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Up-to-date *UBV* light and O–C curves analyses of the eclipsing binary V477 Cygni[⋆]

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Abstract. New and complete *UBV* light curves and times of minimum are presented for the Algol–type eclipsing binary *V477 Cygni* (Sp. A3 V+F5 V, $m_v = 8.5$, $P = 2.347$ days). The binary orbit of the system is highly eccentric and the system shows an apsidal motion. Using the Wilson-Devinney method, two photometric models, without (MODEL A) and with (MODEL B) third–body light contribution to the total light of the system, are obtained. Period analysis also gives some slender evidence for the unseen third-body in the system with the orbital period of about 157 years. In the MODEL A approximation the apsidal motion period is obtained to be 371 years while it is about 434 years in the MODEL B approximation. The photometric mass ratio ($q \sim 0.75$) is in good agreement with the spectroscopic value given by Popper (1968). The masses we obtained are $1.80 \pm 0.10\ M_\odot$ and $1.35 \pm 0.08\ M_\odot$ and the radii are $1.60 \pm 0.03\ R_\odot$ and $1.42 \pm 0.03\ R_\odot$ for the primary and secondary components, respectively. Absolute dimensions have been compared with the models using a moderate amount of convective overshooting and mass loss given by Claret & Giménez (1991). In the $\log M - \log R$ diagram both components are located above but close to the ZAMS. It is possible to say from the $\log T_\mathrm{e} - \log L$ diagram that the secondary component is just coming to the main sequence while the primary is slightly evolved from the ZAMS. The theoretical evolutionary models give an age of 6.4×10^8 yrs for the system.

Key words. stars: individual: V477 Cygni – stars: binaries: eclipsing – stars: fundamental parameters

1. Introduction

The eclipsing binary *V477 Cygni* (BD +31° 3932, HIP 98955, $V = 8\overset{\mathrm{m}}{.}51$, $P = 2\overset{\mathrm{d}}{.}346989$) was discovered in 1947 by Tamm (1948). Wallenquist (1949) observed the star photoelectrically and derived the orbital elements with an eccentricity of 0.22. The first spectroscopic study of V477 Cyg was carried out by Pearce (1958) based on spectroscopic plates with prismatic dispersions of 51 Å mm^{-1} and 30 Å mm^{-1} taken at Dominion Astronomical Observatory. He classified the primary as A3 and estimated the secondary to be about F5.

Despite the small luminosity ratio, Popper (1968) could obtain the radial velocity curves of both components of *V477 Cyg* based on high-resolution spectral observations at Mt. Wilson Observatory with dispersions of 10 Å mm^{-1} and 20 Å mm^{-1}. He obtained radial velocity semi–amplitudes of 105 and 140 km s^{-1} for the primary and secondary stars, respectively, adopting a value of 0.30 for the orbital eccentricity. He also estimated the minimum masses of the components to be $1.78 \pm 0.12\ M_\odot$ and $1.34 \pm 0.07\ M_\odot$ and classified the system as A3+F2.

Photoelectric light curves of *V477 Cyg* were obtained by Chisari & Saita (1963), Rodono (1967), O'Connell (1970) and most recently by Lacy et al. (1987). The light curve by Lacy et al. (1987) however, is so incomplete that it seems to be inappropriate for the analysis. Therefore the last complete light curves are those obtained by O'Connell (1970) using the standard *UBV* system. His light curves contain the data obtained from 1962 to 1966 and their orbital solution seems to be a serious problem due to the apsidal motion observed in the system.

O'Connell (1970) presented eight times of mid–eclipses and orbital parameters of the system. From the light curve analysis he calculated the ratio of surface brightnesses of the components in *B* and *V* bands as 3.291 and 4.271, respectively. Lacy et al. (1987) discussed the surface–brightness anomalies of the components, which were pointed out first by Popper (1968), but did not find any satisfactory explanation. Lacy et al. compared the surface–brightness ratio obtained for the system from their light curve analysis with the calibrations of Popper (1980), and Barnes et al. (1978), based on the observed color indices, and found an important discrepancy.

Giménez & Quintana (1992) re–analyzed *B* and *V* light curves obtained by O'Connell with synthetic light-curve

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[⋆] Table 1 is only available in electronic form at the CDS via anonymous ftp to `cdsarc.u-strasbg.fr` (`130.73.128.5`) or via `http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/409/959`

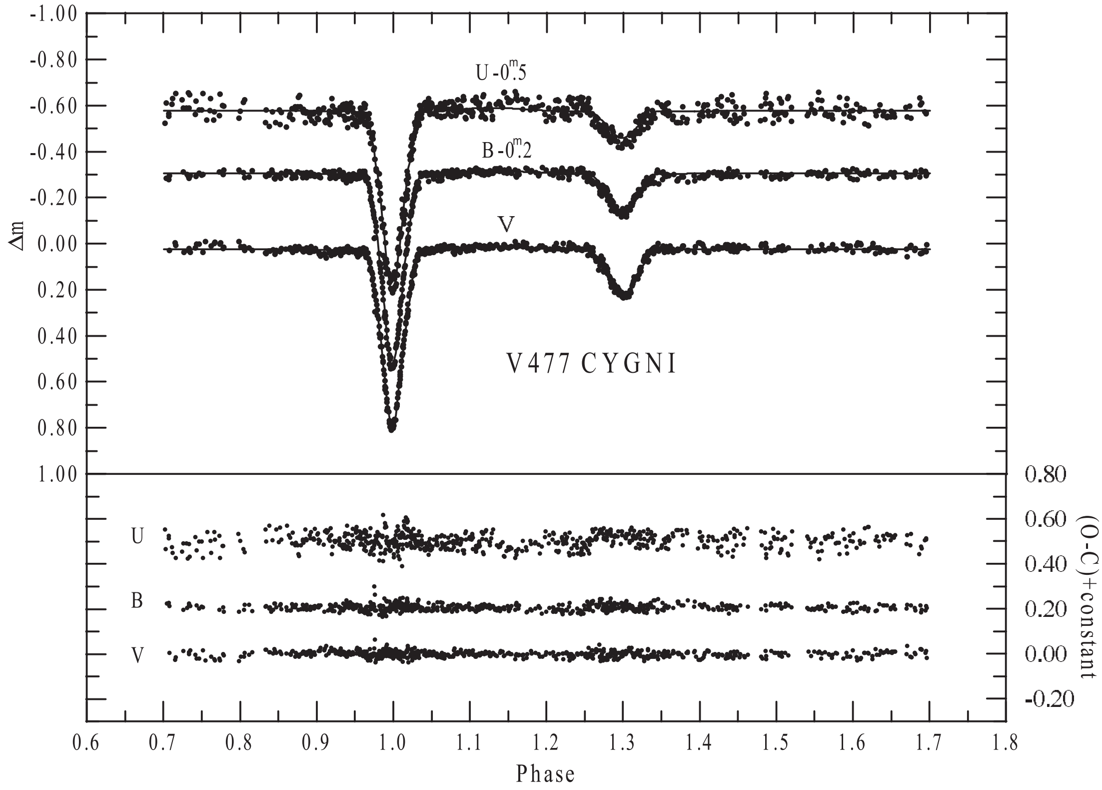

Fig. 1. *U*, *B* and *V* light curves of *V477 Cyg*. The upper panel shows the computed *U*, *B*, and *V* light curves (solid lines) formed with the parameters of Model B in Table 4 among observations while the bottom panel shows the (O–C) differences between the observations and computed curves.

analysing code EBOP (based on the model by Nelson et al. (Popper & Etzel 1981)). Giménez & Quintana (1992) emphasized that the absolute parameters of *V477 Cyg*, comparing with models by Claret & Giménez (1991), are acceptable. They calculated the age of the system to be 2.5×10^8 yrs from the location of the primary on the H–R diagram. According to this value *V477 Cyg* has components located on the ZAMS. The mean apsidal motion constant (in logarithmic scale) for *V477 Cygni* has been obtained by Giménez & Quintana (1992) as $\log k_2 = -2.20$. For the same parameter, however, the theoretical evolutionary models with convective overshooting of Claret & Giménez (1991) gives a value of -2.33. Thus the components of *V477 Cyg* have a somewhat less centrally-concentrated configuration than predicted by the theoretical models.

The first aim of this paper is to obtain a more reliable photometric solution of the system using the light curves obtained within one observational season and the second is to determine the apsidal motion parameters of the system with the aid of new data which expand the observational time span to 97 yrs.

2. The observations and data acquisition

The photoelectric light curves of *V477 Cyg* presented here were obtained during June–August 1998. All measurements were made in the *U*, *B* and *V* passbands of the Johnson system on 16 nights. An unrefrigerated Hamamatsu R4457 type photomultiplier attached to the 48 cm Cassegrain telescope of the Ege University Observatory was used during the observations. The individual measurements were obtained differentially with respect to BD +31° 3924. BD +31° 3926 was observed as a check star.

A total of 662, 615 and 672 observational points were obtained in the *U*, *B* and *V* filters, respectively. The differential magnitudes, in the sense of variable minus comparison, were corrected for atmospheric extinction with Hardie's method (Hardie 1962) and the observing times were reduced to the Sun's center. The probable error of a single observation was estimated to be ±0.012, ±0.007 and ±0.009 in the *U*, *B* and *V* filters, respectively. The instrumental differential *U*, *B*, *V* magnitudes corrected for atmospheric extinction are given in Table 1 (accessible in electronic form). The *U*, *B*, *V* light curves of the system are shown in Fig. 1. The orbital phases given in Table 1 and Fig. 1 were calculated with Eq. (2) in Sect. 4.

3. Period analysis

During the observations, we obtained three primary and two secondary times of minimum. These times of minimum and their errors, which were determined by using the method of Kwee & van Woerden (1956) are presented in Table 2 among the others found in the literature. In Table 2 each time of minimum obtained by us is an averaged value of the times of minimum obtained in the *U*, *B* and *V* filters in the same observational night.

The photoelectric times of minimum light obtained up to 1988 were collected by Giménez & Quintana (1992). We added

Table 2. Times of minimum light for *V477 Cyg*.

JD (Hel.) 2 400 000+	Type	Min.	*E*	O–C	Weight	Ref.
16 400.807	pg	I	–14 737	–0.0099	1	Gaposchkin (1951)
20 001.116	pg	I	–13 203	0.0349	1	Gaposchkin (1951)
23 200.08	pg	I	–11 840	0.0678	1	Gaposchkin (1951)
26 199.543	pg	I	–10 562	0.0929	1	Gaposchkin (1951)
29 999.35	pg	I	–8943	0.1425	1	Gaposchkin (1951)
32 508.282	pg	I	–7874	0.1551	1	Tamm (1948)
32 745.322	pg	I	–7773	0.1503	1	Filin (1953)
32 846.2445	pe	I	–7730	0.1527	10	Wallenquist (1949)
32 847.1355	pe	II	–7729.5	–0.1298	5	Wallenquist (1949)
37 881.3623	pe	II	–5584.5	–0.1708	5	O’Connell (1970)
37 913.4069	pe	II	–5571	0.1896	10	O’Connell (1951)
37 942.3845	pe	II	–5558.5	–0.1700	5	O’Connell (1970)
37 960.3469	pe	I	–5551	0.1900	10	Chisari & Saita (1963)
37 961.1637	pe	II	–5550.5	–0.1666	5	Chisari & Saita (1963)
38 251.3739	pe	I	–5427	0.1918	10	Semeniuk (1968)
38 258.4155	pe	I	–5424	0.1924	10	O’Connell (1970)
38 265.4565	pe	I	–5421	0.1925	10	O’Connell (1970)
38 287.39	pe	II	–5411.5	–0.1703	5	O’Connell (1970)
38 291.2735	pe	I	–5410	0.1927	10	Semeniuk (1968)
38 294.4319	pe	II	–5408.5	–0.1693	5	Semeniuk (1968)
38 320.2489	pe	II	–5397.5	–0.1691	5	Semeniuk (1968)
38 650.3632	pe	I	–5257	0.1948	10	O’Connell (1970)
38 664.448	pe	I	–5251	0.1977	10	Pohl & Kızılırmak (1966)
38 665.25	pe	II	–5250.5	–0.1738	5	O’Connell (1970)
38 697.3018	pe	I	–5237	0.1938	10	Semeniuk (1968)
38 883.5192	pe	II	–5157.5	–0.1735	5	Semeniuk (1968)
38 941.392	pe	I	–5133	0.1983	10	Pohl & Kızılırmak (1966)
38 948.432	pe	I	–5130	0.1974	10	Rodono (1967)
38 955.473	pe	I	–5127	0.1975	10	Rodono (1967)
38 962.514	pe	I	–5124	0.1975	10	Rodono (1967)
39 383.422	pe	II	–4944.5	–0.1770	5	O’Connell (1970)
39 692.4286	pe	I	–4813	0.2020	10	Giménez & Quintana (1992)
39 695.5698	pe	II	–4811.5	–0.1773	5	Giménez & Quintana (1992)
39 983.4555	pe	I	–4689	0.2036	10	Pohl & Kızılırmak (1970)
40 091.4174	pe	I	–4643	0.2045	10	Pohl & Kızılırmak (1970)
40 382.4425	pe	I	–4519	0.2043	10	Pohl & Kızılırmak (1970)
40 422.3434	pe	I	–4502	0.2066	10	Pohl & Kızılırmak (1970)
41 128.7873	pe	I	–4201	0.2101	10	Scarfe et al. (1976)
41 135.829	pe	I	–4198	0.2109	10	Scarfe et al. (1976)
41 178.8527	pe	II	–4179.5	–0.1845	5	Scarfe et al. (1976)

the times of minimum obtained by Ogloza (1995), Lacy & Fox (1994), Jordi et al. (1996), Borkovits & Biro (1998), Agerer & Hübscher (1999 and 2001), Sandberg et al. (2001) and by us. Thus, we had a total of 85 times of minimum, 8 photographic and 77 photoelectric and ccd, with 58 primary eclipses among them. These data cover a time span of 97 yrs from 1903 to 2000. The O–C values in Table 2 are calculated with the linear elements of our final solution given below (Solution II in Table 3). *V477 Cyg* is a system which shows apsidal motion with a period about 350 yrs. The first detailed period analysis of the system was made by O’Connell (1970). He made an O–C analysis and deduced an eccentricity of 0.302 and an apsidal period of 349 yrs. However, Budding (1974) rediscussed the photometric data and obtained $e = 0.2525$ and an apsidal

Table 2. continued.

JD (Hel.) 2 400 000+	Type	Min.	*E*	O–C	Weight	Ref.
41 182.7688	pe	I	–4178	0.2111	10	Scarfe et al. (1976)
41 464.406	pe	I	–4058	0.2110	10	Todoran (1973)
41 478.4896	pe	I	–4052	0.2127	10	Todoran (1973)
41 908.7563	pe	II	–3868.5	–0.1911	5	Scarfe et al. (1976)
41 915.7983	pe	II	–3865.5	–0.1900	5	Scarfe et al. (1976)
41 926.7649	pe	I	–3861	0.2152	10	Scarfe et al. (1976)
41 931.4592	pe	I	–3859	0.2156	10	Kızılırmak & Pohl (1974)
42 253.7642	pe	II	–3721.5	–0.1889	5	Scarfe et al. (1976)
42 260.8043	pe	II	–3718.5	–0.1898	5	Scarfe et al. (1976)
42 285.8537	pe	I	–3708	0.2164	10	Scarfe et al. (1976)
42 628.515	pe	I	–3562	0.2189	10	Pohl & Kızılırmak (1976)
43 013.415	pg	I	–3398	0.2145	10	Ahnert (1976)
43 053.3216	pe	I	–3381	0.2225	10	Pohl & Kızılırmak (1977)
44 189.2639	pe	I	–2897	0.2274	10	BAV-M 32
44 499.8136	pe	II	–2764.5	–0.1975	5	Giménez & Quintana (1992)
44 517.8433	pe	I	–2757	0.2299	10	Giménez & Quintana (1992)
44 853.4621	pe	I	–2614	0.2308	10	Pohl et al. (1982)
44 886.32	pe	I	–2600	0.2310	10	BBSAG Bull. 57
45 106.9368	pe	I	–2506	0.2319	10	Lacy et al. (1987)
45 139.7944	pe	I	–2492	0.2318	10	Lacy et al. (1987)
46 219.4095	pe	I	–2032	0.2370	10	BBSAG Bull. 77
46 614.44	pe	II	–1863.5	–0.1983	5	BBSAG Bull. 80
46 639.52	pe	I	–1853	0.2385	10	BBSAG Bull. 80
47 052.5946	pe	I	–1677	0.2449	10	Wood (1988)
47 304.431	pe	II	–1569.5	–0.2188	5	BBSAG Bull. 88
48 066.4895	pe	I	–1245	0.2453	10	Ogloza (1995)
48 458.4343	pe	I	–1078	0.2448	10	BBSAG Bull. 98
48 850.3827	pe	I	–911	0.2479	10	BBSAG Bull. 102
49 251.7117	pe	I	–740	0.2436	10	Lacy & Fox (1994)
49 550.4946	pe	II	–612.5	–0.2132	5	BBSAG Bull. 107
49 895.4988	ccd	II	–465.5	–0.2147	5	BBSAG Bull. 109
50 043.3598	pe	II	–402.5	–0.2133	5	Jordi et al. (1996)
50 237.448	ccd	I	–320	0.2492	10	Borkovits & Biro (1998)
50 693.4784	pe	II	–125.5	–0.2076	5	Agerer & Hübscher (1999)
50 974.4054	pe	I	–6	0.2555	10	Borkovits & Biro (1998)
50 988.4856	pe	I	0	0.2538	10	present paper
51 031.434	pe	II	18.5	–0.2169	5	present paper
51 035.4247	pe	I	20	0.2534	10	present paper
51 038.480	pe	II	21.5	–0.2118	5	present paper
51 042.4670	pe	I	23	0.2547	10	present paper
51 430.424	ccd	II	188.5	–0.2131	5	Agener & Hübscher (2001)
51 434.4127	pe	I	190	0.2551	10	Agener & Hübscher (2001)
51 481.3554	pe	I	210	0.2582	10	Agener & Hübscher (2001)
51 714.403	pe	II	309.5	–0.2185	5	BBSAG Bul. 123
51 720.7450	ccd	I	312	0.2561	10	Sandberg et al. (2001)

Table 3. Parameters of apsidal motion and third body orbit.

Element	Unit	Solution I	Solution II
T_o	(HJD)	2 450 988.261 ± 0.002	2 450 988.232 ± 0.002
P_a	(day)	2.347017 ± 0.000001	2.347013 ± 0.000001
P_s	(day)	2.346971 ± .000001	2.346978 ± 0.000001
e		0.319 ± 0.002	0.328 ± 0.002
ω_o	(°)	172.3 ± 1.4	166 ± 1
$\dot{\omega}$	(° cycle^{-1})	0.0070 ± 0.0002	0.0053 ± 0.0002
U	(year)	371 ± 12	434 ± 14
$a_{12} \sin i'$	(AU)	–	4.6 ± 0.5
e'		–	0.70 ± 0.15
ω'	(°)	–	297 ± 7
P'	(year)	–	157 ± 21
T'	(HJD)	–	2 414 834 ± 1525
σ	(day)	0.0059	0.0019

period of 249 yrs. The period variation of the system was also studied by Scarfe et al. (1976), Todoran (1977), Scarfe (1986), Mossokovskaya & Khaliullin (1989) and Giménez & Quintana (1992). All of them, except Todoran, indicate a uniform apsidal motion and give a value of about 350 yrs for the apsidal motion period.

The geometrical theory for apsidal motion in eclipsing binaries was reviewed several times in the literature, see e.g. Martynov (1971), Giménez & Garcia-Pelayo (1983), and Giménez & Bastero (1995). The equation for the predictions of eclipse timings given by Giménez & Bastero (1995), which we used in our analysis, is a series up to the sixth power of the eccentricity.

Assuming the orbital inclination to be $i = 85\overset{\circ}{.}6$ from the light curve solution in the next section and using times of minimum given in Table 2 we applied a weighted least squares method to obtain the corrections on the apsidal motion parameters of the system. The weights we used are 1 for photographic primary, 5 for photoelectric secondary and 10 for photoelectric and CCD primary times of minimum.

The results are given in Table 3 (Solution I). In this table, P_a and P_s are the anomalious and sidereal periods, respectively, e is the eccentricity and $\dot{\omega}$ is the rate of apsidal motion. The zero epoch is given by T_o and the corresponding position of the periastron is represented by ω_o. In Fig. 2a we show O–C values obtained with the linear elements of Solution I in Table 3 and the corresponding computed O–C values obtained with the apsidal motion parameters of the same solution. We also show the residuals from the computed curves in the bottom panel of Fig. 2a. As seen from the figure, the residuals display a nonlinear variation. Such a variation may be interpreted as part of a parabolic or sinusoidal variation. A parabolic variation for this system seems difficult to understand, if we consider the well detached configuration of the system. One expects a sinusoidal O–C variation for an eclipsing binary if there is an unseen tertiary object in the system. The amplitude of the sinusoidal variation is a function of the third body's mass and its orbital period around the mass center of the triplet system. Therefore, *V477 Cyg* might have a third component. The value of 172° given in Table 3 for the longitude of periastron does not agree with the value of 163° obtained from the light curve analysis (next section). This situation also supports that there is an effect, for example light–time effect, other than apsidal motion in the system. We have taken into account the existence of a hypothetical third body in the next part of our period analysis.

The additional time delay or advance (light–time effect) of any observed eclipse due to the orbiting binary system around the mass center of the triple system was given by Irwin (1952, 1959) as follow:

$$\tau = \frac{a_{12} \sin i'}{c} \left[\frac{1 - e'^2}{1 + e' \cos \nu'} \sin(\omega' + \nu') + e' \sin \omega' \right] \qquad (1)$$

where a_{12}, e', i' and ω' are the semi–major axis, eccentricity, inclination and the longitude of the periastron of the eclipsing pair's orbit around the third–body, respectively, while ν' is the true anomaly of the position of the eclipsing pair's mass center on the orbit and c is the speed of light. The transition time T' of the eclipsing pair's mass center from the periastron of its orbit and its orbital period P' are hidden parameters in Eq. (1). The results of the least–squares solution which takes into account both apsidal motion and light–time effect are given in Table 3 (Solution II). Because the data used in this analysis are insufficient to keep all light–time parameters as adjustable at the same time, first we performed a period–search procedure with fixed values of P' between 80 and 250 yrs. We obtained the smallest standard deviation for a value of 155 yrs. Then we divided the parameters into two subsets and performed the analysis keeping one set of parameters as adjustable and the other set as fixed, in turn. The computed O–C curves obtained with the parameters of Solution II in Table 3 are given in Fig. 2b among the O–C values obtained with the linear light elements of the same solution. The residuals from the computed curves are also plotted in Fig. 2b (bottom panel). As seen from the figure, the agreement between observations and computed fits seems satisfactory. The value (166°) of the longitude of periastron is consistent with the value obtained from the light curve analysis (next section). The first analysis which takes into account

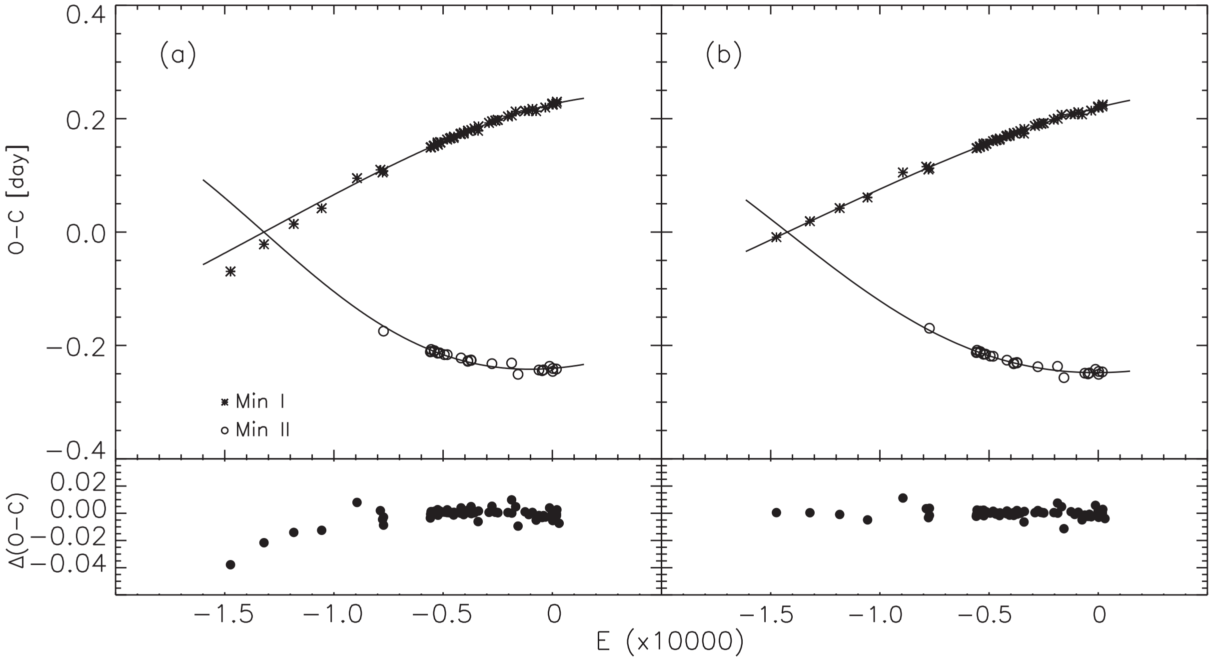

Fig. 2. O–C diagram for the times of minimum light of *V477 Cyg* obtained with the parameters of **a)** Solution I, and **b)** Solution II in Table 3. In both diagrams the residuals of O–C values from the computed curves are also shown in the bottom panels.

only apsidal motion gives a period of 371 yrs that is near the values given in the literature but the second, which takes into account both apsidal motion and light–time effect, gives a value of 434 yrs. This apsidal period is longer by about 25% than the value given in the literature. If the third body hypothesis is true, then, the observational time span covers only about 22% of the whole period of apsidal motion and about 62% of the orbital period of the third body.

4. Photometric analysis

Our photometric analysis was based on the *U*, *B* and *V* observations. To phase the light curves we used the following linear light elements which is obtained by applying the linear least–squares fit to the latest times of primary minimum:

$$\mathrm{Min\,I} = \mathrm{HJD}\,2\,450\,988.4887 + 2\overset{\mathrm{d}}{.}346989 \times E. \quad (2)$$

We used the Wilson–Devinney (WD) method (Wilson & Devinney 1971) in the analysis. We solved the *U*, *B* and *V* light curves simultaneously and used all observational points. The solutions were performed with the 1992 version of the DC (Differential Correction) code of the WD method. The method assumes the star surfaces to be equipotentials and computes the ligth curves as a function of the following parameters: phase shift, orbital eccentricity e and inclination i, surface potentials $\Omega_{\mathrm{h,c}}$, flux–weighted average surface temperature $T_{\mathrm{h,c}}$, mass ratio $q = M_{\mathrm{c}}/M_{\mathrm{h}}$, unnormalized monochromatic luminosities $L_{\mathrm{h,c}}$, linear limb darkening coefficients $x_{\mathrm{h,c}}$, gravity darkening exponents $g_{\mathrm{h,c}}$, bolometric albedos $A_{\mathrm{h,c}}$ and third star light l_3. Throughout this paper, the subscripts h and c refer to the primary (hotter) and secondary (cooler) component, respectively. The DC program gives a least–squares solution to a given light curve for the Roche model. In this method, some parameters of the components should be fixed. These parameters may be estimated from the known characteristics of the stars. Since the spectral type of the primary and secondary components were given by Popper (1968) as A3V and F2V, respectively, we may take some parameters as fixed for these spectral types. The temperature of the primary component was taken from Drilling & Landolt (2000) as equal to 8727 K, corresponding to the A3V spectral class. The linear limb darkening coefficients $x_{\mathrm{h,c}}$ were taken from Wade & Rucinski (1985). The gravity darkening exponents $g_{\mathrm{h,c}}$ were taken from von Zeipel (1924) to be 1.0 for radiative atmospheres (primary component) and from Lucy (1967) to be 0.32 for convective atmospheres (secondary component). Also, the bolometric albedos $A_{\mathrm{h,c}}$ were set to 1.0 and 0.5 for radiative and convective atmospheres, respectively. The mass ratio, $q = M_{\mathrm{c}}/M_{\mathrm{h}}$, is also a very important parameter because the WD method is based on the Roche geometry of the system which is very sensitive to the mass ratio. The radial velocity analysis made by Popper (1968) yields a value, $q = 0.75$. We used this as an initial value and chose the mass ratio as adjustable parameter to obtain its photometric value.

It is clear from the photometric study by O'Connell (1970) and Giménez & Quintana (1992) that the system is well detached. Therefore we performed the solutions in MODE 2, which corresponds to the detached configuration. In this analysis we obtained two different models for the system: Model A and Model B. In Model A, the solution is obtained without third body light while in Model B we took into account the existence of an unseen third body in the system and chose the third light l_3 as adjustable parameter to obtain its contribution to the total light of the system.

The results obtained from the simultaneous solutions of the *U*, *B* and *V* light curves are given in Table 4. Errors given in this table are the output errors of the WD code. With the

Table 4. The results obtained by the WD method. The errors given for the adjustable parameters are the output errors of the WD code.

Parameters	Model A	Model B
PSHIFT	0.9065 ± 0.0002	0.9065 ± 0.0002
e	0.331 ± 0.001	0.331 ± 0.001
ω	$162\overset{\circ}{.}6 \pm 0^\circ.1$	$162\overset{\circ}{.}8 \pm 0\overset{\circ}{.}1$
i	$85\overset{\circ}{.}47 \pm 0\overset{\circ}{.}02$	$85\overset{\circ}{.}66 \pm 0\overset{\circ}{.}03$
$x_\mathrm{h}*$	0.514 (U) 0.606 (B) 0.473 (V)	
$x_\mathrm{c}*$	0.730 (U) 0.666 (B) 0.554 (V)	
$A_\mathrm{h}*$	1.0	
$A_\mathrm{c}*$	0.5	
$g_\mathrm{h}*$	1.00	
$g_\mathrm{c}*$	0.32	
$T_\mathrm{h}*$	8727 K	
T_c	6536 ± 7 K	6528 ± 7 K
Ω_h	7.89 ± 0.02	7.94 ± 0.03
Ω_c	7.44 ± 0.02	7.36 ± 0.02
q	0.758 ± 0.003	0.749 ± 0.002
$L_\mathrm{h}/(L_\mathrm{h} + L_\mathrm{c} + L_3)$	0.863 ± 0.002 (U)	0.783 ± 0.009 (U)
	0.825 ± 0.002 (B)	0.805 ± 0.006 (B)
	0.801 ± 0.002 (V)	0.773 ± 0.006 (V)
$L_\mathrm{c}/(L_\mathrm{h} + L_\mathrm{c} + L_3)$	0.137 (U)	0.126 (U)
	0.175 (B)	0.174 (B)
	0.199 (V)	0.216 (V)
$L_3/(L_\mathrm{h} + L_\mathrm{c} + L_3)$	–	0.091 ± 0.001 (U)
	–	0.021 ± 0.001 (B)
	–	0.011 ± 0.001 (V)
r_h (mean)	0.1482 ± 0.0004	0.1469 ± 0.0004
r_c (mean)	0.1303 ± 0.0004	0.1307 ± 0.0004
σ	0.035	0.034

[(*)] **assumed**.

Table 5. The instrumental color indices of the components of *V477 Cygni*.

	$U - B$	$B - V$
Primary	0.030	–0.044
Secondary	0.350	0.235
Third–body	–1.592	–0.702

Model B parameters, given in Table 4, we obtained computed light curves using the LC (light curve) code of the WD method, and showed them in Fig. 1 together with the observational points.

From the contributions of the components to the total light of the system in the U, B and V colors we derived the instrumental $U - B$ and $B - V$ color indices for the components and gave them in Table 5. According to these color indices the third body should be a compact star, rather than a normal star.

Table 6. The absolute parameters of the eclipsing pair's components of *V477 Cygni*.

Parameters	Primary	Secondary
$M/M_\odot$	1.80 ± 0.10	1.35 ± 0.08
$R/R_\odot$	1.60 ± 0.03	1.42 ± 0.03
$\log g$ (cgs)	4.29 ± 0.04	4.26 ± 0.04
$\log T_\mathrm{eff}$	3.941 ± 0.012	3.815 ± 0.012
M_bol	1.93 ± 0.16	3.45 ± 0.17
B.C.	–0.18	–0.12
$\log L/L_\odot$	1.12 ± 0.06	0.52 ± 0.06
Spectral Type	A3V	F5V
$(B - V)_\mathrm{o}$	0.10 ± 0.03	0.38 ± 0.05

5. Discussion

5.1. Eclipsing pair

The spectroscopic analysis of the system by Popper (1968) gives $a \sin i = 10.88 \pm 0.20\ R_\odot$. He also gave the unreddened $B - V$ color indices to be 0.10 ± 0.03 for the primary and 0.38 ± 0.05 for the secondary component. Using these and the values obtained from our photometric analysis (Model B in Table 4), we computed the absolute parameters of the components. The results are given in Table 6. The errors in the effective temperatures given in Table 6 are calculated from the table given by Drilling & Landolt (2000) using the errors in $(B - V)_\mathrm{o}$ color indices of the components. The bolometric corrections and the spectral types for the corresponding temperatures were taken from the same table. The relative errors are about 2% for the radii and about 6% for the masses. All parameters, except the radius of the secondary components, are in agreement with those given by Giménez & Quintana. We found a value larger by about 12% than that given by Giménez & Quintana for the secondary's radius.

The surface–brightness ratio of the components in a binary system was defined by Barnes & Evans (1976) as follows:

$$\Delta F_V = \frac{1}{4} \log \left[\frac{J_\mathrm{c}(1 - \frac{x_\mathrm{c}}{3})}{J_\mathrm{h}(1 - \frac{x_\mathrm{h}}{3})} \right] \tag{3}$$

where $J_\mathrm{c}/J_\mathrm{h}$ is the ratio of central surface brightnesses of the secondary and primary components. Our photometric analysis gives the surface brightness ratio of the components to be $\Delta F_V = -0.115 \pm 0.010$. If we assume the unreddened $(B - V)_\mathrm{o}$ color indices to be +0.10 and 0.38 mag as given by Popper (1968) for primary and secondary components, respectively then from the calibration table given by Popper (1980) we obtain $\Delta F_V\ (B{-}V) = -0.106$. Alternatively if we use the temperatures given in Table 4 then we have $\Delta F_V\ (T_\mathrm{e}) = -0.121$. Thus it may be possible to say that the discrepancy between observed and theoretical values of ΔF_V is not larger than about 0.01 (in logarithmic scale). The possible explanation for this discrepancy may be a large difference between the luminosities of the components or an error in the calibration data in this spectral region.

From the bolometric magnitudes and bolometric corrections in Table 6 we obtained the visual absolute magnitudes

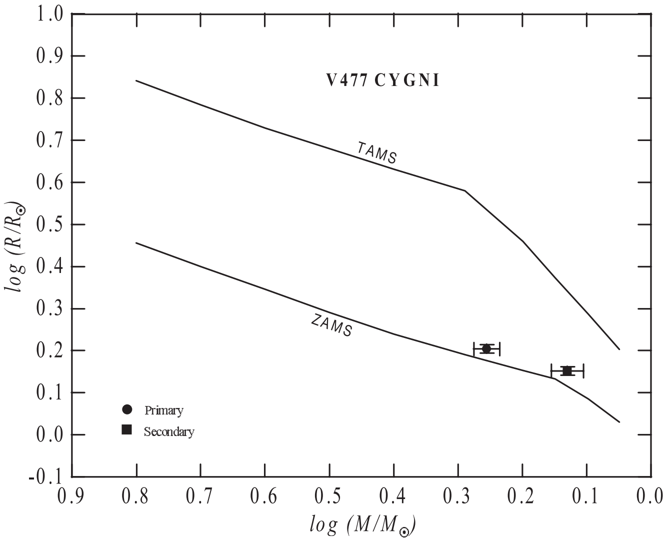

Fig. 3. The locations of the components of *V477 Cyg* in the log M – log R diagram. The ZAMS and TAMS lines are taken from Claret & Giménez (1991).

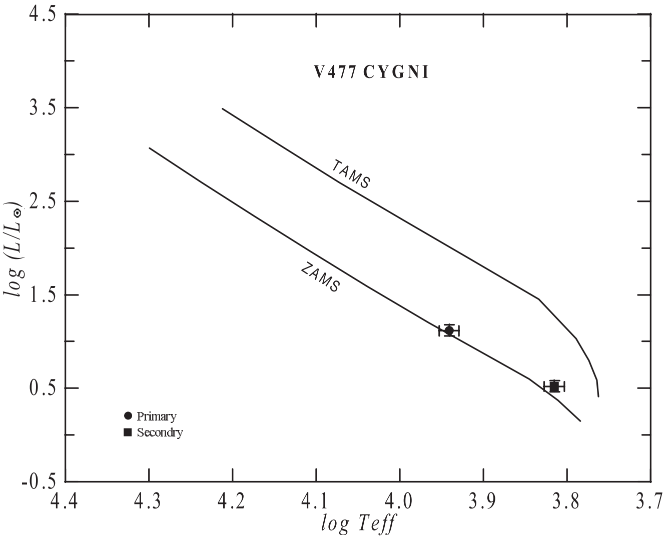

Fig. 4. The locations of the components of *V477 Cyg* in the log T_e – log L diagram. The ZAMS and TAMS lines are taken from Claret & Giménez (1991).

to be 2.11 ± 0.16 mag and 3.57 ± 0.16 mag for the primary and secondary components, respectively. The visual apparent magnitude of the system is also given as 8.51 mag in the Hipparcos Catalogue. An excess of 0.03 mag for the system in *b–y* was given by Olson (1975). According to the relationship given by Friedemann et al. (1993) this value corresponds to an excess of 0.040 mag in $B - V$. Thus the distance of the system is obtained as $r = 205 \pm 15$ pc while it was given to be 220 pc by Giménez & Quintana (1992). The Hipparcos Catalogue gives a value of 192 ± 39 pc. The locations of the components in log R vs. log M and log T_e vs. log L diagrams are shown in Figs. 3 and 4, respectively. The theoretical ZAMS and TAMS lines were taken from the evolutionary models given by Claret & Giménez (1991) which takes into account both convective overshooting and mass loss. An initial chemical composition $(Y, Z) = (0.28, 0.02)$ has been adopted.

It is possible to say from Fig. 3 that both components of the system are slightly evolved from the ZAMS. However, it should be noted that locations of the components on mass-radius and HR diagrams are not in fully agreement as it seen from Figs. 3 and 4. Figure 4 hints a discrepancy between the models and observations concerning temperatures of the components.

Using both apsidal motion parameters of Solution II in Table 3 and the absolute dimensions given in Table 6 the mean apsidal motion coefficient $\overline{k_2}$ for the system can be determined. After correction for the relativistic effect ($\dot{\omega}_{\rm rel}$ = $0\overset{\circ}{.}00074$ cycle^{-1}) and using the rotational velocities given by Olson (1984), 64 ± 11 km s^{-1} for the primary and 50 ± 9 km s^{-1} for the secondary star, we obtain $\log \overline{k_2}_{\rm obs} = -2.492$. Using the theoretical models by Claret & Giménez (1991) and taking into account the effect of rotation in internal structure of the component stars we predicted $\log k_{21} = -2.407$ for the primary and $\log k_{22} = -2.424$ for the secondary component. Therefore, the theoretical mean apsidal motion coefficient for the system is about, $\log \overline{k_2}_{\rm theo} = -2.415$. Thus the observed value of $\overline{k_2}$ is about 16% smaller than its theoretical value. This means that the components are slightly more centrally condensed than theoretically predicted. However Giménez & Quintana (1992) had obtained less centrally condensed components than theoretically predicted. From the same models by Claret & Giménez (1991) we also predicted the evolutionary age to be 6.4×10^8 yrs for the primary component. This value corresponds to about 30% of the main sequence lifetime of the primary star.

5.2. Third body

According to the third body parameters given in Table 3 the mass function of the third body is $f(M_3) = 0.00395\ M_\odot$. One can obtain a lower limit for the mass of the unseen third component in the system assuming a coplanar orbit ($i_3 = 90°$). If we do so we obtain a value, $M_3 = 0.37\ M_\odot$. If the instrumental color indices given in Table 5 imply that the third body is really a compact object then its mass could be about 0.5 $M_\odot$ which corresponds to $i_3 = 49°$. Thus the semi–major axis of the relative orbit of the third body would be 44.8 AU. With this and the distance of the system from us (205 ± 15 pc) we obtain the projected angular seperation between the third body and the eclipsing pair to be $0\overset{''}{.}049$ and $0\overset{''}{.}277$ at the periastron and apastron points of the orbit, respectively. These values are within the observing limits of modern technology. To verify the existing of the third body in the system more spectroscopic, photometric and especially systematic speckle–interferometric observations are needed.

6. Conclusion

We present *UBV* light and O–C curves analyses of the eclipsing binary *V477 Cygni*. We obtained two photometric models, with and without third light in the system. The orbital eccentricity and longitude of the periastron point are well established in both O–C and light curves analyses. The photoelectric mass ratio we obtained is in good agreement with the spectroscopic value given by Popper (1968). The fractional radius of the secondary component was obtained to be somewhat larger than that given by Giménez & Quintana (1992). The surface brightness ratio of the components is in agreement with the theoretical value obtained from the calibration table given by Popper (1980).

Third light contributions to the total light in the *B* and *V* bands are small while in the *U* band it is comparable with the contribution of the secondary component. The instrumental color indices obtained from the light curve analyses imply that the third body should not be a normal star.

Combining the photometric parameters with the spectroscopic results of Popper (1968) the absolute physical parameters of the system were recalculated and compared with the theoretical models, using a moderate amount of convective overshooting and mass loss, given by Claret & Giménez (1991). From this comparison we decided that the secondary component is just coming to the main sequence while the primary as already completed about 30% of its main sequence lifetime. We also compared the observed mean apsidal motion coefficient with those predicted from the same models and found that the components of *V477 Cygni* are slightly more centrally condensed than theoretically predicted.

The O–C analysis gave an orbital period of 157 yrs and a very high eccentricity (0.7) for the hypothetical third–body in the system. We predicted a lower limit for the third body as 0.37 $M_\odot$ assuming an orbital inclination of 90°. But, taking into account the color indices obtained from third light contributions found in the light curves analysis we assumed it's mass to be 0.5 $M_\odot$ which is the mean value for white dwarfs. Angular separations, especially at apastron point of the third body orbit, between eclipsing pair and third body are within the observing limits of modern technology.

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