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Cyclic Nature of the Orbital Period Variations of some Algol-type Binaries

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Abstract

The long-term period variations of the classical algol-type binaries XZ And, U Cep, β Per, RT Per, ST Per and TX UMa were studied by using all available observed times of eclipse minima. The (O-C) diagrams formed by the times of eclipse minima were found to be representable by one or more cyclic variations superimposed on a secular parabolic variation. The secular variations in the orbital periods should be caused by the mass transfer between the component stars and the mass loss from the systems. For our sample of Algol systems, none of the cyclic variations were found caused by the apsidal motion. The cyclic variations were interpreted in terms of the cyclic magnetic activity effect of the late-type secondaries and/or the light-time effect due to additional unseen component stars around the systems.

1. Introduction

Classical Algol-type systems are formed by an early-type main sequence primary and a late-type subgiant or giant secondary component. We have clear evidences from the literature that most of the Algol-type binaries have shown multiple period changes [1-3]. Hall [4-5] showed that almost all secondaries in Algols are sharing the same properties with the chromospherically active binaries (CAB). He also pointed out that at least one of the cyclic variations of the orbital periods of Algol-type binaries should be associated with magnetic activity cycle of cool secondaries.

In the present work we chose six most frequently observed classical Algol systems for the study of long-term period variations. The well known systems are: XZ And, U Cep, β Per, RT Per, ST Per and TX UMa. Physical parameters for our sample systems collected from the literature were listed in Table 1. The columns in the table are self explanatory

Table 1. The physical parameters of the sample systems

System	Incl. i(°)	Sepr. a($R_\odot$)	Dist. d(pc)	Spectral Type	Mass ($M_\odot$)	Radius ($R_\odot$)	Luminosity ($L_\odot$)	Eff.Temp. (°K)	Ref
XZ And	89	8.5	833	A0-1V	3.2	2.4	37.2	9200	[6,7]
				G5IV	1.3	2.6	4.8	5300	
U Cep	86.3	13.6	205	B8Ve	3.6	2.4	83.2	11250	[8]
				G8III	1.9	4.4	10.7	4980	
β Per	81.4	14	29.2	B8V	3.7	2.9	217	13000	[9,10]
				K2IV	0.81	3.5	4.53	4500	
RT Per	87	4.9	180	F2V	1.7	1.41	4.39	7030	[11]
				G5-8IV	0.4	1.27	0.93	5030	
ST Per	86	12.6	350	A3V	3.3	2.32	32	9000	[12,13]
				K1-2IV	0.5	2.95	6	5200	
TX UMa	83.5	16.1	211	B8V	4.8	2.83	199	12900	[14]
				G0III-IV	1.2	4.24	14.8	5500	

and the references were given in the last column for each system. These parameters were used during the interpretations of the period variations.

2. Data

All available times of eclipse minima for our sample of classical Algols (XZ And, U Cep, β Per, RT Per, ST Per and TX UMa) were collected from the literature, and some new data were obtained for the four systems (XZ And, RT Per, β Per, and TX UMa) at the Ankara University Observatory. The statistics for all times of eclipse minima used in this study for each system were given in Table 2. The numbers in paranthesis denote the number of secondary minima. Most of the timings are visual and obtained by the groups of amateur astronomers (BBSAG, BAV and others). The mean error of an individual timing is not more than 0.005 and 0.0005 days in visual/photographic and photoelectric minima respectively. Some of the photographic minima were obtained by the measurements on the survey plates and their mean error were exceeding 0.005 days in some cases. Such data were not considered in curve fitting processes but they were displayed in the (O-C) diagrams. All available times of eclipse minima which are obtainable on request from the authors were used to define the character of long-term period variations.

3. The (O-C) Diagrams

The (O-C) diagrams were constructed by using an initial linear light element for each system. The long term variations were observed to be continuous rather than irregular

Table 2. The statistics of times of minima used in this study

System	Data interval	Visual	Photographic	Photoelectric	Total
XZ And	1890-1997	609(-)	40(-)	21(5)	670
U Cep	1880-1996	734(-)	18(-)	159(-)	911
β Per	1782-1996	*2117(-)	6(-)	125(4)	2248
RT Per	1889-1996	543(-)	47(3)	108(30)	698
ST Per	1907-1997	260(-)	2(-)	10(2)	272
TX UMa	1903-1996	220(-)	5(-)	57(2)	282
				Total	5081

* These visual minima of β Per were converted to 191 yearly normal points.

jumps and as a general form they can be represented very well with the relation given below,

$$(O-C) = O - \left[T_o + P * E + \frac{1}{2}\frac{dP}{dE} * E^2 + \sum_{i=1}^{n} A_i sin\left(2\pi\frac{E-T_i}{P_i} - \frac{\pi}{2}\right)\right] \qquad (1)$$

where E is the epoch number for a given cycle of the eclipsing pair, P is the orbital period of the eclipsing pair, $T_o + P * E$ terms are the linear light element, $\frac{1}{2}\frac{dP}{dE} * E^2$ is the quadratic term of the light element and the parameters A_i, P_i and T_i in the last term are the semi-amplitude, period and moment of minimum of the i th cyclic variation in the (O-C) diagrams respectively. All six parameters ($T_o, P, \frac{dP}{dE}, A_i, T_i,$ and P_i) were fitted for each system and the resulting best values were listed in Table 3. We have calculated the residuals from the combined fits for each system and generated the sum of squared residuals χ^2 as the goodness of fit parameter. The values of χ^2 parameters were listed in Table 3. for all data and only for photoelectric data sets individually.

The (O-C) diagrams and their respective fits are shown through Fig.1-7 for each system. In these figures the dashed curves are for the individual parabolic and sine curve fittings while the solid curves are the combined effects of these individual variations and denote the final best fits to the (O-C) variations. Key to the legends are also given for each data type in these diagrams and numbers next to these keys are the number of data for the corresponding type of minimum. The parabolic fit to the (O-C) diagram of the U Cep was shown separately in Fig.2 and residual from this parabola can be seen in Fig.3 along with their respective sine curve fits. The residuals from the best fit to the (O-C) diagram of β Per were reasonably represented by the light-time effect of the third component which was discovered in 1933 by McLaughlin [15].

4. Interpretations and Discussion

Resulting fits to the (O-C) diagrams with quadratic terms in case of U Cep, β Per and RT Per are the clear indications to the mass transfer/loss effects in these systems.

Table 3. The best fitting parameters of the (O-C) variations of sample systems

	XZ And	U Cep	β Per	RT Per	ST Per	TX UMa
T_o(HJD 24..)	49313.6055	34195.5750	41934.0302	49634.5405	42436.6270	48594.5264
P(days)	1.3572865	2.4929935	2.86729685	0.8494003	2.6483572	3.0632973
$\frac{dP}{dE}\left(\frac{days}{cycl}\right)$	0	1.4 10^{-8}	-8 10^{-10}	-2.4 10^{-10}	0	0
A_1(days)	0.090	0.080	0.106	0.020	0.082	0.060
P_1(E)	34000	16409	20445	18834	17791	9539
P_1(years)	126.35	112.0	160.5	43.8	129.0	80.0
T_1(E)	-5400	900	-6620	-25800	2200	0
A_2(days)	0.028	0.022	0.011	0.002	0.0175	0.016
P_2(E)	9900	6593	4127	8600	3241	3458
P_2(years)	36.8	45.0	32.4	20.0	23.5	29.0
T_2(E)	-700	400	1450	-30000	1500	-1300
A_3(days)	-	0.008	0.005	-	-	-
P_3(E)	-	1758	255	-	-	-
P_3(years)	-	12.0	2.0	-	-	-
T_3(E)	-	2500	1550	-	-	-
χ^2 (all)	0.02628	0.04934	0.02100	0.02811	0.02168	0.04216
χ^2 (pe)	0.00013	0.00506	0.00479	0.00223	0.00013	0.00227

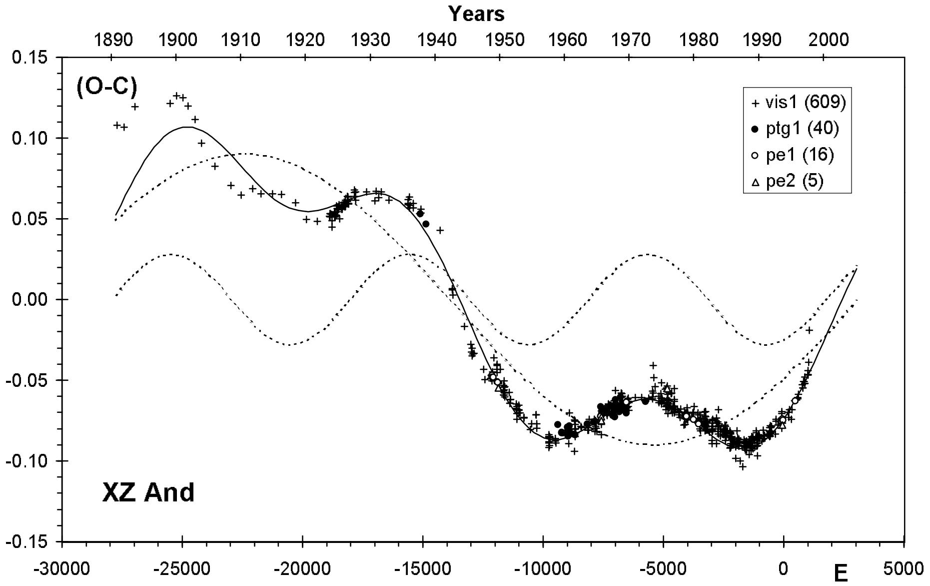

Figure 1. The (O-C) diagram and best fitted curves for XZ And

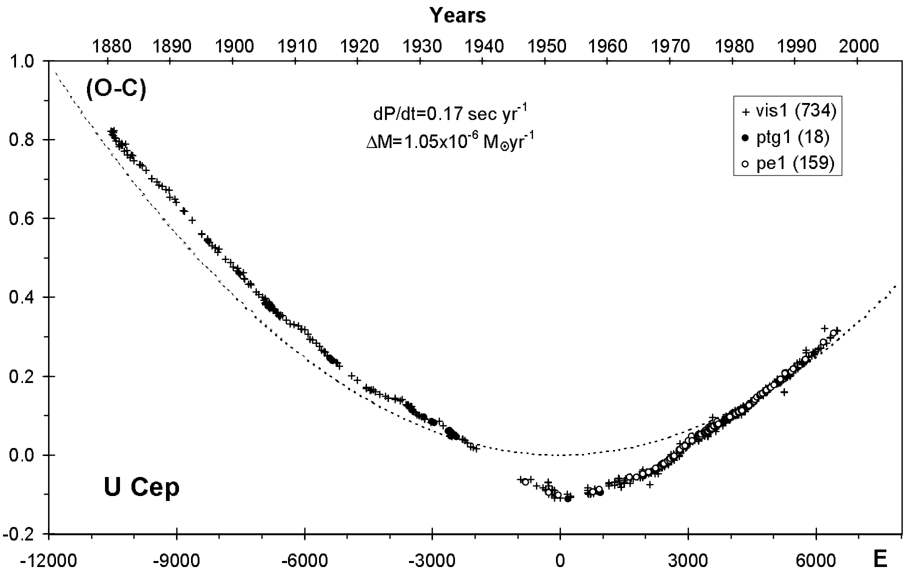

Figure 2. The (O-C) diagram and the best fitted parabola for U Cep

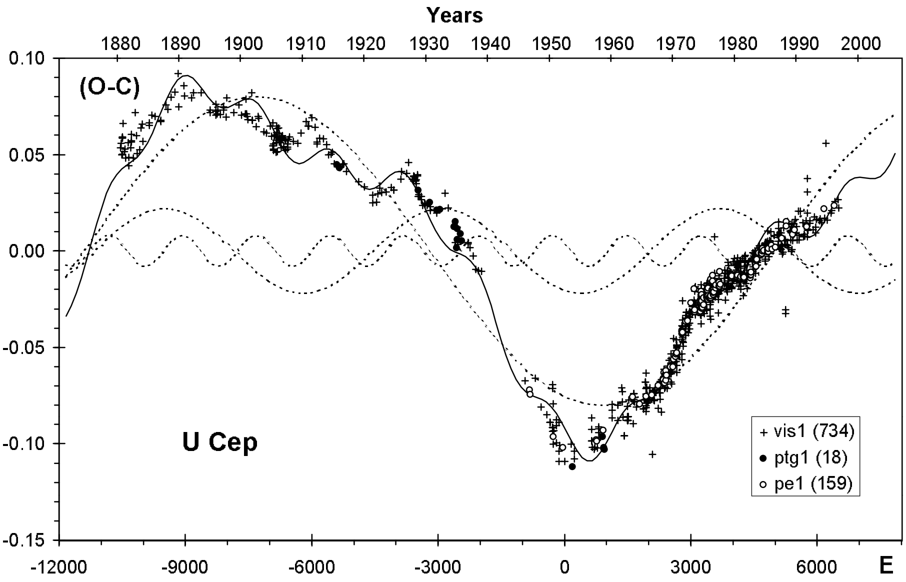

Figure 3. The residuals from the fitted parabola to the (O-C) diagram of U Cep in Fig.2.

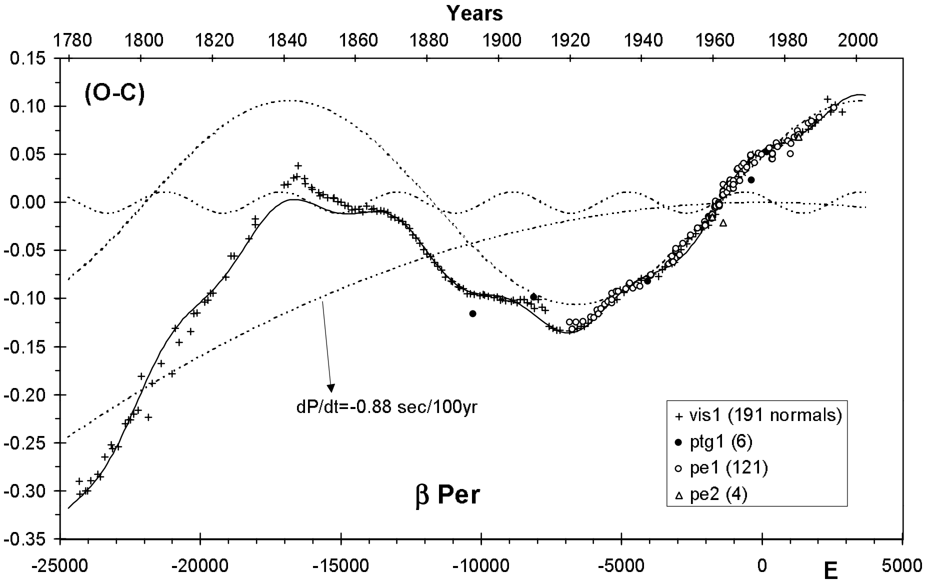

Figure 4. The (O-C) diagram and best fitted curves for β Per

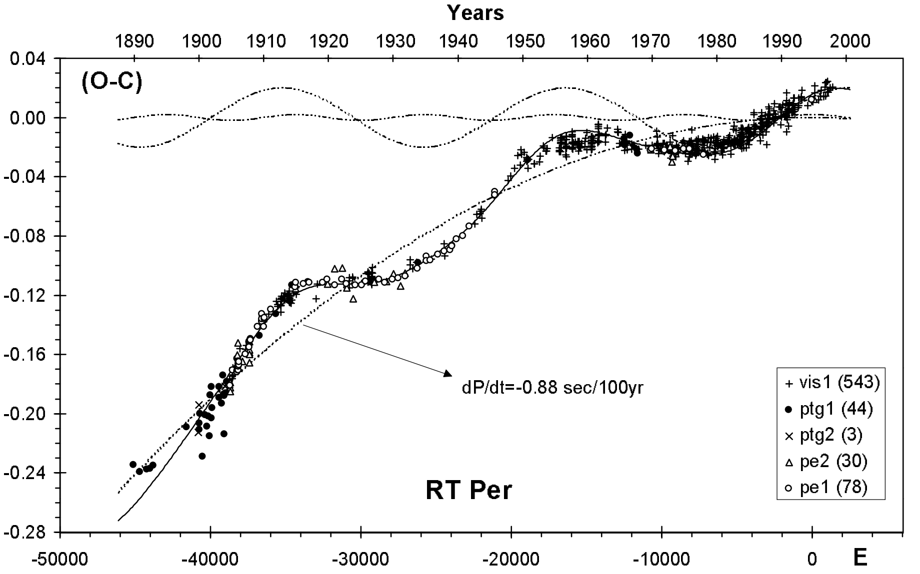

Figure 5. The (O-C) diagram and best fitted curves for RT Per

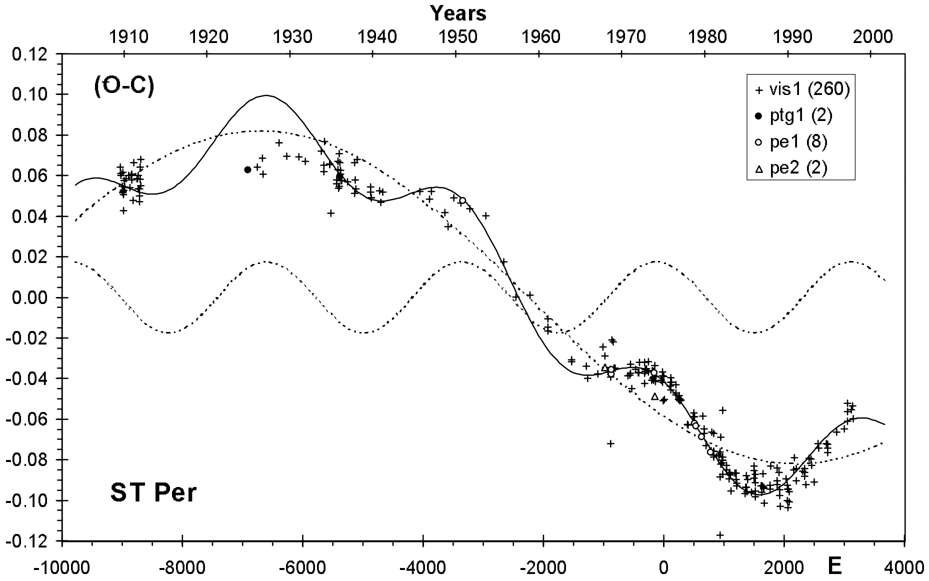

Figure 6. The (O-C) diagram and best fitted curves for ST Per

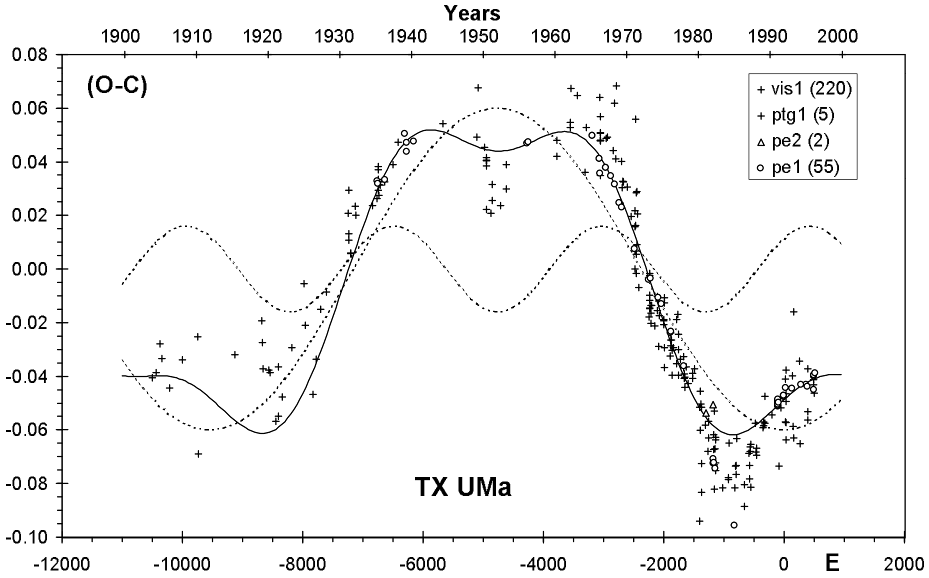

Figure 7. The (O-C) diagram and best fitted curves for TX UMa

From the theoretical point of view, the mass transfer in Algols should be from the less massive secondary to the more massive primary which increases the orbital period in the conservative case and the resulting (O-C) diagram should be a parabola with positive quadratic term. But as a consequences of the non-conservative mass transfer and/or magnetically induced stellar wind processes, considerable amount of mass loss will occur also in these systems and the (O-C) diagram is inverted to show period decreases. So the shape of the observed secular (O-C) variation of an Algol type binary will depend on two major effects (mass transfer and mass loss). We think, in some cases these two effects can balance each other and the resulting effect on the orbital period will be nothing as in the case of XZ And, ST Per and TX UMa. Downward curving parabolic variations in the (O-C) diagrams of β Per and RT Per indicates that the dominat effect is the mass loss from the system, resulting the same and a very slow continuous decrease rate of period as dP/dt=-0.88 sec/100yr in both systems. The upward curving parabolic variation in the (O-C) diagram of U Cep indicates that the dominat effect is the mass transfer between the components and the corresponding rate of period increase is dP/dt=0.17 sec/yr with a lower limit to the mass transfer rate of 1.05 10^{-6} $M_{\odot}$/yr.

The remaining cyclic variations in the (O-C) diagrams of our sample systems can be interpreted in terms of the cyclic magnetic activity effect of the late-type secondaries and/or the light-time effect due to additional unseen component stars around the systems. The observational characters of the secondary times of minimum on the (O-C) diagrams invalidates any interperation in term of apsidal motion as a cause of cyclic period variations in our case. It is important to distinguish the responsible mechanism for the observed cyclic variations in the (O-C) diagrams. The light-time effect should give more strict periodicities than the magnetic activity cycle on the (O-C) diagrams. From the analogy of magnetic activity cycles in Chromospherically Active Stars, we know that the cycle periods and amplitudes can vary even from cycle to cycle and give a quasi-periodic nature to the (O-C) diagrams. The basic idea of the magnetic activity cycle effect on the orbital period of a binary system depends on the existance of the spin-orbit coupling. Any change in the rotational regime of a binary star component due to the magnetic activity, will be reflected to the orbit as a consequence of the spin-orbit coupling [16].

We followed the Applegate's [16] formulation to calculate the activity related parameters for all individual cyclic variations in our (O-C) diagrams and listed in Table 4. These parameters are the cycle lenght P_{cyc}, amplitude of the period variation ΔP, angular momentum transfer of ΔJ required to produce the observed cyclic effects on the period, required energy ΔE for the ΔJ transfer, corresponding luminosity change ΔL and the brightness variation Δm of the secondary, and finally the subsurface magnetic field B of the secondary component. It is seen in Table 4 that all estimates are reasonable, but they neither prove nor refute the hyphothesis. Especially the expected amplitudes of brightness variations are very small and out off the detection limit of the classical photometry. Additionally our sample systems do not have enough precise and long-term observations to check such brightness variations. According to Applegate's theory, only one of the cyclic variations can be associated with the activity cycle for a given system

Table 4. Estimates of the magnetic activity cycle related parameters

	XZ And	U Cep	β Per	RT Per	ST Per	TX UMa
CYCLE 1						
P_{cyc} (years)	126.35	112.0	160.5	43.8	129.0	80
ΔP (s/cyc)	1.44	2.65	2.82	0.58	2.50	3.42
ΔJ (cgs)	$6.1\ 10^{47}$	$1.3\ 10^{48}$	$4.2\ 10^{47}$	$6.3\ 10^{46}$	$1.8\ 10^{47}$	$8.6\ 10^{47}$
ΔE (cgs)	$1.3\ 10^{41}$	$1.4\ 10^{41}$	$5.7\ 10^{40}$	$1.8\ 10^{40}$	$2.4\ 10^{40}$	$1.3\ 10^{41}$
ΔL (cgs)	$1.1\ 10^{32}$	$1.3\ 10^{32}$	$3.5\ 10^{31}$	$4.1\ 10^{31}$	$1.8\ 10^{31}$	$1.3\ 10^{32}$
Δm	0.0007	0.0004	0.00004	0.01	0.0001	0.0002
B (Gauss)	4002	2718	2091	6906	2040	3074
CYCLE 2						
P_{cyc} (years)	36.79	45.0	32.4	20.0	23.5	29.0
ΔP (s/cyc)	1.54	1.81	1.45	0.13	2.93	2.51
ΔJ (cgs)	$6.6\ 10^{47}$	$8.8\ 10^{47}$	$2.2\ 10^{46}$	$1.4\ 10^{46}$	$2.1\ 10^{47}$	$6.3\ 10^{47}$
ΔE (cgs)	$1.5\ 10^{41}$	$6.7\ 10^{40}$	$1.5\ 10^{40}$	$8.6\ 10^{38}$	$3.3\ 10^{40}$	$5.8\ 10^{40}$
ΔL (cgs)	$4.1\ 10^{32}$	$1.5\ 10^{32}$	$4.6\ 10^{31}$	$4.3\ 10^{30}$	$1.4\ 10^{32}$	$2.0\ 10^{32}$
Δm	0.0027	0.04	0.00006	0.0002	0.001	0.0003
B (Gauss)	7667	3547	3336	4782	5174	4379
CYCLE 3						
P_{cyc} (years)	-	12.0	-	-	-	-
ΔP (s/cyc)	-	2.47	-	-	-	-
ΔJ (cgs)	-	$1.2\ 10^{48}$	-	-	-	-
ΔE (cgs)	-	$1.3\ 10^{41}$	-	-	-	-
ΔL (cgs)	-	$1.0\ 10^{33}$	-	-	-	-
Δm	-	0.003	-	-	-	-
B (Gauss)	-	8021	-	-	-	-

and based on the statistical work by Maceroni et al. [17] and Bianchini [18] the relatively short period cyclic variations (5yr<P_{cyc}<25yr) might have stellar activity origin. Maceroni et al. [17] attracted our attention to the upper limit value for this interval that may be effected by the selection effect regarding with the time span of the existing precise obervations and they were concluded that the upper limit might be much longer than 25 years. Accordingly the cycles indicated as "CYCLE 2" for all systems, "CYCLE 3" for U Cephei and "CYCLE 1" for RT Persei in Table 4 may well be due to magnetic activity effect of the secondaries.

The remaining relatively longer period cyclic variations may well be due to the light-time effects of additional components stars around the system. The general formulation for the light-time effect of the additional component to the orbital period of a binary was adopted from the work by Irwin [19]. We were calculated the additional component parameters for each cyclic variation observed in the (O-C) diagrams. These parameters are the orbital period P_{orb}, the mass function $f(M_i)$, the mass M_i, the distance from the center of mass of the binary a, the maximum angular distance from the center of mass of the binary as viewed by observer α and by using the main sequence luminosity estimates the brightness difference with the binary Δm of the additional component under the assumptions of co-planar circular orbits. The estimated parameters were listed in Table 5. A minus sign in front of the Δm parameter means that the additional component

Table 5. Estimates of the additional components related parameters

	XZ And	U Cep	β Per	RT Per	ST Per	TX UMa
CYCLE 1						
P_{orb} (years)	126.35	112.0	160.5	43.8	129.0	80
$f(M_3)$ ($M_\odot$)	0.2375	0.2123	0.2405	0.0217	0.1723	0.1755
M_3 ($M_\odot$)	2.20	2.35	2.25	0.54	1.75	2.30
a (AU)	47.5	46.0	55.8	17.2	45.2	37.5
α (arcsec)	0.057	0.225	1.912	0.096	0.129	0.178
Δm	-0.633	-1.235	-2.348	-4.382	-1.504	-2.218
CYCLE 2						
P_{orb} (years)	36.79	45.0	32.4	20.0	23.5	29.0
$f(M_4)$ ($M_\odot$)	0.0844	0.0273	0.0066	0.0001	0.0505	0.0253
M_4 ($M_\odot$)	1.44	1.05	0.56	0.08	1.06	1.08
a (AU)	20.0	23.6	17.5	9.6	13.9	18.1
α (arcsec)	0.024	0.115	0.598	0.053	0.040	0.086
Δm	-2.442	-4.657	-8.260	-12.48	-3.618	-5.414
CYCLE 3						
P_{orb} (years)	-	12.0	2.0	-	-	-
$f(M_5)$ ($M_\odot$)	-	0.0185	0.1625	-	-	-
M_5 ($M_\odot$)	-	0.91	1.91	-	-	-
a (AU)	-	9.7	2.95	-	-	-
α (arcsec)	-	0.047	0.101	-	-	-
Δm	-	-5.274	-3.050	-	-	-

is fainter than the binary. The "CYCLE 3" parameters for the β Per in Table 5 are the estimates for known third component star. In almost all cases the masses of the hypothetical components turn out to be quite large and their brightness diferrences from their related binary becomes small enough to permit their astrometric and spectroscopic detection. But we can not found any trace of such detections in the literature for these systems. Therefore the hypothetical components (if they exist) around these systems should be very under-luminous in comparison to the main-sequence stars (like WDs or neutron stars) or they may also be close binary or multiple systems.

The existence of the predicted additional components around these systems can be checked by speckle interferometry and/or high resolution spectroscopy. As we stated before, the magnetic activity cycles of the secondary cool stars cause some brightness variations. However, these components can contribute to the total light of the system only about 0.05-0.1%. Such a brightness variation can be detected by the long-term IR photometry at primary minimum phases, because the contribution of the bright primary to the total light of the system is minimum at these phases.

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