АСТРОФИЗИКА

ТОМ 64 ФЕВРАЛЬ, 2021 ВЫПУСК 1

LIGHT CURVE ANALYSIS OF SOME ECLIPSING BINARY SYSTEMS

M.S.ALENAZI[1], M.M.ELKATEEB[1,2]

Received 16 July 2020
Accepted 23 December 2020

We present the first photometric observations and light curve modelling of the discovered systems GSC 01870-00458 and USNO-A2.0-0975 04721840. Our modelling was carried out using a recent Windows interface version of Wilson and Devinney code based on model atmospheres provided by Kurucz. The accepted models revealed absolute and physical parameters that can be used to study the evolutionary states of systems. The parameters show that primary component is more massive and hotter than the secondary component for both systems, and spectral types of the system components were adopted. Locations of both systems on theoretical mass-luminosity and mass-radius curves revealed a good fit for components of both systems except for the secondary component of the system GSC 01870-00458.

Keywords: *light curve: eclipsing binary: GSC 01870-00458: USNO-A2.0-0975 04721840*

1. *Introduction*. Studies of eclipsing binaries are the primary source of our knowledge of the fundamental properties of stars, which often a combination of photometric and spectroscopic data (Kallrath, Milion [1]). Photometric and spectroscopic observations of eclipsing binary systems are essential in deriving absolute parameters of the components, such as the stellar radii and effective temperatures. These parameters and many others are important to understanding the evolutionary stage and stellar structure of eclipsing binary systems (Yilmaz et al. [2]). The present paper models the light curves of the discovered systems GSC 01870-00458 and USNO-A2.0-0975 04721840. Table 1 lists the coordinates of the systems together with their comparison and check stars. The remainder of the paper is organized as follows. Section 2 briefly describes the studied systems while section 3 models light curves. Section 4 discusses the evolutionary status for both systems. The summary of the results and conclusions of the study are presented in section 5.

2. *Observations*.

2.1. *GSC 01870-00458*. The system GSC 01870-00458 was used as a comparison star for the system V781 Tau by Liu et al. [3] and discovered to be a variable star by Nakajima and Nagai [4] during their observations of the system V781 Tau. Nakajima, Nagai listed the system as an Algol-type eclipsing binary

Table 1

COORDINATES AND *BV* MAGNITUDE OF THE VARIABLE, COMPARISON AND CHECK STARS

Star Name	α (2000.0)	δ (2000.0)	*B*	*V*	*B-V*
Variable (GSC 01870-00458)	$05^h50'25''.88$	$+26°56'50''.60$	10.91	10.89	0.02
Comparison (GSC 01870-00582)	$05^h50'20''.80$	$+26°56'42''.36$	11.92	11.46	0.46
Check (GSC 01870-00514)	$05^h50'22''.39$	$+26°59'55''.00$	10.13	9.68	0.45
Variable (USNO-A2.0-0975 04721840)	$07^h09'56''.34$	$+12°06'08''.20$	16.06	15.18	0.88
Comparison (USNO-A2.0-0975 04707248)	$07^h09'26''.30$	$+12°12'16''.92$	14.6	-	-
Check (GSC 00770-00051)	$07^h09'25''.84$	$+12°11'42''.43$	13.53	-	-

variable star with a period $P = 1^d.08481$. Complete *BVRc* light curves were observed by Nakajima and Nagai [4] on 37 nights from December 15, 2003 to January 7, 2005 using a Meade LX200 0.25-m f/6.3 SCT telescope with a CV-04 (KAF-401) (CCD) detector. The systems GSC 01870-00582 and GSC 01870-00514 were used as comparison and check stars respectively during the observations. Table 1 lists their basic information while Fig.1 presents observed light curves in *BVRc* pass bands. The ephemeris adopted by Nakajima and Nagai [4] was used to calculate the individual phases of all observational data:

$$\text{Min. I} = \text{HJD}\, 2452996.043 + 1.084737 \times \text{E}. \qquad (1)$$

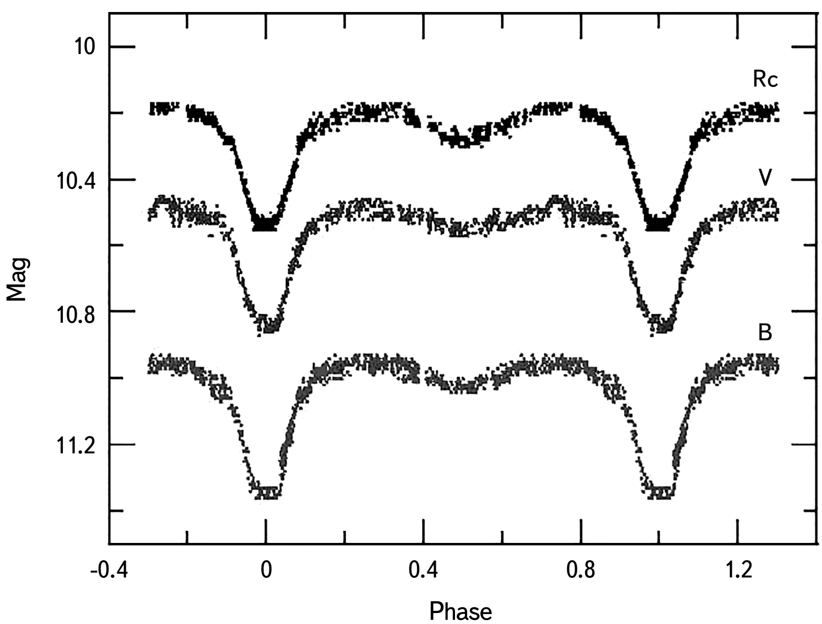

Fig.1. CCD light curves of the system GSC 01870-00458 in the *BVRc* pass band.

2.2. *USNO-A2.0-0975 04721840*. Liakos and Niachros [5] discovered the system USNO-A2.0-0975 04721840 ($P = 0^d.50460$) to be a variable star in the field of the systems AV CMi and GSC 00770-00523 and classified as an EB-type light curves. They carried out the first CCD photometric observations of the new system in *VI* (Bessell) pass bands using a 0.4-m Cassegrain f/8.1 telescope equipped with an SBIG ST-10XME CCD camera at the observatory of the University of Athens, Greece. The systems USNO-A2.0-0975 04707248 and GSC 00770-00051 were used as comparison and check stars respectively during the observations. Their basic information is listed in Table 1, while the observed light curves are presented in Fig.2 in *VI* (Bessell) pass bands. The phases of the individual observations were calculated using the first ephemeris estimated by Liakos and Niachros [5]:

$$\text{Min.I} = \text{HJD}\,2455594.4123(6) + 0.50460(3) \times \text{E}. \quad (2)$$

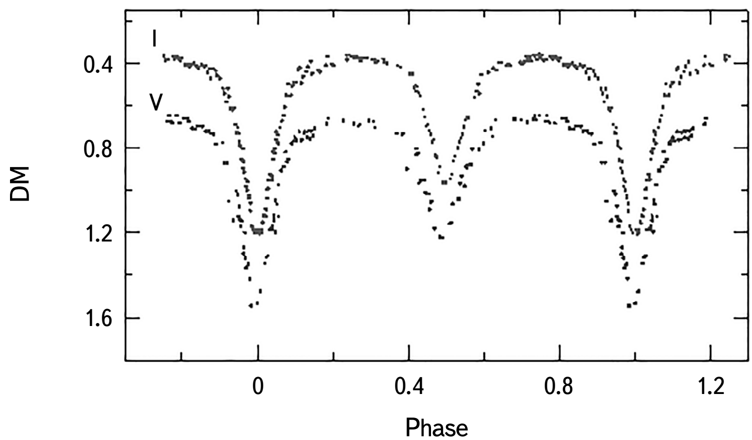

Fig.2. CCD light curves of the system USNO-A2.0-0975 04721840 in the *VI* (Bessell) pass band.

3. *Photometric analysis*. The observed light curves of the studied systems were analysed using the 2009 version of the Wilson and Devinney code (Windows interface version by Nelson [6]) to estimate the orbital elements describing the observed curves. The used code applies a model atmosphere created by Kurucz [7] and produces synthetic light curves similar to observed light curves using constructed models and adopted absolute parameters. The initial values of temperatures of the primary component T_1 for both systems were estimated using the color index ($J - H$) for each system listed in SIMBAD (http://simbad.u-strasbg.fr/simbad/sim-fbasic), where the corresponding temperature was estimated using the ($J - H$) color index relation of Pecaut, Mamaek [8]. The temperature adopted for the primary component of each system was used as an initial value in the modelling of light curves. Gravity darkening exponents (g_1, g_2) and bolometric

albedo values (A_1, A_2) were adopted following Lucy [9] and Rucinski [10] for the convective envelopes (T_{eff} > 7500 K) of late-type stars as $g_1 = g_2 = 0.32$ and $A_1 = A_2 = 0.5$. Limb darkening coefficients based on the interpolated logarithmic law were taken from the tables of Van Hamme [11]. Spectroscopic measurements of the radial velocity for eclipsing binary systems are known to be important in adjusting the mass ratio q. The studied systems are new systems and thus do not have a history of spectroscopic observations, and we thus adopted a q-search to estimate the initial values for the systems mass ratio q. A q-search based on mass ratios q with values ranging from 0.10 to 0.9 was conducted by means of Mode (5) for the system GSC 01870-00458 and Mode (2) for the system USNO-A2.0-0975 04721840. A convergent solution was obtained for each assumed q value. The sum of squared deviations $\Sigma(\mathrm{O-C})^2$ for each q value is presented in Fig.3a, b for the two studied systems. The mass ratio q corresponding to the minima of $\Sigma(\mathrm{O-C})^2$ was used as an initial value. Adjustable parameters in modelling were the orbital inclination i, mass ratio q, mean temperature of the secondary star T_2, potential of the components Ω_1, Ω_2, and luminosity of the primary star L_1. The relative brightness of the secondary star L_2 was calculated from stellar atmospheric models.

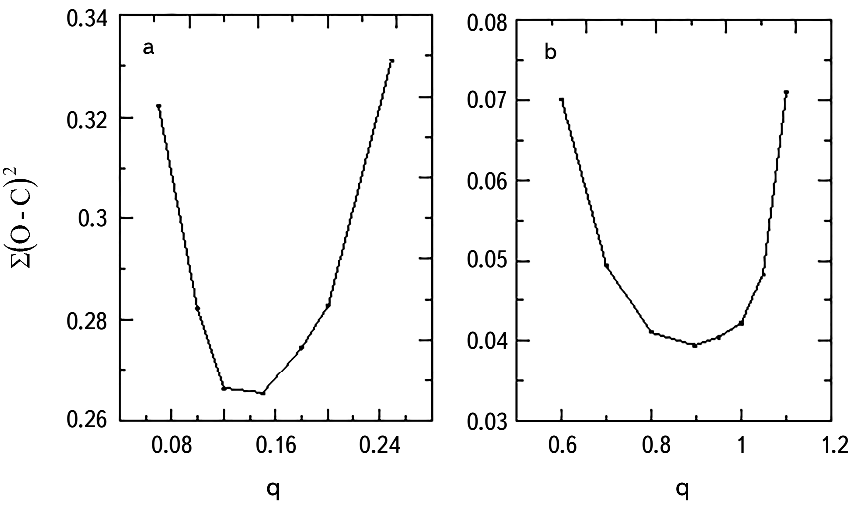

Fig.3. q-search of binary systems: a) GSC 01870-00458, and b) USNO-A2.0-0975 04721840.

3.1. *GSC 01870-00458*. The first observed *BVRc* light curves of the discovered system GSC 01870-00458 were analysed using Mode 5 (semidet-Algol) of the Wilson and Devinny code (Windows interface version) developed by Nelson [6]. As mentioned earlier, the initial value of the mass ratio q was adopted according to a q-search (see Fig.3a). An acceptable model was adopted following

Table 2

PHOTOMETRIC SOLUTION FOR THE SYSTEMS GSC 01870-00458 AND USNO-A2.0-0975 04721840

Parameter	GSC 01870-00458	USNO-A2.0 0975-04721840
i (°)	78.29 ± 0.10	84.95 ± 0.26
$g_1 = g_2$	0.32	0.32
$A_1 = A_2$	0.5	0.5
q (M_2/M_1)	0.1556 ± 0.0009	0.8955 ± 0.0045
Ω_1	2.3941 ± 0.0035	4.1105 ± 0.0126
Ω_2	2.1182	3.6777 ± 0.0119
T_1 (°K)	7110 (fixed)	5300 (fixed)
T_2 (°K)	4272 ± 11	4896 ± 5
Ω_{in}	2.1182	3.5780
Ω_{out}	2.0178	3.0826
r_1 pole	0.4441 ± 0.0009	0.3073 ± 0.0055
r_1 side	0.4705 ± 0.0011	0.3163 ± 0.0062
r_1 back	0.4806 ± 0.0013	0.3290 ± 0.0075
r_2 pole	0.2165 ± 0.0009	0.3345 ± 0.0073
r_2 side	0.2251 ± 0.0009	0.3490 ± 0.0088
r_2 back	0.2571 ± 0.0009	0.3746 ± 0.0122
$\Sigma(O - C)^2$	0.25045	0.03947

trials with adjustable parameters. The parameters obtained using the model are listed in Table 2, which shows that the primary component of the system GSC

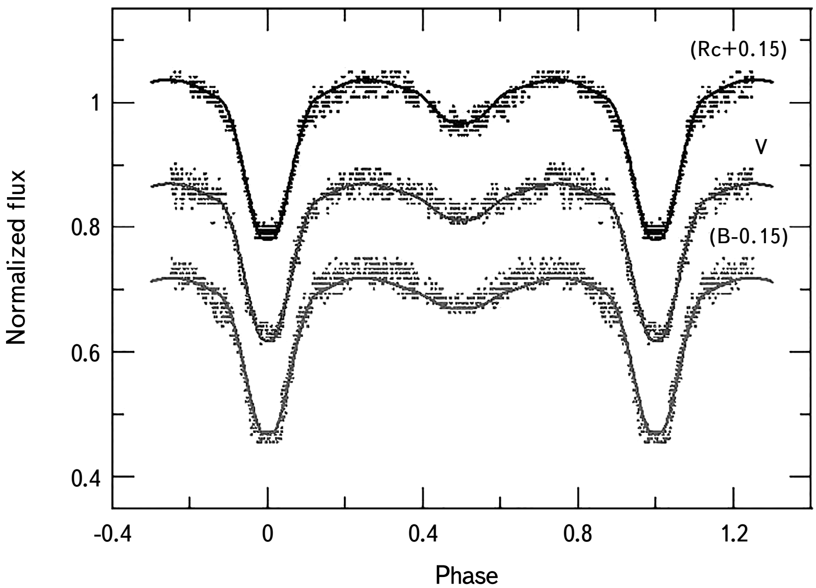

Fig.4. Synthetic and observed curves for the system GSC 01870-00458.

01870-00458 is hotter than the secondary component by 2838 K, and consequently, their spectral types are F1 and K6 respectively according to their adopted temperatures (Popper [12]). Fig.4 presents the observed light curves (normalized flux) of the system GSC 01870-00458 (filled circles) together with synthetic light curves (solid line) obtained using the adopted model in *BVRc* pass bands.

3.2. *USNO-A2.0-0975 04721840.* A photometric study of the discovered EB system USNO-A2.0-0975 04721840 was first carried out using the observed light curves in the *VI* (Bessell) pass band adopting Mode 2 (detached) of the Wilson and Devinney code developed by Nelson [6]. The accepted model shows that the spectral types of the primary and secondary components are G8 and K2 respectively and that the primary component is 404 K hotter than the secondary component. Table 2 lists the estimated parameters of the photometric solution while Fig.5 displays the reflected observed points (normalized flux) in *VI* (Bessell) pass bands together with the corresponding theoretical light curves obtained using the model.

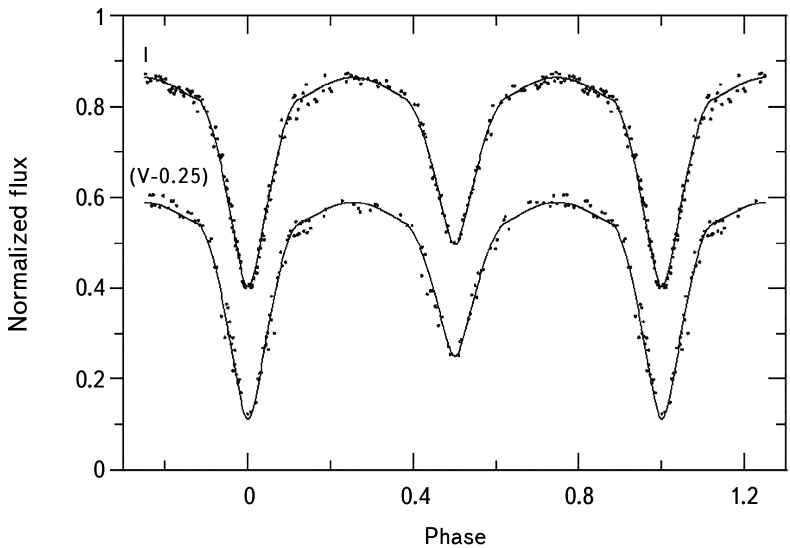

Fig.5. Synthetic and observed curves for the system USNO-A2.0-0975 04721840.

Spectroscopic observations of the radial velocity are the main source of data used in estimating physical parameters of the eclipsing binary components. For the discovered systems there are no previous spectroscopic observations, and the absolute physical parameters were estimated using the empirical T_{eff}-mass relation given by Harmanec [13]. Table 3 lists the calculated absolute physical parameters of the components of the studied systems. The parameters show that the primary components are more massive than the secondary component for both systems.

Table 3

ABSOLUTE PHYSICAL PARAMETERS FOR GSC 01870-00458 AND USNO-A2.0-0975 04721840

Element	Star name	
	GSC 01870-00458	USNO-A2.0-0975 04721840
M_1 ($M_\odot$)	1.5399 ± 0.0629	0.9477 ± 0.0387
M_2 ($M_\odot$)	0.2396 ± 0.0098	0.8487 ± 0.0347
R_1 ($R_\odot$)	1.5944 ± 0.0651	1.0460 ± 0.0427
R_2 ($R_\odot$)	0.6670 ± 0.0272	0.9011 ± 0.0368
T_1 ($T_\odot$)	1.2305 ± 0.0502	0.9173 ± 0.0375
T_2 ($T_\odot$)	0.7394 ± 0.0302	0.8474 ± 0.0346
L_1 ($L_\odot$)	5.8205 ± 0.2376	0.7735 ± 0.0316
L_2 ($L_\odot$)	0.1328 ± 0.0054	0.4180 ± 0.0171
M_{bol_1}	2.8376 ± 0.1159	5.0289 ± 0.2053
M_{bol_2}	6.9423 ± 0.2834	5.6970 ± 0.2326
Sp. Type	$(F1)^1$, $(K6)^2$	$(G8)^1$, $(K2)^2$

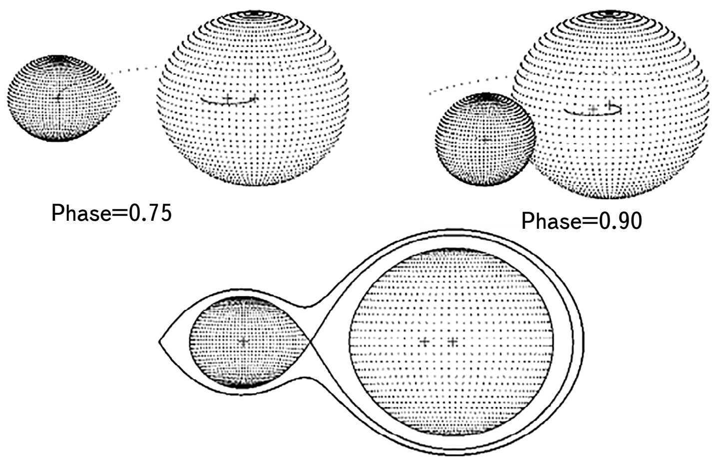

Fig.6. Three-dimensional structure of the binary system GSC 01870-00458.

Geometrical structures of the studied systems were created according to the calculated parameters using the software package Binary Maker 3.03 (Bradstreet, Steelman [14]) and are displayed in Fig.6, 7.

4. *Evolutionary states*. Evolutionary states of the studied systems were investigated using the estimated physical parameters listed in Table 3 by means of mass-luminosity *M-L* and mass-radius *M-R* relations and the evolutionary tracks computed by Girardi et al. [15] for both zero age main sequence stars

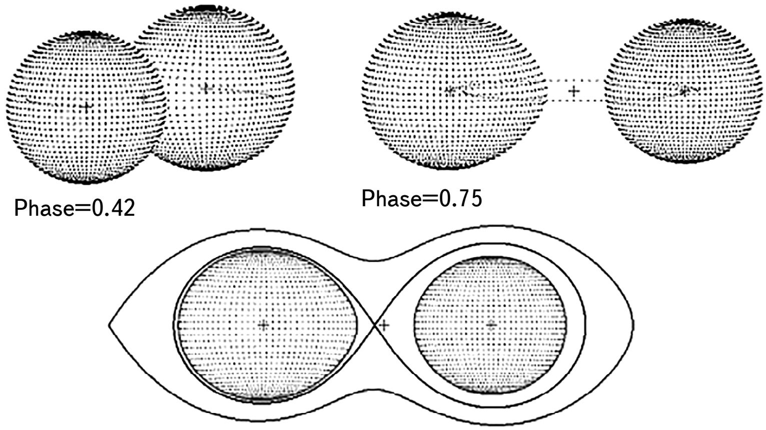

Fig.7. Three-dimensional structure of the binary system USNO-A2.0-0975 04721840.

(ZAMS) and thermal age main sequence stars (TAMS) with metallicity $z = 0.019$. We also used the luminosity-effective temperature L-T_{eff} relation of non-rotating models and the empirical mass-effective temperature M-T_{eff} relation of intermediate and low-mass eclipsing binaries. Fig.8a, b present the locations of the components of the studied systems on the curves of mass-luminosity M-L and mass-radius M-R relations. The figures show that the components of the system USNO-A2.0-0975 04721840 (S_1, S_2) are located near the ZAMS while the primary component S_1 of the system GSC 01870-00458 is located on the ZAMS, and the secondary

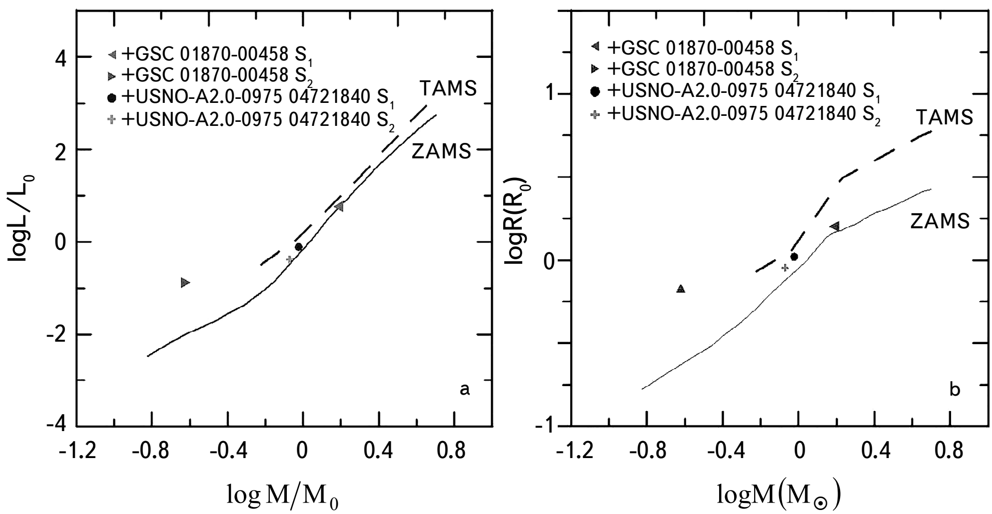

Fig.8. Positions of the components (S_1,S_2) of the systems GSC 01870-00458 and USNO-A2.0-0975 04721840 on the a) theoretical mass-luminosity diagram and b) theoretical mass-radius diagram of Girardi et al. (2000).

component S_2 lies above the TAMS track. The deviation of secondaries is ascribed to energy transfer from the primary to secondary through the common convective envelope, as suggested by Lucy [16]. Using the non-rotating evolutionary models of Ekstrom et al. [17] at solar metallicity $z = 0.014$, we assigned components of the two systems on the T_{eff}-L relation as shown in Fig.9. Both components of system USNO-A2.0-0975 04721840 (S_1, S_2) and the primary component S_1 of

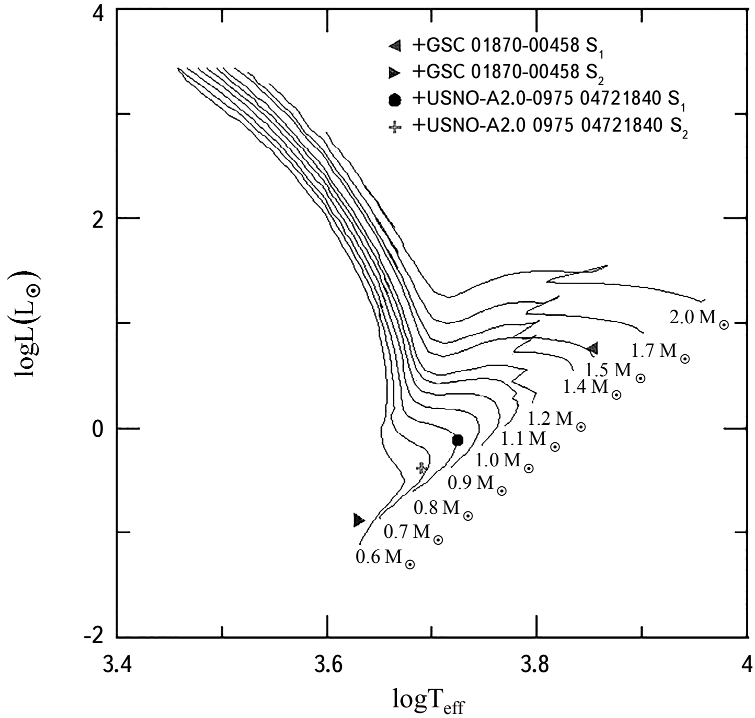

Fig.9. Positions of the components (S_1,S_2) of the systems GSC 01870-00458 and USNO-A2.0-0975 04721840 on the effective temperature-luminosity diagram of Ekstrom et al. (2012).

system GSC 01870-00458 lie on expected tracks, while the secondary component S_2 of system GSC 01870-00458 deviates from the expected track. The mass-effective temperature relation M-T_{eff} for intermediate and low-mass stars (Malkov [18]) is displayed in Fig.10 for both systems. The locations of the studied systems on the M-$T_{\rm eff}$ diagram have a good fit for the components of system USNO-A2.0-0975 04721840 (S_1, S_2) and the primary component S_1 of system GSC 01870-00458, while the secondary component S_2 of system GSC 01870-00458 has a poor fit. The components thus have the same behaviour in terms of mass-luminosity and mass-radius relations.

5. *Discussion and conclusion*. The semidetached system GSC 01870-00458 and detached system USNO-A2.0-0975 04721840 were discovered as

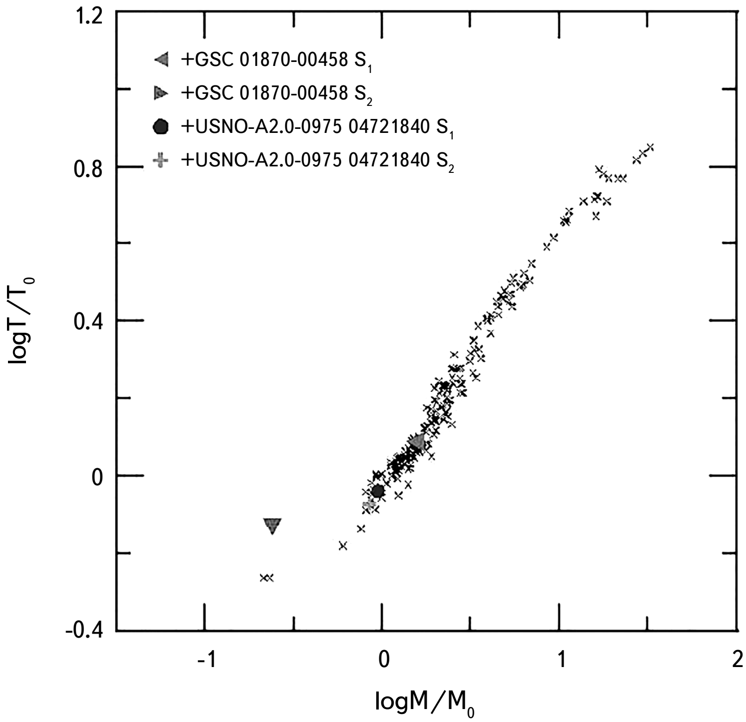

Fig.10. Positions of the components S_1, S_2 of the systems GSC 01870-00458 and USNO-A2.0-0975 04721840 on the empirical M-$T_{\rm eff}$ curve for low-intermediate-mass stars provided by Malkov (2007).

eclipsing binary systems in 2006 and 2011 respectively. CCD observations of the two systems were used to estimate orbital solutions, which revealed absolute and physical parameters. The estimated parameters showed that the primary component is hotter and more massive than the secondary component for both systems. Spectral types of the system components were adopted according to estimated temperatures. The evolution of the studied systems was investigated to explore behaviours in terms of *M-R* and *M-L* relations. The locations of components of both systems on *M-R* and *M-L* relations fitted ZAMS tracks except in the case of the secondary component of the system GSC 01870-00458. The system GSC 01870-00458 is semidetached whereby the secondary component star is filling its Roche lobe and transferring mass to the primary on a thermal time scale. The secondary star is out of thermal equilibrium, which may explain its behaviour.

Acknowledgements. The authors gratefully acknowledge approval and support of this research from the Deanship of Scientific Research at Northern Border University, Arar, Saudi Arabia under grant no. 2019-1-10-F and thank Glenn

Pennycook, MSc, from Edanz Group (https://en-author-service-edanzgroup.com/ac/) for editing a draft of this manuscript.

[1] Physics Dept., Faculty of Science, Northern Border University, Arar, 91431-1321, Saudi Arabia, e-mail: Elkhateeb@nbu.edu.sa

[2] Astronomy Dept., National Research Institute of Astronomy and Geophysics (NRIAG), 11421, Helwan, Cairo, Egypt

АНАЛИЗ КРИВЫХ БЛЕСКА НЕКОТОРЫХ ЗАТМЕННЫХ ДВОЙНЫХ СИСТЕМ

М.С.АЛЕНАЗИ[1], М.М.ЭЛЬХАТИБ[1,2]

Представлены первые фотометрические наблюдения и моделирование кривых блеска обнаруженных систем GSC 01870-00458 и USNO-A2.0-0975 04721840. Моделирование проводилось с использованием последней версии кода Уилсона и Девинни для интерфейса Windows на основе моделей атмосфер Куруца. Принятые модели позволили определить физические параметры, которые могут быть использованы для изучения эволюционных состояний систем, а также спектральные классы компонентов системы. Параметры показывают, что для обеих систем первичный компонент более массивный и горячий, чем вторичный. Расположение систем на теоретических кривых масса-светимость и масса-радиус хорошо соответствует ожидаемому расположению для компонентов обеих систем за исключением вторичного компонента системы GSC 01870-00458.

Ключевые слова: *кривая блеска: затменная двойная: GSC 01870-00458: USNO-A2.0-0975 04721840*

REFERENCES

1. *J.Kallrath*, *E.Milion*, in Eclipsing Binary Stars Modelling and Analysis, New York Springer, 1999.
2. *M.Yilmaz*, *R.Nelson*, *H.Senavci et al.*, RMxAA, **53**, 29, 2017.

3. *Q.Liu*, *Y.Yang*, Astron. Astrophys. Suppl., **142**, 31, 2000.
4. *K.Nakajima*, *K.Nagai*, Inf. Bull. Var. Stars, 5700, 2006.
5. *A.Liakos*, *P.Niachros*, Inf. Bull. Var. Stars, 5998, 2011.
6. *R.Nelson*, http://members.shaw.ca/bob.nelson/software1.htm, 2009.
7. *R.Kurucz*, In: E.Milon (Ed.), Light Curve Modeling of Eclipsing Binary Stars. Springer-Verlag, New York, p.93, 1993.
8. *M.Pecaut*, *E.Mamaek*, Astrophys. J. Suppl. Ser., **208**, 9, 2013.
9. *L.Lucy*, Z. Astrophys., **65**, 89, 1967.
10. *S.Rucinski*, Acta Astronaut., **19**, 156, 1969.
11. *W. van Hamme*, Astron. J., **106**, 2096, 1993.
12. *D.Popper*, Ann. Rev. Astron. Astrophys., **18**, 115, 1980.
13. *P.Harmanec*, Bull. Astron. Inst. Czechosl., **39**, 329, 1988.
14. *D.Bradstreet*, *D.Steelman*, Astron. Astrophys. Suppl., **201**, 7502, 2002.
15. *L.Girardi*, *A.Bressan*, *G.Bertelli et al.*, Astron. Astrophys. Suppl., **141**, 371, 2000.
16. *L.Lucy*, Astrophys. Sp. Sci., **22**, 381, 1973.
17. *S.Ekstrom*, *C.Georgy*, *P.Eggenberger et al.*, Astron. Astrophys., **537**, 146, 2012.
18. *O.Y.Malkov*, Mon. Not. Roy. Astron. Soc., **382**, 1073, 2007.