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Synchronization in binary stars

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Abstract. Radiative dissipation of the dynamical tide is found to be inadequate in explaining the observed synchronization between orbital and rotational motions of the main sequence components of early-type binary stars. The rotational behaviour of binary components suggests the possible existence of two sequences of binary stars of which one is synchronous even at large separation between the binary components. The primaries of Algol systems are not found to behave any differently from detached binaries thereby negating any evidence for large scale angular momentum transfer in the recent past. The rotational behaviour of binary components is analogous to the bimodal rotational velocity distribution of main sequence singal stars. We argue that the members of the synchronous sequence possess high subsurface magnetic field strengths which extend their main sequence lifetime considerably.

Key words : binary stars—stellar rotation

1. Introduction

In close binary stars there is a tendency towards synchronization between orbital and rotational motions (Plavec 1970). The critical period at which synchronization sets in is different for different spectral types (Levato 1976). Tidal effects in close binary systems have been suggested as the mechanism mainly responsible for the observed synchronization of orbital and rotational periods (Zahn 1966a, b, c; Kopal 1968). However, Plavec (1970) questioned the applicability of such theories to binary systems which are predominantly of early spectral types, on the ground that the radiative dissipation of the equilibrium tide is not expected to synchronize these stars during their main sequence age. He suggested that the pre-main sequence stage was the most important phase where the components of the binary systems rotate synchronously and arrive on the main sequence probably with velocities slightly higher than synchronous velocities. However, Zahn (1975, 1979) has shown that the radiative dissipation of the dynamical tide is indeed theoretically capable of synchronizing the system within their main sequence lifetimes provided the ratio of the separation between the components to the radius of the star is not larger than about seven.

We have reconsidered the problem to see if nonsynchronism of binary components can be understood in terms of the theories already developed. This is of special importance since such asynchronism in some of the semi-detached systems is attributed to mass and angular momentum transfer from the subgiant secondary to the main sequence primary star. Preliminary results of this investigation have already been reported (Rajamohan & Venkatakrishnan 1980).

2. The data

Tables 1 and 2 list all binary systems relevant to the present discussion for which the data are available. Rotational velocities are taken from the compilation of Levato (1974). The references to the absolute dimensions of the eclipsing binary systems given here can be found in Herczeg (1979). For the double-lined binary systems the mass and the radii corresponding to their spectral types have been taken from Allen (1973). This assumed mass was utilised to derive the inclination of the line of sight to the orbital axes. We have also asumed that the rotation and orbital axes are parallel. For Am spectroscopic binaries the $V \sin i$ values were taken from Abt (1975) and Abt & Moyd (1973). The masses of these systems correspond to their hydrogen spectral types and/or colours.

Figure 1 is a plot of the observed rotational velocity $V \sin i$ against $V_{\text{syn}} \sin i$, where V_{syn} is the rotational velocity required for synchronisation between orbital and rotational periods. Figure 1a refers to eclipsing systems and indicates that most of these systems rotate slightly faster than perfect synchronism would require. That

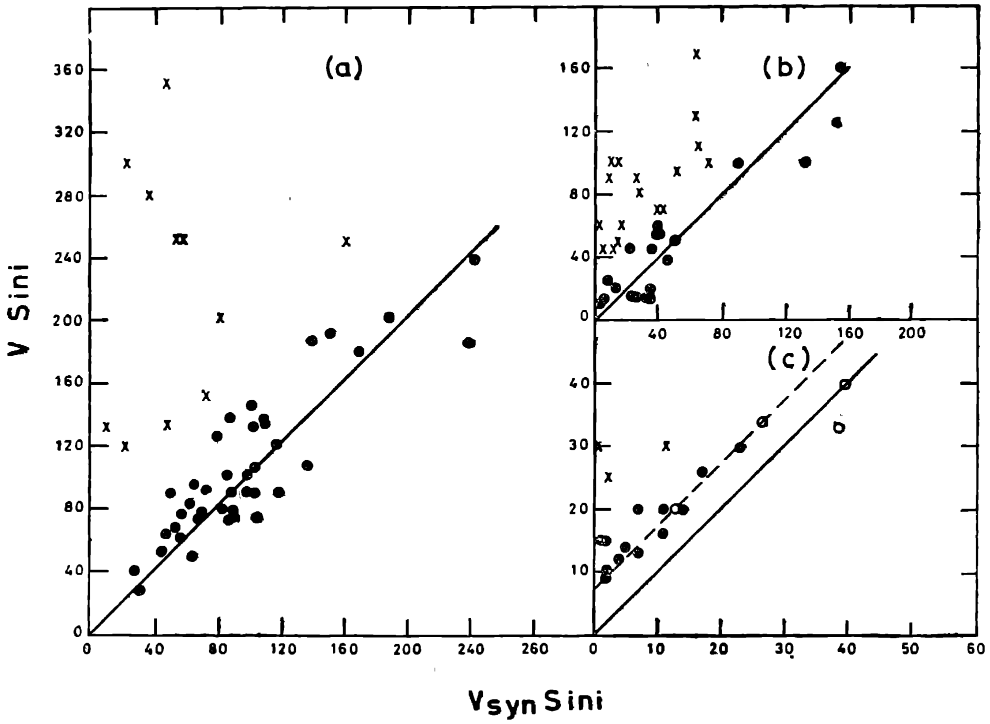

Figure 1. A plot of the observed rotational velocity $V \sin i$ against $V_{\text{syn}} \sin i$ required for synchronism for (a) eclipsing binaries, (b) double lined spectroscopic binaries and (c) Am binaries. The dashed line in (c) is shifted by 8 km s^{-1} with respect to the 45° line.

the majority really rotate synchronously can be assumed for the following reason. Such discrepancy between the observed synchronous velocities is probably caused by small zero point error in the established rotational velocity scale. Slettebak *et al.* (1975) in their redetermination of rotational velocities (which depends on the comparison of observed line profile with the line profiles determined from model atmospheric calculations) find that in the old scale the velocities are over-estimated by about 5 per cent at spectral type A to 15 per cent at early B. In addition to such scaling errors, depending on the methods employed, the probable errors of the derived rotational velocity range from 10–20 per cent. Further, the blending of lines in double-lined binary systems would result in over estimating the rotational velocity of a binary component and sometimes grossly so whenever the measurement refers only to one of the components of such systems. Finally, the derived absolute dimensions of interacting binary components are not very reliable.

Figures 1b and 1c refer to normal double-lined spectroscopic binaries and Am binaries respectively. It can be noticed that for the majority of the Am stars we need to correct the observed rotational velocities by about 8 km s^{-1} to place them on the synchronous rotation line. Part of this zero point shift is probably inherent in the calibration of low rotational velocities and may have also been partly caused by the adopted spectral type-mass-radius relationship. No observational evidence exists for any zero point errors at low rotational velocities (H. Abt—personnel communication). In view of all these factors we shall consider only such systems as truly non-synchronous whose observed $V \sin i$ exceed $V_{\text{syn}} \sin i$ by more than a factor of 1.5. Such systems are marked by an asterik in Tables 1 and 2 and indicated by a cross in Figure 1.

Table 1. Some parameters of eclipsing and spectroscopic binary systems utilised in this study

HD number	Name	Spectral type	log r/a	Mass ($m_\odot$)	Radius ($R_\odot$)	V km s^{-1}	log P_0/P_s	log t_{ms}/t_{syn}
A. Eclipsing binaries—detached systems								
4161	YZ Cas	A2m	0.85	2.1	2.40	34	0.10	−0.26
				1.3	1.29	—	—	—
6882	ζ Phe	B8V	0.58	3.8	2.84	101	0.07	1.91
		A0V	0.77	2.5	1.85	76	0.13	1.47
25833	AG Per	B4V	0.68	4.6	2.90	91	0.10	1.56
		B5V	0.71	4.2	2.70	73	0.04	1.43
36695	VV Ori	B1V	0.44	7.6	4.44	192	0.10	2.91
		B5–9V		3.4	2.13	—	—	—
44691	RR Lyn	A3m	1.08	2.1	2.50	20	0.20	−2.04
				1.6	2.00	—	—	—
46052	WW Aur	A3m	0.79	2.0	1.97	33	−0.08	0.69
		A3m	0.82	1.8	1.83	33	−0.46	0.43
77464	CV Vel	B2V	0.94	6.1	4.05	28	−0.03	−0.56
		B2V	0.94	6.0	4.05	28	−0.03	−0.52
116658	α Vir	B1V	0.51	10.9	8.1	106	0.02	2.48
		B3V	0.84	6.8	3.7	64	0.14	0.83
139006*	α CrB	A0V	1.17	2.5	2.9	132	1.19	−3.69
				0.9	0.87			
156247	U Oph	B5V	0.57	5.1	3.4	90	−0.06	2.56
		B5V	0.62	4.6	3.0	75	−0.08	2.21

HD number	Name	Spectral type	log r/a	Mass ($m_\odot$)	Radius ($R_\odot$)	V km s^{-1}	log P_0/P_s	log t_{ms}/t_{syn}
167647*	RS Sgr	B3V	0.58	5.9	3.93	202	0.39	1.48
		A		2.2	4.9	—	0.10	2.48
185507	σ Aql	B3V	0.55	6.8	4.22	137	0.20	1.91
		B3V	0.70	5.4	3.05	126	0.05	1.78
170757	RX Her	B9V	0.64	2.7	2.43	78	0.11	1.30
		A0V	0.76	2.3	1.84	68	0.19	−0.91
190786	V477 Cyg	A3V	0.95	1.7	1.2	40	0.19	−0.91
		F2		1.3	0.9	—	—	—
198846	Y Cyg	B0IV	0.67	16.3	6.0	146	0.16	2.48
		B0IV	0.67	17.0	6.0	144	0.15	2.48
209147	CM Lac	A3	0.73	1.9	1.6	56	0·04	1.04
		A8		1.5	1.4	—	—	—
216014	AH Cep	B0V	0.45	14.4	6.6	201	0.03	3.87
		B1V	0.58	12.4	4.9	187	0.13	3.00
218066	CW Cep	B0.5IV–V	0.63	11.8	5.5	132	0.11	2.13
		B0.5IV–V	0.70	11.1	4.7	138	0.20	1.69
221253*	AR Cas	B3V	0.72	7.0	5.5	134	0.46	0.00
				2.1	1.9	—	—	—
B. Semi-detached and contact systems								
1486	TV Cas	B9V	0.53	3.1	3.08	72	−0.08	1.91
				1.4	3.36			
5679*	U Cep	B7V	0.70	4.2	2.9	250	0.62	1.00
			0.48	2.8	4.8			3.30
17034*	RY Per	B3V	0.87	5.3	3.71	280	1.01	−1.74
				0.8	7.42			
17138	RZ Cas	A2V	0.64	1.8	1.45	83	0.13	0.87
				0.6	1.83			
19356	β Per	B8V	0.66	3.7	3.1	61	0.05	0.22
				0.8	3.2			
21985	AS Eri	A3V	0.82	1.9	1.57	⩽46	⩽0.19	−1.61
				0.2	2.19			
25204	λ Tau	B3V	0.51	6.8	6.4	80	−0.01	1.52
				1.8	5.4			
33357	SX Aur	B3V	0.31	10.2	5.8	238	−0.01	4.08
				5.5	4.6			
37021*	BM Ori	B3V	0.99	5.9	3.0	300	1.11	−1.78
				1.8	7.0			
57167	R CMa	F1V	0.52	1.6	1.96	101	0.06	0.61
				0.2	1.60			
65818	V Pup	B1V	0.35	17.0	6.9	185	−0.11	4.52
		B2	0.50	9.2	4.9	180	0.02	3.87
82610	S Ant	A9V	0.37	0.8	1.5	120	0.01	2.78
		F		0.5	1.1			
132742	δ Lib	B9.5V	0.53	4.9	4.1	79	−0.05	1.69
		G		1.7	4.2			
139319	TW Dra	A0V	0.54	2.2	3.5	50	−0.10	0.22
		K0III		0.6	5.1			
150265	W UMi	A3V	0.41	2.4	3.5	76	0.14	2.95
		G9IV		1.2	2.8			
151890*	μ Sco	B1.5V	0.52	13.6	4.6	251	0.19	3.13
				9.0	6.0			

HD number	Name	Spectral type	log r/a	Mass ($m_\odot$)	Radius ($R_\odot$)	V km s^{-1}	log P_0/P_s	log t_{ms}/t_{syn}
153345	A1 Dra	A0V	0.57	2.2	2.0	101	0.08	1.91
		G2		1.0	2.1			
156633	U Her	B2.5V	0.46	10.2	5.5	107	−0.10	3.82
		B5	0.52	3.2	4.8	90	−0.14	2.95
169753*	RZ Scu	B0V	0.62	15.0	16.0	252	0.67	0.52
		A0II–III		3.0	16.0			
173787*	V356 Sgr	B3V	0.76	12.2	8.5	350	0.86	−0.04
		A2II	0.50	4.7	15.4	90	0.01	3.17
180939*	RS Vul	B5V	0.59	4.4	4.2	90	0.28	1.00
		A2		1.4	5.5			
181182	U Sge	B8.5V	0.65	5.8	4.2	95	0.18	0.78
		G3III–IV		1.9	5.6			
181987*	Z Vul	B4V	0.52	5.4	4.5	151	0.21	2.00
		A2III		2.3	4.6			
187949	V505 Sgr	A2V	0.50	2.3	2.3	101	0.01	2.61
		F8IV		1.2	2.3			
199454	S Aqu	B8V	0.66	3.0	2.9	52	0.08	−0.30
				0.4	2.7			
206155	EE Peg	A4V	0.74	1.9	2.1	40	0.01	0.56
		F5V		1.2	1.2			
207956*	AW Peg	A4V	0.80	2.0	4.5	120	0.75	−1.65
		F5IV		0.3	4.3			
222217	XX Cep	A7V	0.62	1.7	2.0	47	0.03	0.13
				0.3	1.8			

Table 2. Some parameters of spectroscopic binary systems

HD number	Spectral type	log r/a	Mass ($M_\odot$)	Radius ($R_\odot$)	V km s^{-1}	log P_0/P_s	log t_{ms}/t_{syn}
4058	A5V	0.78	2.09	1.74	62	0.140	1.00
							1.00
4727	B5V	0.81	6.46	3.80	130	0.463	0.26
	F8V						
12534	B9.5V	0.78	3.56	2.64	88	0.246	0.96
	B9.5V	0.75	3.56	2.64	82	0.214	0.78
22203*	B8V	0.99	4.52	3.03	65	0.420	−1.00
	B8V	0.98	4.52	3.03	52	0.33	−1.00
23625*	B2V	0.49	13.25	5.97	419	0.430	3.26
23642	A0V	0.73	3.24	2.51	43	0.078	0.83
	A5V						
27376	B8.5V	0.92	4.52	3.03	<90	0.470	−0.48
29376*	B3V	0.54	10.99	5.25	279	0.366	2.35
	B5V						
32964	B9.5V	0.98	3.56	2.64	<51	0.328	−0.87
	B9.5V		3.56	2.64	<51	0.328	−0.87
34790	A2V	0.74	2.78	2.20	17	−0.468	1.04
35411	B1V	0.89	15.52	6.69	67	0.199	0.35
	B2V	0.93	13.25	5.97	52	0.094	−0.09
39357*	B9.5V	0.98	3.56	2.64	89	0.599	−1.30
39698	B2V	0.87	13.25	5.97	23	−0.218	−0.56
75759*	B0V	1.27	17.78	7.41	45	0.600	−2.74
83808/9	A2V	1.29	2.78	2.20	$\leqslant 64$	0.923	−3.69
	F6III				$\leqslant 64$		

HD number	Spectral type	log r/a	Mass ($M_\odot$)	Radius ($R_\odot$)	V km s^{-1}	log P_0/P_s	log t_{ms}/t_{syn}
98353*	A2V	0.77	2.78	2.20	171	0.584	0.56
104337	B1.5V	0.58	14.38	6.33	120	0.047	2.26
107259	A2V	1.74	2.78	2.20	12	0.90	−7.73
110854	A0V	1.08	3.24	2.51	27	0.22	−1.91
112014	B9V	0.82	3·24	2.51	14	—0.43	0.17
	A2V	0.88	2.78	2.20	14	—0.37	0.39
116656	A2V	1.40	2.78	2.20	16	0.46	4.47
	A2V	1.40	2.78	2.20	16	0.46	4.47
139892*	B7V	1.18	5.17	3.29	100	0.79	—2.43
	B7V				100	0.79	—2.43
140008*	B6V	1.15	5.81	3.54	146	1.00	—2.26
143018	B1V	0.40	15.52	6.69	165	—0.12	4.12
	B1V						
144217*	B0.5V	0.80	16.65	7.05	95	0.26	0.74
144208/9	A2V	1.86	3.24	2.51	120		—7.90
	F7III						
153808*	A0V	0.86	3.24	2.51	115	0.56	—0.43
	A2V						
159176	O7V	0.44	31.0	13.64	168	0.02	5.86
	O7V	0.43	31.0	13.64	213	0.02	5.47
161783*	B3V	0.67	10.99	5.25	118	0.15	1.69
	B4V	0.72	8.72	4.52	150	0.32	1.52
162724	B9V	0.75	3.88	2.77	<54	0.03	0.69
	B9V		3.88	2.77	50	0.03	0.69
171978	A2V	1.30	2.78	2.20	54	1.08	—3.65
	A2V						
175286	A0V	0.90	3.24	2.51	22	—0.14	—0.30
	A0V						
178322	B6V	1.16	5.81	3.54	<59	0.61	—2.30
	B5V					0.61	—2.30
191747	A3V	1.19	2.55	2.05	104	0.97	—2.74
202447/8	A5V	1.94	2.09	1.74	≤137		—8.60
	G3III				≤137		
206644	A0V	0.65	3.24	2.51	75	0.01	1.87
207650	A0V	0.97	3.24	2.51	85	0.55	—0.96
8374*	A1m	1.67	1.78	1.43	24	1.07	—6.78
12869	A1m	1.35	2.32	1.89	25	0.61	—4.04
23277*	A2m	1.33	2.55	2.05	79	1.07	—3.95
26591	A2m	0.96	2.09	1.74	32	0.12	—0.61
36403	A2m	0.96	2.01	1.66	32	0.13	—0.74
41357	A7m	1.59	1.85	1.50	17	0.79	—6.21
42083*	A5m	1.91	2.32	1.89	34	1.58	—8.82
73619*	Am	1.34	1.85	1.50	135	1.40	—3.99
89822	B9	1.15	3.88	2.77	22	0.26	− 0.35
93075	Am?	0.79	1.85	1.50	65	0.19	0.61
112486	A5m	1.08	2.01	1.66	30	0.26	—1.48
125337	A1m	0.75	2.32	1.89	71	0.15	1.04
168913	A2.5m	1.10	1.85	1.50	20	0.17	—2.26
171653	A8m	1.31	2.55	2.05	22	0.48	—3.73
173524	A0P	1.14	3.24	2.51	40	0.49	—2.48
174933	B8	1.37	4.52	3.03	97	0.60	—4.95
206546	A3m	1.16	1.85	1.50	31	0.42	—2.48

Main sequence stars earlier than F2 alone are included in Table 1 so as to restrict our discussion to systems which have radiative envelopes. Systems with outer convection zones are known to have extremely low synchronization time scales and hence are not included in the present discussion.

3. Results and discussion

A parameter which quantifies the tidal braking is the ratio of t_{ms}, the main sequence lifetime to t_{syn} the synchronization timescale. The synchronization timescale was calculated according to Zahn (1979) whereas t_{ms} was taken from Iben (1964) appropriate to the masses of the stars. A plot of the ratio of the orbital period P_0 to the spin period P_S of the star versus the ratio t_{ms}/t_{syn} is shown in Figure 2. Eclipsing binaries are denoted by filled circles, double-lined binaries by crosses and the Am stars by open circles. The extent of the region occupied by binaries which rotate synchronously is indicated by horizontal lines, one referring to Am binaries and the other to detached, semi-detached and contact systems. The two lines are shown displaced for the sake of clarity. Figure 3 which refers only to the eclipsing systems in Table 1 is a plot of the ratio of orbital to spin period against r/a the ratio of radius to the semi-major axis. It can be immediately noticed from Figures 2 and 3 that there are possibly two sequences of stars. A sequence which in Figure 3 always remains near synchronism whatever be the fractional radius r/a, and a second sequence which tends towards synchronism as a/r, takes smaller and smaller values.

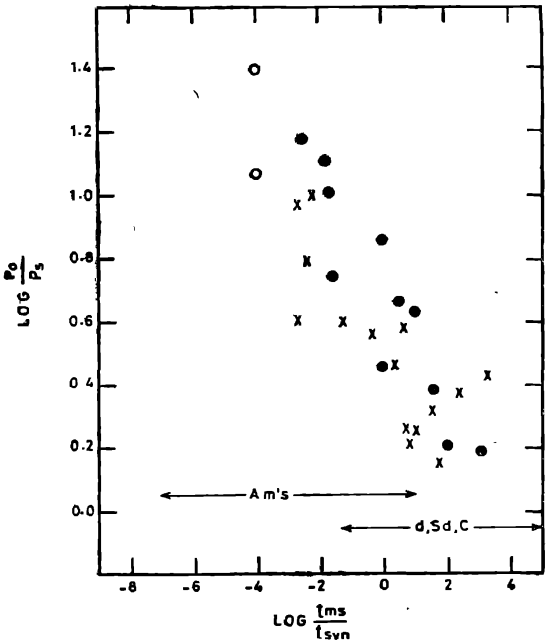

Figure 2. Ratio of the orbital to spin period plotted against the ratio of main sequence lifetime to synchronization timescales. Filled circles refer to eclipsing binaries, open circles to Am stars. Spectroscopic binaries are denoted by crosses The horizontal lines denote the extent occupied by synchronous systems amongst Am binaries and the normal binaries.

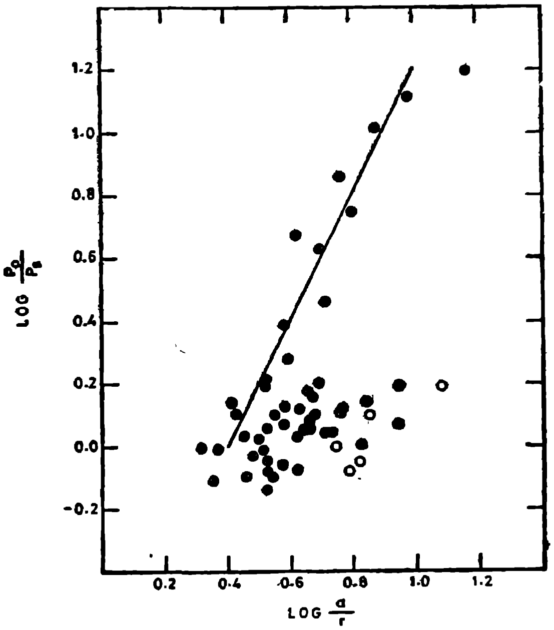

Figure 3. Ratio of the orbital to spin period plotted against the ratio of semi-major axis to the radius of the binary star. Only eclipsing binaries are shown. Am stars are indicated by open circles.

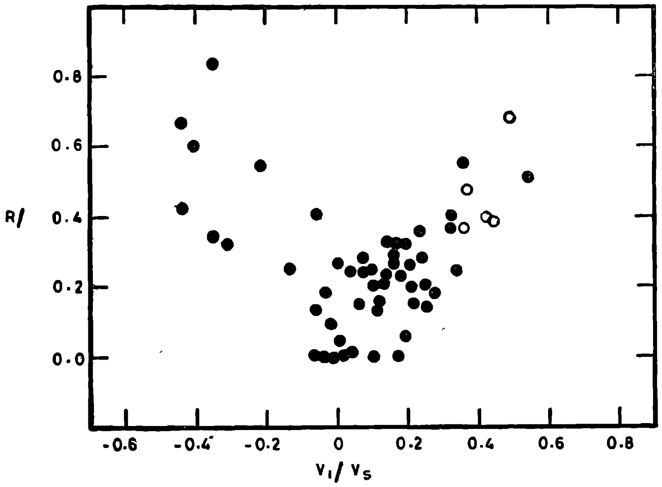

Figure 4. Ratio of the initial rotational velocity V_i to the observed rotational velocity V_s plotted against the ratio of the Roche radius R to the observed radius r. Only eclipsing binaries have been plotted. Open circles refer to Am stars.

Figure 4 is a plot of the ratio of the initial rotational velocity V_i and the observed rotational velocity V_s against the ratio of the Roche radius R to the observed radius r. We have assumed here that all binary components rotate synchronously while filling their Roche lobe. This velocity is denoted as the initial velocity V_i. This assumption is justified since the data in Table 1 indicate that all stars which have radii close to their Roche radii do rotate synchronously.

The behaviour of the rotational velocities of the members of the non-synchronous sequence in Figures 3 and 4 indicates that these stars contracted onto the main sequence conserving angular momentum from a circumstance of synchronism while filling the Roche lobe. However, the good degree of synchronism between the rotational and orbital periods of the members of the synchronous sequence indicates that the tidal forces play an important role in their rotational behaviour. Any other mechanism should have produced a much larger scatter in Figures 3 and 4.

One possibility is that the members of synchronous sequence have longer main sequence lifetimes compared to the members of the non-synchronous sequence. Probably they have strong subsurface magnetic fields which increase the main sequence lifetime. The presence of such fields would also brake rotation even on the pre-main sequence and leave these systems close to their synchronous value on the main sequence. Such a possibility is not unreasonable since the final stages of stellar evolution leave behind remnants such as neutron stars and white dwarfs with a wide range in magnetic field strengths. What tempts us to consider such a picture more seriously is the fact that the lower mass end of the synchronous sequence in Figures 2, 3 and 4 is made up of mostly Am stars. It has been shown by Abt (1979) that Ap stars which possess considerable magnetic field on the main sequence are slowed down quite rapidly during their main sequence lifetime. The Am stars are also slowed down, though to a lesser degree. The absence of obvious peculiarity amongst the higher mass members of the synchronous sequence could well be due to the temperature not being favourable to detection of such peculiarities. On the other hand the peculiarities could be physically wiped out amongst stars in closely spaced systems due to tidal actions. To simultaneously explain the spectral peculiarity and the synchronous rotational velocities we would be forced to invoke the presence of a magnetic field even in their subsurface layers.

In view of the above arguments, we feel inclined to call the synchronous sequence a *peculiar* sequence analogous to the group of slowly rotating peculiar stars amongst the single stars. The non-synchronous sequence seems to be the analogue of the normal single stars. In the region where the two sequences merge, it is impossible to uniquely assign any given system to either of the sequences.

The position of the non-synchronous systems amongst Algols is no different from that of similar objects of the detached systems. There is a tendency for the non-synchronous primaries of Algols to lie slightly above the detached systems. However, we do not consider this to be significant so as to attribute it to angular momentum gain by mass transfer. The non-synchronous sequence of detached systems is more or less defined by data from double-lined binaries for which masses and radii have been assumed. (There are only three eclipsing binaries which are detached and non-synchronous in Table 1.) Therefore, this tendency suggests that in the radii-spectral type relation taken from Allen (1973) the radii are probably systematically underestimated. A second source of scatter is the systematic errors in the calibration of rotational velocities which is larger for earlier spectral types (Slettebak *et al.* 1975). The majority of the non-synchronous Algols are earlier than B8. Finally, the spread in the ages of the stars also introduces a certain amount of scatter. In fact one of the semi-detached non-synchronous system BM Orionis is known to be extremely young and its secondary is interpreted to be a pre-main sequence object (Popper & Plavec 1976).

Van den Heuvel (1970) has interpreted semi-detached systems later than B8 which are all synchronous as products of case B mass exchange where most of the mass is exchanged in a short time and tidal forces can effectively synchronise. The primaries earlier than B8 being non-synchronous are interpreted as products of case A mass exchange where after rapid mass transfer a long-lasting stage of slow mass transfer exists. Hence, such systems possess surface layers of newly accreted high angular momentum material. Plavec (1970) also has suggested that the non-synchronous rotation of Algol primaries is caused by large scale transfer of angular momentum and mass. We find that this explanation is not necessary in so far as the detached and the semi-detached systems exhibit similar rotational behaviour.

The absence of rotational anomalies in the primaries of the Algol systems could be interpreted either in terms of the entire mass and angular momentum being lost to the system or in terms of additional angular momentum which has been acquired by the primary being transferred to the orbit on short timescales.

However, an anomaly in the proposed explanation of the origin of those systems exists. Lucy & Ricco (1979) have shown that there is a definite tendency for the distribution of mass ratios of detached binary stars to peak at unity. If one considers the fact that semi-detached systems are close binaries of low mass-ratio and that fission mechanism can produce only systems of low mass-ratio (Lucy 1977), one is tempted to attribute different mechanisms for the formation of detached and semi-detached systems. Lucy (1980) has done numerical experiments to demonstrate the formation of equal mass systems by a mechanism different from fission. Then, could it be that the secondaries in semi-detached systems are lagging behind in evolution and are always kept in synchronous rotation by their more massive main sequence counterparts ? The primaries of Algols are not different from the primaries of detached systems in mass, radii, luminosity, chemical abundances and rotational velocities. Unless an extended lifetime for them, especially for those that occupy the synchronous sequence, is ruled out, we must be sceptical about accepting the role of mass transfer in such systems.

4. Conclusions

We find that the tidal effects during the main sequence lifetime of early type stars cannot explain the observed rotational behaviour of close binary stars. We have shown the existence of two sequence of stars, a *synchronous* or a *peculiar* sequence and a *non-synchronous* or a *normal* sequence. An initial distribution of magnetic fields of the stars might explain the existence of the two sequences. The normal binaries have rotational velocities close to the synchronous value only when their radii are within a factor of two of their Roche radii. The rotational behaviour of semi-detached systems is found to be no different from that of stars in detached systems. This could be interpreted either as an absence of angular momentum transfer during mass transfer or as an absence of mass transfer itself. The key to the understanding of the evolutionary stage of Algol binaries, and of the rotational behaviour of stars in general may well lie in the role of the magnetic fields in the theories of stellar evolution.

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