68	−4.53
Ca II	−5.60	−5.48	−5.71
Ti II	−5.52	−5.34	−5.52
Cr II	−4.98	−4.92	−4.88
Mn II	−5.01	−4.96	−4.93
Fe I	−3.43	−3.23	−3.58
Fe II	−3.45	−3.41	−3.33
Fe III	−3.54	−3.49	−3.26
Ni II	−5.35	−5.38	−5.19
Sr II	−6.21	−6.02	−6.39
Y II	−7.81	−7.62	−7.89
Zr II	−7.37	−7.19	−7.40
Ce II	−6.79	−6.62	−6.87
Eu II	−7.23	−7.04	−7.39
Hg II	−6.02	−6.00	−5.90

4. ABUNDANCE ANALYSES

We determined the metal abundances from the average equivalent widths of the spectra using the WIDTH9 code (Kurucz 1995, private communication). The program requires the selection of a model atmosphere, the assumed atomic data (oscillator strength, excitation potentials, damping constants, etc.) and the measured EW of the line. This code calculates a theoretical equivalent width for an initial input abundance (taken from the model atmosphere) and compares this value with the measured EW. Then it modifies the abundance iteratively to achieve a difference between theoretical and measured equivalent width < 0.01 mÅ. The process is repeated for each measured spectral line.

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 & Bell (1995). For lines of CII, multiplet 6, and MgII, multiplet 4, the adopted values for Stark broadening were based on data of Sahal-Brechot (1969), and for SiII and CaII, 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) in favor of homogeneity with our previous work.

To determine the abundances we need an initial estimation of the microturbulent velocity (ξ). For this estimation we have used the standard method. We computed abundances from Fe II lines for HD 87405 and HD 146555 for a range of possible microturbulent velocities (ξ). For determining the final values (Table 2), we looked for the conditions that the abundances of FeII were not dependent on the equivalent widths (ξ_1) or 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) (KB values). The sources of gf values showed in the last column of Table 2 determine the number of lines, n. From FeII a mean microturbulence of 1.3 km s^{-1} is found for HD 87405, while for HD 146555 the Fe II lines indicate a microturbulence of 1.6 km s^{-1}. For HD 87405, CrII and TiII indi-

TABLE 4

COMPARISON OF DERIVED AND SOLAR ABUNDANCES

HD Species	87405 log N/H	n	146555 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	-3.44 ± 0.39	2	-3.54 ± 0.33	2	−4.72	−3.16	−3.08	−3.78	−3.73	−3.45
Mg I	-4.95 ± 0.23	2	···	···	−3.71	−5.10	···	−5.01	−4.90	−4.42
Mg II	-4.66 ± 0.32	4	-4.72 ± 0.26	4	−4.54	−4.70	−4.26	−4.72	−4.52	−4.42
Al I	···	···	-5.28 ± 0.14	2	−4.38	−5.33	···	···	−5.46	−5.53
Si II	-3.87 ± 0.15	5	-3.92 ± 0.25	5	−3.59	−4.06	−3.36	−3.88	−3.82	−4.45
Si III	-3.97 ± 0.45	3	···	···	−4.49	···	···	···	−4.16	−4.45
S II	-4.74 ± 0.41	4	-4.81 ± 0.36	4	−5.52	−4.67	−4.84	−5.46	−4.19	−4.67
Ca II	-5.60 ± 0.00	1	-5.54 ± 0.00	1	−5.83	−5.33	−5.72	−5.12	−4.91	−5.64
Sc II	···	···	-8.32 ± 0.30	···	−6.94	−8.68	···	−9.11	−8.09	−8.83
Ti II	-5.52 ± 0.22	43	-5.40 ± 0.25	38	−5.28	−5.60	−6.02	−5.81	−5.11	−6.98
Cr I	···	···	···	···	···	−3.60	···	−4.69	···	−6.33
Cr II	-4.98 ± 0.21	28	-5.10 ± 0.27	33	−4.95	−4.92	−4.15	−5.02	−4.80	−6.33
Mn II	-5.01 ± 0.35	11	-4.95 ± 0.35	10	−4.95	−4.76	−5.00	−5.55	−5.08	−6.61
Fe I	-3.43 ± 0.14	47	-3.32 ± 0.19	40	···	−3.26	−3.32	−3.48	−3.17	−4.50
Fe II	-3.45 ± 0.26	68	-3.54 ± 0.29	71	−3.47	−3.36	−3.28	−3.66	−3.50	−4.50
Fe III	-3.54 ± 0.31	4	···	···	−4.65	−2.68	−3.18	−3.70	−2.92	−4.50
Ni II	-5.35 ± 0.28	4	-5.78 ± 0.29	4	−5.14	−5.26	−5.70	−6.49	−5.73	−5.75
Sr II	-6.21 ± 0.30	4	-6.25 ± 0.31	3	−5.72	−5.03	−7.01	−5.63	−5.74	−9.03
Y II	-7.81 ± 0.21	4	-7.85 ± 0.25	4	−5.76	−7.59	−7.79	···	−7.48	−9.76
Zr II	-7.37 ± 0.23	5	-7.44 ± 0.26	5	−5.67	−7.22	−7.53	−7.81	−6.98	−9.40
Ba II	···	···	-8.22 ± 0.00	1	−7.37	−8.52	−8.68	···	···	−9.87
Ce II	-6.79 ± 0.15	16	-6.84 ± 0.29	15	−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	-6.92 ± 0.22	5	-6.86 ± 0.17	5	···	−6.81	−6.72	−7.34	···	−10.50
Sm II	···	···	···	···	−5.09	−6.34	···	···	−6.40	−10.99
Eu II	-7.23 ± 0.34	4	-6.78 ± 0.28	3	−6.11	−5.29	−8.44	−8.15	−6.27	−11.49
Gd II	···	···	···	···	···	−7.44	···	−7.18	···	−10.88
Dy II	···	···	-6.72 ± 0.27	3	···	−6.56	···	···	···	−10.86
Hg II	-6.02 ± 0.00	1	-5.89 ± 0.00	1	−6.11	−5.12	−6.57	···	−4.39	−10.83
$T_{\rm eff}$	12850		12650		14385	10900	11200	11300	10750	
log g	3.45		3.50		3.9	3.4	3.8	3.2	3.5	

cate a similar microturbulent velocity to the value derived from Fe, while for HD 146555, the microturbulent velocity derived from CrII and TiII suggest slightly different values. Once a ξ value has been fixed the abundances corresponding to all chemical species measured are determined using the WIDTH9 code.

In our abundance determination we did not include seriously blended lines. To give an idea of the sensitivity of our results, raising the temperature of HD 87405 by 3.9% (500 K) increases the average abundance by 2.12%, and raising the surface gravity by 14.5% (0.5 dex) increases the average abundance by 0.44%. Table 3 shows the amount of the changes in the results for the abundances.

5. DISCUSSION

We present in Table 4 the derived abundances for HD 87405 and HD 146555 (both members of open clusters) compared 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, Adelman, & Pintado 2001). The five comparison stars are also Ap(Si) stars. 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 HD 87405 no He I lines were seen. For HD 146555 we calculated HeI 4471 profile in LTE using the program SYNTHE and derived log He/H $= -1.30$, i.e. approximately one-half the solar He/H ratio. For both stars, C and Ca (only one line) are mostly solar, Mg and S are slightly underabundant, while Si is overabundant by factors between $\sim 4-6$. All the heavier elements are overabundant. Ti and Cr are overabundant in the two stars studied by a factor of ~ 50. Mn is also overabundant by a factor ~ 50 and ~ 120, and Fe is ~ 10 times solar in HD 87405 and HD 146555, respectively. The iron peak abundances are similar to the ones calculated for field stars. Sr is a ~ 100 times the solar value while Y and Zr are about 1000 times solar in both stars. The rare earths are ~ 1000 times overabundant. Then, cluster and field Ap(Si) stars share many of their abundance anomalies (see Table 4).

HD 87405 and HD 146555 are members of the open clusters NGC 3114 and NGC 6087, respectively. In a previous work, we have studied another two Ap(Si) stars (HD 87240 and HD 96729, Saffe et al. 2005) which belong to the clusters NGC 3114 and NGC 3532, respectively. Taking the four stars together, we have three different ages: HD 96729 (NGC 3532, 310 Myr), HD 87405 and HD 87240 (both in NGC 3114, 173 Myr), and HD 146555 (NGC 6087, 85 Myr). The stars HD 87405 and HD 87240 that belong to NGC 3114 present similar abundance values (within the errors). With the small sample of stars we did not attempt to find a tendency between the abundances of Si or Cr with the age of the clusters. We are continuing the work by increasing the number of stars and clusters studied, in order to make a statistically meaningful discussion in the context of the diffusion theory.

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