Peculiar Versus Normal Phenomena in A-Type and Related Stars
ASP Conference Series, Vol. 44, 1993
M.M. Dworetsky, F. Castelli, and R. Faraggiana (eds.)

HAVE NON-MAGNETIC STARS A COMPLEX GEOMETRY ?

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ABSTRACT The existence of non-magnetic CP stars among the ones in the CP2 and CP4 groups is discussed. Assuming to be non-magnetic a star in which the magnetic field has been measured but no value in excess of the 3σ level has been detected, the implications of the spectrum and/or light variability observed in some such stars are discussed. Since the overall properties of *non-magnetic* stars do not differ significantly from those of the magnetic ones and a similar variability phenomenology has been observed in several such stars, the probable presence of a weak large scale organized magnetic field is argued.

INTRODUCTION

Since the recognition of the existence of peculiarities in the spectra of a number of A stars in the HD Catalogue, the first systematic study of the spectral peculiarities of the so called Ap stars was done by Morgan, who demonstrated the *existence of a peculiar branch of the spectral sequence in the interval B8–F0* in which such elements as Si, Cr, Mn, Sr, Eu show abnormally strong lines (Morgan 1931a, b, 1932, 1933a, b).

After Babcock (1947, 1958) discovered large magnetic fields to be present in a number of Ap stars, a great interest has raised and a lot of studies have been devoted to understand the properties of such a class of stars. Among several recent review papers available in the literature, perhaps the most comprehensive discussion of the properties of the peculiar A and B stars is given in Wolff's (1983) monograph.

Now it is quite generally accepted that, among non-degenerate stars, large-scale organized magnetic fields are only present in the following subgroups (identified as usual by the most outstanding chemical peculiarity) ranging from spectral type B1 through F0:

(a) – He weak, He variable and He strong (henceforth called He abnormal stars).
(b) – Si λ4200 and Si (henceforth Si stars);
(c) – Si combined with Cr, Eu, Fe, Mg, Sr, etc. (henceforth Si + stars);
(d) – Cr, Eu, Sr and combinations (henceforth CrEuSr stars);

All of these stars are also commonly referred to as magnetic CP stars.

Although stars are observed in all (a) – (d) subgroups to possess detectable magnetic fields, it is by no means clear that all the stars belonging to the above mentioned subgroups do possess large-scale organized magnetic fields. Indeed in this talk I will be concerned with those stars, among the stars of subgroups

(a) – (d), in which a magnetic field has not been detected and I will discuss the implications. For the sake of brevity, in the following I will cumulatively refer to the four above mentioned subgroups as CPa/d.

THE NON-MAGNETIC CPA/D STARS

At present 6684 upper main sequence stars are known (or suspected) to be chemically peculiar (Renson et al. 1991). Among them, 3492 stars (i.e. 52.2 %) are classified as Am, or CP1 stars, according to Preston's (1974) classification. Excluding the 270 stars for which no peculiarity classification is available and the 124 HgMn stars (CP3, according to Preston), there remain 2798 (i.e. 41.9 %) Ap and Bp stars, i.e. CPa/d stars, according to our convention. Among these 2798 CPa/d stars we have 190 (6.9 %) He abnormal stars, 1365 (48.8 %) Si, 278 (9.9 %) Si +, and 965 (34.5 %) CrEuSr stars.
It is important to note that the above given classification into subgroups, as well as every other, is only schematic and for practical use, in fact no two stars are found which are perfectly alike: large individual differences exist from star to star and cases intermediate between two subgroups are found, so that the boundaries of the subgoups in no case should be considered as rigid. However the necessity arises to select and order the occurence of the peculiarities: this may provide useful hints in picking-up common properties in each subgroup which can be useful for successive interpretation. In this respect it looks to be useful the extension of Preston's classification, proposed by Maitzen (1984) on the basis of the odd-even effect with respect to the presence of magnetic fields (CP1 and CP3 non-magnetic, CP2 magnetic), and consisting in introducing the subgroups CP4 and CP5 for He-weak and the subgroups CP6 and CP7 for the He-strong stars. A recent thorough discussion of CP star detection and classification has been given by Faraggiana (1987) and will not be pursued here. The properties of the magnetic fields of CP stars have been extensively investigated since more than fourty years and a considerable amount of papers have hence accumulated. For a recent thorough review on the measurement of magnetic fields in nondegenerate stars see Mathys (1989).
From this large body of published papers a strict relation between large-scale organized magnetic fields (LSOMF) and CPa/d stars is quite firmly assessed. However for a number of such stars the measured magnetic field is dubious or below detection. In Tables I – IV we list, separated into subgroups, the stars for which magnetic field measurements have been carried out but no evidence has been found or no values in excess of the 3σ level have been detected. Hereafter we shall refer to the stars listed in Tables I – IV as non–magnetic CPa/d stars (or NMCPa/d stars). However it has to be noted that a null result in a few measurements does not mean at all that a LSOMF is absent. In this respect the history of the magnetic field measurement in the A1 CrEuMn star ε UMa (HD 112485 = HR 4905), the brightest known Ap star, is illuminating. Babcock (1958) could not measure the magnetic field. Landstreet et al. (1975) and Borra & Landstreet (1980) were also unable to detect a field larger than a few hundred gauss, while Glagolevskii et al. (1982, 1983) and Hubrig (1988) found a variable field, although with different values and ranges according to the techniques and lines (H_γ or metal lines) used in the measurements. Only recently Bohlender

TABLE I The non-magnetic He abnormal stars. Last two columns: total number of magnetic measurements and references: c Conti (1970), h Borra & Landstreet (1979), j Borra (1981), k Brown et al. (1981), m Borra et al. (1983), n Glagolevskii et al. (1986), p Bohlender et al. (1987), q Thompson et al (1987).

HD		HR	Name	Sp. type	var.	P(d)	n	ref.
19400		939	θ Hyi	B8 He wk	—	—	4	m
23408		1149	20 Tau	B7 He wk Mn	—	—	5	n
28843		1441	DZ Eri	B9 He wk Si	s, ℓ	1.3738	5	m
37043	B	1899	ι Ori B	B4 He wk PGa	—	—	4	c, m
37129		—	BD–4°1190	B3 He wk	—	—	1	m
37151		—	GC 6961	B8 He wk Si	ℓ	0.8044	4	j, k
37807		—	BD–3°1171	B4 He wk Si :	—	—	2	c
49333		2509	HK CMa	B7 He wk Si	s, ℓ	2.180	2	m
51688		2605	40 Gem	B8 He wk SiMn	—	—	2	n
60344		—	CoD–23°5673	B3 He	—	—	4	h, p
93030		4199	θ Car	B0 HeSiNP	s, v	1.7788	4	h
120640		5206	278G. Cen	B3 He :	—	—	5	h
120709	A	5210	3 Cen A	B5 He wk PGa	s	?	4	m
131120		5543	376G. Cen	B7 He wk Si	—	—	4	m
133518		—	CoD–51°8745	B3 He	—	—	5	h, p
142250		5910	GC 21352	B6 He wk :	—	—	3	q
142884		—	GC 21422	B9 He wk Si	ℓ	0.803	4	m
143699		5967	151G. Lup	B6 He wk	—	—	4	m
145792	A	6042	GC 21814	B6 He wk	—	—	2	q
146001		6054	46G.Sco	B8 He wk	—	—	5	m
151346		—	CoD–23°12923	B7 He wk	—	—	1	m
162374		6647	V957 Sco	B7 He wk Si	s, ℓ	1.6586	5	m
175156		7119	32G. Sct	B5 He var	—	—	8	m
202671		8137	30 Cap	B7 He wk	—	—	4	m
224926		9087	29 Psc	B8 He wk	—	—	4	m

https://doi.org/10.1017/S0252921100020686 Published online by Cambridge University Press

TABLE II The non-magnetic Si stars. Last two columns: total number of magnetic measurements and references: a Babcock (1958), b Gollnow (1962), f Landstreet et al. (1975), i Borra & Landstreet (1980), j Borra (1981), q Thompson et al (1987), r Mathys (1991), t van den Heuvel (1971).

HD		HR	Name	Sp. type	var.	P(d)	n	ref.
14392		682	63 And	B9 Si	ℓ	1.31:	2	f, i
16545		—	GC 3204	A0 Si	—	—	—	a
20283	A	979	GC 3914	B9 Si	—	—	—	a
29305	A	1465	α Dor A	A0 Si	ℓ	2.9432	4	i
37470		—	BD-6^o1274	B8 Si	—	—	4	j
45827		2362	GC 8430	B9 Si :	—	—	—	a
59256		2863	93G. Pup	B9 Si	—	—	—	b
98457		—	LS Hya	A0 Si	ℓ	11.535	2	r
98664		4386	σ Leo	B9 Si :	—	—	—	a
103192	A	4552	β Hya A	B9 Si	ℓ	2.34	1	i
114365		4965	V824 Cen	A0 Si	ℓ	1.2719	4	q
126759		—	GC 19503	B9 Si :	—	—	5	q
128775		—	26G. Lup	B9 Si	—	—	1	q
128974		5466	367G. Cen	A0 Si	—	—	4	q
134759	A	5652	ι^1 Lib	B9 Si	—	—	4	f, i
136347		5697	GC 20630	B9 Si	—	—	4	q
139525		—	GC 21051	B9 Si	—	—	4	q
145102		—	V952 Sco	B9 Si	ℓ	1.42	4	q
147550		6096	GC 22019	B9 Si :	—	—	4	t
150549		6204	LP Tra	A0 Si	ℓ	3.76	2	f, i
157779	A	6485	ρ Her	B9 Si	—	—	—	a
169952		—	BD$+38^o$3166	B9 Si	—	—	—	a
179527		7283	V471 Lyr	B9 Si	ℓ	1.1609:	2	i
182381		—	GC 26769	A0 Si	—	—	—	a
183056		7395	4 Cyg	B9 Si	ℓ	0.69:	2	f
199728		8033	AO Cap	B9 Si	ℓ	2.241	—	a
202627		8135	EP Mic	A1 Si	—	—	3	i
206742	A	8305	ι Psc A	A0 Si	—	—	6	i
219749		8861	ET And	B9 Si	ℓ, s	1.619	—	a

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& Landstreet (1990) and Donati et al. (1990) independently have succeeded in measuring a weak magnetic field undergoing a sinusoidal variation in the range +128 to −64 gauss. It is important to note that the magnetic field geometry

TABLE III The non-magnetic Si + stars. Last two columns: total number of magnetic measurements and references: a Babcock (1958), d Gollnow (1971), f Landstreet et al. (1975), g Wood & Campusano (1975), i Borra & Landstreet (1980), k Brown et al. (1981), q Thompson et al (1987), r Mathys (1991), s Mathys & Lanz (1992).

HD		HR	Name	Sp. type	var.	P(d)	n	ref.
10221		478	V557 Cas	A0 SiSr	ℓ	3.2:	3	i
32549		1638	V1032 Ori	B9 SiCr	ℓ	4.59	4	i
35497		1791	β Tau	B9 SiCrMn	—	—	—	a
39317		2033	V809 Tau	B9 SiEuCr	ℓ, s, v	2.654	1	i
49713		—	BD−1°1395	B9 CrEuSi	—	—	—	a
56022		2746	OU Pup	A0 SiCrSr	ℓ	0.918	4	i
71066		3302	κ^2 Vol	A0 SiMn	—	—		g, s
90044		4082	SS Sex	B9 SiCrSr	ℓ	4.3789	—	d
116656	A	5054	ζ UMa A	A2 SrSi :	—	—	—	a
140728		5857	BP Boo	A0 SiCr	s, ℓ	1.2956	2	f, i
147890		—	GC 22076	A0 SiSr	ℓ	4.336	4	q
149822		6176	V773 Her	B9 SiCr	ℓ	1.459	—	a
157486		6470	GC 23534	A1 SiCr	—	—	—	s
168605		—	BD+19°3594	A0 SiCr :	—	—	—	a
170973		6958	MV Ser	A0 SiCrSr	—	18.3 ?	1	r
176437		7178	γ Lyr	B9 SiMg	—	—	—	a
177517		7230	138G. Sgr	B9 HgSi	ℓ	0.4:	3	i
193344		—	BD+35°4059	B9 SiCrEu	—	—	—	a
201616		8098	6 Equ	A1 SiSrCr :	—	—	—	a
209515	A	8407	V1942 Cyg	A0 CrSiMg	ℓ	0.64:	4	f, i
214783		—	BD+38°4831	A0 FeSi :	—	—	1	k
225119		—	CoD−29°18945	B9 SiCr	ℓ	2.9 ?	—	a

derived by these authors is consistent with the surface maps of ε UMa calculated by Hatzes (1988, 1991b) and Rice & Wehlau (1990). From this example we see that the only way of being sure that the magnetic field is absent is to have several measurements well distributed along the whole rotation period.
Let us assume for the moment that the NMCPa/d stars listed in Tables I – IV do not possess any magnetic field, we will discuss later such a hypothesis.
The fact that LSOMF are not detected in NMCPa/d stars has valuable implications on the problem of understanding the origin of the anomalous abundances and their consequences (among which are spectrum and light variability). At present the most widely accepted mechanism relevant for the origin of spectral peculiarities in CP stars is given by the diffusion theory firstly proposed by Michaud (1970) and developed in a series of papers by Michaud and coworkers

(for references see Wolff 1983 and Michaud 1991).

TABLE IV The non-magnetic SrCrEu stars. Last two columns: total number of magnetic measurements and references: a Babcock (1958), b Gollnow (1962), e Borra & Landstreet (1975), f Landstreet et al. (1975), i Borra & Landstreet (1980), k Brown et al. (1981), q Thompson et al. (1987), s Mathys & Lanz (1992).

HD		HR	Name	Sp. type	var.	P(d)	n	ref.
15089	A	707	ι Cas A	A4 Sr	s, ℓ	1.7405	13	f, i
22401		—	BD+47°865	A0 CrYSr	—	—	1	k
67751		3190	GC 11066	A4 Sr :	—	—	—	b
96616	A	4327	V815 Cen	A3 Sr	ℓ	2.4394	1	e
107612		—	GC 16863	A2 Sr	—	—	—	a
108945		4766	21 Com	A3 Sr	s, ℓ	2.004	3	i
120198		5187	CR UMa	A0 EuCr	ℓ	1.380	3	i
133792		5623	GC 20347	A0 SrCr	—	—	—	s
135382		5671	γ Tra	A1 Eu :	—	—	1	i
140160		5843	χ Ser	A1 Sr	s, ℓ	1.596	9	f, i
147105		—	CoD–25°11483	A3 SrCrEu	ℓ	1.91:	4	q
148898		6153	ω Oph	A6 SrCrEu	s, ℓ	1.8/4.7 ?	4	i
150035		—	CoD–27°11054	A3 CrEuSr	ℓ	0.54:	4	q
151525		6234	V776 Her	B9 EuCr	s, ℓ	4.1164	—	a
152308		6268	V823 Her	A0 CrEu	ℓ	1.1 ?	—	a
165474	B	6758	BD+12°3382	A7 SrCrEu	—	—	—	a
168481		—	GC 25002	A7 SrCr	—	—	—	a
171279		—	BD–7°4623	A0 SrCrEu	—	—	—	a
203006		8151	θ^1 Mic	A2 CrEuSr	s, ℓ	2.1221	3	i
215661	B	—	BD+67°1463	A2 CrEu	s	3.8 :	—	a
217401	A	—	BD+13°5037	A2 Sr	—	—	—	a
220825		8911	κ Psc	A1 CrSrEu	ℓ, s, v	1.412	8	f, i
221760		8949	ι Phe	A2 SrCrEu	ℓ	12.5 ?	5	i

https://doi.org/10.1017/S0252921100020686 Published online by Cambridge University Press

The basic idea is that the observed anomalous abundances originate from a selective diffusion of the chemical elements in the outer stellar layers and are the result of the competing effects of gravitational settling and radiative lifting. The main requisite for the diffusion process to be efficient in building up the observed anomalous abundances is that the upper stellar layers should be sufficiently stable. This constraint is given by the low axial rotation and/or the presence of a LSOMF. In the case of NMCPa/d stars, of course, the magnetic field should be absent (or very weak) so that the stabilizing effect remains on the slow rotation only. Among the stars listed in the above mentioned Tables I – IV several have large values of axial rotation ($v_e \sin i \geq 100 kms^{-1}$), and this fact by itself could challenge the requisite for the diffusion to operate. However the situation is even more complex if we consider the fact that some NMCPa/d stars are found to be spectrum and/or light variable. This very important item will be discussed in the next section.

THE VARIABILITY AND THE SURFACE ABUNDANCE DISTRIBUTION

In addition to the spectroscopic peculiarities and the magnetic field, CPa/d stars are observed to show periodic variations in light, spectrum (line equivalent width, profile, radial velocity), and magnetic field, all occuring with the same period.

Spectral and low amplitude light variations in some such stars were known since long time (Ludendorff 1906, 1909; Belopolsky 1913; Guthnik & Prager 1914; Guthnik 1917), but the first systematic study of the spectral variations was carried out by Deutsch (1947), who compiled a catalogue of twenty stars in which spectral variations were analyzed. An important result of Deutsch's investigation was the finding that the phase relations among lines originating from different elements are different from star to star: this characteristic is now fully confirmed to be present in all spectrum variables and represents one of the most intriguing unanswered questions.

The variations of CPa/d stars mainly occur in two time scales:

a) the short one, with periodicities ranging from 4 to 20 minutes, is mainly found in the coolest stars with photometric amplitudes of the order of a few thousands of a magnitude;

b) the long one, with periodicities ranging from about half a day to several years, is quite common among CPa/d stars and is associated with larger photometric amplitudes, up to one or two tenths of a magnitude in some exceptional cases.

Here we are concerned with the long time scale variability, which, in the large majority of the cases (if not all) is quite satisfactorily explained in terms of the oblique rotator model (Stibbs 1950). In the framework of this model, the star is assumed to rotate rigidly and to possess an essentially dipolar magnetic field whose axis forms a certain angle with respect to the rotation axis. The chemical elements are inhomogeneously distributed over the stellar surface in a way probably related to or determined by the geometry of the magnetic field. The thermodynamic structure of the atmosphere being different from place to place, the stellar surface presents a patchy aspect with regions of different chemical composition and unequal brightness. As a result of the rotation, the aspect of the visible stellar disk changes and light, spectrum, and/or magnetic field variations result. The period of the observed variations is hence nothing else than the rotation period.

In view of the interpretation of the observations, it is important to stress out here that accurate determination of the period of variability of CP stars is a fundamental requirement to understand their complex behavior, especially as far as it concerns the phase relation between the various types of variations. Out of the above mentioned 2798 CPa/d stars only for 311 stars (i.e. 11.1 %) the variability has been ascertained up to now (Catalano & Renson 1984, 1988; Catalano et al. 1991b, 1992). Moreover, among the 311 known variables, a sufficiently accurate value of the period is available for 163 stars (52.4 %), while for the remaining 148 stars (47.6 %) the value of the period is still uncertain or at least needs to be confirmed.

However the existence of spectrum and light variables among the NMCPa/d stars is indisputable, as it is evident from Tables I – IV, where the types of the observed variations are indicated in column 6. For example, the Si star α Dor (HD 29305 = HR 1465, Table II) shows large photometric variations in the visible (Heck et al. 1987) as in the infrared (Catalano et al. 1991a), but no evidence of a magnetic field: in fact, out of four measurements distributed at various phases along the variability cycle, no magnetic field in excess of 100 gauss has been detected (Borra & Landstreet 1980). Unfortunately no spectroscopic study of α Dor is yet available.

The observed variability of some NMCPa/d stars poses an important constraint on the surface distribution of the abundances.

Since the pioneering work by Deutsch (1958, 1970), who first devised the possibility of deriving the surface distribution of elements from the temporal changes in stellar line profile, considerably improved techniques have been developed and applied by a number of authors. In particular the so called Doppler imaging method (Goncharskii et al. 1977, 1982; Vogt et al. 1987; Rice et al. 1989) has allowed the surface distribution of the elements to be obtained with whatever detail may be regarded as appropriate. Accurate surface maps of several CP stars have been recently obtained by means of Doppler imaging techniques. The results of these investigations show that the abundance inhomogeneities are concentrated in large patches where some elements are overabundant or underabundant. Generally these patches appear to be located near one of the poles of the (essentially dipolar) magnetic field, while a ring-like distribution is found in proximity to the (magnetic) equator. However different elements show different locations also differing from star to star. This scenario is in fair agreement with the predictions of a magnetic field driven diffusion process.

If LSOMF are really absent in the NMCPa/d stars, what other mechanism could give rise to such an inhomogeneous distribution of the abundances? If we exclude mechanisms coming from the star being member of a close binary, the most plausible one could be the meridional circulation induced by the stellar rotation. A rotating star is expected to be ellipsoidal in shape with the temperature at the poles exceeding that at the equator. Fluid motions are hence present in the meridional planes in the form of circulation of matter from the poles toward the equator, the loop being closed by flows deeper within the star. If the velocities associated with such a circulation pattern remain not too large, then diffusion may establish or maintain an abundance gradient. This means that one might expect abundance anomalies to appear only in stars not too fast rotating, i.e. with $v_e \leq 100\, km\, s^{-1}$ (Wolff 1983), nor too slowly rotating. This possibility, however, appears to be difficult to occur since some NMCPa/d stars are known to be fast rotators as, for example: HD 49333 ($v_e \sin i \simeq 150\, km\, s^{-1}$), HD 143699 ($\simeq$200), HD 146001 ($\simeq$180), HD 14392 ($\simeq$105), HD 202627 ($\simeq$127), HD 177517 ($\simeq$100), HD 135382 ($\simeq$214), and HD 165474B ($\simeq$218). Moreover, even if the condition for the abundance gradient to originate is fulfilled, the resulting surface abundance distribution would be in the form of patches or rings concentric to the rotation axis, therefore no variability would be observed.

A more stringent condition comes out from the observations: three NMCPa/d stars – HD 140728 (BP Boo, Hatzes 1990), HD 140160 (χ Ser, Goncharskii et al. 1983), and HD 151525 (45 Her, Hatzes 1991b) – have been recently studied by the Doppler Images technique and the resulting distribution of Si, Sr, and Cr have been found to be in the form of rings and patches. In this context a number of features led Hatzes (1990, 1991b) to interprete the observed inhomogeneities in terms of the presence of a non-axisymmetric magnetic field such as, for example, a decentered dipole.

On the other hand CPa/d stars with a weak magnetic field, i.e. having strengths of a few hundred gauss, do exist which are known to show spectral and light variations (Table V). From our point of view, the stars HD 40312, HD 112185, and HD 148112 are particularly interesting. Although the magnetic fields of

TABLE V The weak field magnetic stars. References are: 1: Borra & Landstreet (1980), 2: Bohlender & Landstreet (1990).

HD	HR	Name	Sp. type	m_v	P(d)	$v_e \sin i$	m. f. extr.	ref.
12767	612	ν For	A0 Si	4.69	1.89	80	−230/+290	1
19832	954	SX Ari	B8 Si	5.79	0.728	135	−346/+384	1
25267	1240	τ^9 Eri	A0 Si	4.66	1.21	30	−345/−15	1
40312	2095	θ Aur	A0 Si	2.62	3.619	53	−240/+360	1
112185	4905	ε UMa	A1 CrEu	1.77	5.089	35	−64/+128	2
148112	6117	ω Her	A0 CrEu	4.57	3.043	45	−251/−87	1

these stars are weak, the observed surface distribution of some elements in the form of rings and patches (Rice & Wehlau 1990; Totochava & Khokhlova 1991; Hatzes 1991a, b) lends support to the idea that such structures will form whenever there is a magnetic field strong enough to stabilize the atmosphere so that radiation driven diffusion is effective (Rice & Wehlau 1990). Moreover, since irregularities are found in the rings and the patches in all stars observed by the Doppler Image technique, the magnetic fields themselves must have complex geometries superimposed on a basic axisymmetric field (Rice & Wehlau 1990; Hatzes 1990, 1991a, b).

https://doi.org/10.1017/S0252921100020686 Published online by Cambridge University Press

CONCLUSION

Among the about 320 CPa/d stars for which magnetic field measurements are in so far available in the literature, less than one third (99 stars) are found to be non-magnetic, in the sense that the measured values are below detection or in any case below the 3σ level. Moreover, among such 99 NMCPa/d stars, 42 are known to vary in spectrum and/or light. It is important to note here indeed that the percentage of variables might well be larger, since several stars of the sample have not yet been checked for variability.

From the observed variations we are led to assume that the mechanism originating the patchy distribution of the abundances be the same as for magnetic CP stars. This implies that, at least in the cases of the variable NMCPa/d stars, the abundances should have a patchy distribution similar in geometry to the one found in the magnetic CP stars, otherwise different mechanisms for variability should be looked for. The latter possibility however does not seem plausible since, apart from the presence of the magnetic field, no differences in the overall properties of the NMCPa/d stars, with respect to those of the magnetic ones, are reported. On the other hand, the strict similarity of behavior in the few cases where detailed studies have been carried out lends support to the above said hypothesis.

We can therefore conclude that at least in the cases of the variable NMCPa/d stars, they do have a complex surface geometry, very likely due to the presence of until now non detected weak LSOMF.

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