Contrib. Astron. Obs. Skalnaté Pleso **55/1**, 18 – 37, (2025)
https://doi.org/10.31577/caosp.2025.55.1.18

Light curve analysis for the two eclipsing binary stars V869 Car and V2184 Sgr

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Received: August 31, 2024; Accepted: December 9, 2024

Abstract. We present the first light curve analysis for two detached eccentric eclipsing Algol-type binaries V869 Car and V2184 Sgr, using the PHOEBE code. The stars were selected from the PZP catalogue. The light curve for V869 Car is from the OgleII project. For V2184 Sgr, we analyzed two available light curves from the ASAS and the TESS mission. We determined 8 new times of minima for V 2184 Sgr and preliminary orbital and physical parameters for both systems. The analysis shows e, ω(rad) and q_{ph} equal to 0.070(1), 2.976(52) and 0.951(8) for V869 Car, while 0.4896(5), 5.750(2) and 0.9004(70) for V2184 Sgr. The analysis shows that both stars are of late F-Spectral types in which one may expect magnetic activity or star spots due to their convective envelopes.

Key words: binaries: eclipsing – stars: eccentric – apsidal motion – V869 Car – V2184 Sgr

1. Introduction

Contact and semi-detached binaries of short orbital periods are distinguished by their circular orbits due to the large mutual tidal interaction and the mass transfer between their components. On the other hand, detached eccentric binaries are with longer orbital periods and characterized by the phenomenon of apsidal motion due to the mutual tidal interaction between their components.

Apsidal motion in detached binary systems, driven by tidal forces, rotational deformation, dynamical interaction of triples, including so-called dynamical delays (see, e.g., Rappaport et al. (2023, 2024); Borkovits et al. (2015); Borkovits & Mitnyan (2023)) and relativistic effects, involves the gradual precession of the orbit's major axis. This phenomenon is crucial for constraining the internal structure of the stars' components in these systems, offering valuable information through the internal structure constant, k_2. However, it is important to note that the apsidal motion measurements provide a weighted average mean of k_2, reflecting combined contributions rather than detailed individual internal structures. For a deeper understanding, see studies by Petrova & Orlov (2002) and Claret & Gimenez (1989). Systems with eccentric orbits exhibit unique tidal effects due to the varying gravitational forces throughout their orbits. These interactions can cause significant stellar distortions and periodic pulsations, particularly evident in heartbeat stars. These stars, named for their distinct light curve patterns that resemble a heartbeat, showcase how tidal forces can induce oscillations and variations in stellar temperatures and shapes, especially at periastron. Notable examples from the Kepler mission, such as KOI-54, have provided profound insights into these tidal interactions.

Observational data of long-period binaries using normal ground-based telescopes are relatively limited due to the difficulties facing observers to covering their full light curves. This has led to a lack of data available for binaries of this class. Fortunately, during the past three decades, great advances in instruments and many satellites and automated ground telescopes have obtained high-quality observations. Examples include the Kepler space telescope, the Optical Gravitational Lensing Experiment (OGLE), All Sky Automated Survey (ASAS), Super-WASP survey, and the Transiting Exoplanet Survey Satellite (TESS) (Ricker et al., 2015). These large-scale photometric surveys have reported tens of thousands of new eclipsing binaries in our Galaxy and in other nearby galaxies (Kim et al., 2018). Hence, analysis of these data is necessary and required. Consequently, several authors have compiled catalogues for detached eclipsing binary stars that show apsidal line rotation. Examples of such catalogues include Petrova & Orlov (1999), Hegedüs et al. (2005), Bulut & Demircan (2007), Prša et al. (2011), Slawson et al. (2011), Kirk et al. (2016) and Kim et al. (2018). For a preferred summary of most of these catalogues, see Kjurkchieva et al. (2017).

Several researchers have investigated individual eccentric binaries, e.g., Frandsen et al. (2013), Gaulme et al. (2013, 2014, 2016), Borkovits et al. (2014), Maceroni et al. (2014), and Rawls et al. (2016). Kjurkchieva & Vasileva (2015a,b) modeled several systems from the Kepler catalogue of eccentric binaries and obtained their orbital and stellar parameters using the PHOEBE code. In the present work, we aim to follow their procedure in analyzing the light curves of two long-period eccentric eclipsing binaries (EEB) that were observed from different sources such as OGLE, ASAS, and TESS.

In the next section, we provide information and a brief description of the available data of the two systems. Section 3 deals with the analysis of light curves using the PHOEBE code, while Section 4 deals with the results and discussion.

2. Source of data

From the Peremennye Zvezdy Prilozhenie catalogue (volume 12 and volume 11), we selected two detached systems, OGLEII CAR-SC1 46493 (= V869 Car) and ASAS 194617-3724 (= V2184 Sgr = TIC 299888115), as their light curves exhibit a secondary minimum deviation from the phase value 0.5 (Fig. 4 &

Table 1. Stars magnitudes and effective temperatures from different sources.

Name	G	J	H	K	B	V	$T_{eff.}$
V869 Car	-	14.46[1]	13.96[1]	13.63[1]	-	-	6264[4]
V2184 Sgr	12.5688[2]	11.547[2]	11.318[3]	11.240[3]	13.29[1]	12.70[1]	6183[4]

[1] Gaia Collaboration (2018), yCat. 1345.
[2] Cutri et al. (2003), yCat. 2246.
[3] Høg et al. (2000).
[4] Bai et al. (2019) .

Fig. 5). Also, we included the recent light curve observed for V2184 Sgr via TESS in June/July 2019 (Fig. 6). The magnitudes in different bands for both systems and the effective temperature $T_{1eff.}$ were collected from various sources and are listed in Table 1.

2.1. V869 Car

Huemmerich & Bernhard (2012) classified the star OGLEII CAR-SC1 46493 ($\alpha_{2000} = 11^h05^m\ 59^s.24$, $\delta_{2000} = -61°50^{'}58^{''}.9$) as an Algol eccentric eclipsing binary with a secondary eclipse at 0.45 phase. They recorded the line elements,

$$HJD(Min.I) = 2450551^d.628 + 2^d.23281\ E. \quad (1)$$

The star was then named V869 Carina, by Kazarovets et al. (2015), in the GCVS.

2.2. V2184 Sgr

The variable nature of V2184 Sgr (TIC 299888115) ($\alpha_{2000} = 19^h46^m17^s.49$, $\delta_{2000} = -37°24^{'}52^{''}.7$) was discovered by Hoffmeister (1963). It was included in the GCVS as an EA-type star without light elements. Later, Kreiner (2004) introduced the light elements:

$$HJDMinI = 24\,52505^d.1325 + 16^d.495833\ E, \quad (2)$$

$$HJDMinII = 24\,52509^d.0615 + 16^d.494994\ E. \quad (3)$$

Other light elements were given by Paschke & Brát (2006):

$$HJD(MinI) = 24\,53214^d.456 + 16^d.496\ E. \quad (4)$$

$$HJD(MinII) = 24\,53630^d.645 + 16^d.496\ E. \quad (5)$$

Kim et al. (2018) presented the light elements,

$$HJD(MinI) = 24\,53212^d.280 + 16^d.49541\ E. \quad (6)$$

While the international Variable Star index (VSX) gave the light elements,

$$HJD(MinI) = 24\,53614^d.205 + 16^d.496\ E. \tag{7}$$

Seven times of minima (Table 2) were taken from the online O-C gateway website (Paschke & Brát, 2006). Besides, we deduced 8 new minima times from the light curves of the TESS mission (Ricker et al., 2022) by using the AVE program that uses Barbera (1996) method. The O-C residuals are calculated using equation (6) of Kim et al. (2018), and plotted in Fig.1.

Table 2. Time of minima for V2184 Sgr.

HJD (+2400000)	O-C (day)	Type	Method	Ref.
53214.4565	2.4565	P	pe V	[1]
53713.2249	-1.8851	S	pe V	[1]
53940.2470	2.4490	P	pe V	[1]
53944.1188	-1.9269	S	pe V	[1]
54055.7606	2.4947	p	pe V	[1]
54142.0650	-1.9257	S	pe V	[1]
54897.0283	2.4965	P	pe V	[1]
58658.00532±0.00014	2.5200	P	CCD (I)	[2]
58661.82509±0.00011	-1.9079	S	CCD (I)	[2]
58674.50037±0.00027	2.5197	P	CCD (I)	[2]
58678.32066±0.00028	-1.9078	S	CCD (I)	[2]
59037.40158±0.40158	2.5218	P	CCD (I)	[2]
59041.22167±0.00008	-1.9058	S	CCD (I)	[2]
59053.89716±0.00009	2.5220	P	CCD (I)	[2]
59057.71695±0.00015	-1.9059	S	CCD (I)	[2]

[1] Paschke & Brát (2006).
[2] present work obtained from TESS LCs.

Recently, in 2019 and 2020, the Transiting Exoplanet Survey Satellite (TESS) provided 4 new light curves for V2184 Sgr. Due to the high accuracy of the data we aimed to analyze the first LC observed during June-July 2019 too, and compare results obtained from both ASAS and TESS observations.

3. Light curve analysis

The morphology of the light curves of both systems shows that the secondary eclipse has shifted from phase 0.5 and exhibits constant brightness outside the eclipses. Therefore, to proceed with the analysis of the light curves using the PHOEBE code (Prša & Zwitter, 2005) we chose the detached mode. In analyzing

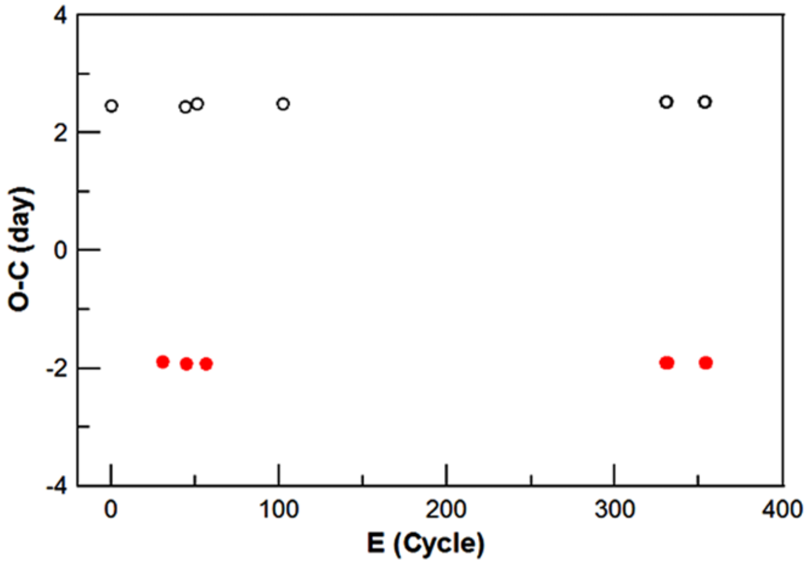

Figure 1. The O-C diagram of V 2184 Sgr; open circles stand for primary minima, while dots for secondaries.

the light curve we kept the primary component effective temperature, T_1, as a constant and run the program to fit T_2 (Zasche, 2016). We used $T_{1\ eff.} = 6264\ K$ for V869 Car and 6183 K for V2184 Sgr, both values were taken from the Gaia catalogue (Bai et al., 2019). Bolometric albedo and gravity-darkening coefficients were also used as constant input parameters. After Lucy (1967) and Ruciński (1973), one can obtain the gravity-darkening coefficient. The effective temperature, $T_{1\ eff.}$, for both systems is below 7200 K, thus, when considering convective envelope components, the gravity-darkening coefficient is assumed to be $g_1 = g_2 = 0.32$ and the bolometric albedo $A_1 = A_2 = 0.5$ (Zasche, 2016). To proceed to the solution of the light curve for such binaries without wasting time, we have to calculate roughly the values of orbital eccentricity, $e_\circ$, and the longitude of periastron, $\omega_\circ$. This can be done by solving the following two equations which are the approximate equations (9.25) and (9.37) given by Kopal (1978),

$$e_o \cos \omega_o = \frac{1}{2} \cdot \pi[(\phi_2 - \phi_1) - 0.5], \tag{8}$$

$$e_o \sin \omega_o = (W_2 - W_1)/(W_2 + W_1), \tag{9}$$

where $e_\circ$ and $\omega_\circ$ are the orbital eccentricity and longitude of periastron; W_1 and W_2 are the duration widths of the primary and secondary minima (in phase

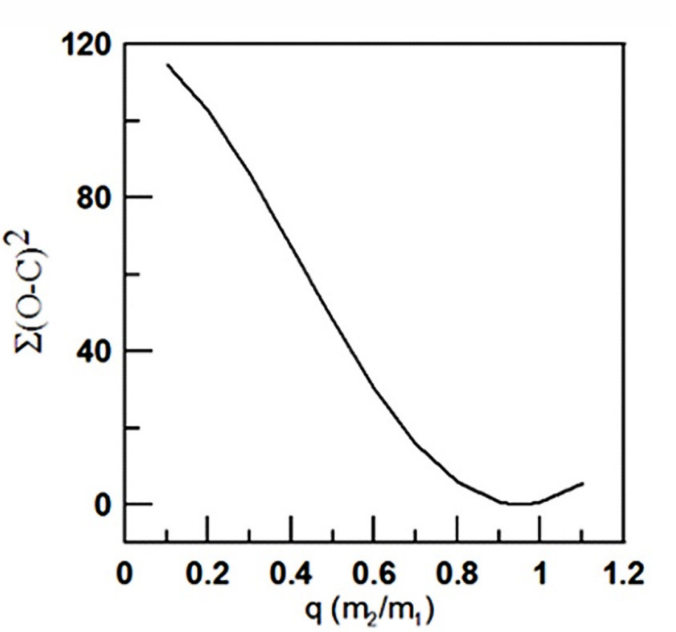

Figure 2. The $q_{ph} - \sum(O-C)^2$ relation for V869 Car.

units); ϕ_2 is the phase of the secondary minimum, while $\phi_1 = 0$ (see Table 3). One has to note that equation (9) is valid for orbits close to edge-on (inclination close to 90°). The inclination of long-period eclipsing binaries is close to 90° because the eclipse would not occur for low inclination angles. One can easily estimate the minimum inclination angle i for eclipses to occur as cos $i < r_1 + r_2$, where r_1 and r_2 are the fractional radii of the components ($r_{1,2} = R_{1,2}/a$), noting that their values are very small in detached long period binaries (Table 4). We have obtained $e_\circ = 0.0732$ and $\omega_\circ = 2.829$ (rad.) for V869 Car. Also for V2184 Sgr$_{ASAS}$, we determined $e_\circ = 0.4512$ and $\omega_\circ = 5.910$ (rad) and for V2184 Sgr$_{TESS}$, we determined $e_\circ = 0.4720$ and $\omega_\circ = 5.823$ (rad). Both $e_\circ$ and $\omega_\circ$ are used as input raw parameters for PHOEBE.

In the absence of spectroscopic observations, the mass ratio q $(= m_2/m_1)$ can be estimated from photometric data by following a q-search procedure (see, e.g., Djurašević et al. (2016), Awadalla et al. (2016), El-Sadek et al. (2019) and Hanna et al. (2024)). However, at the beginning of the analysis, we kept the mass ratio value at one. This approach is justified because both binaries are well-detached and the elliptical differences outside of their eclipse are nearly negligible (Zasche et al., 2018). Wyithe & Wilson (2002) indicated that in the

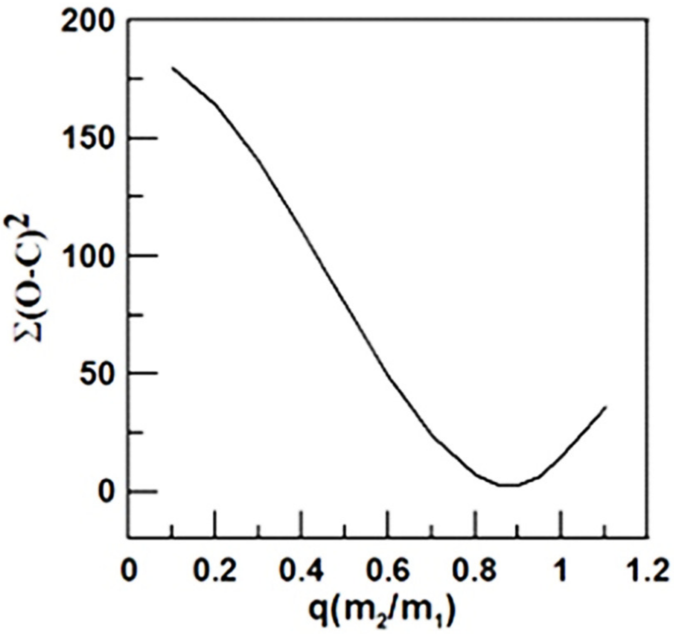

Figure 3. The $q_{ph} - \sum(O-C)^2$ relation for V2184 Sgr.

case of a detached binary, the effect of the mass ratio, generally, during the analysis of the LC can be effective if the system has a very low mass ratio or if one of the components is too advanced (the case in which the radius R increases to half the total separation, a). The preliminary tests show that no component of our two binaries has its fractional radius $r_i (= R_i/a)$ larger than 0.2, see Graczyk (2003). Hence, we started the program with $q = 1$ and after arriving at the best fit solution, we ran the program including fitting q.

We validated our final estimate of q by the well-known q-search procedure by constructing the relationship between the sum of squared weight deviation $(O-C)^2$ and q (Fig. 2 & 3). This method requires creating a series of simplified models with different values of the mass ratio q, chosen to cover a reasonable range. In this study, the search is carried out from $q = 0.1$ to 1.1. We determined the photometric mass ratio, q_{ph}, to be 0.951(8) for V869 Car, 0.885(13) for V2184 Sgr_{ASAS} and 0.9004(70) for V2184 Sgr_{TESS}. For the analysis, we followed the same implementation of Zasche (2016). We considered the effective temperature of the primary component, $T_{1\ eff.}$, and the mass ratio, $q_{ph} = 1$, as constant parameters. We first started by adjusting the inclination, i, with the

Table 3. The measured parameters from the light curves. The eccentricity (e_o) and periastron angle (ω_o) are calculated to be the initial input orbital parameters to PHOEBE.

	W_1	W_2	ϕ_2	e_o	ω_o (Rad.)
V869 Car_{OGLE}	0.1250	0.1210	0.4560	0.0732	2.829
V2184 Sgr_{ASAS}	0.0310	0.0223	0.7677	0.4512	5.910
V2184 Sgr_{TESS}	0.0328	0.0214	0.7689	0.4720	5.823

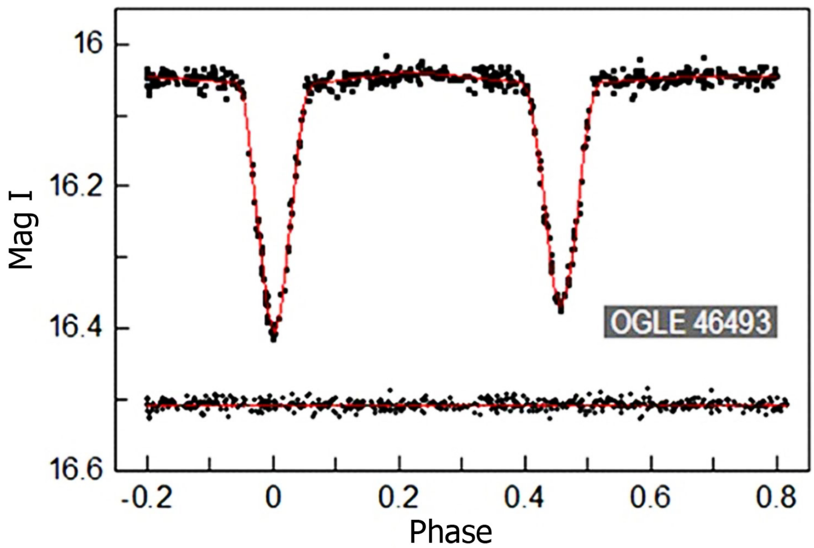

Figure 4. Top: The V869 Car light curve (dots) and its fit in the red solid line; bottom: corresponding residuals (moved vertically to save space).

primary luminosity. We then included the surface potentials of the primary and secondary components (Ω_1 & Ω_2) in the process of the fitting, in an effort to come up with a better approach. We then included the eccentricity, periastron longitude and the phase shift as variable values in the analysis. We followed the fitting step by step until the solution converged giving an acceptable good fit. Moreover, we include the mass ratio in the fitting process and continue till we reach the best fit with the lowest cost function value. The final solution set parameters along with standard errors are listed in Table 4, while the synthetic light curves extracted with these parameters are plotted as red solid lines in Fig. 4, Fig. 5 and Fig. 6 along with residuals at the bottom of each figure.

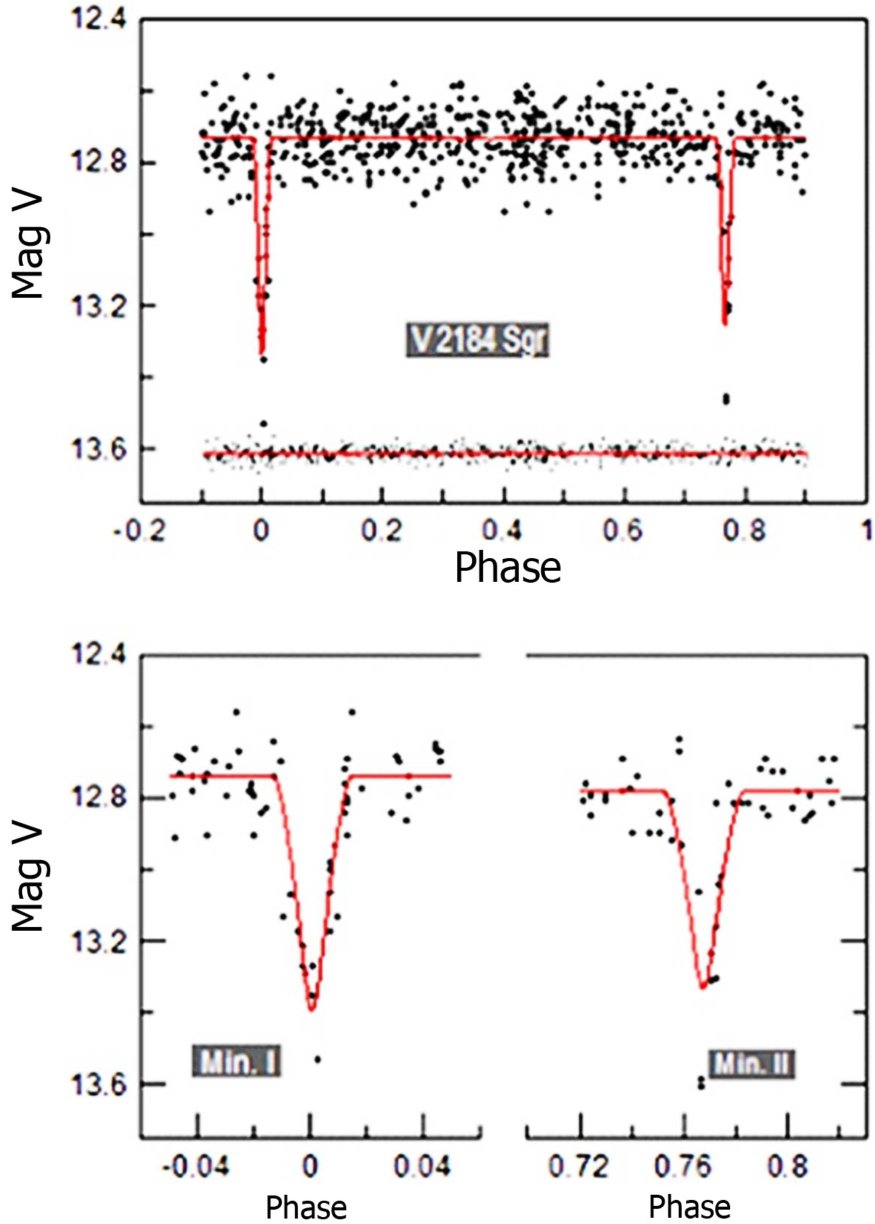

Figure 5. Top panel: V2184 Sgr_{ASAS} light curve (dots) and its fit in the red solid line with the corresponding residuals (moved vertically to save space). Bottom panel: The two minima in a different scale just for clarity.

Table 4. Orbital and physical parameters of V869 Car and V2184 Sgr

Parameters	V869 Car	V2184 Sgr_{ASAS}	V2184 Sgr_{TESS}
Wavelength	8000 Å	5500 Å	8100 Å I central band=7865 Å
T_o (day)	2450551.628	2453614.205	2458663.999 ±0.000102
P (day)	2.23281 ± 0.00002	16.4960 ± 0.00003	16.4959 ± 0.00001
e	0.07023 ±0.001	0.43348 ±0.0004	0.48963 ±0.0005
ω (rad)	2.976 ±0.052	6.270 ±0.011	5.75 ±0.001
$T_{1eff.}$ (K)	6264 (fixed)	6183 (fixed)	6183 (fixed)
$T_{2eff.}$ (K)	6069.381 ±19.031	6088 ±134	6130 ±17
Phase shift	0.02103 ±0.00016	0.13446 ±0.00009	0.1587 ±0.000006
i (°)	81°.528 ±0.063	89°.6 ±0.022	89°.72 ±0.014
q	0.951 ±0.008	0.886 ±0.013	0.885 ±0.007
$l_1/(l_1+l_2)$	0.4807 ±0.0971	0.47020 ±0.1831	0.49854 ±0.019
$l_2/(l_1+l_2)$	0.5193 ±0.0971	0.52979 ±0.1831	0.50145 ±0.019
r_1	0.1900	0.0419	0.0426
r_2	0.1868	0.0419	0.0425
x_1	0.369 ±0.085	0.552 ±0.123	0.686 ±0.013
x_2	0.385 ±0.096	0.749 ±0.213	0.687 ±0.03
Ω_1	6.479 ±0.034	23.8110 ±0.139	26.724 ±0.230
Ω_2	5.9402 ±0.0303	18.152 ±0.173	23.580 ±0.2218
f_1	-0.375	-0.732	-0.721
f_2	-0.320	-0.653	-0.635
ALB1	0.5	0.5	0.5
ALB2	0.5	0.5	0.5
g_1	0.32	0.32	0.32
g_2	0.32	0.32	0.32

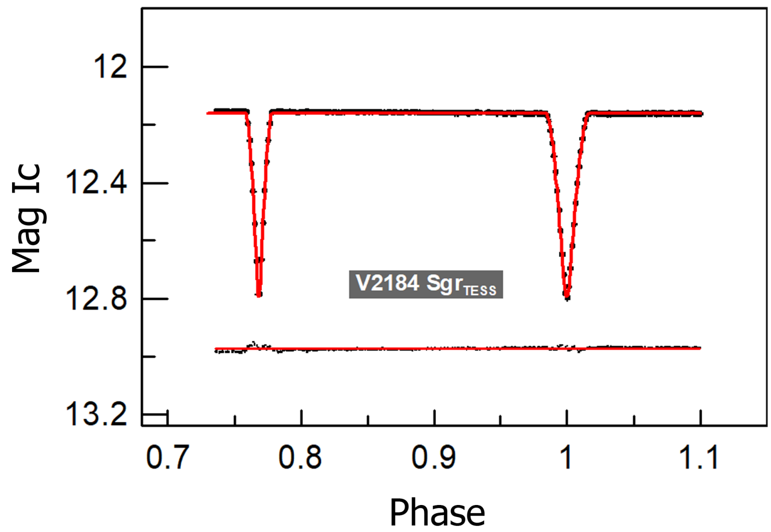

Figure 6. Top: V2184 Sgr_{TESS} light curve (dots) and its fit in the red solid line with the corresponding residuals (moved vertically to save space).

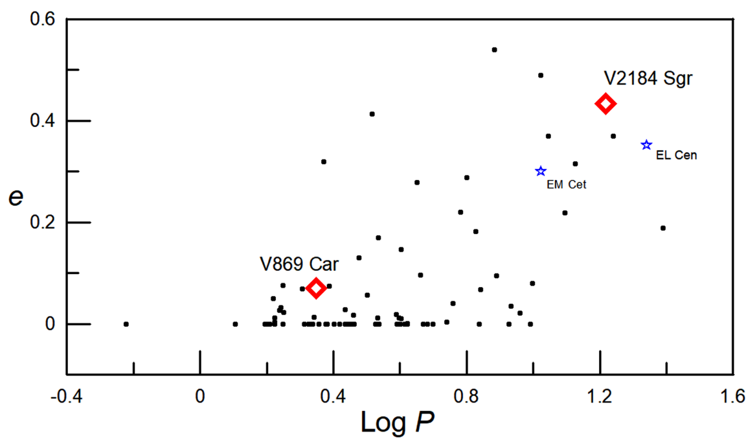

Figure 7. The (e-Log$P$) plane for a binary sample of 78 well-studied binaries listed in Mayer & Hanna (1991) (dots). The present two targets V2184 Sgr and V869 Car are denoted by the red square symbols, while the blue star symbols represent EM Cet and EL Cen that were studied recently by Hanna et al. (2024).

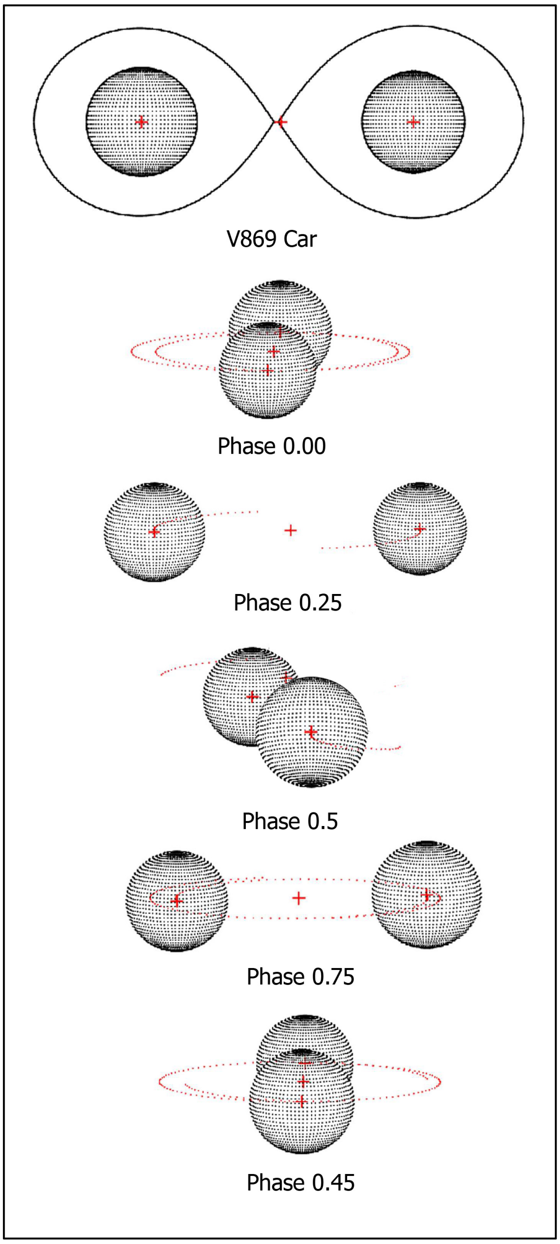

Figure 8. Up: The Roche Lobe configuration of V869 Car. Bottom: The orbital phases represent the situation in different phases 0.0, 0.25, 0.5, 0.75. The phase 0.45 shows the shape at the secondary eclipse.

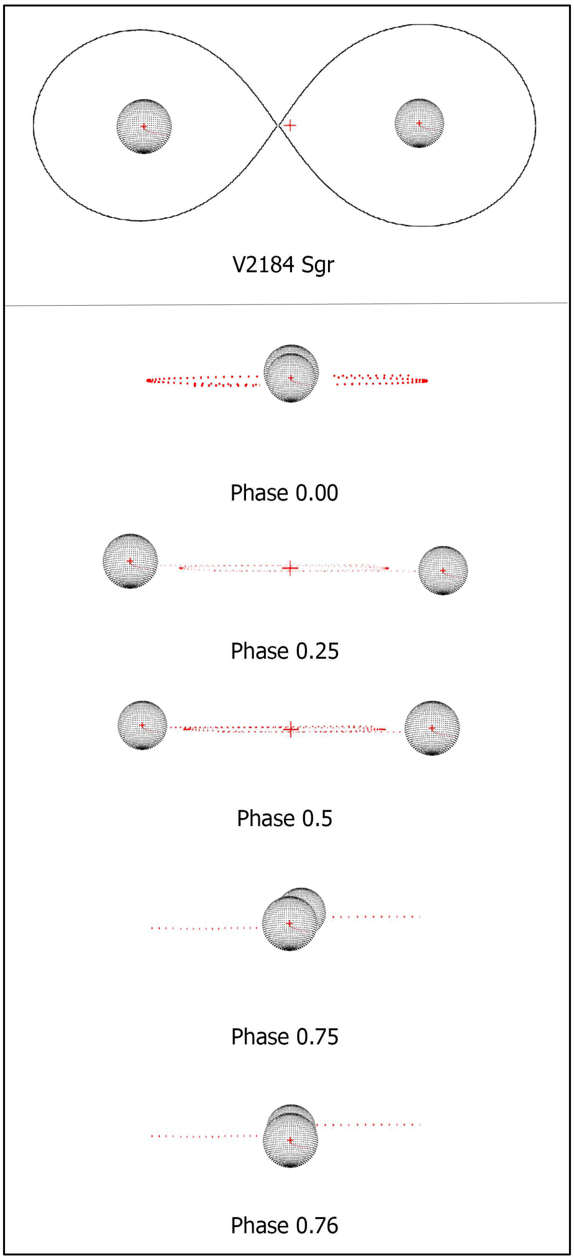

Figure 9. Up: The Roche Lobe configuration of V2184 Sgr. Bottom: The orbital phases represent the situation in different phases 0.0, 0.25, 0.5, 0.75. The phase 0.76 shows the shape at the secondary eclipse.

Table 5. Orbital and physical parameters of V869 Car and V2184 Sgr.

Star Name	Comp.	M $M_\odot$	R $R_\odot$	T_{eff} K	L $L_\odot$	M (bol.)	Log g	Sp.type
V869 Car	Pri.	1.250 (2)	1.33 (02)	6264	2.70 (16)	3.65 (03)	4.28 (01)	F8
	Sec.	1.19 (10)	1.27 (10)	6069 (19)	1.95 (55)	4.88 (04)	4.34 (04)	F9
V2184 Sgr (ASAS)	Pri	1.23 (03)	1.31 (03)	6183	2.389 (60)	3.79 (3)	4.290 (2)	F8
	Sec.	1.203 (8)	1.282 (7)	6088 (124)	2.148 (61)	3.906 (30)	4.302 (2)	F9
V2184 Sgr (TESS)	Pri.	1.230 (08)	1.312 (7)	6183	2.389 (60)	3.79 (3)	4.296 (2)	F8
	Sec.	1.210 (8)	1.295 (7)	6130 (17)	2.25 (6)	3.85 (3)	4.298 (2)	F9

4. Discussion and conclusion

Eclipsing binaries, especially those with eccentric orbits, are fundamental stellar systems that provide both the physical parameters (e.g., mass, radius, temperature and luminosity) and orbital parameters (e.g., period, eccentricity, and longitude of periastron). These two sets of parameters allow testing different tidal theories (e.g., Alexander's weak friction theory, Alexander (1973); Zahn's theory, Zahn (1977) and Tassoul's theory, Tassoul (1988)), deducing the apsidal motion parameters and calculating the synchronization & circularization timescales Hanna (1993) & Hanna et al. (1998). Hence, studying the evolution and internal structure of stars.

- On analyzing the light curve of V2184 Sgr of the ASAS (Fig. 5), one may notice that the fit at the minima does not adequately match the data. This has been observed in other similar studies. More than 13 out of 54 systems studied by Zasche et al. (2018) did not adequately describe the data, e.g., CzeV 688, CzeV 364, CD-33 2771, V611 Pup, TYC 8603-723-1, PS Vul and V839 Cep. They stated that this may be due to the fact that the mass ratio is based on the assumption of a main sequence of star components and that they may be giants or some over-luminous stars according to their effective temperatures. Zasche (2016) also reported that this may only be due to the limitations of the software itself and the limited physics built into it. However, basically in the analysis, we keep the light curves so that the cost function does not drop dramatically, only varies around some value and shows no further progression. Also, even the residual values are distributed relatively symmetrically around the zero line and no systematic deviations appear there.

- On comparing the obtained two sets of parameters of V2184 $\mathrm{Sgr}^{ASAS}_{TESS}$ (see, Table 4), one can notice that the differences are in the range of the estimated errors for each parameter. For example, the eccentricity, longitude of periastron and inclination are quite similar, while there are small differences in some other parameters such as T_2, surface potentials Ω_1 & Ω_2 and limb darkening x_1 & x_2. However, it is preferable to consider the results of the TESS light curve since its morphological profile is better than the scattered light curve of ASAS, and it was observed over a shorter interval of time.

- The obtained orbital inclination from the analysis of the two light curves of V2184 Sgr are nearly the same, within the error range ($i_{ASAS} = 89^{\circ}.60 \pm 0.022$ and $i_{TESS} = 89^{\circ}.72 \pm 0.014$). Both values are very close to 90°, which is typically expected for eclipses of binaries with orbital periods greater than eight days (Kjurkchieva & Vasileva, 2015b).

- We deduced the spectral type of V869 Car and V2184 Sgr using the tables given by Cox (2000). The effective temperatures, $T_{1,2\ eff}$ for V869 Car are 6264 K & 6069(19)K, which correspond to spectral types $F8$ & $F9$. For V2184 Sgr_{ASAS}, $T_{1,2\ eff}$ are 6183 & 6088(134) K which correspond to $F8$ & $F9$, while for V2184 Sgr_{TESS}, $T_{1,2\ eff}$ are 6183 K & 6130(17) K which correspond to $F8$ & $F9$, respectively. This result is expected, suggesting that both stars are essentially solar-type main sequence stars.

- It is worth noticing that the light curve by TESS (Fig. 6) is clearly of very good quality, as compared with the scattered ASAS light curve (Fig. 5), and consequently, its fit could be better than that of ASAS. The ASAS observations cover about 7.2 years while the light curve of TESS is continuous and covering the two minima (prim. & sec.) of the light curve only in about 11 successive days.

- It is important to note that the solutions presented in Table 4 are still only preliminary results based on photometry, and the individual parameter errors based on the errors provided by the PHOEBE software.

- We have determined 8 new times of primary and secondary minima from the four TESS light curves, all are listed in Table 2 together with the available minima times in the O-C gateway (Paschke & Brát, 2006) . We attempted to study the period variation due to the apsidal motion by the $O - C$ plot analysis, but we could not come up with an acceptable solution due to the lack of minima time available.

- The absolute physical parameters of the components were calculated using the empirical relations adopted by Harmanec (1988) and listed in Table 5.

- The main choice of the two systems under analysis is simple and does not depend on their location or brightness. The criterion based on analyzing new light curves for systems that have not been studied before, since our main goal is to expand the present set of eclipsing binaries in the period-eccentricity diagram. Another criterion for our selection is systems with good phase light curves, i.e., photometry must cover the entire light curve and especially the duration and depths of both eclipses.
  We have constructed the e-Log$P$ plane to check the location of our two targets among a set of 78 detached eclipsing binaries brighter than 9^m in maxima. They are well-studied binaries collected from the GCVS (58 systems) together with other fainter detached binaries with well determined parameters, as compiled by Harmanec (1988) as well as several others from different sources. All are listed in Mayer & Hanna (1991). We have plotted our two targets together with another two systems EM Cet & EL Cen of our recent paper (Hanna et al., 2024). The four systems follow the same trend distribution of the group as seen in the plot (Fig. 7).

- Using the PHOEBE software, we determined the orbital elements and stellar parameters of the two detached systems V869 Car and V2184 Sgr. The analysis shows that both stars are of late spectral types in which one may expect magnetic activity or star spots due to their convective envelopes.

- The geometrical configuration for both systems and the model solution at different orbital phases using the Binary Maker program (Version 3) are also illustrated by Figures 8 & 9.

- The light curves' morphology clearly show that both systems are detached eccentric eclipsing binaries, and the analysis contributed for orbital eccentricities equal to ($e = 0.4896 \pm 0.0018$) and ($e = 0.0702 \pm 0.001$) for V2184 Sgr and V869 Car, respectively.

Acknowledgements. This research makes use of the SIMBAD and Vizier data base, the NASA Astrophysics Data Service, the PZP catalogue, the O-C gateway, the All Sky Automated Survey (ASAS) data, the Transiting Exoplanet Satellite mission (TESS) data and the PHOEBE software in the light curve analysis. The authors are grateful to an anonymous referee for valuable notes and propositions.

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