The A-Star Puzzle
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Frequencies of CP2 stars in open clusters and the galactic field

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Abstract. The Michigan Catalogue (Vol. I - V) is an excellent database to study the distribution of CP2 stars in the galactic field in the Southern hemisphere. A cross-check with the Bidelman-Catalogue (1973) and the "Catalogue Général des Étoiles Ap et Am" (Renson 1991) shows that in the Michigan Catalogue 3.6% of all stars in the relevant spectral region are CP2 stars. Any discrepant classified stars could be verified photometrically in the Δa-system. The distribution of CP2 stars does not show any particular preferred region in the Southern hemisphere.

The ages of these stars and an evolutionary dependence of the CP2 effect was another important question. We conclude that the CP2 stars occupy the full Main Sequence band.

Keywords. Stars: chemically peculiar, evolution, catalogs, methods: statistical

1. Frequency of CP2 stars in the galactic plane

1.1. *Introduction*

Magnetic chemically peculiar stars, the so-called magnetic Ap or CP2 stars, are on the upper Main Sequence. The CP2 stars shows overabundances of one or more chemical elements like silicon, strontium, chromium and the Rare Earth europium in their spectra. CP2 stars show one or more flux depressions centered near λ4100, λ5200, and λ6300. These flux depressions are most certainly a consequence of the nonsolar elemental abundance of CP2 stars and can be used to identify such objects via Δa photometry. This narrow-band, three filter photometric system measures the flux depression at λ5200 by sampling the depth of this flux depression. It compares the flux at the center with the adjacent regions at λ5000 and λ5500 using a band-width of 130 Å.

1.2. *Catalogues*

The University of Michigan Catalogue of Two-Dimensional Spectral Types for the HD Stars as published by Houk & Cowley (1975), Houk (1978, 1982), Houk & Smith-Moore (1988), and Houk & Swift (1999) includes more than 50000 late B, A and early F stars of the Southern hemisphere, brighter than $V = 12$ mag. A search for bona fide or possible magnetic chemically peculiar stars in this catalogue results in a percentage of 3.6% of objects which could be classified as more or less peculiar. Within this "peculiar subsample", we find 44% B-type, 52% A-type and 4% early F-type objects. A cross-check of the photometric Geneva catalogue of Rufener (1988) and the Catalogue of CP and Am stars of Renson (1991) with the published Δa values gives an comprehensive database for statistical studies.

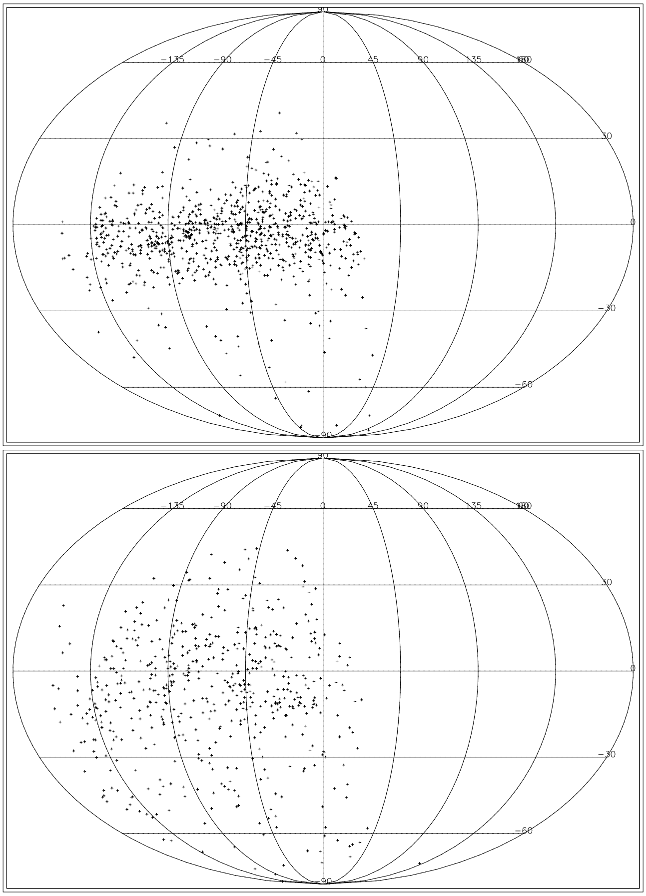

Figure 1. Distribution of the galactic coordinates for the Si and Si+ group (upper panel) as well as the Sr and SrCrEu group (lower panel).

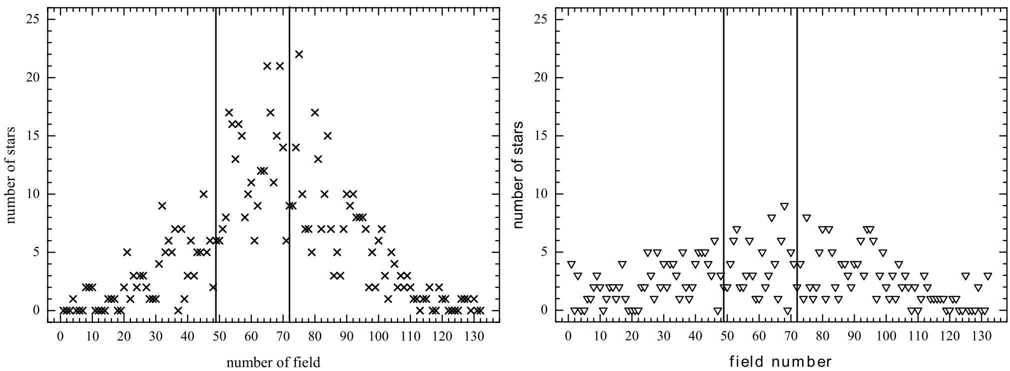

Figure 2. Partition numbers 49 to 72 are in the region of the galactic plane ($-5^\circ < b < 5^\circ$) and are marked with straight lines for the Si and Si+ group (left panel) as well as the Sr and SrCrEu group (right panel).

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Table 1. Objects with discrepant classifications.

HD	DM	α_{1900}	δ_{1900}	m_{phot}	Michigan	Bidelman	Renson	m_V
—								—
19712	BD-02 563	3 05 13,9	-02 04 29	7,32	B9 V	CrEu	A0 Cr Eu	
21201	CP-52 394	3 20 8,6	-52 14 53	9,1	A1MA8-A9	SrCr	A1-A9	8,9
24212	CP-79 114	3 46,1	-79 53	9,3	B9 III/IV	SiCr	A0 Si Cr	9,6
32145	BD+03 739	4 55 50,4	+03 34 10	7,11	B8 II	Si	B8 Si	
32966	BD-14 1045	5 01 48,8	-14 49 51	6,97 V	B8 II	Si	B9 Si	7,1
33917	BD-02 1176	5 08 25,5	-02 44 43	9,8	A0 V	Si	A0 Si	
34607	BD-12 1126	5 13 35,9	-12 35 54	10,4	A0 V	Si	A0 Si	9,8
35177	BD+01 991	5 17 50,8	+01 36 04	8,4	B8/9 V	Si	B9 Si	
36668	BD+00 1113	5 28 17,3	+00 33 02	8,06	B8 II A	Si	B7 HE FBL	
36997	BD-02 1305	5 30 12	-02 26 50	8,31	B9 II	Si	B9 Si Sr	
40146	BD-03 1243	5 52 00,3	-03 46 08	9,7	B9 III/IV	Si	A0 Si	
40966	BD-07 1255	5 57 05,3	-07 58 04	10,4	B8 II	Si	B9 Si	
43408	BD+00 1352	6 10 55,7	+00 54 31	8,1	B9 V A	SrEu	B9 Sr Eu	
45931	BD-00 1312	6 25 20,9	+00 18 18	8,8	B9 V	Si	A0 Si	
47026	CO-48 2371	6 31 18,9	-48 04 18	9,2	B9 V	SrCrEu	B9 Sr Cr Eu	9,6
47634	BD-00 1380	6 34 31,1	+00 43 59	8,8	B9 IV/V	Si	A0 Si	
48160	BD-08 1521	6 36 52	-08 25 45	9,7	B9 III/IV	Si	A0 Si	
51088	CO-24 4586	6 50 46,3	-24 35 26	7,9	B9 V	Si	B8 Si ?	8,3
52669	BD-14 1687	6 57 1,7	-14 54 32	8,76	B9 II/III	Si	A0 Si	9,1
53204	BD+01 1663	6 59 05,3	01 39 18	8,2	B9 III A	Si	B9 Si	
54288	CO-45 2928	7 03 7,1	-45 06 36	9,7	G8/K1(II)+A/F	Sr GBand	F2 Sr	10,0
54772	CO-33 3532	7 05 03,2	-33 53 59	8,2	A0 V	Si	A0 Si	8,9
55839	CO-35 3417	7 09 29,9	-35 28 54	9,7	A3	Sr	A3 Sr	10,2
58443	CO-36 3586	7 20 29,1	-36 28 24	8,9	A4 V	SrCrEu	A3 Sr Cr Eu	9,1
59758	CO-37 3624	7 26 17,9	-37 51 54	10,5	A0 II	Si	A0 Si	10,9
60210	BD+00 1991	7 28 21,3	+00 29 05	8,9	B9 V	SrEu	A2 Sr Eu	
61260	BD-21 2042	7 33 17,9	-21 30 53	9,8	B8/9 II	Si	B9 Si ?	10,1
61382	BD-04 2031	7 33 55,9	-04 34 00	8,5	B9 V	Si	B9 Si	
62005	BD-22 1980	7 36 48,5	-22 28 10	9,8	B9 II	Si	A1 Si	10,2
62512	BD-00 1799	7 39 09,2	+00 28 52	8,8	A0 V	SrEu	A0 Sr Eu	
63843	BD-05 2269	7 45 52,9	-05 47 47	9,7	A1 (IV)	CrEu	A0 Cr Eu	
64901	CO-40 3618	7 50 56	-40 35 41	8,4	B8/9 II/III	Si	A0 Si	8,6
64972	CO-27 4729	7 51 17,5	-28 01 10	7,3	B8/9 II	Si	B8 Si	7,2
64988	BD-09 2289	7 51 21,8	-09 35 52	7,8	B9 IV/V	Si	A0 Si	
65941	BD-16 2242	7 56 07,1	-16 17 36	8,9	B9 IV	Si	B9 Si ?	9,8
65943	CO-26 5342	7 56 10,5	-26 13 36	9,2	A0 V	SrEu	A2 Sr Eu	9,6
66273	BD-20 2345	7 57 34,1	-20 34 52	8,7	B9 IV	Si	B9 Si ?	8,8
67982	CO-44 4089	8 05 17,2	-44 50 30	9,3	A1 IV	Si	B9 Si	10,0
68326	CO-49 3382	8 06 42	-49 55 43	8,9	B9 IV/V	Si	A0 Si	9,7
68826	CO-48 3586	8 08 54,1	-48 26 47	9,2 V	B9 III	Si	B9 Si	9,3
69193	CO-47 3716	8 10 40,6	-47 28 10	9,6	B9 II	Si	A0 Si	10,3
69932	CO-45 3963	8 14 09,9	-45 22 42	9,6	B9 III	Si	B9 Si	10,1
70325	CO-29 5976	8 16 13,3	-29 13 28	7,3	B9 IV	Si	A0 Si	7,3
72770	CO-27 5635	8 29 32,6	-27 47 32	8,8	A2 IV/V	CrEu	A0 Cr Eu	9,1
74041	CO-41 4363	8 36 28,3	-41 34 48	9,7	A0 V	Si	A0 Si	10
78201	CO-34 5573	9 01 48,5	-34 08 03	8,3	B8/9 IV	SrEu	A0 Sr Eu	8,1
79718	CP-56 2052	9 10,5	-56 15	9,7	A0/1 VN	Si	A Si	9,7
84629	CP-55 2483	9 41,4	-55 13	9,5	B9,5 II	Si	B9 Si	9,4
84907	CP-54 2700	9 43,3	-54 53	8,9	A0 IV/V	Si	A0 Si	8,9
87432	CO-45 5717	9 59 44,7	-45 16 44	8,9	A2 IV	CrEu	A0 Cr Eu	9,1
88242	CO-51 4511	10 05 18,5	-51 37 50	8,9	B9,5 V	(*)	A0 Si Cr	9,5
91756	CO-38 6572	10 30 36,5	-39 02 09	8,4	FM DELTA DEL	SrEu	A0 Sr Eu	8,7
92385	CP-64 1374	10 34,8	-64 32	6,6	B8/9 V	Si	B9 Si	6,7
95442	CO-25 8385	10 55 53,5	-25 10 48	8,2	A1 V(M)	SrCr	A0 Sr Cr Eu	7,9
101724	CP-63 1944	11 37,2	-63 14	7,5	B9 II/III	Si	B9 Si	8,0
103671	CP-55 4727	11 51,1	-55 53	8,7	B8 III	Si	B8 Si	8,7
105379	CO-30 9691	12 02 52,1	-30 35 2	8,1	A0 V	SrCr	A0 Sr Cr	8
115000	CP-61 3532	13 9,1	-61 51	9,8	B9 III	Si	B9 Si	9,4
117055	CO-47 8353	13 22 36,1	-47 53 25	9	B9 III	Si	B8 Si	9,4
120059	CP-58 5187	13 42	-58 18	08,8	B9 III	Si	B8 Si	8,8
121208	CP-57 6394	13 48,9	-57 57	9,5	A9 V	Sr	B9 Sr	9,4
126198	CP-52 7213	14 18,9	-53 00	8	B8/9 II	Si	B9 Si	8,0
128075	CP-66 2588	14 29,7	-66 54	8,8	B9 II/III	Si	B9 Si	8,4
128997	CP-66 2616	14 35	-66 21	8,9	B9 V	Si	B9 Si	8,9
129460	CP-53 6083	14 37,5	-54 06	10,1	B9 III	Si	B9 Si	9,9
132319	CP-53 6186	14 53,3	-53 40	9,6	A0/1 V	Si	A0 Si Sr	9,3
133428	CP-76 977	14 59,2	-76 34	9	A2 V	Si	A0 Si	9,1
133755	CP-52 7861	15 01,1	-52 29 30	8,7	B9 II/III	Si	B9 Si	8,7
134185	CO-51 8801	15 03 14,1	-51 46 57	9,6	F0/2 V	Si	F0 Si	9,1
138218	BD-05 4089	15 25 31,9	-05 27 47	9,3	A3/5 II	Sr	A2 Sr	
138777	BD-06 4237	15 29 07,8	-06 33 08	9,4	F2 IV	SrEu	A3 Sr Eu	
141100	CP-65 3150	15 42,1	-65 31	9,4	A1MA6-A9	Cr	A1-A9	8,9
142070	BD-00 3026	15 47 25,9	+00 43 55	8,3	B9 V	SrCrEu	A0 Sr Cr	
142778	CP-60 6256	15 51,2	-60 23	9,3	B9 II	Si	B8 Si	10,0
142884	CO-23 12597	15 51 52	-23 14 14	6,8 V	B8/9 III	Si	B9 Si	6,8
142960	CP-60 6280	15 52,4	-60 42	9,3	B9 IV	SrCrEu	A0 Sr Cr Eu	9,7
143881	CO-44 10603	15 57 43,2	-45 03 47	10,4	B8 II/III	Si	B9 Si	10,9
146971	BD-09 4353	16 14 02,1	-09 22 57	8,7	A0 III/IV(p)	SrCrEu	A0 Sr Cr	
146998	CO-25 11477	16 14 4,4	-25 36 54	9,5 V	A8/9 V	Sr	A6 Sr Cr	9,5
149046	BD-06 4450	16 27 04,3	-06 58 15	9,6	B9,5 V	SrCrEu	A0 Sr Cr	
149334	CO-33 11273	16 28 52,7	-33 48 17	9,2	A9 IV	Sr	A6 Sr	9,1
149923	CP-60 6605	16 32,6	-60 23	8,7	A0 II	CrEu	B9 Cr Eu	8,9

The Michigan-catalogue describes the characteristic spectral lines which are typical for most of CP stars. Therefore we have divided the sample in the four groups defined in

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Table 2. Table 1 – contiued

HD	DM	α_{1900}	δ_{1900}	m_{phot}	Michigan	Bidelman	Renson	m_V
150592	CO-46 10973	16 36 56	-46 52 29	8,5	A0/1 V	Si	B9 Si	8,7
152044	CP-52 10302	16 45 49,7	-52 35 59	8,7	A1 V	SrCrEu	A0 Sr Cr Eu	9,0
156791	CP-52 10606	17 14 25,5	-52 25 17	9,2	B9 III/IV	Si	A0 Si	9,9
159545	BD-02 4402	17 30 17,3	-02 49 33	7,5	B8 II	Si	B9 Si	
162306	CO-35 11994	17 45 14	-35 03 18	8,3	B8 IV	Si	B9 Si	8,9
162651	BD+01 3525	17 46 55,9	+01 07 28	7,9	B9 IV	Si	A0 Si	
164827	BD-00 3404	17 57 52,8	+00 27 24	9,4	B9 V	CrEu	A0 Cr Eu	
166053	BD-19 4871	18 03 42,2	-19 22 23	8,2	B9 IB/II	Si	B9 Si ?	8,3
166596	CO-41 12534	18 06 7,7	-41 21 33	5,3	B2 III	Si	B3 Si	5,5
166968	CO-27 12588	18 07 53,8	-27 31 45	7,4	B8 II/III	Si	B9 Si	7,2
167444	CO-42 13073	18 10 5,1	-42 14 56	8,8	B9 IV	Si	A0 Si	9,2
168163	BD-16 4806	18 13 17,5	-16 20 26	8,9	B8 III	Si	B4 Si ?	8,7
171279	BD-07 4623	18 28 47	-07 47 19	7,3	B9 V A	SrEu	A0 Sr Cr	
172032	BD-16 4963	18 32 50,5	-16 23 45	8,2	FM DELTA DEL	Sr	A9 Sr Cr	7,7
173612	BD-08 4699	18 41 04	-08 32 19	9,5	B9 IV/V	Si	A0 Si	
174595	BD-20 5297	18 46 7,6	-20 43 09	8,8	B9 II	Si	A0 Si	9,1
174646	BD-01 3581	18 46 28	-01 09 45	8,1	B8/9 II	Si	B9 Si	
176332	BD-20 5358	18 54 30,7	-20 01 16	8,9	B9 III	Si	B8 Si	9,3
176555	CO-45 12940	18 55 43,9	-45 51 31	7,1	B9 (III)	Si	B9 Si	8,0
179902	BD-21 5306	19 09 12	-21 55 04	10,1	A0 III	SrCrEu	A1 Sr Cr Eu	10
180058	BD-11 4921	19 09 52	-11 53 18	9,5	A7/8 V	Sr	A3 Sr	
182340	BD-05 4959	19 19 03,6	-05 37 26	9,4	B8/9 II	Si	A0 Si	
185129	BD-16 5383	19 32 29,5	-16 01 53	9,2	B9 IV/V	CrEu	B9 Cr Eu	9,9
185280	CO-41 13623	19 33 17,8	-41 06 12	8,9	A1 V	CrEu	A2 Cr Eu	9,4
189963	BD-06 5346	19 57 38,7	-06 42 35	9,6	A3/5 II	SrCrEu	A0 Sr Cr	
191000	BD-04 5022	20 02 30,5	-04 25 20	9,1	B9 IV	Si	A0 Si	
192723	CO-28 16547	20 11 13,3	-28 48 22	9,8	A0 III/IV	Si	A0 Si	10,4

(*) ... without line notation by Bidelman; ? ... doubtful

Jaschek & Jaschek (1990). It shows that 55.2% of these stars exhibit only significant Si-lines, 7.4% Si-Cr-Sr, 33.9% Sr-Cr-Eu and 1.4% only Sr lines. Table 1 lists the discrepant objects from all investigated catalogues.

1.3. *Distribution in the galactical plane*

The sample was further divided in a hotter Si and Si+ as well as a Sr and SrCrEu group to investigate the distribution of the stars in galactic coordinates. Figure 1 shows the results for these two subgroups. First, we can conclude that the CP2 phenomenon is not clustered in specific regions. The well known effect that the hotter Si-stars are more concentrated in the galactic plane is also visible in Figure 1. For more clarity the region about the galactic plane ($-30° < b < 25°$, $240° < l < 360°$) was divided in rectangular fields ($l = 10°$ and $b = 5°$) and the stars in these fields were counted. Figure 2 shows the number of stars vs. the marked fields.

A similar study for the Northern sky is in preparation.

1.4. *Photometric values*

The Geneva index $\Delta(V1 - G)$ and the Δa system are capable of identifying CP2 stars photometrically. They were both developed to measure the flux depression at $\lambda 5200$. The spectral types of our sample were checked with published photometrical values of both systems. The photometric measurements were taken from the literature as referenced in Rode-Paunzen (2003)

Nearly three decades ago, Maitzen (1976) introduced the narrow-band, three filter Δa photometric system to investigate the flux depression at $\lambda 5200$ which samples the depth of this flux depression by comparing the flux at the center ($\lambda 5220$, g_2), with the adjacent regions ($\lambda 5000$, g_1 and $\lambda 5500$, y) using a bandpass of 130 Å. The respective index was introduced as:

$$a = g_2 - (g_1 + y)/2$$

Since this quantity is slightly dependent on temperature (increasing towards lower tem-

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Table 3. Summary of results for true CP2 stars in our program clusters; HD 65987 and CP−60 981 are binary systems for which we list the values for the primary component. The errors in the final digits of the corresponding quantity are given in parenthesis; τ is the age of the star, τ_{HR} the time for a star on the Main Sequence and τ_{Cl} the known age of the individual cluster.

Cluster	[Fe/H] [dex]	Object	$\log T_{\rm eff}$	$\log L/L_\odot$	$M/M_\odot$	τ [Myr]	τ_{HR} [Myr]	τ_{Cl}/τ_{HR}
NGC 2451 A	−0.26	HD 63041	4.155(19)	2.26(8)	3.58(11)	20	215	0.23
NGC 2516	−0.23	HD 65712	4.002(19)	1.42(12)	2.16(9)	90	870	0.12
		HD 65987	4.107(19)	2.31(16)	[3.18]	[105]	[295]	[0.36][1]
		HD 66295	4.039(19)	1.64(12)	2.44(10)	95	615	0.17
		HD 66318	3.979(15)	1.29(81)	2.00(5)	140	1100	0.10
		CP−60 944A	4.104(19)	2.10(12)	3.14(13)	105	305	0.33
		CP−60 944B	4.096(19)	1.96(12)	3.03(12)	105	340	0.32
		CP−60 978	4.076(19)	1.90(12)	2.82(7)	110	410	0.26
		CP−60 981	3.975(15)	1.51(8)	[1.95]	[100]	[1180]	[0.10][2]
IC 2391	−0.04	HD 74169	3.998(19)	1.41(7)	2.25(10)	< 10	775	0.07
		HD 74535	4.418(19)	2.33(7)	3.80(11)	35	185	0.29
IC 2602	−0.20	HD 92385	4.043(19)	1.69(6)	2.47(6)	95	590	0.05
		HD 92664	4.176(19)	2.47(6)	3.99(12)	45	165	0.18

[1] ... probable binary; [2] ... binary

Table 4. Data about our program clusters. The errors in the final digits of the corresponding quantity are given in parenthesis.

Name	NGC 2451 A C0743−378	NGC 2516 C0757−607	IC 2391 C0838−528	IC 2602 C1041−641
l/b	252/−7	274/−16	270/−7	290/−5
$E(B-V)$	0.01	0.13	0.01	0.04
π(Lit)	5.31(19)	2.89(21)	6.85(22)	6.58(16)
π(our)	5.35(21)	2.69(22)	6.98(18)	6.99(15)
d [pc]	187(7)	372(33)	143(3)	143(3)
$\log t$	7.70	8.00	7.70	7.46
[Fe/H]	−0.26	−0.23	−0.04	−0.20
n(CP2)	1	8	2	2

peratures), the intrinsic peculiarity index had to be defined as

$$\Delta a = a - a_0[(b-y);(B-V);(g_1-y)]$$

i.e., the difference between the individual a-values and the a-values of non-peculiar stars of the same colour. The locus of the a_0-values has been called normality line. It was shown that virtually all peculiar stars with magnetic fields (CP2 stars) have positive Δa-values up to 95 mmag. Extreme cases of the CP1 and CP3 group may exhibit marginally peculiar positive Δa values whereas Be/Ae and λ Bootis stars exhibit significant negative ones. Note that (g_1-y) shows an excellent correlation with $(b-y)$ and can be used as an index for the effective temperature.

2. On the evolutionary status of chemically peculiar stars

The question, if the CP-phenomenon is a evolutionary effect, was discussed in the last years. We present evidence that the magnetic chemically peculiar stars (CP2) of the upper Main Sequence already occur at very early stages of the stellar evolution significantly before they reach 30% of their lifetime. A detailed description is given in Pöhnl *et al.* (2003).

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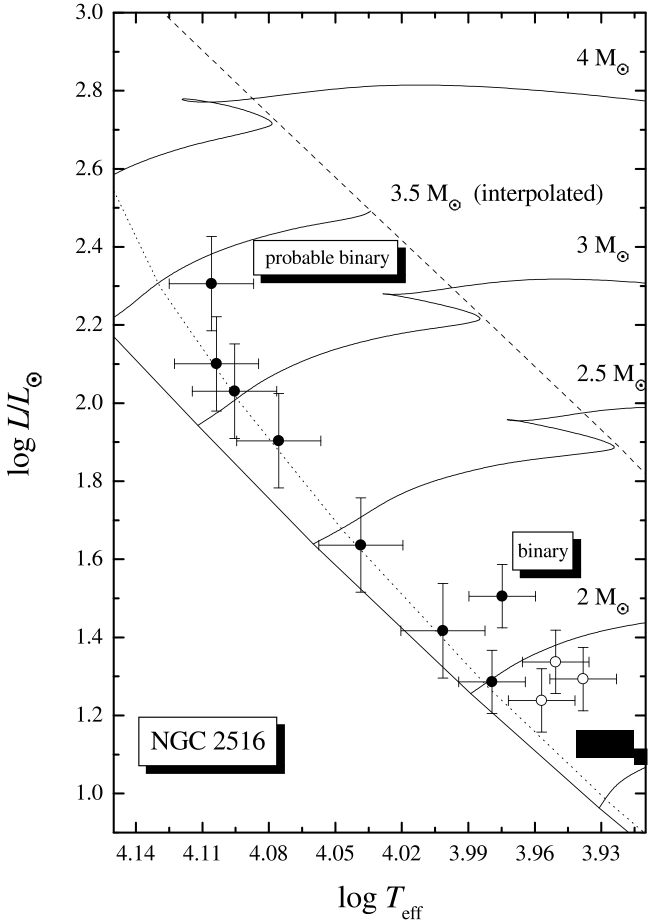

Figure 3. The location of the CP2 stars for NGC 2516. Filled circles are well established CP2 objects and open circles are doubtful cases. The dotted line is the isochrone for log $t = 8.00$ and [Fe/H] $= -0.23$ dex taken from Schaller *et al.* (1992) whereas the dashed line denoted the Terminal Age Main Sequence; the evolutionary tracks for individual masses are interpolated.

We have used the measurements and calibrations of the Geneva 7-color photometric system to derive effective temperatures and luminosities. Taking into account the overall metallicities of the individual clusters, isochrones and evolutionary tracks were used to estimate ages and masses for the individual objects. The derived ages (between 10 and 140 Myr) are well in line with those of the corresponding cluster and further strengthens the membership of the investigated CP2 stars. In total 13 CP2 stars can be found in four open clusters: IC 2391, IC 2602, NGC 2451A and NGC 2516.

Figure 3 shows the location of the CP2 stars in NGC 2516 together with the isochrone for log $t = 8.00$ and [Fe/H] $= -0.23$ dex and the evolutionary tracks for individual masses. All but two (HD 65987 and CP $-60°$ 981) lie very well on the apparent Main Sequence of this cluster and are members of it. The two deviating objects are both binaries. Their location above the corresponding isochrone can be very well reproduced taking the binarity into account. The masses and ages for the visual binary system CP$-60°$ 944A + B, both in very good agreement with the values from Debernardi & North (2001), infer that they are physically coupled. The mean value of the age for all six single CP2 stars is 106(17) Myr which is in excellent agreement with the overall age of this cluster (100 Myr). The values and properties of the investigated open clusters are listed in Table 3 and 4. τ is the age of the star, τ_{HR} the time for a star on the Main Sequence and τ_{Cl} the known age of the individual cluster. As a confirmation, Bagnulo *et al.* (2003) have discovered a strong magnetic field of 14.5 kG in the NGC 2516 star HD 66318. They estimate that this star has completed only about 16(5)% of its main sequence life.

3. Conclusion

The Michigan Catalogue was studied to derive the distribution of CP2 stars in the galactic field in the Southern hemisphere. A cross check with other catalogues results that in the Michigan Catalogue, 3.6% of all stars in the relevant spectral region are CP2 stars. Any discrepant classified stars could be verified photometrically in the Δa-system. The distribution of CP2 stars does not show any particular preferred region in the southern hemisphere.

The location of all investigated CP2 stars within the relevant Hertzsprung-Russell-diagrams qualify them as being members of the corresponding aggregate. Furthermore, their ages (10 < ages < 140 Myr) are within the expected error of the overall age of the individual open cluster. This proves that CP2 stars do exist at very young evolutionary stages clearly before they have reached 30% of their Main Sequence lifetime.

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