АСТРОФИЗИКА

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PHOTOMETRIC STUDY AND ORBITAL SOLUTION FOR SOME NEWLY DISCOVERED ECLIPSING BINARY SYSTEMS

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We present an orbital solution and light curve analysis for the three newly discovered W UMa systems: V0757 And, IK Lyn, and V0996 Per by means of first CCD observations. New times of minima were estimated and the observed light curves were analyzed using the most recent version of Wilson-Devinney modeling code (WD code) based on model atmospheres by Kurucz. The accepted models revealed some parameters describing the orbit of each system which showed that the primary components in all systems are massive and hotter than the secondary components. The spectral types of the systems' components were adopted and the locations of the systems on the theoretical mass-luminosity and mass-radius relations revealed a good fit for all the systems components except the secondary components of the systems V0996 Per and V0757 And are located above the TAMS track.

Keyword: *eclipsing binaries: orbital solution: evolutionary state*

1. *Introduction*. W UMa variables are known as low mass contact binaries of late type spectral type (F, G or K). They are termed contact binaries because the systems' components (primary and secondary) are in contact and transfer mass and energy through the connecting neck and share a common envelope. The systems are characterized by a short period range between 0.25 to around 1.0 days. Physical parameters of the W UMa systems can be estimated through orbital solution and light curve modelling of the systems' photometric and spectroscopic observations. The parameters can be used to establish and follow their evolutionary status.

The importance of light curve analysis in describing the orbits of newly discovered eclipsing binary systems and hence revealing their evolutionary status has caught the attention of many authors. In this paper we present the first orbital solutions and photometric investigations for three new discovered W UMa systems, V0757 And, IK Lyn, and V0996 Per to estimate their absolute parameters and follow their evolutionary status. The paper consists of five sections: Section 2 is devoted to the systems' observations and times of minima. In section 3, light curve analysis of the systems is performed. Section 4 deals with the evolutionary state of the systems' components. Summary of the results and conclusion are outlined in Section 5.

2. *Observations and times of minima.* The variability of the systems V0757 And, IK Lyn, and V0996 Per were detected for the first time during the observations of other eclipsing binaries. The system V0757 And ($P = 0^d.4386$), was observed in the field of view of the known variable star CP And in 2011 by Liakos and Niachros [1], while the system IK Lyn ($P = 0^d.258275$) was discovered in the field of view of the known variable star CL Lyn in 2011 by Liakos and Niachros [2]. The system V0996 Per ($P = 0^d.38801$) was discovered in the field of view of the variable star V881 Per in 2012 by Liakos and Niachros [3]. Table 1 listed basic information about the studied systems together with the used

Table 1

BASIC INFORMATION OF THE VARIABLE, COMPARISON, AND CHECK STARS

Star Name	α (2000.0)	δ (2000.0)	B	V	B-V
Variable (V0757 And)	$02^h12'13".79$	$+45^o33'14".80$	14.45	13.96	0.49
Comparison (GSC 03281-01868)	$02^h12'15".38$	$+45^o32'40".42$	13.96	-	-
Check (GSC 03281-01193)	$02^h12'30".46$	$+45^o34'38".78$	12.84	-	-
Variable (IK Lyn)	$07^h58'44".09$	$+54^o25'13".80$	14.76	14.08	0.68
Comparison (GSC 3787-00524)	$07^h58'47".28$	$+54^o24'15".77$	13.31	-	-
Check (GSC 3783-00027)	$07^h58'45".65$	$+54^o20'40".34$	13.92	-	-
Variable (V0996 Per)	$03^h00'31".00$	$+37^o59'07".60$	15.67	15.01	0.66
Comparison (USNO A2.0 1275-01924782)	$03^h00'27".84$	$+37^o59'32".49$	-	-	-
Check (USNO A2.0 1275-01922582)	$03^h0025".19$	$+37^o59'20".48$	-	-	-

comparison and check stars for each system. All observations were carried out at the Gerostathopoulion observatory of Athens University during the period from Jul 2010 to Nov 2011, using a 40-cm Cassegrain telescope equipped with ST-8XMEi and ST-10XME CCD camera and the BVRI Bessell photometric filters.

The systems V0757 And, IK Lyn were observed in BI pass bands, while the system V0996 Per was observed in BR pass bands. The corresponding phases to each observed data were calculated for all systems observations according to the ephemeris in Table 2 adopted by Liakos and Niachros [1-3]. Fig.1a, b, c displays the observed light curves for the systems.

Table 2

EPHEMERIS EQUATIONS FOR STUDIED SYSTEMS

Star Name	Ephemeris
V0757 And	Min I = HJD 2455493.2680 + 0.438600 E
IK Lyn	Min I = HJD 2455576.5833 + 0.258275 E
V0996 Per	Min I = HJD 2455819.5027 + 0.388010 E

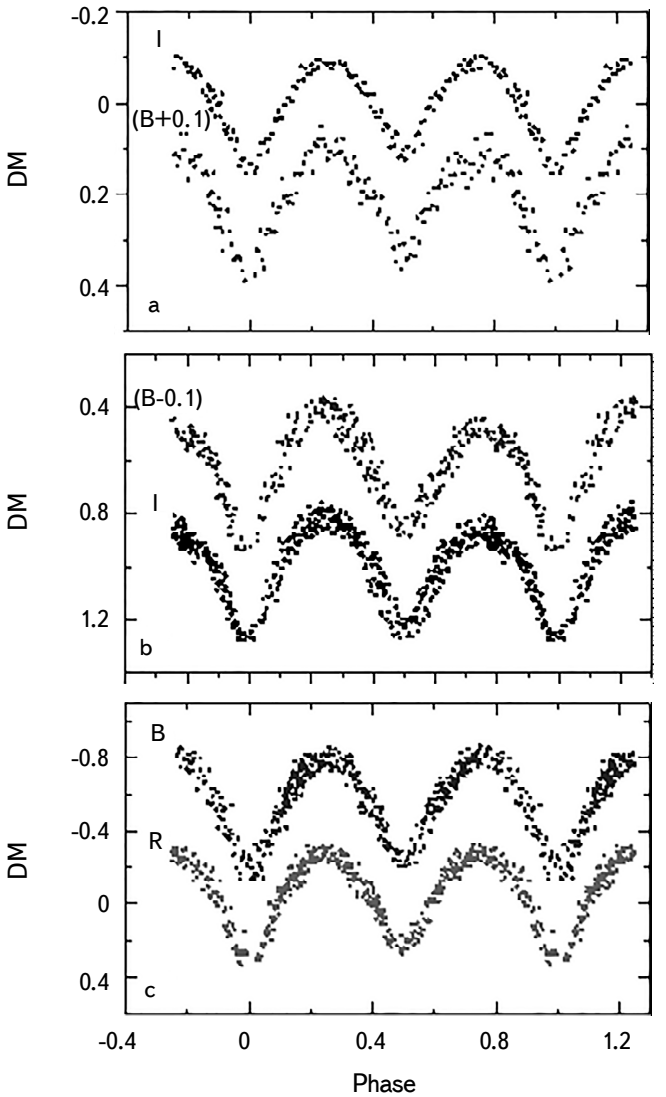

Fig.1. Observed light curves for the systems: a) V0757 And, b) IK Lyn, and c) V0996 Per.

A total of 18 new times of primary and secondary minima were derived for all studied systems using the method of Kwee and Van Worden [4] using the software Minima V2.3 (Nelson [5]) and are listed in Table 3. Since the studied systems are new discovered, the estimated minima can be use with additional estimated ones revealed from future observations to study the period behavior of the systems.

The light levels were measured at four characteristic phases (Max I, Min I, Max II, and Min II) for all the observed light curves of the systems. The bright

Table 3

LIGHT MINIMA OF V0757 And, IK Lyn AND V0996 Per

Star name	HJD	Error	Min	Filter
V0757 And	2455493.2663	0.0009	I	B
	2455493.2668	0.0013	I	I
	2455493.4875	0.0008	II	B
	2455493.4899	0.0022	II	I
IK Lyn	2455598.2754	0.0001	I	B
	2455598.5373	0.0007	I	B
	2455602.2830	0.0012	II	B
	2455598.2719	0.0005	I	I
	2455598.5329	0.0007	I	I
	2455602.2777	0.0007	II	I
V0996 Per	2455819.5099	0.0011	I	B
	2455833.4741	0.0005	I	B
	2455818.5314	0.0007	II	B
	2455835.5996	0.0037	II	B
	2455819.4917	0028.0	I	R
	2455833.4828	0.0013	I	R
	2455818.5274	0.0005	II	R
	2455835.6030	0.0008	II	R

difference between both maxima D_{max} (Max I - Max II) and minima D_{min} (Min I - Min II) has been measured together with the amplitude (depth) of the primary A_p (Min I - Max I) and the secondary A_s (Min II - Max I) minima for the observed light curves of the systems V0757 And, IK Lyn and V0996 Per. The calculated parameters are listed in Table 4.

Table 4

LIGHT CURVE LEVELS FOR THE SYSTEMS V0757 And, IK Lyn AND V0996 Per

Star name	D_{max}	D_{min}	A_p	A_s	Filter
V0757 And	0.0050±0.0002	0.0450±0.0018	0.3100±0.0127	0.2650±0.0108	B
	0.0080±0.0003	0.0100±0.0004	0.2480±0.0101	0.2380±0.0097	I
IK Lyn	-0.0800±0.0003	0.0500±0.0020	0.5800±0.0237	0.5300±0.0216	B
	-0.0500±0.0020	0.0200±0.0008	0.5100±0.0208	0.4900±0.0200	I
V0996 Per	0.0300±0.0012	0.0800±0.0033	0.7050±0.0288	0.6250±0.0255	B
	-0.0100±0.0004	0.0400±0.0016	0.6250±0.0255	0.5850±0.0239	R

3. *Orbital solution*. A photometric analysis for the systems V0757 And, IK Lyn and V0996 Per was performed using the synthetic light curve and

differential corrections program of WD code (Wilson et al. [6]) based on model atmospheres by Kurucz [7]. Temperature of the primary star T_1 was estimated using the (B-V) color index for each system listed in AAVSO (https://www.aavso.org/vsx/index.php?view=search.top) by means of colour index temperature relation by Tokunaga [8]. The adopted primary stars temperatures were used as initial values in the light curve modelling. All individual observations of the observed light curves in each band were analyzed instead of normal points. Gravity darkening and bolometric albedo exponents were adopted for the convective envelopes ($T_{eff} < 7500$ K), therefore we adopted $A_1 = A_2 = 0.5$ (Rucinski [9]) and $g_1 = g_2 = 0.32$ (Lucy [10]). Tables of Van Hamme [11] were used to adopt the bolometric limb darkening using the logarithmic law for the extinction coefficients.

Because of the lack of spectroscopic measurements (radial velocity) for the studied systems, the initial value of mass ratio q was determined using a q-search method. The test solutions in this technique were done at a series of assumed mass-ratios q with the values ranging from 0.10 to 0.90 using mode 3 for over-

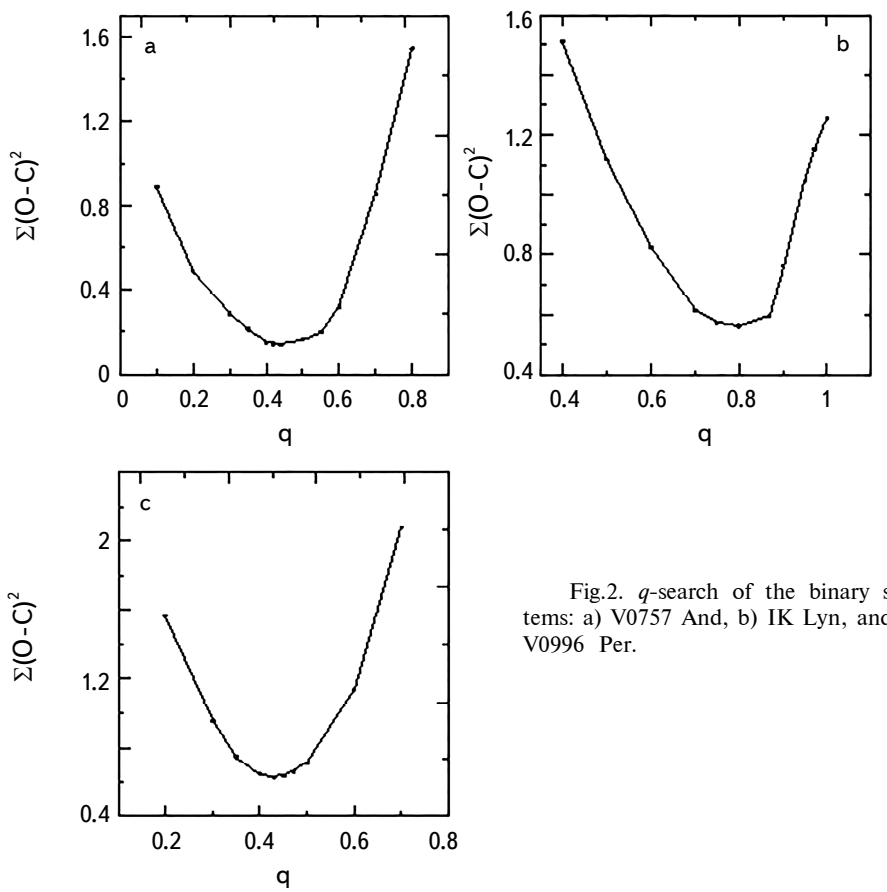

Fig.2. q-search of the binary systems: a) V0757 And, b) IK Lyn, and c) V0996 Per.

contact in WD code. A convergent solution was obtained for each assumed q, and the resulting sum of the squared deviations $\Sigma(O-C)^2$ for each value of q were plotted in Fig.2a, b, c for all studied systems. Initial values of q corresponding to the minima of $\Sigma(O-C)^2$ that obtained for each system are adopted as an initial value in the modeling. In computing the photometric solution, the employed commonly adjustable parameters are; the mass ratio q, the orbital inclination i, the temperature of the primary component T_1 and the temperature of the secondary component T_2, the surface potential Ω (for Mode 3, $\Omega_1 = \Omega_2 = \Omega$) and the monochromatic luminosity of primary star L_1. Relative brightness of secondary star was calculated by the stellar atmosphere model.

Table 5

PHOTOMETRIC SOLUTION FOR THE SYSTEMS V0757 And, IK Lyn, AND V0996 Per

Parameter	V0757 And	IK Lyn	V0996 Per
i (°)	60.44±0.25	67.75±0.29	78.32±0.45
$g_1 = g_2$	0.32	0.32	0.32
$A_1 = A_2$	0.5	0.5	0.5
q (M_2/M_1)	0.4418±0.0016	0.7844±0.0035	0.4222±0.0030
$\Omega_1 = \Omega_2$	2.7562±0.0057	3.2396±0.0091	2.5829±0.0078
T_1 (°K)	6333±87	5275±43	5503±33
T_2 (°K)	5718±7	4943±5	5373±10
Ω_{in}	2.7621	3.3902	2.7193
Ω_{out}	2.4951	2.9474	2.4641
r_1 pole	0.4256±0.0034	0.3983±0.0075	0.4545±0.0030
r_1 side	0.4534±0.0046	0.4243±0.0100	0.4917±0.0042
r_1 back	0.4811±0.0062	0.4662±0.0162	0.5304±0.0063
r_2 pole	0.2912±0.0049	0.3582±0.0083	0.3140±0.0044
r_2 side	0.3039±0.0059	0.3793±0.0107	0.3321±0.0057
r_2 back	0.3372±0.0100	0.4256±0.0194	0.3913±0.0135
Spot A of star 2			
Latitude		120±4.90	
Longitude		130±5.31	
Spot radius		22±0.90	
Tem. factor		1.30±0.05	
$\Sigma(O-C)^2$	0.03693	0.31561	0.38067

The observed light curves of the studied systems undergo photometric solution analysis. Some trials were made to derive a set of parameters which marginally represent the observed light curves. Condition of Mode 3 (overcontact) in the WD code [6] was applied and the best photometric fitting was reached after several runs.

The accepted solution shows that the primary components in all systems are hotter than the secondary ones. Parameters of the accepted models are listed in

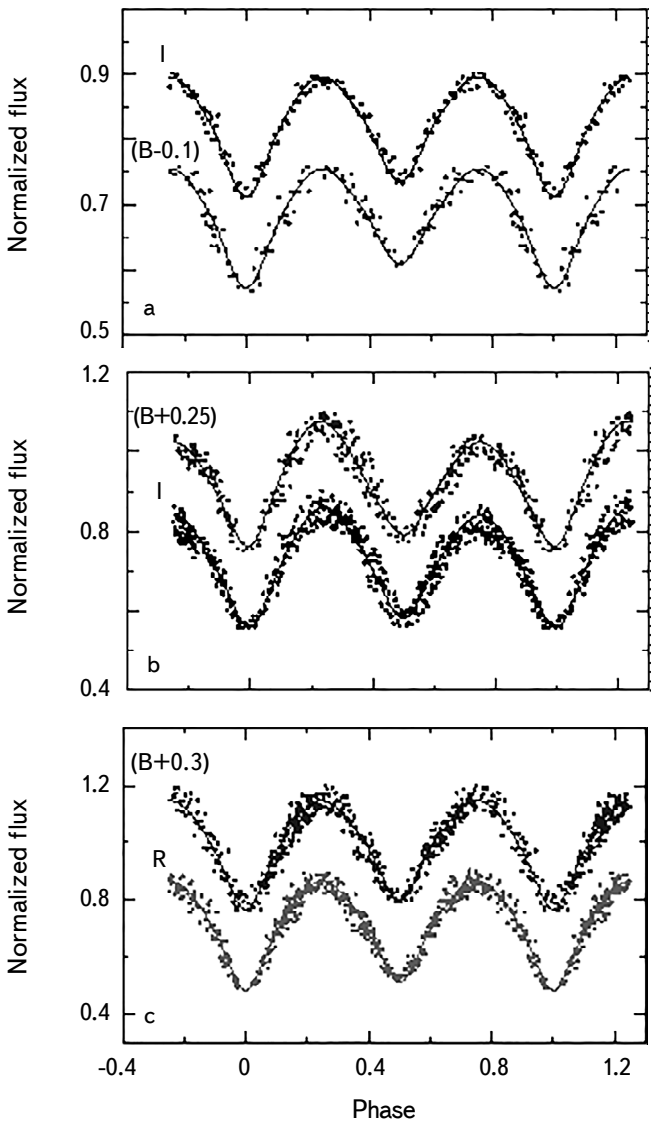

Fig.3. Synthetic (lines) and observed (dots) light curves for the systems: a) V0757 And, b) IK Lyn, and c) V0996 Per.

Table 5, while Fig.3 displays the observed light curves (dots) together with the synthetic light curves (lines). As can be seen in Fig.3b, the observed light curves of the system IK Lyn in BI pass bands show asymmetries, where the observed magnitude between phases 0.1 and 0.3 is brighter than that between 0.7 and 0.9, which could be attributed to O'Connell effect. We treated such change in the curves, by adopting the model solution with suitable spot position in parallel with a non-spot solution to achieve an acceptable matching to the reflected observed

points. As a result, a spotted model was adopted with a hot spot on the secondary star that shows a good agreement between the observed and synthetic light curves. The parameters of the accepted model for the system IK Lyn are listed in Table 5.

Absolute physical parameters for the components of the studied systems were calculated using the empirical $T_{\rm eff}$-mass relation by Harmanec [12], All the calculated physical parameters for the systems were listed in Table 6. It's clear that the accepted photometric solution and the estimated physical parameters show that the primary components are hotter and massive than the secondary ones in all systems. The spectral types of the systems' components were adopted according to the parameters of the accepted orbital solutions (Popper [13]). Three-dimensional geometrical structure for the studied systems were constructed as shown in Fig.4 using the software Package Binary Maker 3.03 (Bradstreet and Steelman [14]) based on the calculated parameters resulted from the adopted models.

Table 6

ABSOLUTE PHYSICAL PARAMETERS FOR THE SYSTEMS: V0757 And, IK Lyn AND V0996 Per

Parameter	Star name		
	V0757 And	IK Lyn	V0996 Per
$M_1 / M_\odot$	1.2937±0.0528	0.9390±0.0383	1.0175±0.0415
$M_2 / M_\odot$	0.5716±0.0233	0.7366±0.0301	0.4296±0.0175
$R_1 / R_\odot$	1.3797±0.0563	1.0372±0.0423	1.1159±0.0456
$R_2 / R_\odot$	1.1878±0.0485	0.9183±0.0375	1.0714±0.0437
$T_1 / T_\odot$	1.0961±0.0448	0.9130±0.0373	0.9524±0.0389
$T_2 / T_\odot$	0.9896±0.0404	0.8555±0.0349	0.9299±0.0380
$L_1 / L_\odot$	2.7434±0.1120	0.7463±0.0305	1.0232±0.0418
$L_2 / L_\odot$	1.3513±0.0552	0.4511±0.0184	0.8572±0.0350
M_{bol1}	3.6543±0.1492	5.0677±0.2069	4.7252±0.1929
M_{bol2}	4.4231±0.1806	5.6145±0.2292	4.9174±0.2008
Sp. Type	(F7)[1], (G3)[2]	(G8)[1], (K1)[2]	(G6)[1], (G7)[2]

Note: The subscript/superscript 1 and 2 refers to the primary and secondary components, respectively.

4. *Evolutionary state*. Evolutionary state of the studied systems was investigated using their estimated physical parameters as listed in Table 6 by means of mass-luminosity (*M-L*) and mass-radius (*M-R*) relations and the evolutionary tracks computed by Girard et al. [15] for both zero age main sequence stars (ZAMS) and thermal age main sequence stars (TAMS) with metallicity $z = 0.019$. Luminosity-effective temperature (L-$T_{\rm eff}$) relation of non-rotated models and the empirical mass-effective temperature (M-$T_{\rm eff}$) relation of the intermediate and low mass eclipsing binaries were also used in investigating the evolutionary states of

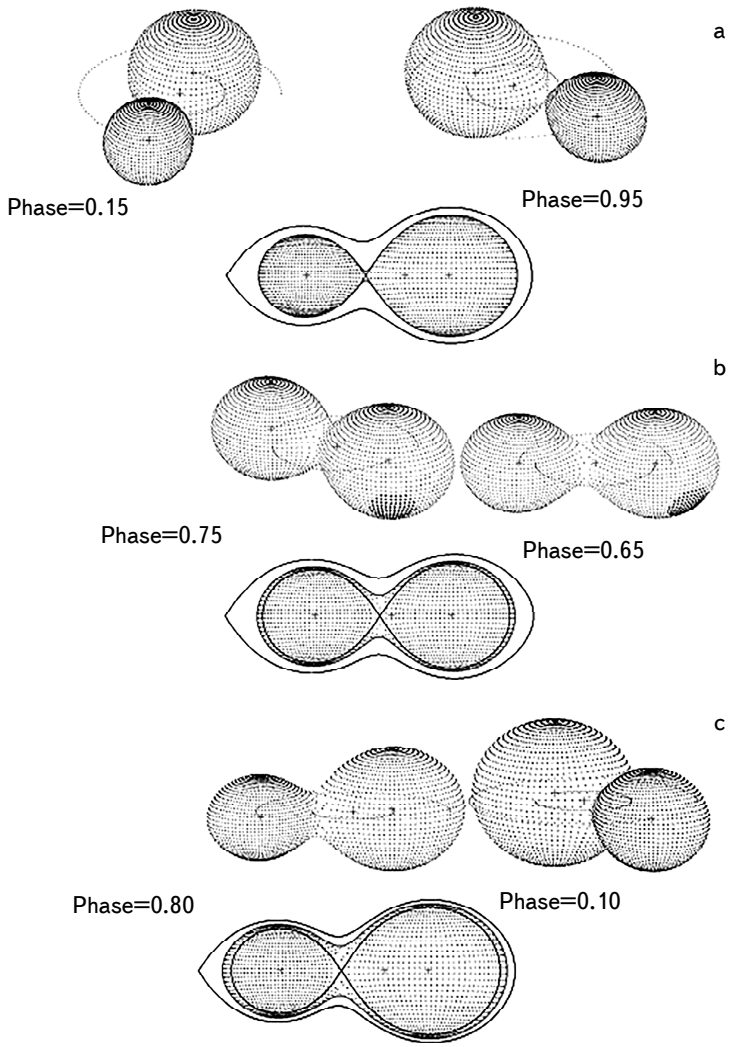

Fig.4. Three dimension structure of the binary systems: a) V0757 And, b) IK Lyn, and c) V0996 Per.

the systems. Fig.5a, b displays the locations of the studied systems' components (S_1, S_2) on the mass-luminosity (*M-L*) and mass-radius (*M-R*) relations. As shown in Fig.5, the components of the systems are located near the ZAMS for (*M-R*) relation and (*M-L*) relation except for the secondary components of the systems V0996 Per and V0757 And where they lied above the TAMS track. Deviation of these secondary components can be ascribed to the energy transfer from the primary components to the secondary ones through the common convective envelope of these two systems, as suggested by Lucy [18]. Using the non-rotating evolutionary models of

Ekstrom et al [16] at solar metallicity $z = 0.014$, we assigned the components of the studied systems to the $T_{\rm eff}$-luminosity relation as shown in Fig.6 where all components of the studied systems lie on their expected positions.

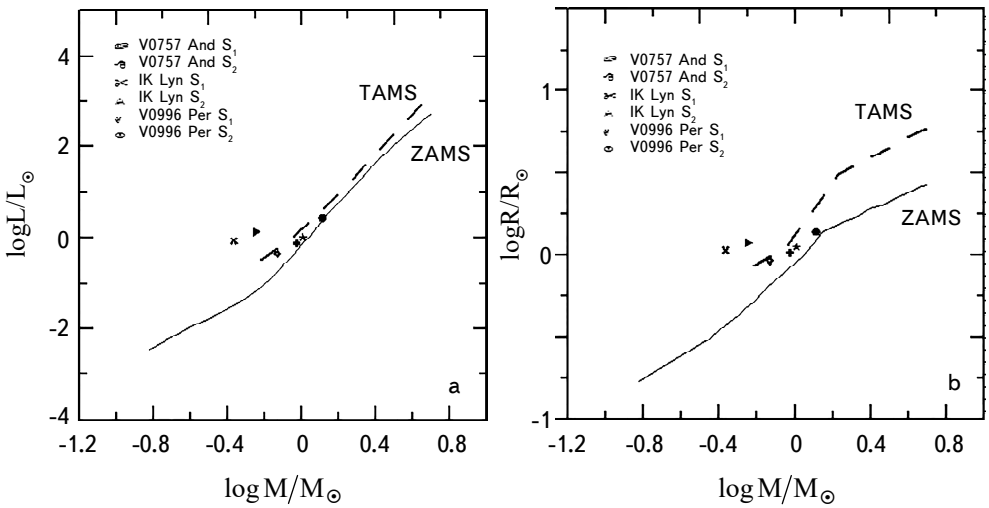

Fig.5. Positions of the components (S1, S2) of the systems V0757 And, IK Lyn and V0996 Per on the theoretical: a) mass-luminosity diagram and b) mass-radius diagram of Girardi et al. [15].

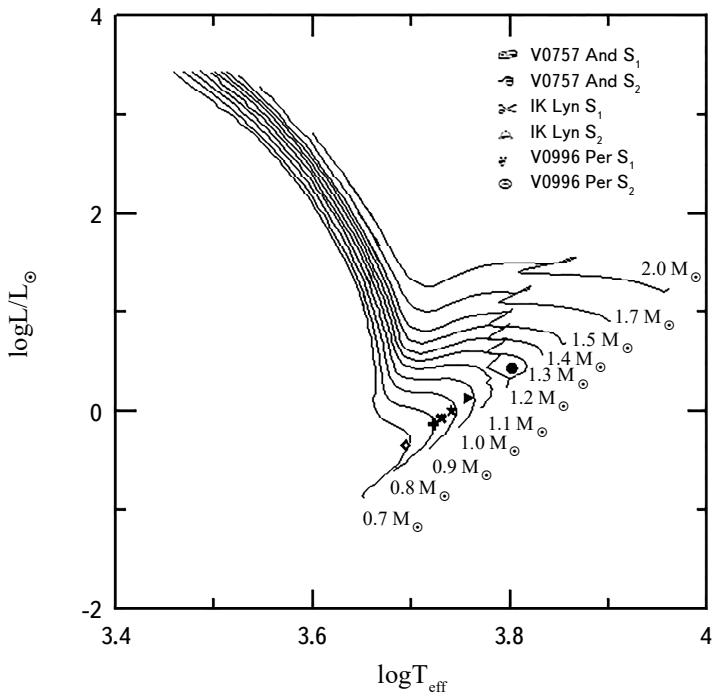

Fig.6. Positions of the components (S1, S2) of the systems V0757 And, IK Lyn and V0996 Per on the effective temperature-luminosity diagram of Ekstrom et al [16].

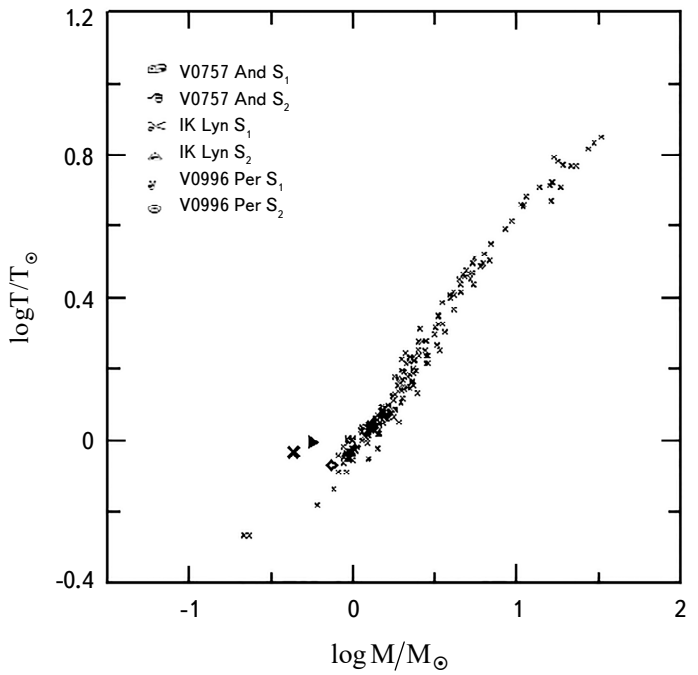

Fig.7. Positions of the components (S1, S2) of the systems V0757 And, IK Lyn, and V0996 Per on the empirical M-$T_{\rm eff}$ relation for low-intermediate mass stars by Malkov [17].

Mass-effective temperature relation (M-$T_{\rm eff}$) for the intermediate and low mass stars (Malkov [17]) is displayed in Fig.7 for all the studied systems. The locations of the studied systems on the (M-$T_{\rm eff}$) diagram showed a good fit for the systems' components excepts for the secondary component (S2) of systems V0996 Per and V0757 And. The behaviour of the components on the M-$T_{\rm eff}$ diagram is similar to their behaviour on the previously discussed M-L and M-R diagrams, shown in Fig.5a, b, and we ascribed the reason for such behaviour to the same previous argument, that is; energy transfer from the primary to the secondary component of these two systems through the common convective envelope, as suggested by Lucy [18].

5. *Discussion and conclusion*. The new overcontact systems V0757 And, IK Lyn were discovered in 2011, while the system V0996 Per is discovered in 2012, all by Liakos and Niachros [1-3]. A complete light curves were observed for the systems from July 2010 to Nov 2011 and new times of minima (primary and secondary) were calculated for all studied systems. Results of the first photometric analysis for the systems showed that the primary components in all systems are hotter and massive than the secondary components. The evolutionary state of the systems under study has been investigated to explore their behavior on M-R and M-L relations. Locations of the components of the systems on

M-R and *M-L* relations reveled a good fit to the ZAMS track except for the secondary components of the systems V0996 Per and V0757 And where they located above the TAMS track. In similar fashion, locations of the systems' components on the M-$T_{\rm eff}$ diagram showed a good fit for the components of systems except for the secondary components of systems V0996 Per and V0757 And. We ascribed such behaviour, in both cases, to an energy transfer from the primary to the secondary component of the two systems through the common convective envelope, as suggested by Lucy [18].

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ФОТОМЕТРИЧЕСКОЕ ИССЛЕДОВАНИЕ И ОРБИТАЛЬНОЕ РЕШЕНИЕ ДЛЯ НЕДАВНО ОТКРЫТЫХ ЗАТМЕННО-ДВОЙНЫХ СИСТЕМ

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Представлено орбитальное решение и анализ кривых блеска для трех недавно открытых систем W UMa: V0757 And, IK Lyn и V0996 Per с помощью первых ПЗС-наблюдений. Были оценены новые времена минимумов и проанализированы наблюдаемые кривые блеска с использованием самой последней версии кода моделирования Уилсона-Девинни (код WD), основанного на моделях атмосфер Куруца. Принятые модели позволили выявить некоторые параметры, описывающие орбиту каждой системы, которые показали, что первичные компоненты во всех системах массивнее и горячее, чем вторичные компоненты. Спектральные классы компонентов систем и расположение систем по теоретическим соотношениям масса-светимость и масса-радиус показали хорошее соответствие для всех компонентов систем, кроме вторичных компонентов систем V0996 Per и V0757 And, расположенных выше последовательности TAMS.

Ключевые слова: *затменно-двойные системы:моделирование кривой блеска: эволюционное состояние*

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