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Do the physical properties of Ap binaries depend on their orbital elements?

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ABSTRACT

We reveal sufficient evidence that the physical characteristics of Ap stars are related to binarity. The Ap star peculiarity [represented by the $\Delta(V1-G)$ value and magnetic field strength] diminishes with eccentricity, and it may also increase with orbital period (P_{orb}). This pattern, however, does not hold for large orbital periods. A striking gap that occurs in the orbital period distribution of Ap binaries at 160–600 d might well mark a discontinuity in the above-mentioned behaviour. There is also an interesting indication that the Ap star eccentricities are relatively lower than those of corresponding B9–A2 normal binaries for $P_{\mathrm{orb}} > 10$ d. All this gives serious support to the pioneering idea of Abt & Snowden concerning a possible interplay between the magnetism of Ap stars and their binarity. Nevertheless, we argue instead in favour of another mechanism, namely that it is binarity that affects magnetism and not the opposite, and suggest the presence of a new magnetohydrodynamical mechanism induced by the stellar companion and stretching to surprisingly large P_{orb}.

Key words: hydrodynamics – MHD – binaries: close – stars: chemically peculiar – stars: early-type – stars: magnetic fields.

1 INTRODUCTION, THE ‘BINARITY × MAGNETISM’ HYPOTHESIS

There exists a rather heterogeneous group of so-called chemically peculiar (CP) stars on the upper main sequence. The backbone of current research into CP stars is their modern classification scheme by Preston (1974). He clearly distinguished a non-magnetic sequence of Am and HgMn stars, as well as a magnetic sequence of Ap and some He-weak stars (also Borra, Landstreet & Thompson 1983). Table 1 schematically summarizes the basic facts about Am and Ap stars, the well-known and populated subgroups, along with the known physical processes invoked for their explanation. While, at present, we have at hand some explanation of most of the CP star distinguishing characteristics, such as the origin of abundance anomalies and slow rotation, this is not the case with their magnetism and binarity. Both of the latter phenomena are referred to as primordial causes for CP peculiarity in the corresponding area of the Hertzsprung–Russell (HR) diagram. Nevertheless, it is slow rotation that is generally accepted as a more direct reason for the CP phenomenon, and which is closely related to the primordial causes, namely being a result of tidal or magnetic braking mechanisms (Abt 1965, 1979; Stift 1976; Wolff 1983; Stępień 1998). Consequently, the role of binarity effects is reduced to merely slowing down rotation, with magnetism, slow rotation and atmospheric parameters considered as the only ‘free parameters’ determining the CP characteristics.

The pioneering works of Babcock (1958), Abt (1961) and Abt & Snowden (1973), completed and reanalysed e.g. by Abt (1965), Floquet (1983), Abt & Levy (1985), Gerbaldi, Floquet & Hauck (1985), Lebedev (1987), Seggewiss (1993), North (1994), Mathys et al. (1997), North et al. (1998) and many others revealed that the frequency of occurrence in binaries is much higher for Am than for Ap stars. Short-period orbits are much more frequent, and the SB2/SB1 ratio is also higher in Am than in Ap binaries. Lebedev furthermore mentioned a lack of correlation between inclinations of rotational and orbital axes in Ap binaries. However, it is the Ap stars that exhibit measurable magnetic fields, while the Am stars do not (see e.g. recent review by Landstreet 1992). The mutual exclusion of magnetism and binarity in Am and Ap stars arouses our suspicion concerning a possible relationship between these two fundamental CP characteristics, and we will label such an idea as a ‘binarity × magnetism’ hypothesis. The interplay between stellar magnetism and binarity was first suggested for Ap binaries by Abt & Snowden (1973), who favour the claim that ‘for those

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Table 1. A *schematic* sketch of some distinguishing characteristics of CP stars and their possible sources.

Characteristics	Ap	Am	Physical cause
abundance anomalies	Yes	Yes	diffusion, conv. zones, stellar winds, mag. fields, rotation
slow rotation	Yes	Yes	rot. mixing selection, tidal and magnetic braking
mag. fields	Yes	No	?
binarity	No	Yes	?

Ap stars (Si and Sr–Cr–Eu group) having strong external magnetic fields, the formation of binaries with separation of 10^6–10^9 km is inhibited …'.

Nevertheless, tidal effects might play a unique role in driving CP phenomena. Their analysis is unfortunately limited to only the synchronization and circulation mechanisms. There are two competing views of this problem. While the dynamical tide theory of Zahn (1977) (supported recently by Pan 1997) predicts that synchronization prevails within orbital periods of about 4 d and circularization within periods of about 2 d, the hydrodynamical mechanism of Tassoul & Tassoul (1992) (supported recently by Claret, Giménes & Cunha 1995) '… can remain operative for larger orbital periods, up to $P_{\rm orb} \approx 100$ d – without bringing complete pseudo-synchronization beyond $P_{\rm orb} \approx 15$–25 d, however' and up to $P_{\rm orb} \approx 10$ d as far as the circularization is concerned. Nevertheless, these two competing mechanisms are not mutually exclusive (Tassoul 1995). Apart from these classical tidal effects, Budaj (1994, 1996, 1997a,b) and Iliev et al. (1998) have shown that the physical characteristics of Am binaries depend on the orbital period and eccentricity of the binary. Their orbital period distribution (OPD) exhibits a 180–800 d unpopulated gap, which contrasts with a peak in the OPD of the corresponding normal binaries. The peculiarity of Am binaries seems to increase with orbital period up to at least $P_{\rm orb} \approx 50$ d, but probably up to $P_{\rm orb} \approx 180$ d, and increases with eccentricity. In the subsequent preliminary analysis of Ap binaries, Budaj (1995) and Budaj et al. (1997) pointed out the presence of an analogous period gap, and a possible analogous dependence of their peculiarity [$\Delta(V1-G)$ value and magnetic field, $\langle B_{\rm e}\rangle$] on the orbital period. At the same time the peculiarity seemed to decrease with eccentricity on the short-period side of the period gap, but not on the long-period side.

The principal aim of this paper is a more elaborate analysis of the possible dependence of the physical properties of Ap binaries on their orbital elements and a thorough discussion of a possible interplay between magnetism and binarity. We will attempt to present a more concise and integrated view of the whole problem.

2 SAMPLE STARS

Most of the data about Ap binaries analysed here is extracted from the data base of Renson, Kobi & North (1991). The root mean square of the effective magnetic field, $\langle B_{\rm e}\rangle$, was taken from Glagolevskij et al. (1986). The following rules were obeyed to avoid any ambiguity when compiling the sample of Ap stars: we carefully selected all Ap binaries of Si, Sr, Cr or Eu peculiarity within B5–F5 spectral type; we did not take into account which component is responsible for this peculiarity, but it is the primary in a great majority of cases. A few binaries of mixed peculiarity (Si, Sr, Cr or Eu accompanied by e.g. He-w, Hg or Mn) were also considered if they exhibited light or spectral variations, or a detectable magnetic field. For suspected triple systems we ignored the orbital periods of third bodies. All selected binaries were then complemented by the recent data from North (1994) and Wade et al. (1996). Owing to the scarcity of data, it probably does not make sense to distinguish between cool and hot Ap binaries at present. Although the resulting sample is a little inhomogeneous, the spectral types of most objects fall within B9–A2. The total number of Ap binaries included is 50. The relevant information is listed in Table 2.

The sample of normal binaries for comparison with the Ap binaries was extracted from the list of Seggewiss (1993), which is based on the Eighth Catalogue of Orbital Elements of SB Systems (Batten et al. 1989). We consider here only B9–A2 V–IV binaries, the positions of which correspond to the position of our Ap sample in the HR diagram. From the original list of Seggewiss we also omitted orbital periods of third bodies, excluded HD 57103 and 132742 because their $m_1 \sin^3 i$ values are too large (exceeding 4.3) to refer to main-sequence objects and excluded systems with apparently evolved companions (HD 74307, 41511, 40632). The total list of normal binaries for comparison thus consists of 104 objects, as shown in Table 3.

3 $\Delta(V1-G)$ PARAMETER IN THE $P_{\rm orb} \times e$ PLANE

The $\Delta(V_1-G)$ value is a measure of the $\lambda5200$ depression in Ap stars. The larger the value, the more pronounced the depression and, consequently, Ap star peculiarity. Gerbaldi et al. (1985) first mentioned a very interesting tendency, that the $\Delta(V_1-G)$ reaches its highest values for low eccentricity, short-period orbits ($P_{\rm orb} < 200$ d). Unfortunately, their finding was not very convincing at the time, as it was based on only two points at low eccentricities, but the presumption turned out to be right. Later Budaj (1995) and Budaj et al. (1997) presented statistically significant evidence that the $\Delta(V_1-G)$ value decreases with eccentricity for $P_{\rm orb} < 160$ d, while there is an opposite tendency for larger periods. They have also tried to disentangle possible eccentricity and orbital period dependences, and showed that $\Delta(V_1-G)$ seems to increase with $P_{\rm orb}$ for $P_{\rm orb} < 160$ d. However, there is certainly a correlation of $P_{\rm orb}$ with e, which could affect the above findings and mask the true cause of the $\Delta(V_1-G)$ behaviour. To avoid this effect the problem is reanalysed in 3D in Fig. 1, which displays $\Delta(V1-G)$ over the $P_{\rm orb} \times e$ plane. We distinguish between the stars with $P_{\rm orb} < 160$ d and $P_{\rm orb} > 160$ d. There are at least three reasons for doing so:

(1) the period gap mentioned in Section 6 naturally splits the data and $P_{\rm orb} < 160$ d coincides with the short-period side of the period gap;

(2) a first-group star may be subjected to Tassoul's tidal retardation mechanism, while no tidal effects are expected for a second-group star at the long-period side of the period gap;

(3) this choice maximizes the correlations and one would find no significant effect on the whole orbital period sample.

To *illustrate* the behaviour of the $\Delta(V1-G)$ value in this figure, we plot here two planes: one for $P_{\rm orb} < 160$ d and the other for $P_{\rm orb} > 160$ d, obtained using the least-squares method of the

Table 2. List of Ap binaries.

HD	P_{orb}	e	$v \sin i$	$\Delta(V1-G)$	$\langle B_e \rangle$	Sp	Note
128898	1.00	0.00	0	−0.007	895	A9 SR EU	
26961	1.52	0.02	80			A2 SI	
200405	1.63	0.02		0.024		A2 SR CR	a
12534A	2.67	0.30	70			B8 SI	d
18296	2.90	0.00	20	0.016	810	A0 SI SR	
24769	2.97	0.00	60	−0.005		B9 SI	
15144A	2.99	0.03	15	0.015	830	A5 SR CR EU	
201433A	3.31	0.00	10	−0.001		B9 SI MG	
208835	4.72	0.00				B9 SI	
224801	4.88	0.00	45	0.018	1570	B9 SI EU	
147869	5.00	0.50	50	−0.008		A1 SR	
205073	5.50	0.00	20	0.000	0	A1 SI SR	
98088A	5.90	0.18	25	0.013	795	A8 SR CR EU	d
25267	5.95	0.10	35	0.027	220	A0 SI	d
151199	6.14	0.00	65	0.001		A3 SR	
162588	6.14	0.50	30	0.011		B9 CA wk SI	
25823	7.22	0.20	20	0.022	510	B9 SR SI	
65987	9.00	0.00	15	0.021		B9 SI SR	
60179	9.21	0.50	10	−0.015		A0 SR EU	d
89822	11.57	0.30	5	−0.003	315	A0 HG SI SR	d
168733	12.00	0.00	30	0.018	750	B8 TI SR	
94334	15.83	0.30	20	−0.004		A1 SI	
216533	16.04	0.00	5	0.026		A1 SR CR	
23964A	16.70	0.00	18	−0.005		B9 SI SR CR	
116656	20.54	0.50	25	−0.009		A2 SR SI	d
170973	25.67	0.00	10	0.034		A0 SI CR SR	
123515	26.00	0.20	40	−0.005		B8 SI	
170000A	26.77	0.40	85	0.001	0	A0 SI	d
183056	35.02	0.40	35	0.002	180	B9 SI	
55719	46.30	0.10	65	0.015	1470	A3 SR CR EU	d
2054	48.30	0.40	200	−0.003		B9 SI	
219749	48.30	0.50	90	0.006		B9 SI	
123299	51.40	0.40	15	−0.008		A0 SI CR	
196133	88.00	0.80		0.000		A1 SI SR	
8441	106.44	0.13	10	0.010	350	A2 SR	a
116458	126.00	0.00	40	0.042	1920	A0 SI EU CR	
28319	140.73	0.75	75	−0.001		A8 SR	
221568	159.00	0.00	10	0.011		A1 SR CR EU	
9996	273.00	0.50	0	0.024	700	B9 CR EU SI	
68351	636.00	0.00	35	0.019		A0 SI CR	
187474	690.00	0.45	5	0.033	1860	A0 EU CR SI	
7374	801.00	0.00	25	−0.006		B9 SI HG MN	
59435	1387.30	0.28	5	0.017		A4 SR CR SI	b,d
77350	1401.00	0.00	25	0.000	580	B9 SR CR HG	
125248	1643.00	0.20	12	0.024	1100	A1 EU CR	
65339	2432.00	0.70	12	0.021	3410	A3 SR EU CR	
137909A	3873.00	0.50	20	−0.001	540	A9 SR EU CR	
134759A	8176.00	0.00	55	0.013	130	B9 SI	
196524A	9709.00	0.00	55	−0.012		F5 SR	
90569	12658.00	0.70	15	0.021	220	A0 SR CR SI	

P_{orb} is in days, $v \sin i$ in km s^{-1}, $\Delta(V1-G)$ in magnitudes and $\langle B_e \rangle$ in G.
Notes: a – orbital elements from North (1994); b – $v \sin i$, orbital elements from Wade et al. (1996); d – double-lined binary.

GNUPLOT code version 3.6 (Williams & Kelley 1995). The fitting functions and coefficients (with 1σ errors) are

$$\Delta(V_1 - G) = a_1 \log P_{\mathrm{orb}} + b_1 e + c_1, \qquad \text{for } P_{\mathrm{orb}} < 160\,\mathrm{d},$$

$$\Delta(V_1 - G) = a_2 \log P_{\mathrm{orb}} + b_2 e + c_2, \qquad \text{for } P_{\mathrm{orb}} > 160\,\mathrm{d};$$

$$a_1 = 0.0068 \pm 0.0039, \qquad a_2 = -0.0102 \pm 0.0069,$$

$$b_1 = -0.0351 \pm 0.0093, \qquad b_2 = 0.0273 \pm 0.0127,$$

$$c_1 = 0.0068 \pm 0.0045, \qquad c_2 = 0.0389 \pm 0.0229.$$

Coefficient b_1 apparently differs from zero by more than 2σ, and the decrease of $\Delta(V_1 - G)$ with eccentricity for $P_{\mathrm{orb}} < 160\,\mathrm{d}$ is thus statistically highly significant. To check this finding, we calculated Pearson's linear (r_l) correlation coefficient together with its two-sided significance or p value (p_l, see Press et al. 1986). The latter simply represents the probability of the accidental occurrence of a better correlation coefficient (i.e. its larger absolute value) than that found here under the assumption that the quantities like e.g. $\Delta(V1-G)$ and $\log P_{\mathrm{orb}}$ do not correlate at all. Generally a p value less than about 0.05 is accepted as a serious support for the presence of the (anti)correlation. Looking at Table 4, one can see that the correlation coefficient for $P_{\mathrm{orb}} < 160\,\mathrm{d}$ is statistically highly significant.

Table 3. List of non-CP B9–A2 IV–V binaries.

HD or BFC	P_{orb} [d]	e	HD or BFC	P_{orb} [d]	e
222133	0.50	0.	5408	4.24	0.46
120166	0.64	0.	14688	4.32	0.05
203470	0.65	0.	152912	4.40	0.
577[1]	0.69	0.	206821	4.43	0.11
196628	0.72	0.	71581	4.60	0.1
48049	0.77	0.12	22637	4.67	0.13
135681	0.88	0.09	352682	4.81	0.2
933[1]	0.91	0.	492[1]	5.10	0.
21981	0.94	0.	162085	5.26	0.
205372	0.94	0.	193964	5.30	0.04
209278	0.95	0.	207650	5.30	0.53
72698	1.08	0.	1318[1]	5.55	0.24
187949	1.18	0.	161165	5.88	0.2
153345	1.20	0.	158261	5.92	0.03
102465	1.36	0.	39357	5.97	0.
16907	1.43	0.	320861	6.05	0.37
95878	1.49	0.	162780	6.62	0.54
163175	1.55	0.08	162515	6.68	0.02
163726	1.68	0.	96881	6.93	0.
206644	1.73	0.	203858	6.95	0.
240208	1.75	0.03	96896	7.23	0.
170757	1.78	0.	11860	7.44	0.
1486	1.81	0.	110854	7.90	0.03
189371	1.81	0.11	24118	8.22	0.
115122	1.81	0.	158013	8.22	0.33
178001	1.82	0.05	39780	8.57	0.04
259986	1.91	0.	58713	9.30	0.16
449[1]	2.12	0.	162630	9.50	0.64
34790	2.15	0.	169981	9.61	0.47
218154	2.18	0.03	307[1]	9.86	0.1
68884	2.19	0.	169691	9.95	0.
170470	2.20	0.	149632	10.56	0.43
91636	2.45	0.06	222098	11.23	0.04
23642	2.46	0.02	96307	11.50	0.
98353	2.55	0.43	126983	11.82	0.33
162724	2.78	0.18	49521	12.21	0.30
173847	2.86	0.	87191	12.57	0.
164898	2.92	0.02	174369	13.08	0.39
582[1]	3.02	0.	87751	14.32	0.
1318[1]	3.04	0.	188164	14.99	0.56
162679	3.05	0.	79763	15.99	0.5
163708	3.28	0.41	67198	16.22	0.
188728	3.32	0.	139006	17.36	0.37
145519	3.36	0.33	66824	18.72	0.17
86619	3.37	0.	203439	20.30	0.44
213631	3.38	0.	22805	20.49	0.61
425[1]	3.58	0.28	220318	22.64	0.07
157978/9	3.76	0.	141458	28.95	0.64
31278	3.88	0.	161940	41.78	0.36
2421	3.96	0.15	6118	81.12	0.9
153808	4.02	0.02	86360	137.3	0.7
175286	4.12	0.01	17198	674.95	0.66

Note:
[1] – number in Batten, Fletcher & MacCarthy (1989) (BFC number).

Thus, we conclude that the peculiarity [$\Delta(V1-G)$ value] decreases towards larger eccentricities and possibly also towards shorter periods; however, this does not hold for periods of more than a few hundred days.

4 $\langle B_e \rangle$ IN THE $P_{orb} \times e$ PLANE

It is convenient to represent stellar magnetism by the root mean square of the effective magnetic field, $\langle B_e \rangle$. It was defined in the following way (Brown et al. 1981):

$$\langle B_e \rangle = \sqrt{\sum_i (B_{e,i}^2 - \sigma_i^2)/N}, \tag{1}$$

and calculated for each star by Glagolevskij et al. (1986). σ_i, N and $B_{e,i}$ are the standard deviation, number of measurements and ith measurement of the effective magnetic field, respectively. Budaj et al. (1997) have already found sufficient evidence that $\langle B_e \rangle$ decreases with eccentricity for $P_{orb} < 160$ d, but, in contrast, there is the opposite tendency for larger periods. Consequently, they allowed for such eccentricity dependence and found that $\langle B_e \rangle$ increases with P_{orb} for $P_{orb} < 160$ d. However, the result strongly depends on the accepted steepness of the $\langle B_e \rangle$ versus e relation, and a possible $P_{orb} \times e$ correlation could mask the true orbital element correlated with $\langle B_e \rangle$. This can again be avoided (Fig. 2) by using the same 3D method as previously described. It is hardly an accident that two apparently different planes – one for $P_{orb} < 160$ d and the other for $P_{orb} > 160$ d – can again fit the data. The expressions and coefficients obtained are

$$\langle B_e \rangle = a_1 \log P_{orb} + b_1 e + c_1, \qquad \text{for } P_{orb} < 160\,\text{d}$$

$$\langle B_e \rangle = a_2 \log P_{orb} + b_2 e + c_2, \qquad \text{for } P_{orb} > 160\,\text{d};$$

$$a_1 = 340 \pm 230, \qquad a_2 = -580 \pm 760,$$

$$b_1 = -2700 \pm 940, \quad b_2 = 1700 \pm 1500,$$

$$c_1 = 680 \pm 260, \qquad c_2 = 2300 \pm 2600.$$

The aim of these numbers is not to 'calibrate physical equations', but rather to *illustrate* the qualitative behaviour of the mentioned quantities. Coefficient b_1 again significantly differs from zero (i.e. by more than 2σ). This is confirmed by Table 4, where one can see that the p value of the correlation $\langle B_e \rangle \times e$ is less than 0.05.

Thus, we conclude that the decrease of peculiarity ($\langle B_e \rangle$ in this case) with eccentricity for $P_{orb} < 160$ d is again statistically significant, while its increase with P_{orb} is rather weak and cannot be confirmed by these data. Again, this pattern does not hold for periods of more than a few hundred days.

Notice that the general behaviour of Ap star magnetism as pictured by the two planes in Fig. 2, including the discontinuity at the orbital periods of several hundred days, is qualitatively the same as for the $\Delta(V1-G)$ value. This lends a firmer footing to the observed patterns of Figs 1 and 2, because if the behaviour of the peculiarity sketched by these figures were not real the probability that we would accidentally observe the same pattern in both $\Delta(V1-G)$ and $\langle B_e \rangle$ would be much less than indicated by the p values in Table 4 or, e.g., by the b_1 coefficients, because these p values would multiply. However, the similar behaviour of $\langle B_e \rangle$ and $\Delta(V1-G)$ cannot be considered as fully independent confirmation of such a pattern, as both quantities probably correlate, with $\Delta(V1-G)$ possibly reflecting the Ap star magnetism (e.g. Hauck 1975; North 1980).

5 ECCENTRICITIES OF Ap BINARIES

Eccentricities of Ap binaries are discussed from time to time with the conclusion that there is a lack of circular orbits and that this fact probably reflects a deficit of short orbital periods. Nevertheless, most previous studies have not considered the orbital period and mix the eccentricities of different P_{orb} values. The plots such as Fig. 3 (see e.g. Gerbaldi et al. 1985; North et al. 1998), where we show the eccentricities of Ap and corresponding normal

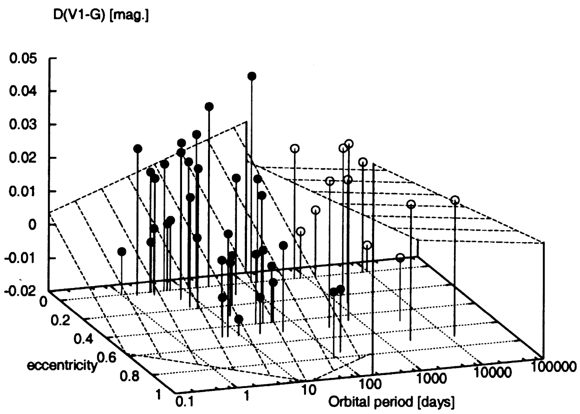

Figure 1. $\Delta(V1-G)$ over the $P_{\rm orb}\times e$ plane. Two planes, for $P_{\rm orb}<160$ d (full circles) and $P_{\rm orb}>160$ d (open circles), illustrate the apparently different behaviour of $\Delta(V1-G)$.

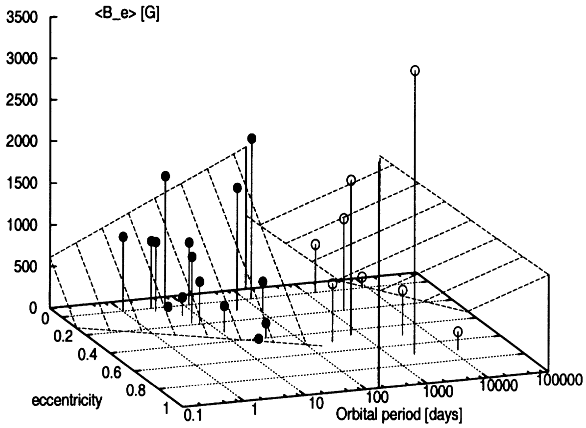

Figure 2. $\langle B_{\rm e}\rangle$ over the $P_{\rm orb}\times e$ plane. Two planes, for $P_{\rm orb}<160$ d (full circles) and $P_{\rm orb}>160$ d (open circles), illustrate the apparently different behaviour of $\langle B_{\rm e}\rangle$.

Table 4. Linear correlation coefficients for the relation between $\Delta(V1-G)$ and $\langle B_{\rm e}\rangle$ versus eccentricity, together with corresponding significances.

	$\Delta(V1-G)\times e$		$\langle B_{\rm e}\rangle\times e$	
	$P<160$	$P>160$	$P<160$	$P>160$
r_l	-0.49	0.52	-0.55	0.44
p_l	0.003	0.08	0.03	0.27

binaries, particularly avoid this problem, but, unfortunately, the most interesting effects are masked by a heavy point concentration at short orbital periods and around $e=0$, as well as by the broad scatter of eccentricities.

To compare the behaviour of Ap and normal star eccentricities at the same orbital period, we smooth the data in the following way. We choose a 0.5 wide interval of $\log P_{\rm orb}$ and slide it along the abscissa with a step of e.g. 0.025 (in $\log P_{\rm orb}$). At each position of this sliding window we calculate the mean eccentricity of the Ap (normal) stars occurring within this window and plot it versus the mean $\log P_{\rm orb}$ of the corresponding stars. In this way, we can simultaneously scan both samples along the $\log P_{\rm orb}$ axis with the same sliding window. One can see in Fig. 3 that the Ap star eccentricities tend to be relatively low for $10<P_{\rm orb}\lesssim 10^2$ d, and the increase of their mean eccentricity with $P_{\rm orb}$ does not seem so continuous and steep as in the case of normal binaries. There is, however, a large uncertainty in the upper boundary of the above interval as the number of normal stars for comparison drops sharply for $P_{\rm orb}>30$ d.[1]

To provide a reader with some level of confidence in the aforementioned trend, we performed the following test. We removed the trend of normal stars from the eccentricities of both sample stars by means of subtracting the mean normal star curve of Fig. 3 and calculated the rectified Ap and normal star eccentricities. Then we calculated the mean rectified eccentricities following the above-mentioned procedure with the same width of sliding window, and at each step we performed the non-equal variance Student's *t* test (if there were at least three stars of each kind in the window, Press et al. 1986) to check whether the Ap and normal star eccentricities occurring within the window have the same mean values. One can see then more clearly in Fig. 4 how the Ap star eccentricities deviate from the normal ones, and what is the approximate level of confidence for that deviation. The *p* value drops sharply below 0.1 for $P_{\rm orb}>10$ d. This value, however, is only illustrative and strongly depends on the width of the window used. If one compares e.g. the mean values of eccentricities of both kind of stars within the interval of our main interest, $10<P_{\rm orb}<160$ d, one would find a statistically highly significant difference with p value $=5\times10^{-3}$. However, this result is not definite, mainly because of the lack of long-period normal binaries, and should certainly be reanalysed in the future. We can only conclude that there are interesting indications that the Ap star eccentricities tend to be lower than corresponding normal star eccentricities for $P_{\rm orb}>10$ d.

6 ORBITAL PERIODS OF AP BINARIES

In order to study the Ap phenomenon in its complexity, it is also interesting to look at the orbital period distribution (OPD) of Ap binaries and compare it with that of corresponding normal binaries. Both distributions are discerned in Fig. 5, representing the number of systems occurring within 0.5 wide intervals of $\log P_{\rm orb}$ plotted versus the central value of the interval and divided by the total number of binaries of each kind. The interval window slides along the x axis with steps of 0.025 in $\log P_{\rm orb}$. The most apparent feature seen in Fig. 5 is the well-known lack of short periods, especially for $P_{\rm orb}<2.6$ d (see also Tables 2 and 3) and, on the other side, the relatively enhanced population of longer periods among Ap binaries compared with normal binaries. The Kolmogorov–Smirnov test (Press et al. 1986) revealed that the probability (p value) that orbital periods of Ap and corresponding normal binaries are drawn from the same distribution function is very low, $\approx10^{-6}$, what means that OPDs of Ap and corresponding normal binaries are apparently different. The same test applied on the orbital periods of Ap and Am binaries (taken from Budaj 1996) gives a p value $\approx 3\times10^{-3}$, i.e. the OPD of Ap and Am binaries (apparently not that of Ap+Am from Fig. 5) are also significantly different. This occurs in spite of a common feature – a gap at $P_{\rm orb}\approx 3\times10^2$ d in Ap and Am binaries – and reflects the relative deficit of short-period Ap binaries

[1] Note that mean eccentricity of normal binaries falls off rapidly at about $P_{\rm orb}\approx 15$ d. This is a simple indication of the range of possible circularization mechanisms and means that normal binaries undergo apparent circularization up to $P_{\rm orb}\approx 15$ d.

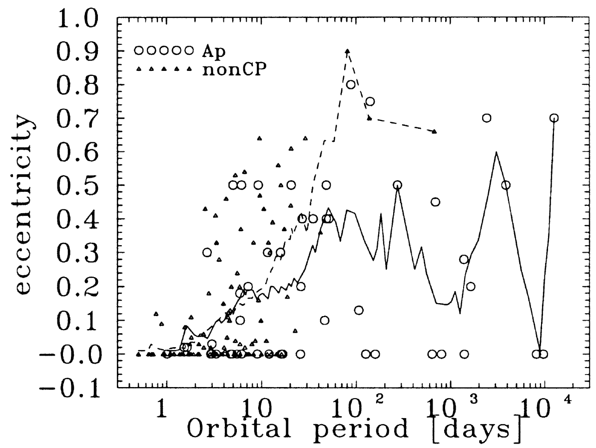

Figure 3. Eccentricity versus orbital period. Circles represent Ap binaries, triangles normal B9–A2 binaries, the full line represents mean Ap star eccentricities averaged over 0.5 in $\log P_{\mathrm{orb}}$ and the dashed line represents mean normal star eccentricities averaged over 0.5 in $\log P_{\mathrm{orb}}$; see the text.

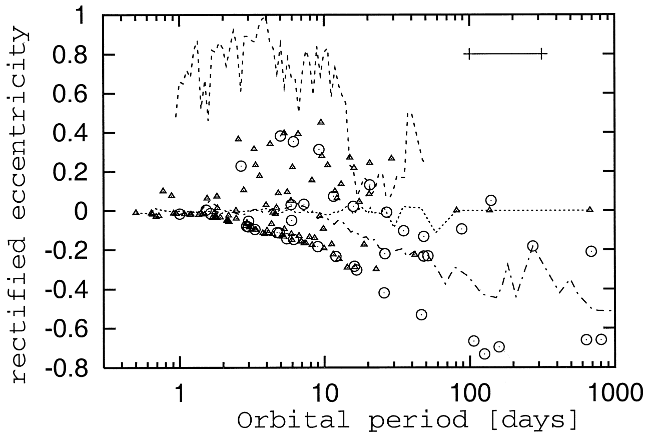

Figure 4. Rectified eccentricity versus orbital period. Circles represent Ap binaries, triangles normal B9–A2 binaries, the dot–dashed line mean Ap star rectified eccentricities averaged over 0.5 in $\log P_{\mathrm{orb}}$, the dotted line mean normal star rectified eccentricities averaged over 0.5 in $\log P_{\mathrm{orb}}$ and the dashed line the probability that the means are the same; the interval at the top right-hand corner indicates the width of a sliding and smoothing window.

compared with Am ones. While the relatively sharp fall-off and deficit of normal binaries for $P_{\mathrm{orb}} > 20$ d may be, at least partly, caused by a selection effect resulting from their larger rotation velocities and, consequently, the more difficult detection of radial velocity variations, the lack of Ap binaries with short periods is real. The depression around 3×10^2 d for Ap binaries is not particularly pronounced, but it remains the most remarkable feature of this distribution, supporting our earlier findings. There is just one star, the well-known Ap binary HD 9996, within the 160–600 d interval. This deficit cannot be caused by a selection effect around a 1-yr period, because it is rather wide. Neither can it result from the separation between spectroscopic and visual binaries, because all stars are spectroscopic binaries, while only three stars with very large P_{orb}: HD 196524A, 134759A and 137909A are also visual binaries. Also, it cannot be an artefact of the method or scale used, as the same method applied to e.g. normal A4–F1 binaries results in a peak instead of the gap.

The appearance of such a period gap becomes more obvious if studied for the sample of Ap+Am binaries (see the solid line in Fig. 5). If we multiply the OPD by the total number of Ap+Am stars, we expect about 11 stars in the centre of the gap, but only one is observed; consequently, one can very roughly estimate the expected ‘signal to noise’ ratio: $\sigma = \sqrt{11} = 3.3$. The bottom of the gap is thus $(11 - 1)/3.3 = 3\sigma$ away. If we take the Ap binaries alone, the level of confidence estimated in this way for the period gap would be about 2σ. The last eye-catching feature is that a curious gap at about $P_{\mathrm{orb}} \approx 1$ d, seen in A4–F1 non-CP binaries (Budaj 1996), is not present in B9–A2 normal binaries.

We conclude that there is sufficient evidence for the depression around 3×10^2 d in the OPD of Ap+Am binaries.

7 DISCUSSION, INTERPRETATION AND DISENTANGLING

It is very difficult to explain most of the above-mentioned findings within the framework of current views on CP stars, i.e. as a result of slow rotation and magnetism in the corresponding area of the HR diagram, thus reducing the role of binarity effects to merely slowing down rotation. In the following we briefly discuss our interpretation of the above points.

7.1 Orbital periods and eccentricities

Let us start from the deficit of short-period orbits for $P_{\mathrm{orb}} < 2.6$ d in Ap binaries. The filling of the Roche lobe as the orbital period shrinks cannot be responsible for this deficit, because it can only be considered for about $P_{\mathrm{orb}} < 1$ d (see e.g. fig. 3 of Budaj 1996). One can speculate that there might be some critical equatorial rotation velocity, as in single Ap stars, and that this could limit the orbital periods through synchronization. However, this critical rotation would have to be rather slow. Considering stellar radius $R = 3\,\mathrm{R}_{\odot}$, the well-known relation gives $v = 50.6 \times R/P_{\mathrm{orb}} = 58\,\mathrm{km\,s^{-1}}$, which is the value that many single Ap stars or long-period Ap binaries exceed (see e.g. $v \sin i$ in Table 2). This is why it is generally accepted that the Ap star magnetism is responsible for this effect. This is, however, not definite, as one would not expect tidally locked binaries and differentially rotating single stars to have the same critical rotation velocity. In fact, we have found that such a velocity is a function of the orbital period in the case of Am binaries.

It is very exciting to observe that the above-mentioned depression in the OPD of Ap binaries occurs at exactly the same position, around $P_{\mathrm{orb}} \approx 3 \times 10^2$ d, as the gap in Am binaries and the peak in normal A4–F1 binaries. The latter are complementary to Am binaries, thus *three independent samples (Am, Ap, normal A4–F1) confirm the existence of this gap*. Moreover, the behaviour of various physical characteristics ($\Delta(V1 - G)$, $\langle B_{\mathrm{e}} \rangle$ and δm_1, see Figs 1 and 2, fig. 2 of Budaj 1997a; Iliev et al. 1998) breaks at the same orbital periods where the above-mentioned gaps (the peak in normal A4–F1 binaries) are seen, thus independently indicating that something happens at these P_{orb}. Note that the stars in the area of the short-period side of the period gap, where we observe the above-mentioned pronounced eccentricity dependence, i.e. $P_{\mathrm{orb}} < 160$ d, are subjected to the Tassoul’s hydrodynamical retardation mechanism. We suggested the ‘tidal mixing + stabilization’ hypothesis to account for this gap in Am stars (Budaj 1996) and propose that there is an area of enhanced turbulent motion inside the star within the period gap so that the He superficial convection zone cannot disappear as a result of He settling and, consequently, the Am phenomenon

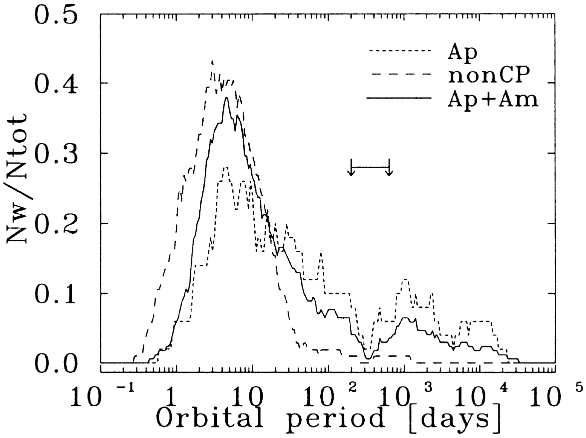

Figure 5. The OPD of 50 Ap binaries (dotted line) accompanied by the OPD of 104 corresponding normal B9–A2 binaries (dashed line) and the OPD of 169 Ap+Am binaries (full line; 119 Am binaries were taken from Budaj 1996). Arrows indicate the width of the running window.

cannot develop. Such an area of enhanced turbulence may be caused by an interplay between tidal mixing, which progressively increases towards shorter orbital periods, and a proposed stabilization mechanism for lowering the efficiency of mixing processes and stabilizing the stellar envelope at the short-period side of the period gap. This might also be the case with Ap binaries, but this would mean that the disappearance of the He superficial convection zone occurs in Ap stars too.

Finally, notice that OPD of Ap and normal B9–A2 stars are not complementary, unlike the OPD of Am and corresponding A4–F1 normal binaries (e.g. Budaj 1996). This is probably caused by the relatively small fraction of (magnetic) Ap binaries, and raises an interesting question as to why non-magnetic A0–A3 binaries are not peculiar, while non-magnetic A4–F1 binaries become Am and non-magnetic B8–B9 binaries occur among HgMn stars.

Our finding that the degree of peculiarity [$\langle B_e \rangle$, $\Delta(V1-G)$] in Ap binaries decreases with eccentricity (for $P_{orb} < 160$ d) is well-established, and one might expect Ap binaries to have lower eccentricities than normal binaries, at least in the P_{orb} range where the orbits are not affected by the possible circularization mechanism. It is very interesting to see that the behaviour of eccentricities fits well into this pattern and Ap star eccentricities tend to be lower than those of normal stars for $P_{orb} > 10$ d. No circularization mechanism that could alter the eccentricities for such orbital periods is known within the (pre-)main sequence. Thus, slightly lower Ap star eccentricities in this region are probably a pure selection effect and a consequence of the above-mentioned eccentricity dependence. *Eccentricities of normal and Ap binaries thus independently confirm the above-mentioned decrease of Ap peculiarity with eccentricity.* Why, then, are Ap star eccentricities not lower than normal ones for $P_{orb} < 10$ d? This is probably not an accident, and it also finds a nice explanation in the framework of tidal effects because there is strong observation evidence of the circularization mechanism in early-type stars (see footnote 1, or, e.g., Matthews & Mathieu 1992; Pan, Tan & Shan 1998), which is effective only for $P_{orb} < 10$ d and which lowers the eccentricities of both kinds of stars. It is also in accordance with the Tassoul's hydrodynamical circularization theory.

7.2 $\Delta(V1-G)$ and $\langle B_e \rangle$

Based on the pronounced dependence of $\langle B_e \rangle$ and $\Delta(V1-G)$ on eccentricity, their possible dependence on P_{orb}, as well as on other well-known features of Ap stars such as their low frequency of occurrence among binaries, low SB2/SB1 ratio, deficit of short periods, and indication of a lack of correlation between inclinations of rotational and orbital axes (we will call these 'major arguments'), one could conclude that (1) magnetism, as a necessary condition for the Ap phenomenon, is affected by binarity (let us call this the 'binarity ⇒ magnetism' hypothesis) or (2) the opposite is the case ('magnetism ⇒ binarity' hypothesis). Abt & Snowden (1973) favour the latter, ascribing it to the pre-main-sequence stage of evolution, and this is more or less generally accepted. Nevertheless, in the light of above findings, it seems to be much more complicated and thus more unlikely than the former possibility. If the 'magnetism ⇒ binarity' hypothesis is true then strong magnetic fields should either prevent the formation of short-period orbits (for $P_{orb} < 2.6$ d and partly for $P_{orb} < 160$ d), as well as the formation of eccentric orbits, (for $P_{orb} < 160$ d) or change these orbital elements. Consequently, the magnetic fields should not have changed very much since that time, so that e.g. the created eccentricity dependence does not dissipate. It is not very clear how this might happen. At the same time, a tight $\Delta(V1-G)$ versus magnetism relation is inevitable to account for the behaviour of the $\Delta(V1-G)$ value in Fig. 1. There would still remain problems with the explanation of the low SB2/SB1 ratio, with explaining the mentioned period gap, and with the unification of Am and Ap phenomena.

On the other hand, the 'binarity ⇒ magnetism' hypothesis requires the presence of a new magnetohydrodynamical mechanism and tidal effects that are much more 'far-reaching' than thought so far. This is, however, nothing strange as there are now both sufficient observational evidence of far-reaching tidal effects in Am binaries that are considered non-magnetic and theories concerning a sufficiently effective and far-reaching hydrodynamical retardation mechanism (e.g. Tassoul & Tassoul 1992). Within the framework of this hypothesis all the 'major arguments' can find a natural explanation if one admits that an Ap star can only undergo tidal stresses of a certain intensity and duration, or that Ap peculiarities cannot develop under such conditions. One could speculate for example that (pseudo-)synchronization might play an important role. Generally, the shorter the orbital period, the higher the degree of (pseudo-)synchronization, and the binary components tend to rotate as rigid bodies. One would expect that this suppresses the differential stellar rotation, which is thought to have a strong amplification effect on the magnetic field. This could explain the 'major arguments', including the decrease of peculiarity with eccentricity, as tidal effects are much more intensive for eccentric orbits than for circular orbits of comparable P_{orb}, because of smaller separation between the components at periastron. Binaries with highly eccentric orbits also exhibit higher velocities at the periastron than those with circular orbits, and therefore also have a higher degree of pseudo-synchronization.[2] The period gap (peak in normal A4–F1 binaries) in Am and Ap stars, which is

[2] However, one could suggest a 'fossil field' version, where for example an eccentric orbit results in some additional movements inside a star that bury the original magnetic field. In the light of our results this version seems less probable, because the enhanced movements in stars with eccentric orbits should cause decreased Am peculiarity with eccentricity, while the opposite is observed.

accompanied by a break in the behaviour of various CP peculiarities, might simply represent a break in the (magneto-) hydrodynamics of the CP (normal) binaries studied (see Section 7.1).

Thus, it seems that *magnetism is affected by binarity* rather than vice versa. Schematically, a semi-empirical principle of the 'binarity ⇒ magnetism' hypothesis in CP stars then reads that binarity suppresses magnetism. In connection with eccentricity dependence in (magnetic) Ap stars, it may be interesting to note that (non-magnetic) Am stars are again contrary in this feature, because their peculiarity increases with eccentricity (Iliev et al. 1998; Budaj 1997b) for the corresponding orbital periods. It is then an attractive idea that such effects could be just another manifestation of the semi-empirical principle of the 'binarity ⇒ magnetism' hypothesis or, in other words, that the same stabilization mechanism (e.g. connected with tidal retardation–synchronization) amplifies the Am characteristics while suppressing the Ap characteristics. This may not only provide a basis for the unification of Ap and Am phenomena (including even single Ap stars, which could be understood as e.g. binaries with long P_{orb} or low-mass companions), but may also put CP stars in a more general context and, for example, shed more light on the behaviour of peculiarity in RS CVn binaries. The latter exhibit a decrease in peculiarity towards larger eccentricities and shorter orbital periods (Rodonò 1995) with a possible discontinuity at about $P_{\mathrm{orb}} \approx 100\,\mathrm{d}$, a pattern that closely resembles that of Ap binaries.

8 CONCLUSION

In the sample of Ap and corresponding B9–A2 normal binaries, we uncovered the following effects, which cannot be understood within the framework of the current view on CP stars, i.e. that they are a result of slow rotation, magnetism and position of a star in the HR diagram (or atmospheric parameters involving age).

(i) The $\Delta(V1 - G)$ value, which is a peculiarity indicator, exhibits a pronounced decrease with eccentricity and a possible increase with P_{orb} for $P_{\mathrm{orb}} < 160\,\mathrm{d}$, but this is not the case for larger periods and the discontinuity occurs at the orbital period of the above-mentioned period gap.

(ii) The magnetism of Ap binaries represented by the root mean square of the effective magnetic field, $\langle B_{\mathrm{e}} \rangle$, behaves in exactly the same manner.

(iii) The Ap star eccentricities seem lower than the normal star eccentricities for $P_{\mathrm{orb}} > 10\,\mathrm{d}$.

(iv) A curious depression is present in the OPD of Ap+Am binaries at $3 \times 10^2\,\mathrm{d}$.

The above evidence strongly supports the 'binarity × magnetism' hypothesis of Abt & Snowden (1973) but, contrary to the suggestion of the pioneers, it suggests to us that it is the magnetism that is affected by the binarity ('binarity ⇒ magnetism' hypothesis) and not vice versa. In other words, the answer to the question of this paper's title is 'Yes'. This leads us to the simplest conclusion, that it is the companion of an Ap star that is responsible for the effect, and that affects the magnetohydrodynamics in an Ap component up to a surprisingly wide separation between the components (up to an orbital period of several hundred days), so that one can observe the dependence of various Ap characteristics on orbital elements, as well as various well-known features like the low frequency of occurrence among binaries, the deficit of short orbital periods or the low SB2/SB1 ratio in Ap binaries. Thus, no account of CP stars is complete in which the role of binarity is reduced to being simply a tool to slow down the rotation velocity.

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REFERENCES

Abt H. A., 1961, ApJS, 6, 37
Abt H. A., 1965, ApJS, 11, 429
Abt H. A., 1979, ApJ, 230, 485
Abt H. A., Levy S. G., 1985, ApJS, 59, 229
Abt H. A., Snowden M. S., 1973, ApJS, 25, 137
Babcock H. W., 1958, ApJS, 3, 141
Batten A. H., Fletcher J. M., MacCarthy D. G., 1989, Publ. Dominion Astrophys. Obs. Vol. 17, Eighth Catalogue of Orbital Elements of Spectroscopic Binary Systems, NRC of Canada, Victoria, B.C.
Borra E. F., Landstreet J. D., Thompson I., 1983, ApJS, 53, 151
Brown D. N., Landstreet J. D., Thompson I., 1981, in Les etoiles de composition chimique anormale, Inst. d'Astrophys, Univ. Liege, 195
Budaj J., 1994, poster at 22nd General Assembly Meeting, The Hague,
Budaj J., 1995, Strassmeier K. G., ed., IAU Symp. 176, Stellar Surface Structure – Poster Proceedings, Institut für Astronomie, Universität Wien, p. 147
Budaj J., 1996, A&A, 313, 523
Budaj J., 1997a, A&A, 326, 655
Budaj J., 1997b, PhD thesis
Budaj J., Elkin V. G., Romanyuk I. I., Wade G. A., Žižňovský J., Zverko J., 1997, in Glagolevskij Yu.V., Romanyuk I. I., eds, Stellar Magnetic Fields, SAO, Moscow, p. 176
Claret A., Giménes A., Cunha N. C. S., 1995, A&A, 299, 724
Floquet M., 1983, in Les journées de Strasbourg, Véme Réunion. Observatoire de Strasbourg, Strasbourg, p. 83
Gerbaldi M., Floquet M., Hauck B., 1985, A&A, 146, 341
Glagolevskij Yu. V., Romanyuk I. I., Chunakova N. M., Shtol V. G., 1986, Astrophys. Issled. (Izv. SAO), 23, 37
Hauck B., 1975, in Weiss W. W., Jenkner H., Wood H. J., eds, Physics of Ap stars. Universitätssternwarte Wien, Vienna, p. 365
Iliev I. Kh., Budaj J., Zverko J., Barzova I. S., Žižňovský J., 1998, A&AS, 128, 497
Landstreet J. D., 1992, in Heber U., Jeffery C. S., eds, The Atmospheres of Early Type Stars, Springer-Verlag, Heidelberg, p. 170
Lebedev V. S., 1987, Astrophys. Issled. (Izv. SAO), 25, 41
Mathys G., Hubrig S., Landstreet J. D., Lanz T., Manfroid J., 1997, A&AS, 123, 353
Matthews L. D., Mathieu R. D., 1992, in McAlister H., Hartkopf W. I., eds, ASP Conf. Ser. Vol. 32, Complementary Approaches to Double and Multiple Star Research. Astron. Soc. Pac., San Francisco, p. 244
North P., 1980, A&A, 82, 230
North P., 1994, in Jankovics I., Vincze I. J., Proc. 25th Workshop and Meeting of EWG on CP stars, Gothard Astrophys. Obs., Szombathely, p. 3
North P., Ginestet N., Carquillat J.-M., Carrier F., Udry S., 1998, Contrib. Astron. Obs. Skalnaté Pleso, 27, 179

Pan K., 1997, A&A, 321, 202
Pan K., Tan H., Shan H., 1998, A&A, 335, 179
Preston G. W., 1974, ARA&A, 12, 257
Press W. H., Flannery B. P., Teukolsky S. A., Vetterling W. T., 1986, Numerical Recipes, Cambridge Univ. Press, Cambridge
Renson P., Kobi D., North P., 1991, A&AS, 89, 61
Rodonò M., 1995, in Huang L. et al., eds, Proc. 4th Workshop on Multi-Site Continuous Spectroscopy. ESA-ESTEC, p. 69
Seggewiss W., 1993, in Dworetsky M. M., Castelli F., Faraggiana R., eds, ASP Conf. Ser. Vol. 44, Peculiar Versus Normal Phenomena in A-type and Related Stars. Astron. Soc. Pac., San Francisco, p. 137
Stępień K., 1998, Contrib. Astron. Obs. Skalnaté Pleso, 27, 205
Stift M. J., 1976, A&A, 50, 125
Tassoul J.-L., 1995, ApJ, 444, 338
Tassoul J.-L., Tassoul M., 1992, ApJ, 395, 259
Wade G. A., North P., Mathys G., Hubrig S., 1996, A&A, 314, 491
Williams T., Kelley C., 1995, Gnuplot Version 3.6 manual
Wolff S. C., 1983, The A-type Stars: problems and perspectives, NASA SP-463, CNRS, NASA, Paris, Washington DC
Zahn J. P., 1997, A&A, 57, 383

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