Period changes in six semi-detached Algol-type binaries

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Abstract: Six semi-detached Algol-type binaries lacking a period analysis were chosen to test for a presence of a third body. The $O-C$ diagrams of these binaries were analyzed with the least-squares method by using all available times of minima. Also fourteen new minima, obtained from our observations, were included in the present research. The light-time effect was adopted as a main factor for the detailed description of the long-term period changes. Third bodies were found with orbital periods from 46 up to 84 years, and eccentricities from 0.0 to 0.78 for the selected binaries. The mass functions and the minimal masses of such bodies were also calculated.

Keywords: stars: binaries: eclipsing; stars: individual: DK Cep, TY Del, RR Dra, TZ Eri, VX Lac, UZ Sge; stars: fundamental parameters

1 Introduction

Eclipsing Binaries (hereafter EBs) are excellent objects for determining the physical properties of stars and detecting additional components in these systems. The long-time behavior of the period of an EB could reveal the presence of another component orbiting with the EB around the common center of mass. Photometric observations of EBs sometimes cover more than a century, so the periods of such third bodies could reach the same time interval.

The motion around the barycenter causes apparent changes of the observed binary period with a period corresponding to the orbital period of the third body, called the Light-Time Effect (or ‘light-travel time’, hereafter LITE). Irwin (1959) improved the method developed by Woltjer (1922) for analyzing the long-term variation of the times of minima caused by the third body orbiting the eclipsing pair. Useful comments and limitations were discussed by Frieboes-Conde & Herczeg (1973) and by Mayer (1990). Nowadays there are more than one hundred EBs showing LITE, where the effect is certainly presented or supposed (see e.g. Borkovits & Hegedues (1996), Albayrak et al. (1999), Wolf et al. (2004), Hoffman et al. (2006), etc.). For the apparent period changes in EBs according to their $O-C$ diagrams, see e.g. the catalogue by Kreiner et al. (2001). From the same paper the look of the $O-C$ diagrams, presented in the present paper, was adopted. In the figures 1 to 8 of the present work the full circles represent the primaries and the open circles the secondaries, the bigger the point, the bigger the weight. For the limitations and consequences of the $O-C$ diagram analysis, see e.g. Sterken (2005).

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The computation of the parameters of the third-body orbit is a classical inverse problem with 5 parameters to be found – \( p_3, T_0, A, \omega, e_3 \), which indicate the period of the third body, the periastron passage, the semi-amplitude of the light-time effect, the argument of periastron and the eccentricity, respectively (for a detailed description see e.g. Mayer [1990]). The ephemerides for the individual system (\( JD_0 \) and \( P \) for the linear one and \( q \) for the quadratic one) have to be calculated together with the parameters of LITE. The mass function \( f(M_3) \) and the minimal mass of the third component \( M_{3,\text{min}} = M_3 \cdot \sin i_3 \) (for \( i_3 = 90^\circ \)) could be computed from this set of parameters. The weights assigned to individual observations were used as following: \( w = 1 \) for visual observations, 3-5 for photographic and 10 for CCD and photoelectric observations. The computing code itself could be downloaded via the web pages of the author.

All of the selected systems are Algol-type EBs, semi-detached and also their spectral types are similar. The primary components have spectral types from B to F, while the secondaries from G to K. Except for 14 observations in Table 1 all the times of minima used in this paper were collected from the published literature and from minima databases available in the internet.

According to a recent paper on the period changes in Algols by Hoffman et al. (2006), there could be a connection between the spectral type of the secondary component and the nature of the period changes. Systems with spectral types of secondaries later than F5 show \( O-C \) variations, which could be caused by the magnetic activity cycles and convective envelopes. This effect was discussed by Hall (1989), Applegate (1992), Lanza et al. (1998), etc. The role of magnetic cycles on the period changes is discussed below, but due to lack of information about the systems such an analysis is a difficult task. For some of the systems selected in this paper the spectral types of secondaries are known with a low confidence level, light-curve analysis is missing and spectroscopy has never been done.

2 Observations

The photometric observations were obtained by CCD detectors at two different observatories. The first one is situated in Ondřejov Observatory, Czech Republic. The 65-cm telescope was equipped with the Apogee AP-7 CCD camera. All of the observations were secured during 2006 and 2007 and only \( R \) filter was used. The exposure times depend on the particular target and observing conditions, ranging from 20 to 60 seconds.

The second observatory is situated at Athens University campus, Athens, Greece. The 40-cm telescope is equipped with the SBIG ST-8XMEI CCD camera. All of the observations were obtained during 2007, using only the \( R \) filter. The exposure times depend on the individual stars and observing conditions, ranging from 15 to 120 seconds.

\[ \text{http://sirrah.troja.mff.cuni.cz/~zasche/} \]


3 Analysis of individual systems

3.1 DK Cep

The first system is the eclipsing binary DK Cep. This neglected system is about 12.2 mag bright in $B$ filter. The spectrum was classified as A8 + G4IV in Svechnikov & Kuznetsova (1990), but only on the basis of photometric indices. Its photometric variability was discovered in 1966 by Romano & Perissinotto, but since then no analysis of this system was performed (neither photometric nor spectroscopic one). Also period analysis has not been performed so far.

Altogether 157 observations of minimum light were collected for the analysis. One secondary and two primary times of minima were also observed at Athens observatory (see Table 1).

The analysis was carried out and the resultant plot is given in Fig. 1 where the theoretical curve is shown together with the individual observations. The parameters computed from our analysis are given in Table 2. Regrettably, the phase near the periastron is not covered with the data. This affects the values of $\omega$ and $e$ and their respective errors, so the orbit could have slightly different eccentricity. This hypothesis could be proved in the upcoming periastron passage, which will occur near 2010.

From the parameters of the third-body orbit, the predicted minimal mass of this component can be also derived. Using the masses of the primary and secondary of the EB pair as $M_1 = 1.65 \, M_\odot$ and $M_2 = 0.92 \, M_\odot$ (according to Svechnikov & Kuznetsova 1990), the minimal mass results in $M_{3,\text{min}} = 0.32 \, M_\odot$. Due to large difference between this value and the values of masses of the eclipsing pair components, one could speculate about the possible detectability of such a body. This mass indicates a spectral type about M3 (according to Harmanec 1988).

Table 1: New times of minima based on CCD observations (Kwee-van Woerden (1956) method was used). All of them were obtained in $R$ filter. For the explanation of the observatory abbreviations see the text.

| Star    | HJD-2400000 | Error  | Type | Observatory |
|---------|-------------|--------|------|-------------|
| DK Cep  | 54348.35978 | 0.00010| II   | Ath         |
| DK Cep  | 54372.51532 | 0.00008| I    | Ath         |
| DK Cep  | 54376.45890 | 0.00005| I    | Ath         |
| TY Del  | 54252.56885 | 0.00020| I    | Ond         |
| TZ Eri  | 54368.55806 | 0.00008| I    | Ath         |
| RR Dra  | 54203.36519 | 0.00003| I    | Ond         |
| VX Lac  | 54350.36051 | 0.00006| II   | Ath         |
| VX Lac  | 54359.49220 | 0.00003| I    | Ath         |
| VX Lac  | 54373.46069 | 0.00003| I    | Ath         |
| UZ Sge  | 54035.31348 | 0.00028| I    | Ond         |
| UZ Sge  | 54252.45613 | 0.00019| I    | Ond         |
| UZ Sge  | 54293.45120 | 0.00023| II   | Ath         |
| UZ Sge  | 54313.39219 | 0.00021| II   | Ath         |
| UZ Sge  | 54314.49758 | 0.00013| I    | Ath         |
Table 2: The final results (part 1): Parameters of the third-body orbits from the analysis of times of minima. The table is divided into two parts. In the first one the computed parameters are presented, while in the second one the derived quantities are given (the mass $M_{12} = M_1 + M_2$ is taken from the literature).

| Parameter | DK Cep | TY Del | RR Dra |
|-----------|--------|--------|--------|
| $JD_0$ [HJD] | 2433590.556 ± 0.005 | 2442959.471 ± 0.001 | 2434913.728 ± 0.022 |
| $P$ [day] | 0.9859085 ± 0.0000004 | 1.1911264 ± 0.0000002 | 2.8812140 ± 0.00000053 |
| $P_3$ [yr] | 31.3 ± 2.5 | 64.9 ± 2.3 | 84.3 ± 0.6 |
| $T_0$ [HJD] | 2454900 ± 1200 | 2449192 ± 1017 | 2450058 ± 442 |
| $\omega$ [deg] | 273 ± 32 | 38.5 ± 18.2 | 110.2 ± 3.5 |
| $e$ | 0.780 ± 0.256 | 0.221 ± 0.055 | 0.503 ± 0.028 |
| $A$ [day] | 0.009 ± 0.002 | 0.0268 ± 0.0012 | 0.0731 ± 0.0017 |
| $q$ [day] | – | – | $(−126.2 ± 0.1) \cdot 10^{-10}$ |
| $M_{12}$ [M$_\odot$] | 2.57 | 3.64 | 2.75 |
| $f(M_3)$ [M$_\odot$] | 0.0039 ± 0.0002 | 0.025 ± 0.001 | 0.300 ± 0.002 |
| $M_{3,\text{min}}$ [M$_\odot$] | 0.32 ± 0.01 | 0.79 ± 0.07 | 1.85 ± 0.09 |

The magnitude difference between the primary and the tertiary component is therefore more than 6 mag, or the amount of the third light in the light curve less than 1 percent, which is undetectable. Also, in the spectrum of the system such a body will be, probably, hardly detectable. Since the distance to the system is not known, one cannot estimate the predicted angular separation of the third component.

### 3.2 TY Del

TY Del (AN 141.1935, BD+12 4539) is another EB with apparently variable period. The spectrum was classified as B9+G0IV (Hoffman et al. 2006) and the relative brightness about 10.1 mag in $V$ filter. There is a consensus about the spectral types of the components of TY Del, but there is a difference between the masses. Brancewicz & Dworak (1980), and also
Figure 2: The $O-C$ diagram of TY Del (for the description see Fig. 1).

Budding (1984) and Budding et al. (2004) have proposed masses $M_1 = 5 M_\odot$, $M_2 = 2 M_\odot$, while Svechnikov & Kuznetsova (1990) gave $M_1 = 2.8 M_\odot$, $M_2 = 0.84 M_\odot$. The latter are more likely to the proposed spectral types.

The star was discovered to be a variable by Hoffmeister (1935). There was only one attempt to observe the whole light curve of TY Del photoelectrically by Faulkner (1983), unfortunately only about a half of the curve was observed. No analysis of these data was carried out so far. The star was also studied by Cook (1993) on the basis of his visual observations for the long-time scale intrinsic variations, but the results were not very conclusive.

The spectroscopic observations in $H\alpha$ were obtained by Vesper et al. (2001). They concluded that there was no activity in $H\alpha$ and no evidence for the mass transfer structures was found in this system.

Altogether 368 times of minima were collected, from which only 5 were omitted due to their large scatter. One period of the third body is already sufficiently covered by the data points (see Fig. 2), but further observations are still needed. From the LITE parameters (see Table 2) and with the approximate masses of the EB components as $M_{12} = 3.64 M_\odot$ (Svechnikov & Kuznetsova, 1990) it was possible to derive the minimal mass of the third component as $M_{3,min} = 0.67 M_\odot$. Due to lack of any other observations, this hypothesis cannot be proved. The spectral types and masses were derived only on the basis of the photometric indices and are not very conclusive. A spectroscopic analysis, as well as an analysis of the light curve of the system is needed, but the third light is hardly detectable in the light-curve solution. Regrettably, the star was not measured by Hipparcos, so the distance is not known and one cannot derive the predicted angular separation of the third component. There is also clearly visible some additional short-periodic variation, which could not be described by the LITE. For a discussion about its possible explanation see Section 3.7.

3.3 RR Dra

Another eclipsing binary which exhibits apparent period changes is RR Dra (AN 188.1904). Its relative brightness is about 9.8 mag in $V$ filter, and the spectrum was classified as A2+G8IV
The star was discovered to be a variable by Ceraski (1905). The minimum is so deep that visual observers could also provide reliable observations. That is the reason why most of the collected times of minima are visual ones (193 out of 219). Kreiner (1971) collected all available minima for the period analysis. The long-term increase of the period, evident from his $O-C$ diagram, is very probably due to the mass transfer between the components. The most recent period study of this system was performed by Qian et al. (2002), who considered (besides the mass transfer) the abrupt period jumps - altogether 8 jumps were introduced to describe the $O-C$ diagram in detail. Almost the same goodness of fit could be reached by applying the LITE hypothesis besides the mass transfer.

A total of 219 times of minima were used for the present analysis. The $O-C$ plot is...
presented in Fig[3], where LITE and the quadratic term were plotted together. In Fig[4] only LITE is shown. It is obvious that the period increase is very rapid, and the amplitude of LITE is still quite high. This leads to the relatively high mass function, which results in high predicted minimal mass $M_{3,\text{min}} = 1.85 \, M_\odot$. This is larger than the secondary and should be probably observable in the light-curve solution as well as in the spectrum. Regrettably, no such analysis has been performed so far.

The quadratic term coefficient $q = (126.1 \pm 0.1) \cdot 10^{-10} \, \text{day}$ leads to a period change about $3.25 \cdot 10^{-6} \, \text{day/yr}$. From this value the conservative mass transfer rate could be derived $\dot{M} = 3.2 \cdot 10^{-7} \, M_\odot/\text{yr}$. This relatively high value of mass transfer rate arises from the very rapid period change, which was attributed to the quadratic ephemeris. The spectroscopic observations during the primary eclipse made by Kaitchuck et al. (1985) indicate a possible presence of a transient accretion disc in the system. The presence of such a disc also supports the hypothesis of mass transfer in the system.

For the estimation of the angular separation of the third body and the astrometric confirmation of the LITE hypothesis, the distance to the system has to be known. The star was not measured by Hipparcos and the distance is not known precisely. The only information about the distance comes from Kharchenko (2001), where is surprisingly introduced an inaccurate value of the parallax $\pi = (0.40 \pm 11.50) \, \text{mas}$. A distance with such a large error is useless for the estimation of the angular separation of the predicted component.

### 3.4 TZ Eri

The system TZ Eri (AN 40.1929, BD-06 880) is an EB with orbital period of about 2.6 days and apparent brightness of about 9.7 mag in $V$ filter. It has a deep primary minimum (about 2.8 mag), so the visual observations could be also reliable.

Its variability was discovered by Hoffmeister (1929), who recognized the system to be of Algol-type. The spectral type was firstly classified by Cannon (1934) as F. Later, the spectrum was re-classified by Barblan et al. (1998) as A5/6 V (primary) and K0/1 III (secondary). In this latter paper the light-curve observations in the Geneva 7-color photometric system were
Table 3: The final results, part 2. The distance \( d \) of the system TZ Eri is taken from the literature.

| Parameter | TZ Eri \( [\text{HJD}] \) | VX Lac \( [\text{HJD}] \) | UZ Sge \( [\text{HJD}] \) |
|-----------|-----------------------------|-----------------------------|-----------------------------|
| \( JD_0 \) | 2446109.730 ± 0.009 | 240908.901 ± 0.001 | 2445861.420 ± 0.002 |
| \( P \) [day] | 2.6061120 ± 0.0000034 | 1.074976 ± 0.00000002 | 2.2157425 ± 0.00000007 |
| \( p_3 \) [yr] | 48.8 ± 6.8 | 68.2 ± 0.3 | 47.0 ± 2.4 |
| \( T_0 \) [HJD] | 2451107 ± 2290 | 2440000 ± 1100 | 2449248 ± 2036 |
| \( \omega \) [deg] | 0.0 ± 0.2 | 111 ± 15 | 293.6 ± 46.7 |
| \( e \) | 0.005 ± 0.105 | 0.41 ± 0.12 | 0.281 ± 0.130 |
| \( A \) [day] | 0.0423 ± 0.0138 | 0.0210 ± 0.0016 | 0.0235 ± 0.0029 |
| \( q \) [day] | (18.0 ± 0.2) \cdot 10^{-10} | (3.15 ± 0.01) \cdot 10^{-10} | – |
| \( M_{12} \) [\( M_\odot \)] | 2.34 | 1.92 | 2.34 |
| \( d \) [pc] | 270 ± 12 | – | – |
| \( f(M_3) \) [\( M_\odot \)] | 0.165 ± 0.013 | 0.0108 ± 0.0003 | 0.031 ± 0.002 |
| \( M_{3,\text{min}} \) [\( M_\odot \)] | 1.30 ± 0.10 | 0.385 ± 0.008 | 0.65 ± 0.05 |
| \( a \) [mas] | 77 ± 7 | – | – |

analyzed together with the radial-velocity curves of both components. The Wilson-Devinney code was used, resulting in a set of parameters describing both components. For our analysis the masses \( M_1 = 1.97 \ M_\odot \), \( M_2 = 0.37 \ M_\odot \) were used (Barblan et al., 1998).

Several studies about the presence of an accretion disc in the system have also been made by Kaitchuck & Honecutt (1982), Kaitchuk & Park (1988), Vesper et al. (2001) and others. This disc as well as mass transfer from the secondary to the primary is in agreement with our result about the increasing orbital period (see below). The system was also included in the sample of Algol-type binaries with radio emission (Umana et al., 1998). Recently, the star was investigated according to a possible connection between the orbital and pulsational periods (see Soydugan et al. 2006).

The analysis of the long-term period changes was based on a set of 108 observations (mostly the visual ones). The resultant \( O - C \) diagram is presented in Fig.3 and the parameters of the predicted LITE are given in Table3. The minimal mass of the third component results in \( M_{3,\text{min}} = 1.3 \ M_\odot \), or the spectral type F6 (according to Harmanec 1988). Such a body could be detected in the light-curve solution as well as in the spectra of TZ Eri. Regrettably, there was no attempt to detect such a body during the detailed analysis by Barblan et al. (1998). The long-term period increase is due to the mass transfer from the secondary to the primary, with the conservative mass-transfer rate \( \dot{M} = 3.2 \cdot 10^{-8} \ M_\odot/\text{yr} \).

Despite the fact that the star was not observed by Hipparcos, Barblan et al. (1998) estimated the photometric distance to \( d = (270 ± 12) \ \text{pc} \). Assuming a coplanar orbit of the third component, then \( M_3 = M_{3,\text{min}} \) and one could calculate the predicted angular separation of the third body to \( a = 77 \ \text{mas} \) and a magnitude difference between the eclipsing pair and the predicted component about 1.7 mag. Therefore, the final result is that such a body is detectable with the modern stellar interferometers.

3.5 VX Lac

The eclipsing binary system VX Lac (BD +37 4662, GSC 03214-01295) has its apparent brightness about 10.55 mag in V filter. The orbital period is close to one day. Its spectral type was
firstly derived by Cannon (1934) as F0, nowadays the adopted spectral type is F0 + K4IV (Svechnikov & Kuznetsova, 1990).

Unfortunately, neither light curve analysis nor spectroscopic mass ratio exists for the system. Kreiner (1971) included this star to his study of systems with period changes, but at that time the LITE variation could not be identified conclusively. Nowadays there are 370 times of minima. It is clearly visible from this data set that, besides the quadratic term, there is a periodic variation in the times of minima (see Fig. 6). The parameters of the fit are given in Table 3.

The mass transfer coefficient leads to the conservative mass transfer rate about \( \dot{M} = 4.7 \times 10^{-8} \, M_\odot/\text{yr} \). Such a result is in agreement with the previous study by Chis (1998), who concluded that the star is currently in the mass loss state.

The LITE parameters indicates the predicted minimal third-body mass about \( 0.4 \, M_\odot \). The secondary component \( (M_2 = 0.47 \, M_\odot) \) is only slightly more massive, but, despite this fact, the expected magnitude difference between the primary and the tertiary component is too high (about 5 mag) to be detected. The derived contribution of the third star to the total luminosity is only about 1 percent and therefore is hardly detectable. Having no information about its distance one cannot estimate the angular separation of the third body. The additional variation in \( O - C \) diagram after subtracting the LITE and quadratic term is shown in Fig. 8 (see the possible explanation in Section 3.7).

3.6 UZ Sge

The EB system UZ Sge (AN 435.1936) has orbital period of about 2.2 days and its spectrum is classified as A3V+G0IV (Svechnikov & Kuznetsova, 1990).

The photometric variability of UZ Sge was discovered by Guthnick & Schneller (1939). Since then, there was no attempt for any detailed analysis, neither photometric nor spectroscopic one. The only spectroscopic observation was done by Halbedel (1984) for the derivation of the spectral type of primary component.

Five new times of minima were obtained for this paper (see Table 1). Altogether 125
measurements of times of minima were found in literature, but 14 observations were neglected due to their large scatter. Taking as masses of the individual components those given by Svechnikov & Kuznetsova (1990), $M_1 = 2.05 \, M_\odot$ and $M_2 = 0.29 \, M_\odot$, the minimal mass of the third component results in $M_{3,\text{min}} = 0.65 \, M_\odot$. But due to absence of any detailed analysis of this system, this value cannot be proved.

### 3.7 Alternative explanation of the orbital period changes

One can see some additional non-periodic variations in the $O - C$ diagrams, which cannot be described by applying only the LITE hypothesis. In Fig. 8 four cases with the most evident variations are shown. The amplitudes of these variations are usually about 10 minutes in $O - C$ diagram and these are not strictly periodic. This could be caused by the presence of stellar convection zones, in an agreement with the so-called Applegate’s mechanism, see e.g. Applegate (1992), Lanza et al. (1998), or Hoffman et al. (2006). This effect could play a role, because the spectral types of the secondary components are later than F5 (see Zavala et al. (2002) for a detailed analysis). To conclude, for a better description of the observed period variations of these systems, the magnetic activity cycles could be present together with the LITE. On the other hand, one has to take into consideration that the spectral types of most of these binaries were derived only on the basis of their photometric indices (Svechnikov & Kuznetsova, 1990) and are not very reliable.

The only system, where one could estimate the variation of the quadruple moment (see Applegate (1992) required to explain the long-term period variations, is TZ Eri, where the semi-major axis of the orbit from the light curve and radial velocity curve solution is known. Using the following equation

$$\Delta P = A \sqrt{2(1 - \cos\{2\pi P/p_3\})}$$

(Rovithis-Livaniou et al. 2000) one could compute the amplitude of the period oscillation. The period variation $\Delta P/P$ can be used for calculating the variation of the quadruple moment $\Delta Q$, 

![Figure 7: The $O - C$ diagram of UZ Sge (for the description see Fig.1).](image)
using the equation \citep{Lanza2002}

\[
\frac{\Delta P}{P} = -9 \frac{\Delta Q}{P a^2}.
\]

This quantity results in \(\Delta Q = 3.6 \times 10^{51} \text{ g cm}^2\), which is well within the limits for active binaries and therefore the variation in TZ Eri could be also explained by this mechanism.

## 4 Discussion and conclusions

Six Algol-type semi-detached eclipsing binaries were analyzed for the presence of LITE on the basis of their \(O - C\) diagram analysis and the times-of-minima variations. A few new observations of these systems were obtained and used in the present analysis. All of the studied systems show apparent changes of their orbital periods, which could be explained as a result of orbiting the EB with a third component around their common center of mass.

Such a variation has usually a period of the order of decades, as one can see from Figs. 1-7, which can be described by applying the LITE hypothesis sufficiently. In three cases (RR Dra, TZ Eri and VX Lac) the quadratic term in the light elements was also used. This could be explained as a mass transfer between the two components, which is a common procedure in semi-detached systems. The conservative mass-transfer rates were calculated.

About half of the systems show also an additional variation in \(O - C\) diagram after the subtraction of LITE. Such a variation is not strictly periodic, it has usually an amplitude about 10 minutes and a ”period” from 5 to 20 years. Because all of the systems have the spectral types of secondaries later than F5, the variation could be caused by the convection and the magnetic activity in these binaries. This explanation would clarify the non-periodicity and the changes in amplitude of such variations, as well the existence or non existence of such phenomena in some EBs.

Regrettably, in most of the systems no detailed analysis (neither photometric nor spectroscopic) has been made so far. The spectral types and the masses of the individual components
in the systems are only approximate, so the parameters of the predicted third bodies are also
affected by relatively large errors. Due to missing information about the distances to these
binaries, any prediction about the angular separation could be done. It is obvious that only
further detailed photometric, as well as spectroscopic and interferometric analysis would reveal
the nature of these systems and confirm or reject the third-body hypothesis.

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