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Photometric Elements, Apsidal Motion, Brightness Variations, and Light-time Effect in the Eclipsing Binary System V957 Cephei

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We obtained several light curves of V957 Cep in 2009, 2011, 2013, 2016, and 2019 at the Crimean Astronomical Station of M.V. Lomonosov Moscow State University and at the Tien Shan Observatory of the V.G. Fesenkov Astrophysical Institute. Using the TESS satellite observations, we found brightness variations of V957 Cep with the period $P_\mathrm{p} = 0\overset{\mathrm{d}}{.}664$ and amplitude $A_\mathrm{p} = 0.0076^\mathrm{m}$. For our light curves (2009–2019) and TESS light curves (2019–2020), orbital elements were computed and a new value of the apsidal motion rate $d\omega/dt = 1.47^\circ \pm 0.15^\circ$ yr^{-1} was derived. We found a possible light-time effect that can indicate gravitational influence of one or several additional bodies in the system on the central binary. Based on the currently available data, the amplitude and period of the light-time effect still cannot be reliably estimated.

1 Introduction

V957 Cep was recognized as an eclipsing variable (its orbital period being $1\overset{\mathrm{d}}{.}98873$) in an analysis of NSVS survey data on variable stars in the northern hemisphere (Woźniak et al., 2004), and it was included in the list of 50 new eclipsing stars with elliptical orbits found in data of ASAS, Hipparcos, and NSVS (Otero et al., 2006).

We obtained the variable's light curves in the V band at the Tien Shan Astronomical Observatory of the V.G. Fesenkov Astrophysical Institute (in 2009, 2011 using the 35-cm Ritchey-Chrétien telescope with an ST-402 CCD; in 2013, 2016, 2019 using the 1-m Zeiss telescope with an Apogee 49000D9 CCD; in 2016, 2019 using the 60-cm Zeiss telescope with an Apogee Aspen CCD). Studies of the light curves, parameters of the components, orbital elements, and the determination of the apsidal motion rate were published by Kozyreva et al. (2012), Kozyreva & Kusakin (2014).

The system was also observed in two series of observations by the TESS space telescope in 2019–2020, the data were taken from the MAST archive[1]. The precision of TESS observations is about a few thousandths of a magnitude, it is several times better than the precision of ground-based observations. Figure 1 shows the combined light curve of the system obtained by TESS in 2019–2020.

The spectral types of the components were estimated as B7V–A3V using spectrophotometric observations made in Barnesville near Washington using an 18-inch Newton telescope (Kozyreva et al., 2012).

[1] https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html

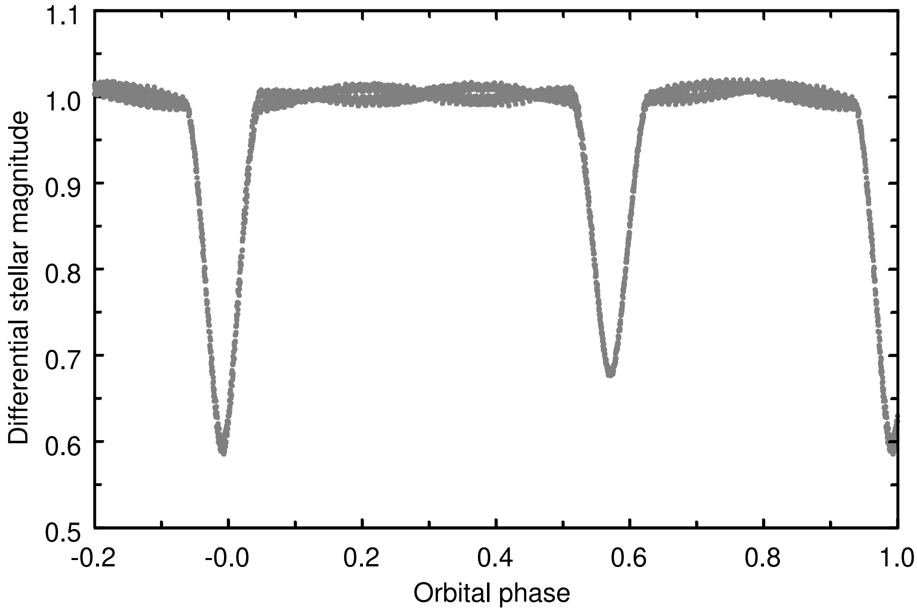

Figure 1. The combined TESS light curve of V957 Cep obtained in 2019–2020.

Table 1: Parameters of pulsations according to TESS observations

ν, d^{-1}	$P_{\rm p}$, d	$A_{\rm p}$, mag	φ	E, HJD	σ	σ_0	θ
1.505	0.664	0.0076	0.61	2458766.22	0.0043	0.0069	0.39
$\pm$0.015	$\pm$0.006	$\pm$0.003	$\pm$0.01	$\pm$0.15			

2 Analysis of TESS light curve pulsations

We analysed TESS observations using the PERDET code, based on the Fourier analysis (Breger, 1990), outside minima and obtained a frequency analysis of pulsations of the object's luminosity in the following form:

$$m = \sum_{i=1}^{N} A_i \sin(2\pi(\nu_i t + \varphi_i)) + c, \tag{1}$$

where m is the differential magnitude of the object; N, the number of pulsations; t, time; A_i is the amplitude of pulsations; ν_i, the frequency of pulsations; φ_i is the initial phase of pulsations, and c is the normalizing constant.

Figure 2 shows the spectral amplitude, its highest peak corresponds to the frequency 1.505 ± 0.001 d^{-1} and amplitude $A = 0\overset{\rm m}{.}0076$.

The reliability of the pulsations can be characterized by $\theta = (\sigma/\sigma_0)^2$, where σ_0 is the root-mean-square error of initial observations, σ is the root-mean-square error obtained after subtraction of the pulsation (Stellingwerf, 1978). The lower is this criterion, the higher is the reliability of the process. For the 1.505 ± 0.001 d^{-1} pulsation, the criterion is $\theta = (0.0043/0.0069)^2 = 0.39$, so the reliability is reasonably high. Table 1 shows parameters of the pulsation.

The spectral window and spectral amplitude are shown in Figure 3. It can be seen from this plot that maxima of these functions are at different frequencies, and they are shifted

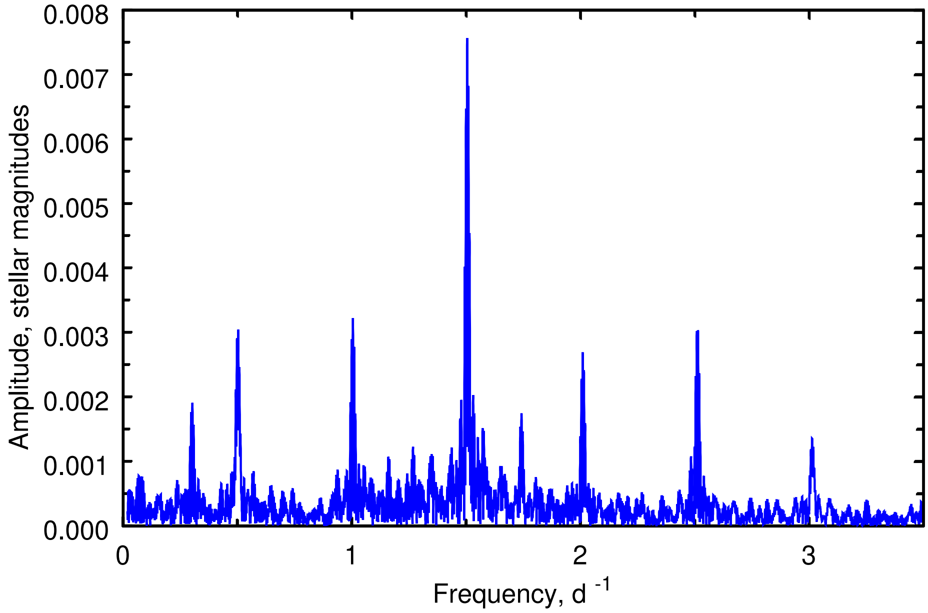

Figure 2. The spectral amplitude of periodic pulsations in the TESS light curve.

by at least a half of their widths, so the pulsations found in the light curve seem to be real. Figure 4 shows the 1.505 ± 0.001 d^{-1} pulsation during 10 days between JD 2458766 and 2458777.

3 Photometric elements

Table 2 presents orbital elements and parameters of the system found from the light curves obtained from ground-based observations in 2009 at the Tien Shan observatory and from observations by TESS. We use the following designations: r_1 and r_2 are relative radii of the components in units of the semi-major axis of the system; i is the orbital inclination; e, eccentricity of the orbit; ω, the periastron longitude of the orbit of the primary; L_1 and L_2 are luminosities of the components in units of the binary's total luminosity; L_3 is the third light in the same units; u_1 and u_2 are limb darkening coefficients; σ is the standard deviation. The model and method of minimization were described by Khaliullina & Khaliullin (1984), Kozyreva & Zakharov (2001). The parameters were calculated in a free search except the limb darkening coefficients that had been fixed at values taken from van Hamme (1993) taking into account the spectral types of components and the band of observations.

The model of spherical stars (that was used in the computer program) describes detached systems adequately. The binary under investigation, with relative radii of stars 0.2 and 0.15, is close to contact. This is a potential explanation of the difference of radii of stars that can be found between the "ground-based" and "space" observations.

4 Times of minima

Tables 3 and 4 present times of minima of V957 Cep, from ground-based observations (from the literature and from our data) as well as from space observations. Minima from our ground-based light curves and from TESS space light curves were calculated using the program by Kozyreva & Zakharov (2001) jointly with the photometric elements by

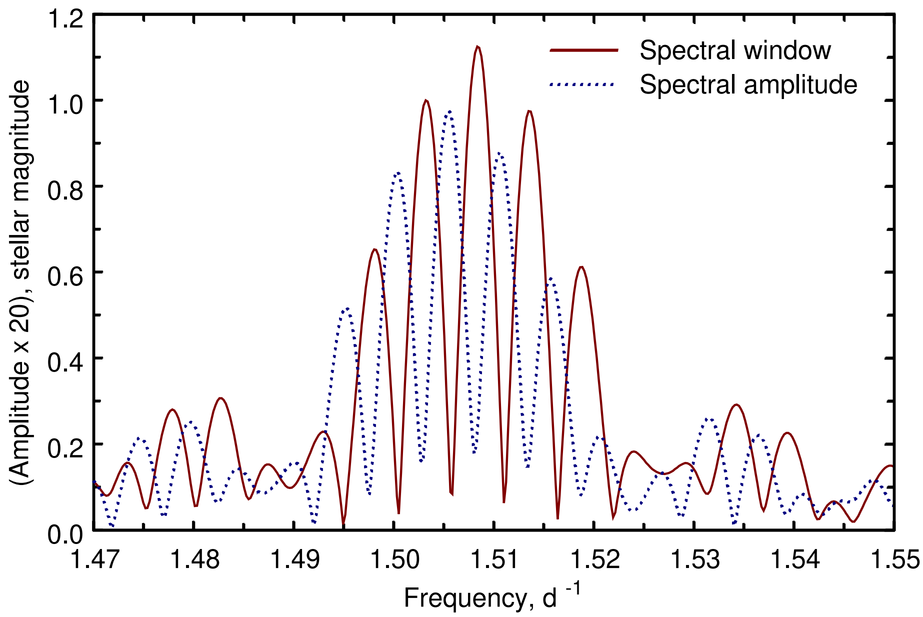

Figure 3. A part of the spectral amplitude of periodic pulsations in the TESS light curve figure around the 1.505 d^{-1} frequency and the spectral window. The amplitude is multiplied by 20.

minimization of differences between the theoretical and observed light curves. In Table 3, $(O–C)^{I}$ are residuals from light elements (2) (see Section 5) and $(O–C)^{II}$, from light elements (4). In Table 4, $(O–C)^{I}$ are residuals from light elements (3) (see Section 5) and $(O–C)^{II}$, from light elements (5).

Due to features of the TESS duty cycle, an individual light curve within a particular minimum contains insufficient number of points, therefore the time of minimum can be calculated with a high uncertainty. Therefore, we were forced to combine two light curves in neighboring minima. The time of the minimum in Tables 3 and 4 belongs to the earliest of the two neighboring minima.

5 Apsidal motion

During recent nights of observations, ω was close to 360°. In such a configuration (similarly to the case of $\omega \approx 180°$), a precise determination of the eccentricity e and the primary's periastron longitude ω was very difficult, because widths of minima were very close to each other, the phase shift rate of the secondary minimum was strongly reduced (the orbit practically was "stopped" for the observer). In this configuration, the apsidal motion rate, calculated as the linear change of ω with fixed eccentricity, has a very high uncertainty, so this method was not apt for this case.

An analysis that included all times of minima permitted a more precise determination of the apsidal motion rate for V975 Cep in such orientation of its orbit with respect to the observer. Minimizing residuals between observed and calculated times of the primary and secondary minima, O–C, we found the following parameters: E_{01}, E_{02}, P_a, ω_0, $d\omega/dt$. Ephemerides (2) and (3) were used as calculated (C) times (E is the number of cycles from the initial epoch):

$$\text{Min I} = 2458767.58602 + 1.9887331 \times E, \qquad (2)$$

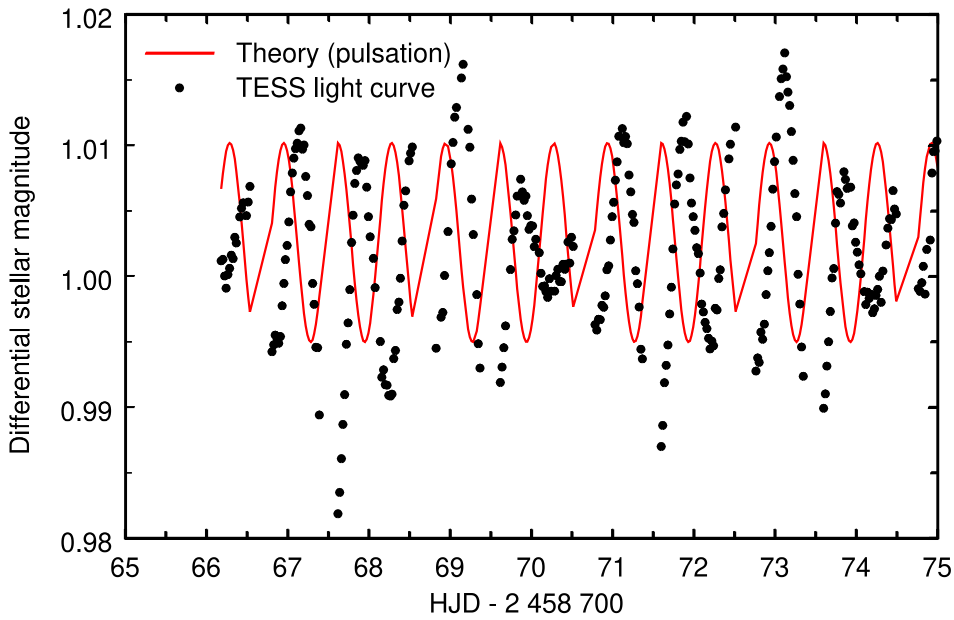

Figure 4. A light curve of V957 Cep outside minima obtained by TESS.

$$\text{Min II} = 2458766.58990 + 1.9887331 \times E. \tag{3}$$

Ephemerides that include the apsidal motion of the system are the following:

$$\text{Min I} = E_{01} + P_a \times E - c \times \cos(\omega_0 + \frac{d\omega}{dt} \times E), \tag{4}$$

$$\text{Min II} = E_{02} + P_a \times E + c \times \cos(\omega_0 + \frac{d\omega}{dt} \times E). \tag{5}$$

The results are collected in Table 5 and shown in Fig. 5. The figure presents residuals (O–C) and theoretical curves that reflect sinusoidal variations of the times of minima due to apsidal motion. For clarity, we show the point where the primary's periastron longitude was 270° (close to the year 1960) and the phase of the secondary minimum was 0.5.

6 Light-time effect

Figures 6 and 7 show $(\text{O–C})^{\text{II}}$ for minima of V957 Cep, where O is the observed time and C, the calculated time (equations (4) and (5)). The changes of these residuals (Fig. 6) for primary and secondary minima are synchronous, so the system exhibits the light-time effect and thus we may expect the presence of one or several additional bodies. Parameters of the light-time effect are presented in Table 6. Figure 7 shows the recent part of observations, it contains two curves: "P1a+P1b" describes the sum of two periodical variations "P1a" and "P1b", "P2" describes the light-time effect as a single variation.

Attempts to compute parameters of the orbit of the third body by minimization of the light-time effect, as it was done by Kozyreva & Khaliullin (1999), show a period about 1240 d $\approx$ 3.4 yr and eccentricity $e \approx 0.8$ (this solution is not shown in the figures). The duration of observations of this star from 2009 to 2021 is insufficient to reliably confirm this orbit. A lot of times of minima obtained by TESS only weakly influence

Table 2: Orbital elements of V957 Cep found using V data from ground-based observations ("ground") in 2009 and from TESS observations ("space") in 2019–2020. See text for details

Element	"Ground"	"Space"
r_1	0.199 ± 0.005	0.2131 ± 0.0005
r_2	0.151 ± 0.005	0.1545 ± 0.0005
i	$86.1^\circ \pm 0.4^\circ$	$83.6^\circ \pm 0.1^\circ$
e	0.131 ± 0.005	0.125 ± 0.005
ω_0	$336.0^\circ \pm 0.3^\circ$	$357.9^\circ \pm 1.5^\circ$
L_1	0.615 ± 0.020	0.685 ± 0.02
L_2	0.293 ± 0.020	0.298 ± 0.02
L_3	0.090 ± 0.020	0.017 ± 0.02
u_1	0.43 (fixed)	0.37 (fixed)
u_2	0.45 (fixed)	0.42 (fixed)
σ	0.0082	0.0033

the accuracy of the determination of parameters of the third body's orbit, because these minima compactly lie within a short time interval. The current set of observations makes it possible to more or less reliably estimate the period and amplitude of the light-time effect. To find these parameters, we used the PERDET code. Figure 8 shows the power spectrum of $(O–C)^{II}$. The analysis of $(O–C)^{II}$ residuals shows that the sum of two periods, $P_1 = 3090^d$ and $P_2 = 187^d.5$, satisfies the light-time effect with minimal $\theta = 0.124$ (marks "1" and "2" in Fig. 8). The contribution of the P_1 period is most important to reduce the mean-square scatter between the theoretical and observed times, $(O–C)^{II}$ ($\theta_1 = (0.00095/0.00247)^2 \approx 0.15$, see Table 6). If the process with only one period is considered, then the best $\theta = 0.149$ corresponds to the light-time effect with the period $P = 2890^d$ and amplitude $0^d.0028 \pm 0^d.0005$.

7 Conclusions

Using observations by the TESS satellite, we found pulsations of the V957 Cep brightness with the period $0^d.664$ and amplitude $0^m.0076$. We also derived new photometric elements of the system based on our light curve (2009–2019) and on the light curve by TESS (2019–2020), and re-estimated the apsidal motion rate $d\omega/dt = 1.47 \pm 0.15^\circ$ yr^{-1}.

Analyzing all times of minima, we found evidence for the presence of light-time effect in the system. It can be caused by the gravitational influence of an additional body (or even additional bodies), gravitationally bound with the binary. Our calculations show a very high eccentricity of the third body (0.8), but this result needs confirmation with future observations, because a longer set of observations is required. Currently we can only indicate most probable values for the amplitude of the light-time effect (4 minutes) and for its period (8 years). It is important to precisely find spectral types of both components of the binary and to increase the number of observed times of minima in order to derive orbital parameters of the third body (probably also using the radial velocity curve that has not been obtained yet).

Table 3: Times of primary minima (Min I) of V957 Cep

HJD–2400000	(O–C)^{I}	(O–C)^{II}	Reference
51504.6660	0.0016	0.0020	Otero et al., 2006
54710.4925	–0.0021	–0.0004	Brat et al., 2008
55076.4176	–0.0032	–0.0010	Brat et al., 2008
55122.1580	–0.0036	0.0007	Kozyreva & Kusakin, 2014
55806.2827	–0.0021	–0.0017	Kozyreva & Kusakin, 2014
56536.1511	0.0021	–0.0003	Kozyreva & Kusakin, 2014
57558.3524	–0.0045	–0.0023	ground
58123.1541	–0.0027	0.0016	ground
58125.1421	–0.0034	0.0009	ground
59141.3869	–0.0009	–0.0010	ground
58767.5053	–0.0008	0.0006	TESS
58771.4828	–0.0007	0.0005	TESS
58775.4601	–0.0009	0.0002	TESS
58781.4262	–0.0010	–0.0001	TESS
58785.4039	–0.0008	–0.0000	TESS
58793.3587	–0.0009	–0.0002	TESS
58797.3359	–0.0011	–0.0005	TESS
58805.2911	–0.0009	–0.0002	TESS
58809.2685	–0.0009	–0.0002	TESS
58813.2458	–0.0012	–0.0003	TESS
58958.4238	–0.0007	–0.0001	TESS
58962.4014	–0.0005	–0.0001	TESS
58966.3789	–0.0005	–0.0002	TESS
58970.3562	–0.0006	–0.0004	TESS
58974.3339	–0.0004	–0.0003	TESS
58978.3109	–0.0009	–0.0009	TESS
58986.2665	–0.0002	–0.0003	TESS
58990.2436	–0.0005	–0.0005	TESS
58994.2211	–0.0005	–0.0005	TESS
59000.1874	–0.0004	–0.0003	TESS
59006.1536	–0.0004	–0.0001	TESS

Table 4: Times of secondary minima (Min II) of V957 Cep

HJD–2400000	$(O-C)^{I}$	$(O-C)^{II}$	Reference
54741.4657	–0.0044	–0.0012	Brat et al., 2008
55089.4948	–0.0042	–0.0013	Brat et al., 2008
55093.4725	–0.0039	–0.0008	Brat et al., 2008
55113.3595	–0.0043	–0.0002	ground
55121.3147	–0.0040	0.0003	Kozyreva & Kusakin, 2014
55819.3656	0.0005	0.0013	Kozyreva & Kusakin, 2014
56533.3253	0.0042	0.0018	Kozyreva & Kusakin, 2014
57557.5182	–0.0014	0.0008	ground
58649.3333	–0.0013	0.0011	ground
58842.2403	–0.0014	0.0007	ground
58766.6693	–0.0005	0.0009	TESS
58770.6465	–0.0008	0.0005	TESS
58780.5907	–0.0003	0.0006	TESS
58784.5683	–0.0002	0.0006	TESS
58792.5228	–0.0006	0.0001	TESS
58796.5004	–0.0004	0.0002	TESS
58804.4556	–0.0002	0.0006	TESS
58808.4330	–0.0003	0.0005	TESS
58812.4101	–0.0006	0.0003	TESS
58957.5880	–0.0002	0.0003	TESS
58961.5652	–0.0005	–0.0001	TESS
58965.5426	–0.0006	–0.0004	TESS
58969.5202	–0.0005	–0.0003	TESS
58973.4978	–0.0004	–0.0003	TESS
58977.4754	–0.0002	–0.0002	TESS
58985.4302	–0.0004	–0.0004	TESS
58989.4073	–0.0007	–0.0007	TESS
58993.3852	–0.0003	–0.0003	TESS
58999.3513	–0.0004	–0.0003	TESS
59005.3174	–0.0005	–0.0002	TESS

Table 5: Parameters of the apsidal motion in ephemerides (4) and (5)

E_{01}	E_{02}	P_a	c	ω	$d\omega/dt$	$d\omega/dt$
HJD	HJD	d	d	°	$1/P_{orb}$	°/year
2458767.5860	2458766.5899	1.9887331	0.08	358.0	0.0081	1.47
±0.0004	±0.0004	±0.0000003	±0.03	±0.3	±0.00001°	±0.15

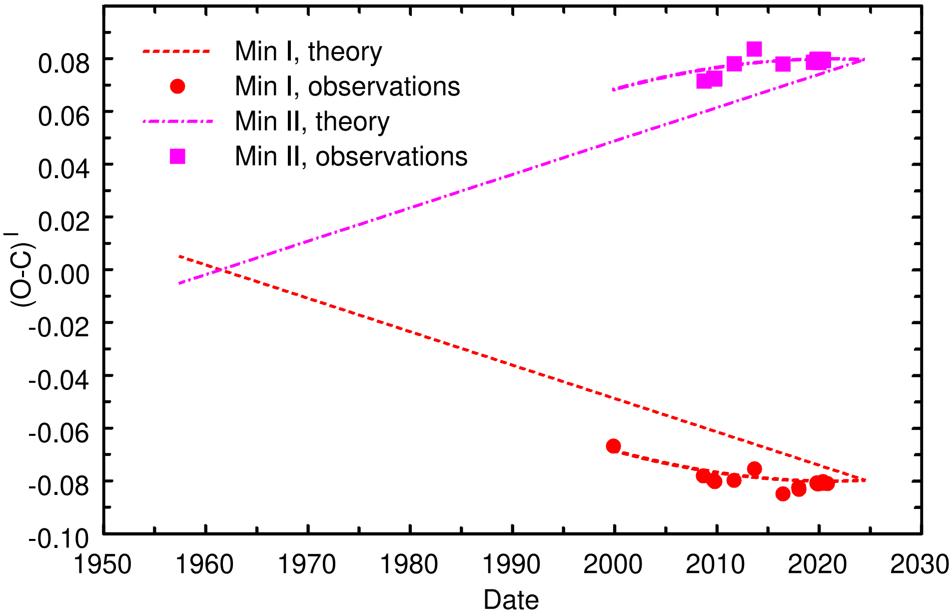

Figure 5. (O–C)$^{\mathrm{I}}$ for minima of V957 Cep, where O is the observed time and C is the calculated time (equations (2) and (3)).

Table 6: Parameters of the light-time effect

Parameter	P1a	P1b	P2	P3
Period, d	3090 ± 50	187.5 ± 4	2890 ± 50	1240 ± 40
Amplitude, d	0.0022 ± 0.0005	0.0016 ± 0.0008	0.0028 ± 0.0005	0.0060 ± 0.005
Initial phase	0.87 ± 0.01	0.81 ± 0.01	0.665 ± 0.005	
Initial epoch, HJD		2455933 ± 5		2455553 ± 40
e	0	0	0	$0.8^{+0.01}_{-0.2}$
σ	0.00087 ("P1a+P1b")		0.000955	0.00130
	$\sigma_0 = 0.00247$ (all models)			
θ	0.124		0.149	0.28

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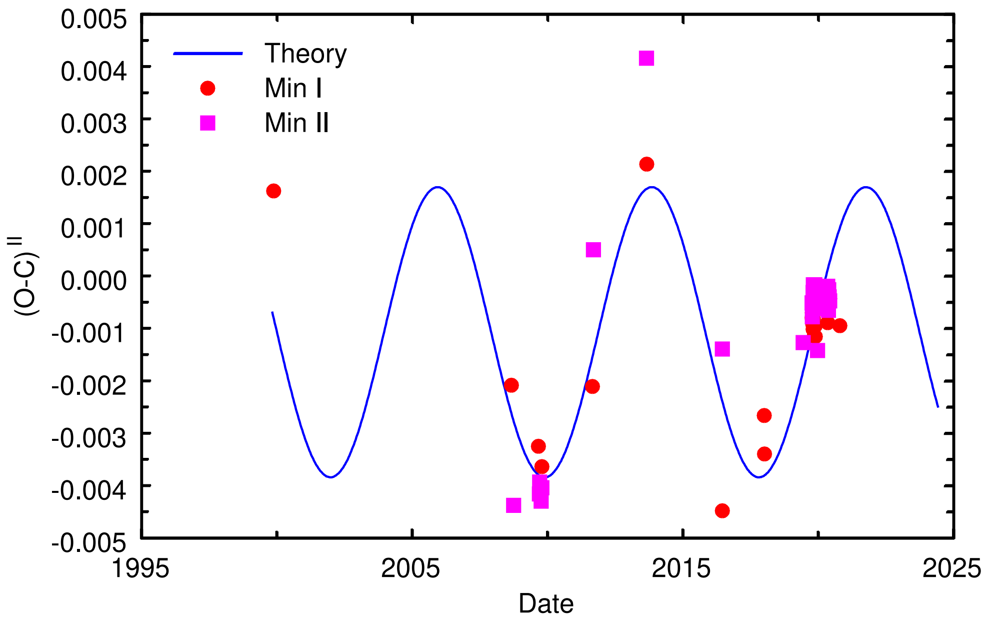

Figure 6. (O–C)^{II} for minima of V957 Cep, where O is the observed time and C, calculated time (equations (4) and (5)). "Theory" is the light-time effect, see Table 6 ("P2").

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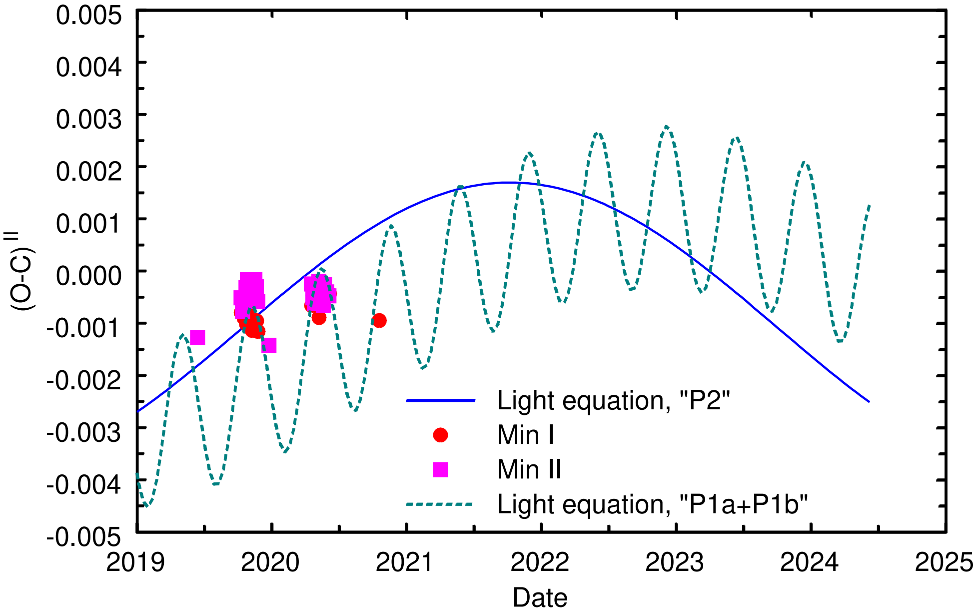

Figure 7. Same as in Fig. 6, shorter time interval, see Table 6 ("P1a+P1b", "P2").

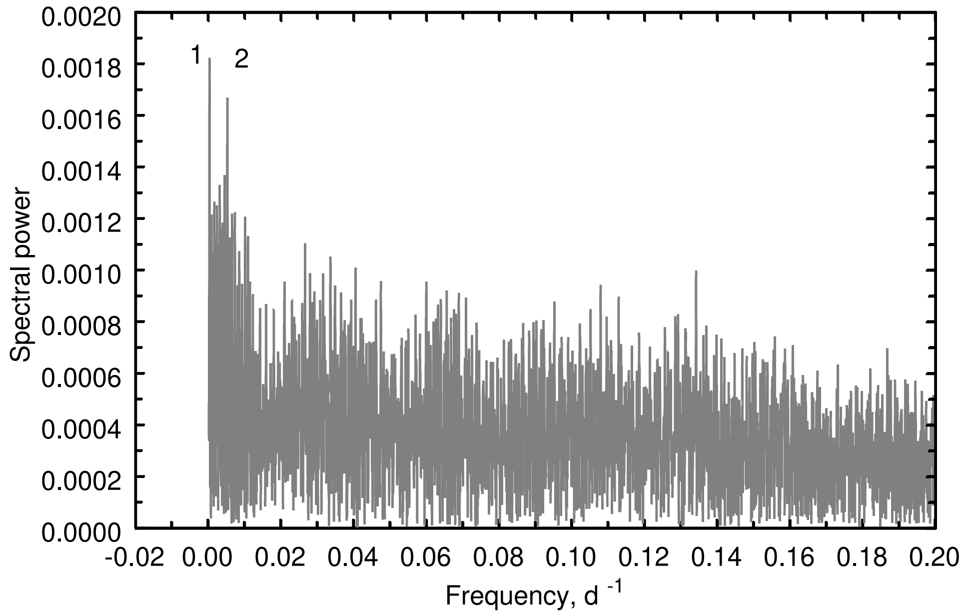

Figure 8. Spectral power of variations of the $(O\text{–}C)^{II}$ residuals (O is the observed time and C, that calculated using equations (4) and (5)). "1" and "2" are variations respectively with the periods $P_1 = 3090^d$ and $P_2 = 187\overset{d}{.}5$.