New spectroscopic classifications of 35 chemically peculiar candidate stars

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The chemically peculiar (CP) stars of the upper main sequence are perfect tracers for several astrophysical processes. Their study especially in open clusters further helps to establish their evolutionary status. The latter is most important to understand the origin and evolution of the CP phenomenon, i.e. the connection between diffusion and a stellar magnetic field. There are two important topics, we cover with this paper. First of all, we investigate the reliability of the CCD Δa photometry for fainter objects in open clusters. The latter method is able to detect CP stars very efficiently, but still a spectroscopic verification is needed to verify the photometric candidates. On the other hand, already published spectral classifications on the basis of photographic plates and prism technology have to be tested with modern instruments. Classification resolution spectroscopy is presented for thirty five bona-fide CP candidates. Twenty six of them are located within the boundaries of fourteen open clusters, for which we also investigated their membership probabilities. Apart from five objects, they seem to be members of the respective clusters. The objects were classified in the framework of a refined Morgan-Keenan system with the extension of well established CP star spectra. We confirm the CP nature of all but one target. The results of Δa photometry and the spectral classifications are in excellent agreement. For the cluster members we find a continuous sequence of CP stars from 10 to 850 Myr, the whole range of investigated cluster ages.

1 Introduction

Classification resolution spectroscopy is a very powerful as well as efficient astrophysical tool since more than 100 years. Beside the huge efforts to compile the Michigan Spectral Catalogue (Sowell et al. 2007), even recent and forthcoming all-sky-surveys (e.g. SDSS and LSST) as well as satellite missions (e.g. Gaia) will incorporate classification resolution spectroscopy.

The group of chemically peculiar (CP) stars on the upper main sequence display peculiar lines and line strengths as well as other peculiar features. Generally, one distinguish between He-weak/strong, HgMn, Si, SrCrEu, and Am stars. The subgroup of SrCrEu objects, for example, typically have overabundances of up to several dex for e.g. Sr, Cr, Eu, and other rare earth elements compared to the Sun. However, some CP stars can not be strictly catalogued in this scheme. There are also transition objects within these groups. Furthermore, for some groups the existence of a strong global stellar magnetic field was established, the first detected by (Babcock 1947).

Due to the typical flux depression in magnetic CP stars at λ 5200 Å, at least two photometric systems, the Δa and Geneva ones, are able to detect them in an economic and most efficient way (Paunzen, Stütz & Maitzen 2005) by comparing the flux at the depression centre with the adjacent regions.

Whereas the available Geneva photometry is almost exclusively limited to bright (and therefore close) Galactic field stars and open cluster members, Δa photometry was even applied to the Large Magellanic Cloud (Paunzen et al. 2006). The latter was performed with CCD detectors, introducing several new aspects for the transformation and efficiency compared to the original photoelectric one (Maitzen, Paunzen & Rode 1997). Therefore, the confirmation of the bona-fide photometric CP candidates using spectral classifications is absolutely essential to further strengthen the results of CCD Δa photometry.

In this paper we present classical classification resolution spectroscopy of thirty five CP candidates, twenty six located in the fields of open clusters, to establish their true nature. For the cluster stars, we analyse as well as discuss their membership probability and estimate their evolution-

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Table 1 The observed open clusters with their parameters based on the list by Paunzen & Netopil (2006).

Cluster	D [pc]	$E(B-V)$ [mag]	Age [Myr]
IC 4725	615 (65)	0.48 (2)	75 (15)
NGC 3532	492 (8)	0.04 (1)	262 (46)
NGC 3960	1868 (272)	0.28 (3)	848 (212)
NGC 5460	673 (76)	0.12 (2)	167 (54)
NGC 5662	684 (60)	0.32 (1)	77 (20)
NGC 6031	1560 (314)	0.43 (6)	205 (66)
NGC 6087	893 (57)	0.20 (3)	78 (19)
NGC 6268	1056 (28)	0.40 (2)	238 (72)
NGC 6281	516 (35)	0.15 (1)	285 (58)
NGC 6405	473 (16)	0.14 (2)	71 (21)
NGC 6475	258 (21)	0.07 (3)	267 (62)
Rup 115	2000 (330)	0.74 (5)	500 (115)
Stock 16	1798 (112)	0.49 (2)	6 (3)

ary status. In summary, all but two objects, one normal type and one spectroscopic binary system, are indeed CP stars of the upper main sequence.

2 Target selection, observations and reduction

Twenty three targets are established as candidate CP stars in thirteen open clusters (Table 1) by our extensive photoelectric and CCD Δa survey (e.g. Maitzen 1993; Netopil et al. 2007). Additionally, three suspected cluster CP stars within Melotte 227 and nine Galactic field objects were chosen from the General Catalogue of Ap and Am stars by Renson (1991), for which no Δa measurements are available.

In Table 2, the targets with their main SIMBAD identifier, WEBDA[1] numbers, spectral determinations, and additional information are given. The data for the V magnitudes and Δa measurements were taken from WEBDA.

The observations were performed at the 2.15 m telescope at the Complejo Astronómico el Leoncito (CASLEO) in the nights between the 12th and the 18th of June 2006 by one of us (OIP) using a Tektronik 1024×1024 CCD and the REOSC echelle spectrograph in the single mode with the 600 lines mm^{-1} grating, resulting in a resolution of 2 Å pixel^{-1} and a spectral coverage of 3630 to 5220 Å.

The integration times range from fifteen minutes up to one hour for the fainter targets, with signal-to-noise ratios between 50 and 200, respectively.

Due to the resolution, all lines except the hydrogen and CaK ones are blended. Transformed to a velocity resolution for one pixel results into 120 $\mathrm{km\,s}^{-1}$ at Hβ and 150 $\mathrm{km\,s}^{-1}$ at Hϵ, respectively. Even if it is possible to determine the centres of the useful lines up to half a pixel accuracy, the derived radial velocities will be too uncertain to be used for, e.g., a membership analysis. However, we checked all target stars for significant shifts of the lines, but found none.

[1] http://www.univie.ac.at/webda

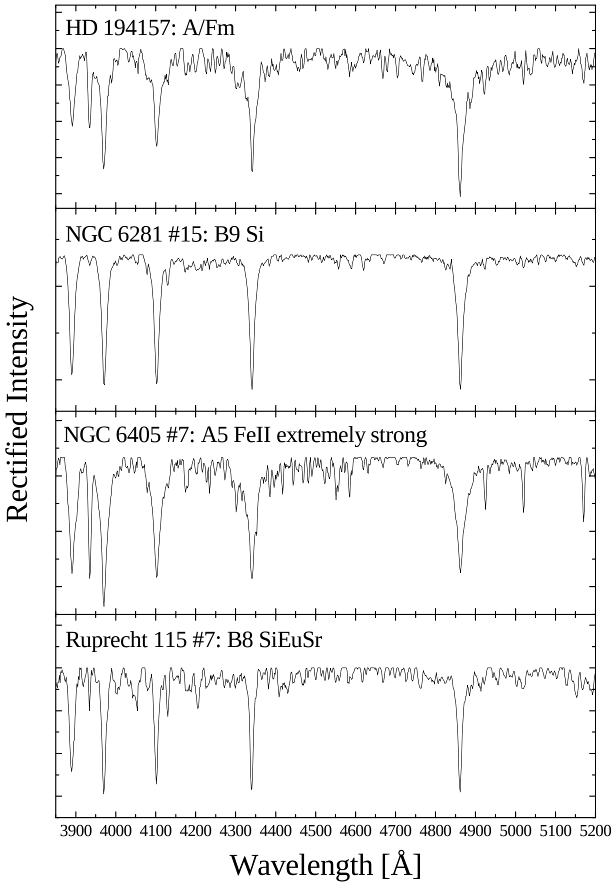

Fig. 1 Normalized spectra of four targets showing the whole range of peculiarities detected.

All reductions were performed with standard IRAF routines[2]. After the bias, dark, and flat field corrections, the spectra were wavelength calibrated using ThAr standard spectra observed before the respective target. Furthermore, no smoothing was applied.

The final normalized spectra are available in electronic form from the first author.

3 Membership

As in Paunzen et al. (2010), a careful membership analysis of the cluster CP objects was performed. Some stars of the present study coincide with the latter reference, hence their membership results were adopted. For the remaining objects we proceeded likewise to divide membership into y (member), p (probable member), ? (probably non-member), and n (non-member) using all available information. Due to a lack of already published radial velocity data or parallaxes for the remaining stars, the analysis is based on proper motions and photometric criteria only. As mentioned in Sect. 2, the obtained spectra are not helpful in this respect due to the low resolution. Additionally, the mean radial velocities

[2] http://iraf.noao.edu/

Table 2 Results for the observed sample of stars in the Galactic field (upper panel) and fourteen open clusters (lower panel). The data for the V magnitude and all available Δa measurements were taken from WEBDA (number W); the membership flag as determined in Sect. 3 (Mem); the spectral types from Renson & Manfroid (2009) (RM) and this paper (TP); magnetic field detected (MF) – see Sect. 4 for a short discussion.

Cluster	Object	W	V [mag]	Δa [mmag]	Mem	Spec. RM	Spec. TP	MF
	HD 1913		10.13			A3–A8	A/Fm	
	HD 193921		10.80			A0 Si	A0 SiSr	
	HD 194157		9.85			A3–F0	A/Fm	
	HD 198216		9.89			A0–	A2 SiSr	
	HD 208759		10.02			A0 SrEuCr	A5 SrCrEu	
	HD 212765		10.61			A2–F2	A/Fm	
	HD 214985		10.77			A0 Si	A0 Si	
	HD 221157		10.23				SB A + G type	
	HD 223184		10.01			A0–	A/Fm	
IC 4725	BD−19°5044L	98	10.20	+16	p	B8	B9 Si, SB?	n
	HD 170836	167	8.95	+46	y	B7	B6 He strong	y
	HD 170860 (A)	153	9.40	+22	p	B8	B9 Si	n
Melotte 227	HD 188136	17	8.01			A5–Sr dD	A/Fm	
	HD 190290	28	9.92			A0 EuSr	A2 EuSrCr	y
	HD 192118	24	10.26			A Si	A0 Si II very strong	
NGC 3532	HD 96729	449	10.00	+65	n	B9 Si	B9 Si	y
	HD 303821	704	11.67	+61	n	A	A0 SiSr	n
NGC 3960		1	14.31	+85	y		A5 SrCrEu, very peculiar	
NGC 5460	HD 122983	142	9.90	+20	p	A0	A0 Si	y
	HD 123225	55	8.85	+14	y	B9 Si?	B8 Si	n
NGC 5662	CPD−56°6330	85	10.60	+33	n	A2	A0 Si	n
	HD 127924	187	9.20	+29	p	B8	B8 Si	n
NGC 6031		73	13.53	+20	?		A5 marginal Si	
NGC 6087	CPD−57°7817	25	10.03	+27	p		B8 Si	y
	HD 146555	5	10.28	+38	y	B9 Si	A0 Si	n
NGC 6268	HD 322549	21	11.18	+19	p		B8 marginal Si	
		39	12.16	+23	p		A3 marginal Si	
		80	11.97	+56	?		A0 SiSr	
NGC 6281	HD 153948	15	9.35	+40	y	A2 Si	B9 Si	y
NGC 6405	CD−32°13119	7	10.95	+33	p		A5 Fe II extremely strong	n
	HD 318100	19	8.82	+67	y	B9	A0 SiSr	y
	HD 318107	77	9.35	+94	y	B8	A0 Si	y
NGC 6475	HD 320764	23	8.90	+20	y	A6	A1V	n
Ruprecht 115		7	13.52	+58	p		B8 SiEuSr	
Stock 16		12	13.38	+24	p		A2 Si, strong metals	

for the clusters presented by Mermilliod et al. (2008) and the updated catalogue by Dias et al. (2002) are all smaller than 22 km s^{-1} with most of them well below 10 km s^{-1}. Hence, only a considerable shift in the spectra (which was not detected) would indicate a non-membership.

Concerning membership determination based on photometry, we have to note that on the one hand magnetic CP stars appear bluer than normal stars of the same temperature, on the other hand variability introduces an additional difficulty. We used averaged photometric values taken from WEBDA and the GCPD catalogue[3] in order to minimize the influence of variability. However, the typical amplitudes of CP stars are rather small compared to the width of the cluster main sequence. Furthermore, for several objects data in various photometric systems are available, which are used in the following also to determine effective temperatures (see Sect. 4). Additionally, the above mentioned "blueing effect" is corrected by the use of an appropriate temperature calibration (Netopil et al. 2008). However, larger errors have to be taken into account, if photometry is the only possibility to deduce membership.

The results can be found in Table 3, objects which deserve closer attention are discussed in the following. We did

[3] http://obswww.unige.ch/gcpd/gcpd.html

Table 3 Membership analysis of objects not included in the study by Paunzen et al. (2010). Their results were adopted and are given in Table 2. For the remaining stars, the final membership was deduced from proper motion (μ) and position in the HRD (ph). If available, in parenthesis the membership obtained by Landstreet et al. (2007) is given, which is based on the same criteria (photometry and proper motion). The analysis of stars marked with a) are discussed in the text

	CP Star		Membership	
			μ/ph	Final
a)	NGC 3532 #704	(HD 303821)	?/n	n (?)
	NGC 3960 #1		y/p	p
	NGC 6031 #73		?/p	?
	NGC 6087 #5	(HD 146555)	y/y	y (y)
	NGC 6087 #25	(CPD$-57°$7817)	y/p	p (p)
a)	NGC 6268 #21	(HD 322549)	y/p	y
a)	NGC 6268 #39		y/p	y
a)	NGC 6268 #80		p/p	p
	Rup 115 #7		p/p	p
a)	Stock 16 #12		p/p	p

not treated the three stars within Melotte 227, since its true cluster nature was not confirmed by Orellana & de Biasi (2008) as well as by Baumgardt (1998).

The proper motion of NGC 3532 #704 (HD 303821), extracted from UCAC3 (Zacharias et al. 2010) and PPMX (Röser et al. 2008), compared to published mean cluster motions indicates a non-membership. Unfortunately, not sufficient photometric data are available to place the object on the Hertzsprung-Russell-diagram (HRD hereafter). Beside photographic UBV measurements by Koelbloed (1959), the only available source is Maitzen & Schneider (1987), who list a via Δa transformed $(b-y)$ index of 0.014 mag. If considering the cluster reddening, the intrinsic colour index agrees with the spectral type of A0. However, even if taking a larger error of the photographic visual magnitude into account, the absolute magnitude indicates that it is a probable background object. Since also its distance to the cluster centre is larger than the cluster radius, this object was classified as non-member in agreement to Landstreet et al. (2007).

The effective temperature of the object NGC 6031 #73 was estimated using the B,V photometry by Piatti, Clariá & Bica (1999) and the mean cluster reddening. The position in the HRD does not contradict membership, in contrast to proper motion data. All available catalogues (UCAC2 and UCAC3) list values which deviate more than 3σ from the cluster mean. Hence, we classify this object as probable non-member.

For two CP objects within NGC 6268, the proper motions indicate an unambiguous cluster membership, but a discrepancy was found for NGC 6268 #80. Proper motions by Tycho-2, UCAC2, and Kharchenko et al. (2004) agree with the cluster mean, whereas UCAC3 data deviate somewhat and the results by Röser et al. (2008) would completely deny a membership. However, we assign this object as probable member, additional radial velocity data would be very helpful to clarify its status. Like for HD 303821 discussed above, we were not able to determine accurate effective temperatures for the stars in NGC 6268 due to a lack of appropriate photometric data. However, their position within the colour-magnitude diagram using the $(b-y)/V$ data by McSwain & Gies (2005) do not contradict membership. Furthermore, the absolute magnitudes are in good agreement with the obtained spectral types.

Although the UCAC2 data for Stock 16 #12 deviate significantly compared to the mean cluster proper motion, its successor UCAC3 as well as PPMX data support a kinematic membership. Using the mean cluster reddening and the photoelectric UBV photometry by Turner (1985), the calibrated effective temperature indicates a spectral type about A0. Taking into account the differential reddening, reported e.g. by Vázquez et al. (2005), the obtained spectral type A2 is within the error range compatible. In the HRD, the object is located slightly above the corresponding cluster isochrone, but we assign a probable membership for that star. Also for this open cluster a radial velocity study is desirable, to establish definite (non)memberships.

4 Results

All programme stars were classified in the framework of a refined Morgan-Keenan system (MK hereafter) described in Gray & Garrison (1987, 1989a,b). In addition, we used well established CP stars to guide us in the identification of the various peculiarities. We classified the stars using the standard techniques of MK classification. For a precise classification of the objects and to identify possible peculiarities, the spectra were compared visually with the MK standards. The detection of spectral peculiarities is straightforward with the achieved signal-to-noise ratio, whereas the error for the spectral classification is about ±1 subclass (Paunzen 2001).

In Table 2, our classification together with the spectral types listed in Renson & Manfroid (2009) and the information about the detection of a magnetic field is listed. For the latter, we considered mainly the catalog of magnetic CP stars by Romanyuk & Kudryavtsev (2008), since they also provide the references for objects studied by several authors. Here, we just want to mention the studies for the rather well investigated object HD 318107 (NGC 6405 #77), for which magnetic field measurements are available by Mathys et al. (1997), Mathys & Hubrig (1997), and Bagnulo et al. (2006). For all other objects we refer to the work by Romanyuk & Kudryavtsev (2008). The stars HD 122983, HD 153948, and HD 318100 are not included in the latter reference, but at least a probable magnetic field was detected by Bagnulo et al. (2006). However, for nine objects they failed to detect a magnetic field (marked as ‘n’ in Table 2). This is unexpected, since usually large positive Δa values are correlated with strong stellar magnetic fields. Since the listed S/N values are rather large, the most probable reason for the discrepancy is an unfavourable phase dur-

Table 4 Derived logarithmic effective temperatures, luminosities, and masses of open cluster targets. Due to the lack of photometric data, not all investigated objects were calibrated. The derived temperatures and luminosities of stars included in Paunzen et al. (2010) were adopted from the reference.

Star	$\log T_{\rm eff}$	$\log L/L_\odot$	$M/M_\odot$	Mem
IC 4725 #98	4.094	2.25	3.4	p
IC 4725 #153	4.137	2.63	4.2	p
IC 4725 #167	4.162	2.89	4.8	y
NGC 3532 #449	4.083	(1.58)	(2.8)	n
NGC 3960 #1	3.910	1.04	1.8	p
NGC 5460 #55	4.084	2.40	3.6	y
NGC 5460 #142	4.032	1.89	2.8	p
NGC 5662 #85	4.088	(1.95)	(3.1)	n
NGC 5662 #187	4.113	2.50	3.8	p
NGC 6031 #73	3.945	(1.40)	(2.1)	?
NGC 6087 #5	4.099	2.13	3.3	y
NGC 6087 #25	4.081	2.25	3.4	p
NGC 6281 #15	4.026	1.84	2.7	y
NGC 6405 #7	3.914	1.05	1.8	p
NGC 6405 #19	4.025	1.60	2.5	y
NGC 6405 #77	4.070	1.90	2.9	y
Rup 115 #7	3.949	2.00	2.8	p
Stock 16 #12	3.981	1.70	2.5	p

ing the respective single measurement of the longitudinal magnetic field.

Apart from one star (HD 320764), all targets with available (and positive) Δa measurements are indeed classical CP stars. The latter object was also considered as normal in the abundance study by Folsom et al. (2007). It can not be clarified, why this object shows a positive Δa value. It might be connected to the large $v \sin i$ value of 225 km s^{-1}, determined by the latter reference, or to an undetected binary nature.

A comparison of the spectral types presented in this work with those of the literature, mostly obtained using photographic plates and prism technology, shows an excellent agreement; some of them even coincide exactly.

The overall good agreement between the measured positive (CCD) Δa values and the peculiar spectral types gives further confidence in this observational technique to detect CP stars very efficiently. This fact is very important when observing much fainter stars, for example in the Large Magellanic Cloud (Paunzen et al. 2006).

For the targets within open cluster boundaries we estimated their astrophysical parameters making use of the cluster parameters based on a set of literature values (Table 1). Starting with the comprehensive compilation of Paunzen & Netopil (2006), we searched the literature for additional (new or overseen) parameters. They were all checked for plausibility by using appropriate isochrones and available photometric data taken from the WEBDA database. Just strongly deviating results were removed and finally a strict average and standard deviations were calculated. The $\log T_{\rm eff}$ values were determined using the calibration of Netopil et al. (2008) for CP stars. We made use of the GCPD catalogue and the WEBDA database to extract all available photometric data for the programme stars in the UBV, Geneva, and Strömgren system. In order to obtain absolute magnitudes (assuming that all programme stars are indeed cluster members), we took averaged values and the mean cluster distances (see Table 1). Finally, the luminosity was derived using the bolometric correction for magnetic CP stars of the latter reference. In Table 4, the individual values are listed. The errors for $\log T_{\rm eff}$ are typically 0.02, whereas the ones for $\log L/L_\odot$ are 0.15, respectively.

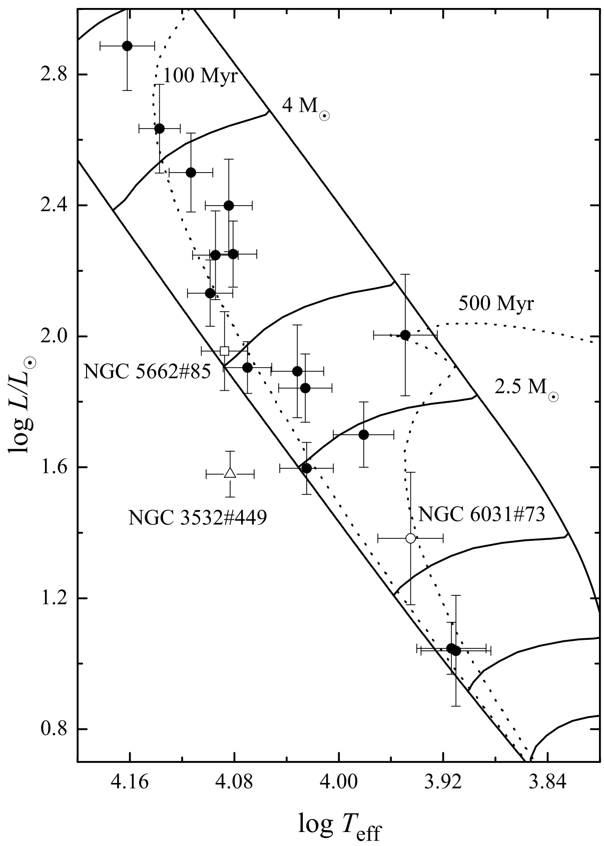

Fig. 2 The location of the open cluster CP stars in a $\log L/L_\odot$ versus $\log T_{\rm eff}$ diagram. Certain members are presented by filled circles, whereas probable members by open circles. The evolutionary tracks for individual masses are taken from Schaller et al. (1992). We also included lines, representing the fractional main sequence ages of 30 and 80 %.

The target stars cover the typical mass range for mid B to late A type main sequence objects from about 1.8 $M_\odot$ to 4.8 $M_\odot$ as other members of this group (Pöhnl, Paunzen & Maitzen 2005). Investigating the probable and established cluster members, we find a continuous sequence of CP stars from 10 to 850 Myr. This result is very important in the light of the mechanism responsible for the CP phenomenon connected with the presence of a stellar magnetic field as discussed by Landstreet et al. (2007).

Figure 2 shows the location of the stars listed in Table 4 in a $\log L/L_\odot$ versus $\log T_{\rm eff}$ diagram. To increase the sample, we included also ten additional certain or probable cluster CP members from the variability study by Paunzen et al. (2010), belonging to the clusters NGC 2516, NGC 3114, NGC 3228, NGC 3532, and NGC 6475. The evolutionary tracks for individual masses and ages for solar metallicity were taken from Schaller et al. (1992). Furthermore, some fractional ages (percentage of the main sequence lifetime already elapsed) are given.

In the literature there is a long lasting discussion about the latter parameter. Hubrig, North & Mathys (2000) proposed that the magnetic field of stars with masses below $3\,M_\odot$ appear only for objects that have already completed at least 30 % of their main-sequence-lifetime. In contrast to Landstreet et al. (2007), who have presented some clear counter-examples. Assuming that all CP stars are also showing a magnetic field, Fig. 2 would favour the latter reference, since several objects are located well below the line representing a fractional age of 30 %. However, one further important parameter has to be also considered: the cluster (and therefore also the star) metallicity, which has a rather large influence on the position in the HRD, and hence on the fractional age. Although several works are already presented during the last years on the topic of open cluster metallicity, the overall knowledge is still rather poor. The work e.g. by Pöhnl & Paunzen (2010), to deduce metallicity on a statistical basis using photometry, is probably a good possibility to estimate this property and therefore to improve also the knowledge of the evolutionary status of (cluster) CP stars.

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