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Synchronization in the early-type detached binary stars

Kai-ke Pan

Yunnan Observatory and United Optical Lab., Chinses Academy of Sciences, Kunming, 650011, People's Republic of China

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Abstract. With a set of homogeneous and refined rotational velocities, we discuss the synchronism in the "normal" (all the particular stars, such as Ap, Am and Of, are excluded) early-type detached binaries. Being different from previous statistical studies, the present paper not only investigates the rotational synchronism of each component, but also estimates its age from new stellar evolutionary grids, and calculates its synchronization time scale with Zahn's dynamically tidal theory. Significantly, we find that the dynamically tidal synchronization mechanism is substantially compatible with the observed data from the comparison of the rotational properties of our components with the theoretical predictions.

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

1. Introduction

It has long been recognized that the tidal interactions between close binary components offer insight into the internal structure of stars and provide a test for the current stellar evolutionary theories. One of the main observable effects of the interactions is the rotational synchronism in binaries. A pronounced tendency towards synchronization between the axial rotation and the orbital revolution has been observed in close binary systems. Plavec (1970) and Levato (1976) discussed the correlation between the rotational synchronism and the orbital period. Giuricin et al (1984a, b) correctly learnt that the orbital period P is much more model-dependent than the fractional radius r. So, they investigated the relation between the rotational synchronization and r in the early-type binaries and found that the degree of synchronism clearly increases when the fractional radius goes up. Tan (1989) discovered similar correlations for the Algol-type binaries.

As mentioned above, previous studies generally searched for the relations between the rotational synchronization and the orbital period or the fractional radius. In the present paper, we take a different way to investigate the same problem. At first, we establish a synchronization criterion according to the uncertainties of our data, and judge whether a component is in synchronization or not (Sect. 2.2). Next, we estimate the age of each star (Sect. 3), and calculate the synchronization time scales for all of our samples with Zahn's (1977) dynamically tidal theory (Sect. 4). In Sect. 5, we compare the theoretical predictions with the observed results and draw some conclusions.

2. Samples and data

2.1. Selecting samples

Tan (1986a, b) measured the projected rotational velocities for 43 components in 38 binaries with the convolution method. By using the same method, Pan, Tan & Wang (1994) (hereafter PTW) determined $V_e \sin i$ values for 99 stars in 75 pair systems. PTW analyzed in detail the uncertainties in their measurements and proved that their rotational velocities have an excellent internal consistency and satisfying accuracies. We believe that these homogeneous, refined $V_e \sin i$ values will provide reliable clues to the problem of synchronism in close binaries. In order to get the most trustworthy conclusions, some restrictions are placed on the samples of the present investigation. Firstly, we limit our objects to the components in detached eclipsing binary systems. One reason for setting this limit is that the components of detached binaries are almost free from the effects of the matter transfer between the components. The other is that the orbital inclinations and fractional radii of stars in eclipsing binaries can be directly determined from photometric studies. Secondly, because the early-type and the late-type components are dominated by different synchronization mechanisms (Zahn, 1977, 1992), in this present article only the early-type stars with radiative envelopes ($m \geq 1.6\, m_\odot$) are discussed. Finally, we exclude all of the Ap, Am and Of stars since they may have undergone (or undergoing) some particular evolutionary processes, like the magnetic braking. Under these restrictions, 48 components are picked from 142 stars whose projected rotational velocities have been determined by ourselves by using the same method. The first three columns of Table 1 list the names, spectral types and orbital periods of the 48 components.

2.2. Rotational properties

All the projected rotational velocities in the present study are taken from our measurements by using the convolution method which has been clearly described by Tan (1986a) and Tan & Liu

Table 1. The rotational properties of 48 detached binaries and their estimated ages, calculated time scales of synchronization

star name	SP.	Period (day)	$V_e \sin i$ (km/sec.)	F	F_e	Age (year)	T_{syn} (year)	References
σ Aql	B3V	1.95	108	1.05		4.2×10^7	9.3×10^5	1, 2, 3
	B3V		125	1.40			1.1×10^6	
V805 Aql	A2	2.41	47	1.09		8.0×10^8	1.6×10^8	4,5
	A7		48	1.27			2.4×10^8	
V889 Aql	B9V	11.12	24	2.25		$\leq5.0\times10^7$	8.1×10^{10}	1,2
	A0V		25	2.35			1.1×10^{11}	
DV Aql	late A	1.58	92	1.13		8.0×10^8	1.8×10^7	2, 6
TU Cam	A2V	2.93	72	1.14		9×10^7	9.2×10^7	1,2
AR Cas	B3V	6.07	128	2.84	1.65	2.4×10^7	4.8×10^8	1,2
YZ Cas	A2	4.47	33	1.16		4.0×10^8	5.4×10^9	7,8
δ Cap	A9III	1.02	75	0.84	0.82	1.4×10^9	9.0×10^6	9
AH Cep	O8	1.77	175	1.01		6.0×10^6	4.0×10^3	10,11
	O9		160	1.0			4.5×10^3	
CW Cep	B0.5	2.73	123	1.16	1.07	1.0×10^7	2.6×10^5	4,5,12,13,14
	B0.5		112	1.26	1.17		3.9×10^5	
EK Cep	A1V	4.43	22	1.21	0.97	$\leq1.0\times10^8$	7.3×10^9	15, 16
NY Cep	B0IV	15.3	80	2.34	0.95	1.0×10^7	4.3×10^9	17,18
	B0IV		71	2.53	1.18		1.2×10^{10}	
XZ Cep	O9.5V	5.10	81	0.70	0.56	2.0×10^7	6.0×10^7	7,8
TU Cnc	A0V	5.56	49	2.26		3.0×10^8	1.8×10^{10}	1,2
α Crb	A0V	17.36	120	13.6	5.80	5.0×10^8	1.2×10^{13}	1,2,19
Y Cyg	B0IV	3.00	155	1.48	1.10	4.0×10^6	1.4×10^5	4,5,20,21
V380 Cyg	B1.5III	12.43	100	1.55	0.97	1.1×10^7	1.5×10^9	2,22
V444 Cyg	O6	4.21	130	1.09		3.0×10^6	2.0×10^5	1,23
V477 Cyg	A3V	2.35	54	1.63	0.84	$\leq4.0\times10^8$	1.6×10^8	4,5,24
V478 Cyg	O9.5V	2.88	128	1.02	1.0	8.0×10^6	8.4×10^4	4,5,25
BH Dra	A0V	1.82	60	0.98	0.88	2.5×10^8	1.8×10^7	1,2
RY Gem	A2V	9.30	154	10.9	7.82	6.0×10^8	2.1×10^{12}	4, 26,27
RX Her	B9.5V	1.78	73	1.09		3.0×10^8	7.7×10^6	4,5,28
	A0V		60	1.03			1.7×10^7	
DI Her	B4V	10.55	83	6.09	1.80	3.0×10^7	2.9×10^{10}	5,29
HS Her	B6III	1.64	83	0.88	0.80	8.0×10^7	3.1×10^6	2,30
CM Lac	A3V	1.60	65	1.20		2.0×10^8	1.7×10^7	4,5
TX Leo	A2V	2.45	27	0.47	0.42	8.5×10^8	1.9×10^8	2
IM Mon	B5V	1.19	140	1.47	1.29	1.0×10^7	5.4×10^4	1,2
U Oph	B5V	1.68	100	0.99	0.96	7.0×10^7	8.1×10^5	4,5,22
	B4V		100	1.03	1.01		1.3×10^6	
V451 Oph	B9V	2.20	48	0.84	0.80	3.0×10^8	2.3×10^7	4,5,31
	A0		45	0.99	0.96		5.5×10^7	
VV Ori	B1V	1.49	145	0.75		8.0×10^6	2.1×10^4	1,2

(1987). The fourth column of Table 1 tabulates these velocities. 41 of the 48 $V_e \sin i$ values come from PTW, and the others from Tan's (1986a, b) measurements. PTW detailed the errors in their rotational velocities. They concluded that their $V_e \sin i$ values have an excellent internal consistency, and that the uncertainty of these velocities is better than ±3 km/sec (or, safely say, better than 10%).

In Table 1, the parameters F and F_e are listed which indicate the synchronistic characters of the components. Here F is the ratio of $V_e \sin i$ to the synchronized rotational velocity, $(V_e \sin i)_{syn}$, and F_e equals $V_e \sin i$/ $(V_e \sin i)_e$. Following the definition of Giuricin et al (1984b), $(V_e \sin i)_e$, called the pseudosynchronized rotational velocity, corresponds to a synchronization with the instantaneous orbital angular velocity at the periastron of orbit of eccentricity e. The two velocities are respectively formulated by

$$(V_e \sin i)_{syn} = 50.6 \sin i/P, \quad (1)$$

Table 1. continued

star name	SP.	Period (days)	$V_e \sin i$ (km/sec.)	F	F_e	Age (year)	T_{syn} (year)	References
η Ori	B0.5V	7.99	44	0.93	0.88	1.2×10^7	9.8×10^7	1,2
AW Peg	A5V	10.62	125	6.7		1.2×10^9	7.7×10^{12}	4,26,32
EE Peg	A3V	2.63	36	1.0		4.0×10^8	3.1×10^8	5,33
RZ Sct	B3	15.19	200	3.90		1.1×10^7	2.1×10^{10}	26
EG Ser	A0	9.95	48	4.31		3.0×10^8	2.5×10^9	1,2
	A2		68	6.80			1.1×10^{10}	
DR Vul	B0V	2.25	130	1.18	0.96	1.0×10^7	7.9×10^4	2,34
	B0.5V		110	1.08	0.88		1.0×10^5	

References for Table 1:

1. Brancewicz et al. (1980)	2. Cvechnikov et al. (1990)	3. Cester at al. (1978)
4. Wilson (1989)	5. Poper (1980)	6. Okazaki et al. (1985)
7. Antokhina et al. (1991)	8. Giuricin et al. (1984c)	9. Batten et al. (1992)
10.Bell et al. (1986)	11.Drechsel et al. (1989)	12.Terrell (1991)
13.Poper et al. (1991)	14.Clausen et al. (1991)	15.Tomkin (1983)
16.Poper (1987)	17.Holmgron et al. (1990)	18.Fernie (1973)
19.Tomkin et al. (1986)	20.Stickland et al. (1992)	21.Giuricin et al. (1980)
22.Hilditch & Bell (1987)	23. Robert et al. (1990)	24.Gimenez et al. (1992)
25.Sezer et al. (1983)	26.Giuricin et al. (1983)	27.Pustylink et al. (1984)
28.Jeffreys (1980)	29.Poper (1982)	30.Hall et al. (1971)
31.Clausen et al. (1986)	32.Wilson et al. (1988)	33.Lacy et al. (1984)
34.Khaliullina et al. (1988)		

where R is the radius of a component in the unit of $R_\odot$ and P the orbital period in the unit of day, and

$$(V_e \sin i)_e = (V_e \sin i)_{syn} \cdot (1+e)^{\frac{1}{2}}/(1-e)^{\frac{3}{2}}, \qquad (2)$$

where $(V_e \sin i)_{syn}$ and $(V_e \sin i)_e$ are computed in Expressions (1) and (2), respectively. The stellar parameters are taken from the references listed in the last column of Table 1. If the stellar parameters, R, P, $\sin i$ and e, of a component are given by two or more references, the mean values of these quantities are firstly computed. Then, the computed mean values are used to calculate $(V_e \sin i)_{syn}$ and $(V_e \sin i)_e$. Because our samples are all the components of the detached binaries, the measuring errors of P, $\sin i$ and e are much smaller than the one of radius R. The uncertainties of $(V_e \sin i)_{syn}$ and $(V_e \sin i)_e$ are mainly determined by the error of the parameter R. According to Poper (1980), the accuracy of the radii of components in detached binaries is about 15% or better. Therefore, we believe that the uncertainties of $(V_e \sin i)_{syn}$ and $(V_e \sin i)_e$, calculated from the Eqs. (1) and (2), are about 20% or better. i.e. 20% is safe enough to be taken as the error of these quantities.

As noted above, our $V_e \sin i$ data and calculated quantities $(V_e \sin i)_{syn}$ and $(V_e \sin i)_e$ are in error. Naturally, the F and F_e of real synchronized or pseudosynchronized components will not exactly equal 1.0. So, the best we can do is to establish a criterion to judge whether a star is in synchronism or not. According to the definitions of F and F_e, and to the uncertainties of $V_e \sin i$, $(V_e \sin i)_{syn}$ and $(V_e \sin i)_e$, we consider a component with F $\leq$1.40 (or $F_e \leq$1.40) to be a synchronized (or pseudosynchronized) rotator. By this criterion, we find that, among our 48 stars, 10 components are in asynchronism, 6 stars in pseudosynchronism (but not synchronism), and the others are in full synchronism within reasonable uncertainties. The asynchronized rotators are DI Her, V889 Aql, TU Cnc, αCrb, RY Gem, AW Peg, EG Ser and RZ Sct. The pseudosynchronism stars are NY Cep, IM Mon, V380 Cyg, V477 Cyg and Y Cyg.

3. Ages

Since new opacity data were obtained (Iglesias & Gogers, 1991, Gogers & Iglesias, 1992), many new stellar evolutionary models have been constructed (e.g. Claret & Gimenez, 1992, Meynet et al, 1994 etc.). Overshooting and mass losses are taken into account in these new models. Claret and Gimenez (1992) have paid particular attention to stellar internal structures. Their evolutionary grids, being suitable for the present investigation, are mainly devoted to the interpretation of double-lined eclipsing binaries. With the radius and the effective temperature, we estimate age of each component from Claret & Gimenez's (1992) evolutionary grids. The standard chemical composition, (X, Z) = (0.700, 0.020), is chosen, and the mass losses are taken into account for stars of m$>$ 10 $m_\odot$ in the age reckoning. Our estimates show that two components in the same binary system have the same age within a reasonable error. Therefore, a mean value is taken as the age of the two components and listed in Table 1.

To examine the trustworthiness of the ages listed in Table 1, we arbitrarily chose four stars, AI Phe, V1031 Ori, αPer and θ^2Tau from literature. The ages, masses and radii of these stars have been determined. By the same method employed above, we estimate the ages of the four stars from Claret and Gimenez's

(1992) stellar evolutionary grids. we figure that AI Phe and V1031 Ori are respectively about 4.2×10^9 years and 6.8×10^8 years old, while Andersen et al (1988, 1990) separately gave the ages of 4.0×10^9 yr and 7.0×10^8 yr for the two stars. For αPer and θ^2Tau, Eggen and Iben (1988) thought that their ages are about 6.0×10^7 yr and 1.0×10^9 yr, respectively, and our estimates are 5.9×10^7 yr and 1.0×10^9 yr. As one can see, our stellar age estimates are in good agreement with the results obtained by others with different methods. Consequently, we think that our age estimates, listed in Table 1, have satisfying accuracy and are all reliable.

4. Synchronization time scales

The dynamical tide is suggested to be the most efficient synchronization mechanism in the early-type components with radiative envelopes (Zahn, 1977, 1992). However, previous statistical studies, concerning the relation between the synchronization and the period or fractional radius, indicated that the dynamically tidal theory might be difficult to account for the high degree of synchronism in the radiative envelope stars. In the present paper, we take a different way to discuss the synchronism of the early-type stars. First, we compute the synchronization time scale from Zahn's theory for each component. By comparing the time scales with the ages, we can know that which components are expected to be synchronized or asynchronized by the dynamically tidal theory. Then, we can clarify whether and to what extent the predictions of the dynamically tidal theory are compatible with observation results.

Following Zahn's (1977) dynamically tidal theory, the synchronization time scale of a component is defined as

$$\frac{1}{T_{syn}} = 3.06 \times 10^5 (\frac{M}{R^3})^{\frac{1}{2}} \cdot (\frac{MR^2}{I}) \cdot q^2 \cdot (1+q)^{\frac{5}{6}} \cdot E_2 \cdot r^{\frac{17}{2}} . \quad (3)$$

In order to compare the age, the synchronization time scale of each component is calculated by using its parameters at the Zero-Age Main-Sequence (ZAMS). In the result, the ZAMS masses of the stars must be determined at first. For stars with $\mathrm{m} < 10\,\mathrm{m}_\odot$, the present mass values, taken from the references in the ninth column of Table 1, are taken as their ZAMS masses. The ZAMS masses of components with $\mathrm{m} > 10\,\mathrm{m}_\odot$ are estimated from Claret & Gimenez's evolutionary grids by considering the mass losses. Then, All ZAMS radii and moments of inertia are interpolated from the same evolutionary grids by the ZAMS masses. The structure constants are obtained from Zahn's (1975) calculations according to ZAMS masses and radii. The mass ratios are determined by ZAMS masses of two components.

Theoretically, the semi-major axis of a binary system should alter with evolution. However, we ignore this change in computing the fractional radius of a component at ZAMS. Because all of our samples are "normal" stars lying in the main sequence, in our opinion, the alteration of the semi-major axes of these systems should be very small.

The synchronization time scale of each star is calculated with Eq. (3) and listed in Table 1.

5. Discussion

From the comparison of our calculations with the rotational properties of the components, we find that, *for most of our samples,* the theoretical predictions of dynamically tidal theory are consistent with the observated results. On the other hand, we also note that the rotational synchronization of YZ Cas, EK Cep and η Ori appear to be incompatible with the theory. Their ages are considerably smaller than the corresponding time scales of synchronization, but they have already been synchronized. Nevertheless, one can explain the synchronizations of YZ Cas and η Ori by two facts: (1) the surface layers, which experience a higher torque per unit mass, are synchronized at a much faster rate than the interior of the star (Zahn,1984; Goldreich and Nicholson, 1989); (2) the two stars are being the late stages of their main sequence evolutions, increases of their moments of inertia will spin down their rotational velocities. In our opinion, EK Cep keeps to be a puzzling at the present. According to Tomkin (1983) and Poper (1987), the primary of EK Cep has just arrived at its zero-age main-sequence. A ZAMS component should depart from synchronization as a result of the decrease in the moment of inertia. At the present level of our knowledge of binary evolution and synchronism, we cannot provide a clear explanation for the synchronization of EK Cep. However, we are quite sure that the synchronization of EK Cep cannot be imputed to the error in our $\mathrm{V}_e \sin i$ data. From several of other determinations almost the same rotational velocity is obtained for this star (e.g. Tomkin, 1983). Accordingly, we think that EK Cep is worth further studies, especially its pre-main sequence evolution. TX Leo seems to provide some evidence of subsynchronous rotation. On our request, Dr. Jiang Suyun kindly calculated the evolutionary track for the primary of this binary (for her calculation method, see Jiang and Huang, 1995). The track shows that the primary component has almost exhausted its core hydrogen, and therefore, the subsynchronous rotation can be partly explained by expansion of its radius.

In summary, only one star in our 48 samples appears to display incompatible rotational properties with the dynamic tidal theory. For overwhelming majority of selected stars, the theoretical predictions of the dynamically tidal theory are substantially consistent with the observed data. Consequently, we conclude that the dynamic tide is the main synchronizaion mechanism of early-type components in close binary systems, at least, one of the most efficient processes.

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