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Light curve analysis for the two eclipsing binary stars EM Cet and EL Cen

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Abstract. We present the first light curve analysis of the two eccentric eclipsing binary stars EM Cet and EL Cen by using the PHOEBE Code. The selected stars were taken from the Peremennye Zvezdy Prilozhenie supplement (PZP). Both were observed by the All Sky Automated Survey (ASAS) in the V band. Another light curve for EM Cet was observed via the Transiting Exoplanet Satellite (TESS). From the TESS observations we determined 4 new minima times. Orbital and physical parameters were determined. The analysis showed that the two targets confirming the concept of orbital circularization theories that stars with lower eccentricities are with later spectral types. A comparison between the results obtained from the two light curves of ASAS and TESS for EM Cet has been investigated.

Key words: detached binaries – EM Cet – EL Cen

1. Introduction

The study of apsidal motion of detached Eccentric Eclipsing Binary stars (EEBs) is important because it provides information about the internal structure of the stars. Apsidal motion refers to the rotation of the line connecting the two stars in an elliptical orbit. By measuring the rate of apsidal motion, astronomers can determine the structure constants k_2 specifying the density distribution in each of the components. Apsidal motion in binary star systems can be caused by several factors: (i) mutual tidal deformation of the components due to the gravitational interaction between them, affecting their orbits; (ii) deformation of the components due to the axial rotation of the stars which can also cause shape variations, (iii) the relativistic effects that introduces subtle corrections to the orbital dynamics, impacting the apsidal motion, and (iv) the compactness of triples that was investigated by Rappaport et al. (2024) can lead to interesting and important dynamical interactions, including so-called dynamical delays, driven apsidal motion in the inner binary (see also, e.g., Rappaport et al., 2023; Borkovits et al., 2015; Borkovits & Mitnyan, 2023). Hence, to investigate and probe the internal structure of the stars many astronomers have focused their attention on studying detached eclipsing binary systems whose light curves exhibit a secondary minimum phase shift out of the value 0.5.

Researchers have difficulty observing detached systems with ordinary telescopes, because their orbital periods are long, making it difficult to cover the entire light curve compared to binaries with short periods. Fortunately, modern robotic space telescopes and significant advances in instrumentation over the past three decades have enabled several large-scale optical surveys to report tens of thousands of new eclipsing binaries in our Galaxy and other nearby galaxies (Kim et al., 2018). Consequently, several catalogues have been formed by several authors, especially for detached binary stars showing apside line rotation, such as 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 view of these catalogs, see Kjurkchieva et al. (2017). We have used in the present analysis light curves from the ASA-Survey (Pojmanski, 1997) and the TESS (Ricker et al., 2015) mission. Pojmanski (2002) explained the description of the All-Sky Automated Survey that started at the beginning of 1996. It is a long-term project that provides long-baseline light curves for sources brighter than V=15 mag across the whole sky. The Transiting Exoplanet Survey Satellite (TESS), launched by NASA in 2018, is a space telescope designed to discover thousands of exoplanets orbiting the brightest dwarf stars. It has also produced high-quality light curves with a baseline of at least 27 days, eventually for most of the sky. The combination of ASAS and TESS light curves probes both long- and short-term variability in great detail, especially towards the TESS Continuous Viewing Zones (CVZ) at the ecliptic poles.

2. Source of data

We selected light curves for two detached systems, EM Cet and EL Cen, from the Peremennye Zvezdy Prilozhenie Supplement (Khruslov, 2012); and Kazarovets & Pastukhova (2017) that are characterized by an apparent secondary minimum phase shift apart of 0.5. However, Nedoroščík et al., 2014; presented an effective way to quickly classify eclipsing binaries from the ASAS data via performing the Fourier decomposition of the phase light curves. They used the relations between the Fourier coefficients to infer principal properties of eclipsing binaries and, hence, the systems with eccentric orbits could be distinguished. The light curves of both systems were observed by the ASAS. In the analysis we also included another light curve for EM Cet from the TESS observations which is available with the 120-second cadence.

Table 1 displays the magnitudes in different bands, the color index and the effective temperatures of both stars. The next two sub-sections 2.1 and 2.2 give short accounts about both targets.

Table 1. Magnitudes, colors and effective temperatures of the two targets.

	EM Cet	EL Cen
J	08.685[1]	11.351[1]
H	08.426[1]	11.237[1]
K	08.400[1]	11.171[1]
B	10.23[3]	12.67[2]
V	09.64[3]	12.27[2]
J-H	0.259	0.114
B-V	0.590	0.310
$T_{eff.}$	6381[5]	6841[4]

[1]Cutri et al., 2003, -yCat. 2246
[2]Høg et al., 2000
[3]Watson et al., 2006= VSX. 2005
[4]Bai et al., 2019
[5]Zhang et al., 2023

2.1. EM Cet

The star EM Cet ($\alpha_{2000} = 03^{\rm h}\ 22^{\rm m}\ 37\overset{\rm s}{.}91, \delta_{2000} = -0^\circ\ 31'\ 42\overset{''}{.}5$) was discovered by the Hipparcos mission and listed under serial number HIP 15728 (ESA, 1997) with a primary minimum $2448510\overset{\rm d}{.}883$ and an orbital period, $P = 13\overset{\rm d}{.}2714$ day. Subsequently, it was named in the GCVS as EM Cet by Kazarovets et al. (1999) who classified the star as an eclipsing Algol (EA:). Kazarovets & Pastukhova (2017) selected the star from the ASAS photometric catalogue (ASAS 032238-0031.7) and reported $F8$ as a spectral type and gave a new period $P = 10^d.5240$ instead of the false period, $P = 13\overset{\rm d}{.}2714$, given in the Hipparcos and Tycho Catalogues (ESA, 1997). They gave the line elements:

$$HJDMinI = 24\ 54783\overset{\rm d}{.}709 + 10\overset{\rm d}{.}5240E \qquad (1)$$

Another light curve has been observed via TESS mission with serial number TIC 279097963, magnitude $(T_{mag}) = 9.1854$, and effective temperature $T_{eff} = 6381.06$ K with the ephemeris:

$$HJDMinI = 24\ 58414\overset{\rm d}{.}498384 + 10\overset{\rm d}{.}5242227E. \qquad (2)$$

On the other side, two ephemerids were given for both primary and secondary minimum in the online O-C Gateway catalogue as:

$$HJDMinI = 24\ 48510\overset{\rm d}{.}883 + 10\overset{\rm d}{.}5141E, \qquad (3)$$

$$HJDMinII = 24\ 48517\overset{\rm d}{.}296 + 10\overset{\rm d}{.}5141E. \qquad (4)$$

The times of minimum light listed in Table 2 were taken from the online O-C gateway website (Paschke & Brat, 2006). Besides, we deduced 4 new minima times from the TESS observations by using the AVE program that depends on Barbera (1996) method. The O-C residuals were calculated using equation (2), and plotted in Fig. 1.

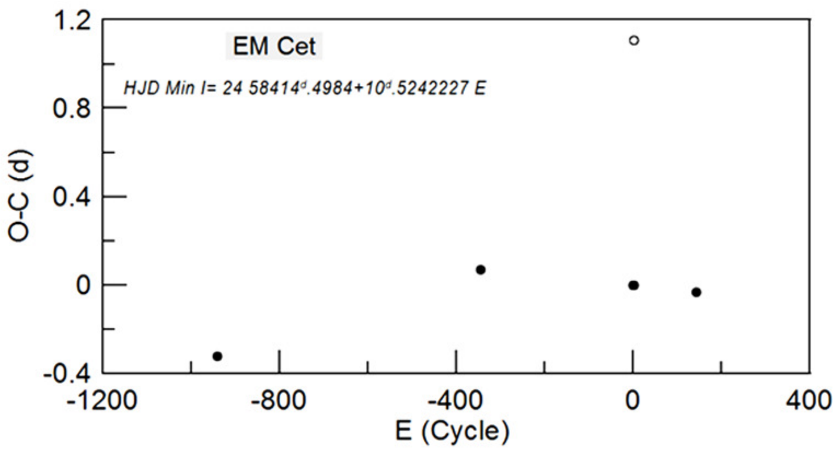

Figure 1. The O-C Diagram of EM Cet, dots stand for primary minima, an open circle for the secondary one.

Table 2. Time of minima for EM Cet.

HJD (+2400000)	Error	O-C	Type	Method	Ref.
48510.8830:		-0.32182	P	pe V	[1]
54783.7090		0.06745	P	pe V	[1]
58414.498818	0.000029	0.00043	P	CCD I	pw
58425.022845	0.000041	0.00024	P	CCD I	pw
58431.391731	0.000077	1.10701	S	CCD I	pw
58435.546786	0.000030	-0.00004	P	CCD I	pw
59929.954		-0.03245	P	Ic	[1]

Ref: [1] Paschke & Brat (2006). pw: present work (from TESS observations).

2.2. EL Cen

The star EL Cen ($\alpha_{2000} = 13^{\rm h}\ 30^{\rm m}\ 25\overset{\rm s}{.}2, \delta_{2000} = -56^\circ\ 54'\ 52\overset{''}{.}2$; TIC 68295752; ASAS 133025-5654.9) was discovered as an eclipsing variable by Hoffleit (1930) taking Harvard serial number HV 4757. It was discovered while surveying the southern Milky Way by examining the Modified Forster-plates (MF), which was developed by the German astronomer Paul Forster to be more sensitive to shorter wavelengths of light than the traditional photographic plates, and taken by a refracting 10-inch Metcalf telescope located at the Boyden Observatory in South Africa.

An earlier version of GCVS classified the system as an eclipsing variable star without specifying its light elements. Khruslov (2012) confirmed its eclipsing nature according to the Automated Survey (ASAS-3) data and recorded secondary minimum phase shift ϕ_2 at 0.312 and minima differ in duration: DI $= 0.012\ P$ and DII $= 0.022\ P$. He also gave the light elements:

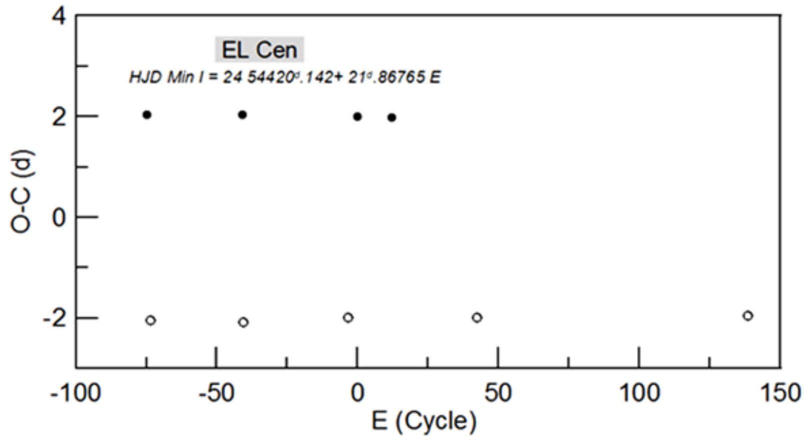

Figure 2. The O-C Diagram of EL Cen, filled circles stand for primary minima, open circles for secondary ones.

$$HJD(Min.I) = 24\ 53525^{\mathrm{d}}_{.}600 + 21^{\mathrm{d}}_{.}8677 E. \tag{5}$$

The eclipse times of minima are listed in Table 3 from the O-C gateway catalog with the primary and secondary light elements:

$$HJD(Min.I) = 24\ 53525^{\mathrm{d}}_{.}600 + 21^{\mathrm{d}}_{.}8677\, E, \tag{6}$$

$$HJD(Min.II) = 24\ 53532^{\mathrm{d}}_{.}423 + 21^{\mathrm{d}}_{.}8677\, E. \tag{7}$$

EL Cen is also included in the Galactic eccentric eclipsing binary stars catalogue which is based on the eclipse timing diagram (Kim et al., 2018), with

Table 3. Times of minima for EL Cen.

HJD (+2400000)	O-C	Type	Method	Ref.
52782.1040	2.03575	P	pe V	[1]
52810.8320	-2.037725	S	pe V	[1]
53525.6000	2.03165	P	pe V	[2]
53532.4230	-2.079175	S	pe V	[2]
54341.6200	-1.985225	S	pe V	[1]
54422.1420	0	P	pe V	[1]
54684.5480	1.9942	P	pe V	[3]
55347.5338	-1.983325	S	pe V	[1]
57446.8630	-1.948525	S	-	[3]

Ref: [1] Kim et al. (2018). [2] Khruslov (2012). [3] Paschke & Brat (2006).

maximum $mag_V = 12.3$, and secondary minimum phase shift at 0.317. They gave the light elements:

$$HJD(Min.I) = 24\ 54420^{\mathrm{d}}_{.}142 + 21^{\mathrm{d}}_{.}86765\, E. \tag{8}$$

The O-C residual diagram is shown in Fig. 2, where the residuals were calculated using the ephemeris of equation (8).

3. Light curve analysis

To model the light curves, we used the package PHOEBE v0.31 (Prša & Zwitter, 2005). The light curves' morphology shows constant out-of-eclipse parts and a secondary minimum phase shift value out of 0.5 for the two targets, then we used the mode Detached. To proceed with the use of PHOEBE one has to prepare some input initial parameters. For EM Cet and EL Cen the light curves' morphology shows difference between the depths of both eclipses, so the temperatures and radii of the primary and secondary components have to be different. Hence, the task is to set the temperature of the primary component as a constant value and to fit the temperature of the secondary one (Zasche, 2016).

The ASAS light curves of the two systems were observed in the V-band, while the light curve of TESS was observed in the 8100 Å I central band (=7865 Å); we have chosen the Cousins I filter in PHOEBE. We used $T_{1eff} = 6381$ K (Zhang et al., 2023) for EM Cet and 6841 K for EL Cen from Bai et al. (2019). Given some other parameters, such as gravity-darkening and bolometric albedo, one can begin to model the two systems. The gravity darkening can be found following Lucy (1967) and Ruciński (1973). For both systems, assuming convective envelope components ($T_1 < 7200$ K), the gravity-darkening $g_1 = g_2 = 0.32$ and the primary star albedo $A_1 = A_2 = 0.5$ (Zasche, 2016).

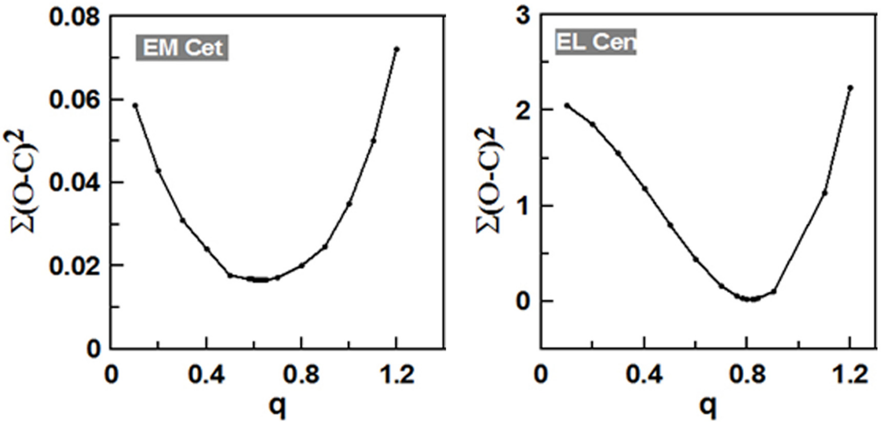

Figure 3. The $q_{ph} - \sum(O-C)^2$ relation

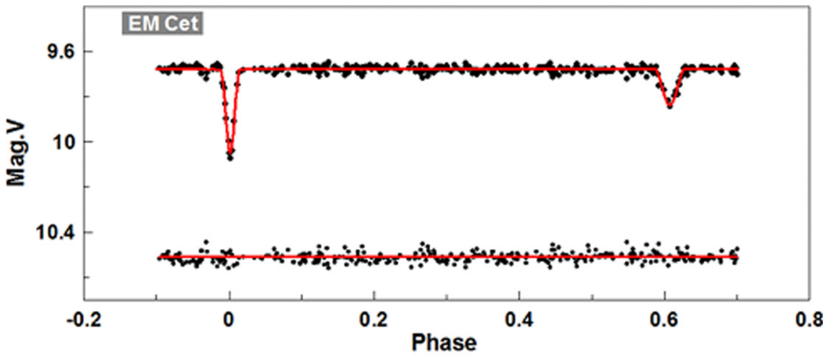

Figure 4. Top: The ASAS light curve of EM Cet and its fit. Bottom: The corresponding residuals (shifted vertically to save space).

Light curves of detached eccentric eclipsing binaries are mostly characterized by deviations of their secondary minimum from the phase 0.5. Hence, to proceed in solving the light curves, without a waste of time, one has to deduce, not guess, the initial values of both the eccentricity, e_o, and the longitude of periastron, ω_o. We follow the method of Kjurkchieva & Vasileva (2015a) by solving the two equations:

$$e_o \cos \omega_o = \frac{1}{2} \cdot \pi[(\phi_2 - \phi_1) - 0.5], \tag{9}$$

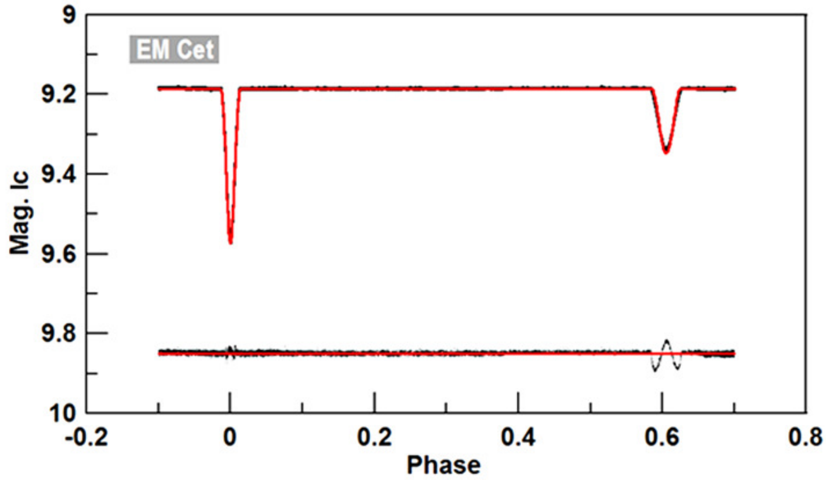

Figure 5. Top: The TESS light curve of EM Cet and its fit. Bottom: The corresponding residuals (shifted vertically to save space).

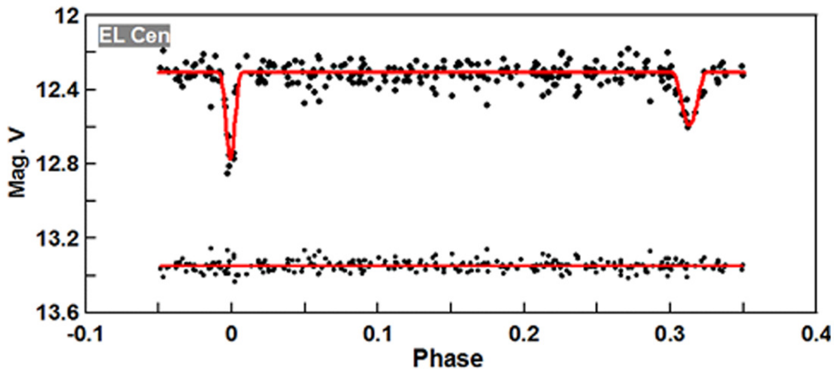

Figure 6. Top: The ASAS light curve of EL Cen and its fit. Bottom: The corresponding residuals (moved vertically to save space).

$$e_o \sin\omega_o = (W_2 - W_1)/(W_2 + W_1), \tag{10}$$

where W_1 and W_2 are the measured widths of the primary and secondary minima in phase unit; ϕ_2 is the phase of the secondary minimum, while $\phi_1 = 0$. Equations (9) and (10) are the approximate equations 9.25 and 9.37 given by

Kopal (1978). All these values are shown in Table 4. Both e_o and ω_o were used as raw parameters for PHOEBE. Also, we followed a q-search procedure implemented by several authors (e.g., Djurašević et al. (2016); Awadalla et al. (2016); El-Sadek et al. (2019)) to obtain the photometric mass ratio, q_{ph}. This can be performed by constructing the relation between the sum of weight squares deviation $(O-C)^2$ and q for both systems (Fig. 2). We obtained $q_{ph} = 0.63$ for EM Cet and 0.82 for EL Cen .

Table 4. The measured width of LC minimum, phase of sec. minimum and the estimated initial e_o and ω_o

	W_1^*	W_2^*	ϕ_2^*	e_o	ω_o (Rad.)
EM Cet$_{ASAS}$	0.027	0.0420	0.6080	0.2758	0.9080
EM Cet$_{TESS}$	0.033	0.0440	0.6074	0.2208	0.7012
EL Cen$_{ASAS}$	0.010	0.0216	0.3120	0.4927	0.9270

* in phase unit.

We put the deduced effective temperature, $T_{1eff.}$, as a constant parameter, and the estimated q_{ph}, e_o and ω_o as initial values. Then we proceed to the analysis by adjusting the inclination i, T_2, surface potential of the primary and secondary components, e, ω and phase shift. We proceed step by step until the solution converges giving the best fit with the lowest value of χ^2 ($\chi^2 = 0.00528$ for EM Cet$_{ASAS}$, 0.0053 for EM Cet$_{TESS}$, and 0.0217 for EL Cen). The obtained solution parameters, including the standard errors, are shown in Table 5. In the first column of the table, the suffix 1 stands for the primary component and 2 for the secondary one. Synthetic light curves computed with these parameters are plotted as solid lines in Figs. 4, 5 and 6, with residuals at the bottom of each figure.

4. Discussion and Results

When using tables by Cox (2000), the temperatures $T_{1,2}$ (6381 & 6173(43) K) of EM Cet$_{ASAS}$ correspond to the spectral types F7 + G7; and $T_{1,2}$ (6381 & 5899(17) K) of EM Cet$_{TESS}$ correspond to the spectral types F7 + G3. Also, for EL Cen, $T_{1,2}$ (6841 & 6613(162) K) correspond to F3 + F 5 (see, Table 6). This result is expected considering that both stars are mainly solar-type stars. The orbital inclinations of the two targets are around 87° which is quite close to 90°. This is normally expected for eclipsing binaries with orbital periods over eight days (Kjurkchieva & Vasileva, 2015a). The light curve morphology of both systems shows partial eclipses (see also Figs. 7 & 8).

Table 5. Orbital and physical parameters of EM Cet and EL Cen.

Parameters	EM Cet$_{ASAS}$	EM Cet$_{TESS}$	EL Cen
Wavelength	5500 Å	8100 Å I central band =7865 Å	5500 Å
HJD (2400000+)	54783.709	58414.498384	53525.6
Orbit. Per. (d)	$10^{\mathrm{d}}.524$	$10^{\mathrm{d}}.5242227$	$21^{\mathrm{d}}.8677(4417)$
Eccentricity (e)	0.2987(63)	0.30000(11)	0.3527(52)
ω (rad)	0.9958(149)	1.006(19)	2.538(19)
$T_{1eff.}$ (K)	6381 (fixed)	6381 (fixed)	6841 (fixed)
$T_{2eff.}$ (K)	6173(43)	5913(17)	6613(162)
Phase shift	0.0444(21)	0.04251(8)	-0.08009(92)
Orb. incl. (i)	$87^{\circ}.19 \pm 0.81$	$87^{\circ}.082 \pm 0.002$	$87^{\circ}.10 \pm 0.09$
Mass ratio (q)	0.7323(136)	0.7146(3)	0.815(42)
$l_1/(l_1+l_2)$	0.6361(132)	0.7151(3)	0.6441(18)
$l_2/(l_1+l_2)$	0.3638(132)	0.2849(3)	0.3559(18)
Frac. rad. r_1^*	0.0632	0.0703	0.0281
Frac. rad. r_2^*	0.0452	0.0517	0.0237
Limb dark. x_1	0.537	0.349	0.48(25)
Limb dark. x_2	0.562	0.385	0.502(225)
Surf. pot. Ω_1	17.975(340)	16.049(4)	14.00(32)
Surf. pot. Ω_2	16.752(335)	16.682(4)	13.00(37)
Fillout factor f_1	-0.812	-0.789	-0.6028
Fillout factor f_2	-0.798	-0.797	-0.5727
Albedo ALB_1	0.5	0.5	0.5
Albedo ALB_2	0.5	0.5	0.5
Grav. bright. g_1	0.32	0.32	0.32
Grav. bright. g_2	0.32	0.32	0.32
χ^2	0.0053	0.0053	0.027

* Calculated following Ivanov et al. (2010).

In our discussion we shall consider the obtained parameter values of EM Cet$_{TESS}$ not EM Cet$_{ASAS}$ to avoid any confusion for the reader. We chose the obtained parameter values of the TESS light curve rather than those of ASAS for two reasons. The first is due to the good quality of the TESS light curve compared to the ASAS light curve. The second is that the light curve by ASAS was observed during 8.8 years, while it was 27 days by the TESS. There are no radius parameters to fit in the PHOEBE code, but the radii of the components are stocked in the parameters like "PHSV" and "PCSV" (or POT1, POT2- primary and secondary surface potentials) (Zasche, 2016). However, we have obtained roughly the fractional radii from the empirical relations, assuming MS-stars given by Ivanov et al. (2010). We found $r_1 = 0.07032$ & $r_2 = 0.0517$ for EM Cet$_{TESS}$ and $r_1 = 0.0281$ & $r_2 = 0.0237$ for EL Cen. These values do not provide error values, however, Prša et al. (2011) estimated that 90% of the sample of detached and semi-detached EBs had a corresponding error smaller than 10% (Kjurkchieva & Vasileva, 2015b). We have attempted to study the period variation due to apsidal motion by analyzing the $O-C$ plot but we could not find an acceptable solution for the lack of the observed times of minima. For the same reason Kim et al. (2018) did not include the apsidal motion parameters of EL Cen within the eclipse timing diagram in their extensive catalogue of EEBs. The absolute physical parameters of the components were calculated using the empirical relations adopted by Harmanec (1988) and listed in Table 6. The geometrical configurations for both systems and the model solution at 0.0, 0.25, 0.50 and 0.75 orbital phases, using the Binary Maker Code (ver. 3.0), are illustrated in Figures 7 & 8. The geometrical configurations at the secondary minimum phase, ϕ_2, at 0.6 (for EM Cet) and 0.31 (for EL Cen) are also shown at the lower panel of each figure. The partial eclipses are clearly shown.

Table 6. Orbital and physical parameters of EM Cet and EL Cen.

Star Name	Comp.	M ($M_\odot$)	R ($R_\odot$)	T (K)	L ($L_\odot$)	$M_{bol.}$	Log g	Sp. type
EM Cet$_{ASAS}$	Pri.	1.271 (8)	1.347 (7)	6381	2.783 (74)	3.652 (29)	4.281 (2)	F7
	Sec.	0.971 (8)	1.051 (8)	6173 (43)	0.913 (31)	4.876 (04)	4.378 (3)	G7
EM Cet$_{TESS}$	Pri.	1.271 (8)	1.354 (3)	6381	2.783 (74)	3.622 (29)	4.281 (3)	F7
	Sec.	1.088 (8)	1.170 (8)	5899 (17)	1.415 (44)	4.360 (33)	4.338 (3)	G3
EL Cen	Pri.	1.438 (8)	1.496 (7)	6841	4.67 (11)	3.08 (3)	4.244 (2)	F3
	Sec.	1.365 (8)	1.432 (7)	6613 (162)	3.75 (09)	3.33 (3)	4.260 (2)	F5

The analysis shows that the orbital eccentricity of EM Cet is 0.3(0) with Sp-Type F7+G3 while for EL Cen, $e = 0.3527(52)$ with Sp-Type F3+F5, which matches Zahn (1977) and Tassoul (1988) theories of circularization, in which eccentric eclipsing binaries tending to circularize their orbits due to tidal interaction between their components. Mayer & Hanna (1991) emphasized the dependency of eccentricity evolution, towards orbital circularity, upon spectral type and the age of the binary. The obtained eccentricity and spectral type for both systems are matching the ($e - Sp.type$) diagram given by Hanna (1993) and Hanna et al. (1998).

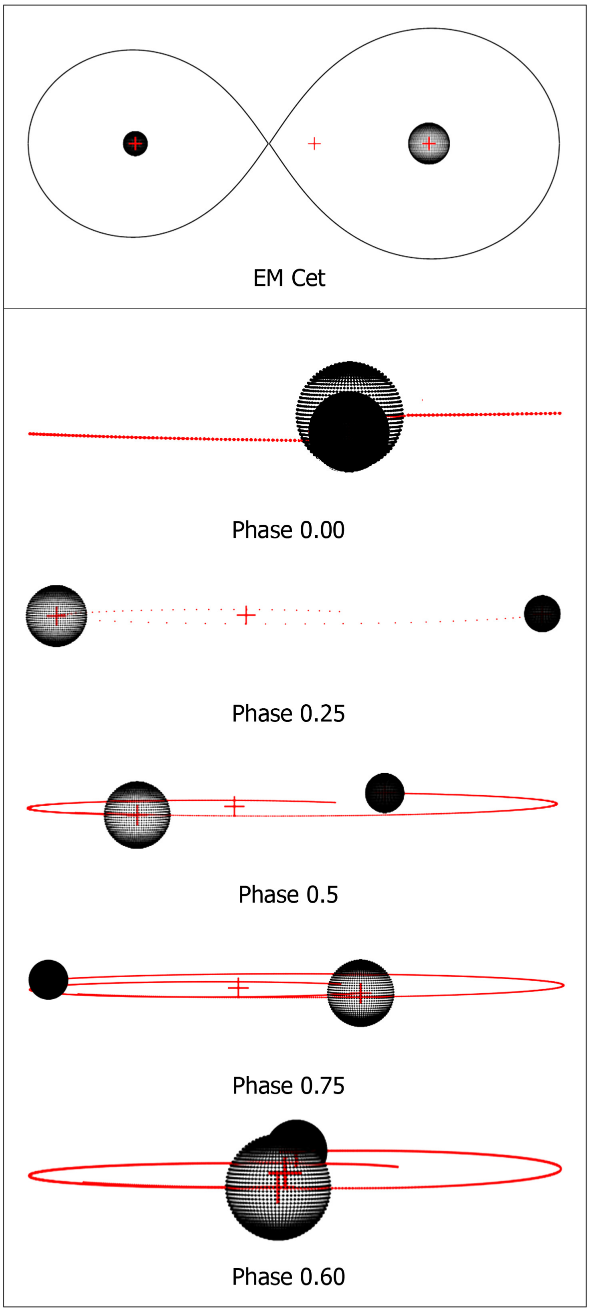

Figure 7. Top panel: Roche Lobe configuration. Bottom: The description of the model solution at different orbital phases for EM Cet.

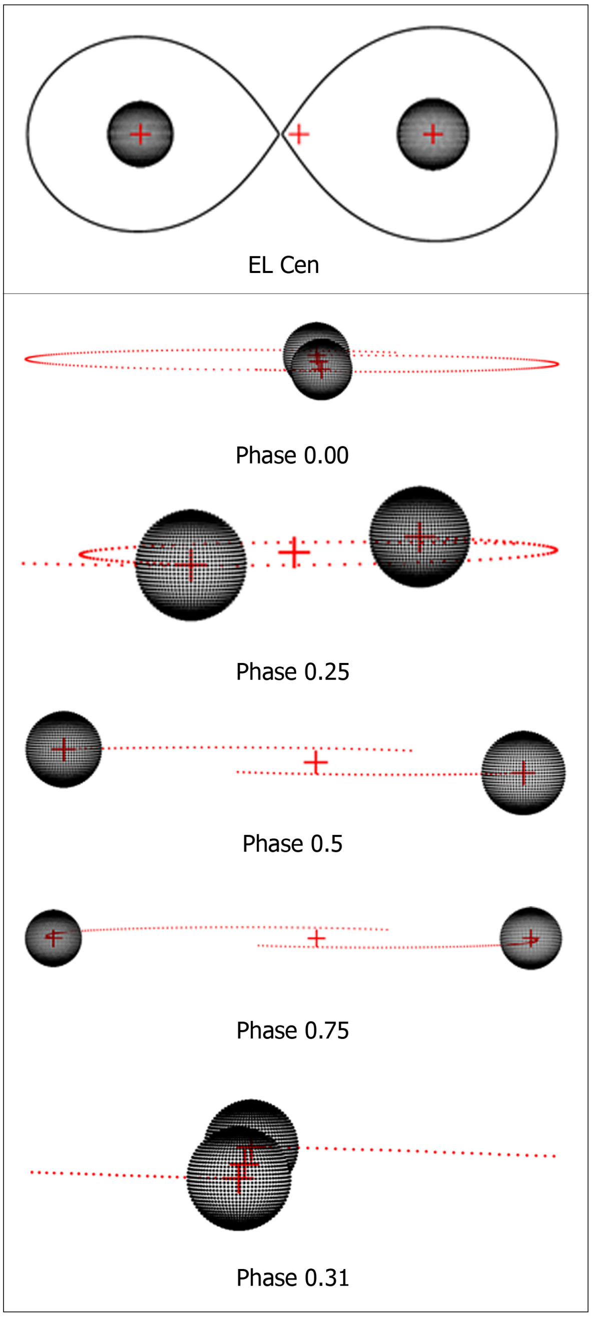

Figure 8. Top panel: Roche Lobe configuration. Bottom: The description of the model solution at different orbital phases for EL Cen.

5. Conclusion

The main results from the analysis of the two light curves are as follow:
(1) We determined the orbital elements and stellar parameters for the two detached systems EM Cet and EL Cen.
(2) The analysis show that EM Cet_{TESS} is of late spectral type, F7 + G3, where one can expect magnetic activity or star spots due to its convective envelope, which is a common characteristic of stars like our sun. However, we did not notice any considerable smooth or even abrupt variation in the out of eclipse range of the light curve.
(3) The morphology of the light curves clearly shows that both systems are detached eccentric eclipsing binaries and the analysis verified significant orbital eccentricity 0.3(0) for EM Cet and 0.3527(52) for EL Cen. Also, the obtained small fractional radii are expected values for detached systems having long orbital periods.
(4) The analysis of the light curves shows a relatively high eccentricity, $e =$ 0.3527(52), for the early type star EL Cen (Sp.type F3 + F5) rather than EM Cet of the later spectral type (F7 + G3) which has a lower eccentricity. This is consistent with tidal interaction theories that postulate the evolution of the orbit towards circularity (Mayer & Hanna, 1991).
(5) The analysis shows a high orbital inclination of both stars $87^{\circ}.06 \pm 0^{\circ}.05$ and $87^{\circ}.10 \pm 0^{\circ}.09$ for EM Cet and EL Cen, respectively, which is expected for such long period binaries (Kjurkchieva & Vasileva, 2015a).
(6) On comparing the two sets of parameters obtained from the analysis of the two light curves EM Cet_{ASAS} & EM Cet_{TESS}, one can notice that the differences are in the range of the estimated errors by PHOEBE for most parameters such as the eccentricity, the longitude of periastron, the inclination, the mass ratio and the phase shift. All are having almost the same values, while there is a considerable difference in $T_{2eff.}$ by about 270 K. This may be due to the the scatter seen in the ASAS data. Also, the limb darkening coefficients x_1, x_2 for the TESS light curve are smaller by about 30% than those of the ASAS light curve. However, it is preferable to consider the results of the TESS light curve since its profile is better than the scattered light curve of ASAS, and it was observed over a shorter interval of time.
Due to the absence of spectroscopic observations, we consider the present solution as a preliminary one. Spectroscopic observations are indeed necessary for accurate determination of the absolute parameters. In addition, we recommend observing times of minima of both systems to be able to study the period variability and the apsidal motion.

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