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The fast brightness decline eclipses study - the case of V471 Tau

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Abstract. V471 Tau is a semi-detached binary classified as a pre-cataclysmic system of a post-common envelope consisting of a white dwarf and a main sequence star of the spectral type K2 V. The eclipsing system is characterized by very fast decreases to the minima as well as the steep increases from minima. The change of brightness caused by the eclipse of the white dwarf lasts only 55 seconds and the total eclipse from the whole orbital period (0.5 day) takes 49 minutes, which is 0.07 of the phase. This behaviour of the system complicates obtaining of eclipses of the high quality from which we can determine the time of minima with expected precision. In the past we tried to observe similar fast changes of brightness by high speed photometry at the expense of a signal-to-noise ratio. In this work we present minima of V471 Tau obtained by CCD photometry that enabled to obtain seven time minima with quite high precision. Whereas the (O–C) diagram of V471 Tau shows long term and gentle changes of values (on average 19 seconds per year), it was therefore necessary to use as the basic time system the heliocentric ephemeris Julian date. We used the time of minima corrected by the difference between the two time systems to construct the (O–C) diagram. Whereas during our observations the (O–C) diagram trend changed we could determine the right model of V471 Tau system, interpret the changes of the (O–C) diagram by a third body in the system and determine the geometry of its orbit as well as the mass function.

Key words: eclipsing binaries – CCD photometry – physical and geometrical parameters

1. Introduction

V471 Tauri (BD +16 516) is a detached binary with a short orbital period studied for the first time by Nelson and Young (1970). The system consists of a main sequence cool star on the H-R diagram of spectral type K2 V, with significant chromospheric activity (Guinan and Sion, 1984), and a hot white dwarf. The question of V471 Tau location in the Galaxy and its distance from the solar system was studied also by Martín et al. (1997). On the basis of observations of proper motion of V471 Tau with CAMC (Carlsberg Meridian Circle) on La Palma ($\Delta\alpha = 0''.126 \pm 0''.004$ y^{-1}, $\Delta\delta = -0'', 021 \pm 0'', 004$ y^{-1}) he ruled on

Table 1. Basic data for V471 Tau; α-right ascension; δ - declination; d - distance

V471 Tau and comparisons	
V471 Tau	GSC 01252-00212, BD +16 516
α_{2000} [h m s]	03 50 24.97
δ_{2000} [$^{\circ}\,'\,''$]	+17 14 47.42
d [pc]	48
B [mag]	10.24
V [mag]	9.48
spectral type	K2 V+WD
orbital period [h]	$\sim$ 12.5
comparison star BD +16 515	
B [mag]	10.73
V [mag]	9.46
check star USNO-A2.0 1050 - 01038658	
B [mag]	12.6
V [mag]	11.7

Heintz's conclusions (167±66 pc) (Heintz, 1991) that V471 Tau is not a component of the open cluster of Hyades. The results of proper motion measurements and parallax of V471 Tau by the satellite Hypparcos (High Precision Parallax Collecting Satellite) confirmed that this system belongs to Hyades (46.8 pc) (Provencal et al. 1996; de Bruijne et al. 2001). The basic parameters of V471 Tau are introduced in Table 1.

The evolutional state was discussed by Paczynski (1976). The binary system of V471 Tau probably passed through the evolutional phase of a common envelope (post CE) and tends to be the a cataclysmic variable star. V471 Tau is considered to be a prototype for pre-CVs (Bond, 1985) and is one of two known post-CE stars in the Hyades (the second one of post-CE is HZ 9). Drake and Sarna (2003) analyzed the spectra from the detector LETG (Low Energy Transmission Grating) on the Chandra satellite and obtained the first evidence about existence of the common envelope. They detected in spectra of the secondary component that the abundance of carbon is lower in comparison with that of nitrogen. A detected ratio of abundances was expected in the case of contamination of the K dwarf by an evolved and diffused envelope of the primary star.

Young et al. (1988), Skillman and Patterson (1988) announced the observation of bright, complicated and varying shapes of the spectral line H_α that changed by rotation from absorption to emission. An observation of further chromospheric lines, for example CaII H and K as well as CaII triplet in infrared spectra, showed the same changes with rotation of the system as H_α line and confirmed that this activity (changes from absorption to emission) is created in the chromosphere of the K dwarf. Various authors presented the traces after magnetism powered activity of the K dwarf based on the activity of the brightness observed photometrically by Young et al. (1991) in the X-ray region by Young et al. (1983) and in radio by Patterson et al. (1993), Nicholls and Storey (1999). Jensen et al. (1986) and Sion et al. (1998) noticed a periodic 9.25 minute change of intensity in soft X-ray and extreme UV spectra (EUV) that was later confirmed in optical spectra by Robinson et al. (1988). Clemens et al. (1992) and Barstow et al. (1993) expected that the 9.25 minute periodicity is caused by changes of influence of magnetic field of rotating of the white dwarf. Wheatley (1998) noticed that rotation and brightness in the X-ray of the K dwarf of V471 Tau are values typical for K dwarfs in the Hyades.

Presence of spots on the surface of the K dwarf was also studied by Ramseyer et al. (1995), Hussain et al. (2006) and Kamiński et al. (2007). With respect to inclination 77° of this system they could study the spot covering depending on the orbital phase in the range from $-77°$ to $+77°$ of the star latitude. Kamiński et al. (2007) discovered from photometric observations of the MOST satellite that the smallest spot covering was for the orbital phase $0.6-0.7$ and the largest one for $0.2-0.3$. Hussain et al. (2006) discovered the maximum in the phase ~ 0.07. The amplitude of a spot occurrence factor determined by Kamiński et al. (2007) $(0.01-0.02)$ is much lower than 0.15 (Hussain et al., 2006). Kamiński et al. (2007) explain the difference of their results by an observation of K dwarf activity variations in comparison with Hussain et al. (2006). It is necessary to note that the difference time between observations analyzed in two papers is in fact, more than 3 years.

In the system of V471 Tau there is observed a total eclipse of the white dwarf taking ~ 49 minutes. Decrease to minimum or increase of brightness from minimum takes only 55 seconds. During the last 45 years there have been published less than 200 times of minima because for the exact detection of the time of minimum an observation with a higher time resolution is required, covering mainly decrease to and increase from minima. To explain the (O–C) diagram constructed according to ephemeris (1) (Guinan and Ribas, 2001), have been proposed several models. With a growing amount of observations of the total eclipses, the accuracy of calculation of ephemeris improved as well.

$$Min_I = \mathrm{HJED}\,2\,440\,610.06406 \;+\; 0.521183398 \;\times\; E \tag{1}$$

Variations in the (O–C) diagram can be caused by the presence of a third body on a long period orbit. Its mass is sub-stellar or nearly in the lower limit of the mass of main sequence stars on the H-R diagram and it is estimated to be from 0.045 to 0.09 $\mathrm{M}_\odot$. Another suggested model is the apsidal motion. In systems similar to V471 Tau a circular orbit is assumed. To explain the (O–C) the small eccentricity $e = 0.0121 \pm 0.0006$ is sufficient, which is also in agreement with solutions of radial velocity curves (Kamiński et al., 2007). At that time the last proposed explanation of the (O–C) diagram of V471 Tau were period changes. It is possible to explain the time interval of epoch from 2 500 to 10 500 and time of epoch of 15 000 by two different periods. Such a change of the period in the case of V471 Tau can be due to mass transfer of $3.8 \times 10^{-7} - 3.6 \times 10^{-6}$ $M_{\odot} y^{-1}$. On a time scale of 40 years in the (O–C) diagram there is observed an increase and decrease of the period. The above-mentioned models were reexamined by Kamiński et al. (2007) without doubts. To determine a suitable physical model explaining all the observed changes of the (O–C) diagram, it is inevitable to obtain and analyze other new and accurate photometric observations of eclipses.

2. Observations and instrumentation

We have obtained the presented observational material at the Observatory of Astronomical Institute of the Slovak Academy of Sciences in Stará Lesná (G1) and at the Kolonica Observatory (KS). The basic parameters of used telescopes are listed in Table 2. Used telescopes were equipped with Johnson's and Cousin's filters.

Table 2. Positions and parameters of the telescopes and detectors placed at the Kolonica Observatory, Stará Lesná G1 and G2

Observatory	Kolonica saddle	Stará Lesná, G1	Stará Lesná, G2
obs. abbreviation	KS	G1	G2
terrestrial longitude	$22^{\circ}\,16'\,26''$ E	$20^{\circ}\,17'\,21''$ E	$20^{\circ}\,17'\,28''$ E
terrestrial latitude	$48^{\circ}\,56'\,06''$ N	$49^{\circ}\,09'\,06''$ N	$49^{\circ}\,09'\,10''$ N
altitude [m]	460	785	785
manufacturer	AO of National	J. Drbohlav	Zeiss
	University in Odessa	Czech Republic	Jena Germany
type	modified optical sys.	Newton	Cassegrain
	Argunov - Faschevsky	reflector	reflector
diameter	1.0 m	0.5 m	0.6 m
focal length	9.0 m	2.5 m	7.5 m
detector	FLI proLine PL1001E	SBIG ST10MXE	EMI 9789 Q
	CCD	CCD	photomultiplier
photometric sys.	Johnson $B\,V$	Johnson $U\,B\,V$	Johnson $U\,B\,V$
	Cousins $R_C\,I_C$	Cousins $R_C\,I_C$	

With respect to the orbital period, the size of the components and their distance, the decrease and increase of brightness takes only 55 seconds during the eclipse. A correct determination of the time of the primary minimum requires to cover this decrease by the largest amount of observational points. The largest decrease of brightness and a suitable time resolution in our data during the eclipse was in Johnson's B filter (by 0.08 magnitudes), therefore we observed minima of V471 Tau at both observatories only in this filter. The photometry

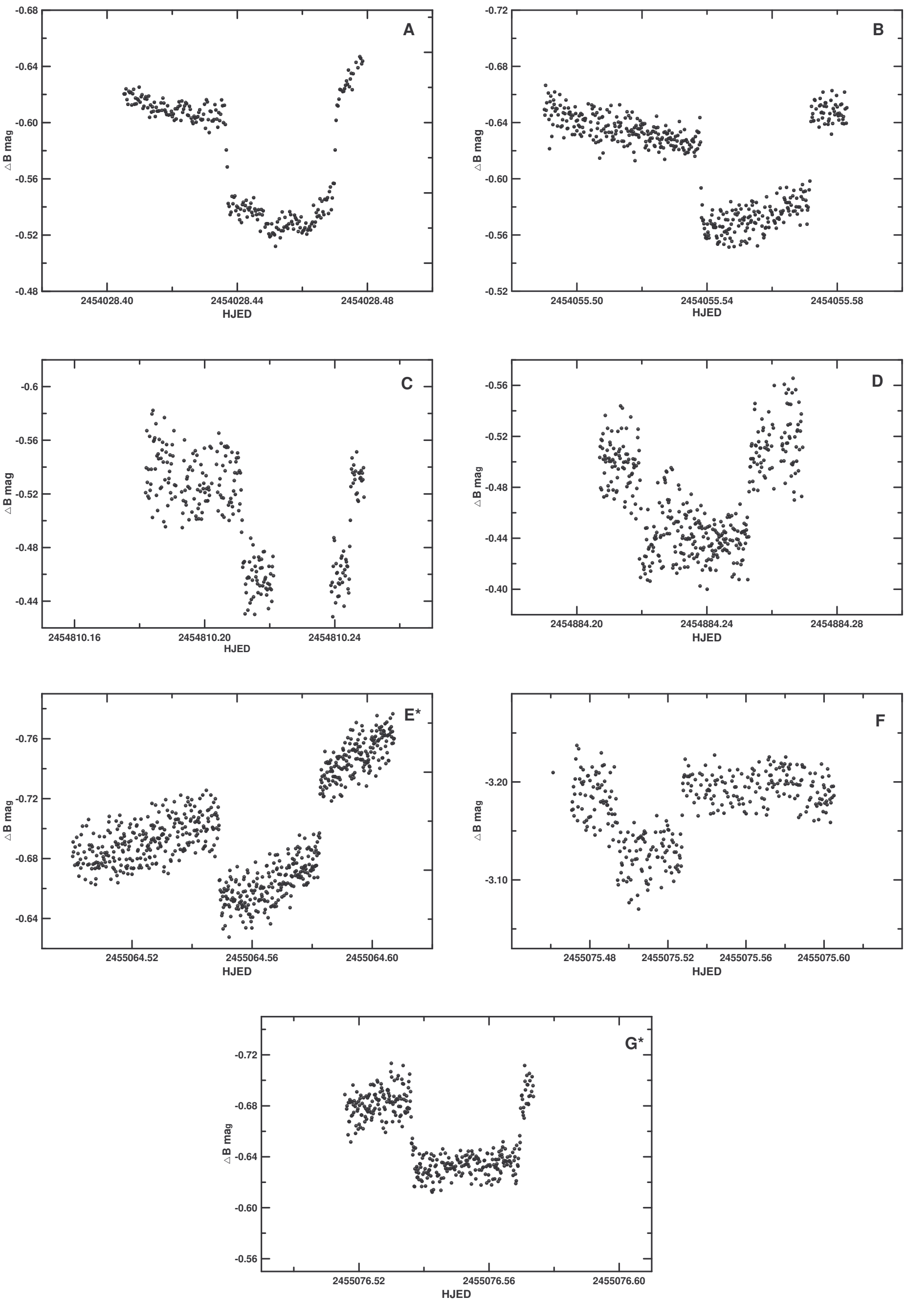

Figure 1. An illustration of all eclipses used for the exact determination of the times of minima. Assignation by alphabet corresponds to dates in Table 4.

of variable stars using CCD detectors was described by Parimucha and Vaňko (2005), but in the next paragraphs we must describe our new experience with CCD photometry in more detail, because it will be useful for other observers at our observatories. An optimal exposure time was important because we wanted to obtain the largest amount of frames for a covering of decrease and increase of minima. We must note that with shortening of the exposure time, a signal-to-noise ratio decreases and quality of data gets worse. During the observation of V471 Tau we used the exposure time 10 or 15 seconds in dependence on observational conditions. The comparison and checking stars were BD + 16 515 and USNO-A2.0 1020-01038658 and their magnitudes are given in Table 1.

We tried to obtain the primary times of minima by high speed photometry with one channel photometer. A signal-to-noise ratio in high speed photometry caused uncertainties of measurements larger than the change of the brightness caused by the eclipse. In one channel photometry it was not possible to guarantee the a sufficient coverage of decrease and increase observational points of brightness during the eclipse because during an alternating measurement of the star brightness could happen that it was not measured the variable star signal but the comparison or control star signal or the sky. It means that decrease or increase to or from minima could get away of an observation.

To reduce observations by the program C - Munipack (Motl, 2004) we requested to follow all needed steps introduced in details. The time needed for reading the frame obtained in full resolution takes for our camera (G1) 8.7 seconds, which is not negligible for short exposure times (10 to 15 seconds). Therefore, we lowered the maximal resolution by binning, during an observation by CCD and thus shortened the time needed for reading the frame and improved the time resolution of the data. The time needed for reading the frame and saving on the disk takes only 5 seconds in case of binning 2×2, therefore we used this frame resolution at the observatories G1 and KS too. Moreover, the binning improves a signal-to-noise ratio and effectiveness of the CCD photometry. In our experience (our instrumentation, equipment and weather condition - seeing) 2×2 binning is the best compromise. CCD observation processing requires to obtain the calibration frames (bias, dark and flat). Before the first frame we gradually cooled down CCD sensor to reduce the contribution of a thermal noise. The flat frames were done during the sunset or sunrise (before or after an observation). In each filter we acquired at least 10 flat frames to avoid saturation and a maximal signal-to-noise ratio. Bias and dark frames were exposed before an observation of variable stars, or in the morning after the observation. Exposure times of dark frames were the same as those we used during observations of variable stars at the same night. Similar steps were used during observations at the Kolonica Observatory.

A survey of observations is given in Table 3. To determine the right time of minima it is not necessary to transform the instrumental magnitudes to the international system. We succeed in measuring the time of minima at the Observatory Stará Lesná, Pavilion G1, and the Kolonica Observatory.

Table 3. CCD observations of V471 Tau in Pavilion G1 in Johnson's B and V and at the Kolonica Observatory in Johnson's B filter (marked by asterisk). The times of the beginning and end of an observation are in UT. The photometric data for particular nights are available upon request.

Date	Time	Filter	Date	Time	Filter
06.10.2006	20:56 - 01:01	BV	28.09.2008	21:35 - 03:55	B
19.10.2006	21:34 - 23:32	B	13.10.2008	19:53 - 01:11	V
15.11.2006	21:34 - 02:16	B	27.10.2008	22:30 - 23:30	V
16.11.2006	22:06 - 02:38	BV	09.11.2008	19:08 - 23:13	V
01.10.2007	00:03 - 03:51	B	09.12.2008	16:14 - 21:05	B
06.10.2007	00:37 - 01:43	B	13.12.2008	19:51 - 23:43	B
07.10.2007	00:20 - 04:08	B	09.01.2009	21:06 - 23:29	B
05.11.2007	22:34 - 02:31	B	10.01.2009	16:17 - 20:20	B
27.12.2007	21:29 - 23:57	B	19.01.2009	16:28 - 23:29	B
28.01.2008	16:38 - 21:28	B	15.02.2009	16:52 - 20:03	B
07.02.2008	16:57 - 21:33	B	21.02.2009	16:58 - 18:13	B
07.03.2008	17:47 - 19:11	B	20.08.2009	00:57 - 02:44	B
21.08.2008	22:47 - 00:00	B	20.08.2009	00:59 - 02:43	B*
27.08.2008	22:17 - 03:00	B	31.08.2009	22:43 - 02:29	B
01.09.2008	23:10 - 02:38	B	09.09.2009	21:03 - 03:21	B
02.09.2008	23:00 - 02:43	B	27.09.2009	22:26 - 02:49	B
07.09.2008	22:16 - 00:01	B	01.09.2009	00:21 - 01:44	B*
27.09.2008	20:32 - 03:23	BV	31.10.2009	21:20 - 00:30	B*

3. Time system

The IAU recommends the use of the terrestrial time. As the standard Julian date fixed to the universal time (UT) is used. The universal time is not a physical time system, because it is connected with irregular Earth's rotation. This is valid also for UT1 and UTC (coordinated UT) that are fixed to UT. The terrestrial time (TT) is a sequel of the ephemeris time (ET) and defined as TT = TAI + 32.184 s where TAI is the international atom time. The time scale is represented by Julian ephemeris date (JED) in day units. The trend between TT and UT was considerably changed (see a figure in the paper by Jordi et al. (1994)). For transformation from JD to JED we use a very easy equation (2), where n_s is a cumulative quantity of seconds added to JD. For the period before 1972, when there was not added a second to correct the time, the differences between ET and UT are published in the Astronomical Almanac.

$$JED = JD + (32.184 + n_s)/86\,400 \qquad (2)$$

To eliminate influence of the revolution of the Earth around the Sun and right determination of time observed events we transform JED to HJED. A wrong choice of the time system influences physical conclusions of an observational material analysis. For example, in the (O–C) diagram of a long term observed variable system with a perfectly constant period, the choice of the wrong time system is manifested by changes in the (O–C).

4. Analysis and results

Observations and the analysis of the eclipsing binary V471 Tau were aimed to obtain minima of the highest quality distributed in the widest interval of epochs.

In this paper we obtained seven total primary minima with a whole period of brightness decrease and increase. It is worth noting that from detection of the orbital period of V471 Tau (Nelson and Young, 1970) it was theoretically possible to observe more than 20 000 minima of this system. In the matter of fact there have been published only 200 minima. One of the reasons can be difficulties during detection of all phases of the total eclipse. With respect to a 400 seconds peak-to-peak amplitude of the (O–C) diagram we require quite high precision of minima. In our case we have a change of the (O–C) value on average 19 seconds per year (it is obvious that this change is not linear). All used eclipses are shown in Fig. 1 where it is seen that the brightness of the system changes not only outside the eclipse, but even during the eclipse, which obstructs its exact observation and subsequently determination of exact times of minima. Behaviour of the V471 Tau light curve is, aside from the eclipse, caused by a tidal deformation of the red dwarf, spots on its surface that migrate with a period of 182.17 days and moreover their number changes with activity of a solar-like cycle type with a period of about 18 years (Evren et al., 1986).

Table 4. Obtained times of minima of V471 Tau in units of HJED - Heliocentric Julian Ephemeris Date. Assignation by alphabet corresponds to particular eclipses in Fig. 1. Eclipses marked by an asterisk were observed at the Kolonica Observatory.

Date	Times of minima (HJED)	
19. Oct 2006	2454028.45413 ± 0.00017	A
15. Nov 2006	2454055.55555 ± 0.00021	B
09. Dec 2008	2454810.22895 ± 0.00019	C
21. Feb 2009	2454884.23699 ± 0.00018	D
20. Aug 2009	2455064.56636 ± 0.00020	E*
31. Sep 2009	2455075.51140 ± 0.00023	F
01. Sep 2009	2455076.55364 ± 0.00018	G*

The time of minimum during the total eclipse is usually determined from four points defined on the light curve, minimum of the beginning and end of the brightness decrease and beginning and the end of brightness increase. In consequence of used exposure (10 or 15 seconds) and length of brightness change during the eclipse it is not possible to determine all four points. Before determination times of minima we detrended light curves of V471 Tau containing the primary minimum by program *EQWREC2* (Budaj and Komžík, 2001) to eliminate all influences causing the deformation of light curve as it is mentioned above. To determine the times of minima we therefore used the mirror method of program *MINIMA* (Nelson, 2002) where the minima wings are put one's back. By moving of wings where brightness decrease overlays its brightness increase we obtained times of minima that are listed in Table 4. Moreover, due to testing of minima we detected them also by overlay eclipse points in wings with a straight line and we got the same results within the errors. For construction of the (O–C) diagram we used in our paper a new ephemeris (3) from minima obtained by us, minima obtained at our observatories in the past (Hric et al., 2003) and minima from accessible works of various authors collected by Ibanoglu et al. (2005). In these works we met with inaccuracy of 0.003 days, whicht is approximately 260 seconds. Even if such observations were in coincidence with the trend of the (O–C) diagram the inaccuracy of minima determination was comparable with the amplitude of the (O–C) diagram and, in our opinion, they were useless for further analysis and, therefore, we omitted them. Unfortunately, we were not very successful in obtaining of minima of the inaccuracy mentioned hereinabove, therefore it was not possible to use weighting of the individual minima and improve the precision of calculations. After construction of the (O–C) diagram (Fig. 2) is seen that our data agree with one of the assumed trends of the (O–C) diagram, namely a repeated decrease of (O–C) data. If we compare our (O–C) diagram constructed on the basis of old ephemeris by Guinan and Ribas (2001) we can see that the last change of the trend of the (O–C) diagram happened at higher (O–C) values than predicted by Guinan and Ribas (2001), Ibanoglu et al. (2005) and Kamiński et al. (2007). For better understanding, see Fig. 6 in the paper by Kamiński et al. (2007).

Kamiński et al. (2007) discussed three different models for an explanation of the changes in the (O–C) diagram. There could have been two abrupt period changes in the orbit of the system in the last 35 years, there could be apsidal motion due to a slightly eccentric orbit, or the V471 Tau object might be a triple system.

The second explanation by apsidal motion has low probability, because there is influence of an orbit circularisation. A non-zero eccentricity from the radial velocity solution by Kamiński et al. (2007) actually makes it a little more probable.

The first explanation by abrupt period changes could be caused by mass transfer in the system. For this mechanism it is inevitable to have the mass transfer with a value of 10^{-6} $M_{\odot}y^{-1}$, which would very probably cause detectable variations of light curve. Such light variations have not been observed yet, which markedly decreases the existence of such model. Moreover, this model is not able to explain the third observed change of the trend of the (O–C) diagram in this paper and, therefore, we think of the model not to be real.

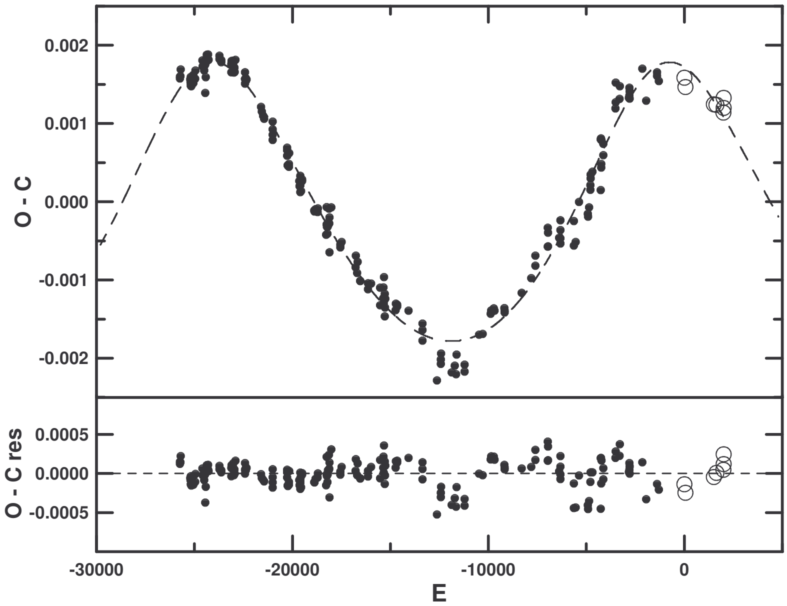

Figure 2. The (O–C) diagram of V471 Tau calculated according to the ephemeris of the close binary determined by us (equation (3)). Our new observations are drawn as open circles and points represent all older minima.

The model based on the assumption of the trend increase of the (O–C) diagram towards higher positive values (Kamiński et al., 2007) as a consequence of a period change was excluded on the basis of our latest observations that change the trend of the (O–C) diagram as seen in Fig. 2.

From the previous discussions the explanation of the (O–C) diagram trend by the third component is most probable from our observations and therefore we use up to now published parameters of its orbit (Guinan and Ribas, 2001) as initial parameters in the code *3T* (Pribulla et al., 2005) for a modeling of the system i.e. for determination of the third component's physical and orbital parameters. The precision of this method does not allow us to study other physical mechanisms that cause the smaller changes of the (O–C) diagram.

In the next step we tried to determine the model parameters of the third body like the orbital period P_3, eccentricity e, argument of the periastron ω_3, time of periastron passage $T_{periastron}$, main axis projection to the orbital plane $a_{12}\sin(i)$ and the mass function $f(M_3)$. Except for the third component's parameters, we modified also the linear ephemeris of the close binary with inaccuracy on the last decimal places in parentheses as follows:

$$Min_I = \mathrm{HJED}\,2\,454\,028.452551\,(41) + 0.521183439\,(2) \times E. \tag{3}$$

Table 5. Final physical and geometrical parameters of the third component of V471 Tau system. P_3 - orbital period of the third body, e - eccentricity of the third component, ω_3 - argument of periastron, $T_{periastron}$ - time of periastron passage, $a_{12}\sin(i)$ - main axis orbital projection of the close binary round the center of gravity to the orbital plane; T_0 - time of minimum of the close binary selected for the zero epoch, P_0 - period of the close binary, $f(M3)$ - mass function of the third component.

Parameter	Value	Unit
P_3	33.2 ± 0.2	year
e	0.258 ± 0.024	
ω_3	64.1 ± 0.1	$\circ$
$T_{periastron}$	$2\,453\,272 \pm 149$	HJED
$a_{12}\sin(i)$	0.309 ± 0.003	AU
T_0	$2\,454\,028.452551$	HJED
	$\pm 4.1 \times 10^{-5}$	
P_0	0.521183439	day
	$\pm 2.01 \times 10^{-9}$	
$f(M_3)$	2.6906×10^{-5}	$M_\odot$
	$\pm 9.59 \times 10^{-7}$	

After precising of the linear ephemeris for the close binary, we went on with a modelling of the third component parameters to get the lowest residuals. The results by such method are shown in Table 5. The (O–C) diagram for our model does not fit the times of minima around epoch $E = -12\,000$ (Fig. 2). The most probable explanation of this fact is inaccuracy of the times of minima determination around the mentioned epoch because they only come from a single work by Ibanoglu et al. (1994).

We assume that by explanation of the (O–C) diagram by presence of the third component in V471 Tau the abrupt change of the orbital period of the close binary does not occur as it was proposed by Kamiński et al. (2007).

From equation (4), which connects the mass function ($f(M_3)$), inclination (i_3) and third component mass (M_3), we determine for the selected inclination the mass of the third component M_3. We used for calculation the published sum of the mass of the primary and secondary star $1.72\,M_\odot$ (Kamiński et al., 2007).

$$f(M_3) \equiv \frac{M_3^3 \sin^3 i_3}{(M_1 + M_2 + M_3)^2}. \tag{4}$$

We get, for a wide range of inclinations, a relatively small interval of the third component mass (Table 6). The third body has the orbital period of 33.2 years and the mass dependent on inclination in the interval from $0.044\,M_\odot$ to $0.106\,M_\odot$. The mean value of the third component mass determined by us is $0.075\,M_\odot$, which is the limit for stable nuclear hydrogen-burning in its core. On the basis of this result the third component could be a brown dwarf or a

Table 6. —The mass of the third component for different inclinations of its orbit. $M_\odot$ - mass of the Sun, M_J - mass of Jupiter

Inclination	Mass	
°	$M_\odot$	M_J
85	0.044	46
60	0.051	53
45	0.062	65
30	0.089	93
25	0.106	111

lower mass star. If we discuss the triple system, then it is more probable that the orbital plane of the third component is approximately the same as that of the close binary and in that case the third component is a brown dwarf.

We can see an irregular variability of the brightness on a long-term light curve that is possible to explain by the presence of spots on the surface of the cool red dwarf in the close binary. Irregularity of these variations suggests the activity on the surface of this star that is similar to a well known chromospheric activity of stars of a similar spectral type (Ibanoglu, 1978).

Obtaining the exact times of minima of close binary total eclipses in pre-cataclysmic system V471 Tau and their detailed analysis ruled out two out of three discussed models to explain the trend of the (O–C) diagram. The most probable solution of the observed changes of the (O–C) diagram is the presence of the third component in the system.

The further very precisely determined time minima during further revolution of the third body in the system lead to more precise orbital parameters and enable to study also further mechanisms causing changes of the orbital period in the pre-cataclysmic system in the future, for example, changes of the orbital period due to a common envelope.

5. Discussion and conclusions

We aimed this study of V471 Tau to solve the problem of precise times of minima obtaining for eclipses with fast decrease and increase of brightness. We tried to use photoelectric one channel photometry, high speed photoelectric photometry as well as CCD photometry. Classical photoelectric photometry gives us a lower time resolution and is not able to cover all changes during the eclipse and to determine the exact time of minimum. High speed photometry is suitable for covering of fast eclipses but the signal-to-noise ratio fails short for small amplitude eclipses in particular filters. Moreover, in cases with an inaccuraty determined ephemeris it is hard to synchronize a high speed photometry mode with a decrease/increase observation. In our opinion, the best method for this purpose is CCD photometry like a multichannel detector (all measured objects are in the field of view) with an adequate time resolution which is a combination of the exposure time (10 to 15 seconds in our case) the detector readout time (8.7 seconds for a full frame) and frame the binning (2×2) for a shorter readout time.

Such skill with stellar photometry mentioned above enables us to secure eclipses with a good covering (Fig. 1) for the determination of precise times of minima and the construction of the (O–C) diagram of V471 Tau to solve the problem of its behaviour. Many models have been proposed to explain the behaviour of the (O–C) diagram of V471 Tau, but each model was refined by further observations. During the period of gathering of photometric material of V471 Tau for this paper the trend of the (O–C) diagram changed, which enabled the most probable solution of the problem. By obtained times of minima determined with the high precision that represents the changes in the (O–C) diagram we ruled out the model based on the mass transfer between the components of V471 Tau. From the reason of a change of the (O–C) diagram trend we ruled out the model predicting a further increase of the (O–C) diagram values and the model based on the orbital precession we consider as low probable. In addition to models mentioned above, the authors tried to explain the (O–C) diagram changes also by the existence of a third component in the system. Thanks to our minima we improved the precision of ephemeris of the close binary and approved the model with the third component in the system V471 Tau, while we determined the geometry of the third component's orbit as well as its mass function.

The result of this paper is also the new ephemeris of the close binary (equation (3)). The mass of the third component in the system V471 Tau for the inclination range from 25 to 85 degrees is in the interval from 0.044 to 0.106 $M_{\odot}$. On the basis of this result, the third component can be either a brown dwarf or a low mass star. If we discuss the triple system, then it is from a view of evolution more probably a system where the orbital plane of the third component is approximately collinear to the orbital plane of the close binary, and in that case a better candidate of the third body is a brown dwarf. On the basis of parameters of the third component it is interesting to note that in the near future, during 2013, the brown dwarf will be in V471 Tau at the greatest distance from the closest binary (almost 250 AU)) and there will be good conditions to detect it in close infrared spectrum while this component should have 15 magnitude in K colour. It is a challenge also for owners of detectors with quite high quality.

As the obtained observations do not cover the whole phase curve, we could not study any chromospheric activity of the red dwarf in the system. This is another argument why to study this system in the future and to obtain complete (continuous) light curves in more colours for the purpose of a deeper understanding of active processes.

In the case of pre-cataclysmic variable V471 Tau from a long-term view we will obtain minima with a high time resolution and minimal frequency, one or two minima yearly. The aim is to observe the trend of the (O–C) diagram in the near future but also over a longer time horizon.

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