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A NEW EPHEMERIS AND FUNDAMENTAL PARAMETERS FOR THE ECLIPSING BINARY STAR GSC 03612-1565 = V2647 CYG

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Abstract

High precision light curves were obtained for the GSC 03612-1565 = V2647 Cyg eclipsing binary system in 2009 and in 2018. The solution for these curves allowed to estimate the limb darkening coefficients and spectral classes of components (F5V–F8V). Also a new ephemeris was computed, it is very different in comparison to a previous study by Otero et al. (2006). The circular orbit instead the elliptical was found.

The investigated star (V2647 Cyg, its $\mathrm{RA_{J2000}}$ is 21:47:03, its $\mathrm{Dec_{J2000}}$ is +50:03:17, its orbital period is $P_{orb} = 3.9035242$ days) was discovered in ASAS survey (Pojmanski, 2002). It was included in the list of fifty new eclipsing binaries with elliptical orbits found in ASAS, Hipparcos and NSVS databases by Otero et al. (2006), who also noted that primary eclipses of this star can be secondary eclipses and gave following ephemeris for V2647 Cyg:

$$\mathrm{Min\ I} = \mathrm{HJD}\,2453671.255 + 5.85527 \times E, \quad (1)$$

where E is the number of orbital cycles since the initial epoch. The secondary minimum phase was equal to 0.334, this high shift relative to the phase 0.5 indicated that the star's orbit could be an ellipse with a high eccentricity. Such stars are very interesting objects, because they possess the apsidal motion that helps to study the concentration of the matter of the star to its center and to compare the star's matter distribution with theoretical models.

Our photometric observations of V2647 Cyg were conducted using three telescopes: (1) at Tien Shan Observatory of Fesenkov Astrophysical Institute using the V filter in August 2009 (with the Ritchey–Chritien-350 telescope and the ST-402 CCD sensor), (2) at Astrokolkhoz observatory (New Mexico) in December 2009 with the ACP AAVSOnet Wright 30 telescope using V filter, and an SBIG ST-9 CCD sensor, (3) during 2018 at Tien Shan Observatory with Zeiss-1000 telescope and the Apogee U900 CCD sensor, in V and R filters.

Observations inside minima were obtained in August 2009 (Min II) and in December 2009 (Min I). These minima occurred practically according to Equation 1. Reference stars

TYC 3612-718-1 (V=10.71^m) and TYC 3612-1006-1 (V=11.24^m) were almost constant during observations (they showed a variability less than 0.005^m). The depth of Min II in V filter in 2009 was 0.725^m, and the depth of Min I was 0.475^m. So, it seemed that the primary star was the secondary and and vice versa as was noted by Otero et al. (2006).

Subsequent observations of V2647 Cyg were conducted in 2018. On 8 and 10 January both kind of minima were obtained, and the depths of these minima corresponded their names (i.e., Min I was deeper than Min II). In August 2018 we obtained Min I that was of the same value as Min I in January 2018, and it is the same as the value of Min II in 2009. The difference between minima in 2009 and 2018 can be related to the change of the orbit's inclination or to the variability of the components of the system. For the first explanation the change should be catastrophic (too rapid). Practically precise coincidence of the primary minimum's value in 2018 and the secondary minimum's value in 2009 also excludes the variability as an explanation.

V2647 Cyg also was observed by Super-WASP project (Butters et al., 2010, Paunzen et al., 2014), data were downloaded[1,2], and compiled light curves were analysed using Equation 1. These data gave three minima for this system, all minima followed each other strictly after 1/3 of the orbital period. The explanation of such effect could be the only one: Ephemeris 1 was wrong. Using a set of five minima we found an exact ephemeris. We also found that the orbit was almost a circle. So, the primary minima (according to Equation 1) in 2009 were the secondary minima and vice versa, whereas in 2018 positions of minima coincided with predictions of Equation 1. Our new ephemeris is:

$$\text{Min I} = \text{HJD}\, 2458127.1346 + 3.9035242 \times E. \tag{2}$$

To find times of minima for the system the photometric elements were computed. For Super-WASP observations it was impossible to calculate times of minima, because they did not contain minima with both branches.

For estimations of the system's parameters we used a computer code by Kozyreva & Zakharov (2001). The components assumed to be spherical and the limb darkening was linear. These assumptions can be good approximations, because the system should be well detached. A minimization algorithm was quasi-newtonian with analytically calculated derivatives of the functional (Gill & Murray, 1978). The minimizing functional includes the sum of the squares of observed minus calculated values of the stars' magnitudes in all points and simple linear limitations on the parameters. The influence of limb darkening coefficients u_1 and u_2 on the brightness of the system appears on such parts of light curves that correspond to intersections of disks of components. A reliable determination of u_1 and u_2 from light curves can be made only with very high precision observations ($\sigma_{o-c} \leq 0.005^m$), and light curves obtained during the intersection of disks should be continuous.

Two minima obtained in 2018 (Min II in January and Min I in August, see Figure 1) satisfied the described requirements. Limb darkening coefficients in V filter were: $u_1 = 0.59$, $u_2 = 0.61$. Usually such quantities correspond to stars with spectral types F5-F8 (van Hamme, 1993). Earlier it was not possible to obtain limb darkening coefficients from calculations of photometric elements, because the mean square error σ_{o-c} was higher than 0.005^m, and only in latest observations σ_{o-c} became equal to 0.004^m. It would be interesting to compare such simple estimations of the spectral type with determinations made using independent methods (until now there are no spectral observations of V2647

[1]https://exoplanetarchive.ipac.caltech.edu/docs/SuperWASPMission.html
[2]http://wasp.cerit-sc.cz/

Cyg). Obtained photometric elements can be found in Table 1. Eccentricity of the orbit was found to be close to zero in contradiction with Otero et al. (2006). The notations in Table 1 are following: r_1 and r_2 are radii of stars in units of the semi-major axis, i is the inclination angle of their orbit to the plane of the sky, e is its eccentricity, ω is the periastron longitude, L_1 and L_2 are the luminosities of the components in units of the total system's luminosity, L_3 is the third light in the same units, u_1 and u_2 are limb darkening coefficient of components, L_1/L_2 is the ratio of luminosities of both stars, I_1/I_2 is the ratio of their surface brightnesses, σ_{o-c} is the standard deviation of the light curve.

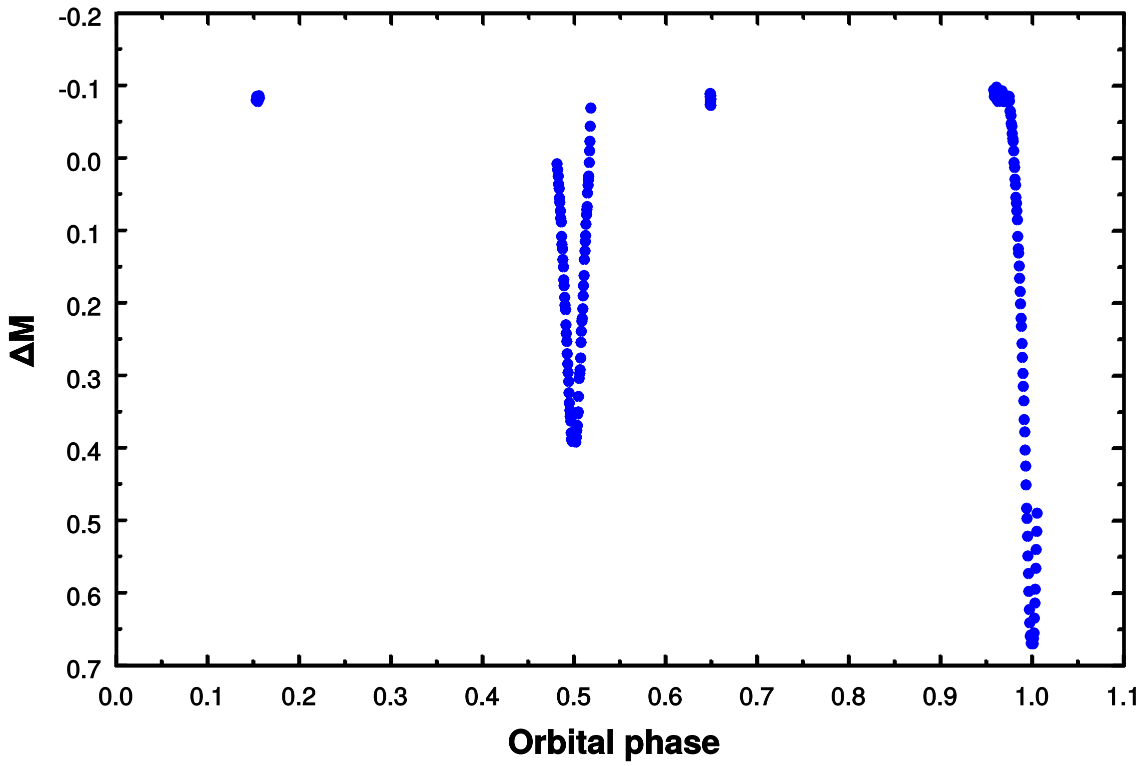

Figure 1. A sample light curve of V2647 Cyg in V filter. Horizontal axis presents the orbital phase in Ephemeris 2, vertical axis presents the difference of the stellar magnitude between V2647 Cyg and TYC 3612 1006-1.

It is possible to make some constraints on spectral classes of the components. The star's parallax is $0.00276'' \pm 0.00006''$ (Lindegren et al., 2018), it corresponds to the distance to the object $358.4^{+8.0}_{-7.7}$ parsecs (Bailer-Jones et al., 2018). It is possible to estimate absorption in V band, A_v is less than 0.1^m according to the mean absorption in V filter in the galactic plane. The visual stellar magnitude and $B-V$ colour index for V2647 are $m_V = 11.05^m$ and $B-V = 0.48^m \pm 0.07^m$ (Høg et al., 2000). Taking into account estimations of spectral types made above, the difference between apparent and absolute stellar magnitudes, and the estimation of absorption one can obtain the distance to the star to be equal to 370 ± 30 parsecs. This value is in adequate agreement with the estimation of the distance from the parallax value (and $B-V = 0.48^m$ does not contradict it). So we can claim that spectral types of both components are in the range F5V-F8V.

Non-symmetry of minima of light curves of systems with elliptical orbits, physical fluctuations of brightness, and errors of measurements lead to differences in results obtained using different methods. In our method we take a conjunction as the time of minimum, i.e., such configurations when the distance between centers of stars projected to the plane of the sky are minimal. To find times of conjunctions we used all set of minima and took additional information from other light curves (for example, a possible existence of systematic errors from light curves of reference stars) assuming several geometric parameters to be constant. Such a method allows to find times of conjunctions with higher precision than estimations of times of minima using only light curve points from an individual minimum of brightness.

To calculate times of minima for V2647 Cyg in Table 2 obtained from our observations in 2009 and 2018 we used fixed parameters from the column 3 (2018 *V*) in Table 1. Minima were found for observations in *V* and *R* filters for 2018 observations and their average values were calculated for Table 2. Also we showed times of minima published by Brat et al. (2008). In the table, (O–C) is the difference between the observed time of minima (in the first column) and the value calculated using Ephemeris 2. "Min" is the type of a minimum (primary or secondary). To find variations of the orbital period due to the influence of additional companions or physical processes the observations of the system should be continued.

The value of the V2647 Cyg orbital period in General Catalogue of Variable stars (Samus et al., 2017) should be updated: a new period is $P_{orb} = 3.9035242$ days.

Light curves obtained at Tien Shan Observatory can be found as additional tables.

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Table 1. Photometric elements of V2647 Cyg computed using observations in 2009 in V filter, and in 2018 in V and R filters. See text for notations.

Element	2009 (V)	2018 (V)	2018 (R)
r_1	0.088 ± 0.001	0.089 ± 0.01	0.089 ± 0.01
r_2	0.075 ± 0.001	0.077 ± 001	0.076 ± 0.01
i	$89.6° \pm 0.2°$	$89.9° \pm 0.1°$	$89.9° \pm 0.1°$
e	0.002 ± 0.001	0.003 ± 0.001	0.007 ± 0.003
ω	$280.3° \pm 0.5°$	$264.1° \pm 0.3°$	$268.0° \pm 0.4°$
L_1	0.644 ± 0.020	0.628 ± 0.01	0.618 ± 0.030
L_2	0.351 ± 0.020	0.353 ± 0.01	0.360 ± 0.030
L_3	0.010 ± 0.020	0.02 ± 0.020	0.02 ± 0.020
u_1	0.59 (fixed)	0.59 ± 0.4	0.49 (fixed)
u_2	0.61 (fixed)	0.61 ± 0.4	0.48 (fixed)
L_1/L_2	1.835 ± 0.015	1.837 ± 0.005	1.720 ± 0.015
I_1/I_2	1.320 ± 0.04	1.325 ± 0.10	1.260 ± 0.04
σ_{o-c}	0.0086^m	0.0040^m	0.0040^m

Table 2. Times of minima of V2647 Cyg from our observations and from the literature. See text for notations.

HJD-2400000	(O–C)	Min	Reference
53817.6437	–0.0002	II	Brat et al. (2008)
53905.4734	0.0002	I	Brat et al. (2008)
55043.3510	0.0005	I	this study
55193.6373	0.0011	II	this study
58127.1346	0.0000	I	this study
58129.0864	0.0000	II	this study
58357.4432	0.0007	I	this study