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Alignment of rotational axes in asynchronous late type binaries[⋆]

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Abstract. 41 RS CVn and BY Dra type binaries with reliable orbital and physical parameters have been found to rotate asynchronously with the orbital revolution. For this sample inclinations of the rotational axes, $i_{\rm r}$, of the primaries and the orbital inclinations, $i_{\rm o}$, are independently determined to test the alignment between the equatorial and the orbital planes. The observed difference $\Delta i = |i_{\rm o} - i_{\rm r}|$ measures a deviation from coplanarity of these planes. It turns out that most asynchronous systems prove to be misaligned, especially when the influence of the position angle is taken into account. Thus, the generally accepted assumption that rotational axes are perpendicular to orbital planes is not valid for asynchronous RS CVn and BY Dra type binaries. The influence of the position angle of the observer on the derived values of Δi can be studied only by statistical methods. The distribution of the observed Δi is compared wih the expected values of $\Delta i^{\rm e}$ for two cases: a) the rotational axes are randomly inclined to the orbital planes, and b) the rotational axes are perpendicular to the orbital planes. The best fit to our observed sample of asynchronous binaries is obtained for the case a), while for the synchronous RS CVn and BY Dra type binaries the rotational axes are perpendicular to their orbital planes.

Key words: stars: binaries: close – stars: rotation

1. Introduction

Tidal interactions in binaries with the ratio $(a/R) < 10$ (where a is the semi-major axis and R is the radius of the primary) should be effective on time scales shorter than the evolutionary lifetime of the systems (Zahn 1977, 1984). It means that G-K III-IV binaries with orbital periods less than 150 days and G-K V binaries with periods less than about 10 days should rotate synchronously with the orbital revolution, and their orbits should be circular. As shown by Hut (1981) the time scale for alignment is comparable with the periastron synchronization time scale and is not very different from the time scale for circularization when α (defined as the ratio of orbital to rotational angular momentum at the equilibrium configuration) is around 10. It implies that these systems should have rotational axes perpendicular to the orbital plane. Indeed most of the RS CVn and BY Dra type binaries are synchronized ($P_{\rm orb} = P_{\rm rot}$) and the eccentricities of their orbits are usually low. Generally, it is *a priori* assumed that their orbital planes are coplanar with the equatorial rotational planes.

RS CVn and BY Dra type stars are recognized as active binaries. In addition to strong Ca II and Mg II emissions, these systems also typically exhibit strong H_α, X-ray and microvawe emission. Most active binaries show periodic photometric variability, which is thought to be due to rotational modulation of light from the hemisphere covered by large dark spots. Over the past twenty years rotational periods were determined for a few hundreds of active stars. Knowing P_{rot}, the radius, R_1 for the active component and its projected rotational velocity, $v_{\rm r} \sin i_{\rm r}$, the inclination of its rotational axis, $i_{\rm r}$, can be independently determined and compared with the inclination of orbital plane $i_{\rm o}$. If the rotational axis is perpendicular to the orbital plane (the equatorial rotational plane is coplanar with the orbital plane), then both angles should be equal within the limit of error.

However in the above mentioned range of (a/R) there are binaries which do not rotate synchronously. Stawikowski and Głębocki (1994a, hereafter called Paper I) determined the inclinations of the rotational axes for 12 asynchronous long period RS CVn systems and found that for the majority of them rotational axis is misligned ($i_{\rm r} \neq i_{\rm o}$). In a comparative study of 44 synchronous long period RS CVn type binaries, Stawikowski and Głębocki (1994b, hereafter called Paper II) found no system for which the absolute value of the difference between the inclination angles $\Delta i = |i_{\rm o} - i_{\rm r}|$ is greater than the error of its determination. Thus the assumption that the rotational axes are perpendicular to the orbital plane is fully justified for synchronous systems. Our preliminary statement that synchronous systems are coplanar while asynchronous systems are misaligned was further confirmed in the analysis of Głębocki and Stawikowski (1995) for short period RS CVn and BY Dra type binaries (hereafter called Paper III).

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[⋆] The appendix is available only electronically with the on-line publication at http://link.springer.de/link/service/journals/00230

The very existence of asynchronous systems among close binaries is quite puzzling. Pseudorotation effect (Hut 1981, Hall 1986) and magnetic breaking (Habets et al. 1989), although helpful in some individual cases, cannot explain the phenomenon of asynchronous rotators for the entire sample. Our statement that asynchronous systems are non-coplanar is intriguing not only because it contradicts the commonly accepted assumption that rotational axes are perpendicular to orbital planes, but it might be essential for tidal evolution of asynchronous systems. However, that statement should be confirmed on a larger sample of asynchronous binaries. In this paper we analyse a sample of 41 asynchronous close binaries of G and K spectral types giants, subgiants and dwarfs (Sect. 2).

There is one serious observational problem concerning any test of alignment. Two binaries may have in reality the same true inclinations Δi_{t} but because they are viewed at different position angles, their observed Δi might be quite different. It turns out that the observed difference Δi is only a lower limit of the true difference between the inclination angles Δi_{t}. This ambiguity of the observed Δi as a measure of alignment can not be removed for individual stars; only statistical approach is appropriate for testing the effect of the position angle.

We have calculated the distribution of the expected values of Δi, $f(\Delta i^{\mathrm{e}})$, assuming various distributions of the true differences between i_{o} and i_{r}. The results are then compared with the distributions of the observed values of Δi, $f(\Delta i)$, both for asynchronous and synchronous binaries (Sect. 3). We finally discuss the implications of our results on the tidal evolution of binary systems (Sect. 4).

2. Observational data

Our present analysis concerns asynchronous binaries of spectral type G-K giants (long period RS CVn stars), subgiants (both long and short period RS CVn stars) as well as main sequence binaries (BY Dra stars). As already mentioned, we have selected only those systems, which are in the same range of P_{orb} and (a/R) values as the sychronized systems published in Papers II and III. The observed rotational period refers only to the active component in a binary. Even when both components are active, the present observations of light variability due to dark spots, do not permit a straightforward determination of the rotational period for the secondary, less active component. Whenever we identify a non-coplanar system we refer to the fact that the equatorial rotational plane of the more active component is not coplanar with the orbital plane. Quite often the rotational period for the less active secondary has been evaluated from its projected rotational velocity, $v_{\mathrm{r2}} \sin i_{\mathrm{r2}}$, assuming *a priori* that the system is coplanar ($i_{\mathrm{r2}} = i_{\mathrm{o}}$), what certainly is not justifiable for asynchronous systems.

Most of the data concerning orbital elements, rotational periods, P_{rot}, and projected rotational velocities, $v_{\mathrm{r}} \sin i_{\mathrm{r}}$, are taken form Strassmeier et al. (1993), herafter called CCABS. But in recent years the number and the precision of photometric and spectroscopic observations due to dedicated telescopes and sophisticated new software tools increase rapidly. An excellent illustration of that progress are papers by Henry et al. (1995), hereinafter called HFH, and by de Medeiros and Major (1995) where CORAVEL high precision rotational velocity are published for 144 single and binary late type gaints. Most recently Fekel (1997), hereafter called FCF97, determined rotational velocities for 111 active late-type stars. His analysis is based on measuremens of the full width at half maximum of selected spectral lines. Macroturbulent velocities have been assumed for various ranges of spectral types and removed from the observed stellar line broadening.

In consequence the sample of asynchronous active binaries, for which the set of data allows a reliable determination of i_{o} and i_{r} is instantly growing. Apart from the 12 asynchronous binaries analyzed previously (see Table 1 in Paper I), the recent observations permit to include in our present analysis 8 binaries with less reliable data listed in Table 2 of Paper I and to add 9 new long period asynchronous RS CVn type stars. As for the short period RS CVn and BY Dra type stars we have appended 5 new asynchronous systems to the 7 stars analyzed in Paper III. The total number of analyzed asynchronous systems is now 41. This enlargement of the sample is a fortunate circumstance for the necessary statistical investigation carried out in Sect. 3.

The procedures for determination of i_{o} and i_{r} are described in Paper I. For double line spectroscopic binaries, (SB2), the inclination of the orbital plane, i_{o}, is calculated from $M_1 \sin^3 i_{\mathrm{o}}$ and $M_2 \sin^3 i_{\mathrm{o}}$. The error of determination of i_{o} does not usually exceed 4° especially when the secondary is a main sequence star and $i_{\mathrm{o}} < 70°$. For single line spectroscopic binaries (SB1) i_{o} can be determined with a similar accuracy only when the secondary has been recognized as a white or red dwarf of known mass and/or the mass function, $f(m)$, takes extreme values (see Paper I). The masses of the primaries are evaluated from their position on the H-R diagram using the evolutionary tracks calculated by Schaller et al. (1992, hereinafter called SSMM).

The inclination of the rotational axis, i_{r}, is determined by comparing the equatorial rotational velocity v_{r} given by $v_{\mathrm{r}} = 50.61 R/P_{\mathrm{rot}}$ where R is in $R_{\odot}$ and P_{rot} is in days, with the projected rotational velocity, $v_{\mathrm{r}} \sin i_{\mathrm{r}}$, known with reliable accuracy. Methods of determination of the radius, R are presented in Papers I - III. The accuracy of i_{r} depends mainly on the errors of the determination of the radius and the projected rotational velocity.

The results are summarized in Table 1. The first three columns list the identifications of the binaries and their spectral types. Columns 4-5 give the mass of the primary, m_1 and the mass ratio $q = m_2/m_1$, both parameters are essential for the determination of i_{o}. Column 6 gives the radius of the primary, R in solar radii. The projected rotational velocity in km/s listed in column 7 represents an average value from various determinations, mainly from FCF97, HFH, CCABS, De Medeiros and Major (1995), Strassmeier et al. (1994), Randich et al. (1993, 1995). Columns 8-10 list the orbital period in days, the eccentricity of the orbit and the rotational period in days, derived from the observed variability of the primary due to dark spots. More information about data listed in columns 3-10 are given in the comments to individual stars (appendix, only in electronic

Table 1. Summary of properties of asynchronous binaries

HD/BD	NAME	SPECTRUM	m_1 ($M_\odot$)	q	R_1 ($R_\odot$)	$v_\mathrm{r} \sin i_\mathrm{r}$ (km/s)	P_orb (days)	e	P_rot (days)	i_o (°)	i_r (°)	Δi (°)
7672	AY Cet	G5 III+wd	2.09	0.26	6.8	4.3	56.82	0.040	77.22	26 A	74 C	48
8357	AR Psc	K1 IV + G7 V	1.1	0.82	2.7	6.7	14.30	0.186	12.24	30 A	37 B	7
10909	UV For	K0 IV	1.6	0.30	4.2	4.5	15.05	0.390	32.28	22 C	43 C	21
17433	VY Ari	K3-4 IV-V	1.5	0.45	4.3	9.4	13.20	0.085	16.42	60 A	45 C	15
19942	V510 Per	G5 III-IV	1.8	0.52	5.6	12.8	45.78	0	22.00	71 D	83 D	12
22694	HIC 17076	K0-1 V+K0-1 V	0.77	0.96	0.85	7.1	8.65	0.390	7.17	59 B	90 C	31
30050	RZ Eri	G6 III-IV+F0 IV	1.62	1.04	6.8	11	39.28	0.360	31.40	89 A	85 B	4
34029	α Aur	G9 III+G0 III	2.49	1.02	8.7	36	104.02	0	8.00	43 A	41 B	2
34802	YZ Men	K1 IIIp	2.5	0.70	14	17.5	19.31	0	20.38	46 C	30 B	16
39743	HR 2054	G8 III	2.5	0.24	12.5	8.8	83.19	0.180	73.10	32 C	90 B	58
42504	TY Pic	G8-K0 III+F	2.2	0.72	17.3	20	106.78	0.309	43.76	77 C	90 C	13
45088	OU Gem	K3 V +K5 V	0.73	0.83	0.76	5.6	6.99	0.150	7.36	78 A	90 B	12
71071	LU Hya	K1 IV	1.2	0.35	3.4	8	16.54	0.130	21.00	25 B	77 D	52
72688	VX Pyx	K0 III	2.0	0.50	11	8	45.13	0	19.34	20 C	16 B	4
77137	TY Pyx	G5 IV + G5 IV	1.2	0.98	1.72	23	3.20	0	3.32	88 A	61 B	27
83442	IN Vel	K2 III	1.8	0.55	16	7.5	52.27	0.130	54.95	47 D	31 B	16
90385	DW Leo	G8 III	2.2	0.45	7	3	99.85	0	13.00	43 D	6 B	37
91816	LR Hya	K0 V +K0 V	0.75	1.00	0.75	6	6.87	0.014	3.14	62 A	30 C	32
102509	DQ Leo	G5 III-IV+A7 V	2.25	0.87	9.1	5	71.69	0	55.00	50 A	37 B	13
108102	ILCom	F8 V +F8 V	1.12	0.96	1.15	35	0.96	0	0.82	52 B	30 B	22
118234	HIC 66286	K0.5 III	2.5	0.64	12	5.3	59.05	0.590	64.00	13 B	34 B	21
118981	HIC 66708	F9 V+K0 V	1.1	0.72	1.15	7.3	14.50	0.478	5.94	43 A	48 B	5
137164	LS TrA	K1 IV+K1 IV	1.6	1.00	9.1	10	49.43	0.516	46.19	54 B	90 D	36
148405	SAO 84381	G6 III	2.5	0.60	10	7.8	52.45	0.020	56.90	61 D	61 C	0
155989	V832 Her	G5 III	2.5	0.48	7.5	8	122.56	0.318	30.00	63 D	39 B	24
175306	*o* Dra	K0 II-III	3.0	0.55	48	16	138.42	0.114	148.80	74 B	79 C	5
181809	V4138 Sgr	K1 III	2.25	0.40	12	6.1	13.05	0.050	60.23	13 B	37 B	26
185510	V1379 Aql	K1 III+sdB	2.4	0.13	18	17.2	20.66	0.100	25.64	70 B	29 C	41
193891	V1971 Cyg	K0 III	2.2	0.50	11	11.7	38.79	0.022	40.65	62 D	59 C	3
202134	BN Mic	K1 IIIp	2.0	0.66	13	6	63.09	0.521	61.73	59 C	34 C	25
205249	AS Cap	K1 III	2.5	0.70	14	9.5	49.14	0.080	57.90	34 C	51 C	17
206301	42 Cap	G2 IV+ G2-5 V	1.6	0.60	3.5	5.2	13.17	0.180	12.10	29 B	21 B	8
212280	KX Peg	G8 IV+F6-8 V	1.7	0.82	4.8	8	45.28	0.500	29.46	78 B	76 C	2
217188	AZ Psc	K0 III	2.25	0.44	12	5.1	47.12	0.500	91.20	20 C	51 C	31
222107	λ And	G8 III-IV	1.6	0.30	7	6.5	20.52	0.040	53.95	17 C	82 B	65
223971	SAO 73597	G6 III + A V	2.5	0.76	8.5	6.4	50.12	0	53.00	85 B	53 C	32
234677	BY Dra	K3.5 V +K3.5 V	0.61	0.89	0.7	8	5.98	0.307	3.84	28 A	60 C	32
-0 4234	CCABS 184	K3 V+K7 V	0.69	0.80	0.62	7.8	3.76	0	4.03	41 A	90 C	49
+8 142	V1285 Aql	K3.5 V+K3.5 V	0.3	0.94	0.23	3.6	10.32	0.200	2.90	32 A	62 C	30
+30 2130	HIC 55135	G1 IV-V	1.0	0.57	1	7.8	6.57	0.004	6.80	68 C	81 C	13
+36 2193	HIC 56132	G6 V	0.89	0.65	0.9	4.4	7.15	0.008	8.31	75 C	53 C	22

form). Finally the derived inclinations of the orbital and rotational planes and their quality ratings are given in columns 11 and 12. Any assignment of quality ratings to the derived inclination angles is certainly partly subjective. We have adopted four classes in our rating system. Class A: the highest accuracy. The inclination angle is determined with an accuracy ranging from a fraction of a degree to four degrees. Obviously only for EB and SB systems of known masses the determination of i_o is possible with this precision. The present accuracy of $v_\mathrm{r} \sin i_\mathrm{r}$ and R determination does not permit to assign class A to any derived value of i_r. Class B: good determination of the inclination angles. The uncertainty of the derived values of i_o and i_r range between 5 and 9 degrees. Class C: average determination, the accuracy is better than 16 degrees. Class D: poor determination of the inclination angles with an accuracy worse than 16 degrees. Column 13 lists the absolute value of the difference between the observed angles of inclination of the planes, $\Delta i = |i_\mathrm{o} - i_\mathrm{r}|$. We show in the subsequent section that this difference is a lower limit of the true inclination of the rotational axis of the primary to its orbital plane. In the following section we shall often refer to Δi for synchronous active binaries. When doing so, we have in mind the corresponding values of Δi listed in Table 1 and 2 of Paper II for long period synchronous RS CVn systems and those listed in Table 3 of Paper III for short period RS CVn and BY Dra synchronous binaries.

3. Statistical analysis of Δi

The orientation of the orbital plane in space with respect to a reference plane is specified by two angles: the inclination of the orbit, $i_{\rm o}$, and the position angle of the line of nodes $\Omega_{\rm o}$. Obviously, $\Omega_{\rm o}$ is known only for visual binaries when radial velocity measurements are available. Similarly the equatorial rotational plane is fixed by $i_{\rm r}$ and the position angle of a reference meridian $\Omega_{\rm r}$, which is completely unknown. The true inclination of the spin axis with respect to the orbital plane $\Delta i_{\rm t}$, depends both on the observed value Δi and $\Delta\Omega = |\Omega_{\rm o} - \Omega_{\rm r}|$ as shown in Fig 1. Let O denote the position of the observer, S - the position of the analysed binary, SP - the direction perpendicular to the orbital plane and SR - the direction of the rotational axis. According to the commonly used definitions, the angle OSP is equal to $i_{\rm o}$, the angle OSR is equal to $i_{\rm r}$, the PSR angle denotes the true inclination difference $\Delta i_{\rm t}$ and the angle at vertex O is equal to $\Delta\Omega$. The true difference of inclinations, $\Delta i_{\rm t}$, is given by:

$$\cos(\Delta i_{\rm t}) = \cos(i_{\rm o})\cos(i_{\rm r}) + \sin(i_{\rm o})\sin(i_{\rm r})\cos(\Delta\Omega) \qquad (1)$$

where $0° \le \Delta\Omega < 180°$.

For any two observed angles $i_{\rm o}$ and $i_{\rm r}$, $\Delta i \le \Delta i_{\rm t} \le i_{\rm o} + i_{\rm r}$ giving an ambiguity in the determination of the alignment of the orbital and equatorial planes. The observed values of Δi listed in column 13 present a lower limit of $\Delta i_{\rm t}$. Obviously, if for any sample of binaries we can presume that they are really coplanar, $\Delta i_{\rm t} = 0$, then the observed values Δi must be zero within the error of their determination. The ambiguity of Δi cannot be removed for an individual binary. It is however possible to study the influence of the position angle by statistical approach. That can be done by estimating, for an artificial sample of binaries, the distribution of the expected values of $\Delta i^{\rm e}$ calculated under some well defined assumptions. The expected values, $\Delta i^{\rm e}$ have to be modified for an error of determination before doing any comparison with the observed values Δi. By comparing the distribution of the calculated values of $\Delta i^{\rm e}$ with that for the observed values of Δi, the adopted assumptions can be verified.

Let the PSR plane in Fig 1 be randomly oriented to the Earth observer. This is equivalent to assigning a random value (between 0° and 180°) for the view angle γ for a binary in the artificial sample. We calculate the distributions of Δi for artificial samples of binaries assuming two hypothetical distributions of $\Delta i_{\rm t}$:

a) the rotational axes are randomly inclined to the orbital planes, $0° \le \Delta i_{\rm t} \le 90°$

b) the rotational axes are perpendicular to the orbital planes, $\Delta i_{\rm t} = 0$

The following procedure is applied in the statistical analysis of the distribution of Δi.

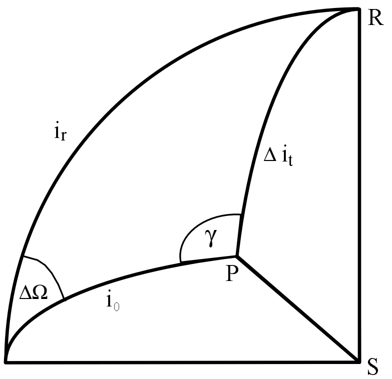

Fig. 1. Spherical triangle presenting relationships for the observed inclination of the orbit, $i_{\rm o}$, the spin axis, $i_{\rm r}$, and the true alignment of equatorial to orbital planes, $\Delta i_{\rm t}$, viewed from different angle γ. $\Delta\Omega$ denotes an angle between the orbital and rotational nodes.

Two samples of 2000 values of artificial orbital inclinations, $i_{\rm o}^{\rm a}$, are generated, within $0° \le i_{\rm o}^{\rm a} \le 90°$. The number of generated values for a given $i_{\rm o}^{\rm a}$, $N(i_{\rm o}^{\rm a})$, in the first sample, is proportional to the observed distribution function for the synchronous binaries , $f(i_{\rm o})$, ($i_{\rm o}$ taken from Table 1 in Paper II and from Table 3 in Paper III). Similarly, the observed distribution function for asynchronous binaries ($i_{\rm o}$ taken from Table 1 of this paper) has been applied as a weighting function for the second artificial sample. The distribution function $f(i_{\rm o}) = N(i_{\rm o})/N_{tot}$, is normalized to unity, i.e. $\int_0^{90} f(i)di = 1$. These two samples are combined with two sets of 2000 values of $\Delta i_{\rm t}$ fulfilling hypothesis a) and b), thus creating alltogether four samples with 2000 pairs of $i_{\rm o}^{\rm a}$ and $\Delta i_{\rm t}$ values. To each pair a random value of γ is added. The expected inclination of the rotational axis of such an artificial binary, $i_{\rm r}^{\rm a}$ is calculated from (see Fig.1):

$$\cos(i_{\rm r}^{\rm a}) = \cos(i_{\rm o}^{\rm a})\cos(\Delta i_{\rm t}) + \sin(i_{\rm o}^{\rm a})\sin(\Delta i_{\rm t})\cos(\gamma) \qquad (2)$$

The difference $\Delta i^{\rm a} = |i_{\rm o}^{\rm a} - i_{\rm r}^{\rm a}|$ is then modified for an error, δi, to obtain the final calculated values of $\Delta i^{\rm e} = |i_{\rm o}^{\rm a} - i_{\rm r}^{\rm a}| + \delta i$ for all binaries in the generated sample. As for δi, Gaussian distribution with $\sigma = 8.^\circ 3$ has been adopted. Finally, smoothed distribution functions, $f(\Delta i^{\rm e})$ and $f(\Delta i)$, have been calculated for the artificial as well as observed values od Δi. Bins of 2° are used to smooth the distribution functions for the sample of observed synchronous binaries ($N_{tot} = 80$) and for that of the generated binaries for case b), while 10° bins are applied for the samples of observed asynchronous binaries ($N_{tot} = 41$) and for the generated samples for case a). The statistical analysis of case b) - the artificial binaries are assumed to be coplanar ($\Delta i_{\rm t} = 0$) - is of course trivial. When ignoring the errors of determination, the expected values of $\Delta i^{\rm e}$ must be equal zero independently of the generated values of γ. It merely means that real coplanar systems should be observed as coplanar no matter from what angle they are viewed. The derived distribution function for that case reflects only the distribution of errors. We have performed this analysis for different values of σ. Two important conclusions can be drawn from the comparison of the

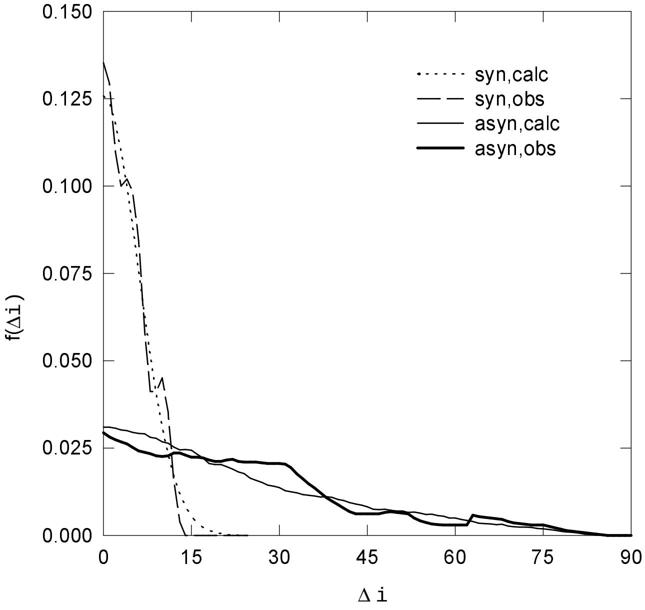

Fig. 2. Distribution functions $f(\Delta i)$ for the analysed samples: observed asynchronous stars (*thick full line*), calculated for random Δi_t (*thin full line*), observed synchronous stars (*dashed line*) and calculated for coplanar case (*dotted line*).

distribution functions for the synchronous binaries presented in Fig 2.

1. The assumption of coplanarity for the observed synchronous RS CVn and BY Dra type binaries is fully justified.

2. The best fit of the calculated, coplanar $f(\Delta i^e)$ to the observed $f(\Delta i)$ for the synchronous sample is obtained when the errors δi are represented by a Gaussian distribution with $\sigma = 8\overset{\circ}{.}3$ (see Fig. 2). We assume this value as a typical error for Δi in our analysis. There is no straightforward relation between σ and the quality ratings we have introduced in Table 1. Our quality rating system is connected with ranges of uncertainty of a single determination of a given inclination angle, while the σ parameter describes the Gaussian distribution of Δi errors for a sample. However, the numerical value of σ describes adequately the accuracy of our data, remembering that 95.4% of the measurement errors should be within the 2σ range.

The distribution function of the observed Δi values for asynchronous binaries is evidently different from the $f(\Delta i)$ for synchronous binaries. As shown in Fig.2 the asynchronous case is almost identical with the theoretical distribution for case a), i.e. rotational axis randomly inclined to their orbital planes. Some small differences (bumps and dips on $f(\Delta i)$ curve) simply reflect the scarcity of the observed sample. For $N_{tot} = 41$, the number of stars in some 10° bins might be quite small, causing fluctuations of the $f(\Delta i)$ function even after a smoothing procedure. An interesting property of the distribution function should be noted. The joint effect of random distributions of γ and Δi_t results in a monotonous decrease of $f(\Delta i^e)$ from its maximum value at $\Delta i = 0$. So, even for case a) the most probable observed value of $\Delta i = |i_o - i_r|$ is close to zero. The evident agreement of the distribution functions for the observed asynchronous sample and that calculated for case a) fully justifies our statement that in the sample of asynchronous binaries the rotational axes are randomly inclined to their orbital planes.

4. Discussion

The existence of asynchronous rotators in binaries with similar (a/R) as for synchronous binaries is inexplicable in terms of present tidal interaction theories. Even the statistics is quite incomprehensible. The percentage of asynchronous G-K giant systems as compared with the synchronous analogs is today already over 30% while for main sequence late type binaries the corresponding number is about 10%. Part of this discrepancy can be explained by observational selection effects, but most probably because the tidal evolution of massive binary systems is different from the low mass systems.

Two mechanisms are proposed to explain the observed asynchronous rotation in RS CVn type binaries. Hut (1981) introduced a new concept of pseudo-synchronization for the case where nearly all angular momentum is in the orbit. Pseudo-synchronization is caused by the fact that tidal interaction is strongest around periastron. Thus, for an eccentric orbit ($e > 0.2$) the pseudo-synchronization equilibrium state is reached at a value of $P_{\rm rot}$ which is less than $P_{\rm orb}$. Following the theory of Hut, Hall(1986) analysed eight asynchronous and eccentric systems having $P_{\rm orb} > P_{\rm rot}$. He showed that at least four of them can reach corotation at pseudo-synchronization periods, much shorter than $P_{\rm orb}$, nearly equal to the observed $P_{\rm rot}$.

In our sample only 20 systems (49%) are asynchronous rotators with $P_{\rm orb} > P_{\rm rot}$. Out of that number only 12 have $e > 0.15$, and only for 6 of them the pseudo-synchronization period approaches the observed $P_{\rm rot}$. For the remaining 6 systems the pseudo-synchronization effect increases asynchronism. Thus we arrive to a more pessimistic conclusion than Hall (1986). Pseudo-synchronization effect cannot explain the phenomenon of asynchronous rotators among active, close binaries. One of the reasons is that perhaps Hut's theory cannot be applied to the late type close binaries. Hut (1981) introduced the concept of pseudo-synchronization for the case where nearly all angular momentum is in the orbit. Besides he applied a very simple model of weak friction for tidal interaction, postulating that the tides assume their equilibrium shape, but with small constant time lag.

Habets and Zwaan (1989) proposed a more complicated mechanism to explain asynchronous rotation for evolved late type components in close binaries with circular orbits. According to Zahn (1977), binaries containing stars with convective envelopes should synchronize much more rapidly (t_s proportional to $(a/R)^6$) than they circularize (t_c scales with $(a/R)^8$). So, the scenario proposed by Habets and Zwaan (1989) assumes intermittent tidal interaction during the evolution of the stars. There are strong tidal interactions during the early pre-main-sequence phase to achieve synchronization and circularization of the orbit followed by a subsequent decrease of the angular rotation due to magnetic braking and/or the increase of the moment of inertia during the red giant phase to achieve secondary asynchronous rotation. Thus, the existence of binaries with circular orbits and low rotational velocities ($P_{\rm orb} < P_{\rm rot}$, sometimes called λ And type binaries) could be explained.

In our sample there are seven λ And type binaries, some of them with rather large rotational velocities. The proposed mechanism, though effective for some individual cases, obviously cannot explain the phenomenon of asynchronism for the whole sample presented in Table 1. We would like to mention here, that we can find many synchronous systems (see Table 1 and Table 2 in Paper II) which are very active (magnetic braking should operate) and are in the red giant phase (increased moment of inertia, reduced angular velocity). Most of them have large linear rotational velocity ($V_{\rm rot} > 20$ km/s), much higher than single G,K type giants, which means that auxiliary braking mechanisms have not been effective in their tidal evolution.

We have found a feature which distinguishes asynchronous systems from synchronous binaries. Asynchronous systems are misaligned, or exactly speaking, the rotational axes of their primaries are randomly inclined to the orbital planes. Additionally, the average eccentricities of asynchronous binaries are slightly higher than those of synchronous binaries. The mean value of eccentricity in our sample is $e = 0.17$, while in the sample of 80 synchronous binaries (Papers II and III) the corresponding value is $e = 0.03$. Both circular and eccentric orbits are observed for asynchronous systems, while synchronous binaries have usually circular orbits.

We cannot decide whether misalignment and asynchronous rotation are coplementary features or if it is a cause-effect relation. The initial conditions of binary formation might be very different. Binary systems can either be formed from the fragmentation of a primordial cloud of matter or by captures in a dense aggregate of stars. The loss of rotational and orbital momentum in the early phases of binary formation can also be quite different, depending on the existence of accretion discs, formation of planets etc. These processes might lead both to a primordial misalignment, and asynchronous rotation. But the essential problem for the theory is to calculate more realistic time scales of tidal evolution for cases when the $differences$ between orbital and spin period and $\Delta i_{\rm t}$ are large. Obviously it is a difficult task, since linearization of the set of equations describing tidal interaction would not be permitted. Two effects from non-linear theory are to be expected: First, the equilibrium state characterized by coplanarity, circularity, and corotation could be unstable or the stability would be achieved after longer time scales. Second, resonance effect could appear for the corresponding orbital and rotational frequencies as a result of including higher order terms in the equations. Some of these resonances might be stable, similar to the 3:2 resonance between rotation and revolution observed for Mercury.

Zahn (1996) suggested that for misaligned binaries precession of axis could be possibly detected. His crude estimate of precession periods encourages an observational test. It is also essential to look after other properties than misalignment which could differentiate asynchronous systems form the synchronous analogs. In the next papers we will look for the difference in evolutionary lifetimes of synchronous and asynchronous systems as well as for differences in elemental abundances and in the level of chromospheric and coronal activities.

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Appendix: comments on individual binaries

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