

Detection of a cyclic period change in the contact binary TU UMi

D. Zengin Çamurdan¹  and B. Özkardes^{2,3}

¹ *Ege University, Science Faculty, Department of Astronomy and Space Sciences, 35100 Bornova, Izmir, Turkey, (E-mail: dicle.zengincamurdan@ege.edu.tr)*

² *Department of Space Science and Technologies, Faculty of Arts and Sciences, Çanakkale Onsekiz Mart University, Terzioğlu Kampüsü, TR-17020, Çanakkale, Turkey,*

³ *Çanakkale Onsekiz Mart University, Astrophysics Research Center and Ulupınar Observatory, TR-17100, Çanakkale, Turkey*

Received: February 7, 2022; Accepted: April 26, 2022

Abstract. This study aims at timing the eclipses of the binary star TU UMi. The times of minima are taken from the literature, from our observations in April 2004 and from TESS observations between 2019 and 2022. The orbital period analysis of the system indicates that there is a cyclic oscillation with an amplitude of 0.0081d and a period of 9.03 yr, accompanied by a continuous decrease at a rate of $dP/dt = -1.12 \times 10^{-7} \text{ d yr}^{-1}$. We study the secular evolution of the orbital period of the system and the possibility of the existence of a third companion or the magnetic activity cycle of the primary component in the system.

Key words: Stars: binaries: eclipsing; Stars: Individual TU UMi

1. Introduction

Variability of TU UMi (BD+76544, HIP 73047) was detected during the Hipparcos mission (ESA, 1997) with a period of $0^d.188546$. Duerbeck (1997) reported the system as a contact binary of EW, or a pulsating star with a doubled period. Kazarovets et al. (1999) and Rodríguez et al. (2000) classified the source as a delta Scuti type variable star. However, Rolland et al. (2002) observed the system in Strömgren filters and showed that TU UMi is outside of the instability strip of delta Sct-type pulsators using a colour-magnitude diagram.

TU UMi was observed spectroscopically by Pych & Rucinski (2004) who reported that TU UMi is a triple system containing a close binary and the light contribution of the third component around the contact binary is $L_3/(L_1+L_2) = 1.25 \pm 0.15$. Pych & Rucinski (2004) also determined the period of TU UMi at twice the Hipparcos original period. Rucinski et al. (2005) presented the first radial velocity orbit of the system: $K_1 = 35 \pm 15 \text{ kms}^{-1}$, $K_2 = 220 \pm 20$

$km\,s^{-1}$ and the radial velocity of for the third companion is $-4.16 \pm 0.20 km\,s^{-1}$. They calculated the mass function of $(M_1 + M_2)\sin^3 i = 0.65 \pm 0.27 M_\odot$ and an extremely low mass ratio of $M_2/M_1 = 0.16 \pm 0.07$ and classified it as an EW/W-type binary. Kjurkchieva et al. (2010) observed brightness changes of the system in *BVR* filters. They reported that the light curves of the system are asymmetric with steeper decreasing branches and unequal maxima and suggested that the third bright companion may be responsible for these variations. Furthermore, TU UMi was included in the Asteroseismic Target List (Schofield et al., 2019) of solar-like oscillators to be observed in 2-minute cadence with TESS and some of the fundamental parameters combining the Gaia DR2 and Hipparcos data were given in this study. Although the minima times of the system were reported by many researchers, the *O-C* period variation was only pointed out by Kjurkchieva et al. (2010), who analyzed the data from the years 2003-2009. Based on a 6-year eclipsing cycle of TU UMi, Kjurkchieva et al. (2010) interpreted that the *O-C* values are increasing linearly in time as the consequence of the low precision of the determined period.

In this paper, we reconsidered all reported minima times in the literature and used the TESS data which were obtained between 2019 and 2022, and the *UBVR* observations that were obtained in 2004 at the Ege University Observatory, as well. The period change was then investigated in detail, based on all available light minimum times and the results are presented. Here, we report on the detection of a long-term period decrease superimposed on a cyclic change in the orbital period of TU UMi and discuss the plausible cause of these period changes. We performed the solution of the light-travel time effect (LITE) via the presence of an additional companion and magnetic activity cycle for TU UMi with new minima times.

2. Observations and determinations of the times of minima

Johnson *UBVR* observations of TU UMi in terms of differential magnitudes with respect to the comparison star HD131358 were carried out at the Ege University Observatory (EUO) with the 0.48-m Cassegrain telescope equipped with a high-speed three-channel photon-counting photometer (Kalytis, 1999). Fainter comparison and check stars (i.e. Comp. and Chk.) were chosen and are listed in Tab. 1. The observations were performed during 8 nights in 2004 in *UBVR* bands and typical exposure times were 10 s. We obtained a total of 432 measurements in all bands. All differential magnitudes were corrected for atmospheric extinction and heliocentric corrections were applied to all observing times. The amplitudes of variable light are 0.055^m , 0.056^m , 0.062^m , and 0.052^m for *UBVR* bands, respectively. Hence, both eclipse depths are shallow and it is difficult to distinguish primary and secondary minima in our observations. The primary eclipse is deeper than the secondary one by up to 0.005^m . Since our

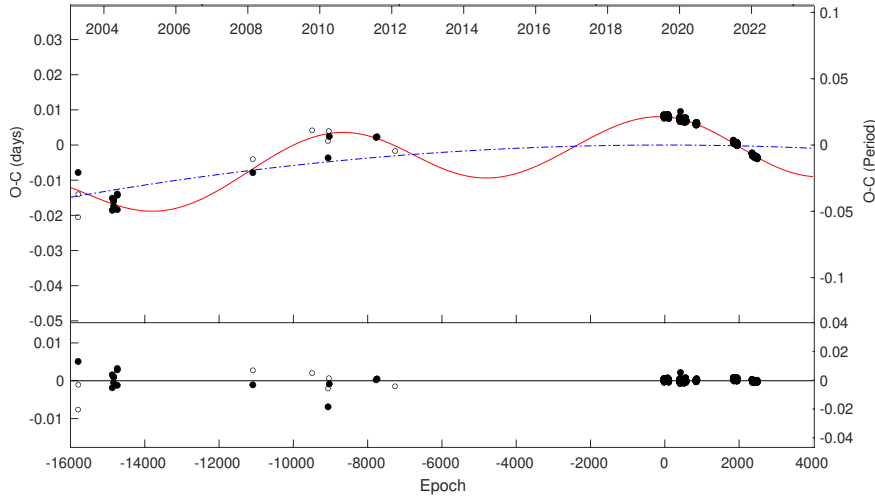


Figure 1. The $O-C$ diagram of TU UMi (upper part), where the solid line represents the theoretical LITE variation caused by a 3rd body and the dashed line represents the quadratic ephemeris, and the $O-C$ residuals obtained after the subtraction of LITE (lower part).

major goal is to obtain differential photometry for program stars, we did not observe photometric standard stars during our runs.

Tab. 1 gives an observing log for data observed at the Ege University Observatory (EUO). To study orbital period changes, we collected a total of 14 light minimum times. From the new observations, eight light minimum timings were determined by the least-squares fit of the observed data using the K-W method (Kwee & van Woerden, 1956). Furthermore, The TESS light curves of TU UMi are used to determine the mid-times of primary and secondary eclipses of the system, where we obtain 904 minima times in total, of which 454 are the primary minima and 450 the secondary times of minimum. The minima times data come from observations sector 14, 15, 20, 21, 22, 26, 40, 41, 47, and 48. Forty-five computed minima times using TESS data are included in Tab. 2, while the rest of them are available upon request. Those individual light minimum times, together with their errors, and the $O-C$ residuals are listed in Tab. 2.

Table 1. Coordinates of the variable, comparison and check stars.

Star	$\alpha_{J2000.0}$	$\delta_{J2000.0}$	mag (V)
TU UMi	14 55 43.80	+76 18 23.65	8.75 ± 0.01
HD 131358 (Comp.)	14 47 10.16	+76 02 32.13	7.38 ± 0.01
HD 135118 (Chk.)	15 06 53.63	+75 59 07.04	8.29 ± 0.01

3. Analysis of period change

The eclipse timing data used in the $O-C$ analysis of TU UMi covers almost 19 years from March 2003 to February 2022. An $O-C$ diagram with all those timings is plotted in Fig. 1 by using the following light element, where $T_0 = 2458696.10801$ (HJD) and $P = 0^d.377088$ are the conjunction time obtained in this study from TESS observations and the orbital period taken from [Rucinski et al. \(2005\)](#), respectively.

The $O-C$ diagram including minimum times using the TESS data is shown in Fig. 1. As it can be seen in the figure, a systematic deviation from the linear ephemeris is present in the current $O-C$ diagram and it has a downward curving parabolic character indicating a period decrease of the system, which was not discovered by the previous $O-C$ diagrams ([Kjurkchieva et al., 2010](#)). However, with the current data, one additional structure in the $O-C$ diagram came out which can be seen in the residuals from the parabolic approximation in Fig. 1. This additional structure has a cyclic character superimposed on the general quadratic trend. We have quickly tested the significance of this cyclic character by looking at the difference in the values of the sum of squared residuals of the fits to the $O-C$ data with only parabolic and parabolic+cyclic approximations. The sum of squared residuals $\Sigma(O-C)^2$ turns out to be 0.021 day^2 and 0.0026 day^2 for only parabolic and parabolic+cyclic fits, respectively. As seen from these values the sum of squared residuals substantially improved when the cyclic variation has been taken into account.

To search for the period of the cyclic variations, a periodogram analysis with PERIOD04 ([Lenz & Breger, 2005](#)) was carried out for the quasi-sinusoidal variation seen in the residuals of $O-C$ after the subtraction of a quadratic term, whose result is displayed in Figure 2. We found a significant peak in the power spectrum mainly located around the frequency of $f_1 = 3.00744 \times 10^{-4} \text{ d}^{-1}$, which corresponds to a period of 3325 days ($\sim 9.1 \text{ yr}$). This value is then used as an initial P_{mod} parameter for the non-linear least-squares fitting the $O-C$ values.

The cyclic variations are usually explained either by the light travel time effect (LTTE) via the presence of a third body, or by magnetic activity cycles in one or both components because they are late-type stars. To search for the LTTE effect, the calculated the $O-C$ values based on all times of minima were fitted by the equation:

$$O - C = O - [T_0 + P_{orb} \times E + \frac{1}{2} \frac{dP}{dE} \times E^2 + \frac{A}{\sqrt{1 - e^2 \cos^2 \omega}} \times \left\{ (1 - e^2) \frac{\sin(\nu + \omega)}{(1 + e \cos \nu)} \right\}] \quad (1)$$

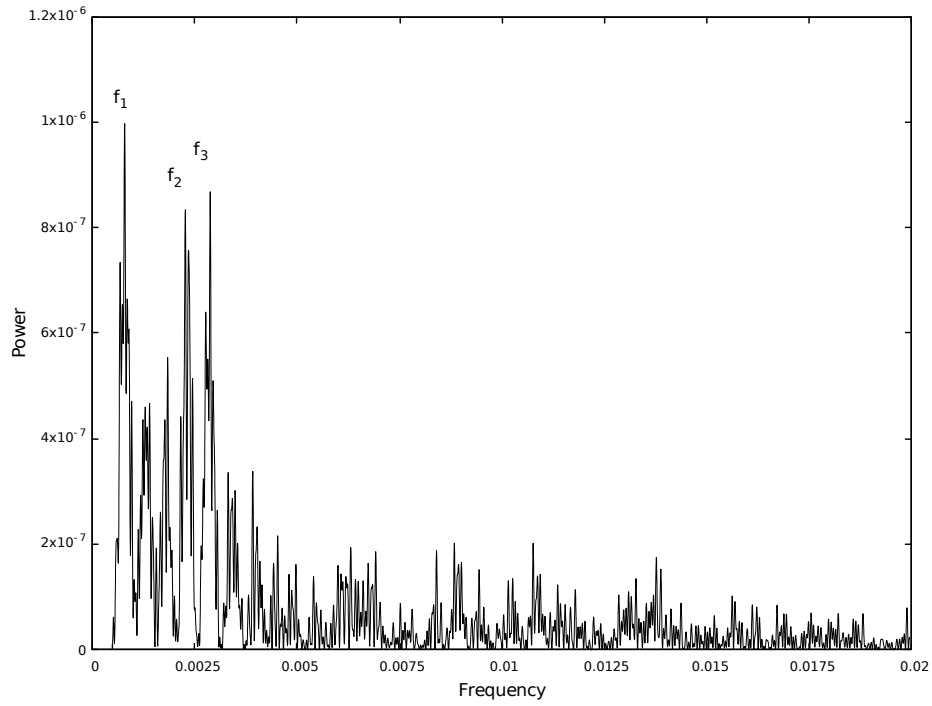


Figure 2. The power spectrum of the residuals from the quadratic fit.

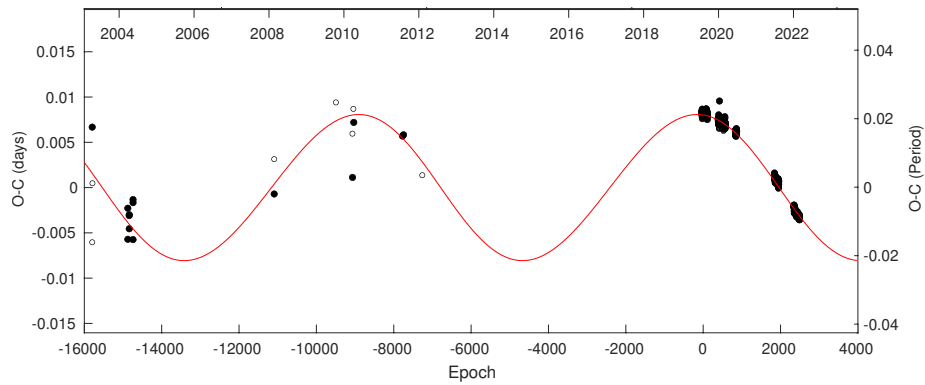


Figure 3. The $O-C$ curve of TU UMi shows the residuals from the quadratic fit. The solid line refers to a theoretical orbit of the additional component in the system.

where

$$A = \frac{a_{12} \sin i \sqrt{1 - e^2 \cos^2 \omega}}{2.590 \times 10^{10}}$$

is the semi-amplitude of the light-time effect in days. E , P_{orb} , T_0 and dP/dE represent the cycle number, orbital period, the reference epoch for the primary minimum and the rate of the secular period change of the binary star, respectively. a_{12} , i , e and ω , 2.590×10^{10} are the semi-major axis, inclination, eccentricity, longitude of the periastron of the absolute orbit of the center of mass of the eclipsing binary around the three-body system and the speed of light in km/day, respectively. ν is the true anomaly of the position of the eclipsing binaries mass center on this orbit and includes T_p that it is the epoch of the passage at the periastron of the eclipsing binaries mass center along its orbit and P_{mod} , which is the modulation period of the third body orbit.

The $O-C$ method was applied in the analysis using a matlab code given by Zasche et al. (2009) to determine the eight free parameters (namely T_0 , P_{orb} , dP/dE , P_{mod} , T_p , $a_{12} \sin i$, e , ω) by least-squares fitting the $O-C$ values taking into account both variations (parabolic+cyclic). The best theoretical fit made to the $O-C$ diagram and the residuals obtained from the fit are shown in Fig. 1 and Fig.3 and the derived parameters and their errors are given in Tab. 3. The sum of square residuals from the best fit is 0.0026 days².

4. Results and conclusions

4.1. Mass transfer between the components

TU UMi is a short-period (0^d.3770) W-type contact binary where the primary component is estimated to be F-type star by Rucinski et al. (2005) and is poorly investigated in detail. By analyzing a total of 926 times of light minimum, the orbital period of TU UMi is changing with a cyclic character superimposed on a decreasing structure. The $O-C$ curve of the system shows a clear long-term period decrease at a rate of $dP/dt = -1.12 \times 10^{-7} \text{ d yr}^{-1}$ ($-0.18 \text{ sec century}^{-1}$). The type of variations, i.e., a long-term decrease combined with a cyclic change, is commonly found in W UMa-type stars that are shown in Tab. 4 for some of the W-type contact binaries between $0.2 \text{ d} < P_{orb} < 0.7 \text{ d}$. Furthermore, Li et al. (2018) studied the light travel-time effect in short-period eclipsing binaries and concluded that the frequency of third bodies found in contact binaries with $P < 0.3 \text{ day}$ reaches a value of 0.65 in their samples including 542 eclipsing binaries. Therefore, there may exist a periodic variation superimposed on a secular decrease in the period in the ($O-C$) curve of TU UMi. The long-term period decrease can be explained by mass transfer from the more-massive component to the less-massive one in the case of a conservative mass transfer, or by the angular momentum loss from the system, or by a combination of both mechanisms.

Table 2. Observed times and $(O-C)^d$ values of minimum light for TU UMi.

BJD ¹ 2400000+	Error	Epoch	$(O-C)_1$	$(O-C)_2$	Residuals	Reference
52739.5938	0.0004	-15796.0	-0.0071	0.0067	0.0051	[1]
52739.7696	0.0008	-15795.5	-0.0198	-0.0061	-0.0076	[1]
52741.6616	0.0003	-15790.5	-0.0133	0.0005	-0.0011	[1]
53086.5050	0.0020	-14876.0	-0.0179	-0.0057	-0.0019	[2]
53086.5084	0.0022	-14876.0	-0.0145	-0.0023	0.0016	[2]
53100.4599	0.0043	-14839.0	-0.0153	-0.0031	0.0010	[2]
53100.4577	0.0023	-14839.0	-0.0167	-0.0046	-0.0005	[2]
53100.4600	0.0011	-14839.0	-0.0152	-0.0030	0.0011	[2]
53137.4122	0.0009	-14741.0	-0.0178	-0.0058	-0.0012	[2]
53137.4163	0.0010	-14741.0	-0.0137	-0.0017	0.0029	[2]
53137.4166	0.0008	-14741.0	-0.0134	-0.0014	0.0032	[2]
54513.4207	0.0006	-11092.0	-0.0075	-0.0007	-0.0011	[3]
54513.6131	0.0008	-11091.5	-0.0037	0.0031	0.0028	[3]
55115.4555	–	-9495.5	0.0049	0.0099	0.0020	[4]
55276.4695	0.0009	-9068.5	0.0019	0.0064	-0.0021	[5]
55277.4074	0.0010	-9066.0	-0.0030	0.0016	-0.0069	[5]
55285.5224	0.0009	-9044.5	0.0046	0.0092	0.0007	[5]
55289.4804	0.0012	-9034.0	0.0031	0.0077	-0.0008	[5]
55765.3665	0.0003	-7772.0	0.0025	0.0059	0.0002	[6]
55774.4168	0.0002	-7748.0	0.0027	0.0060	0.0005	[6]
55957.4895	0.0010	-7262.5	-0.0014	0.0015	-0.0015	[7]
58690.8294	0.0001	-14.0	0.0086	0.0086	0.0001	[2]
58690.6406	0.0001	-14.5	0.0083	0.0083	-0.0002	[2]
58731.3663	0.0001	93.5	0.0084	0.0084	0.0000	[2]
58731.5551	0.0001	94.0	0.0086	0.0086	0.0002	[2]
58853.5425	0.0001	417.5	0.0077	0.0077	0.0000	[2]
58853.7313	0.0001	418.0	0.0079	0.0079	0.0002	[2]
58883.3323	0.0001	496.5	0.0075	0.0075	-0.0001	[2]
58883.5211	0.0001	497.0	0.0076	0.0076	0.0001	[2]
58908.4085	0.0001	563.0	0.0072	0.0072	-0.0001	[2]
58908.5971	0.0001	563.5	0.0072	0.0072	-0.0001	[2]
59021.3459	0.0001	862.5	0.0064	0.0065	0.0002	[2]
59021.5346	0.0001	863.0	0.0065	0.0066	0.0003	[2]
59403.1432	0.0001	1875.0	0.0010	0.0012	0.0004	[2]
59403.3318	0.0001	1875.5	0.0011	0.0013	0.0004	[2]
59431.0473	0.0001	1949.0	0.0005	0.0007	0.0003	[2]
59431.2359	0.0001	1949.5	0.0006	0.0008	0.0004	[2]
59580.7490	0.0001	2346.0	-0.0033	0.0000	0.0002	[2]
59580.9372	0.0001	2346.5	-0.0036	-0.0003	-0.0002	[2]
59606.3901	0.0001	2414.0	-0.0030	-0.0027	-0.0003	[2]
59606.5787	0.0001	2414.5	-0.0029	-0.0026	-0.0002	[2]
59610.5381	0.0001	2425.0	-0.0030	-0.0027	-0.0003	[2]
59610.7267	0.0001	2425.5	-0.0029	-0.0026	-0.0002	[2]
59635.4258	0.0001	2491.0	-0.0032	-0.0029	-0.0001	[2]
59635.6142	0.0001	2491.5	-0.0033	-0.0029	-0.0001	[2]

¹ The minimum times are in the barycentric dynamical time system (BJD).

Notes: [1] Pych & Rucinski (2004); [2] Present work; [3] Brát et al. (2008); [4] Kjurkchieva et al. (2010); [5] Liakos & Niarchos (2010); [6] Soydugan et al. (2017); [7] Hubscher (2013).

Table 3. Parameters derived from (*O-C*) analysis.

Parameter	Value	Error
Parabolic behavior related		
T_0 [BJD]	2458696.1005	0.0001
P_{orb} [days]	0.37708906	0.00000008
dP/dt [days/year]	-1.12×10^{-7}	0.01×10^{-7}
3^{rd} body related		
$a_{12} \sin i$ [AU]	1.398	0.009
e	0.05	0.01
ω [degree]	0.3	24.6
T_p [BJD]	2462732.2	213.7
P_{mod} [year]	9.03	0.02
A [days]	0.0081	0.0001
$f(M_3)$ [M_\odot]	0.03352	0.00001
$M_3(i = 90^\circ)$ [M_\odot]	0.61145	0.00007
$M_3(i = 60^\circ)$ [M_\odot]	0.72665	0.00009
$M_3(i = 30^\circ)$ [M_\odot]	1.48124	0.00022
Magnetic activity cycle related		
ΔJ [$\text{gcm}^2\text{s}^{-1}$]	7.66×10^{47}	
$\Delta\Omega/\Omega$	3.08×10^{-3}	
B[kG]	22.9	

The period investigation of [Kjurkchieva et al. \(2010\)](#) showed that the *O-C* variation of TU UMi was linear. However, only times of light minima observed between 2003 and 2009 were used in their work. In our *O-C* diagram, times of light minima obtained by the high accuracy TESS data are used and these data show a downward tendency. Therefore, the TESS data are very important when the period variation of TU UMi is investigated since they will give a quite different result, as shown in Fig. 1 and Fig. 3. Also, a cyclic period change is revealed for the first time in this study. Assuming that the long-term period change of the system can be explained by mass transfer, then some parameters, including the masses of the two components ($M_1 = 1.313 M_\odot$, $M_2 = 0.21 M_\odot$)¹, period, the rate of change of the period of TU UMi were used in the following equation to calculate the rate of mass transfer:

$$\dot{M} = \frac{M_1 \cdot M_2}{3(M_1 - M_2)} \frac{\dot{P}}{P}; \quad (2)$$

thus, $dM/dt = 0.25 \times 10^{-7} M_\odot \text{yr}^{-1}$ was determined, assuming that the more massive star transfers its present mass to the less massive component on a thermal timescale τ_{th} ([Paczynski, 1971](#)), $\tau_{th} = 1.2 \times 10^7 \text{yr}$ and mass is transferred to the companion at a rate of $M_1/\tau_{th} = 1.1 \times 10^{-7} M_\odot \text{yr}^{-1}$. This value is compatible with the calculated one using the observed period change. This means that mass transfer can describe the parabolic variation.

¹We should state that the absolute values of masses of the system used in this section are taken from [Zhang & Qian \(2020\)](#) calculated by using equations given in [Gazeas \(2009\)](#) (equations 710) where the mass ratio ($q = m_2/m_1$) is about 0.16 (from spectroscopic observation given by [Rucinski et al. \(2005\)](#)).

Table 4. Some of the W-type contact binaries with a period decrease.

Name	P_{orb} (days)	q	M_1 M_{\odot}	M_2 M_{\odot}	dP/dt ($\times 10^{-7}$ day $^{-1}$)	dM/dt ($\times 10^{-7} M_{\odot}$ yr $^{-1}$)	Cyclic	P_{cyc} (years)	LTTE	Ref.
CC Com	0.2207	0.52	0.79	0.41	-0.40	0.51	yes	16.1	yes	[1]
V1104 Her	0.2279	0.63	0.74	0.46	-0.29	0.52	yes	8.28	yes	[2,3]
YZ Phe	0.2347	0.38	0.74	0.28	-0.26	0.17	yes	40.76	yes	[4]
RW Com	0.2370	0.48	0.80	0.38	-0.43	0.44	yes	13.70	yes	[5,6]
EI CVn	0.2608	0.46	0.63	0.29	-3.11	1.03	unclear	4.96	-	[7]
V1197 Her	0.2627	0.38	0.77	0.30	-2.58	1.61	unclear	-	-	[8]
EH CVn	0.2636	0.30	0.67	0.20	-0.52	0.19	unclear	-	-	[9]
GV Leo	0.2667	0.19	1.09	0.19	-4.95	1.42	unclear	-	-	[10]
BM UMa	0.2712	0.54	0.92	0.50	-0.75	1.01	yes	30.8	unclear	[11]
VW Cep	0.2787	0.30	1.13	0.34	-1.69	0.98	yes	7.62	yes	[12]
V1005 Her	0.2789	0.30	0.92	0.98	-1.59	0.76	yes	18.1	yes	[13]
BX Peg	0.2804	0.37	1.02	0.38	-0.98	0.71	yes	16	unclear	[14]
V524 Mon	0.2836	0.48	0.99		-0.002	0.002	yes	23.9	unclear	[15]
RW Dor	0.2854	0.63	0.97	0.61	-0.14	0.27	unclear	49.9	-	[16]
LO Com	0.2864	0.40	0.79	0.32	-1.18	0.74	unclear	-	-	[17]
V842 Cep	0.2889	0.44	0.76	0.33	-1.50	1.01	unclear	-	-	[18]
EP Cep	0.2897	0.15	0.73	0.11	-3.73	0.56	unclear	-	-	[19]
TZ Boo	0.2974	0.21	0.72	0.11	-0.21	0.03	yes	31.2	unclear	[20]
V2284 Cyg	0.3069	0.35	0.86	0.30	-2.67	1.34	yes	2.06	yes	[21]
TY Boo	0.3171	0.47	1.21	0.57	-3.6	0.41	yes	58.9	yes	[22]
FG Hya	0.3278	0.11	1.44	0.16	-1.96	0.36	yes	36.4	unclear	[23]
V781 Tau	0.3449	0.45	1.06	0.43	-0.32	0.22	yes	30.8	unclear	[24]
V417 Aql	0.3700	0.37	1.40	0.50	-0.55	0.39	yes	42.4	unclear	[25]
AP Leo	0.3703	0.30	1.47	0.44	-1.08	0.61	yes	22.4	unclear	[26]

Table 4. Continued.

Name	P_{orb} (days)	q	M_1 M_{\odot}	M_2 M_{\odot}	dP/dt ($\times 10^{-7} \text{d yr}^{-1}$)	dM/dt ($\times 10^{-7} M_{\odot} \text{yr}^{-1}$)	Cyclic	P_{cyc} (years)	LTTE	Ref.
V396 Mon	0.3963	0.39	0.92	0.36	-0.86	0.51	yes	42.4	yes	[27]
SS Ari	0.4060	0.36	1.30	0.40	-1.56	0.74	yes	39.7	unclear	[28]
MR Com	0.4127	0.26	1.40	0.36	-5.30	2.07	yes	10.1	yes	[29]
BS Cas	0.4408	0.28	1.20		-1.51	0.54	yes	13.2	unclear	[30]
TV Mus	0.4457	0.17	1.35	0.22	-2.16	0.42	yes	29.1	unclear	[31]
V502 Oph	0.4534	0.34	1.42	0.48	-1.68	0.88	yes	23	yes	[32,33,34]
GU Ori	0.4706	0.43	1.05	0.45	-0.62	0.35	unclear	-	-	[35]
IK Per	0.6760	0.19	1.99	0.34	-2.52	0.51	yes	50.5	yes	[36]

Notes: [1] Yang & Liu (2003) ; [2] Liu et al. (2015); [3] Latković et al. (2021a);[4] Sarotsakulchai et al. (2019b) ;[5] Yang & Liu (2003) ;[6] Djurašević et al. (2011); [7] Yang (2011); [8] Zhou & Soonthornthum (2020) ; [9] Xia et al. (2018) ; [10] Kriwattanawong & Poojon (2013) ; [11] Yang et al. (2009) ; [12] Mitnyan et al. (2018) ; [13] Zhu et al. (2019) ;[14] Lee et al. (2009) ;[15] He et al. (2012) ;[16] Sarotsakulchai et al. (2019a) ;[17] Zhang et al. (2016) ;[18] Li et al. (2021) ;[19] Zhu et al. (2014) ;[20] Christopoulou et al. (2011) ;[21] Wang et al. (2017) ;[22] Christopoulou et al. (2012) ;[23] Qian & Yang (2005) ;[24] Lu et al. (2020) ;[25] Qian (2003);[26] Qian et al. (2007) ;[27] Liu et al. (2011);[28] Kim et al. (2003);[29] Qian et al. (2013);[30] Yang et al. (2008);[31] Qian et al. (2005) ;[32] Pych et al. (2004);[33] Maceroni et al. (1982);[34] Liu & Yang (2006) ;[35] Zhou et al. (2018) ;[36] Zhu et al. (2005) .

4.2. Cyclic variation

The $O-C$ residuals obtained after the subtraction of the quadratic term are shown in Figure 3, whose shape appears to have a quasi-sinusoidal variation with a period of ~ 9 yr. This can be explained in two ways: the Applegate mechanism (Applegate, 1992) and the light-time effect.

4.2.1. Presence of a possible third component

One of the possible causes of the cyclic $O-C$ variation may be the light travel time effect (LTTE) due to a third body that is physically bound to the system. In order to examine this situation, the LTTE equation given by Irwin (1952) (see Equ. 1) was fitted to the $O-C$ diagram of the system.

According to the parameters given in Tab. 3, TU UMi orbits around the triple systems center of mass in a very low eccentric orbit ($e = 0.05 \pm 0.01$) with a period of $P_{mod} = 9.03 \pm 0.02$ years. The projected distance of the center of mass of TU UMi to the center of mass of the three-body system was estimated to be $a_{12} \sin i = 1.398 \pm 0.009$ AU. Using the P_{mod} and $a_{12} \sin i$ values, the mass function of the third body was found to be $f(M_3) = 0.03352 \pm 0.000001 M_\odot$. The minimum mass of the tertiary ($i = 90^\circ$, where i is the inclination of the third bodys orbit) is estimated as $M_3 = 0.611 M_\odot$. According to Budding & Demircan (2007)'s empirical main sequence table, the spectral type of this companion is estimated to be $\sim K3$. Therefore, the third body deduced from LTTE may be a low-mass star. In this case, the mass of the third body is comparable to the mass of the secondary component in the binary system. Pych & Rucinski (2004) reported that TU UMi is a triple system containing a close binary and about 50 percent of total light coming from the bright tertiary companion in the system. However, this system is also known as a visual binary² with a separation of 0.2 arcsec. Rucinski et al. (2005) suggest that the third, spectroscopic component is probably identical to the visual component. Apart from this, the third body was not confirmed photometrically and further observational evidence for the existence of a third body needs to be investigated. If the third body is really present in the system, it may have an important role in the evolution of the binary system by drawing angular momentum from the central binary via a Kozai cycle (Kozai, 1962) or a combination of a Kozai cycle and tidal friction.

4.2.2. Magnetic activity

The close binary systems with late-type components are well known to be magnetically active, e.g. with chromospheric emission, starspots. The Applegate mechanism suggests that magnetic activity causes a variation of the angular momentum distribution, and then leads to variations in the active component

²The visual component is WDS 14557+7618.

in the system. So any change in the rotational system of a binary star component due to the magnetic activity will be reflected to the orbit as a consequence of the spin-orbit coupling and the orbital period changes slightly periodically.

The observed cyclic variation in the $O-C$ diagram of TU UMi may be explained as resulting from magnetic activity variations due to star spots. We have calculated the activity related parameters by following the Applegate (1992) formulation and assuming the primary component (should be an F2 type dwarf according to the $(B-V)$ color index value given by Duerbeck (1997)) of the system is responsible from the activity. The parameters are the cycle modulation, period $P_{cyc} = 9.03$ years, the amplitude of the cyclic period variation, $\Delta P = 1.005$ sec cycle⁻¹, the angular momentum transfer $\Delta J = 7.66 \times 10^{47}$ g cm² s⁻¹ required to produce the observed cyclic effect on the orbital period, required energy $\Delta E = 2.28 \times 10^{41}$ ergs for the ΔJ transfer, the corresponding luminosity change $\Delta L = 0.633 L_{\odot}$, and, finally the subsurface magnetic field $B = 22.9$ kG of the primary component. The period variation $\Delta P/P$ can be used for calculating the variation of the quadruple moment ΔQ and this quantity results in 2.15×10^{50} g cm², which is within the limits for active binaries (a range of values from 10^{50} to 10^{51} g cm²). Since the parameters of the two components of the binary were adopted by Zhang & Qian (2020), we can calculate the changes of the luminosity to be $\Delta L_1 = 0.633 L_{\odot} < L_1 (3.2 L_{\odot})$. Obviously, the active primary component can provide enough energy to generate such changes. Therefore, the Applegate mechanism can explain the cyclic period change in TU UMi as well. In addition, we should point out that no unequal difference between the two light maxima (Max I-Max II), or the OConnell effect was not remarkable in the TESS and our observations. In addition to this, according to Tran et al. (2013), strong spot activity causes an effect on the variations of the minima times. The trends of primary and secondary minima time variations are expected to show an erratic, and anticorrelated to each other behaviour and these have been observed in many W UMa type systems. To search for such a variation in our case, we decided to plot primary and secondary $O-C$ times determined from TESS data. As TU UMi was observed by TESS intermittently during the period March 2003 to February 2022, we focus on two consecutive data sets (Sector 21, 22 and Sector 47, 48). As it can be seen in Fig. 4, there are no short-term, anticorrelated $O-C$ variations in the primary and secondary curves of TU UMi. The results may suggest that TU UMi has a very weak activity and it may be in an inactive state for decades with no significant spot activities. The Applegate mechanism also supports the long-term light variation and the $O-C$ curve formed by the times of minima should have the same cycle length. Unfortunately, we do not have precise enough long-term photometric observations for TU UMi to check such brightness variations. Long-term photometric monitoring can clarify TU UMi's plausible magnetic activity cycle characteristics.

We calculated the angular momentum loss (AML) via magnetic stellar wind which can be determined by the following equation given by Bradstreet &

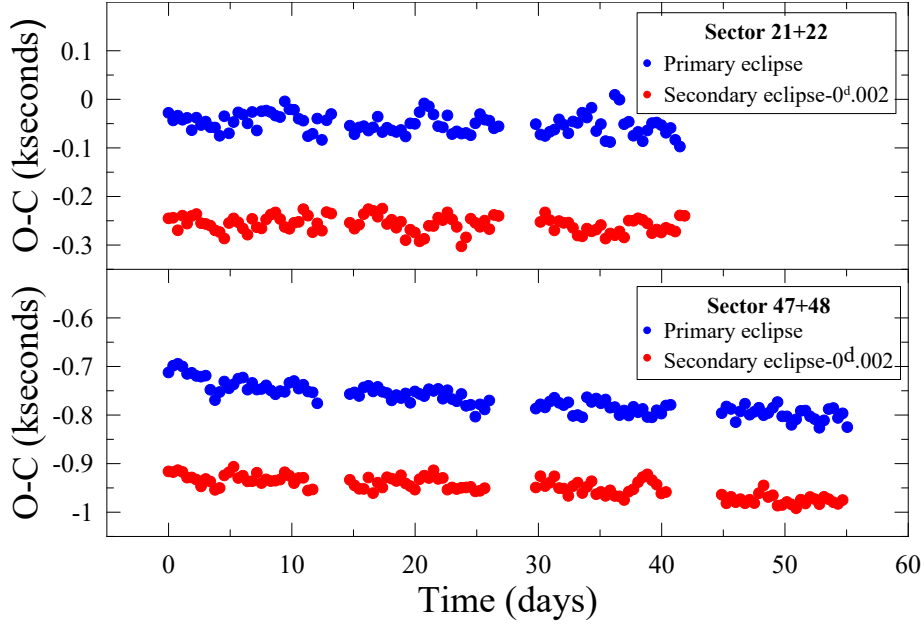


Figure 4. Time-dependent variations of the $O-C$ curves for the primary and secondary eclipses (vertically displaced for clarity) are shown as blue and red colors for Sector 21, 22 (top panel), and Sector 47, 48 (bottom panel), respectively.

Guinan (1994) for the long-term decrease:

$$\begin{aligned} \dot{P} \approx & 1.1 \times 10^{-8} q^{-1} (1 + q^2 (M_1 + M_2))^{-5/3} \\ & \times k^2 (M_1 R_1^4 + M_2 R_2^4) P^{-7/3} \end{aligned} \quad (3)$$

where k^2 is the gyration constant between 0.07 to 0.15 for solar-type stars. By adopting the value of $k^2 = 0.1$, the rate of the orbital period decrease due to AML can be computed as $dP/dt \sim 2.4 \times 10^{-7} \text{ d yr}^{-1}$ and the timescale of the period decrease is $(dP/dt) \sim 1.56 \times 10^6 \text{ yr}$ or $\sim 1.6 \text{ Myr}$ which is close to the timescale from observed the period decrease derived from $O - C$ variation ($P/(dP/dt) = 2.6 \text{ Myr}$). This may lead to the conclusion that the long-term period decrease of TU UMi can also be constrained by AML, but as it can be seen in Sec. 4.1, the period decrease from conservative mass transfer cannot be neglected. Therefore, a plausible explanation for the long-term period decrease in TU UMi is AML, or the combination of the two mechanisms (AML and mass transfer). Nevertheless, observations in the next decades are necessary to clarify the true shape of the $O-C$ diagram.

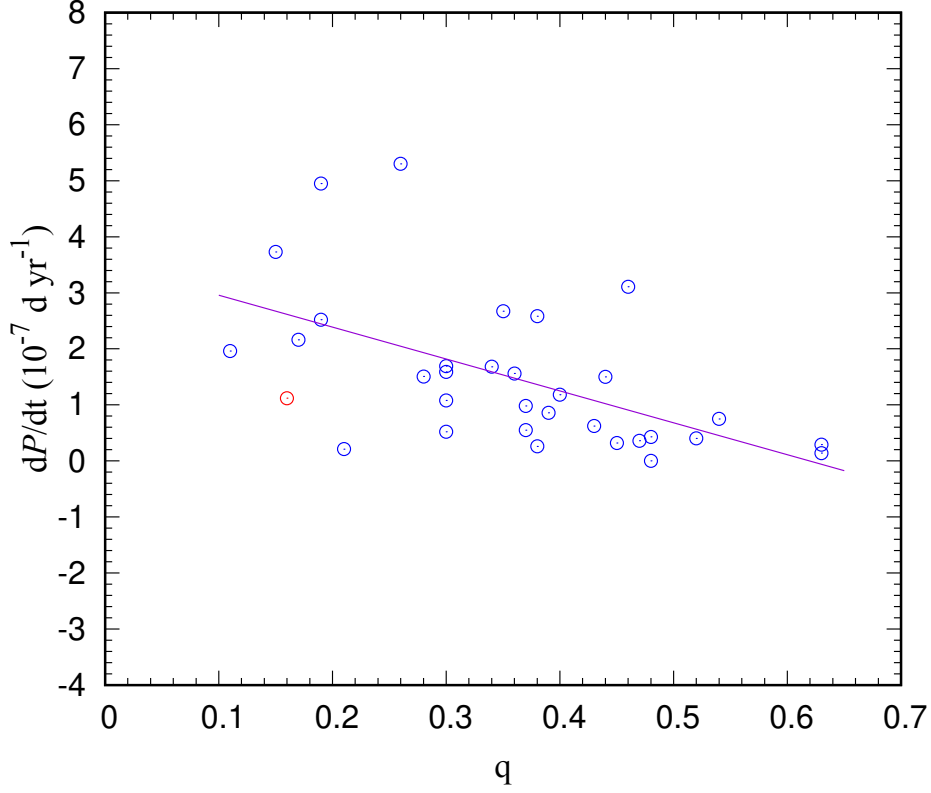


Figure 5. A plot of the period change range versus the mass ratio (dP/dt - q) for some W-type systems (blue circles) listed in Tab. 4. For comparison, the parameters of TU UMi (red circles) are also plotted. The fitted curve is given in Eq. 4.

4.2.3. Long-term period decrease in W-type W UMa stars

Long-term period decreasing and increasing are common for W UMa-type binaries. This variation is usually due to mass transfer or angular momentum loss, which results in orbital period changes. In this study, the analysis of the orbital period of TU UMi was performed and a long-term period decrease was discovered. In general, it is interpreted as caused by conservative mass transfer from the more massive component to the less massive component. In order to find a relation between the observed period change rate using $O - C$ variation and the mass ratios, we compiled the physical parameters and the observed period change rate (dP/dt) for some W-type contact binaries showing a secular period change plus cyclic variations in the literature in a period range of $0.2 < P_{orb} < 0.7$ d. They are listed in Tab. 4 in the order of the increasing orbital

period. The plot of the period change versus the mass ratio rate can be seen in Fig. 4, where the positions of 32 W-type W UMa stars are shown. Based on these parameters, there may exist a correlation (solid line) between the period change, dP/dt , and the mass ratio, q . We fitted the data using the least-squares method and the fitting result yields the following equation:

$$dP/dt = -5.82(\pm 1.55)q + 3.60(\pm 0.60), \quad (4)$$

where dP/dt is in units of $\times 10^{-7} \text{ d yr}^{-1}$. This relation tells us that the secular periods of systems are decreasing with the increasing mass ratio. It seems that the mass transfer between the two components may contribute to changes in the mass ratio of a system, which needs to be confirmed using a large sample of W UMa stars. However, in a statistical study for contact binaries by [Latković et al. \(2021b\)](#), there has been recently investigated the relation between the orbital period change rate (taking into account both period increasing and decreasing) and the mass ratio for A and W-type systems using a large sample of W UMa stars. They pointed out that there is no correlation between the type of period variability and the mass ratio (see their Fig. 7). In our sample, it seems that the derived relation is more obvious for $q > 0.25$. The systems with $q < 0.25$ tend to show dP/dt in a large range of $(2 - 5.3) \times 10^{-7} \text{ d yr}^{-1}$. The maximum dP/dt value is $3 \times 10^{-7} \text{ d yr}^{-1}$ for the systems with $q > 0.25$. The q value of TU UMi shows that it is in agreement with the observed period change rates of W-type W UMa binaries. Tab. 4 also lists the estimated mass transfer rates of samples, we found them to be in the range $(0.002 - 2) \times 10^{-7} M_{\odot} \text{ yr}^{-1}$, while TU UMi appears to have a comparable rate of $0.3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$. The primary masses of samples (M_1) in Tab. 4 apparently show no relationship with the period-change rate (dP/dt). However, there is the same relation between the secondary masses (M_2) and the period-change rate (dP/dt), where dP/dt decreases with increasing q . This is understandable because, in the study of [Latković et al. \(2021b\)](#), the empirical relationship between the secondary masses and the mass ratio shows a linear correlation, M_2 increases with increasing q . Most of the systems in Tab. 4 have a confirmed cyclic change related to the magnetic activity of components, or LTTE in the system. Although we accept that the long-term period decrease is due to conservative mass transfer between components, the contribution of angular momentum loss (AML) via magnetic stellar wind, or by a combination of both processes, on the secular period reducing cannot be ruled out. The cyclic *OC* variation can be explained in terms of the LTTE or solar-like magnetic activity cycle of one of the two components in the system. However, we can not discriminate which mechanism is responsible for the cyclic variation in the *OC* diagram and it is clear that we need more observations to ascertain that.

Acknowledgements. The authors acknowledge generous allotments of observing time at the Ege University Observatory. We thank S. Evren and G. Taş for their support in performing observations at the Ege University Observatory and the staff of the Ege University Observatory. We would like to thank Burak Ulaş for allowing us to use his python code to determine times of minima from TESS observations. And we thank the referee very much for the comments and suggestions that have helped us to improve the manuscript. This paper includes data collected by the TESS mission, which are publicly available from the Mikulski Archive for Space Telescopes (MAST). This research has made use of the SIMBAD online database, operated at CDS, Strasbourg, France, and NASAs Astrophysics Data System (ADS).

References

- Applegate, J. H., A Mechanism for Orbital Period Modulation in Close Binaries. 1992, *Astrophysical Journal*, **385**, 621, DOI: 10.1086/170967
- Bradstreet, D. H. & Guinan, E. F., Stellar Mergers and Acquisitions: The Formation and Evolution of W Ursae Majoris Binaries. 1994, in *Astronomical Society of the Pacific Conference Series*, Vol. **56**, *Interacting Binary Stars*, ed. A. W. Shafter, 228
- Brát, L., Šmelcer, L., Kučáková, H., et al., B.R.N.O. Times of minima. 2008, *Open European Journal on Variable Stars*, **94**, 1
- Budding, E. & Demircan, O. *Introduction to Astronomical Photometry*, , Vol. **6** (Cambridge University Pres)
- Christopoulou, P. E., Papageorgiou, A., Vasileiadis, T., & Tsantilas, S., A Holistic View of the W UMa Type TY Boo. 2012, *Astronomical Journal*, **144**, 149, DOI: 10.1088/0004-6256/144/5/149
- Christopoulou, P. E., Parageorgiou, A., & Chrysopoulos, I., First Modern Photometric Investigation of the Puzzling W UMa Type Close Binary System of TZ Bootis. 2011, *Astronomical Journal*, **142**, 99, DOI: 10.1088/0004-6256/142/4/99
- Djurašević, G., Yılmaz, M., Baştürk, Ö., et al., Physical parameters of close binaries QX Andromedae, RW Comae Berenices, MR Delphini, and BD +079° 3142. 2011, *Astronomy and Astrophysics*, **525**, A66, DOI: 10.1051/0004-6361/201014895
- Duerbeck, H. W., True and Possible Contact Binaries in the Hipparcos Catalogue. 1997, *Information Bulletin on Variable Stars*, **4513**
- Gazeas, K. D., Physical parameters of contact binaries through 2-D and 3-D correlation diagrams. 2009, *Communications in Asteroseismology*, **159**, 129
- He, J.-J., Wang, J.-J., & Qian, S.-B., V524 Monoceroits: A Marginal Contact Binary with a Cyclic Period Variation. 2012, *Publications of the ASJ*, **64**, 85, DOI: 10.1093/pasj/64.4.85
- Hubscher, J., BAV-Results of observations - Photoelectric Minima of Selected Eclipsing Binaries and Maxima of Pulsating Stars. 2013, *Information Bulletin on Variable Stars*, **6084**, 1
- Irwin, J. B., The Determination of a Light-Time Orbit. 1952, *Astrophysical Journal*, **116**, 211, DOI: 10.1086/145604

- Kalytis, R., Three-channel general-purpose astrophotometer. 1999, *Turkish Journal of Physics*, **23**, 347
- Kazarovets, E. V., Samus, N. N., Durlevich, O. V., et al., The 74th Special Name-list of Variable Stars. 1999, *Information Bulletin on Variable Stars*, **4659**
- Kim, C.-H., Lee, J. W., Kim, S.-L., Han, W., & Koch, R. H., A Period Study and Light Synthesis for the W Ursae Majoris Type Binary SS Arietis. 2003, *Astronomical Journal*, **125**, 322, DOI: 10.1086/344808
- Kjurkchieva, D., Dimitrov, D., & Ibryamov, S., BVR photometry of the star TU UMi. 2010, *Bulgarian Astronomical Journal*, **14**, 65
- Kozai, Y., Secular perturbations of asteroids with high inclination and eccentricity. 1962, *Astronomical Journal*, **67**, 591, DOI: 10.1086/108790
- Kriwattanawong, W. & Poojon, P., A photometric study of an EW-type binary system: GV Leo. 2013, *Research in Astronomy and Astrophysics*, **13**, 1330, DOI: 10.1088/1674-4527/13/11/004
- Kwee, K. K. & van Woerden, H., A method for computing accurately the epoch of minimum of an eclipsing variable. 1956, *Bulletin of the Astronomical Institutes of the Netherlands*, **12**, 327
- Latković, O., Čeki, A., & Lazarević, S., Statistics of 700 Individually Studied W UMa Stars. 2021a, *Astrophysical Journal, Supplement*, **254**, 10, DOI: 10.3847/1538-4365/abeb23
- Latković, O., Čeki, A., & Lazarević, S., Statistics of 700 Individually Studied W UMa Stars. 2021b, *Astrophysical Journal, Supplement*, **254**, 10, DOI: 10.3847/1538-4365/abeb23
- Lee, J. W., Kim, S.-L., Lee, C.-U., & Youn, J.-H., The Solar-Type Contact Binary BX Pegasi Revisited. 2009, *Publications of the ASP*, **121**, 1366, DOI: 10.1086/649230
- Lenz, P. & Breger, M., Period04 User Guide. 2005, *Communications in Asteroseismology*, **146**, 53, DOI: 10.1553/cia146s53
- Li, M. C. A., Rattenbury, N. J., Bond, I. A., et al., A study of the light travel time effect in short-period MOA eclipsing binaries via eclipse timing. 2018, *Monthly Notices of the RAS*, **480**, 4557, DOI: 10.1093/mnras/sty2104
- Li, Y.-Y., Li, K., & Liu, Y., The first photometric analysis and period investigation of the K-type W UMa type binary system V0842 Cep. 2021, *Research in Astronomy and Astrophysics*, **21**, 122, DOI: 10.1088/1674-4527/21/5/122
- Liakos, A. & Niarchos, P., CCD Times of Minima of Several Eclipsing Binaries. 2010, *Information Bulletin on Variable Stars*, **5943**, 1
- Liu, L., Qian, S. B., Liao, W. P., et al., Period Changes and Four-color Light Curves of the Active Overcontact Binary V396 Monocerotis. 2011, *Astronomical Journal*, **141**, 44, DOI: 10.1088/0004-6256/141/2/44
- Liu, N. P., Qian, S. B., Soonthornthum, B., et al., The Late K-type Binary V1104 Her Near the Short-period End of Contact Binaries. 2015, *Astronomical Journal*, **149**, 148, DOI: 10.1088/0004-6256/149/4/148

- Liu, Q.-Y. & Yang, Y.-L., On the Period Variation of the W UMa-type Contact Binary V502 Ophiuchi. 2006, *Chinese Journal of Astronomy and Astrophysics*, **6**, 331, DOI: 10.1088/1009-9271/6/3/08
- Lu, H.-p., Zhang, L.-y., Michel, R., & Han, X. L., Magnetic Activity and Period Variation Studies of the Four W Uma-type Eclipsing Binaries: UV Lyn, V781 Tau, NSVS 4484038, and 2MASS J15471055+5302107. 2020, *Astrophysical Journal*, **901**, 169, DOI: 10.3847/1538-4357/abb19b
- Maceroni, C., Milano, L., & Russo, G., Determination of parameters of W UMa systems. III : CC Com, YY Eri, V502 OPH and TY Pup. 1982, *Astronomy and Astrophysics, Supplement*, **49**, 123
- Mitnyan, T., Bódi, A., Szalai, T., et al., The contact binary VW Cephei revisited: surface activity and period variation. 2018, *Astronomy and Astrophysics*, **612**, A91, DOI: 10.1051/0004-6361/201731402
- Paczyński, B., Evolutionary Processes in Close Binary Systems. 1971, *Annual Review of Astron and Astrophys*, **9**, 183, DOI: 10.1146/annurev.aa.09.090171.001151
- Pych, W. & Rucinski, S. M., TU UMi: A Contact Binary in a Triple System. 2004, *Information Bulletin on Variable Stars*, **5524**
- Pych, W., Rucinski, S. M., DeBond, H., et al., Radial Velocity Studies of Close Binary Stars. IX. 2004, *Astronomical Journal*, **127**, 1712, DOI: 10.1086/382105
- Qian, S., A period investigation of the overcontact binary system V417 Aquilae. 2003, *Astronomy and Astrophysics*, **400**, 649, DOI: 10.1051/0004-6361:20030018
- Qian, S. & Yang, Y., Improved astrophysical parameters for the overcontact binary FG Hydrae. 2005, *Monthly Notices of the RAS*, **356**, 765, DOI: 10.1111/j.1365-2966.2004.08497.x
- Qian, S. B., Liu, N. P., Liao, W. P., et al., First Photometric Investigation of the Newly Discovered W UMa-type Binary Star MR Com. 2013, *Astronomical Journal*, **146**, 38, DOI: 10.1088/0004-6256/146/2/38
- Qian, S. B., Xiang, F. Y., Zhu, L. Y., et al., A New CCD Photometric Investigation of the Short-Period Close Binary AP Leonis. 2007, *Astronomical Journal*, **133**, 357, DOI: 10.1086/509499
- Qian, S. B., Yang, Y. G., Soonthornthum, B., et al., Deep, Low Mass Ratio Overcontact Binary Systems. III. CU Tauri and TV Muscae. 2005, *Astronomical Journal*, **130**, 224, DOI: 10.1086/430673
- Rodríguez, E., López-González, M. J., & López de Coca, P., A revised catalogue of delta Sct stars. 2000, *Astronomy and Astrophysics, Supplement*, **144**, 469, DOI: 10.1051/aas:2000221
- Rolland, A., Costa, V., Rodriguez, E., et al., Is TU UMi a W UMa-type system. 2002, *Communications in Asteroseismology*, **142**, 57
- Rucinski, S. M., Pych, W., Ogłóza, W., et al., Radial Velocity Studies of Close Binary Stars. X. 2005, *Astronomical Journal*, **130**, 767, DOI: 10.1086/431226

- Sarotsakulchai, T., Qian, S.-B., Soonthornthum, B., et al., RW Doradus: A solar-type shallow contact binary with a new orbital period investigation. 2019a, *Publications of the ASJ*, **71**, 34, DOI: 10.1093/pasj/psy149
- Sarotsakulchai, T., Qian, S.-B., Soonthornthum, B., et al., YZ Phoenicis: a very short period K-type contact binary with variation of the O'Connell effect and orbital period change. 2019b, *Publications of the ASJ*, **71**, 81, DOI: 10.1093/pasj/psz062
- Schofield, M., Chaplin, W. J., Huber, D., et al., The Asteroseismic Target List for Solar-like Oscillators Observed in 2 minute Cadence with the Transiting Exoplanet Survey Satellite. 2019, *Astrophysical Journal, Supplement*, **241**, 12, DOI: 10.3847/1538-4365/ab04f5
- Soydugan, F., Alicavus, F., Senyuz, T., et al., New CCD Minima Times for Selected Eclipsing Binaries. 2017, *Information Bulletin on Variable Stars*, **6225**, 1, DOI: 10.22444/IBVS.6225
- Tran, K., Levine, A., Rappaport, S., et al., The Anticorrelated Nature of the Primary and Secondary Eclipse Timing Variations for the Kepler Contact Binaries. 2013, *Astrophysical Journal*, **774**, 81, DOI: 10.1088/0004-637X/774/1/81
- Wang, J. J., Jiang, L. Q., Zhang, B., Zhao, S. Q., & Yu, J., Is There a Substellar Object Orbiting the Solar-like Stable Contact Binary V2284 Cyg? 2017, *Publications of the ASP*, **129**, 124202, DOI: 10.1088/1538-3873/aa8bb0
- Xia, Q.-Q., Li, K., Chen, X., Guo, D.-F., & Gao, D.-Y., The first photometric investigation and period study of two W UMa-type binary systems: EF CVn and EH CVn. 2018, *Publications of the ASJ*, **70**, 104, DOI: 10.1093/pasj/psy103
- Yang, Y. & Liu, Q., Period Changes of Two W UMa-Type Contact Binaries: RW Comae Berenices and CC Comae Berenices. 2003, *Publications of the ASP*, **115**, 748, DOI: 10.1086/374913
- Yang, Y.-G., A photometric study of the K-type contact binary EI CVn. 2011, *Research in Astronomy and Astrophysics*, **11**, 181, DOI: 10.1088/1674-4527/11/2/006
- Yang, Y. G., Wei, J. Y., & He, J. J., a Photometric Study of the Neglected Eclipsing Binary BS Cassiopeiae. 2008, *Astronomical Journal*, **136**, 594, DOI: 10.1088/0004-6256/136/2/594
- Yang, Y.-G., Wei, J. Y., & Nakajima, K., On Period Variations of the K-Type Eclipsing Binary BM Ursae Majoris. 2009, *Publications of the ASJ*, **61**, 13, DOI: 10.1093/pasj/61.1.13
- Zasche, P., Liakos, A., Niarchos, P., et al., Period changes in six contact binaries: WZ And, V803 Aql, DF Hya, PY Lyr, FZ Ori, and AH Tau. 2009, *New Astronomy*, **14**, 121, DOI: 10.1016/j.newast.2008.06.002
- Zhang, X.-D. & Qian, S.-B., Orbital period cut-off of W UMa-type contact binaries. 2020, *Monthly Notices of the RAS*, **497**, 3493, DOI: 10.1093/mnras/staa2166
- Zhang, Y., Han, Q. W., & Liu, J. Z., The First Photometric Study of the Short-period Shallow Contact System LO Comae. 2016, *Publications of the ASP*, **128**, 124201, DOI: 10.1088/1538-3873/128/970/124201

- Zhou, X., Qian, S., Boonruksar, S., et al., Photometric investigation of the contact binary GU Orionis with high metallicity. 2018, *Publications of the ASJ*, **70**, 87, DOI: 10.1093/pasj/psy084
- Zhou, X. & Soonthornthum, B., Photometric investigation on the W-subtype contact binary V1197 Her. 2020, *Research in Astronomy and Astrophysics*, **20**, 010, DOI: 10.1088/1674-4527/20/1/10
- Zhu, L. Y., Qian, S. B., Soonthornthum, B., et al., Three Close Binaries in Different Evolutionary Stages in the Old Open Cluster NGC 188. 2014, *Astronomical Journal*, **147**, 42, DOI: 10.1088/0004-6256/147/2/42
- Zhu, L. Y., Qian, S. B., Soonthornthum, B., & Yang, Y. G., Deep, Low Mass Ratio Overcontact Binaries. II. IK Persei. 2005, *Astronomical Journal*, **129**, 2806, DOI: 10.1086/430187
- Zhu, L. Y., Wang, Z. H., Tian, X. M., Li, L. J., & Gao, X., V1005 Her: a solar-type shallow-contact binary in a triply fossil system. 2019, *Monthly Notices of the RAS*, **489**, 2677, DOI: 10.1093/mnras/stz2294