Astron. Astrophys. 313, 523–531 (1996)

ASTRONOMY
AND
ASTROPHYSICS

On the nature of the Am phenomenon or on a stabilization and the tidal mixing in binaries

I. Orbital periods and rotation

Ján Budaj

Astronomical Institute, Slovak Academy of Sciences, 059 60 Tatranská Lomnica, The Slovak Republic (budaj@ta3.sk)

Received 30 September 1994 / Accepted 27 January 1996

Abstract. The paper casts a questioning eye on the unique role of the diffusive particle transport mechanism in explaining the Am phenomenon and argues that the so-called tidal effects might be of great importance in controlling diffusion processes.

A short period cutoff at $\approx 1.2^d$ as well as a $180^d - 800^d$ gap were found in the orbital period distribution (OPD) of Am binaries. The existence of the former can be ascribed to the state of the primaries with the almost–filled Roche lobes. The latter could result from the combined effects of the diffusion, tidal mixing and stabilization processes. Because the tidal mixing might surpass diffusion in the binaries with the orbital periods $P_{\rm orb}$ less than several hundred days and might thus sustain the He convection zone, which would otherwise disappear, no Am stars should lie below this boundary. The fact that they are nevertheless seen there implies the existence of some stabilization mechanism (as, e.g., that recently proposed by Tassoul & Tassoul 1992) for the binaries with orbital periods less than 180^d.

Further evidence is given to the fact that the OPD for the Am and the normal binaries with an A4-F1 primary are complementary to each other, from which it stems that Am stars are close to the main sequence. There are, however, indications that they have slightly larger radii (2.1–3 $R_\odot$) than expected for their spectral type.

The generally accepted rotational velocity cutoff at ≈ 100 km s^{-1} is shown to be of little value when applied on Am binaries as here it is not a single quantity but, in fact, a function of $P_{\rm orb}$ whose shape is strikingly similar to that of the curves of constant metallicity as ascertained from observations. This also leads to the well known overlap in rotational velocities of the normal and Am stars for $40 < v < 100$ km s^{-1}, or the lack of normal stars for $P_{\rm orb} > 2.5^d$. We have exploited this empirical cutoff function to calibrate the corresponding turbulent diffusion coefficient associated with tidal mixing, having found out that the computed form of the lines of constant turbulence fits qualitatively the empirical shape of the curves of constant metallicity. As for larger orbital periods ($20^d < P_{\rm orb} < 200^d$) these are characterized by the more–less constant boundary of rotational velocities of about ≈ 75 km s^{-1}. In the case of synchronized Am binaries here the upper constraint for rotational velocities is tied with the short orbital period cutoff, and thus, probably, with characteristics for primaries with the filled Roche lobe.

Finally, high metallic Am stars seem to possess larger orbital periods. The jump in metallicity for $v \sin i > 55$ km s^{-1} found by Burkhart (1979) would then be nothing but a manifestation of insufficiently populated corresponding area of larger $P_{\rm orb}$.

Key words: stars: chemically peculiar – binaries: close – turbulence – diffusion – hydrodynamics

1. Introduction

A large number of relevant but still not well understood processes operate in stellar envelopes and interiors. Observable effects include possible 'chemical' peculiarities which, at a stellar surface, are, as a rule, well masked by stellar winds, convective zones or other, even weak motions. However, there exists the group of the so-called chemically peculiar (CP) stars, i.e. the group of slowly rotating main sequence stars of the middle B, A, and early F types, which are supposed to be almost devoid of deep convective zones, strong stellar winds as well as of rotationally induced turbulence, and, hence, offer us to see such 'peculiarities' completely naked.

There is a well populated subgroup of CP stars, mainly in the spectral range A4-F1, called metallic (Am or AmFm) stars. They exhibit abnormally strong metallic and unusually weak calcium and scandium lines which can qualitatively be explained by radiatively driven diffusion processes just below superficial convective layers (Michaud 1970, Michaud et al. 1976).

It is generally believed that it is a relatively slower rotation of Am stars that is a principal agent responsible for their peculiarity, as the rotationally driven turbulence – including the meridional circulation (Charbonneau 1993) or shear flow instability (Vauclair et al. 1978) – is kept small enough enabling also particle diffusion to play its own role. Most elaborated calculations of Charbonneau & Michaud (1991), based on the Tassoul

& Tassoul (1982) models of meridional circulation, show that in stars rotating slower than $v \approx 90$ km s^{-1} the He surface convection zone disappears in a 10^6 yr due to a gravitational settling of He, which then fosters diffusion to operate even faster under the remaining H superficial convection zone. This is regarded to be in a good agreement with the observed rotation velocity cutoff at about 100 km s^{-1} (Abt & Moyd 1973) for the Am stars. Meridional circulation was theoretically demonstrated to have little influence on any chemical separation of elements other than He. However, this view is not supported by observations which show either continuous decrease of metallicity with increasing $v \sin i$ (Smith 1971, Kodaira 1975, Hauck 1978, Kitamura & Kondo 1978, Hauck & Curchod 1980) or even its abrupt jump at $v \sin i = 55$ km s^{-1} (Burkhart 1979). On the other hand, Zahn (1992) regards the above mentioned agreement of the observed and theoretical rotation velocity cutoffs as a mere coincidence and treats peculiar A-type stars as lacking any stellar wind and, hence, any angular momentum loss; this results in a nearly uniform internal rotation for slow rotators and, consequently, in disappearance of the rotationally induced mixing.

It is rather striking to observe a binary character of many Am stars (Abt 1965, Abt & Bidelman 1969). This idea was first raised by Abt (1961), who even claimed that all Am stars are binaries. Although in subsequent papers of Batten (1967) and Conti & Baker (1973) it was realized that such a statement is too strict and that some of Am stars may be single, the fact that a high percentage of Am stars are inevitably binaries was not questioned. It seems to us that this feature deserves much more attention than being just a tool to slow down the rotation of a star below a thought cutoff of about 100 km s^{-1} as regarded so far, for it can help us to gain deeper insight into the following problems:

- a possible overlap in rotational velocities of the Am and normal A stars (Wolf & Wolf 1975) [1]. Having performed statistical deconvolution from $v \sin i$ to v Abt & Morrell (1993) obtained the equatorial rotational velocities to be < 150 km s^{-1} and > 50 km s^{-1} for Am and normal stars, respectively. Abt & Hudson (1971) studied the members of binaries with orbital periods $P < 5^d$, for which one would expect a synchronization, and found that all stars with $v <$ 40 km s^{-1} are Am, while those in the range $40 < v < 100$ km s^{-1} may be either Am or normal;
- the two maxima in OPD of Am binaries (Abt 1965); coexistence of Am and normal binaries outside the orbital period interval $2.5^d - 100^d$ (Abt & Bidelman 1969) complemented by the fact that all A4-F1 binaries inside this period interval are Am stars, although Ginestet et al. (1982) found some normal stars here;
- some evidences that Am stars have larger radii and/or ages than those characterizing normal A stars on the main sequence (Kitamura & Kondo 1978, Gomez et al. 1981, Lane & Lester 1984, North 1993);
- observed anticorellation between metallicity and $v \sin i$, standing in contrast to theoretical calculations.

Recently, Budaj (1994a) came up with a principally new mechanism competing against diffusion - that of tidal mixing. As its name suggests it comprises disturbing motions and flows inside and/or on the surface of an Am star, which are induced by its companion and create thus the conditions unfavourable for the formation of any inhomogeneities of chemicals. In particular, in potential candidates for Am stars with $P_{\rm orb} < 10^2$ days such effects could also maintain their He convection zones, which would otherwise cease due to an He settling. This would make conditions incompatible with the occurrence of the Am phenomenon unless there was a sort of stabilization mechanism 'paralyzing' to some extent these effects for the above mentioned orbital periods and offering us a nice explanation of the observed two maxima in OPD with a saddle point situated at 10^2 days (Abt 1965). At this point it is worth mentioning that the retardation mechanism proposed by Tassoul & Tassoul (1992) could be regarded as a potential candidate for such a stabilization, all the more that it is supposed to work in binaries with $P_{\rm orb}$ up to $\approx$ 100 days as required here. However, we should be rather cautious about considering this mechanism since its very existence was recently questioned on physical grounds by Rieutord (1992).

The principal aim of the paper is a thorough discussion of the possible role of tidal mixing in explaining the Am phenomenon with the help of statistical methods applied on best currently available samples of Am binaries and their counterparts among the normal stars. This part I deals with orbital periods and rotation of Am stars, mainly.

2. Sample stars

The statistical analysis has been carried out on the Seggewiss's (1993) sample of Am and normal spectroscopic binaries. The sample is based on the catalogue of Batten et al. (1989) and contains, as far as Am stars are concerned, only binaries with primary (i.e. hotter) components being of the Am type; for suspected triple systems HD 206155 and HD 40932 we left out the orbital periods of third bodies, while the ambiguous multiple system HD 71663 was completely excluded from the analysis. The catalogues of Renson (1991) and Philip et al. (1976) served as a source for the values of $v \sin i$ and δm_1, respectively. The corresponding information about each Am star, complemented by further remarks, is collected in Table 1.

Concerning the normal A-type binaries, we have singled out from the sample only those, whose primaries were close to the main sequence (the spectral class V,IV) and of the A4-F1 type (following Abt & Bidelman 1969 as well as Smith 1973). Here we exclude from our consideration three double lined binaries HD 99946, HD 232121, BFC 155 (BFC being the number in Batten et al. 1989) because their $m_1 \sin^3 i$ are too large (exceeding 3.9) for the stars with spectral types A9n, A6-shell, and A-shell, respectively, to be regarded as main sequence objects. The resulting sample of non CP systems fulfilling our selection

[1] In fact, Abt (1975) and Abt & Moyd (1973) also arrived at some kind of an overlap, but they ascribed its existence to the differences in spectral classification.

Table 1. List of Am binaries

HD	$P_{\rm orb}$ [day]	$v \sin i$ [km s^{-1}]	note:	HD	$P_{\rm orb}$ [day]	$v \sin i$ [km s^{-1}]	note:
204038	0.79	150	s,e	23631	7.35	< 10	s,Pleiades
21912	0.92	85	s	125335	7.37		
106112	1.27	95	s	182490	7.39	45	d
1826	1.43		Hyades?	79193	7.75	< 15	s,e,d
178661	1.54			209625	7.83	20	s
209147	1.60		e,d	184552	8.12	12	s
23848	1.77	100	e	17581	8.25	20	s
93075	1.81	30	s,d	27749	8.42	12	s,Hyades
125337	1.93	15	s,d	205234	8.44		e,d
4058	1.96	A:60,B:70	s,d	144426	8.86	35	
113158	2.0	55	s,e	82191	9.01		d
156965	2.06		e,d	40536	9.36	30	
27628	2.14	25	s,Hyades?	44691	9.95	15	s,e,d
213534	2.34	50	s	92139/40	10.21	0	s,d
190786	2.35	40	s,e,d	6619	10.62		d
46052	2.53	40	s,e,d	179950[1]	10.78	0	s,d
206155	2.63	40	s,e,d	198391	10.88	< 40	
110326	2.70	50	s	196544	11.04	50	
40372	2.74	65		861	11.22		
18597	2.78		e,d	18778	11.67	35	UMa cluster
102660	2.78	20	s	108642	11.78	< 12	s,Coma
139319	2.81	45	s,e	73619	12.91	130	Praesepe,d
162132	2.82			171653	14.35	20+20	d
75737	2.90	25+45	s,d	171978B	14.67	< 10	s,d
39220	2.93	75	e	12869	15.29	15	d
60178	2.93	30	s	23277	15.51	30+30	d
219815	3.22	70	e	36412	16.79		e,Assoc.ORI
112014	3.29	15+15	s,d	20320	17.93	70	
128661	3.33		e	204188	21.72	75	e
149420	3.39	25	s	155375	23.25		
211433	3.57			42954	23.81	50	d
29140	3.57	30	s	216608A	24.16	40	
136403	3.58	20	s,d	104671	24.48	25	Hyades?,d
26591	3.66	30	s,d	148367	27.22	55	d
161321	3.90	35+30	s,e,d	41357	28.28	30	d
40183	3.96	30+25	s,d	434	34.26	60	
193637	4.01		e,d	8374	35.37	20	d
12881	4.12	13	s,d	30050	37.28	70	e
85040	4.15	20	s,d	159560	38.13	50	
28204	4.20	35	s,Hyades?	110951	38.32	65	
174343/4	4.24		d	29479	38.95	60	
71973	4.29	20	s	96528	40.45		
173648	4.30	25	s	108651	68.29	15	Coma
193857	4.34			107259	71.9		d
40932	4.45	25	s,Hyades?	138213	105.95	30	
4161	4.47	25	s,e,d	42083	106.0	30	d
173654	4.77	< 25	s,d	11636	107.0	70	d
56429	4.80		e,d	33254	155.83	20	Hyades
114519	4.80		e,d	183007	164.64	< 50	
120955B	4.84	70		116657	175.55	60	
112486A	5.13	20	s,d	209790	810.9	25	d
162656	5.45	< 40	NGC6475	195725	840.6	55	
168913	5.51	25	s,d	78362/3	1062.4	15	
20210	5.54	25	s	17094	1202.2	50	
93903	6.17	25	s	198743	1566.0	50	
206546	6.37	40	d	56986	2238.6	110	
103578	6.63	40		27176	4035.	105	Hyades?
30453	7.05	20	s	47105	4613.66	20	
275604	7.16		e	48915	18277.	10	
109510	7.34	< 20	s,d				

Note: [1] - probably A of the visual B component; s - 'possible' synchronization; e - eclipsing; d - double lined binary; cluster membership.

rules is presented in Table 2. Our total list thus consists of 119 Am and 61 non CP binaries.

3. Orbital period distribution

Since the landmark paper by Abt (1965) the OPD of Am binaries has been discussed in more detail by Abt & Bidelman (1969), Ginestet et al. (1982), Abt & Levy (1974, 1985) and, most recently, by Seggewiss (1981, 1993). Although the sample of Am binaries used in the last reference is the richest one ever studied, it is rather unfortunate that its analysis is restricted to short orbital periods only. However, in order to study the Am phenomenon in its complexity the analysis in question has to be also extended, along with the appropriate sample of normal comparison stars, to longer orbital periods. This is the subject of what follows.

The OPDs for our sample, smoothed out over the 0.2 interval (expressed in logarithmic scale) are illustrated in Fig. 1. Here either curve, in fact, joins the peaks of ten distinct histograms with the same width of an element (equal to 0.2), but with different position of starting points, which are shifted from the first one in multiples of 0.02. Comparing to a 'simple' histogram this not only makes the distribution under consideration independent

Table 2. List of non-CP A4-F1 binaries

HD or BFC	$P_{\rm orb}$ [day]	HD or BFC	$P_{\rm orb}$ [day]
285892	0.42	78014	2.28
213[1]	0.43	201032	2.30
32[1]	0.51	222217	2.34
1053[1]	0.55	177708	2.41
1124[1]	0.57	116857	2.55
175813	0.59	460[1]	3.31
124689	0.61	18337	6.64
975[1]	0.63	354963	7.23
104350	0.64	349425	9.77
82610	0.65	54520	10.09
151676	0.66	207956	10.62
16506	0.68	153720	11.01
139815	0.73	753[1]	11.67
117362	0.78	205539	12.21
471[1]	0.79	83808/9	14.50
105[1]	0.79	43246	23.18
60265	0.82	1455[1]	23.29
1061[3]	0.84	178449	42.86
12211	0.97	102509	71.69
57167	1.14	217792	178.32
210892	1.15	104321	282.69
141324	1.44	32537	391.7
70958	1.56	37507[3]	445.74
199603[3]	1.58	28910	488.5
62863	1.66	67390[3]	1181.5
75747[3]	1.67	31109[3]	3057.0
24733	1.76	76644	4028.0
687[1]	1.80	28052	5200.0
73463	1.80	205767	8016.0
169985/6	1.85	12111[2]	20146
168092	2.05		

Note: [1] - number in Batten et al. (1989)(BFC number); [2] - provisional orbit; [3] - primary sometimes classified as a sp. class IV star

on the choice of the position of a starting point but also reveals much finer details that would otherwise go unnoticed. First of all, it is the most prominent peak in Am distribution at $2^d - 15^d$ – the region where also synchronization is observed (see Fig.4) – which coincides with the largest gap in the distribution of normal stars. Further, the interval $10^d - 100^d$ that was in Abt & Bidelman (1969) characterized by incomprehensible lack of normal binaries shows here quite a good population of these, in conformity with Ginestet et al. 1982. Also larger periods, although not so densely populated, exhibit many complementarity relations, in particular: the maximum of Am's correlating with the minimum of normals at 100^d; the contrary being true at 4×10^2 days; and, again, a coupling between the maximum of Am's and a lack of normals at 10^3 days. On the other hand, the second maximum at 10^3 days mentioned by Abt (1965) is not so pronounced and his correlation between Am and normal stars for $P_{\rm orb} > 10^2$ days shows here rather a sign of anticorrelation.

The main motivation for this paper as well as the feature of greatest interest for us is just the gap seen at 4×10^2 days. This gap, already indicated in Abt (1965), cannot be caused by selection effects (around one year period) because it is rather wide (extending from 176 to 810 days – see Table 1) and endowed with an **enhanced** number of normal stars (5 of them) in its center. For the same reason it cannot result from the splitting between spectroscopic and visual binaries as well as also because all sample stars are spectroscopic binaries, just two Am's with the largest $P_{\rm orb}$ being, in addition, an astrometric and visual binary, respectively.

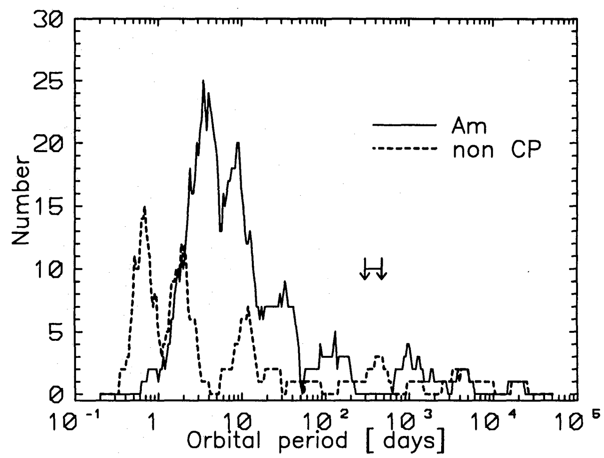

Fig. 1. The orbital period distributions for 119 Am and 61 normal A4-F1 binaries. Arrows indicate the width of a window (i.e. of a smoothing interval – see the text).

Another eye-catching feature is that, if one omits HD 204038 and HD 21912 which have extremely short orbital periods (see Table 1), the number of Am's drops sharply to zero at $P_{\rm orb} \approx 1.2^d$, whereas normal binaries are also found in large quantities even well below this limit. It seems very improbable that this feature is due to the effect of selection with a period of one day, for one could hardly imagine any selection that would reduce the number of stars by 100 per cent and, in addition, allow for the cutoff to differ even slightly from 1^d. Equally, such a selection effect cannot also account for the scarcity of non CP stars at around 1^d, as within $0.84^d - 1.44^d$ region, there are just 3 stars there, moreover situated close to 1^d. At this point it is worth mentioning that the ODP of hotter (i.e. A1-A3 type) normal binaries exhibits only a very tiny trace of such a gap and lacks any perceivable sign of the complementarity to the distribution of Am's.

4. $v \sin i$ versus $P_{\rm orb}$, synchronization, radii, evolutionary status

From what we discussed in the introduction as for the Am phenomenon and from what we found in the previous section, it is rather straightforward to expect that there should be a unique relation between the orbital period of a binary and the maximum (or critical) rotational velocity of its primary at which the latter can still be regarded as an Am star. Based upon currently accepted mechanisms for 'converting' normal stars into CP ones, in the v versus $P_{\rm orb}$ diagram one would expect such relation to be represented by a horizontal line at about 100 km s^{-1}, separating the region with strong predominance of normal stars (above) from that of CP stars (below).

The corresponding situation for our sample is illustrated in Fig. 2, showing the plot of $v \sin i$ versus $P_{\rm orb}$ together with the curves representing synchronous rotation of stars with R = 1.5, 2.1, 3.0 and 4.2 $R_\odot$. Notice the most populated 'main sector' bounded by the R = 2.1 $R_\odot$ and R = 3 $R_\odot$ curves and containing 24 stars, much less denser sectors between R = 1.5 $R_\odot$

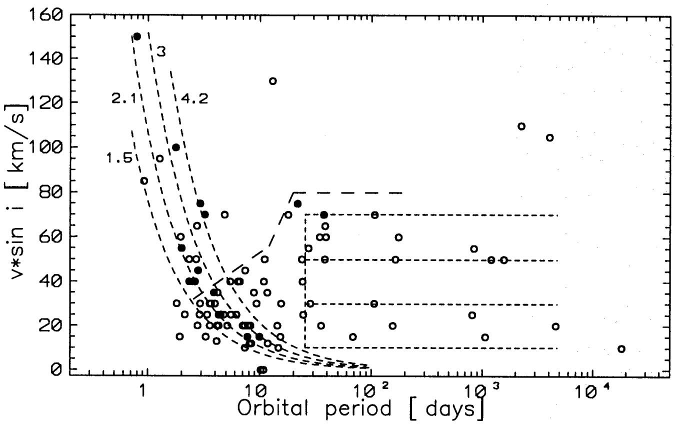

Fig. 2. $v \sin i$ versus $P_{\rm orb}$. The notation is as follows: the synchronization curves corresponding to the stellar radii R = 1.5, 2.1, 3.0 and 4.2 $R_\odot$, respectively, are denoted by short dashes; long dashes represent the maximal rotation allowed for an Am star at corresponding $P_{\rm orb}$ ($V_{\rm max}$ curve); filled (open) circles stand for eclipsing (other spectroscopic) Am binaries; finally, the shortest dashes emphasize "curious" behaviour of $v \sin i$ (see the text).

and R = 2.1 $R_\odot$ (11 stars) and R = 3 $R_\odot$ and R = 4.2 $R_\odot$ (5 stars), as well as the 'residual' sector comprising 11 stars falling below R = 1.5 $R_\odot$ curve.[2] It is obvious that the majority of stars both occupying the area below the curve R = 3 $R_\odot$ and situated above the latter within a ±5 km s^{-1} tolerance, totalling to 49, may be treated as a 'potentially' synchronized (denoted as 's' in Table 1), although it would be, however, fairly unjustified to claim that all the stars in the above mentioned area exhibit this feature, or that we could not find synchronized binaries outside - but the latter would have to be unusually large. A rather sharp contrast between the heavily-populated main sector (containing about half of all 'potentially' synchronized Am's) and its almost depleted right neighbourhood confines the stars' radii to lie within the range from 2.1 to 3 $R_\odot$ and the synchronization to meet the condition $P_{\rm orb}/P_{\rm rot} < 1.4$, $P_{\rm rot}$ being the rotational period of a star, as also found by Kitamura & Kondo (1978) on a sample of eclipsing binaries. Thus Am's really seem to have a bit larger radii than the normal main sequence stars of similar spectral type (typically from 1.5 to 1.9 $R_\odot$ for late A and A5 stars, respectively, Wolf 1983).

Apart from the domain of synchronized Am binaries where the rotation rate is completely determined by the orbital period, Fig. 2 shows also another conspicuous feature, namely an increase of rotational velocity with orbital period for binaries with $P_{\rm orb} \approx 4^d$ up to $P_{\rm orb} \approx 20^d$ (the latter boundary even amounting to $\approx 30^d - 40^d$ if one would consider rotation averaged over certain sufficiently short intervals). That such a property cannot simply trace decreasing power of synchronization follows from the fact that Am stars are completely repudiated from the region above a long-dashed curve, which thus represents the maximum rotational velocity ($V_{\rm max}$) attainable for Am stars the latter favored also by the fact that this curve is parallel to the curves of constant metallicity (see Sect. 5.2). Just for $P_{\rm orb} > 20^d$ up to at least 200^d, where we still have a sufficiently large number of stars for reasonable statistics, $V_{\rm max}$ acquires a constant limiting value of ≈ 75 km s^{-1}.

Another curious feature to be noted in Fig.2 is the obvious lack of binaries for the range $30 < v \sin i < 50$ km s^{-1} and for large orbital periods of about $P_{\rm orb} > 25^d$. As shown in detail later on this fact deserves further exploration for, e.g., a similar gap can be also found in Burkhart's sample of Am stars (Burkhart 1979). In Fig. 1 of the latter work, which displays δm_1 versus $v \sin i$ diagram, such a gap can be seen just below $\delta m_1 = -0.04$; even the only star falling into this region, HD 216608 ($v \sin i$ = 35 km s^{-1}, $\delta m_1 = -0.047$), is found out to lie, in fact, outside the gap as its true δm_1 differs from Burkhart's introduced value by + 0.01 (Philip et al. 1976).

Finally, we should also focus our attention on three stars which are situated well apart from the rest, namely HD 73619, HD 56986 and HD 27176 having $v \sin i > 80$ km s^{-1} and $P_{\rm orb} > 10^d$, as well as on other stars lying beyond the synchronization curve for R = 3 $R_\odot$; here we can rank, e.g., HD 39220, HD 219815, HD 120955 which should be synchronized and would have thus – given their rotation velocities – rather large radii $R > 4.2 R_\odot$. A Catalogue of Parameters for Eclipsing Binaries (Brancewicz & Dworak 1980) gives R = 4.71 $R_\odot$ and R = 3.79 $R_\odot$ for HD 39220 and HD 219815, respectively, while Ferluga et al. (1993) found for the former R = 3.52 $R_\odot$.

5. Interpretations and discussion

5.1. Orbital period distribution

The complementarity of Am and non CP OPDs discussed in Sect. 3 combined with the high percentage of Am stars among the late A stars (50% after Smith 1973) confirm that Am stars are (as already shown by Abt & Levy 1985) on or close to the main sequence, but have probably a little bit larger radii for their spectral type (see Sect. 4 and discussions below.)

As for the Am peculiarity itself we should observe that were the latter only confined to the surface layers, it would be completely destroyed by a mass transfer from an Am primary. Hence, the strong boundary at 1.2 days on the short period side of Am OPD might be an indicator of the radii of Am stars. This becomes more obvious from Fig. 3 where the orbital period versus the secondary-to-primary mass ratio is shown for different values of the Roche radius (i.e., the radius of a sphere with the same volume as the Roche lobe after de Loore & Doom 1992) of primaries, whose mass is kept fixed and being equal to $M = 2M_\odot$. From the figure it follows that a semidetached system with the radius of a primary being $R = 3\,R_\odot$ captures quite well the above-mentioned cutoff for a considerably wide range of the

---

[2] This rough statistics should not be seriously affected by a selection effect resulting from the fact that there certainly exists a limit for the semiamplitudes of a radial velocity curve, adopted here to be 10 km s^{-1}, under which it is practically impossible to find any spectroscopic binaries. Given such an effect it would be only 1/14 to 1/7 (1/6 to 1/3) of the whole number of binaries with orbital periods from 2^d to 15^d which went unnoticed assuming the mass of a secondary component to be $M_2 = 1M_\odot$ ($M_2 = 0.4M_\odot$, which might be viewed as the worst case).

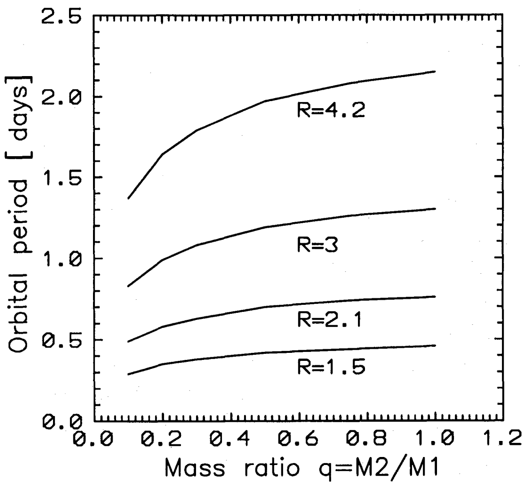

Fig. 3. Orbital periods vs. secondary-to-primary mass ratio for the binary systems with different (and equal to the Roche) radii of primaries, having the mass $M_1 = 2M_\odot$.

masses of secondaries (most probably greater than 0.4 $M_\odot$ as dictated by their mass functions and in an agreement with the findings of Abt & Levy 1985). Of course, we should still keep in mind the possibility that the Am peculiarity might disappear just slightly before the Roche lobe is filled in.

Concerning the 180-800 day gap its occurrence is in a surprisingly good agreement with our earlier findings (Budaj 1994a). Really, if we take into account the value of the turbulent diffusion coefficient still compatible with the He settling $D_{\mathrm{T},0} = 10^3\ \mathrm{cm}^2\,\mathrm{s}^{-1}$ (Charbonneau & Michaud 1991), and take the radius of an Am star, in the light of our recent results, not to deviate much from 3 $R_\odot$, the point below which the tidal mixing starts prevailing allowed turbulence is shifted to $P_{\mathrm{orb}} = 700^d$. It is worth stressing that this value is not much sensitive to the quantities other than the radius of a star; for a 'standard' value, 2 $R_\odot$, the corresponding period is shorter by a factor of 2.25. Nevertheless, the fact that Am's are also found in the binaries whose periods are less than 180^d indicates the presence of some stabilization mechanism there. In connection with this it is worth mentioning here the retardation mechanism recently proposed by Tassoul & Tassoul (1992) that "remains operative for large orbital periods,...- without bringing complete synchronization beyond $P_{\mathrm{orb}} \approx 15 - 25$ days" (see Fig.2). It is rather intriguing to see that for Am primaries with $R = 3\,R_\odot$ and the synchronization times not exceeding their life time, $1 - 2 \times 10^9$ years, this mechanism is found to be efficient up to $P_{\mathrm{orb}} \approx 200^d$, with the latter value being most sensitive on the value of radii. Considering the primary of a 'standard' radius, $R = 2\,R_\odot$, we find this boundary to be about 50-80 days shorter for the wide enough range of masses of a secondary companion. However, we should be rather cautious when considering this mechanism since its very existence was recently questioned on physical grounds by Rieutord (1992). We can, however, think of other possible mechanisms for required stabilization as, e.g., a one-dimensional suppression of large-scale movements. To figure out the way this operates one can draw a parallel with the turning of the sides of a Rubic cube. Restricting oneself to back-and-forth rotations around a single axis only one will not change substantially an original pattern; to find a sufficiently "mixed" pattern one clearly needs to relax the above constraint and have at least two degrees of freedom (i.e. two axes of rotation) when doing the task. Such an effect might thus convert the effective "wave mixing" into a negligible "mixing by pure compression" (Budaj 1994b), and could appear if, for example, a star did not rotate differentially.

In our previous paper (Budaj 1994a) we already reached the conclusion that some stabilization effects should operate below $P_{\mathrm{orb}} \approx 10^2$ days, however, no explicit account of these was given in the expressions for the turbulent diffusion coefficient, which should thus be regarded as giving an upper estimate in those regions where some stabilization is suspected. The presence of such stabilization is also supported by the subsequent findings of Budaj (1996), where we pointed out that the metallicity of Am stars seems to decrease monotonously with increasing P_{orb} on the left hand side of the period gap, while no trace of the prolongation of this trend is seen on its right hand side.

It is almost the rule that after having found the answers to the old questions a number of completely new questions emerge, namely: what is the origin of the gap at 1^d in the OPD of non CP binaries with its right hand slope fitting (although slightly shifted to the left) the OPD of Am binaries? Or could this gap be just an artefact in the sense that the peak at about 0.6^d could be simply a result of, e.g., evolutionary effects? Is the lack of non CP binaries at 10^3 days or Am binaries at $5^d - 6^d$ a real feature? If so, why? Is the period of 50^d also a node point for Am stars? And, finally, why do then A0-A3 type short period binaries not show peculiarity when HgMn binaries, being earlier than B9 type, do show it again?

In order to make further progress in the field, which includes the proper addressing of the above listed questions, it necessitates not only to inspect more closely the interplay between tidally and rotationally induced mixing, but also to examine the role of orbital parameters in modifying quantities like element abundances (mainly lithium), turbulence, age, the rate of rotation, and the degree of synchronization of a star, resp. the imprint of these parameters on the evolution of a binary as a whole, its complex magnetic fields, and possible dust or gas accretion processes.

5.2. $v \sin i$ *versus* P_{orb}, *synchronization, radii, evolutionary status*

Our intriguing finding that Am's, although being still of the main sequence evolutionary status, are, on the average, of a little bit larger radii than the same spectral type normal stars lying on the main sequence, is in a good agreement with the result of Gomez et al. (1981). They have found that the absolute magnitudes of Am's are about 1^m higher than those of their normal main sequence counterparts, which implies that the radii of the former are $\approx 1.5\times$ larger than those of the latter (provided that the temperatures are equal for both types.) This may also serve as a nice compromise for the "apparent" controversy between Lane & Lester (1984), whose $T_{\rm eff}, \log g$ indicates that the Am stars in Hyades are evolved off the main sequence, and Smalley & Dworetsky (1993), who insist on their common main sequence evolutionary stage. The most recent and most elaborated analysis of the HR diagram by North (1993) shows the frequency of Am's to increase significantly with age within the main sequence. Also Kitamura & Kondo (1978) in their complex study of Am eclipsing binaries (EB) reached the conclusion that Am characteristics appear for a slightly evolved stage. We have done similar analysis on Am EB singled out from our sample and, using the homogeneous catalogue of Brancewicz & Dworak (1980), found out the radii for 19 of them; two stars have radii below $1.5 R_\odot$, 4 – between $R = 1.5\,R_\odot$ and $R = 2.1\,R_\odot$, 9 fall into $R = 2.1\,R_\odot$ and $R = 3\,R_\odot$, 3 are within $R = 3\,R_\odot$ and $R = 4.2\,R_\odot$, and for one star the radius exceeds $R = 4.2\,R_\odot$. These stars, favouring the interval between $R = 2.1\,R_\odot$ and $R = 3\,R_\odot$, thus also confirm our "larger radii" theorem. They, however, deserve further attention not only because they might show some selection effects, but also in connection with our suspection that the radii or ages of Am stars might increase with $P_{\rm orb}$. Some clues concerning the evolutionary status of Am's might be drawn from the depleted area between the curves for $R = 3\,R_\odot$ and $R = 4.2\,R_\odot$ in Fig.2, which may either indicate very fast synchronization up to $P_{\rm orb}/P_{\rm rot} < 1.4$ or the fact that the Am stars are old enough to exhibit such synchronization. To conclude this paragraph we would like to underline that all above mentioned pieces of evidence for both larger radii of Am's and the $180^d - 800^d$ period gap might be well understood if the atmosphere of an Am star is stabilized by some synchronization-retardation mechanism; because this mechanism is very sensitive on the value of a star radius, the larger is the latter the easier is the synchronization and, in addition, the more evolved stars with larger radii have longer time to become synchronized (stabilized).

There is, however, more to Fig. 2 than meets the eye. Looking at the shape of the curve $V_{\rm max}$ we find out that its intersection with the 'main sector' corresponds to rotational velocities of about 35 – 40 km s^{-1}, and with the $R = 2.1\,R_\odot$ synchronization curve to an orbital period of 3^d. The two facts make thus understandable the existing overlap in rotational velocities of Am and normal stars as claimed by Wolf & Wolf (1975) as well as the results of Abt & Hudson (1971) who argue that short period binaries with $v < 40$ km s^{-1} are Am's, while those with $40 < v < 100$ km s^{-1} may be either Am or normal ones; really, their short period normal binaries are forced to be synchronized and if having radii not differing much from $R = 2\,R_\odot$ they would have periods $P_{\rm orb} > 2.5^d$ for $v < 40$ km s^{-1} which fall, however, below $V_{\rm max}$, i.e., into the area reserved for Am stars. That is also the reason why there should be a sharp drop in the occurrence of normal stars beyond $P_{\rm orb} > 2.5^d$ (see Fig. 1), the feature already evidenced by Abt & Bidelman (1969).

We have at hand a two-fold explanation for the rise of $V_{\rm max}$ between $P_{\rm orb} \approx 4^d$ and $P_{\rm orb} \approx 20^d$. One possibility is that this area is dominated by tidal mixing. As the latter depends also on the degree of asynchronization the stars whose rotation shows greater departure from being synchronous are more mixed and should thus be rather looked for among normal stars. The other views such a feature as due to an interplay between tidal and rotationally induced mixings. In what follows we will only aim at inspecting the first possibility. Namely, considering only tidal mixing, our effort will be directed to find an appropriate expression for the turbulent diffusion coefficient as a function of two parameters – the rotational velocity and orbital period – to fit properly the corresponding slope of $V_{\rm max}$.

To begin with we will consider the expression for the 'tidal' turbulent diffusion coefficient of Budaj (1994a) which, in order to take also into account some effects of stabilization or lower efficiency of tidal mixing, we will modify as follows

$$D_{\rm T} = \alpha \left(\frac{\Delta g}{g}\right)^{\beta} v_{\rm f} \lambda \tag{1}$$

where g and Δg is the surface gravity and its relative change due to a tidal deformation, respectively, $\lambda \approx R$ denotes the wavelength of a tidal wave, $v_{\rm f} \approx R/P_{\rm o-r}$ stands for the phase velocity of a tidal wave with

$$P_{\rm o-r} = P_{\rm orb} P_{\rm rot}/(P_{\rm orb} - P_{\rm rot}) \tag{2}$$

and where the effects of stabilization are incorporated into the coefficients α and β. The strategy is simple. Assuming

$$\frac{\Delta g}{g} = \frac{G M_{\rm s} R}{a^3} \Big/ \frac{GM}{R^2} = \frac{M_{\rm s}}{M}\frac{R^3}{a^3} \tag{3}$$

where M and $M_{\rm s}$ are, respectively, the masses of a CP star and its companion, a is the distance between them and G – the gravitational constant, we seek the maximum rotational velocity of the CP star for a specified orbital period under the condition that the turbulent diffusion coefficient will not exceed its value $D_{\rm T,0}$, still compatible with the process of He settling. Thus, the third Kepler law enables us to combine (1) and (3) into:

$$P_{\rm o-r} = \alpha_1 P_{\rm orb}^{-2\beta} \tag{4}$$

with

$$\alpha_1 = \frac{\alpha}{D_{\rm T,0}} \frac{R^{2+3\beta}}{(M + M_{\rm s})^{\beta}} \left(\frac{M_{\rm s}}{M}\right)^{\beta} \left(\frac{4\pi^2}{G}\right)^{\beta} \tag{5}$$

viewed as a constant, and Eq.(4) and Eq. (2) imply for the equatorial rotational velocity:

$$v[{\rm km\,s^{-1}}] = 50.6 \frac{R[R_\odot]}{P_{\rm orb}[{\rm d}]} (\alpha_2 P_{\rm orb}^{2\beta+1}[{\rm d}] + 1) \tag{6}$$

where

$$\alpha_2 = \frac{(8.64 \times 10^4)^{2\beta+1}}{\alpha_1} \tag{7}$$

As the next step we calibrate Eq.(1) through Eq.(6) so that the latter fits two points, e.g.: $v = 47$ km s^{-1}, $P_{\rm orb} = 7^d$ and $v = 80$ km s^{-1}, $P_{\rm orb} = 20^d$. The constants thus found are $\alpha_2 =$

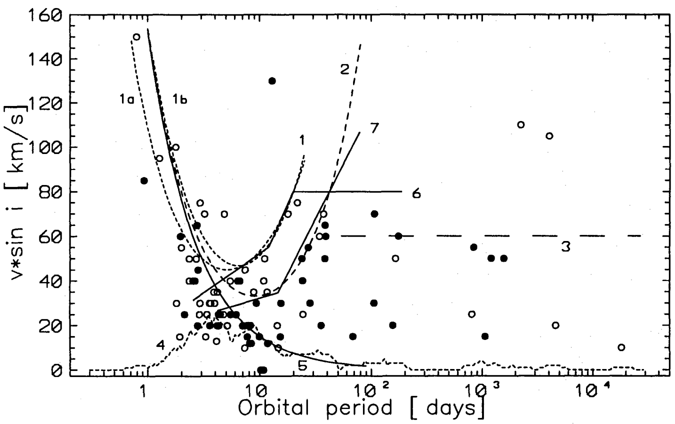

Fig. 4. $v \sin i$ versus $P_{\rm orb}$ with theoretical curves of constant turbulence computed for $D_{\rm T} = D_{\rm T,0}$, $R = 2$ and $3\,R_\odot$ (1a,b) and calibrated to fit the observed $V_{\rm max}$ curve (6), and the curve for $D_{\rm T} = D_{\rm T,0}/2$ and $R = 3\,R_\odot$ (2) which seems to fit highly metallic Am stars with $\delta m_1 < 0.00$ (filled circles). Also shown are: the curve corresponding to Burkhart's jump in metallicity (3), a sketch of the Am OPD (4), the synchronization curve for $R = 3\,R_\odot$ (5), and, finally, the curve of constant metallicity as inferred from observations for $\delta m_1 = 0.00$ (7).

$5.7\,10^{-2}, \beta = 0.40$ for $R = 2\,R_\odot$ and $\alpha_2 = 2.4\,10^{-2}, \beta = 0.50$ for $R = 3\,R_\odot$, and the corresponding behaviour of $V_{\rm max}$ following from Eq. (6) is plotted in Fig. 4. We have thus succeeded in finding a nice theoretical fit for the observed $V_{\rm max}$ up to $P_{\rm orb} \approx 20^d$, having considered tidal mixing alone. The above description of this process is, however, highly phenomenological and is far from being physically understood as e.g. the resulting value of the parameter of effectivity α, of the order 10^{-13}, seems rather small.

From the shape of curves 1a,b and the fact that the observed $V_{\rm max}$ for larger periods is constant (amounting to roughly 75 km s^{-1}) it is, however, evident that, at least for $P_{\rm orb} > 20^d$, tidal mixing must be accompanied by another mechanism, namely e.g. that of meridional circulation (rotationally induced mixing). At this point it is worth pointing out that our 75 km s^{-1} cutoff is much more sympathetic, from the viewpoint of an Am theoretician, than the generally accepted value 100-110 km s^{-1} simply because: a) it leaves space for incorporating other possible effects of turbulence being smaller than the value resulting from the theory considering the effects of meridional circulation only (Charbonneau & Michaud 1991); and b) the latter quantity is an increasing function of atmospheric gravity (Michaud 1982), being 90 km s^{-1} for a rather unusually large $\log g = 4.4$. To sum up, it is obvious that *we must abandon the idea that there exists a fixed rotational velocity cutoff* irrespective of its value. On the opposite, for a great majority of Am binaries *this cutoff is a quantity intimately connected with their orbital periods* and, as a result of filling the Roche lobe, attains its maximum values for those of them, which are synchronized.

To conclude this section let us focus our attention on a possible relation between the gap seen in Fig. 2 for $30 < v \sin i < 50$ km s^{-1} at larger $P_{\rm orb}$, that occurring in Burkhart's jump for $\delta m_1 < -0.04$, and the nature of Burkhart's jump itself. To this end we have checked up twenty of the most metallic stars of her sample on their orbital periods. We have found that all seven stars of the sample, whose orbits are known and published (Batten et al. 1989), have periods greater than 8 days – an interesting feature indeed if we take into account that for most of known Am binaries $P_{\rm orb} < 8^d$. Only two of them, those with the shortest periods, can be regarded as 'potentially' synchronized. We are thus provided with direct evidence that metallicity is rather sensitive on $P_{\rm orb}$ than on $v \sin i$, as it will be further substantiated in Part II of this paper. This also speaks strongly in favour of a crucial role of tidal mixing in Am's and indicates that long period binaries might be less mixed and thus more stabilized than short period ones, even if the latter were synchronized and/or more slowly rotating. Hence, there is a possibility that both gaps are due to the same, yet unknown effect. A number of further arguments can be drawn to show that both $V_{\rm max}$ and metallicity are strongly $P_{\rm orb}$ sensitive quantities. Thus, for example, the curves of constant metallicity and of $V_{\rm max}$ (for $P_{\rm orb} < 20^d$) look very similar to each other, and are well fitted by calibrated theoretical behaviour; in particular, curve 2 in Fig. 4, which corresponds to the subcritical value of turbulence ($D_{\rm T} = D_{\rm T,0}/2$ i.e. the value of α_2 reduced to half of that given for 1b), nicely fits the envelope of the distribution of highly metallic stars with $\delta m_1 < 0.00$ taken from Table 1. Burkhart's jump in δm_1 at 55 km s^{-1} can then be simply a result of an insufficient population of the area both above $v \sin i = 60$ km s^{-1} and below a curve that resembles curve 2 (Fig. 4) but representing even higher metallicities.

6. Conclusions

It has been shown that we should definitely get rid of the idea that, apart from the temperature, the rotational velocity of a star is the only parameter determining its CP character. A number of examples were introduced to demonstrate that the physics of an Am phenomenon acquires a principally new dimension if the binary nature of these stars is taken properly into account, namely:

- $V_{\rm max}$ being determined by $P_{\rm orb}$ for the orbital periods less than 20^d;
- the curves of constant metallicity on $v \sin i$ versus $P_{\rm orb}$ diagram being parallel to the line of $V_{\rm max}$;
- metallicity turning out to be a function of orbital period also as seven most metallic binaries of Burkhart's sample have $P_{\rm orb} > 8^d$ while for most of the known Am binaries $P_{\rm orb} < 8^d$; and
- the gap occurring in OPD of Am's between $180 - 800^d$.

Following these guide-lines we have outlined the model of Am's based on an interplay between the mechanism of tidal mixing and some sort of stabilization in the range coinciding with the stretch of the retardation mechanism proposed by Tassoul & Tassoul (1992). This model dooms the mechanism of rotationally-induced mixing to play the second fiddle for most Am's and, alongside, turns out to be a very fruitful tool, capturing not only those properties of Am's listed above, but also their other well pronounced features like:

– overlap in rotational velocities of the Am and normal A stars, or a lack of normal A binaries for $P_{\rm orb} > 2.5^d$;
– Burkhart's jump in metallicity;
– Am's having slightly larger radii and ages than normal main sequence stars of the same spectral type; and
– occurrence of a short orbital period cutoff in the OPD of Am's at about 1.2^d.

This paper provides also indirect evidence of real disappearance of the superficial He convection zone in Am stars due to He settling (Vauclair et al. 1974); here, however, this is the result of a rather complex interplay between the tidal and rotationally induced mixings on one side, and the mechanism of stabilization on the other.

Finally, as the processes taking place in Am or CP stars are also expected to operate in other stars, all that said above leads us naturally to argue if it is not 'binarity' itself that might be an agent responsible for various peculiarities also in other than Am stars. This is a quite attractive idea all the more that even a single star may be viewed as a limiting case of a binary system characterized by the combination of specific values of its orbital elements, mass ratio and age.

Acknowledgements. It is a pleasure to thank Drs. Seggewiss and Burkhart who have kindly provided me with detailed information about their sample stars, and Drs. Klačka, Komžík, Žižňovský, Zverko, as well as an anonymous referee, for their comments on this paper. I especially thank Dr. Saniga who helped me to improve the presentation and language of the paper. This work was supported by the grant No.1002 of the Slovak Academy of Sciences.

References

Abt H.A., 1961, ApJS 6, 37
Abt H.A., 1965, ApJS 11, 429
Abt H.A., 1975, ApJ 195, 405
Abt H.A., Bidelman W.P., 1969, ApJ 158, 1091
Abt H.A., Hudson K.I., 1971, ApJ 163, 333
Abt H.A., Levy S.G., 1974, ApJ 188, 291
Abt H.A., Levy S.G., 1985, ApJS 59, 229
Abt H.A., Morrell N.I., 1993, in: Peculiar Versus Normal Phenomena in A-type and Related Stars, eds. Dworetsky M.M., Castelli F., Faraggiana R., A.S.P.C.S. Vol.44, San Francisco, p. 384
Abt H.A., Moyd K.I., 1973, ApJ 182, 809
Batten A.H., 1967, ARA&A 5, 25
Batten A.H., Fletcher J.M., MacCarthy D.G., 1989, Eight Catalogue of Orbital Elements of Spectroscopic Binary Systems, Publ. Dominion Astrophys. Obs. Vol.17
Brancewicz H.K., Dworak T.Z., 1980, Acta Astronomica 30, 501
Budaj J., 1994a, in: CP and Magnetic Stars, eds. Zverko J. and Žižňovský J., Astronomical Institute, Tatranská Lomnica, Slovakia, p. 114
Budaj J., 1994b, in: CP and Magnetic Stars, eds. Zverko J. and Žižňovský J., Astronomical Institute, Tatranská Lomnica, Slovakia, p. 72
Budaj J., 1995, in: Stellar Surface Structure (Poster Proceedings), ed. Strassmeier K.G., Astronomical Institute, Wien, p. 147
Budaj J., 1996, Part II
Burkhart C., 1979, A&A 74, 38
Charbonneau P., 1993, in: Peculiar Versus Normal Phenomena in A-type and Related Stars, eds. Dworetsky M.M., Castelli F., Faraggiana R., A.S.P.C.S. Vol.44, San Francisco, p. 474
Charbonneau P., Michaud G., 1991, ApJ 370, 693
Claret A., Giménez A., Cunha N.C.S., 1995, A&A 299, 724
Conti P.S., Barker P.K., 1973, ApJ 186, 185
Ferluga S., Floreano L., Mangiacapra D., 1993, in: Peculiar Versus Normal Phenomena in A-type and Related Stars, eds. Dworetsky M.M., Castelli F., Faraggiana R., A.S.P.C.S. Vol.44, San Francisco, p. 364
Ginestet N., Jaschek M., Carquillat J.M., Pedoussaut A., 1982, A&A 107, 215
Gomez A., Grenier S., Jaschek M., Jaschek C., Heck A., 1981, A&A 93, 155
Hauck B., 1978, A&A 69, 285
Hauck B., Curchod A., 1980, A&A 92, 289
Iliev I.I., Budaj J., 1996, in: Proceedings from 5th Vienna International Workshop on Model Atmospheres and Spectrum Synthesis, in press
Kitamura M., Kondo M., 1978, Astrophys. Space Sci. 56, 341
Kodaira K., 1975, in: Physics of Ap Stars, eds. Weiss W.W., Jenkner H., Wood H.J., Wien, p. 675
Lane M.C., Lester J.B., 1984, ApJ 281, 723
de Loore C.W.H., Doom C., 1992, in: Structure and Evolution of Single and Binary Stars, Kluwer Academic Publishers, Netherlands, p. 319
Michaud G., 1970, ApJ 160, 641
Michaud G., 1982, ApJ 258, 349
Michaud G., Charland Y., Vauclair S., Vauclair G., 1976, ApJ 210, 447
North P., 1993, in: Peculiar Versus Normal Phenomena in A-type and Related Stars, eds. Dworetsky M.M., Castelli F., Faraggiana R., A.S.P.C.S. Vol.44,San Francisco, p. 577
Philip A.G.D., Miller Th.M., Relyea.M., 1976, Dudley Obs. Rp. No. 12
Renson P., 1991, Catalogue Général des Etoiles Ap et Am, Institut d' Astrophys.-Université de Liege
Rieutord M., 1992, A&A 259,581
Seggewiss W., 1981, in: Les etoiles de composition chimique anormale du debut de la sequence principale, Institut d'Astrophysique, Universite de Liege, p. 183
Seggewiss W., 1993, in: Peculiar Versus Normal Phenomena in A-type and Related Stars, eds. Dworetsky M.M., Castelli F., Faraggiana R., A.S.P.C.S. Vol.44,San Francisco, p. 137
Smalley B., Dworetsky M.M., 1993, in: Peculiar Versus Normal Phenomena in A-type and Related Stars, eds. Dworetsky M.M., Castelli F., Faraggiana R., A.S.P.C.S. Vol.44,San Francisco, p. 137
Smith M.A., 1971, A&A 11, 325
Smith M.A., 1973, ApJS 25, 277
Tassoul J.-L., Tassoul M., 1982, ApJS 49, 317
Tassoul J.-L., Tassoul M., 1992, ApJ 395, 259
Vauclair G., Vauclair S., Michaud G., 1978, ApJ 223, 920
Vauclair G., Vauclair S., Pamjatnikh A., 1974, Astr. Ap 31, 63
Wolf S.C., 1983, The A Stars: Problems and Perpectives, NASA SP-463
Wolf S.C., Wolf R.J., 1975, in: Physics of Ap Stars, eds. Weiss W.W., Jenkner H., Wood H.J., Wien, p. 503
Zahn J.-P., 1992, A&A 265, 115

Note added in proof: Recently, a few papers supporting above ideas appeared. The Tassouls mechanism has recently been examined by Claret et al. (1995) who have found strong observational support for it. Further studies of Budaj (1995) revealed similar $P_{\rm orb}$ dependent features also in Ap binaries and Iliev & Budaj (1996) confirmed by means of spectroscopy the pronounced Am characteristics of two long period Am binaries.