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Orbital circularization in detached binaries with early-type primaries

Kaike Pan[1,2], **Huisong Tan**[1], **and Hongguang Shan**[1]

[1] Yunnan Observatory and United Optical Laboratory, Chinese Academy of Sciences, Kunming, 650011, P.R. China
[2] Department of Physics and Astronomy, The University of Toledo, Ohio 43606-3390, USA

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Abstract. Extending our previous study, the present paper reports on the discussion of the orbital circularization in 37 detached binaries with early-type primaries. From comparison of the theoretical predictions with the orbital eccentricities of our binary systems, we find that Zahn's circularization theories are substantially consistent with the observed data for overwhelming majority of our samples. However, we also note that three binaries of whom both components are asynchronized rotators possess circular orbits. How to understand the circularism of the three systems remains a problem not only to Zahn's theories, but to all other present circularization mechanisms.We think that studies on the circularization of pre-main-sequence binary systems could provide some clues for the problem.

Key words: stars: binaries, eclipsing – binaries: close – stars: evolution

1. Introduction

Observed data show that short-period binaries tend to have zero or very small orbital eccentricities, whereas long-period systems demonstrate a wide scatter on orbital eccentricity distribution (e.g. Young & Koniges 1977, Kock & Hrivnak 1981, Middelkoop & Zwaan 1982, Pan & Tan, 1997). This phenomenon is usually explained in terms of tidal interaction between the two components of a binary. Several theories have been proposed to understand tidal evolution in binary systems (Zahn 1966,1977; Hut 1981; Savonije & Papaloizou 1985; Tassoul 1987,1988), and many observational investigations have been made to test these theories (e. g. Kock & Hrivnak 1981; Giuricin, Mardirossian & Mezzetti 1984a, 1984b; Tassoul 1995, Claret, Giemenez & Cunha 1995, Pan 1996).

Studies of circularization and synchronization in close binaries are very useful to obtain an empirical insight into the interior of stars and to test current stellar evolutionary theories. The comparison and contrast of the different available theories on tidal evolution with observational evidence of the actual leval of synchronization and circularization provide a proper way to check our understanding of stellar internal structure and stellar evolution. Very recently, we discussed the synchronization in 37 detached binaries with early-type primaries (Pan 1997, hereafter Paper I), and concluded that Zahn's (1977) dynamical tidal synchronization mechanism is substantially compatible with the observed data. Extending this study, we shall discuss the orbital circularization in these samples by a similar procedure in this present paper.

2. Available data

Table 1 lists Pan's (1997) 37 detached binary systems with early-type primaries. In the paper, Pan has calculated the synchronism character parameter F (and F_e if non-circular orbit), which indicates the synchronism property of a component, for 48 early-type components in the 37 binary systems. This parameter is tabulated in the fifth column of Table 1 for later usage. The first four columns list the names, spectral type, periods and orbital eccentricities of these systems.

Although in Paper I the author has estimated the ages of these 37 binaries with Claret and Gimenez's (1992) stellar evolutionary models, we here re-estimate the ages by the same procedure (see Paper I) with Claret's (1995) new grids of stellar evolutionary models. Mass losses and overshooting are taken into account in the age estimates. The new models give more refined ages on the case of V889 Aql, EK Cep and V447 Cyg, whereas the previous ages of other systems fit the new models extremely well. The ages of the 37 systems are listed in the sixth column of Table 1. Contrasting with Table 1 of Paper I, one can see that the age of V889 changes from $\leq 5.0\times10^7$ yr to 1.6×10^7yr,that of EK Cep from $\leq 1.0\times10^8$yr to 2.0×10^7yr, and that of V447 Cyg from $\leq 4.0\times10^8$yr to $\leq 1.0\times10^7$yr.

3. Circularization time scales

Because *both* components of a binary system affect the orbital circularing process of the system, we have to consider the influences of two stars simultaneously. Taking both components into account, the circularization synchronization time scale of a component is defined as

$$\frac{1}{T_{cir}} = \frac{1}{T_{cir,1}} + \frac{1}{T_{cir,2}} \qquad (1)$$

Send offprint requests to: K. Pan

Table 1. The orbital eccentricities of 37 detached binaries and their estimated ages, calculated time scales of circularization.

Star Name	SP.	Period (day)	e	F	T(age) (year)	T_{cir} (year)
σ Aql	B3V : B3V	1.95	0.0	1.05 : 1.40	4.2×10^{7}	1.4×10^{8}
V805 Aql	A2 : A7	2.41	0.0	1.09 : 1.27	8.0×10^{8}	1.0×10^{7}
V889 Aql	B9V : A0V	11.12	0.0	2.25 : 2.35	1.6×10^{7}	1.4×10^{14}
DV Aql	late A	1.58	0.0	1.13	8.0×10^{8}	3.8×10^{6}
TU Cam	A2V	2.93	0.0	1.14	9.0×10^{7}	1.5×10^{7}
AR Cas	B3V	6.07	0.25	2.84	2.4×10^{7}	2.0×10^{11}
YZ Cas	A2	4.47	0.0	1.16	4.0×10^{8}	7.0×10^{8}
δ Cap	A9III	1.02	0.01	0.84	1.4×10^{9}	1.2×10^{7}
AH Cep	O8 : O9	1.77	0.0	1.01 : 1.0	6.0×10^{6}	2.6×10^{5}
CW Cep	B0.5 : B0.5	2.73	0.04	1.16 : 1.26	1.0×10^{7}	4.2×10^{7}
EK Cep	A1V	4.43	0.11	1.21	2.0×10^{7}	3.0×10^{9}
NY Cep	B0IV : B0IV	15.30	0.48	2.34 : 2.53	1.0×10^{7}	7.9×10^{12}
XZ Cep	O9.5V	5.10	0.12	0.70	2.0×10^{7}	3.0×10^{10}
TU Cnc	A0V	5.56	0.0	2.26	3.0×10^{8}	3.1×10^{8}
α Crb	A0V	17.36	0.37	13.6	5.0×10^{8}	8.0×10^{12}
Y Cyg	B0IV	3.00	0.12	1.48	4.0×10^{6}	2.0×10^{7}
V380 Cyg	B1.5III	12.43	0.22	1.55	1.1×10^{7}	1.5×10^{12}
V444 Cyg	O6	4.21	0.0	1.09	3.0×10^{6}	3.1×10^{7}
V477 Cyg	A3V	2.35	0.30	1.63	$\leq1.0\times10^{7}$	1.5×10^{7}
V478 Cyg	O9.5V	2.88	0.01	1.02	8.0×10^{6}	1.1×10^{7}
BH Dra	A0V	1.82	0.05	0.98	2.5×10^{8}	6.9×10^{9}
RY Gem	A2V	9.30	0.16	10.9	6.0×10^{8}	3.0×10^{13}
RX Her	B9.5V : A0V	1.78	0.0	1.09 : 1.03	3.0×10^{8}	6.0×10^{8}
DI Her	B4V	10.55	0.49	6.09	3.0×10^{7}	8.5×10^{13}
HS Her	B6III	1.64	0.05	0.88	8.0×10^{7}	3.0×10^{8}
CM Lac	A3V	1.60	0.0	1.20	2.0×10^{8}	1.5×10^{6}
TX Leo	A2V	2.45	0.06	0.47	8.5×10^{8}	3.0×10^{10}
IM Mon	B5V	1.19	0.04	1.47	1.0×10^{7}	9.0×10^{6}
U Oph	B5V : B4V	1.68	0.01	0.99 : 1.03	7.0×10^{7}	1.1×10^{8}
V451 Oph	B9V : A0	2.20	0.02	0.84 : 0.99	3.0×10^{8}	1.0×10^{10}
VV Ori	B1V	1.49	0.0	0.75	8.0×10^{6}	1.2×10^{6}
η Ori	B0.5V	7.99	0.03	0.93	1.2×10^{7}	7.0×10^{10}
AW Peg	A5V	10.62	0.0	6.7	1.2×10^{9}	1.2×10^{14}
EE Peg	A3V	2.63	0.0	1.0	4.0×10^{8}	4.0×10^{8}
RZ Sct	B3	15.19	0.0	3.90	1.1×10^{7}	3.0×10^{13}
EG Ser	A0 : A2	9.95	0.0	4.31 : 6.80	3.0×10^{8}	2.9×10^{12}
DR Vul	B0V : B0.5V	2.25	0.10	1.18 : 1.08	1.0×10^{7}	1.5×10^{7}

where $T_{cir,1}$ and $T_{cir,2}$ respectively refer to the circularization time scale only the primary or the second component is singly considered.

According to Zahn's (1966,1977) theories, the orbital circularization time scale due to a single component is defined as

$$\frac{1}{T_{cir,n}} = 2.08\times10^{5}(\frac{M}{R^{3}})^{\frac{1}{2}}\cdot q(1+q)^{\frac{11}{6}}\cdot E_{2}\cdot r^{\frac{21}{2}} \tag{2}$$

or

$$T_{cir,n} = 5.13\times10^{-3}\cdot\frac{1}{q(1+q)}\cdot\frac{1}{k_{2}}\cdot\left(\frac{MR^{2}}{L}\right)^{\frac{1}{3}}\cdot\left(\frac{1}{r}\right)^{8} \tag{3}$$

where M, R and L are the mass, Radius and luminosity of the considered component in the solar units, respectively, while q, r, E_2 and k_2 are respectively the mass ratio, relative radius, tidal torque constant and apsidal motion constant.In Eqs. (2) and (3), n should be chosen as 1 or 2 respectively referring to the primary and secondary of a binary system. If an early-type component with a radiative envelope ($m > 1.6m_{\odot}$) is considered, Eq. (2) should be used to calculate its circularization time scale. For the late-type stars with $m < 1.6m_{\odot}$, which possess the convective envelopes, Formula (3) is employed for the time scales.

Similarly with Paper I, we calculate $T_{cir,n}$ by using parameters of components at their Zero-Age Main-Sequence (ZAMS) in order to compare the time scales with ages of binaries. Therefore, some ZAMS parameters of each component must be determined at first. For the stars with $m < 1.6m_{\odot}$, which Paper I does not concern, ZAMS k_2 and L are interpolated from Claret & Gimenez's (1992) evolutionary grids (because Claret's new

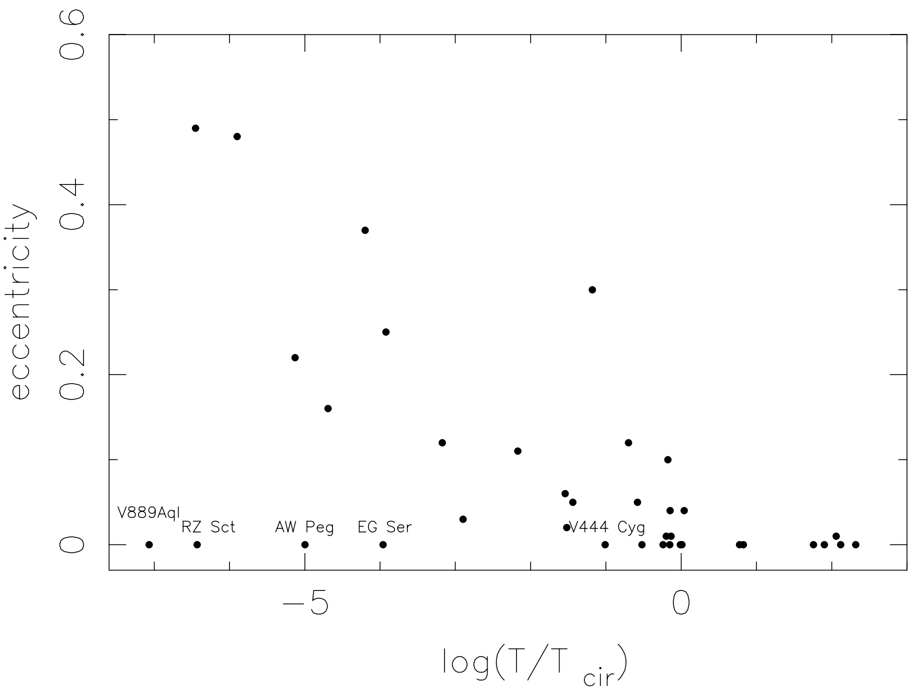

Fig. 1. Plot of orbital eccentricity versus function of $\log(T/T_{cir})$, where T is the evolutionary age of a system, and T$_{cir}$ is its circularization time scale by Zahn's mechanisms. Note a division in two regions: the right one with circular-orbit systems and the left one filled mainly by high eccentricity systems. Five circular orbit binaries in the left region are marked by their names.

models do not give the ZAMS parameters). All other ZAMS quantities are obtained by means of the method used by Paper I. The mass losses are taken into account in the ZAMS parameter estimates of the stars with $m > 7.0m_{\odot}$.

T$_{cir,1}$ and T$_{cir,2}$ of a binary system are calculated from Equaton (2) or (3) according to its component masses, and then the circularization time scale of the system is obtained by using Expression (1). The results are listed in the seventh colunm of Table 1.

4. Discussion and conclusions

From the comparison of our time scales with the eccentricities of 37 binaries, we find that, *for most of our samples*, the theoretical predictions of Zahn's (1966, 1977) circularization mechanism are consistent with the observed results. In order to provide a full illustration of this consistence level, a diagram of the orbital eccentricities versus a function of (logT-logT$_{cir}$), Fig. 1 is plotted. From this figure, it can be clearly seen that there is a cut-off point that divides the plot into two regions: the right one with the systems showing circular orbits and the left one filled mainly by high eccentricities. Furthermore, the cut-off point falls on zero. This means that the predictions of Zahn's theories are substantially compatible with the observed orbital eccentricities, as expected from the tidal evolution.

On the other hand, we also note that there are five circular-orbit binaries, which are marked by their names, in the left section of Fig. 1. Ages of the five systems are considerably smaller than their corresponding time scales of orbital circularization, but they have already been fully circularized. They appear to be incompatible with the theoretical predictions. However, if looking carefully into these "exceptions", one may explain the circularization of V444 Cyg by the strong stellar wind from its Wolf-Rayet component, and the circular orbit of AW Peg by the mass transfer between its two components. According to Prinja et al (1990), the mass loss ratio of the WR component in V444 Cyg is about 2.4$\times 10^{-5} m_{\odot}/\mathrm{yr}$, and therefore, we think that the circular orbit of V444 Cyg can be, at least partly, attributed to the mass loss of its WR component. AW Peg is a binary consisting of a $2.0m_{\odot}$ star and a $0.3m_{\odot}$ component at an age order of 10^9yr. Because the probability of forming a low-mass protobinary with such a small mass ratio is quite rare, we think, more reasonably, AW Peg is probably the outcome from the mass exchange of Case B evolution of a small total mass binary. According to Giannone et al (1970), if an assumed protobinary is composed of a $1.4m_{\odot}$ component and a $0.9m_{\odot}$ star, with an orbital period of about 1 day, it will start the rapid mass transfer phase from its primary ($1.4m_{\odot}$) to the secondary at an age of about 10^9yr, and result in the invertion of the primary component and secondary star, i.e. by the mass transfer, the original secondary obtains some masses from the original primary (now the secondary) and becomes the primary of the binary. The resulting system will be a binary somewhat like the status of AW Peg, composed of a $2.0m_{\odot}$ star and a $0.3m_{\odot}$ component with an orbital period of about 10d. Etzel, Olson and Senay's (1995) recent observed results confirmed the presence of stream and rotating accretion disk in AW Peg. The observations support our above assumption. If this is the case, the asynchronism of the primary (the original secondary) of AW Peg will be simply explained by its mass obtained from the other component, and the circularism of the system can be attributed to the mass transfer phase.

With respect to the other three "exceptions", V889 Aql, RZ Sct and EG Ser, it is a thorny task to explain their circularizations because both components in these systems are the asynchronized rotators. It is known that the circularization of the orbit is a much slower process than the synchronization of orbital and rotation period. In theories of synchronization and circularization, the time scales depend strongly on the ratio A/R, where A is the major axis and R is the radius of the star, with the exponents that differ from one theory to another, but in all present theories, the time scale of synchronization is much shorter than that of circularization, typically two orders shorter. Therefore, not only Zahn's (1966, 1977) theories can not explain the circularizations of V889 Aql, RZ Sct and EG Ser, but also other present mechanisms can't do either. Perhaps, the three systems, or some of them, have circularized their orbits during the pre-main-sequence phase, as suggested by Zahn and Bonchet (1989). Dr. Mathieu (1994) reviewed the orbital eccentricity distribution in late-type pre-main-sequence binaries and found a circular orbit system with a period of 242d in his 25 pre-main-sequence binaries. Comparing with Mathieu's samples, our ”expections” seem one time too much. At the present level of our knowledge on pre-main-sequence binary, it is difficult to conclude how large ratio of long period binaries have circularized their orbits during their pre-main-sequence phase. However, we would like to remind readers that some ZAMS binaries may be born with circular orbits.

In summary, for overwhelming majority of our samples, the theoretical predictions of Zahn's (1966,1977) theories are substantially consistent with the observed data. However, how to understand the circular orbits of the binary sytems with two asynchronized rotators remains a problem not only for Zahn's theories, but for other present circularization mechanisms. We think that studies on the degree of circularization of pre-main-sequence binaries could provide some clues to the problem.

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