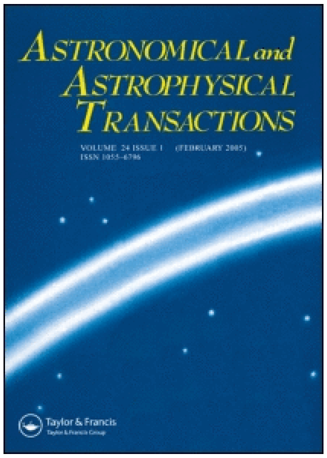

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An investigation of the tidally driven period changes in detached binary systems through **O**-**C** time series analysis: the case of RT And and WY Cnc

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An investigation of the tidally driven period changes in detached binary systems through *O–C* time series analysis: the case of RT And and WY Cnc[†]

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Detached binary systems are subjected to a variety of physical mechanisms which are able to change their period in a continuous way and in a broad band of timescales. Assuming that these changes should be detectable in *O–C* diagrams in a way specified by the physical theory of the underlying mechanisms, we carry out a preliminary study in a properly selected sample of detached binaries, where no mass transfer is expected. We are primarily interested in finding traces of tidal moments in observed orbital period changes (possibly coupled with stellar wind angular momentum losses). We focus our attempts on two short-period chromospherically active binaries (RT And and WY Cnc), whose expected period changes rates are found to be close to those derived by means of time series analysis. Emphasis is also given to systems which show a remarkably constant orbital period, in disagreement with the values expected by theory.

Keywords: Tidal evolution; *O–C* time series; Short-period detached binaries; Main sequence; RT And; WY Cnc

1. Introduction

The tidal interaction between the components of close binaries is one of the basic physical mechanisms driving their evolution. For instance, the interaction of tidal torques with the stellar wind seems to be the main mechanism driving the components of detached configurations into physical contact.

After the research by Claret and Cunha [1] and Goodman and Oh [2], a new era began on the study of tidal interaction. These workers found that the Zahn classical tidal theory anticipates a very low rate of orbital shrinkage or very long circularization timescales (approximately by two orders of magnitude) in binaries with late-type main-sequence (MS) components. Hence, new theories of dynamic tides developed, which take into account the complicated

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non-adiabatic interaction between the tidal flow raised by a close companion to a solar-type star and the normal modes of oscillation of its interior. It was found that resonances between different tidal forcing frequencies and stellar normal g modes could enhance greatly the tidal torque (possibly by a factor of 10^3–10^4 [3]). However, since these resonances are found to be very narrow and widely spaced, each system is influenced by the enhanced tidal torques only for short time intervals. As a result, the discrepancy with the observed circularization cut-off periods remains, unless the binary parameters are such that a low orbital harmonic falls in the frequency regime of the very closely spaced q-mode resonances found by Savonije and Witte [4]. The computed circularization cut-off periods of MS binaries fit the observed periods much better in this case, but not satisfactorily yet!

Given the aforementioned theoretical developments and uncertainties, we intend to check whether traces of tidal evolution could be detectable in the O–C time series of detached binaries with MS components. We are also interested to see whether ‘direct’ tidal torque estimations, which rely on the observed long-timescale variations in the orbital period, can be achieved. In particular, such estimations will be based on the generalized $\dot{J}$–$\dot{m}$–$\dot{P}$-type relation proposed by Kalimeris and Rovithis-Livaniou [5]:

$$\frac{\dot{J}}{J_{\mathrm{orb}}} = \frac{1-q}{M_2}\dot{M}_2 + \frac{2q+3}{3qM_{\mathrm{tot}}}(\dot{m}_{\mathrm{L2}} + \dot{m}_{\mathrm{w}}) - \frac{e}{1-e^2}\dot{e} + \frac{\dot{\Omega}_{\mathrm{kep}}}{\Omega_{\mathrm{kep}}} + \frac{4}{3}\frac{\dot{P}}{P} + \sum_{i=1}^{2}\frac{J_i}{J_{\mathrm{orb}}}\left(5\frac{\dot{R}_i}{R_i} + \frac{\dot{\Omega}_i}{\Omega_i} + \frac{\dot{I}_{N,i}}{I_{N,i}}\right). \tag{1}$$

2. Selection criteria and candidate binaries

To isolate the effects of the classic thermally driven mass transfer from the orbital period variations, we are restricted to detached binaries. Among these, we initially focus on short-period pairs, where O–C data files are the finest and longest and where the stellar parameters are more reliable. As a consequence, the tidal torques and the stellar wind angular momentum losses (AMLs) remain the most significant factors of binary evolution.

Although, under conservative conditions, tidal torques are expected to be very weak in short-period binaries (owing to earlier circularization and synchronization), AMLs due to a stellar wind perpetually impose desynchronization trends on the components and, in this way, tidal interaction remains active. In this case, as the stellar wind diffuses the components’ spin angular momentum, the tidal torques replenishes it from the orbital reservoir. Consequently, the two companions become closer, the tidal torques are enhanced, the components are enforced to spin more rapidly, the stellar dynamo and the rate of AMLs increase and, finally, the orbit shrinks even more quickly. As this cyclic interaction continues, a feedback mechanism (often termed the *tidal* or *orbital instability*) is developed and continuously shrinks the orbit. This instability can be either weak (when the rate of the wind diffuses, the spin momentum is higher than the rate with which the tidal torques transfer momentum from the orbit to the spin) or strong (when the tidal moments transfer angular momentum from the orbit to the spin more rapidly than the wind diffuses it). As a result, a tidally driven or wind-driven orbital decay is expected to be observed in binaries with magnetically active components.

On the other hand, if both components possess radiative envelopes (and presumably they are not surrounded by a magnetically driven stellar wind), then only a weak tidal interaction is expected to drive a long-timescale orbital evolution.

Considering the aforementioned ideas, in a limited time interval of decades, covered by the current O–C time series, a period reduction at a constant rate is expected to appear in O–C

diagrams (through concave parabolic modulation) related to binaries of late-type components (*i.e.* possessing convective envelopes, referred to as C–C binaries hereafter). In the case of binaries consisting of early-type components (i.e. possessing radiative envelopes, referred to as R–R binaries hereafter), the orbital period is expected to be invariable owing to very-low-wind (or no-wind) AMLs.

In this preliminary study, we have collected a large number of detached binaries with MS components and orbital periods less than about 2 days. We have used *An Atlas of O–C Diagrams of Eclipsing Binary Stars* [6] as the main guide of our research. 'A catalog of chromospherically active binary stars' [7] and 'Catalog and atlas of eclipsing binaries' [8] were also used as additional sources. Lack of knowledge of some parameters was completed and checked from the *General Catalog of Variable Stars* [9]. A list initially containing 124 systems was formed in this way. Among these, 61 were detached binaries with MS components whose absolute parameters were available.

However, only 17 systems were suitable for further investigation because of incomplete time-series data files, the high level of noise and, in some cases, a dominant sinusoidal term (owing to either the presence of a third body or possible cycles of intense magnetic activity) or apsidal motion. After careful classification of the remaining binaries according to the envelope type of their components (based on the mass criterion of 1.25 solar masses) and a thorough examination of the modulation of their O–C diagrams, we obtained the following five preliminary results.

(i) No evidence of any kind of period changes was found for eight systems. Four of these (CM Lac, RX Her, MN Cas and BP Vul) belong to the R–R class and remarkably the other four (ER Vul, BH Vir, UV Psc and FL Lyr) belong to the C–C class.
(ii) A nearly parabolic modulation was found to be characteristic for only four systems, all belonging to the C–C group. Three of these reveal a decreasing period (RT And, YY Gem and WY Cnc) while UV Leo (perhaps SV Cam too) reveals an increasing period.
(iii) Irregular changes were found to take place in the remaining five systems, four of which (XY UMa, SV Cam, CG Cyg and EU Hya) belong to the C–C or R–C class and one (TX Her) to the R–R class.
(iv) Only three systems of the C–C class (RT And, YY Gem and WY Cnc) show a consecutively systematic period reduction, while four more C–C-type binaries (ER Vul, BH Vir, UV Psc and FL Lyr) have revealed a remarkably constant orbital period for over a century.
(v) The R–R class behaves in accordance with general expectations, as no systems show a parabolic or an irregular modulation (apart from TX Her, which is highly suspected to contain an unseen companion).

3. The case of RT And and WY Cnc

Our attempts focused on two late-type binaries, whose O–C time series were clear enough to extract reliable information as far as the observed rate of period reduction is concerned. After having collected all the available times of minima (to our knowledge), we removed those determined by visual estimations and by using patrol plates because of their considerable scatter. The final diagrams consisted of 207 points for the case of RT And and 51 points for the case of WY Cnc, covering time intervals of 92 years and 40 years respectively (figure 1). The O–C values were calculated using the following ephemeredes: for RT And,

$$\mathrm{MinI\ (HJD)} = 2\,441\,141.889 + 0.628\,929\,513E$$

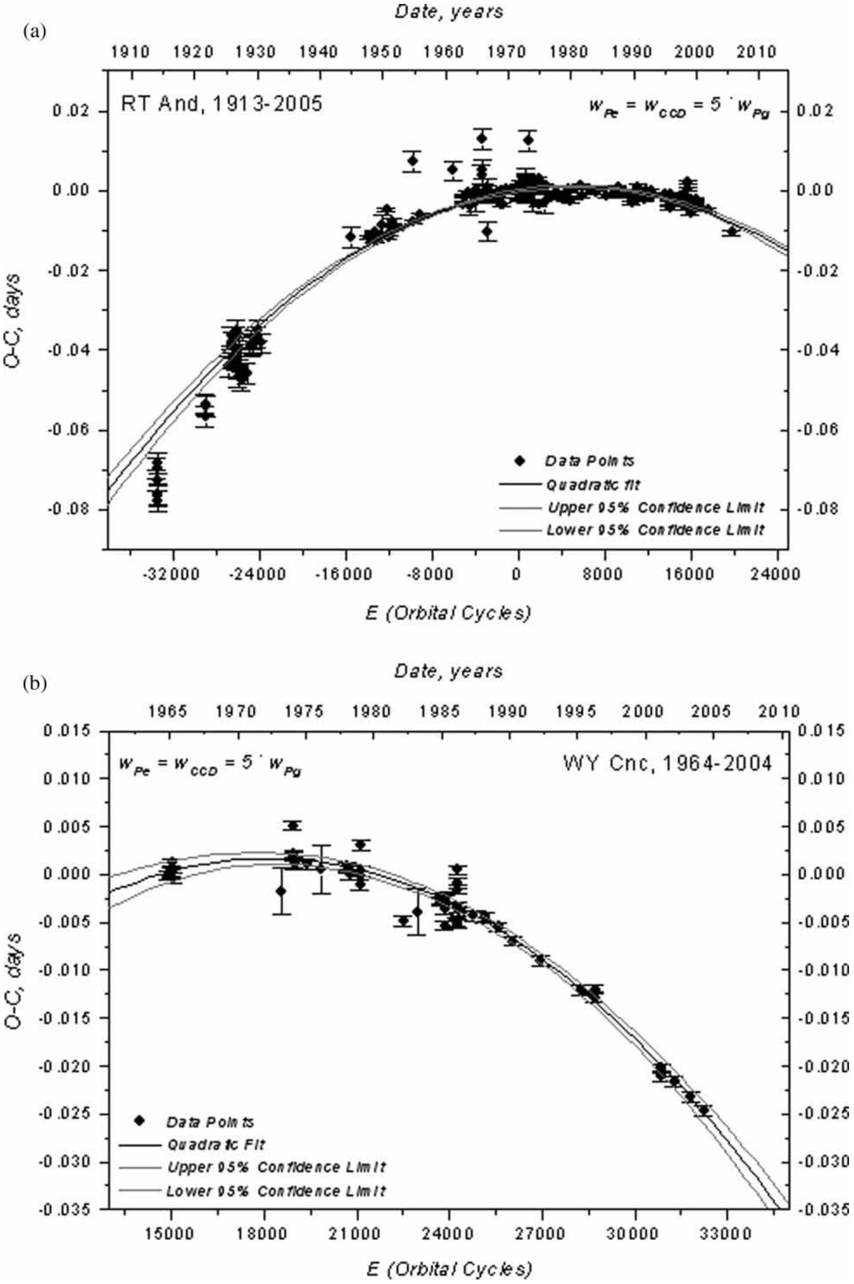

Figure 1. *O–C* diagrams of (a) RT And and (b) WY Cnc fitted by a least-squares quadratic polynomial. Different error bars correspond to times of minima determined by different techniques (*i.e.* using a charge-coupled device camera, a photoelectric photometer or a series of photographic plates as detector). The faint lines near the quadratic line of each diagram hint at the upper and the lower boundaries between which the fit is successful to a 95% confidence level.

and, for WY Cnc,

$$\mathrm{MinI\ (HJD)} = 2\,426\,352.389\,5 + 0.829\,371\,22E,$$

where MinI is the primary minimum and HJD is the heliocentric Julian date.

Table 1. Absolute and orbital parameters of RT And and WY Cnc.

Absolute parameters (units)	Value for the following systems		Orbital parameters (units)	Value for the following systems	
	RT And†	WY Cnc‡		RT And	WY Cnc
T_1 (K)	6095	5520	P (days)	0.6289	0.8294
T_2 (K)	4732	3740	$\Omega_{\rm kep}$ (days^{-1})	9.9908	7.5756
L_1 (units of $L_\odot$)	1.950	0.824	$A_{\rm orb}$ (units of $R_\odot$)	3.9941	4.1334
L_2 (units of $L_\odot$)	0.367	0.074	$k_{2,1}$§	0.0100	0.0207
M_1 (units of $M_\odot$)	1.24	0.86	$k_{2,2}$§	0.0330	0.0641
M_2 (units of $M_\odot$)	0.91	0.51	k_1^2§	0.245	0.284
Q	0.734	0.593	k_2^2§	0.302	0.362
R_1 (units of $R_\odot$)	1.26	0.992	$t_{{\rm syn},1}$ (years)	3287.37	14690.38
R_2 (units of $R_\odot$)	0.90	0.646	$t_{{\rm syn},2}$ (years)	11642.21	111472.55

†From [11].
‡From [12].
§From [13].

Aiming to determine the theoretical rate of the period decrease, we firstly applied the generalized $\dot{J}$–$\dot{m}$–$\dot{P}$ equation, presented above (see equation (1)), taking into account only the terms associated with the tidal interaction between the two components and ignoring, to a first approximation, the other components. Under this condition, the equation reduces to

$$\dot{P} = 3P \sum_{i=1}^{2} \frac{J_i}{J_{\rm orb}} \frac{\dot{\omega}_i}{\omega_i}, \tag{2}$$

where $\dot{\omega}_i = -(\omega_i - \omega_{\rm kep})/t_{{\rm syn},i}$ is the rate at which the angular velocity of each component changes. Likewise, $J_i = I_i \omega_i = k_i^2 M_i R_i^2 \omega_i$ and $J_{\rm orb} = (M_1 M_2 / M_{\rm tot}) A_{\rm orb}^2 \omega_{\rm kep}$ are the angular momentum of each component and the angular momentum of the system, respectively.

Accurate absolute and orbital parameters of the examined systems are listed in table 1. This table also contains two parameters directly connected with the components' internal features (dimensionless gyration radius k_i^2 and apsidal motion constant $k_{2,i}$ of each member i) and precisely computed by models of the stellar structure. Moreover, the orbital radius $A_{\rm orb}$ was simply calculated by the well-known Kepler law. Finally, the synchronization time $t_{{\rm syn},i}$ of each component was determined according to the classical Zahn [10] dissipation theory. Since the examined binaries consist of components that both possess convective envelopes, the tidal friction is conveyed mainly to turbulent viscous dissipation and thus the suggested synchronization time is given by the following formula:

$$t_{{\rm syn},i} = \frac{1}{6q^2 k_{2,i}} \left(\frac{M_i R_i^2}{L_i} \right)^{1/3} k_i^2 \left(\frac{A_{\rm orb}}{R_i} \right)^6 . \tag{3}$$

4. Results according to the Zahn theory

Our preliminary results are listed in table 2. It should be pointed out that, although the equatorial velocity $\upsilon_{{\rm eq},i}$ of each component is determined by high-resolution spectroscopic studies, based on the rotational broadening, the uncertainty which accompanies this velocity is about 2 km s^{-1}. This value plays a major role in the present study and, not rarely, seems too large to render our calculations valid.

Table 2. Observed and theoretical rates at which the orbital period of each system changes.

	Value for the following systems	
Parameter (units)	RT And	WY Cnc
$\upsilon_{\mathrm{eq},1}$ (km s^{-1})	100†	100‡
$\upsilon_{\mathrm{eq},2}$ (km s^{-1})	80†	92‡
Ω_1 (days^{-1})	9.8664	12.5319
Ω_2 (days^{-1})	11.0504	17.7045
$\mathrm{d}\Omega_1/\mathrm{d}t$ (days^{-2})	1.04×10^{-7}	-9.24×10^{-7}
$d\Omega_2/dt$ (days^{-2})	-2.49×10^{-7}	-2.49×10^{-7}
$(\mathrm{d}P/\mathrm{d}t)_{\mathrm{theor}}$	-1.24×10^{-10}	-1.45×10^{-8}
$(\mathrm{d}P/\mathrm{d}t)_{\mathrm{obs}}$	1.31×10^{-10}	-3.22×10^{-10}

†From [11].
‡From [14].

Concerning the case of RT And, the theoretical rate at which the orbital period changes was found to be in excellent agreement with the observed value. This fact is very important because the whole procedure, in this particular case, was supported by very accurate data. Stellar parameters of the secondary component are clearly known, 207 accurate times of minima are available and the *O–C* diagram shows a long-term parabolic trend for a whole century. Unfortunately, as far as WY Cnc is concerned, data used in the procedure were much less accurate and incomplete. The diagram consists of 51 points only, it covers a very limited time interval of 40 years and the absolute elements of the components are not well known. As a result, their equatorial velocities are doubtful (e.g. the primary velocity equals 100 km s^{-1} according to Arevalo and Lazaro [14], but it equals 75 km s^{-1} according to Pojmanski [15]). This could be the reason for the difference of about two orders of magnitude between the theoretical and the observed values.

In any case, despite ignoring the terms related to magnetically driven stellar winds and magnetic braking mechanisms, the Zahn tidal theory seems sufficient to explain the observed period variations. Consequently, no evidence of enhanced tidal interaction was detected in the present study.

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