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Tidal evolution of close eclipsing binaries

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For the first time in the framework of one computational grid constructed on the basis of theoretical stellar evolutionary model tracks by Claret, 2004 the timescales characterizing tidal evolution effects were obtained for 112 close eclipsing binaries of the DMS class (binaries with detached components belonging to the main sequence) from the catalogue by Svechnikov & Perevozkina, 1999. Complex analysis of these timescales with respect to internal structure theory of a star and their comparison with nuclear evolution rate allowed detailed monitoring in unified time sequence the mechanisms responsible for tidal braking.

Keywords: Close eclipsing binaries; Tidal-evolution constants; Apsidal motion

1 DMS class

It is known that close eclipsing binaries (CEBs) with double-line spectra are an important source of basic information about the stellar internal structure. Combined solution of the photometric light curve and the spectroscopic radial velocity curve allows us to investigate stellar interiors using two observational effects: apsidal motion and tidal deformation. Our goal was to calculate an individual set of tidal-evolution constants for each component of a CEB. The statistical sample we deal with is presented by 112 DMS systems taken from the "Catalogue of orbital elements, masses, and luminosities of close eclipsing variables with detached components" by Svechnikov & Perevozkina [16]. According to the modern classification scheme by Svechnikov [15] based on simple criteria such as the localization of the components of a CEB on the Hertzsprung–Russel diagram and Roche lobes filling degree, the abbreviation of DMS is related to a class of binaries in which both components are within the Main Sequence band and have not filled their inner Roche lobes yet. We used theoretical stellar evolutionary models by Claret [2] with built-in tidal-torque constants computed for single stars that is justified because the components of DMS binaries may be considered as single stars which are free from any outflow or exchange of matter.

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2 Observational constraints

All tidal-torque constants presented in the evolutionary models [2] are tabulated as functions of time along evolutionary tracks covering a wide range of initial model mass $M_{\rm mod}$ (0.8–125 $M_\odot$). These are constants of second order associated with radiative damping E_2 and turbulent viscosity λ_2. At the beginning, we must determine the age of a binary and then interpolate to this age all functions associated with the tidal-torque constants. This numerical algorithm generalizing the isochrone method is described in detail in [5]. The tidal-evolution constants computed for CEBs from the catalogue [16] are presented in Table 2 in [7]. Evolutionary models [2] allow us to compute a full family of isochrones in λ_2–M and E_2–M coordinates (Fig. 1).

We relied upon two independent constraints to examine the reliability of the numerical algorithm. The first one is the coincidence of primary and secondary component ages. We analyzed age estimations for CEBs obtained with new models by Claret [2] and old ones by Maeder and Meynet [10] and discussed in [6] the so-called *"rejuvenation effect"* of binaries proper to new evolutionary models. The comparison showed a minimal age gap between components for the majority of CEBs in models by Claret [2] with the exception of low-massive components with masses $\leq$1.5 $M_\odot$.

The second constraint to the numerical algorithm is the agreement between observed $U_{\rm obs}$ and predicted U_A period of apsidal motion. We extracted a sample of 38 eccentric CEBs from the catalogue [16] which are provided with the observational data on $U_{\rm obs}$. Theoretical estimations and observational data are in good agreement (see Table 1 and Fig. 3 in [7]) except several systems with a noticeable relativistic effect indicated in percentage such as AS Cam (20%), NY Cep (28%), V1765 Cyg (7%), AI Hya (20%), DI Her (56%), EW Ori (62%). These systems have been discussed for a long time.

Gaseous clouds in the systems as possible reason of the data divergence were not confirmed by ground-based optical and UV-spectroscopic observations from IUE-satellite. Third body in highly inclined orbit discovered by Kozyreva, Khaliullin [8] in the case of AS Cam could not explain the discrepancy. Attempts to eliminate these differences between U_A and $U_{\rm obs}$ values were made in the framework of non-symmetrical gravitational theory NGT by Mofflat [12]. In spite of its success in some cases we can not recommend NGT as an alternative theory.

For NY Cep ($e = 0.48$) observed period of apsidal motion is estimated 3.5 times as small if compared with theoretical value. Characteristic features of this system (very eccentric orbit and large inclination, $i > 77^\circ$) do not allow to observe secondary eclipse. The incompleteness of light curve could seriously affect the reliability of photometric solution.

Another reason responsible for the discrepancy is a non-coplanarity of the star's equatorial plane with the orbit plane. Observations of DI Her showed that the spin axes of both components are highly inclined with respect to one another and with respect to the orbital axis [1]. The formal difference between the predicted apsidal period $U_A \sim 22620$ yrs and the newly measured value of apsidal motion $U_{\rm obs} \sim 24775$ yrs is now reduced to 10% [3] and the case of DI Her is no more an issue.

For V 1765 Cyg with a rather small relativistic effect of 7% a strong discrepancy between U_A and $U_{\rm obs}$ [11] is noted that may be explained by a very unreliable light curve, which is hardly applied to test apsidal motion.

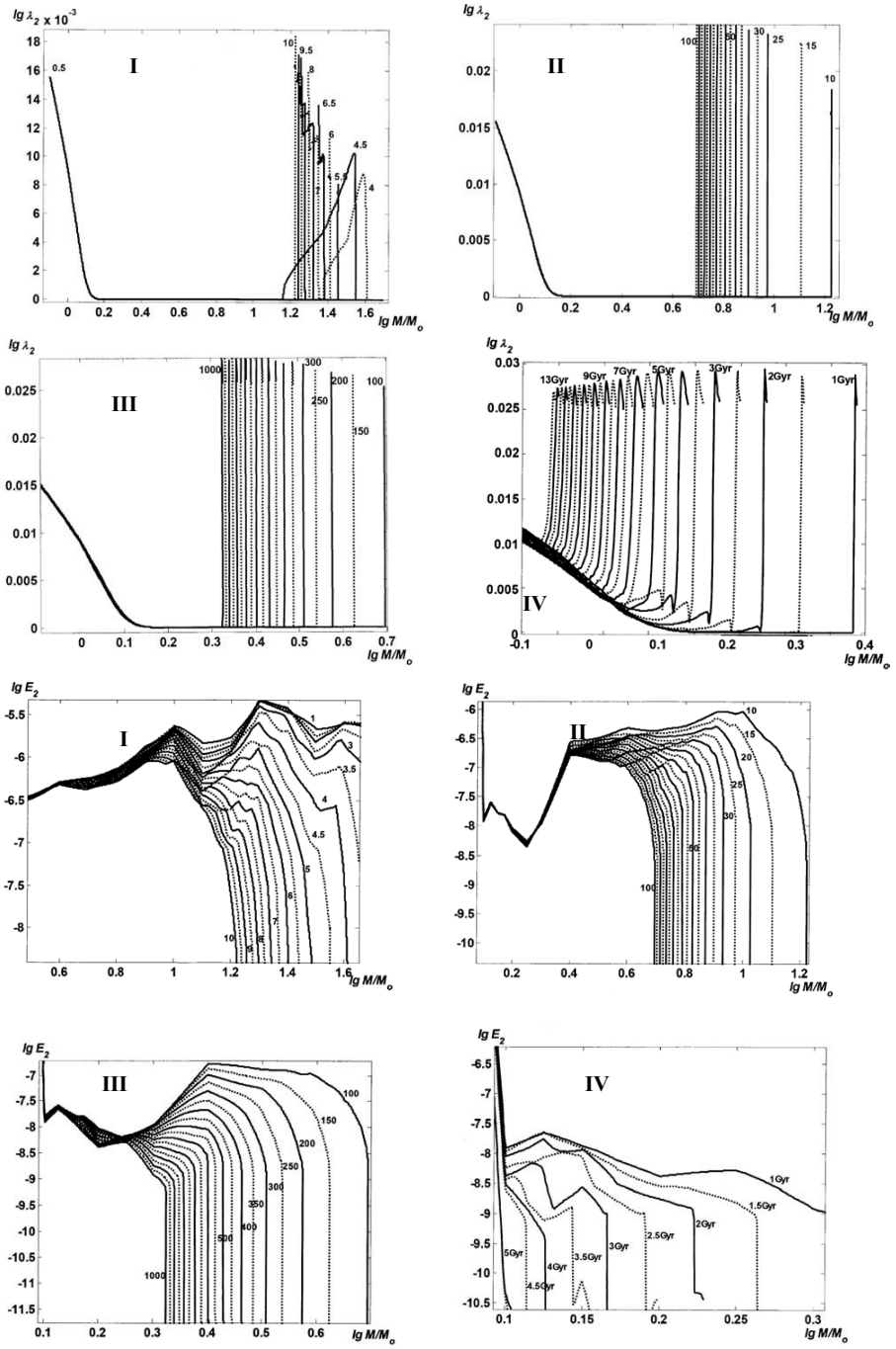


Figure 1 Family of isochrones in coordinates of tidal-torque constants and component's mass: λ_2–M and E_2–M. In windows I–III the isochrones are designated in million years and in window IV – in billion years.

For EW Ori the difference between observed and theoretical apsidal periods according to data by Wolf [17] is eliminated today. Recent photometric and spectroscopic studies of the G0 V detached eclipsing binary EW Ori carried out on the basis of *uvby* light curves and *uvbyβ* standard photometry and high-resolution spectra [4] give $U_{\rm obs} = 16300 \pm 3900$ yrs that is in good agreement with $U_A = 19740$ yrs.

Summing up the results of comparison, we come to the conclusion that the relativistic effect in apsidal motion is no more a conflict between theory and observations. In cases where the divergence between U_A and $U_{\rm obs}$ takes place it is necessary to continue observations. We also note a good agreement of theoretical estimations of apsidal period with the observational ones for the majority of considered CEBs.

3 Upper estimation of the tidal-evolution timescales

Mutual tidal-rotary deformation in the case of an eccentric CEB may be considered as a set of gravity waves running on the surface of each star and damping as they penetrate in the deep interior of the star. This wave packet including forced oscillations of the star is known as the tide, the evolution of which is defined by the stellar structure. Depending on the type of stellar envelope, different dissipation mechanisms are run. Observational proof for the dissipation is a phase shift between surface brightness distributions of components. According to calculations by Zahn [18,19] the turbulent viscosity could be responsible for a phase shift in stars with a large outer convective zone ($M_{1,2} \leq 1.5 M_{\odot}$) as for early spectral class stars it is the radiative damping.

The consequences of mutual tidal effects in a CEB are the spin synchronization of components with orbital revolution and the orbital circularization. Components aim to minimize the time-variation of tidal constituent until the orbital configuration proves to be stable. It becomes apparent in a tendency to decrease the orbital eccentricity with the CEB age. Knowledge of tidal-torque constants allows us to compute the times of synchronization and orbit circularization in the framework of non-adiabatic analysis constructed by Zahn [18, 19].

An alternative method for estimation of circularization timescale for early-type binaries is developed by Khaliullin & Khaliullina [9]. In that paper the problem of unknown initial parameters of the CEB so important for prediction of its dynamical history is resolved by back in-time integration from the current values of orbital and absolute parameters to the zero-age ones. The integration uses evolutionary stellar models by Claret [2]. The reconstructed parameters are then implemented into Zahn's theory [18, 19].

A picture of tidal interactions in a close binary would be incomplete without magnetic braking, which is important for low-massive CEBs able to support intensive thermal stellar magnetic wind. It leads to the deceleration of component spins and hence to orbital angular momentum loss. Magnetic braking forces components to approach one another and opens the possibility of earlier outflow of matter through L_1. If the approach rate of components excels nuclear evolution tempo, then the use of evolutionary models-tracks for age estimation is poorly justified. Observational data on essential deceleration of the rotation rate of single stars with age reflected in the law by Scumanich [14] have served as an empirical basis for the scenario of magnetic braking in CEBs.

We selected 20 CEBs with $M_{1,2} \leq 1.5 M_\odot$ from the catalogue [16] which are able to support magnetic stellar wind. For its efficiency the proximity of major semi-axis to $A_{\min} \approx 6 \cdot (M_1/M_\odot)^{1/3}$ is necessary [13]. Analysis of basic timescales is presented in Table 1.

Table 1 Comparison of timescales (in mln yrs) characterizing different regimes of CEB evolution: nuclear $\tau_{\rm NE}$, component synchronization $\tau_{\rm syn}$, orbit circularization $\tau_{\rm cir}$, magnetic braking $\tau_{\rm MB}$, components merging $\tau_{\rm merge}$.

No	Catalogue number	Star name	$M_1/M_\odot$ $M_2/M_\odot$	$A/R_\odot$ $A_{\min}/R_\odot$	$\tau^1_{\rm syn}$ $\tau^2_{\rm syn}$	$\tau_{\rm cir}$ $\tau_{\rm MB}$	$\tau_{\rm NE}$ $\tau_{\rm merge}$
1	1	*AN And*	1.90 ± 0.05	13.25	3570	$>> \tau_{\rm Hubble}$	1700
			1.12 ± 0.03	7.43	0.001	1000	2370
2	12	*AD Boo*	1.36 ± 0.02	9.29	0.28	37.6	4500
			1.16 ± 0.02	6.65	0.21	3230	5600
3	38	*RZ Cha*	1.52 ± 0.02	12.18	705	$>> \tau_{\rm Hubble}$	3270
			1.51 ± 0.02	6.89	760	2500	4900
4	45	*V442 Cyg*	1.56 ± 0.02	10.79	242	$>> \tau_{\rm Hubble}$	3000
			1.41 ± 0.02	6.95	1.5	4250	6000
5	47	*V477 Cyg*	1.79 ± 0.03	10.88	–	–	2000
			1.35 ± 0.02	7.28		14000	–
6	52	*BH Dra*	2.10 ± 0.05	9.18	20.9	5850	1300
			1.05 ± 0.03	7.68	0.042	3000	3300
7	56	*CW Eri*	1.59 ± 0.03	11.74	463	$>> \tau_{\rm Hubble}$	2900
			1.33 ± 0.03	7.0	0.98	6700	8300
8	57	*YY Gem*	0.59 ± 0.01	3.87	–	–	$>> \tau_{\rm Hubble}$
			0.59 ± 0.01	5.03		4300	–
9	59	*TX Her*	1.62 ± 0.03	9.89	287	$>> \tau_{\rm Hubble}$	2700
			1.45 ± 0.03	7.05	11.3	7700	8100
10	63	*V819 Her*	1.53 ± 0.07	9.92	188	$>> \tau_{\rm Hubble}$	3200
			1.11 ± 0.05	6.91	0.19	5200	6760
11	67	*HS Hya*	1.34 ± 0.02	7.84	0.5	53.8	4700
			1.29 ± 0.02	6.61	0.26	3000	3150
12	70	*CM Lac*	1.88 ± 0.03	8.62	–	1142	1800
			1.47 ± 0.02	7.40	13.26	4500	4500
13	73	*TX Leo*	2.75 ± 0.12	11.91	3.2	760	585
			1.05 ± 0.05	8.40	0.008	925	1315
14	76	*FL Lyr*	1.22 ± 0.02	9.16	0.32	59	6200
			0.96 ± 0.02	6.41	0.49	9300	11575
15	92	*EE Peg*	2.15 ± 0.03	12.14	121	$>> \tau_{\rm Hubble}$	1200
			1.33 ± 0.02	7.74	6.08	7400	7800
16	95	*V467 Per*	2.00 ± 0.09	8.2	4.05	1040	1500
			0.38 ± 0.02	7.55	–	300	1385
17	97	*PV Pup*	1.57 ± 0.02	8.63	80	14680	3000
			1.56 ± 0.02	6.97	93	4100	4450
18	98	*TY Pyx*	1.22 ± 0.02	12.26	0.226	40	6200
			1.20 ± 0.02	6.41	0.15	13500	18300
19	105	*CD Tau*	1.40 ± 0.02	13.35	2.1	495	4150
			1.31 ± 0.02	6.71	0.76	13800	16080
20	111	*HD 84207*	0.97 ± 0.02	6.46	0.022	1.65	12000
			0.95 ± 0.02	5.94	0.025	3000	13120

4 Conclusion

The projection of the observational data on the evolutionary tracks grid is productive to determine the evolutionary status of a star. Knowledge of tidal-torque constants allows us to predict the duration of tidal effects determining the star evolution. The trustworthiness of the computational algorithm for tidal-torque constants realized on the basis of the isochrone concept was checked in the comparison of observational and theoretical values of the apsidal period of CEB. The constraint concerns the problem of the relativistic effect in apsidal motion. New observational data allowing the reconstruction of the projective velocities (Rossiter–McLaughlin effect) improved the situation with some CEBs with a large relativistic effect.

References

[1] S. Albrecht, J. Winn, J. Carter, I. Snellen, E. de Mooij, Astrophysics Journal, **726**, 68 (2011)
[2] A. Claret, Astronomy and Astrophysics, **424**, 919 (2004)
[3] A. Claret, G. Torres, M. Wolf, Astronomy and Astrophysics, **515**, 4 (2010)
[4] J.V. Clausen, H. Bruntt, E.H. Olsen, B.E. Helt, A. Claret, Astronomy and Astrophysics, **511**, 22 (2010)
[5] G.N. Dryomova, M.A. Svechnikov, Astrophysics and Space Science, **283**, 309 (2003)
[6] G.N. Dryomova, M.A. Svechnikov, Astrophysics, **50**, 239 (2007)
[7] G.N. Dryomova, M.A. Svechnikov, Kinematics and Physics of Celestial Bodies, **27**, 62 (2011)
[8] V.S. Kozyreva, Kh.F. Khaliullin, Astronomy Reports, **43**, 679 (1999)
[9] Kh.F. Khaliullin, A.I. Khaliullina, MNRAS, **401**, 257 (2010)
[10] A. Maeder, G. Meynet, Astronomy and Astrophysics Supplement Series, **76**, 411 (1988)
[11] P. Mayer, P. Hadrava, P. Harmanec, D. Chohol, Bulletin of the Astronomical Institute of Czechoslovakia, **42**, 230 (1991)
[12] J.W. Mofflat, Physics Review D, **39**, 474 (1989)
[13] E.I. Popova, A.V. Tutukov, L.R. Youngelson, Letters in Astronomy Journal, **8**, 297 (1982)
[14] A. Skumanich, Astrophysics Journal, **171**, 565 (1972)
[15] M.A. Svechnikov, Catalogue of orbital elements, masses and luminosities of variable stars of close binaries, Scientific Notes of Ural State University, Astronomy series, N88, Issue 5, 271 p., Yekaterinburg, 1969
[16] M.A. Svechnikov, E.L. Perevozkina, Catalogue of orbital elements, masses and luminosities of variable stars of DMS-type and some results of its statistical treatment, Ural State University press, Yekaterinburg, 1–5, 1999 (ftp://cdsarc.u-strasbg.fr/pub/cats/V/121)
[17] M. Wolf, L. Sarounova, V. Kozyreva, T. Pogrocheva, IBVS, N 4542 (1997)
[18] J.-P. Zahn, Astronomy and Astrophysics, **41**, 329 (1975)
[19] J.-P. Zahn, Astronomy and Astrophysics, **220**, 112 (1989)