Cyclic period changes and light-time effect in eclipsing binaries: a low-mass companion around the system VV Ursae Majoris

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- **Abstract**
- In this article, a period analysis of the late-type eclipsing binary VV UMa is being presented. This work is based on the periodic variation of eclipse timings of the VV UMa binary, we determine the orbital properties and mass of a third body orbiting in the system by applying the analysis of the light-travel time effect. The O−C diagram constructed for all available minima times of VV UMa exhibits a cyclic character superimposed on a linear variation. This variation includes three maxima and two minima within about 28240 orbital periods of the system. This can be explained as the light-travel time effect (LITE) due to an unseen third body in a triple system, causing variations of the eclipse arrival times. New values for the parameters of light-time travel effect due to the third body are computed with a period of 23.22 ± 0.17 years in the system. The analysis of the cyclic variation results the value 0.0139 day as the semi-amplitude of the light-travel time effect and 0.35 as the orbital eccentricity of the third body. The mass of the third body orbiting around the eclipsing binary stars is 0.787 ± 0.02 $M_{\odot}$ and the semi-major axis of its orbit is 10.75 AU.

- **1. Introduction**
- VV UMa (BD+561395, HIP 47279) is an interesting eclipsing binary of Algol type (semi-detached) with an orbital short-period of $0^{d}.68738$. The B, V and R magnitudes of VV UMa are given as $10^{m}.42$, $10^{m}.28$, and $10^{m}.135$ mag in the SIMBAD database, respectively. The J, H and K magnitudes of the binary systems in the 2MASS are $9^{m}.627$, $9^{m}.497$ and $9^{m}.420$ mag, respectively. The variability of VV UMa was first reported by Gitz (1936) on the Moscow observatory plates. The first minimum time and the ephemeris were given byKaho (1939). While Hill et al. (1975) classified the primary star of the system as A2V. Struve, 1950 and Struve, 1951, by spectroscopic studies, determined that the primary component of VV UMa was the spectral type of A0V and its mass function was $f(m) = 0.015\ M_{\odot}$. He suggested a mass ratio $q \sim 0.23$ and derived a semiamplitude $K_1 = 59$ kms^{-1} from his radial velocity curve solution. Wilson (1965) was the first who performed the light curve analysis of the system. Broglia and Conconi (1977) presented several minima times and analysed the light curves in the V and B bands. They inferred that the VV UMa variable is a semi-detached eclipsing binary star with the parameters of $M_1 = 1.93\ M_{\odot}$, $R_1 = 1.58\ R_{\odot}$, $M_2 = 0.44\ M_{\odot}$, $R_2 = 1.23\ R_{\odot}$, $q = 0.23$.

- They specified that the spectral types of the primary and secondary components were main sequence types A0-2 and G5-6, respectively. Chaubey (1979) calculated the orbital angular momentum of the VV UMa system with log$H$ = -1.67. Rafert (1990) obtained for the first time the light curve solution of the system including the third light. He derived the parameters M_1 = 0.97 $M_\odot$, R_1 = 1.35 $R_\odot$, M_2 = 0.29 $M_\odot$, R_2 = 0.96 $R_\odot$, q = 0.298, by using $f(M)$ = 0.015 $M_\odot$, with stellar temperatures $T_{eff,1}$ ≈ 9550 K and $T_{eff,2}$ ≈ 5000 K. His solution provided a small contribution of the third light. Using the minima times during 1929-1985, published by Kučera and Mikulášek, 1986 and Šimon, 1996 made the first period analysis of the system in terms of the light travel time effect (LITE) due to the presence of an unseen third body in the system. He found that the cyclic sinusoidal O-C variation was changing with a period of 8138 days (22.28 years) with a minimum 0.4 $M_\odot$ for the third body mass. The apsidal motion must be ruled out because the system was a semi-detached binary according to the earlier investigations. Although Strömgren *uv* photometry of VV UMa was studied by Hilditch and Hill, 1975 and Lázaro et al., 2001 first analysed the light curves of the binary system using two different codes in the Strömgren *uvby*β filters and estimated several minima times. They determined that the effective temperatures of the components were $T_{eff,1}$ = 9000-9600 K, and $T_{eff,2}$ = 5300-5600 K.

- Their work revealed small amplitude and short period brightness variations of the system, and they calculated the mass function of the system, *f(M)* = 5.1×10^{-2} $M_{\odot}$. Arévalo et al. (2001) presented the light curves solution of the system in B, V and R filters. Lázaro et al. (2002) analysed light curves of the VV UMa binary system in B, V, R, J and K filters and performed the spectroscopic study of the system in the region 8440-8870Å and gave a number of minima times. They found that the spectral type of the primary component was A1.5-2V. They derived the effective temperatures of the primary and secondary stars as $T_{eff,1}$ = 9250 ± 150 and $T_{eff,2}$ = 5600 ± 100, respectively; and found that the mass function of the system was *f(M)* = 2.8-$3.1 \times 10^{-2} M_{\odot}$ with the mass ratio of q = 0.26-0.31. It was indicated that VV UMa is a system with unusually low mass components in the spectral solution. Kim et al. (2005) showed that the binary system presented a short-period small amplitude pulsation. Although the minima times of the system have been reported by many researchers, the O–C period analysis was carried out only by Šimon (1996), who analysed the data from the years 1959-1994.
- In this paper we reconsider all the minima times reported in the literature, perform the solution of the light-travel time effect (LITE) for VV UMa with new minima times, and derive new parameters of the third body orbit.

- **2. The orbital period variation of the system**
- **2.1. O–C diagram analysis for light travel time effect (LITE)**
- The minima times of VV UMa were obtained from the different sources reported earlier in the literature. We also added minima times mainly from BBSAG Bull., BAV Mitt., BRNO Contr., Orion, and AAVSO. The interval of the available minima times of VV UMa covers the last 106 years from 1906 to the end of year 2012. All available minima times were collected from their original sources in the literature. The complete list of minima times is given in Table 1, which contains a data set of 320 visual, 28 photographic, 53 photoelectric and 114 CCD minima times. The references cited in Table 1 are marked in bold numbers in parentheses at the end of the reference list in the article. The photometric epoch numbers of all minima times were firstly calculated with the ephemeris (HJDmin 2456016.6904 and period, $0.^{d}6873801$). The linear least-squares fit was applied to the measured minima times after HJD2436600 and the resulting ephemeris were found as:
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- $MinI = HJD2456016.7061(75) + 0.^{d}6873845(4) \times E$ (1)

Table 1. The minima times of VV UMa.

HJDmin +2400000	Type	Ref	HJDmin +2400000	Type	Ref	HJDmin +2400000	Type	Ref
ccd			ccd			ccd		
45006,2873	I	18	53813,6399	I	118	55262,6395	I	117
45006,6310	II	18	53822,9198	II	26	55266,0754	I	26
45815,3365	I	81	53839,7600	I	26	55273,6360	I	117
46914,4530	I	26	54117,4620	I	35	55276,3859	I	93
48500,2300	I	26	54123,6480	I	26	55277,4173	II	93
50130,6650	I	11	54165,5750	I	118	55284,2907	II	93
50533,4644	I	92	54165,5785	I	118	55285,6625	II	118
51241,4599	I	113	54173,8270	I	26	55285,6645	II	118
51519,8474	I	106	54192,3861	I	16	55287,0419	II	26
51534,6353	II	92	54193,4220	II	16	55295,6327	I	118

Visual, photographic, photoelectric, ccd

This ephemeris was used to compute the O–C residuals of all compiled minima times. The O–C diagram with all minima times of the system is plotted in Fig. 1. As the minima times before HJD2436600 generally show a large amount of scatter, as depicted in Fig. 1, the data before HJD2436600 were omitted for further analysis. They are marked in italics in HJD column of the Table 1.

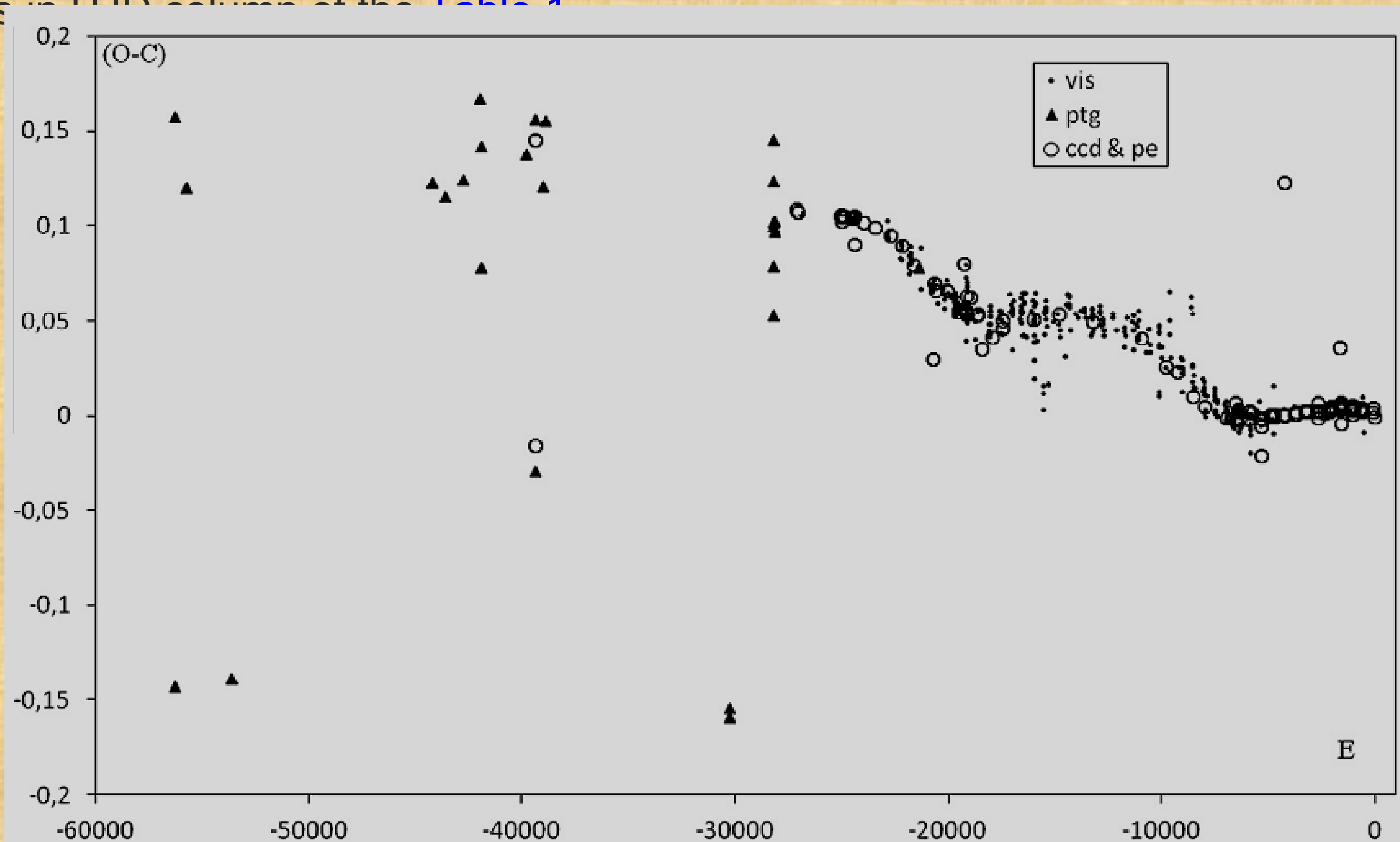

Fig. 1. The O−C diagram for all minima times of VV UMa. The open circles, the filled triangles, and the little filled circles represent ccd and photoelectric, photographic and visual minimum times, respectively.

Some minima times have been incorrectly reported in the literature, as the primary minimum (I) is actually the secondary minimum (II) and vice versa. The actual minima times are marked in italics in the Table 1. The O–C diagram after HJD2436600 is shown in Fig. 2.

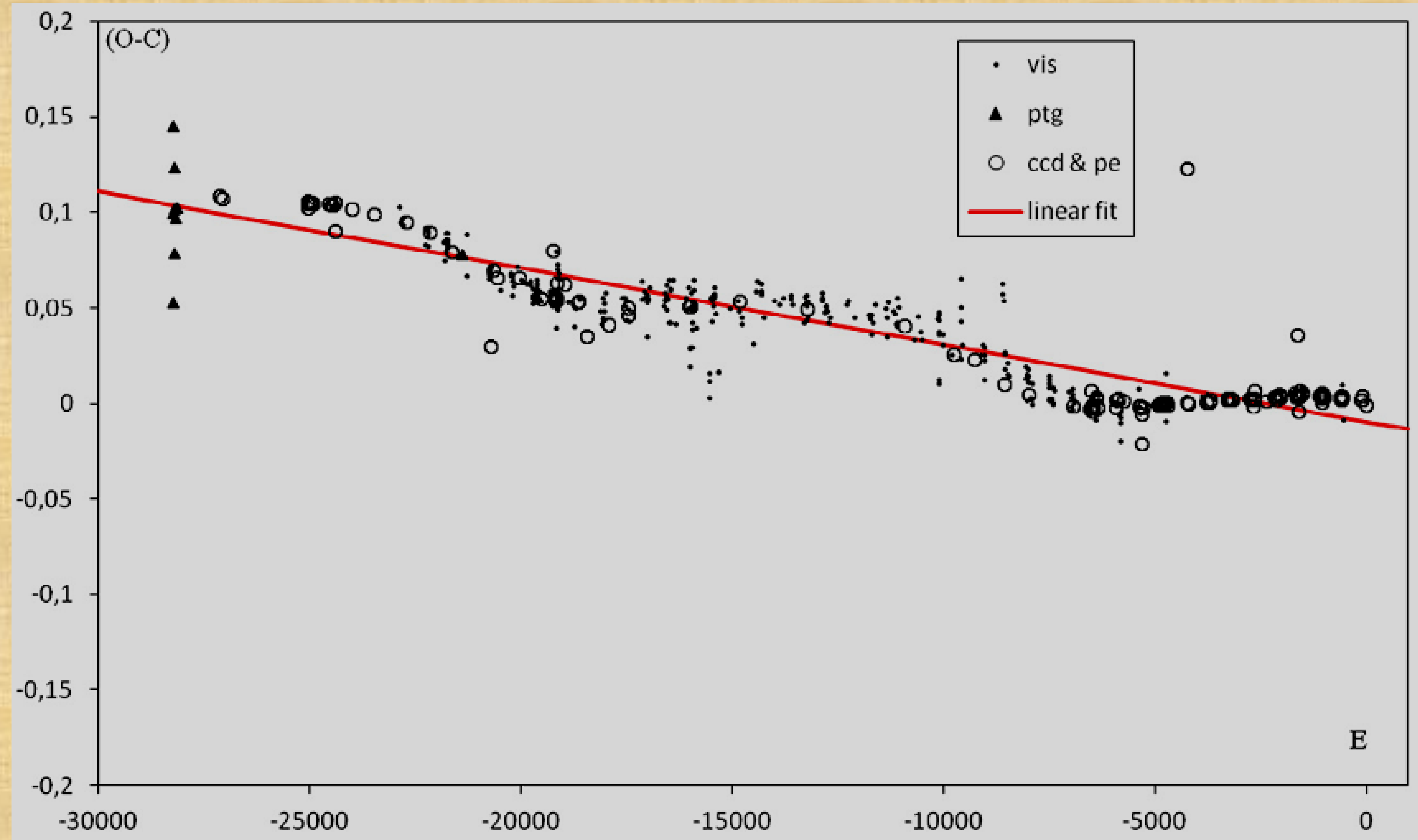

Fig. 2. The O−C diagram for the minimum times of VV UMa after HJD2436600. This represents a sinusoidal variation superimposed on the linear variation. The solid line is linear fit. The symbols are the same as in Fig. 1

- This diagram represents a continuous sinus oscillatory variation with three maxima and two minima superimposed on the linear variation. The linear regression of these data show the systematic differences from the linear variation in the current O−C diagram, with the cyclic sinus oscillatory variation. The apsidal motion can be discarded, as the orbit is nearly circular, but the periodic modulation in the O-C diagram can be produced by the LITE effect due to an unseen third body in the system. The analysis of the cyclic variations allows to derive the orbital parameters of the third body, using the equation proposed by Irwin, 1952 and Irwin, 1959

$$(\mathrm{O-C}) = \mathrm{O} - \left[T_0 + P_{\mathrm{orb}} \times E + \frac{A}{\sqrt{1-e'^2 \cos^2 \omega'}} \cdot \cdot \left\{ \frac{1-e'^2}{1+e' \cos v'} \sin(v' + \omega') + e' \sin \omega' \right\} \right] \quad (2)$$

where e', ω', and v' are eccentricity, the longitude of the periastron and the true anomaly of the third-body orbit respectively.

The observed semi-amplitude A of the light-travel time curve (in days) is:

$$A = \frac{a'_{12} \sin i'}{173.15} \sqrt{1 - e'^2 \cos^2 \omega'} \qquad (3)$$

where a'_{12} and i' are the semi-major axis of the relative orbit of the eclipsing binary around the common centre of mass (in AU) and the inclination of the third-body orbit, respectively. 173.15 is the speed of light in AU/day. A computer code written by us is used to determine the parameters (T_0, P_{orb}, P_{12}, T', $a'_{12}\sin i'$, e', ω') by least-squares fitting the O−C values with the theoretical formula given in Eq. (2).

Applying that to the minima times and using the differential correction method, the parameters of the light-travel time orbit and the third-body are obtained. The weight (w) for the individual observations is based on the reliability of each minima time. We have used w=10 for CCD and the photoelectric points, 5 for the photographic data, and 1 for visual observations. The solution parameters and their standard errors, used to obtain the theoretical O–C curve, are given in Table 2. A sinusoidal fit in the O–C diagram is shown in Fig. 3. The O–C residuals for the minima times from the sinusoidal regression can also be seen in Fig. 4. The value of the sum of the squares of the residuals from Eq. (2) is $\sum(O\text{–}C)^2 = 3.7227\times10^{-4}$ day^2. This shows that the theoretical curve reproduces the general O–C trend very well.

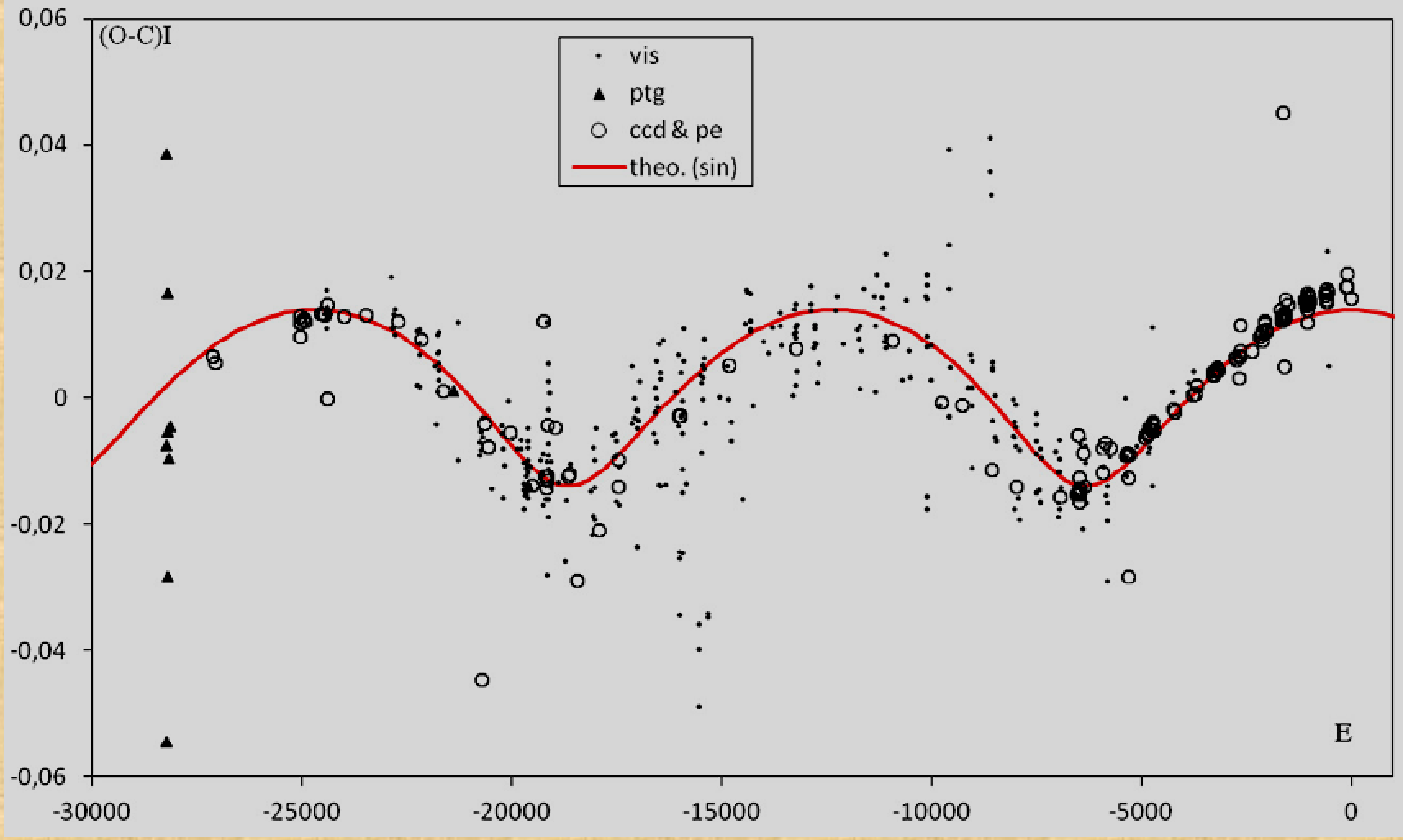

Fig. 3. The residuals from the linear fit applied the minima times after HJD2436600. The data set fitted by the light-travel time effect (LITE) of the hypothetical third body. The solid curve represents the cyclic sinusoidal variation, the best fit with the parameters is given in Table 2. The symbols are the same as in Fig. 1.

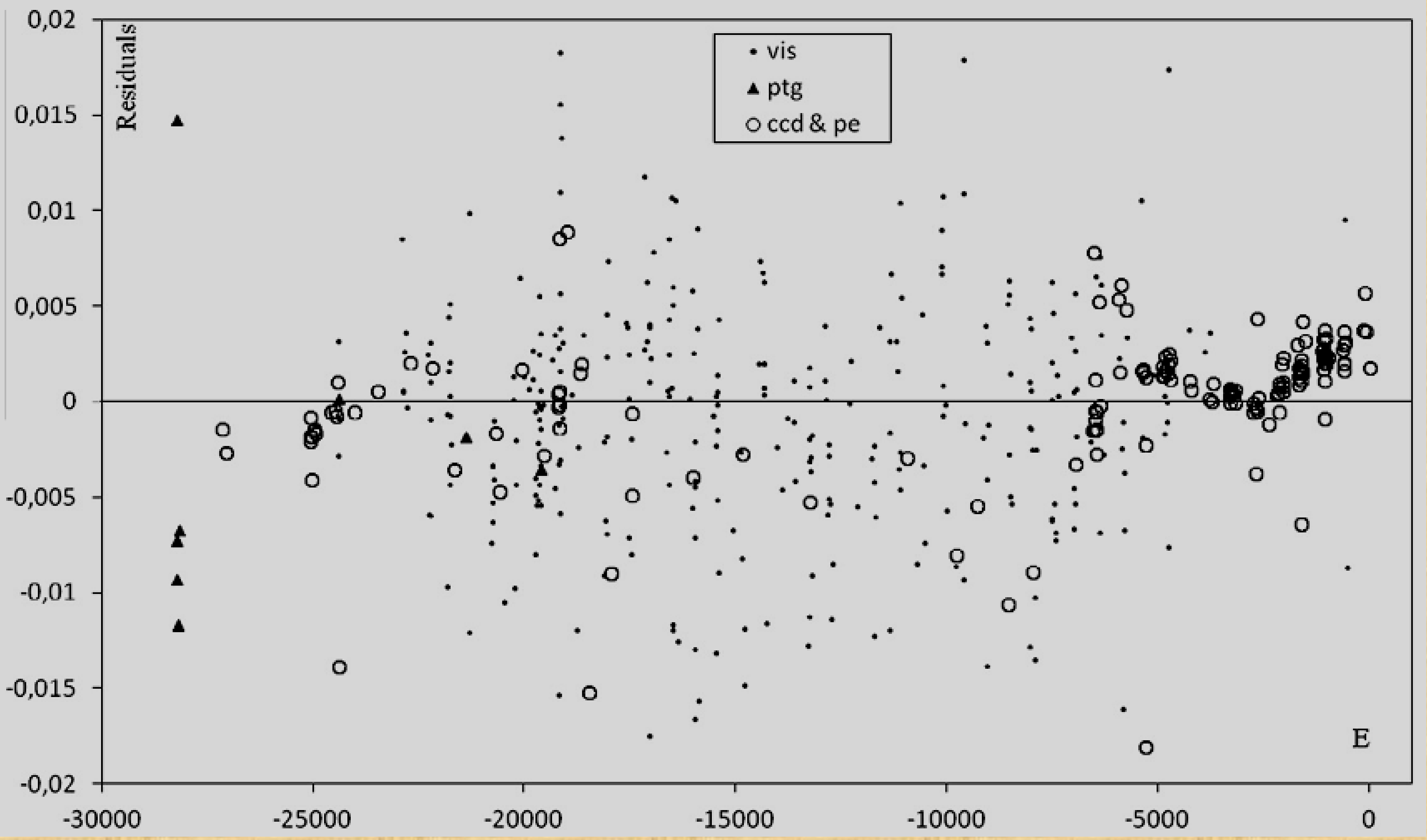

Fig. 4. The final residuals from the fitted sinusoidal curve by LITE analysis with the parameters in Table 2. The symbols are the same as inFig. 1.

Table 2.Parameters of the light-travel time orbit derived from (O−C) analysis of VV UMa

Parameters	unit	Value	Standart deviation
T_0	HJD	2456016.7061	0.0075
P_{orb}	day	0.6873845	0.0000004
$a'_{12} \sin i'$	AU	2.408977	0.05
e′		0.35	0.03
ω'	degree	263	2.6
T′	HJD	56016.71	46.2
P_{12}	year	23.22334	0.17
A	day	0.0139	0.0002
f(M)	$M_\odot$	0.025921	0.0012
M_3 (coplanar)	$M_\odot$	0.7868	0.02
M_3 (for i′=30)	$M_\odot$	1.7897	0.02
M_3 (for i′=60)	$M_\odot$	0.9153	0.02
M_3 (for i′=90)	$M_\odot$	0.7757	0.02
K_{RV}	km/sn	3.2982	0.08

3. Mass of the third body and the semi-amplitude of the systemic radial velocity

The solution parameters of the third body orbit are used to determine the mass function *f(M)* of the triple system using the following equation:

$$f(M) = \frac{(M_3 \sin i')^3}{(M_1 + M_2 + M_3)^2} = \frac{(a'_{12} \sin i')^3}{P_{12}^2} = \frac{1}{P_{12}^2}\left[\frac{173.15A}{\sqrt{1 - e'^2 \cos^2 \omega'}}\right]^3 \quad (4)$$

where P_{12} is the orbital period of the third-body (in years) and M_1, M_2 and M_3 are the masses of components in the triple system. The units of a'_{12}, P_{12}, i' and $M_{1,2,3}$ should be taken as AU, years, degree and solar mass, respectively. According to the above equation, we obtain $f(M) = 0.025921 \pm 0.0012\ M_{\odot}$ and $a'_{12} \sin i' = 2.408977 \pm 0.05$ AU.

Assuming a coplanar orbit ($i' = 80^{\circ}.98$), the mass of the third component M_3 is obtained. We have used the masses $M_1 = 2.624\ M_{\odot}$ and $M_2 = 0.844\ M_{\odot}$ derived from the solutions by Lázaro et al. (2001) for the masses of the two components of the eclipsing binary system, respectively. The orbital parameters of the third body, its mass function and mass are listed in Table 2.

The semi-amplitude K_{RV} of the systemic radial velocity change of the eclipsing pair was given by Mayer (1990) as:

$$K_{RV} = \frac{29.785 a'_{12} \sin i'}{P_{12}\sqrt{1 - e'^2}} \quad (5)$$

where K_{RV}, P_{12} and a_{12} are in kilometres per second, years and AU, respectively, and considering a coplanar orbit (i'=80°.98), the semi-amplitude of the system velocity taking into account the LITE is calculated to be approximately 3.2982 kms^{-1}, which is a little higher than the value determined by Šimon (1996). This value is given in the Table 2. The mass of the third body for the different orbital inclination angles of the triple system has been calculated. This change is presented in the Fig. 5. The mass of the third body is at a comparable level to those of the secondary component in the binary system. Therefore, it is discoverable by spectroscopic observation.

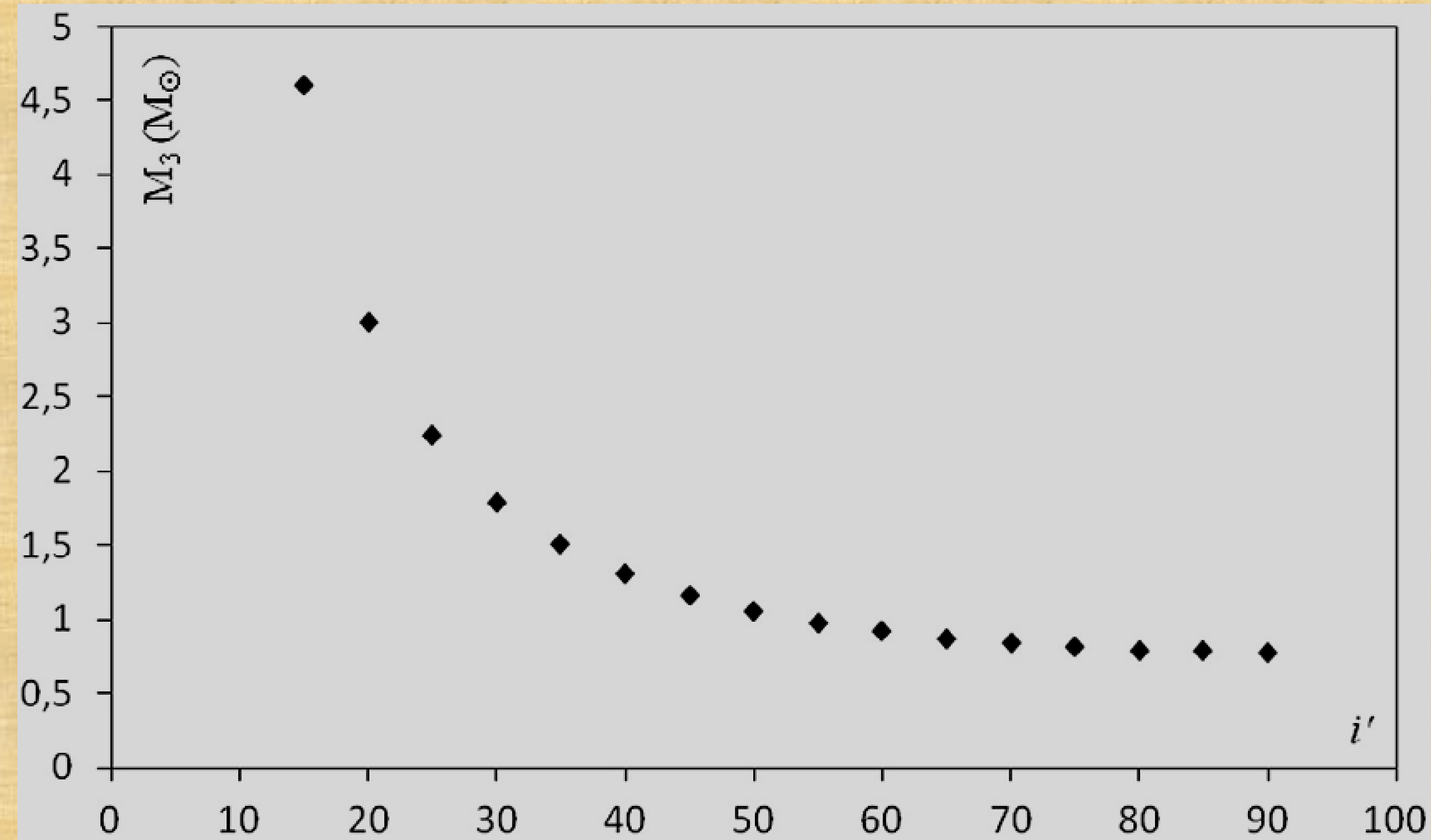

Fig. 5. The mass changing of the unseen third component of VV UMa according to the different orbital inclination.

4. Discussion and Conclusions

This paper presents the orbital period study of the semidetached eclipsing binary VV UMa that shows the light-travel time effects. From the LITE analysis alone, the orbital parameters along with the mass of the hypothetical third component around the eclipsing pair are obtained. It can clearly be seen from the analysis of the O−C diagram that the orbital period of VV UMa is changing with a cyclic character (sinusoidal variation) superimposed on linear structure after HJD2436600.

Assuming the presence of an unseen third body gravitationally bound to the eclipsing binary, and the light-travel time effect (LITE) as the cause of the observed cyclic sinusoidal variation in the O−C diagram, the parameters of the third body orbit have been calculated.

The third body causes to change the relative distance between the Earth and the eclipsing pair because it orbits the barycentre of the triple system, thus causing periodic variations of the eclipse times of the binary stars. The orbital parameters of the hypothetical triple system are determined using Irwin's method (1952,1959). The O–C analysis of VV UMa entails that the eclipsing binary system and connected unseen third body have completed a revolution around their common centre of mass on their orbit in 23.22 ± 0.17 years. The projected distance between the mass centre of the eclipsing pair and the barycentre of the triple system is obtained as 2.4391 ± 0.0506 AU. These values estimate the mass function as *f(M)* = 0.025921 ± 0.0012 M_0 for the hypothetical third body.

The computed mass of the third body for the different orbital inclination angles of the triple system are shown in Fig. 5. In this computation, M_1 = 2.62 $M_\odot$ and M_2 = 0.84 $M_\odot$ (Lazaro et al., 2001) have been used. If the third body orbit is coplanar with the eclipsing binary system (i.e.,*i′* = 80°.98), its mass may be 0.787 $M_\odot$. Then, the distance of the third body to the common centre of mass of the triple system is 10.751 ± 0.05 AU according to Kepler's third law. The semi-major axis of the triple system has also been obtained as 13.19 ± 0.05 AU. By considering the parallax of VV UMa π = 2.56*mas* given in the Hipparcos catalogue– the New Reduction (van Leeuwen, 2007), the distance of the triple system is calculated as 390.625 pc, then the maximum angular separation between the third body and the eclipsing pair is obtained as 0.003377 ± 0.0015.

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By using the mass-luminosity relation for main-sequence stars given by Malkov (2007), the bolometric absolute magnitude of the third body for the given distance is calculated to be about M_{bol} = $6.^{m}49$ ± 0.15, which is about 4^{m} fainter than the combined brightness of the binary system. Table 3 shows a comparison of the results obtained by our analysis and by others for VV UMa. It can be affirmed that the presence of an unseen third body in the system of VV UMa is now better explained.

Table 3.The third body orbit of VV UMa compared with previous work.

Parameters	**unit**	**Šimon (1996)**	**Present work**
P_{O-C}	year	22.28	23.22334
A	day	0.01226	0.0139
e'		0.2	0.35
ω'	degree	219.8	263
f(M)	$M_\odot$	0.0199744	0.025921
M_3	$M_\odot$	0.4	0.7868
K_{RV}	km/sn	2.93	3.2982

- The existence of the third star is just at the detection limit of the different observational techniques. The mass of the hypothetical third body is comparable with the mass of the secondary component of VV UMa, which is large enough to be determined spectroscopically.

- It is desirable to find direct evidence for the presence of the third body in the VV UMa triple system within the infrared wavelengths by interferometric, astrometric or spectroscopic observations, which would definitely verify our final conclusion.

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