А С Т Р О Ф И З И К А

ТОМ 65 МАЙ, 2022 ВЫПУСК 2

DOI: 10.54503/0571-7132-2022.65.2-40

PHOTOMETRIC STUDY AND EVOLUTIONARY STATE FOR SOME NEWLY DISCOVERED W UMA SYSTEMS

M.S.ALENAZI[1], M.M.ELKHATEEB[2]
Received 17 February 2022
Accepted 3 May 2022

First orbital solution and photometric study for the newly discovered systems V968 CEP, ET CMI, and ES CMI was carried out by means of WD code (windows interface version) based on model atmosphere provided by Kurucz. Our modelling revealed absolute and physical parameters, which show that the primary components in all systems are hotter and more massive than the secondary components. According to the estimated parameters, the evolutionary statuses for all systems were estimated on theoretical mass-luminosity and mass-radius curves. Spectral types of the systems components were adopted using the estimated temperatures.

Keyword: *eclipsing binaries: light curve modelling: evolutionary state*

1. *Introduction*. Eclipsing binaries systems are the main target of light curve modelling studies, their orbital solution and radial velocity offer unique conditions to estimate fundamental parameters of stars, such as stellar radii, masses and luminosities. The estimated parameters are used to understanding and follow the evolutionary status and stellar structure of the eclipsing binary systems (Yilmaz et al. [1]). Using a complete set of photometric data in different bands, we performed an orbital solution for a newly discovered eclipsing binary systems of W UMA types, V968 CEP, ET CMI, and ES CMI. In the present paper we performed the first photometric investigation of the studied systems. The structure of the paper is as follow: section 2 provides some basic information about the studied systems, in section 3 we perform light curve modelling, in section 4 we display and discuss the evolutionary status of the studied systems. Finally the reached conclusion is outlined in section 5.

2. *Observations*. The variability of the studied systems V968 CEP, ET CMI, and ES CMI were discovered for the first time by Liakos and Niachros [2] during their observations of other eclipsing binaries. The systems ET CMI ($P=0^d.435898$), and ES CMI ($P=0^d.371038$) were discovered in the field of view of the known variable star AV CMI, while the system V968 CEP ($P=0^d.48404$) was discovered in the field of view of the variable star V405 CEP. Table 1 listed basic information about the studied systems together with used comparison and check stars for each system.

Table 1

THE COORDINATES AND MAGNITUDES OF THE VARIABLE, COMPARISON, AND CHECK STARS

Star name	α(2000.0)	δ(2000.0)	B	V	J	H
Variable (V968 CEP)	$02^h45^m36^s.32$	+79°13'35".33	15.33	14.76	13.29	13.11
Comparison (GSC 4516-01706)	$02^h44^m40^s.00$	+79°10'17".05	13.51	—	—	—
Check (GSC 4516-01124)	$02^h47^m18^s.30$	+79°09'52".00	13.43	—	—	—
Variable (ET CMI)	$07^h09^m21^s.00$	+12°12'14".00	12.96	—	12.28	12.10
Comparison (GSC 0770-00929)	$07^h09^m16^s.70$	+12°12'31".18	11.72	—	—	—
Check (GSC 0770-00911)	$07^h09^m21^s.00$	+12°09'40".00	11.21	—	—	—
Variable (ES CMI)	$07^h08^m40^s.00$	+12°14'43".04	—	—	13.72	13.48
Comparison (GSC 0757-00435)	$07^h08^m48^s.10$	+12°12'14".08	13.63	—	—	—
Check (GSC 0757-00134)	$07^h08^m49^s.00$	+12°11'25".12	13.84	—	—	—

All observations were carried out at the Gerostathopoulion observatory of the University of Athens from 2007 to 2009, using a 40-cm cassegrain telescope equipied with ST-8XMEi and ST-10XME CCD camera and the BVRI Bessell photometric filters. The system V968 CEP was observed in BVRI pass bands, while the systems ET CMI and ES CMI were observed in VRI pass bands. The corresponding phases to each observed data were calculated for all studied systems according to the ephemeris in Table 2 adopted by Liakos and Niachros [2]. Fig.1a, b, c displays the observed light curves for the systems V968 CEP, ET CMI, and ES CMI respectively.

Table 2

EPHEMERIS EQUATIONS FOR STUDIED SYSTEMS

Star Name	Ephemeris
V968 CEP	Min I = HJD 2455149.3084 + 0.484040 E
ET CMI	Min I = HJD 2454107.6042 + 0.435898 E
ES CMI	Min I = HJD 2454115.5345 + 0.371038 E

3. *Light curve analysis*. A photometric light curve analysis for the systems V968 CEP, ET CMI, and ES CMI were applied using the synthetic light curve and differential corrections program based on Wilson-Devinney (WD) binary star modeling code (Windows interface version) [3]. The code uses model atmospheres by Kurucz [4] and constructs a theoretical model with absolute parameters and synthetic light curves similar to the observed ones. Gravity darkening and bolometric albedo exponents appropriate for the convective envelopes ($T_{eff} < 7500°$ K) of the late

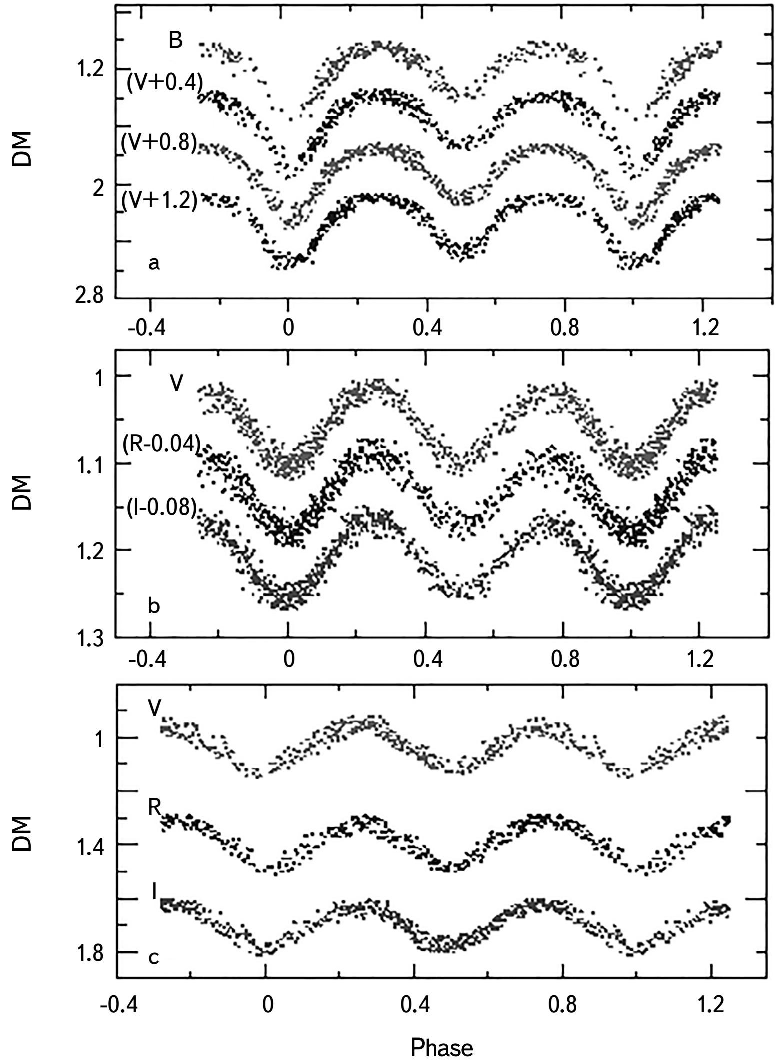

Fig.1. Observed light curves for the systems: a) V968 CEP, b) ET CMI, and c) ES CMI.

type stars were used as: $g_1 = g_2 = 0.32$ and $A_1 = A_2 = 0.5$ (Lucy 1967) [5], Rucinski [6]. The bolometric limb darkening coefficients were taken from the tables of Van Hamme [7] based on the logarithmic law for the extinction coefficients.

Morphology of light curves of the studied systems (continuous light variation) shows that they belong to W UMa systems. Mode 3 (overcontact mode) of the WD code was applied to the systems ES CMI and V968 CEP, while Mode 2 (detached) was applied to the system ET CMI and best matching between the observed and synthetic curves were reached after several runs. As the studied systems are new discovered ones they don't have any previous spectroscopic measurements (radial velocity), the initial value of mass ratio q was adopted by means of q-search method. This technique was carried out by a series of assumed mass ratio q with the values ranging from 0.10 to 0.90 using the adopted mode for each system. A resulting sums of the squared deviations $\sum(\mathrm{O-C})^2$ from convergent solution obtained for each assumed q value were plotted in Fig.2a, b, c for the studied systems. Values of q corresponding to the minima of $\sum(\mathrm{O-C})^2$ obtained for each studied system were adopted as initial values in system modelling runs.

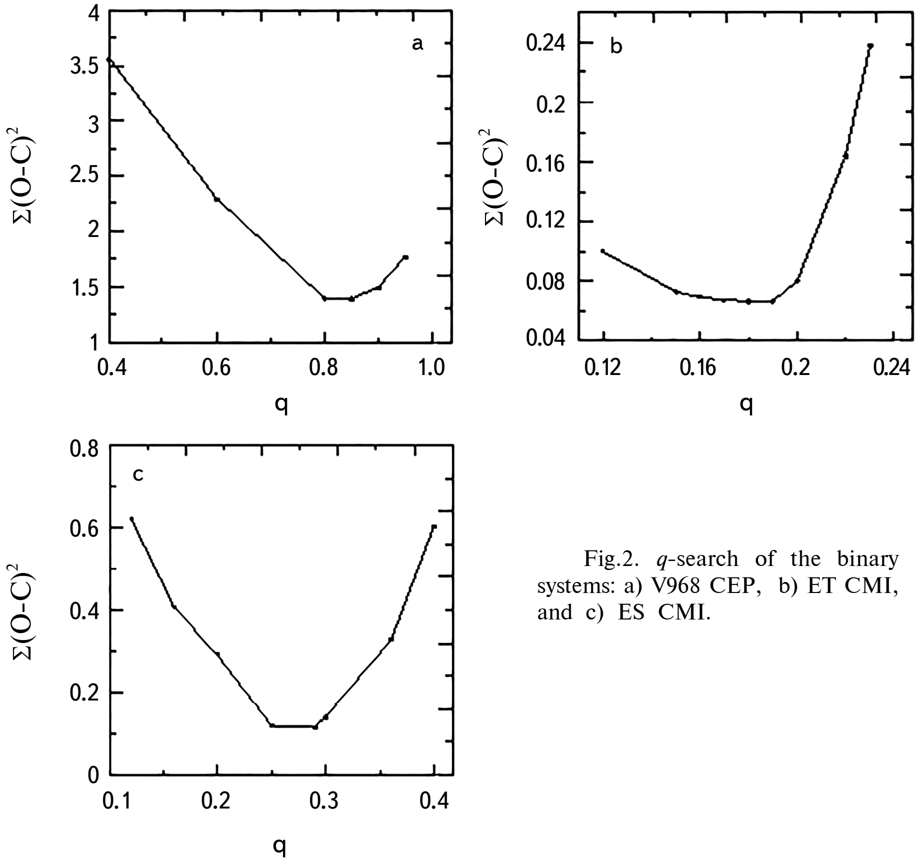

Fig.2. q-search of the binary systems: a) V968 CEP, b) ET CMI, and c) ES CMI.

During the photometric solution for best modelling estimation the adjustable parameters are; the mean temperature of the secondary star T_2, the orbital inclination i, the potential Ω (for Mode 3, $\Omega_1 = \Omega_2 = \Omega$), the mass ratio q, and the primary star luminosity L_1. Secondary star luminosity L_2 was calculated by the stellar atmosphere model. The initial values of the primary star's temperatures of the studied systems T_1 were estimated using the colour indexes $(J - H)$ and $(B - V)$ for each system listed in SIMBAD (http://simbad.u-strasbg.fr/simbad/sim-fbasic), where the corresponding initial temperatures for the primary component's T_1 were

Table 3

PHOTOMETRIC SOLUTION FOR THE SYSTEMS V968 CEP, ET CMI, AND ES CMI

Parameter	ET CMI	V968 CEP	ES CMI
i (°)	51.30±0.15	69.15±0.29	55.42±0.18
$g_1 = g_2$	0.32	0.32	0.32
$A_1 = A_2$	0.5	0.5	0.5
q (M_2/M_1)	0.1900±0.0005	0.8118±0.0030	0.2813±0.0008
Ω_1	2.2212±0.0029	$\Omega_1 = \Omega_2 = 3.3022 \pm 0.0071$	$\Omega_1 = \Omega_2 = 2.4088 \pm 0.0025$
Ω_2	2.2714±0.0027		
T_1 (°K)	7000 (fixed)	6016 (fixed)	6650 (fixed)
T_2 (°K)	6505±13	5251±4	5820±8
Ω_{in}	2.2076	3.4371	3.3501
Ω_{out}	2.0862	2.9811	2.9185
r_1 pole	0.4877±0.0017	0.3927±0.0024	0.4643±0.0014
r_1 side	0.5302±0.0024	0.4175±0.0032	0.5008±0.0018
r_1 back	0.5516±0.0029	0.4580±0.0052	0.5267±0.0019
r_2 pole	0.2138±0.0032	0.3582±0.0027	0.2600±0.0052
r_2 side	0.2207±0.0032	0.3788±0.0034	0.2712±0.0063
r_2 back	0.2423±0.0037	0.4227±0.0060	0.3066±0.0115
$\sum(O - C)^2$	0.06651	0.44107	0.11665

adopted using Tokunaga [8] relation. The photometric solution for the systems V968 CEP, ET CMI, and ES CMI are given in Table 3.

3.1. *V968 CEP*. The observed light curves of the system V968 CEP were analyzed using Mode 3 (over contact) of the WD code [3] in BVRI filters. Series of calculations were applied and best photometric fitting were reached. The

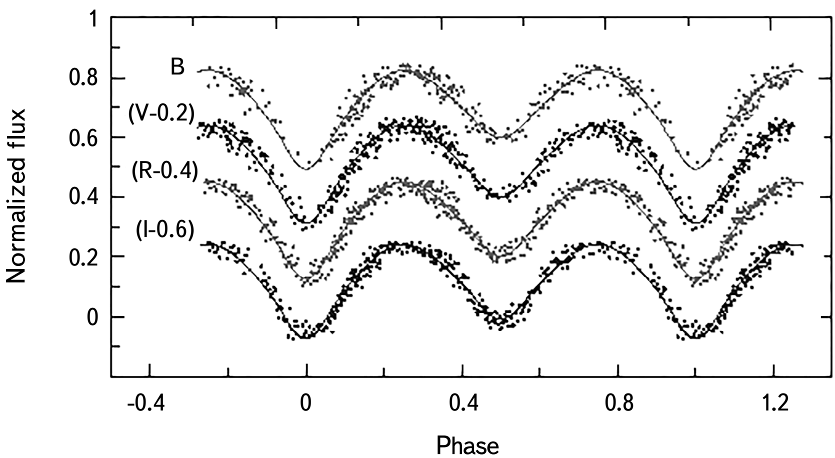

Fig.3. Synthetic (lines) and observed (dots) light curves for the system V968 CEP.

accepted model reveals orbital parameters listed in Table 3, which indicates that the primary component of the system V968 CEP is hotter than the secondary one. According to the estimated parameters, the primary and secondary components are of spectral types G0 and G9, respectively (Popper [9]). Fig.3 displays synthetic and observed light curves for the system V968 CEP in BVRI filters.

3.2. *ES CMI*. Photometric analysis for the observed light curves of the system ES CMI was applied in VRI pass bands using Mode 3 (over contact) of the WD code [3]. The accepted model was adopted after some trials and a set of absolute parameters describing the model were estimated and listed in Table 3. The estimated parameters show that the primary component of the system ES CMI is hotter than the secondary one and belongs to spectral type F5 while the secondary is G2 type (Popper [9]). Fig.4 displays the synthetic light curves together with the observed one in VRI pass bands.

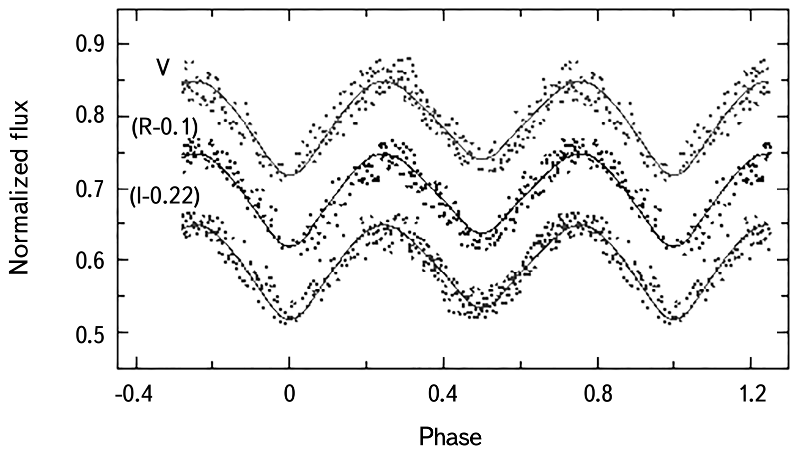

Fig.4. Synthetic (lines) and observed (dots) light curves for the system ES CMI.

3.3. *ET CMI*. Light curve analysis and photometric solution for the system ET CMI was performed using Mode 2 (detached) of the WD code in VRI pass bands [3]. Series of trials were made to derive set of parameters which marginally represented the observed light curves. The best photometric fitting was reached after several runs and the accepted model shows that the primary component is hotter than the secondary one. The estimated parameters were listed in Table 3, while Fig.5 displays the synthetic light curves of the system ET CMI together with the observed ones in VRI pass bands. According to the adopted temperature for the primary and secondary components, they belong to spectral type F2 and F6, respectively (Popper [9]).

Since physical parameters estimations for the eclipsing binary components

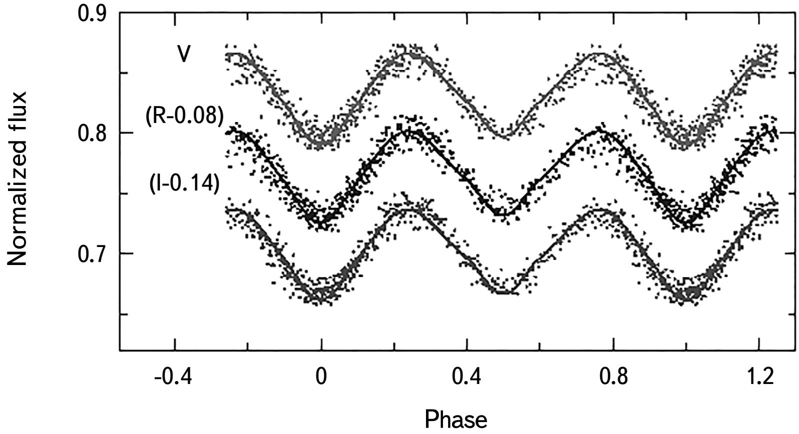

Fig.5. Synthetic (lines) and observed (dots) light curves for the system ET CMI.

depend on the spectroscopic observations of radial velocity and as we mentioned earlier, the studied systems are new discovered objects with no previous spectroscopic observations, therefore, absolute physical parameters were calculated for the star's components by means of the empirical T_{eff} - Mass relation adopted by Harmanec [10]. Table 4 listed the estimated parameters which show that the primary components in all systems are more massive than the secondary ones. A three dimensional structure of the studied systems based on the estimated parameters were constructed by means of the software package Binary Maker 3.03 (Bradstreet and Steelman [11]) and displayed in Fig.6a, b, and c.

Table 4

ABSOLUTE PHYSICAL PARAMETERS FOR THE SYSTEMS V968 CEP, ET CMI AND ES CMI

Element	Star name		
	V968 CEP	ET CMI	ES CMI
M_1 ($M_\odot$)	1.1900±0.0486	1.5056±0.0615	1.3954±0.0570
M_2 ($M_\odot$)	0.9660±0.0394	0.2861±0.0117	0.3925±0.0160
R_1 ($R_\odot$)	1.2833±0.0524	1.5658±0.0639	1.4709±0.0601
R_2 ($R_\odot$)	1.0288±0.0420	1.4298±0.0584	1.2210±0.0499
T_1 ($T_\odot$)	1.0412±0.0425	1.2115±0.0495	1.1509±0.0470
T_2 ($T_\odot$)	0.9088±0.0371	1.1258±0.0460	1.0073±0.0411
L_1 ($L_\odot$)	1.9328±0.0789	5.2742±0.2153	3.7909±0.1548
L_2 ($L_\odot$)	0.7210±0.0294	3.2797±0.1339	1.5325±0.0626
M_{bol1}	4.0346±0.1647	2.9446±0.1202	3.3032±0.1349
M_{bol2}	5.1052±0.2084	3.4604±0.1413	4.2865±0.1750
Sp. Type	(G0)[1], (G9)[2]	(F2)[1], (F6)[2]	(F5)[1], (G2)[2]

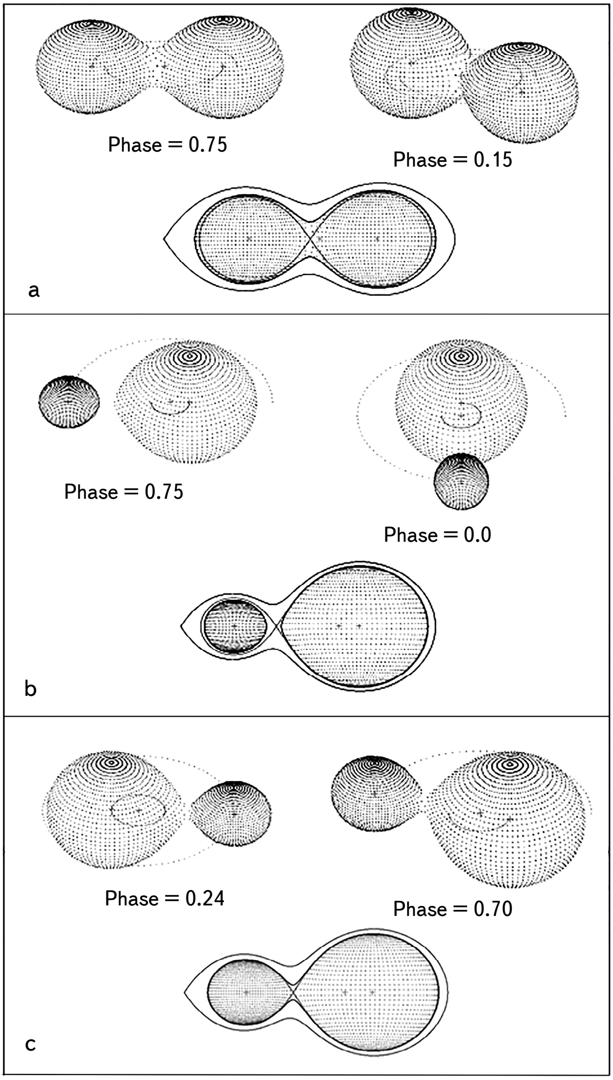

Fig.6. Three dimension structure of the binary systems a) V968 CEP, b) ET CMI, and c) ES CMI.

4. *Evolutionary state*. Based on the estimated physical parameters listed in Table 4 for the systems V968 CEP, ET CMI, and ES CMI, the evolutionary status of the systems were investigated using mass-luminosity *M-L*, mass-radius *M-R* relations, and evolutionary tracks computed by Girardi et al [12] for both thermal age main sequence stars (TAMS) and zero age main sequence stars (ZAMS) with metallicity $z = 0.019$. The empirical mass-effective temperature

relation (M-T_{eff}) of intermediate and low-mass eclipsing binaries and luminosity-effective temperature (L-T_{eff}) relation of non-rotating models were used. Fig.7a, b displays the locations of the primary and secondary components of the studied systems on mass-luminosity curve M-L and mass-radius M-R curve. All the primary components of the studied systems and the secondary component of the system V968 CEP (S_2) lies near the ZAMS track, while the secondary components of the systems ET CMI and ES CMI lies above the TAMS track. Deviation in the locations of the secondary components of the systems ET CMI and ES CMI can be ascribed to energy transfer from the primary to the secondary component through the common convective envelope (Lucy [13]).

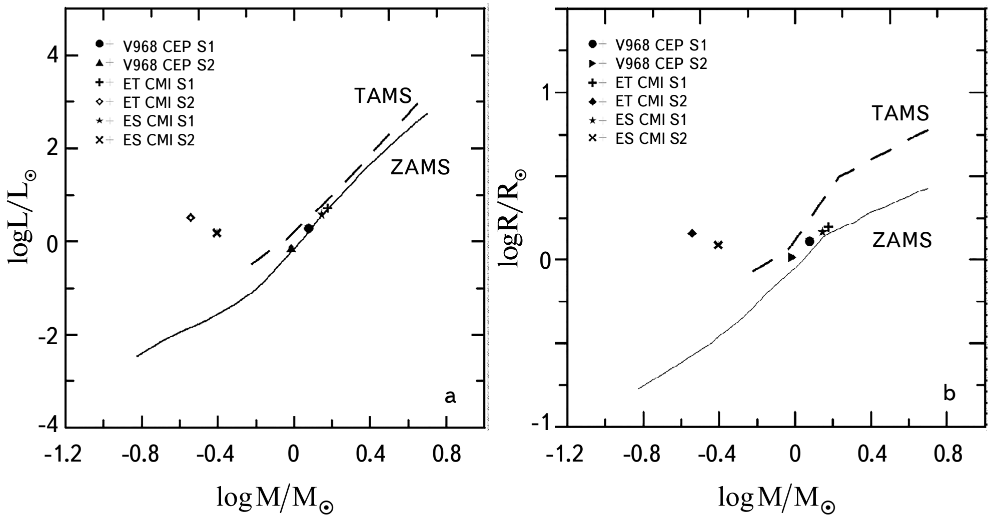

Fig.7. Positions of the components (S_1, S2) of the systems V968 CEP, ET CMI and ES CMI on the theoretical: a) mass-luminosity diagram and b) mass-radius diagram of Girardi et al. (2000).

Components of the studied systems were assigned on the (T_{eff} -L) diagram as shown in Fig.8 by means of the non-rotating evolutionary models of Ekstrom et al. [14] at solar metallicity z=0.014, all systems components lie on the expected tracks as shown in the figure. Fig.9 displays the mass-effective temperature relation (M-T_{eff}) for intermediate and low-mass stars (Malkov [15]) for the studied systems. Locations of the systems components have a good fit except for the secondary components of the systems ET CMI and ES CMI, they show a deviation. The latter two components show the same behaviour as for mass luminosity and mass-radius relations.

5. *Discussion and conclusion*. The systems V968 CEP, ET CMI, and ES CMI were discovered and classified as eclipsing binary objects in 2010. New

CCD observations for the systems were carried out in different pass bands and first orbital solution was estimated and absolute parameters were calculated. The parameters indicate that the primary components in all studied systems are more

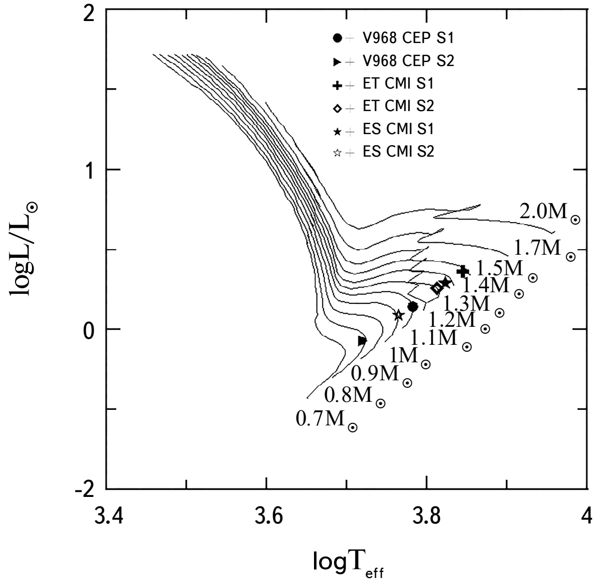

Fig.8. Positions of the components (S_1, S_2) of the systems V968 CEP, ET CMI and ES CMI on the effective temperature-luminosity diagram of Ekstrom et al (2012).

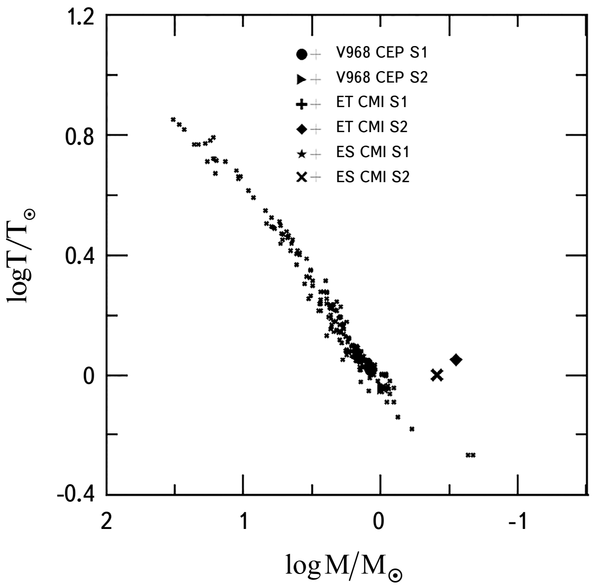

Fig.9. Positions of the components (S_1, S2) of the systems V968 CEP, ET CMI and ES CMI on the empirical mass-T_{eff} relation for low-intermediate mass stars by Malkov (2007).

massive and hotter than the secondary components. Spectral types of the systems components were adopted using the estimated temperatures. The evolutionary status for the studied systems was investigated in terms of *M-R* and *M-L* relations. All the components of the studied systems are located near the ZAMS track except the secondary components of the systems; ET CMI and ES CMI where they lie above the TAMS track, which may be explained by energy transfer from the primary to the secondary through the common convective envelope.

[1] Physics Dept., Faculty of Science, Northern Border University, Arar 91431-1321, Saudi Arabia
[2] Astronomy Dept., National Research Institute of Astronomy and Geophysics (NRIAG), Helwan, Cairo, Egypt, e-mail: magdyelkhateeb55@gmail.com

ФОТОМЕТРИЧЕСКОЕ ИССЛЕДОВАНИЕ И ЭВОЛЮЦИОННОЕ СОСТОЯНИЕ НЕКОТОРЫХ НОВЫХ СИСТЕМ ТИПА W UMA

М.С.АЛЕНАЗИ[1], М.М.ЭЛЬХАТИБ[2]

Впервые представлены орбитальные решения и фотометрические исследования недавно открытых систем V968 CEP, ET CMI и ES CMI, выполненные с помощью кода WD (версия интерфейса Windows), на основе моделей атмосфер Куруца. Наше моделирование выявило абсолютные и физические параметры, которые показывают, что первичные компоненты во всех системах более горячие и массивные, чем вторичные компоненты. Согласно рассчитанным параметрам, эволюционные статусы для всех систем оценивались по теоретическим кривым масса-светимость и масса-радиус. Спектральные типы компонентов систем приняты исходя из расчетных температур.

Ключевые слова: *затменные двойные звезды:моделирование кривой блеска: эволюционный статус*

REFERENCES

1. *M.Yilmaz*, *R.Nelson*, *H.Senavci et al.*, RMxAA, **53**, 29, 2017.
2. *A.Liakos*, *P.Niachros*, Journal Peremennye Zvezdy, **10**, 9, 2010.
3. *R.Wilson*, *E.Devinney*, *W. Van Hamme*, ascl.soft04004W, 2020.
4. *R.Kurucz*, in: E.Milon, (Ed.), Light Curve Modeling of Eclipsing Binary Stars. Springer-Verlag, New York, p.93, 1993.
5. *L.Lucy*, Z. Astrophys., **65**, 89, 1967.
6. *S.Rucinski*, Acta Astronaut., **19**, 156, 1969.
7. *W. Van Hamme*, Astron. J., **106**, 2096, 1993.
8. *A.T.Tokunaga*, Allen's Astrophysical Quantities, fourth ed. AIP Press; Springer, New York, 2000.
9. *D.Popper*, Ann. Rev. Astron. Astrophys., **18**, 115, 1980.
10. *P.Harmanec*, Bull. Astron. Inst. Czechosl., **39**, 329, 1988.
11. *D.Bradstreet*, *D.Steelman*, AAS, **201**, 7502, 2004.
12. *L.Girardi*, *A.Bressan*, *G.Bertelli et al.*, Astron. Astrophys. Suppl. Ser., **141**, 371, 2000.
13. *L.Lucy*, Astron. Astrophys. Suppl. Ser., **22**, 381, 1973.
14. *S.Ekström*, *C.Georgy*, *P.Eggenberger et al.*, Astron. Astrophys., **537**, 146, 2012.
15. *O.Malkov*, Mon. Not. Roy. Astron. Soc., **382**, 1073, 2007.