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A DETAILED LIGHT CURVE ANALYSIS OF TY DELPHINI

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RESUMEN

Se presenta por primera vez un análisis detallado de la curva de luz de la binaria eclisante TY Del. Se observó la curva de luz en B, V, R e I, y se derivaron nuevos tiempos para el mínimo. Se observó el mínimo secundario por primera vez. Es sistema es una binaria separada con componentes muy desiguales. La excentricidad aún es incierta, pero no se descarta un valor distinto de cero. Se discute la influencia de una posible tercera compañera, así como un posible movimiento apsidal. Si la hipótesis sobre el movimiento apsidal fuera confirmada, estaríamos ante el movimiento apsidal de más corto período entre las binarias eclipsantes conocidas.

ABSTRACT

A detailed light curve analysis of the eclipsing binary TY Del is presented for the first time. The B, V, R, and I light curves were observed and also new minima times have been derived. The secondary minimum has been observed for the first time. The system is probably a detached one with rather unequal components. Eccentricity of the system is still uncertain, but not ruled out. Also the influence of a possible third component is discussed together with a potential apsidal motion. If the hypothesis of apsidal motion is confirmed, it will be the shortest apsidal motion period among eclipsing binaries.

Key Words: binaries: close — binaries: eclipsing — stars: fundamental parameters — stars: individual (TY Del)

1. INTRODUCTION

TY Del (AN 141.1935, BD+12 4539, GSC 01116-02030) is an eclipsing binary having a light curve of Algol-type (Malkov et al. 2006). The spectrum was classified as B9+G0IV (Hoffman et al. 2006) and its relative brightness is about 10.1 mag in V filter. There is an agreement about the spectral types of the components of TY Del, but there exists a discrepancy between the derived masses. Brancewicz & Dworak (1980), and also Budding (1984) and Budding et al. (2004) have proposed the individual masses $M_1 = 5\ M_\odot$ for the primary and $M_2 = 2\ M_\odot$ for the secondary component, while Svechnikov & Kuznetsova (1990) gave $M_1 = 2.8\ M_\odot$, $M_2 = 0.84\ M_\odot$. However, the latter ones are more credible for the proposed spectral types. No detailed spectroscopic analysis of this binary has been performed; the radial velocities are not known, therefore here we deal with a lack of information. A recent period analysis of TY Del, applying a third-body hypothesis in the system and the apparent modulation of the orbital period via a light time effect, was given by Zasche et al. (2008).

Hoffmeister (1935) discovered the system to be a variable one. The star has been observed photoelectrically by Faulkner (1983), but his observations cover only about one half of the curve and no analysis of these data has been carried out so far. Long-time photometric variations of TY Del have been studied by Cook (1993) on the basis of his visual observations, but the results are inconclusive.

The only spectroscopic study of TY Del has been published by Vesper, Honeycutt, & Hunt 2001, who found no activity in Hα and no evidence of intercomponent mass transfer.

2. OBSERVATIONS

Accurate CCD photometric observations of the system have been carried out in the standard Johnson-Cousins B, V, R_c, and I_c system. All the measurements were obtained with the 254-mm re-

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TABLE 1

NEW DERIVED TIMES OF MINIMA OF TY DEL[a]

HJD-2400000 [d]	Error [d]	$O-C$ [d]	Type	Filter	Observer
54719.49362	0.00023	0.00602	Pri	R	1
54719.49366	0.00021	0.00606	Pri	I	1
54719.49398	0.00019	0.00638	Pri	V	1
54719.49399	0.00029	0.00639	Pri	B	1
54755.81684	0.00264	−0.00025	Sec	V	1
54755.81645	0.00147	−0.00064	Sec	R	1
54755.82066	0.00128	0.00357	Sec	I	1
54810.61889	0.00145	0.00978	Sec	R	2

[a]Note: The Kwee-van Woerden (1956) method was used. Observers: 1 - R. Uhlař, Jílové u Prahy; 2 - P. Zasche, San Pedro Mártir Observatory.

flector by one of the authors (R.U.) at a private observatory at Jílové u Prahy in the Czech Republic, using the G2/KAF-0402ME CCD camera, and standard B, V, R_c, and I_c filters according to Bessell's (1990) specification. The field of view (FOV) is about $19' \times 12'$, or equivalently the angular pixel size is approximately $1.48'' \times 1.4''$. The observations were carried out from October 2007 to November 2008. The measurements were reduced using the C-MUNIPACK[4] software, based on aperture photometry, employing standard DaoPhot package.

The star has been observed for 13 nights in total. Apart from the telescope described in the previous paragraph, the system was additionally observed also at San Pedro Mártir observatory in Mexico, in order to obtain one more secondary minimum. The 84 cm telescope equipped with a Marconi CCD camera was used and also the same reduction programme. That one night has not been added to the other ones for obtaining the light curve solution; it was used only for deriving the time of the minimum. From all these measurements, 8 new times of minima, 4 primary and 4 secondary, were derived (see Table 1).

Selecting a proper comparison star has turned out to be a quite difficult task. The field near TY Del is not very dense and all of the closer stars are too faint or have spectral types different from the variable itself. For the whole light curve, TYC 1116 01931-1 was used as the comparison star. For controlling the non-variability of this star we used TYC 1116-02387-1 as the check star. No visible variabilities above the level of scatter in individual filters (see the next paragraph) between these stars were observed. For the observation of the secondary minimum GSC 1116-02220 was used as the comparison star.

[4]See `http://integral.sci.muni.cz/cmunipack/`.

Due to the sensitivity profile of the CCD chip on different wavelengths and the observing conditions on the site, there is a different scatter of the light curve (hereafter LC) in different passbands. Particularly outside the minima, the scatter in B is about 0.18 mag, in V about 0.07 mag, in R about 0.06 mag, and in I about 0.07 mag.

Both components are of rather different spectral types, which demands not only unequal depths of both minima, but also variable photometric indices $B-V$, $V-R$, and $R-I$ in different orbital phases of the system. They are shown in Figures 1 to 3. It can be clearly seen that during the primary minimum at phase 0 (when the primary component has been eclipsed), all of the indices increase.

3. ANALYSIS

For the analysis of the LC the programme PHOEBE was used (see e.g. Prša & Zwitter 2005). It is originally based on the Wilson-Devinney algorithm (Wilson & Devinney 1971), with its recent modifications, which deals with the physical model based on equipotential surfaces of the components.

Due to the fact that the spectroscopy of TY Del is still unavailable, the individual spectral types are not known with high accuracy. The proposed spectral types B9+G0IV introduced by Hoffman et al. (2006) are also only estimated, but on the other hand, they represent the most reliable information about the individual components. Neither are the masses presented by Svechnikov & Kuznetsova (1990) very reliable, but they give us at least an estimate about the mass ratio.

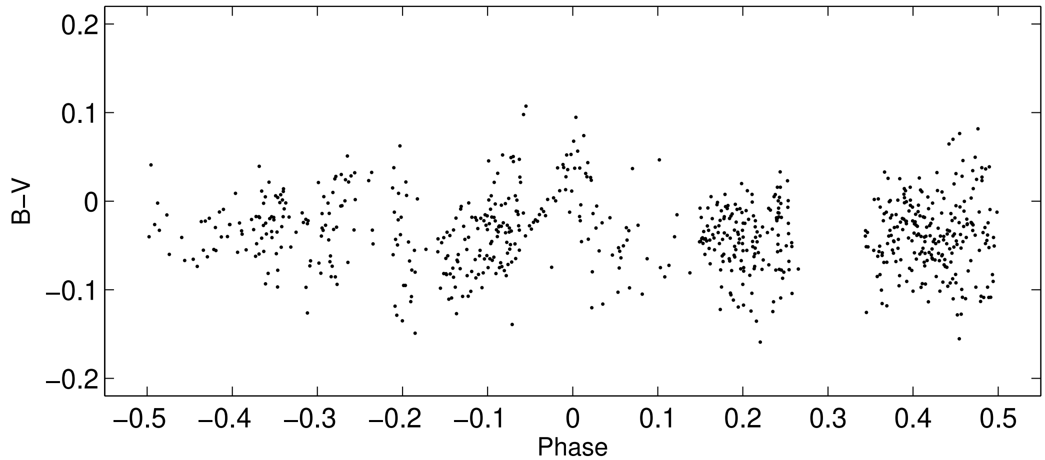

Fig. 1. $B-V$ index during the whole orbital phase.

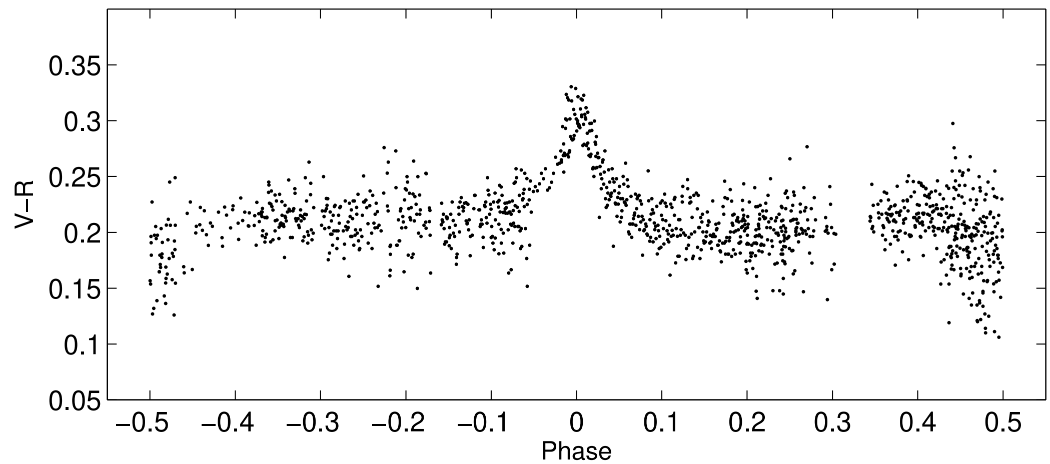

Fig. 2. $V-R$ index during the whole orbital phase.

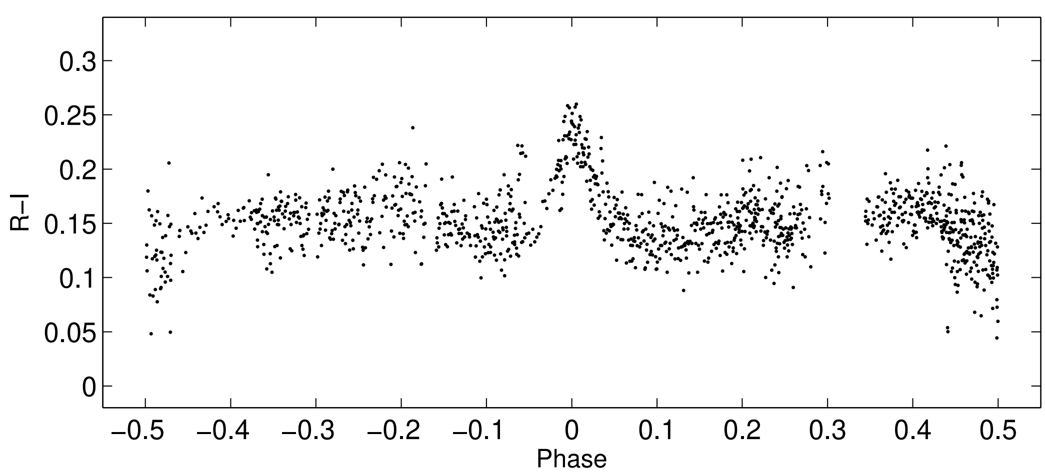

Fig. 3. $R-I$ index during the whole orbital phase.

In what refers to the light curve, there are only few quantities that could be calculated (see e.g. Kallrath & Milone 1999). The other fundamental parameters of the system such as mass ratio, temperature of the primary, or the absolute radii of the components, can be only estimated or assumed. The reason why the value of mass ratio cannot be determined is the following: the system TY Del was found to be a detached one, and in detached eclipsing systems this quantity cannot be calculated. For a detailed analysis of the photometric masses, see Terrell & Wilson (2005).

Being the primary (the deeper one) minimum the transit, and after considering also other models, the detached binary mode has been chosen, as it was able to describe the present data with the highest accuracy (according to the chi-square values).

Due to these reasons, we have made several assumptions before the analysis. Firstly, the temperatures of both components cannot be computed either, only their ratio. Hence, we have proposed a temperature of the primary component to be 10350 K, which agrees with the spectral type of the primary B9, according to Hoffman et al. (2006) and Harmanec (1988). Also the starting value of the secondary component temperature has been taken from its proposed spectral type of G0IV, which is about 6000 K.

Secondly, the mass ratio $q = M_2/M_1$ was found via the q-search method from a value 0.1 to 1.0 with a step 0.1. This approach was applied in Mode 2 (detached system), and Mode 5 (semi-detached system with the secondary component filling its Roche lobe) in order to find the most suitable value of the (photometric) mass ratio q. The χ^2 value reached its minimum for the detached configuration and for $q = 0.3$, which is in agreement with the masses estimated by Svechnikov & Kuznetsova (1990). Other parameters were calculated; only the values of limb darkening coefficients have been interpolated from the van Hamme's tables (van Hamme 1993).

For the whole computation process, the differential corrections method was used (Irwin 1947). The number of data points in the individual filters was the following: 740 in B, 1190 in V, 1262 in R, and 1178 in I filter, respectively. The fitting strategy was to adjust at first only one parameter and then an appropriate combination of parameters. These sets of parameters have been chosen according to the correlation matrix, so their mutual correlation could not be above a certain limit (we have used 0.6).

During the computation process, two rather different solutions were found, that differ only slightly in the χ^2 values (see Table 2 and also Figure 4), but represent unequal orbital parameters. The most important difference is the value of eccentricity of both solutions. Not only a circular-orbit solution was found (hereafter referred as SOLUTION I), but also an eccentric-orbit solution (SOLUTION II). Both of them are presented and compared below. As one can see in Figure 4, the best fit is that using the mass ratio 0.3 in all three different configurations. The two solutions (SOLUTION I and II) differ significantly in χ^2 values, particularly if compared to the difference between circular and eccentric detached solutions. Only the values close to the best solution were plotted for better clarity, because the values out of this interval are much higher.

The final parameters for both solutions are presented in Table 2, while the plots of the light curves in all filters and for both solutions are shown in Figures 5 and 6. The 3D figure of the system is plotted in Figure 7. In Table 2, the following parameters are given: heliocentric Julian date HJD_0, orbital period P, inclination i, mass ratio q, temperatures of primary and secondary T_i, orbital eccentricity e, the argument of periastron ω_0 at zero epoch HJD_0, the ratio of luminosities L_1/L_2, the third light as a fraction of the total light l_3, the Kopal modified potentials Ω_i, synchronicity parameters F_i, albedo coefficients A_i, gravity darkening coefficients g_i, and R_i/a the relative radii of the components, respectively. As one can see, the parameters such as synchronicity parameters, albedos, or gravity darkening coefficients could be estimated from our data only with difficulty and are affected by relatively large errors. All of the presented errors are only formal ones, and indicate the standard deviations of the final fit from the PHOEBE programme.

Despite the fact that most of the classical Algols constitute semi-detached systems, from our analysis it appears that TY Del is probably a detached system. However, this conclusion is based only on the q-search method used, which may not be very reliable. If we adopt this solution, the secondary component is probably a subgiant, but still within its Roche lobe. From the light curve, only relative values of the basic physical parameters of the system could be derived. On the other hand, when we assume not only a mass ratio, but also the absolute values of the masses given by Svechnikov & Kuznetsova (1990), we could estimate the luminosities and radii in Solar units (see Table 3). From this assumption there also results a semi-major axis of about 7.3 $R_\odot$. Also the photometric distance to TY Del has been derived, and we obtain a value of about 630 pc, while Brancewicz &

TABLE 2

LIGHT CURVE PARAMETERS[a]

Parameter	SOLUTION I	SOLUTION II
HJD_0	2454719.4930 ± 0.0002	2454719.4930 ± 0.0003
P [day]	1.1911314 ± 0.0000011	1.1911281 ± 0.0000011
i [deg]	98.11 ± 0.10	98.13 ± 0.10
$q = M_2/M_1$	0.3	0.3
T_1 [K]	10350 (fixed)	
T_2 [K]	4749 ± 18	4774 ± 21
e	0.0	0.0048 ± 0.0012
ω_0 [deg]	–	48.78 ± 7.85
L_1/L_2 (B)	31.19 ± 2.01	30.64 ± 1.95
L_1/L_2 (V)	21.16 ± 1.01	20.79 ± 0.98
L_1/L_2 (R)	12.13 ± 0.36	12.00 ± 0.35
L_1/L_2 (I)	7.48 ± 0.16	7.41 ± 0.16
l_3 (B) [%]	5.23 ± 2.27	5.03 ± 2.26
l_3 (V) [%]	4.14 ± 1.82	4.01 ± 1.71
l_3 (R) [%]	3.15 ± 1.28	3.01 ± 1.47
l_3 (I) [%]	3.91 ± 1.17	3.80 ± 1.26
Ω_1	4.753 ± 0.015	4.775 ± 0.012
Ω_2	2.417 ± 0.013	2.419 ± 0.010
F_1	4.345 ± 0.029	4.388 ± 0.024
F_2	0.201 ± 0.113	0.148 ± 0.135
A_1	1.000 ± 1.380	1.000 ± 1.023
A_2	0.547 ± 0.049	0.555 ± 0.049
g_1	0.31 ± 0.03	0.31 ± 0.02
g_2	0.10 ± 0.14	0.09 ± 0.16
R_1/a	0.265	0.264
R_2/a	0.283	0.284
χ^2	1.9593	1.9528

[a]Note: SOLUTION I stands for the circular orbit. SOLUTION II for the eccentric one. The values of the third light l_3 are in units of the total light of the system $[l_3/(L_1 + L_2 + l_3)]$.

Dworak (1980) estimated the distance about 800 pc. From the physical parameters of both components we could estimate their actual evolutionary status. The primary component seems to be on the main sequence, but the secondary is slightly evolved, to be found in the sub-giant area of the HR diagram (for the evolutionary tracks see e.g. Schaller et al. 1992). However, this result seems to be in disagreement with the close binary evolution models (the less massive star is more evolved), if the secondary does not fill its respective Roche lobe. Hence, a more detailed analysis is needed.

The difference between SOLUTION I and II for most of the parameters is only marginal, but still outside their relative errors. The most important difference is a possible eccentricity of the orbit, which will be discussed in more detail below. The value of the third light and the contribution of a potential third body is also discussed below, in § 4. With the present data, it is not possible to decide which solution is the right one.

There were found no visible pulsations or other variations in the light curve. This agrees with the spectral types of both components, which are located outside the instability strip. The only possible distortion of the curve is near the orbital phase around -0.3, most visible in I filter. This could be caused by a photospheric spot on the surface of either the

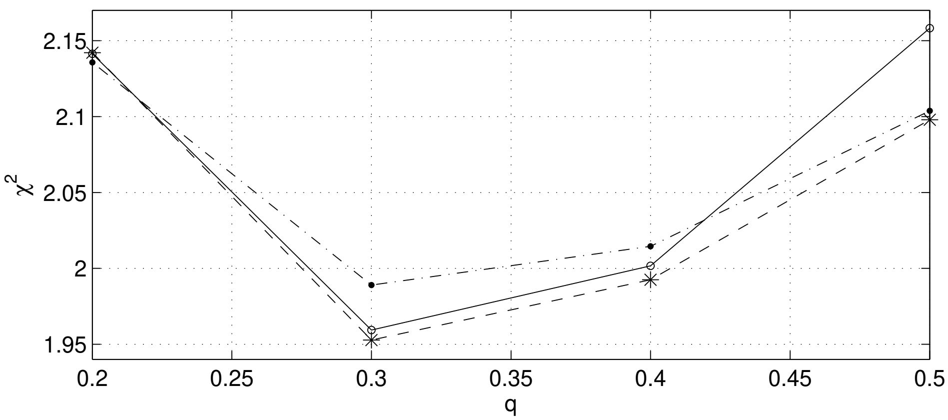

Fig. 4. The χ^2 values of different solutions according to the mass ratio. The solid points correspond to the semidetached circular configuration, the open circles to the detached circular configuration, and the star symbols to the eccentric detached solution.

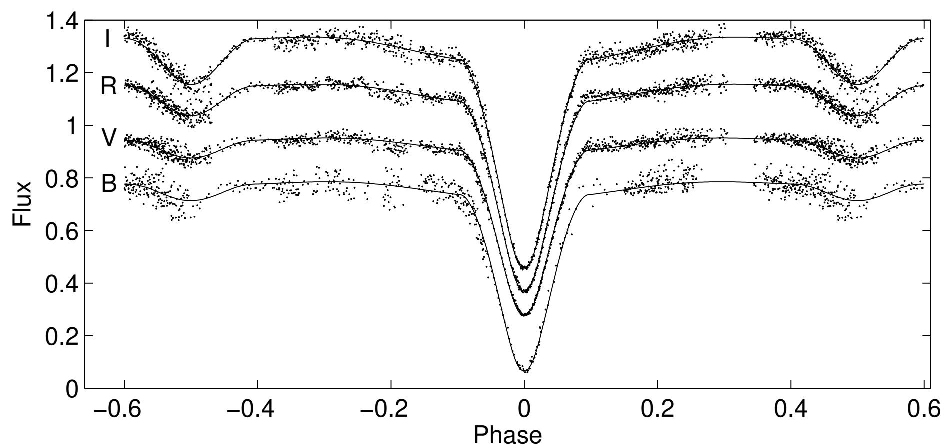

Fig. 5. B, V, R, and I light curves of TY Del with the theoretical fit (see the text). The B light curve is shifted by -0.2 in the y axis for better clarity. The fits correspond to the circular SOLUTION I.

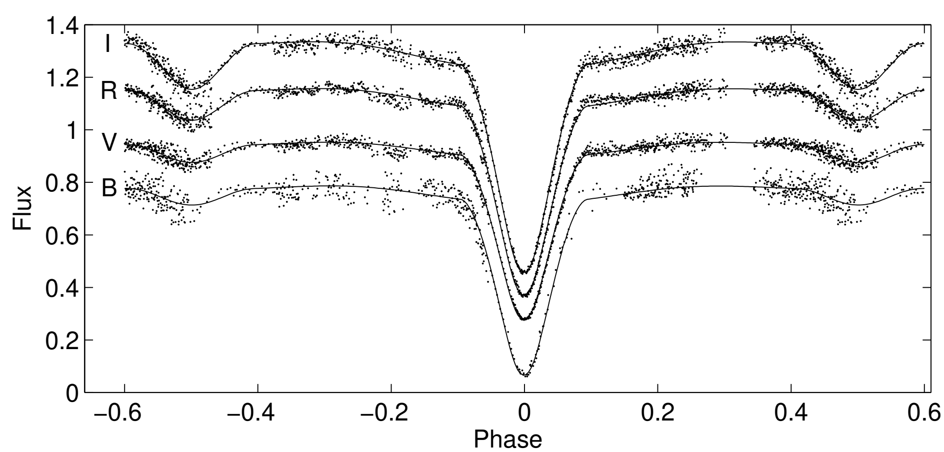

Fig. 6. B, V, R, and I light curves of TY Del with the theoretical fit (see the text). The B light curve is shifted by -0.2 in the y axis for better clarity. The fits correspond to the eccentric SOLUTION II.

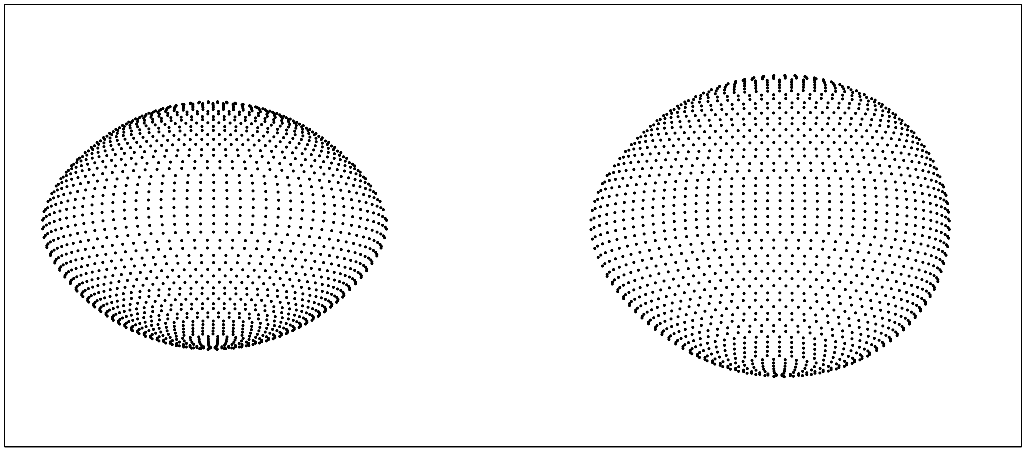

Fig. 7. 3D plot of the system in phase 0.25, according to SOLUTION I. The primary component is the left one.

TABLE 3

BASIC PHYSICAL PARAMETERS OF TY DEL

	M_1 $[M_\odot]$	M_2 $[M_\odot]$	R_1 $[R_\odot]$	R_2 $[R_\odot]$	L_1 $[L_\odot]$	L_2 $[L_\odot]$
SOLUTION I	2.8	0.84	1.92	2.06	36.64	1.87
SOLUTION II	2.8	0.84	1.92	2.06	36.64	1.91

primary or the secondary component. Any such phenomena were not included in our analysis due to the insufficient precision of our data.

The secondary minimum of TY Del has been observed for the first time. All of the times of minima observed during this campaign are presented in Table 1. In this table, the heliocentric Julian date together with the error, type, filter of observation and observer are presented. There are also given the values of $O-C$ residuals according to the following ephemeris

$$\begin{aligned} \mathrm{HJD\,Min\,I} = 24\,54719.4876 \;&+\; 1\overset{\mathrm{d}}{.}19113082\cdot \mathrm{E}. \\ \pm 0.0016 \;&\pm\; 0\overset{\mathrm{d}}{.}00000034\,. \end{aligned} \qquad (1)$$

The depth of the secondary minima strongly depends on the filter used. In the B filter, the depth is only about 0.048 mag, in V about 0.078 mag, in R about 0.115 mag, and in I about 0.156 mag, respectively. On the other hand, the depth of primary minimum also depends on the filter: 1.413 mag in B, 1.299 mag in V, 1.187 mag in R, and 1.104 mag in I.

As a result of LC analysis, two rather different solutions were found, between which we cannot easily distinguish the right one. The eccentricity in SOLUTION II is small, but still below a level of its error. Regrettably, there is no similar test like Lucy & Sweeney (1971) test for eccentricity in spectroscopic binaries to be applied to the light curve solution here.

4. PERIOD ANALYSIS AND POSSIBLE APSIDAL MOTION

A detailed period analysis is that by Zasche et al. (2008), who proposed a light-time effect hypothesis (see e.g. Irwin 1959, hereafter LITE) as an explanation for the period changes. They have also mentioned an additional variation, which is visible after subtracting the LITE term. They have suggested that this could be caused by a magnetic activity of one or both components of the eclipsing pair.

Yet another approach has been chosen for the present analysis. We have used only precise photoelectric and CCD observations of times of minima (whereas Zasche et al. 2008 used all available minima, including the visual ones with large scatter) and did a similar analysis of the period changes. The result is plotted in Figures 8 and 9, where the theoretical curves representing the LITE hypothesis (dash-dotted line) and also the apsidal motion hypothesis (dashed and solid lines) are displayed together with the data used for the analysis. The plots are constructed according to the linear ephemeris

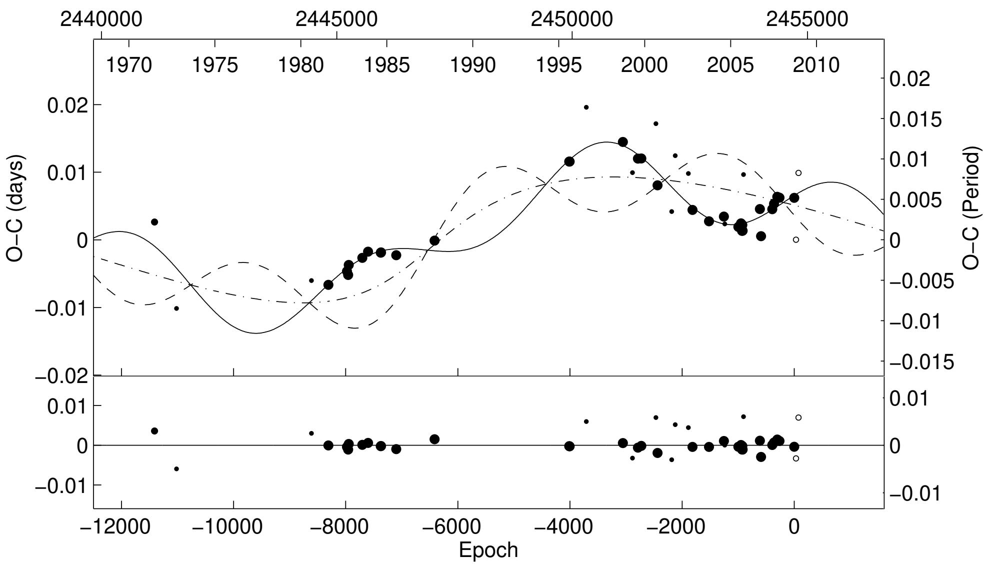

Fig. 8. The $O-C$ diagram of TY Del. The different curves represent theoretical fits: the dash-dotted one for the LITE, the solid one for the primary, and the dashed one for the secondary minima. Dots stand for the primary, open circles for the secondary minima observations. In the bottom plot the residuals after subtracting both LITE and apsidal motion are presented.

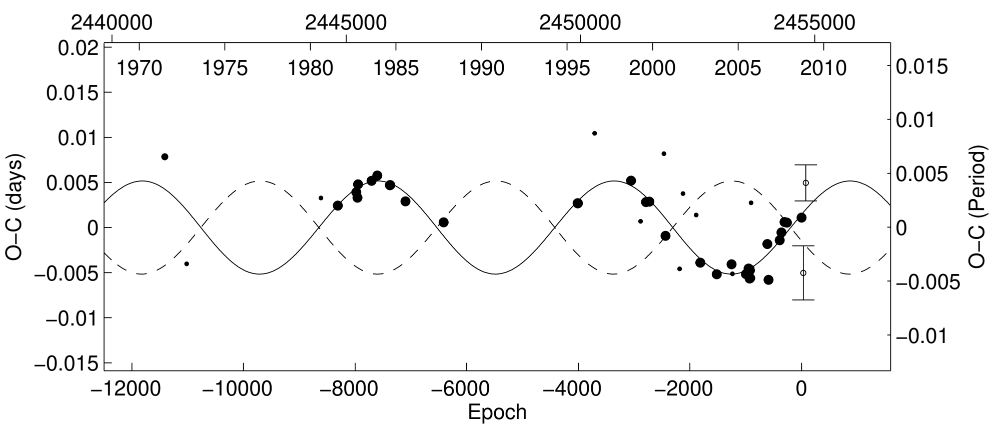

Fig. 9. The $O-C$ diagram of TY Del after subtracting the LITE term. The curve represents hypothetical apsidal motion, solid line for the primary, dashed line for the secondary minima. Dots stand for the primary, open circles for the secondary minima observations.

given in equation (1). The secondary minimum observed in three filters was averaged into one point for better clarity. For the apsidal motion, the method described by Giménez & García-Pelayo (1983) was used.

We have found a somewhat shorter period for the third body (about 50 years) than Zasche et al. (2008) who presented a period of about 65 years. From the parameters of the LITE one could also derive a predicted minimum mass of the third body. While Zasche et al. (2008) presented a minimum mass of about 0.79 $M_{\odot}$, from our new analysis this value turns out to be only about 0.33 $M_{\odot}$. But luminosity from such a small body would be only negligible, less than 1% of total luminosity, which is in contradiction with the value of l_3 derived from the LC analysis. If we suppose that this body is a main-sequence star, then it should be more massive. One solution is that the minimum mass derived by Zasche et al. (2008) is closer to the true mass; another possibility is that the inclination is less than 90°, about only 20°.

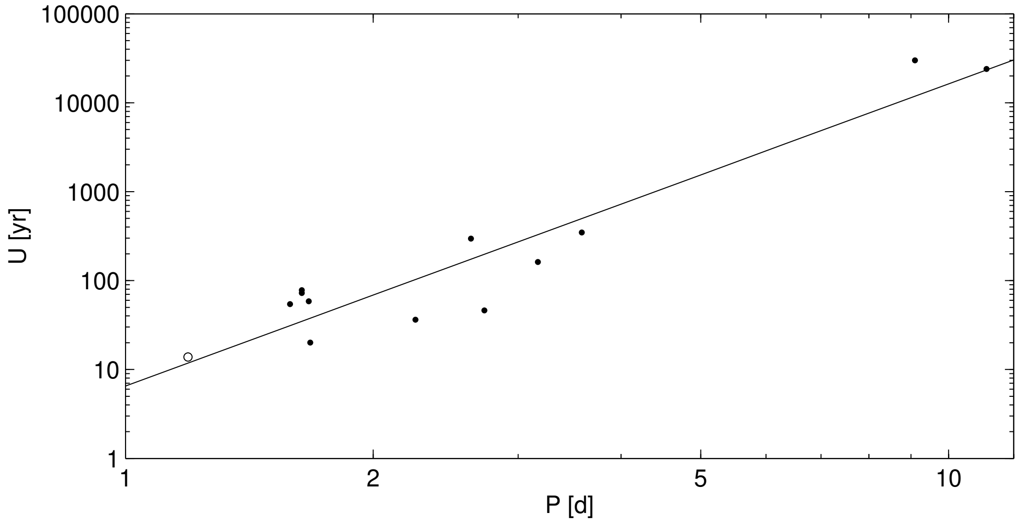

Fig. 10. The plot of orbital period P [day] versus apsidal motion period U [year] in systems where the apsidal motion was detected together with the third body. The circle represents the system TY Del.

TABLE 4

PARAMETERS OF APSIDAL MOTION OF TY DEL

Eccentricity e	Argument of periastron ω_0 [deg]	Apsidal motion rate $\dot{\omega}$ [deg/cycle]
0.0136	106.54	0.0852
$\pm$0.0048	$\pm$ 6.93	$\pm$ 0.0037

If the hypothesis of apsidal motion is proven (see Table 4), we will be dealing with the shortest period of apsidal motion among eclipsing binaries discovered until now. On the other hand, the values of eccentricity and also the argument of periastron ω_0 differ from both methods (LC and period analysis). Therefore, another potential explanation of the period changes is the presence of an additional (fourth) body in the system, which could cause the variation in $O-C$ diagram with a period of about 14 years.

5. DISCUSSION AND CONCLUSIONS

The system TY Del has been studied only on the basis of photometry. Without detailed spectroscopic analysis one is not able to reveal the nature of the system in more detail and some basic physical parameters have to be only estimated. The masses are only known with low precision, and absolute dimensions, such as semi-major axis, have been only estimated. Despite all these facts our new analysis casts new light into this interesting system.

Despite its relatively short orbital period, TY Del is probably still a detached system, with two unequal components. The primary was supposed to be a B9 main sequence star, while the secondary is probably of a later spectral type than that assumed by Hoffman et al. (2006), according to our new values of temperature, luminosity and radius.

Two different light curve solutions have been presented, both of which describe equally well the observed data. Only further detailed analysis will be able to decide which of them is the right one. The question of eccentricity seems to be the most interesting result from this analysis, particularly due to the fact that this may be a system with the shortest apsidal motion period, but also a system with the shortest orbital period among the eccentric binaries. There could be a connection between these two periods, see Figure 10. In this figure are shown only such systems in which both apsidal motion and the third body were discovered (12 known systems until now). Using these 12 systems there has been found no relation between their period of the third body and the apsidal motion period. A theory about an influence of a third body on the apsidal motion in the system has been published in a basic work by Kopal (1959), afterwards refined by Martynov (1973). Nevertheless, this theory could not explain the rate of apsidal motion only on the basis of the presence of additional body. The rate of apsidal motion caused by the third body is in this case below 1% of the observed value.

Besides spectroscopy which could be used for deriving the absolute dimensions of the system, the questionable eccentricity could be elucidated also by accurately measured secondary times of minima in upcoming years. Accepting the hypothesis of eccentricity and apsidal motion, in the next two or three years the predicted difference between primary and secondary will be the most easily recognizable, amounting to about 15 minutes.

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