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V961 Cep: A New Eclipsing Variable with a δ Sct Component

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New observations of V961 Cep, an eclipsing star with elliptical orbit ($P = 7\overset{\mathrm{d}}{.}04$, $V = 10\overset{\mathrm{m}}{.}14$, $e = 0.03$, F0 V+F5 V) revealed that its primary component was a δ Sct variable with the period $P = 0\overset{\mathrm{d}}{.}0482603$ and a pulsation amplitude of $0\overset{\mathrm{m}}{.}009$ in the V band.

1 Introduction

The star V961 Cep was first studied in detail in Volkov et al. (2010). The main characteristics of the component stars were determined, and it was found that the primary component was located at the boundary of the instability strip for δ Sct variables in the Hertzsprung–Russell(HR) diagram. However, no intrinsic variability was detected at that time.

2 Observations and analysis

Our observations were continued with the Zeiss-1000 and Zeiss-600 telescopes of Simeiz INASAN observatory using $UBVRIRcIc$ photometers with CCD VersArray 512UV and FLI PL09000 detectors.

The main goal of our observational program is to study the internal structure of stars by measuring the rate of apsidal motion in elliptical systems (Volkov and Volkova, 2009). Thus, the observations were mainly carried out in minima. There was concern because of the shape of several minima being distorted and the accuracy of timing being much worse than in other our studies (Bagaev et al., 2018). For a long time, we could not figure out the reason. There can be several explanations for poor accuracy: intrinsic variability of one of the comparison stars; intrinsic variability of V961 Cep itself; instrumental reasons related to the fact that nearby comparison stars are too bright for observations with 0.6–1-meter apertures and CCDs, see Table 1 in Volkov et al. (2010). The problem was resolved when we had monitored the star in the secondary minimum and in quadrature at the INASAN Zvenigorod observatory in autumn, 2021 with a relatively small automatic telescope, Celestron RASA 11″, equipped with the ZWO ASI 6200 MM PRO camera. We used comparison stars not so bright as in our previous study: GSC 4479 446 was the primary standard and GSC 4479 771, the check star. The results of this monitoring in the quadrature in V band are presented in Figs. 1, 2.

The accuracy of measurements was $\pm 0\overset{\mathrm{m}}{.}004$ on both nights. We clearly see a δ Sct-like oscillation with a period a little longer than 1 hour. At first we were not sure that

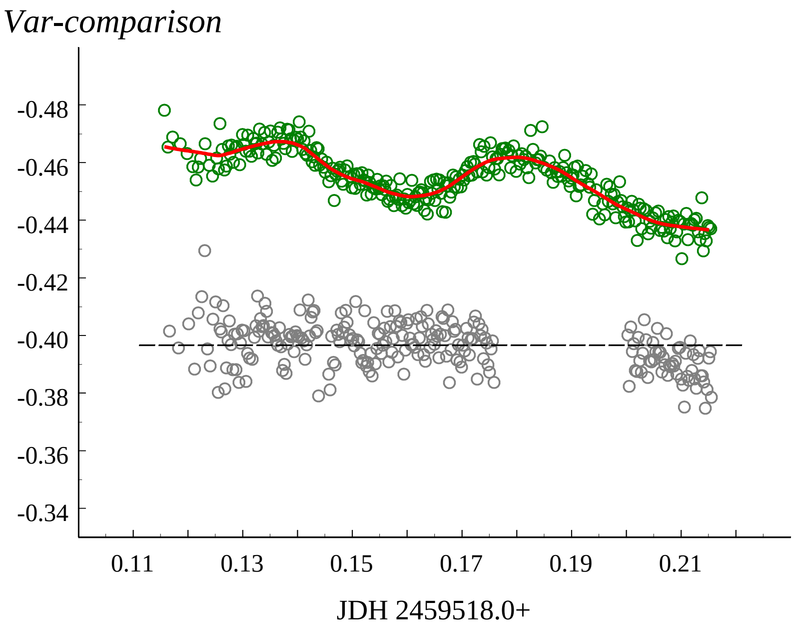

Figure 1. Monitoring of V961 Cep in quadrature. To control the stability of the atmosphere and equipment, the same graph for the check star is shown below.

the accuracy of our previous measurements was sufficient to search for the period of the oscillations over the entire observational set. In addition, we found that there was a third body in the system orbiting the eclipsing star with a period of 18 years – the LIght Time Effect (LITE) is clearly seen in our new minima timings. We discussed such a possibility in our first paper because the addition of a third light slightly improved the accuracy of the Light Curve (LC) solution. However, at that time, we did not have at our disposal a sufficiently long observational series as we have now. The study of the LITE has not yet been completed and will not be discussed here. We would just like to say that, having corrected our observations for the LITE, we made an attempt to clarify the value of the pulsation period and to check its stability. Since most of our observations were made in minima, we removed eclipses from the LC with the help of our program that implements the algorithm described in Khaliullin and Khaliullina (1984). Observations with increased scatter were excluded from the analysis. Finally, we obtained an array of homogeneous V observations containing 684 points covering 13 years. We find that pulsations do not fully disappear in the primary minimum: partial eclipses occur in this minimum. The amplitude of pulsations changes a little, as it is clearly seen in Figs. 1, 2.

3 Implementation of our program of period determination

We use our program of period determination that implements an algorithm for enumerating trial period values in a given interval with a fixed step using the sliding average. For each value of the period in given interval, the phases of each observation point are found. The initial epoch is set arbitrarily. The array is then sorted by phases using the quick sort algorithm (Knuth, 1973). After such a preparation of the array, we calculate deviations

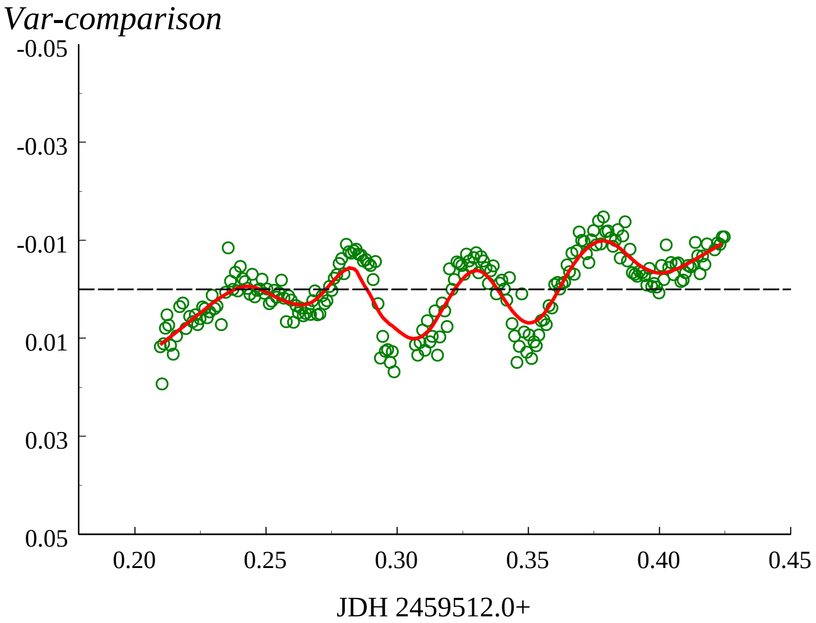

Figure 2. Observations of V961 Cep in Min II. The dashed line is the calculated eclipse model.

from the mean for each point. To calculate the mean value for each point, we take several points before and after the point of interest. Then we find the expected value of the point of interest by linear interpolation between the two mean points, before and after the point of interest. The difference between calculated and observed values is interpreted as the observational error. After finishing this procedure, the mean error for all points in the observational array is calculated and recorded in an archive file along with the trial period value. Then, the trial period is increased by a fixed step, and the procedure is repeated. After finishing the enumerating process, the resulting table is presented as a graph: error – trial period. The extreme values on this plot are interpreted as possible periods of brightness variation. Normally, we have a set of day and year aliases. In the case of V961 Per, one can expect aliases with the orbital period of the star because we mainly observed in minima.

If a period exists, the method simultaneously gives the mean error of the observations. When the period is unknown, we use a wide interval of trial periods searching with relatively rough steps. After identification of the area of interest, we use a more detailed grid. The result for V961 Cep is presented in Fig. 3 (preliminary search) and Fig. 4 (detailed investigation). The mean error of observations is $0\overset{m}{.}0065$. There are many artificial 7-day aliases to the orbital period of variable.

We carefully reviewed the convolutions of observations with periods corresponding to the maxima in Figs. 3, 4 and chose the following ephemeris for the times of maximum brightness:

$$\mathrm{HJD\ Max} = 2{,}459{,}518.1195(5) + 0\overset{d}{.}0482603(9) \cdot E.$$

This ephemeris has no contradiction with individual nights of observations. The LC phased with this period is shown in Fig. 5. In future calculations of brightness maxima,

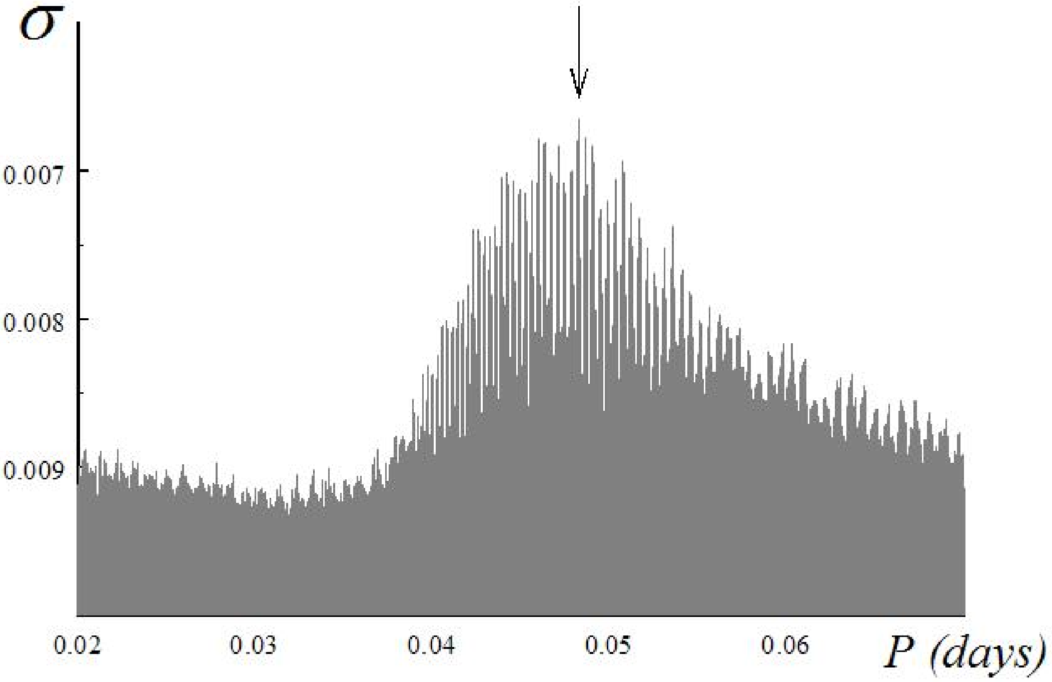

Figure 3. The periodogram of the preliminary period search. The arrow indicated the accepted hump of possible periods.

one should keep in mind that the amplitude of the LITE is up to 10 minutes, so the times of maximum can be shifted within these limits. The full pulsation amplitude is only $0\overset{m}{.}018$ V, see Fig. 5. The real amplitude is almost twice larger, because the brightness of the primary component is close to 60% of the brightness of the triple system.

The pulsation period found by us has been stable for 13 years. The star is similar to V577 Oph (F0 V+F1 V) whose primary component is a δ Scuti pulsator and the system is also triple (Volkov, 1990; Volkov and Volkova, 2010; Volkov, 2015; Jeffery et al., 2017). The HR diagram for eclipsing stars with pulsators presented in Fig. 6 was taken from Soydugan et al.(2006). The positions of the stars V961 Cep and V577 Oph are shown as red circles. The primary components of both stars are at the red border of the instability strip. However, the age and sizes of V577 Oph are larger than those for V961 Cep, and its period ($P = 0\overset{d}{.}06949$) is longer. The temperatures of the stars were derived according to the calibration from Flower (1996), which gives higher temperatures than the Popper (1980) calibration used in our previous work. Higher temperatures put V577 Oph definitely inside the instability strip, with V961 Cep exactly at its red boundary, so Flower's calibrations are better suited for accurate analysis.

Refinement of the temperature scale also reveals that the position of V961 Cep in the HR diagram almost completely coincides with the position of the main component of R CMa (Sp=F0 V). It was very interesting to find that the periods and amplitudes of pulsations of both stars were very close; for R CMa, $P_{\mathrm{p}uls} = 0\overset{d}{.}047146$ and amplitude $\approx 0\overset{m}{.}005$ (Mkrtichian and Gamarova, 2000). This may indicate that the basic physical characteristics of the two stars are also identical. Besides exhibiting pulsations, R CMa is also a triple system (Radhakrishnan et al., 1984).

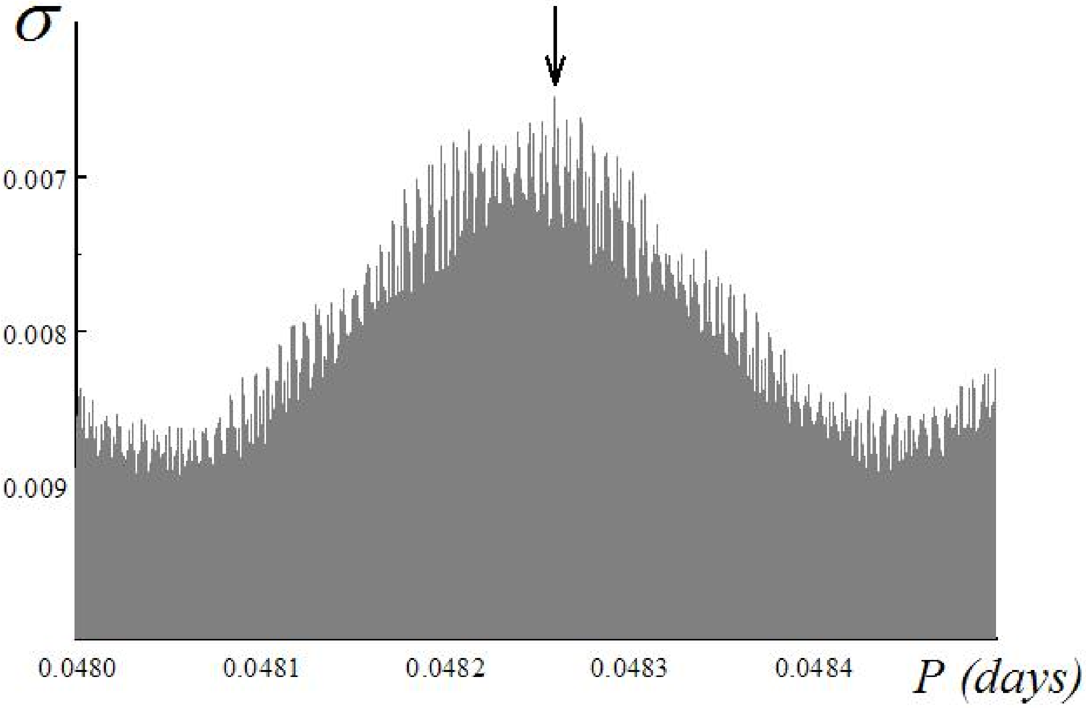

Figure 4. The detailed periodogram in the accepted hump area. The arrow indicates the best period value derived by inspection of the best promising periods with respect to contradictions for individual nights.

4 Conclusions

We have established that V961 Cep belongs to a small class of very interesting eclipsing stars with a pulsating component. We plan to continue observations in order to correct the model of the star for the presence of the third body, not taken into account in our first study.

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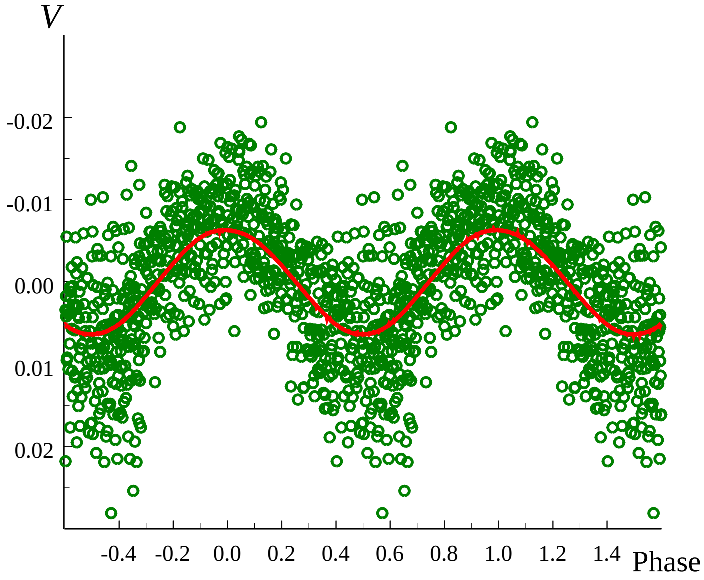

Figure 5. Observations of the star accumulated during 13 years, phased with $P = 0\overset{\rm d}{.}0482603$. The red curve is drawn by the weighted least squares method. It reproduces the sliding mean curve used by our period determination program.

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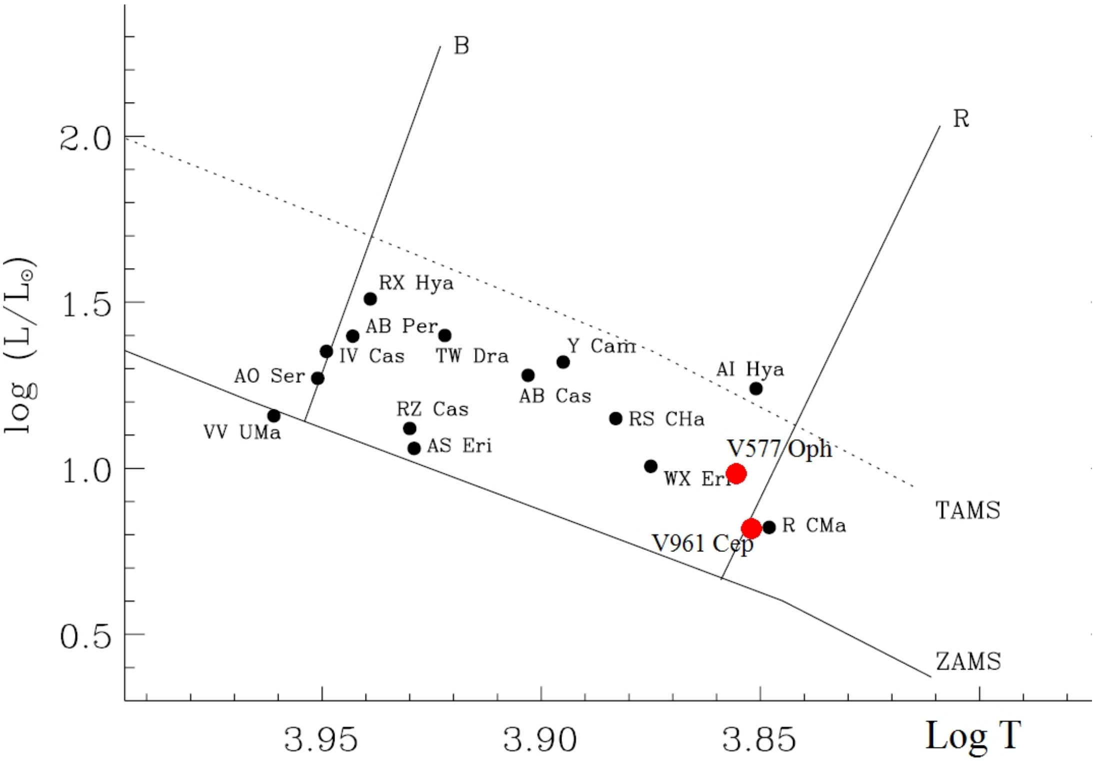

Figure 6. Positions of the δ Sct-type pulsating components of eclipsing binary systems in the HR diagram. The solid and dotted lines represent the zero-age main sequence (ZAMS) and terminal-age main sequence (TAMS), respectively. The observational blue (B) and red (R) borders of the δ Sct instability strip are shown as diagonal lines.