Astronomical and Astrophysical Transactions (*AApTr*), 2014, Vol. 28, Issue 3, pp. 223–234,
ISSN 1055-6796, Photocopying permitted by license only, ©Cambridge Scientific Publishers

Prediction of CBS tidal evolution

G.N. Dryomova*

Russian Federal Nuclear Centre named after E.I. Zababakhin, Snezhinsk, 456770, Chelyabinsk Region, Russia

Received 15 February, 2013

The time series of basic processes, accompanying the tidal evolution of star components of Close Binary Systems (CBS) are predicted in the framework of evolutionary stellar models by Claret (2004). The series includes the apsidal motion period, timescale of synchronization of axial rotation of a star with the orbital revolution, the orbit circularization timescale, and the age. Data from the catalogues by Svechnikov & Perevozkina (1999) and by Torres, Andersen, Gimenez (2010) are used for testing the sensitivity of the numerical prediction algorithm.

Keywords: Stars: close binary systems, tidal evolution, tidal-torque constants, apsidal motion, spin synchronization, orbit circularization

1 Characteristic timescales of CBS tidal evolution

The general conception of any prediction problem can be reduced to the construction of a single source sequence of timescales satisfying the hierarchy principle. Under the single source sequence we mean timescales constructed on the basis of the same physical characteristics. Here we deal with the prediction of timescales characterizing the tidal evolution of Close Binary Systems (CBS).

Let the *period of orbital motion* of CBS components, P, be a reference scale. Its value is derived from transit photometry analysis with extra-high accuracy. Besides, from transit photometry one can also estimate CBS orbit inclination to the picture plane, i, relative radii, r_1 and r_2 as well as relative luminosities of components, L_1 and L_2. If star duplicity is confirmed by spectroscopic observations one can calculate stellar masses, M_1 and M_2, absolute radii R_1 and R_2, distance between components, A, as well as orbit eccentricity, e.

In the case of non-zero eccentricity the motion of CBS components is different from that dictated by classic Kepler's laws. As a result of mutual tidal-rotary deformation of components as well as due to the space curvature according to General Relativity Theory the elliptic orbit of CBS is being distorted and undergoes excessive rotation around the center of mass. The period of revolution known as *apsidal period* is considered as the next level timescale characterizing the tidal evolution of CBS.

*Email: G.N.Dryomova@mail.ru

Another evidence of apsidal effect is the presence of the phase shift in brightness distribution of both components interpreted as retardation (advance) of the tidal "hump" relative to the direction to the companion. Its origin is connected with various dissipation processes dominating in the star envelope such as convective friction, turbulent viscosity, radiative cooling. These processes generate tidal torques aspiring to minimize the retardation (advance) of the tide. Such dissipation processes are accompanied by the synchronization of axial rotation of both components with the orbital revolution of CBS and by the circularization of the CBS orbit. *Synchronization* and *circularization* timescales are considered as the third and fourth level timescales and may be evaluated in the framework of the theory of tidally induced oscillations.

2 Constraints to the prediction of tidal effects

2.1 TEST I: age gap between CBS components

All above-mentioned timescales characterizing the tidal evolution of stars in a CBS were calculated with the use of the same computational isochrones grid constructed on the base of the theoretical stellar evolutionary models-tracks. This makes it possible to avoid model-dependent systematic errors. The main parameter of the grid is a time which correlates with the age of the star. The coincidence of ages of the primary and secondary components is the first constraint the prediction must meet. It is a test of simultaneous origin of CBS components.

The preference was given to evolutionary tracks by Claret (2004) with built-in tidal-torque constants unlike other models. These constants E_2 and λ_2 are responsible for dissipative forces arising in radiative and convective stellar medium, respectively, and aspiring to minimize the action of the tide.

Tidal-torque constants as well as all classical model ingredients including mass, radius, luminosity, effective temperature, surface gravity, internal structure constants, and gyration radius are time-dependent. It enabled organizing the numerical algorithm generalizing the idea of isochrones (Dryomova, Svechnikov (2012)). The family of isochrones constructed in the diagram of the most accurately defined astrophysical parameters such as mass and radius is then projected into the diagrams: "$E_2 - M$", "$E_2 - R$", "$\lambda_2 - M$", "$\lambda_2 - R$". Knowing the age of a star, it is easy to access other individual constants which are also the functions of time.

This numerical algorithm is based on theoretical evolutionary models of single stars and imposes constraints on the class of CBS. Their components must be detached and must belong to the Main Sequence. This requirement eliminates any processes of mass exchange. According to close binary classification elaborated by Svechnikov (1969) these systems obey the status of a DMS class.

Here the systems under consideration are presented by 112 DMS systems taken from the catalogue by Svechnikov & Perevozkina (1999) (SP, 1999) and reflecting the accuracy level of the astrometry in the 20th century when the overwhelming majority of the systems was massively discovered by the photographic method and by 95 systems from the catalogue by Torres, Andersen, Gimenez (2010) (TAG, 2010) that uses the data of modern space missions. It would be interesting to compare the predictions of tidal evolution of CBS from these two catalogues.

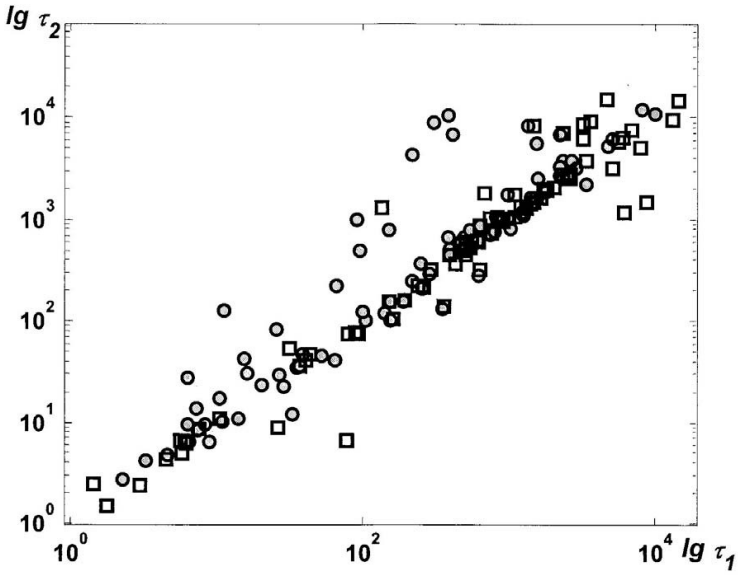


Figure 1 Comparison between primary τ_1 and secondary τ_2 ages of the CBS. Open circles correspond to systems from the catalogue by SP (1999) and open squares – for CBS from the catalogue by TAG (2010).

The first test of the prediction trustworthiness showed that the ages of primary and secondary components for most CBS from both catalogues are in good agreement (Fig. 1). The systematic trend of a deviation from the line of equal ages was revealed only for low-massive stars ($<$1.5 $M_\odot$) and was consistently interpreted in the framework of the dynamic theory of magnetic braking. The matter is that the star components with convective envelopes are capable of supporting intensive magnetic stellar wind which does accelerate the rate of tidal evolution as compared to the nuclear burning rate (Tutukov, Dryomova, Svechnikov (2004)).

2.2 TEST II: apsidal motion

The nature of apsidal motion is linked with mutual tidal-rotary deformation of components when the redistribution of angular momentum between the axial rotation of stars and their orbital motion results in breaking of classical Keplerian orbits of components. The orbital distortion becomes apparent in the rotation of the line of apsides that gave the name to the effect. This phenomenon leads to secular changes in the periastron position, which may be estimated both from the observations and from the classical dynamical theory of apsidal motion (Russell (1928)).

The theory uses the remarkable property of the expansion parameters in the formulae for the apsidal period which are interpreted as internal structure constants, k_2^1 and k_2^2, describing the layer density distribution. Therefore one may formulate the second test for the prediction of tidal evolution effects in a CBS. On the one hand, the value of the apsidal motion period may be estimated in terms of angular velocity of the periastron, accumulating secular changes in its position by simple formulae as

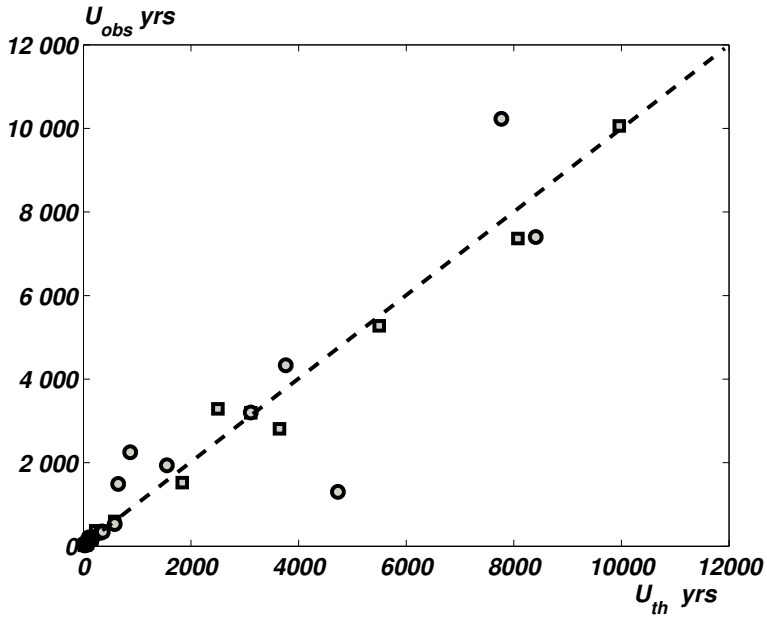


Figure 2 Comparison of theoretical U_A and observational U_{obs} values of apsidal period. The legend is the same as for Fig. 1.

$U_A = 2\pi P_a/\dot{w}$. The value of $\dot{w}$ is extracted from the analysis of the O–C diagram showing changes of the orbital period with times-of-minima variation. Thus, the apsidal period may be taken from the observations. On the other hand, the theoretical estimation may be performed on the basis of stellar evolutionary models (Claret (2004)) and the dynamic theory of apsidal motion.

The results of the second test show (Fig. 2) that for the majority of eccentric binaries (38 CBS from the catalogue by SP (1999) and 22 CBS from TAG's catalogue (2010)) the observed and theoretical values of apsidal period are in good agreement. The exceptions are only the CBS with unreliable light curves.

It is important to emphasize that the problem known for many decades as a relativistic paradox was resolved at last owing to the Rossiter–McLaughlin effect (RM effect). The paradox is attributed to the relativistic effect of apsidal motion originating due to the space curvature and is not connected with the finite sizes of stars. The relativistic correction to periastron advance is to be summed to classical apsidal effect (Mofflat (1984, 1989)).

For a long time, the system DI Her with large relativistic contribution reaching 56% served as a critical test demonstrating a conflict between theory and observation. The RM effect measured for this system from the analysis of the distortion shape of spectral absorption lines (Albrecht et al. (2009)) allowed estimating the non-coplanarity degree of the orbit. It proved that the rotation axes of both components are highly inclined to the orbital axis. Account of a large misalignment between the orbital and rotational axes practically removed the discrepancy between theory and observations, having reduced it to $\sim 10\%$.

AS Cam very much like DI Her demonstrates an anomalously slow rate of apsidal motion and thus challenges our understanding of stellar physics. Shakura in 1985 found that the observed and computed rates of apsidal motion could be brought into agreement if the stars were rotating at three times the synchronous rate around the axes almost perpendicular ($\approx 87^\circ$) to the orbital axis. It is necessary to measure the RM effect for the verification of these calculations.

Contrariwise there is no case of anomalously slow rate for a number of systems with relativistic contribution of up to 100% of the total apsidal-motion rate such as TV Cet, V1143 Cyg, RR Lyn, GG Ori (Wolf et al. (2010)).

2.3 TEST 3: Synchronization of spin rotations of CBS components with orbital motion

One of the important secular effects of tidal evolution is the synchronization of the axial rotation of the components with their orbital motion. The status of the synchronization may be found both theoretically and from spectroscopic observations.

In the first case we compare the age of CBS computed by the isochrone method with the synchronization timescale evaluated for CBS components in the framework of non-adiabatic analysis of tidal oscillations developed by Zahn (1975,1989). The formalism requires tidal-torque constants which are evaluated according to the same algorithm used for the isochrone method. If the age of a CBS component excesses the synchronization timescale one makes a conclusion that spin synchronization is truly established. So far this is only a prediction.

It is quite another thing if one has velocities of spin rotation measured from spectroscopic observations. The coincidence of their values reduced to absolute star sizes $V_1 \sin i/R_1$ and $V_2 \sin i/R_2$ with the orbital angular velocity, $2\pi/P_{\rm orb}$ is the convincing proof of the synchronization. Comparison of the predicted and observed status of synchronization reflects the level of our understanding of the tidal evolution in CBS (Fig. 3). To make the analysis of synchronization timescales easier all CBS were subdivided into homogeneous groups depending on the type of envelope.

The first group contains only CBS for which the envelopes of both components are convective. The number of such CBS in SP catalogue (1999) is 24 and in TAG catalogue (2010) is 31. All CBS components from the first group are already synchronized, which is supported by spectroscopic data on rotational velocities.

The second group includes only CBS with radiative envelopes of both components: 37 of 69 CBS from the catalogue by SP (1999) and 27 of 45 from the catalogue by TAG (2010) are also synchronized.

The third group includes 19 systems from the catalogue by SP (1999) and 9 systems from the catalogue by TAG (2010) representing the "symbiosis" of the massive primary component possessing the radiative envelope and the low-massive satellite with the convective one.

Analysis of tidal-torque constants permits us to formulate the priority of synchronization for CBS components. In low-massive close binaries with components possessing convective envelopes the lower mass component synchronizes the axial rotation with the orbital revolution first, while in massive close binaries with radiative envelopes the situation is the opposite. As for the third group the satellites achieve synchronism faster than the primaries and the difference in time may exceed three

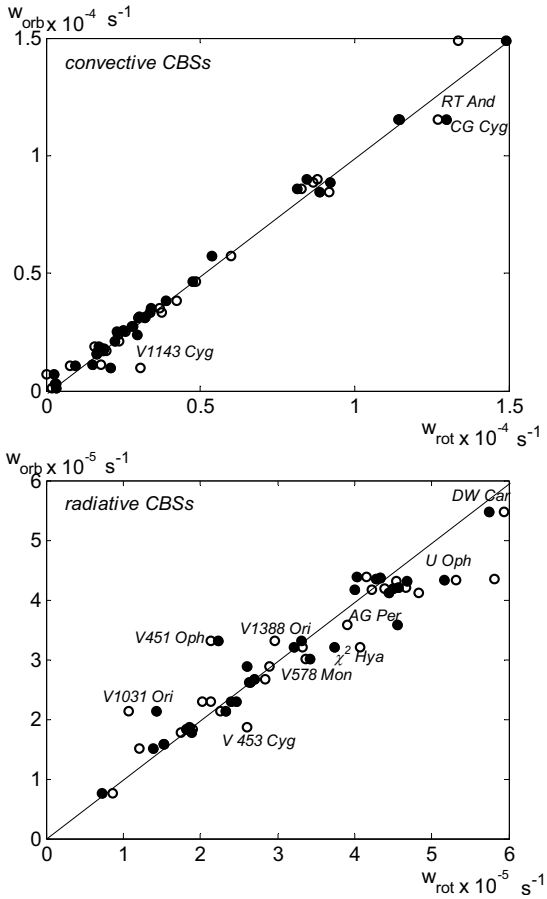


Figure 3 Comparison of orbital $w_{\rm orb}$ and spin $w_{\rm rot}$ angular velocity for CBS from the catalogue by TAG (2010). Black circles indicate primaries and open circles are secondaries. The upper window is for a CBS with convective envelopes of both components and the lower window is for a CBS with radiative envelopes of both components.

orders of magnitude. Just the same gap in values takes place for tidal torque constants characterizing the dissipation nature in a convective and radiative environment, $\lambda_2 \gg E_2$.

2.4 TEST 4: Circularization of the CBS's orbit

The final secular effect of mutual tidal-rotary deformation of the components in a CBS is the circularization of the orbit. Components aim to minimize the time variation of the tidal constituent until the orbital configuration proves to be stable. The tendency to decrease the orbital eccentricity with the age of a CBS is well-known from observations.

In spite of the long-time character of the process its theoretical evaluation can also be checked. As for synchronization, the status of circularization may be predicted as a

result of the comparison of CBS age with the circularization timescale. The timescale is also determined in Zahn's formalism (Zahn (1975,1989)) through the tidal-torque constants responsible for different dissipation mechanisms depending on the structure of the star.

On the other hand, if the eccentricity is available from spectroscopic data then by the closeness of its value to zero one can judge about the circularization status. We kept the same subdivision of CBS into groups when analyzing their timescales of circularization.

For the first group of CBS with both components possessing convective envelopes, 12 of 24 systems from the catalogue by SP (1999) and 22 of 31 systems from the catalogue by TAG (2010) proved to be already circularized. In the second group of CBS with both components possessing radiative envelopes, 15 of 69 systems from the catalogue by SP (1999) and 9 of 45 systems from the catalogue by TAG (2010) already entered a circular orbit. These are massive systems with the separation $R_1/A > 0.25$. Almost for all these systems the status of circularization is confirmed by spectroscopic observations indicative of a zero eccentricity with the exception of V822 Her ($e = 0.009$) and U Oph ($e = 0.003$). Probably it is due to the presence of gaseous material co-rotating with the CBS components that may lead to the so-called false eccentricity formally derivable from the solution of the radial velocity curve (Botsula (1978)).

For most CBS from the third group the timescale of circularization noticeably exceeds the Hubble timescale that excludes these estimations from the category of evolutionary significant results. As a rule these are systems with large separations between components $R_1/A < 0.1$ demonstrating weak dissipative properties indicated by the small values of torques ($\lg E_2 < -8$).

3 Comparative analysis of results

As we already noted, the estimations of synchronization and circularization timescales were performed in the framework of non-adiabatic analysis of tidal oscillations recommended by Zahn (1975, 1989). The analysis uses simple formulas accounting for the different nature of the dissipation mechanism due to turbulent friction or radiative damping. These formulas rely on stellar parameters characterizing the current state of the star instead of solving a differential equation system describing a variation of all orbital elements and astrophysical parameters of CBS components with time. Because of the absence of initial information the upper estimations of synchronization and circularization timescales were done.

It would be interesting to compare these approximate estimations with the results by Khaliullin, Khaliullina (2010) obtained for massive CBS when solving the whole set of differential equations by the method of inverse integration over the aggregate t/t_{cir} (where t is a star age). The integration from the current state of CBS to the Zero-Age Main Sequence represents a more accurate method of the reconstruction of orbital history of a CBS.

As it is seen from Table 1 and Fig. 4 the results of the comparison show quite a good accordance. It can be explained by the fact that all CBS under consideration belong to the Main Sequence within the band of which the changes of tidal-torque constants for stars of a given mass are insignificant.

Table 1 Comparison of ages and circularization timescales obtained by different methods described in Dryomova & Svechnikov (2012) (further below, D&S) and in Khaliullin & Khaliullina (2010) (further below, K&K) for massive ($> 1.5M_{\odot}$) CBS from a common sample of cited papers. Timescales are given in millions years.

CBS name	$\tau_{\rm age}$, D&S	$t_{\rm cir}$, D&S	e, D&S	e, K&K	$\tau_{\rm age}$, K&K	$t_{\rm cir}$, K&K
V805 Aql	500±16 668±3	22000	0?	0	410	26980
σ Aql	26.9±1.74 29.6±0.7	13.6	0.043	0	11.22	12.6
V539 Ara	39.1±0.83 47.4±1.14	327	0.053	0.053	38.9	340
WW Aur	390±3 670±18	10^5	$\neq 0$	0	310	$5.6 \cdot 10^4$
AR Aur	pre-ZAMS 84.7±9.1	10^6	0.019	0	0.32	$3.2 \cdot 10^5$
β Aur	490±20 515±20	$1.1 \cdot 10^5$	0?	0.0018	460	$6.2 \cdot 10^4$
ZZ Boo	1300±60 1230±60	$4.5 \cdot 10^6$	0?	0	1585	$5 \cdot 10^6$
AS Cam	104±0.8 101±2.7	19100	0.17	0.1695	91.2	5000
CW CMa	290±2 290±7	19500		0	280	10250
GZ CMa	550±14 600±18	$1.15 \cdot 10^6$	0?	0	525	10^6
EM Car	4.65±0.045 4.66±0.038	8.16	0.012	0.012	5.5	15.15
QX Car	7.5±0.16 8.4±0.16	2520	0.278	0.278	7.08	195
AR Cas	25.7±0.87 82.8±11.8	7310	0.205	0.211	51.28	20515
PV Cas	153±2.2 153±2.6	318.5	0.033	0.032	145	98
WX Cep	540±21 515±21	3350	0?	0	600	10230
AH Cep	3.28±0.04 4.20±0.014	0.439	0	0	3.72	0.2
CW Cep	6.47±0.045 6.45±0.045	52.3	0.029	0.0293	7.24	17.4
NY Cep	10.5±0.33 17.1±0.6	$3.2 \cdot 10^6$	0.48	0.48	3.3	5620
XY Cet	1040±30 820±20	$8.7 \cdot 10^4$	$e \neq 0$	0	890	10^5
RS Cha	835±30 1060±40	2590	0?	0	310	525
Y Cyg	2.25±0.075 2.7±0.08	34.4	0.146	0.1458	1.66	6
MY Cyg	1000±40 1020±40	$9.4 \cdot 10^5$	0.0048	0.01	980	$7.2 \cdot 10^5$

Table 1 (continued)

CBS name	τ_{age}, D&S	t_{cir}, D&S	e, D&S	e, K&K	τ_{age}, K&K	t_{cir}, K&K
V453 Cyg	11±0.19	70.15	0.022	0.022	14.5	130
	10.2±0.18					
V478 Cyg	6.33±0.07	11.8	0.019	0.019	6.6	7.58
	6.62±0.1					
RX Her	220±7	290	0.022	0.022	214	162
	245±4.5					
DI Her	0.61±1.4	$2.25 \cdot 10^7$	0.489	0.489	0.087	$8.7 \cdot 10^4$
	pre-ZAMS					
HS Her	11.3±2.2	58.8	0.0205	0.0188	24	42
	126 ±126					
V624 Her	645±29	$9.2 \cdot 10^4$	0?	0	600	10^5
	870±27					
AI Hya	940±23	$7 \cdot 10^6$	0.23	0.23	912	$5 \cdot 10^6$
	946±37					
χ^2 Hya	190±10	126	0	0	195	200
	153±1.3					
CO Lac	28.9±1.6	27	0.03	0.027	55	15
	22.8±3.8					
GG Lup	pre-ZAMS	-	0.15	0.15	45.7	110
	pre-ZAMS					
RU Mon	64±2.2	21790	0.396	0.385	75.85	440
	41.6±1.7					
U Oph	52.6±1.2	27.5	0.003	0.003	40	10
	45.8±2.2					
V451 Oph	255±5	965	0.013	0.0125	230	660
	207±2.5					
AG Per	13±0.7	146	0.071	0.071	6.3	40
	pre-ZAMS					
IQ Per	54.1±2.1	160	0.076	0.075	45.7	105
	pre-ZAMS					
ζ Per	77.4±1.5	62.8	0.0113	0.014	115	118
	pre-ZAMS					
PV Pup	350±40	14680	0.05	0.0503	235	5000
	130±82					
VV Pix	510±12	$2.3 \cdot 10^6$	0.0956	0.0956	550	$1.77 \cdot 10^5$
	510±14					
V1647 Sgr	155±13	$3.3 \cdot 10^5$	0.4143	0.413	130	6170
	100±21					
V760 Sco	33.5±0.36	58	0.0265	0.0265	45.7	38.9
	12.2±1.4					
V906 Sco	200±10	612	0.0054	0.0054	204	33
	390±25					
Al Scl	143±6	58	0.074	0.074	170	1620
	pre-ZAMS					
DN UMa	250±14	8870	0.015	0.001	600	560
	370±5					
CV Vel	37.1±0.2	$1.3 \cdot 10^5$	0.003÷0.015	0.0001	35	$8.1 \cdot 10^4$
	35.7±0.16					

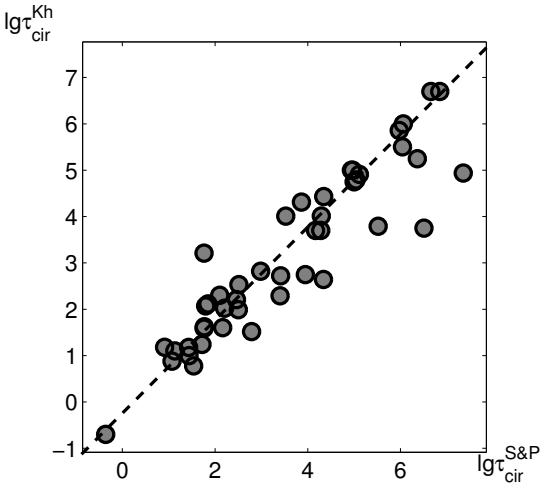


Figure 4 Comparison of circularization timescales obtained by Dryomova, Svechnikov (2012) and by Khaliullin, Khaliullina (2010) within the formalism by Zahn (1975,1989).

Comparison of the predictions for a sample of common CBS from two catalogues (54 common CBS) shows a high level of consistency excepting several CBS. For example, the discrepancy in age estimation for HS Hya may be explained by the difference in masses and radii of its components: according to the data from the SP catalogue (1999) M_1=1.34 $M_\odot$, R_1=1.3 $R_\odot$ and M_2=1.29 $M_\odot$, R_2=1.28 $R_\odot$ while the data from the TAG catalogue (2010) give M_1=1.255 $M_\odot$, R_1=1.275 $R_\odot$; M_2=1.219 $M_\odot$, R_2=1.217 $R_\odot$ (Fig. 5).

The estimations of apsidal period for a common sample of CBS from two catalogues are also in good agreement (Fig. 5). The same conclusion results from the analysis of synchronization timescales excepting RZ Cha. Following the data from the SP catalogue (1999) the masses of both components of RZ Cha specify the structure of the stars with the radiative envelope while according to the TAG catalogue (2010) data the stars possess convective envelopes. By the difference in tidal torque constants $E_2 = 1.3{\cdot}10^{-9}$ and $\lambda_2 = 10^{-3}$ computed for radiative and convective interior of RZ Cha, correspondingly, one may explain the gap of four orders of magnitude between estimations of synchronization timescales equal to 705 and 1.4 million years, respectively.

Analysis of circularization timescales for common CBS from both catalogues considered here reveals four CBSs YZ Cas, V442 Cyg, RZ Cha, EE Peg , for which the use of improved luminosities from the catalogue by TAG (2010) leads to much more realistic timescales of orbit circularization.

Thus, comparative analysis of the timescales characterizing the effects of tidal evolution of CBS with initial data taken from the catalogues belonging to two different astrometry epochs and therefore slightly different from each other, allows us to conclude that the modern model predictions prove to be insensitive to these differences.

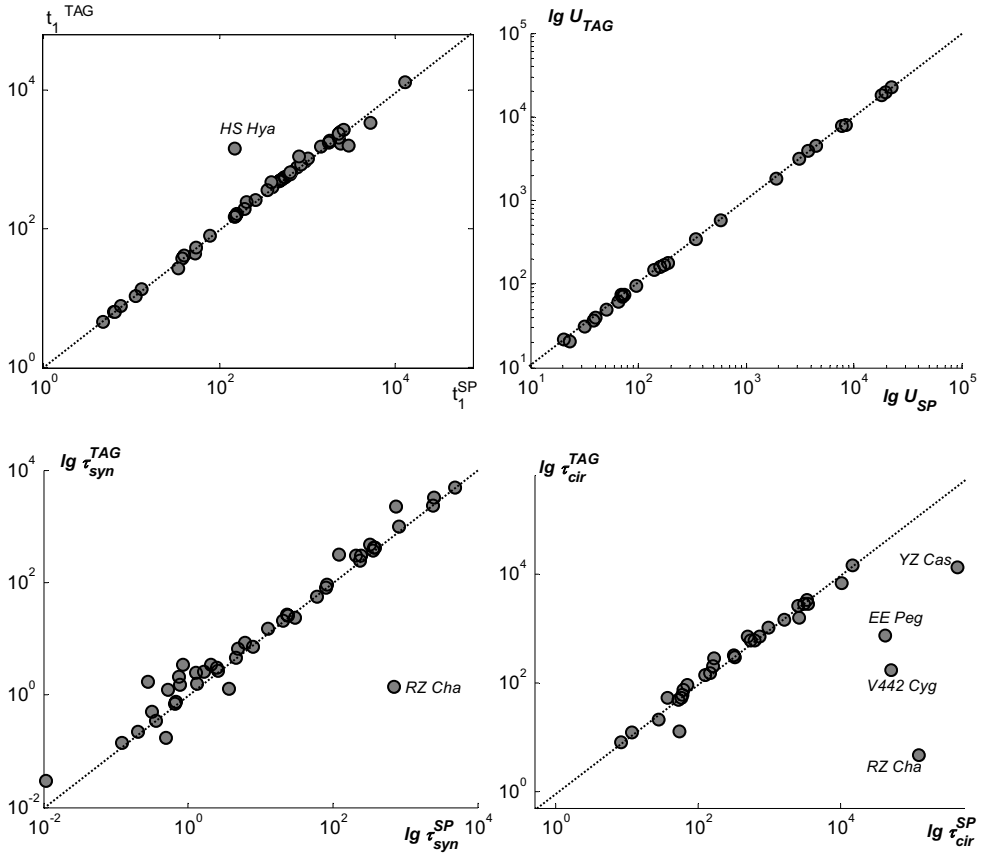


Figure 5 Comparison of all timescales characterizing tidal evolution obtained for a common CBS from two catalogues: SP (1999) and TAG (2010).

References

Albrecht S., Reffert S., Snellen I., Winn J. (2009) Nature 461, 373–376.
Botsula R. A. (1978) Izv. Engelhardt Obs. 44, 70.
Claret A. (2004) Astron. Astrophys 424, 919–925.
Dryomova G., Svechnikov M. (2012) Astrophys. Space Science 338, 103–126.
Khaliullin K., Khaliullina A. (2010) MNRAS 401, 257–274.
Mofflat J.W. (1984) Astrophys. J. 287, 77.
Mofflat J.W. (1989) Phys. Rev. D 39, 474.
Pavlovski K., Southworth J., Kolbas V. (2011) Astrophys. J. Letters, 734, 29–34.
Russell H. (1928) MNRAS 88, 641–643.
Shakura N. I. (1985) Soviet Astronomy Letters 11, 224.
Svechnikov M. A. (1969) "Catalogue of orbital elements, masses and luminosities of close binary stars", Scientific Notes of Ural State University, Sverdlovsk, N88, astronomical series, issue 5, 179.

Svechnikov M. A., Perevozkina E. L. (1999) "Catalogue of Orbital Elements, Masses and Luminosities of Variable Stars of DMS-Type and Some Results of Its Statistical Treatment", pp. 15. Ural State University Press, Yekaterinburg, ftp://cdsarc.u-strasbg.fr/pub/cats/V/121.
Torres G., Andersen J., Gimenez A. (2010) Astron. Astrophys. Rev. 18, 67–1267.
Tutukov A.V., Dryomova G.N., Svechnikov M.A. (2004) Astron. Rep., 48, 219.
Zahn J. P. (1975) Astron. Astrophys. 41, 329.
Zahn J. P. (1989) Astron. Astrophys. 220, 112.
Wolf M., Claret A. et al. (2010) Astron. Astrophys. 509, 18–31.