

Research Article

Moqbil S. Alenazi and Magdy M. Elkhateeb*

A holistic study of the systems V0487 Lac, V0566 Hya, and V0666 Lac

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Abstract: A comprehensive photometric study and evolutionary state for the systems V0487 Lac, V0566 Hya, and V0666 Lac were carried out by means of their first photometric observations. New times of minima were estimated from the observed light curves, and first (O–C) curves were established for all systems. The radiative treatment was carried out using a Windows interface version of the Wilson and Devinney programme (W–D). The adopted models provide some absolute characteristics for the systems under study, which are used to determine the spectral type of the system's constituents and their evolutionary stage. Distances to each system were calculated, and physical properties were estimated. All system components, with the exception of the secondary component of the system V0487 Lac, showed good fit when the systems were positioned on the theoretical mass–luminosity and mass–radius relations.

Keyword: eclipsing binaries, light-curve modelling, evolutionary state

1 Introduction

The light curves of eclipsing binary systems depend on the physical characteristics of the system's components and its geometrical arrangement (Hilditch 2010). According to Roche geometry, the morphologies of the binary components are defined and categorized (detached, semidetached, and contact) based on the level of filling the Roche lobe (Prša 2019). The primary sources of information about the physical and geometrical characteristics of

eclipsing binary systems are their orbital solutions, which reveal, among other things, the relative sizes of the stars, their orbital inclinations, effective temperatures, the eccentricity of the orbit, and potential spots. The masses of the components, their distances, and their radii are revealed via combined orbital solutions employing photometric measurements along with radial velocities obtained from spectroscopic studies. These parameters and many others are important to understand the evolutionary stages of the systems and their stellar structures (Yilmaz *et al.* 2017). In this article, we performed the first light-curve modelling and established the evolutionary status for the systems V0487 Lac, V0566 Hya, and V0666 Lac. The article is organized as follows: Section 2 presents the fundamental data of the systems under study and illustrates the light minima generated from their observations. The modelling of the system's light curve is covered in Section 3. We talk about the systems' evolutionary position in Section 4. Section 5 provides a summary of the findings and a summary of the conclusions.

2 Observations and times of minima

The studied systems V0487 Lac, V0566 Hya, and V0666 Lac were discovered as eclipsing binary systems for the first time by Liakos and Niarchos (2011a,b,c) during their observations of other eclipsing binaries. The systems V0487 Lac ($P = 0.^d3466$) and V0666 Lac ($P = 0.^d44149$) were discovered in 2010, while the system V0566 Hya ($P = 0.^d32243$) was discovered in 2011. The systems V0487 Lac and V0566 Hya were classified as w ursa major (WUMa) systems in the GCVS and AAVSO databases, while the system V0666 Lac light curve has an EB (bet Lyr) morphological type. Table 1 displays the coordinates of the studied systems as well as the comparison and check stars for each system. All observations were carried out at the Gerostathopoulion observatory of the University of Athens from July 2010 to March 2011, using a 0.4 m Cassegrain telescope equipped with ST-8XMEi and ST-10XME CCD cameras and the BVRI

* **Corresponding author: Magdy M. Elkhateeb**, Astronomy Department, National Research Institute of Astronomy and Geophysics (NRIAG), 11421, Helwan, Cairo, Egypt, e-mail: cairo_egypt10@yahoo.com
Moqbil S. Alenazi: Physics Department, Faculty of Science, Northern Border University, Arar, 91431-1321, Saudi Arabia

Table 1: Variable, comparison, and check stars coordinates

Star Name	α (2000.0)	δ (2000.0)	B	V	(B–V)
Variable (V0487 Lac)	22 h 15'46.30"	+48°39'05.57"	11.30	10.30	1.00
Comparison (GSC 03610-00231)	22 h 15'09.57"	+48°42'55.14"	11.40	11.02	0.38
Check (GSC 03610-00685)	22 h 15'08.83"	+48°43'48.74"	12.89	11.49	1.40
Variable (V0566 Hya)	08 h 28'22.92"	+05°36'52.75"	16.32	15.69	0.63
Comparison (USNO-A2.0 0900-05985839)	08 h 28'19.45"	+05°44'04.48"	15.50	—	—
Check (USNO-A2.0 0900-05983689)	08 h 28'06.87"	+05°41'58.58"	14.90	—	—
Variable (V0666 Lac)	22 h 14'15.14"	+48°30'51.50"	14.83	14.23	0.60
Comparison (USNO-A2.0 1350-16151820)	22 h 14'26.07"	+48°32'24.47"	15.30	—	—
Check (USNO-A2.0 1350-16150452)	22 h 14'24.11"	+48°31'53.81"	14.40	—	—

Bessell photometric filters. The systems V0487 Lac and V0566 Hya were observed in visual and red (VR) filters pass bands, while the system V0666 Lac was observed in blue and red filters pass bands. A set of photometric observations were downloaded from Gaia 3rd data release (Gaia Collaboration *et al.* 2016b, 2023j) for the studied systems in different passbands. Only VR light curves for the system

V0487 Lac are suitable for photometric analysis, while the data for the other systems do not give the morphology of a complete light curve. The relevant phases of each observation were calculated for all systems using the ephemeris formulas shown in Table 2, as adopted by Liakos and Niarchos. Figure 1(a) and (b) displays two observed light curves for the system V0487 Lac by Liakos and Niarchos in (a) and Gaia 3rd data release in (b), while Figure 2(a) and (b) displays the observed light curves for the systems V0566 Hya and V0666 Lac by Liakos and Niarchos.

Table 2: Ephemeris formulas for the systems, V0487 Lac, V0566 Hya, and V0666 Lac

Star name	Ephemeris
V0487 Lac	Min I = HJD 2455149.3084 + 0.484040 * E
V0566 Hya	Min I = HJD 2454107.6042 + 0.435898 * E
V0666 Lac	Min I = HJD 2454115.5345 + 0.371038 * E

Using the Minima V2.3 programme (Nelson 2009) and the Kwee and Van Woerden 1956 fitting method, a total of 22 instances of minima were calculated from the observed light curves of the three systems. The new minima for the systems are shown in Table 3 together with the epochs (E)

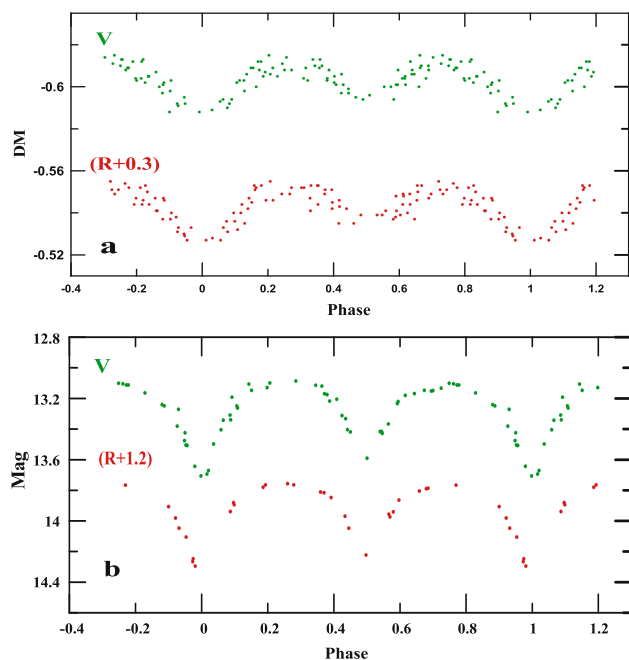
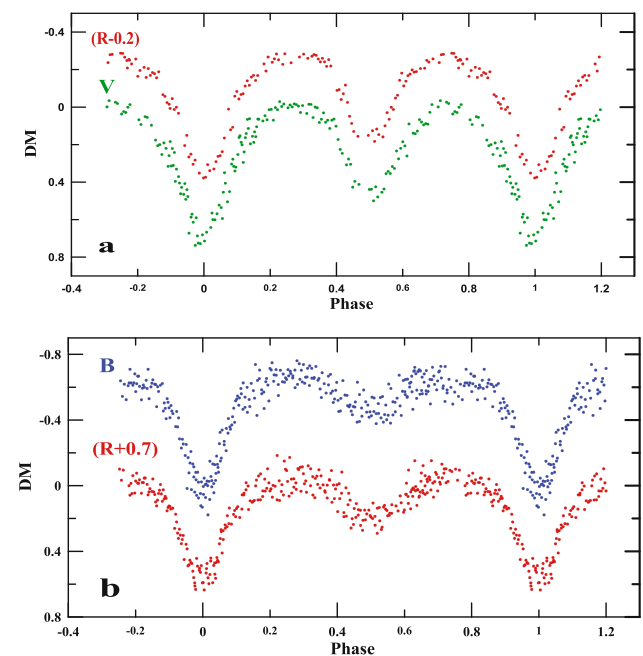
**Figure 1:** Observed light curves for the system V0487 Lac: (a) Liakos and Niarchos data and (b) Gaia 3rd data release.**Figure 2:** Observed light curves for the systems: (a) V0566 Hya and (b) V0666 Lac.

Table 3: Light minima for the systems V0487 Lac, V0566 Hya, and V0666 Lac

Star name	HJD	Error	Min	Filter	E	(O–C)
V0487 Lac	2455436.3552	0.0022	I	V	0	0.0002
	2455436.3528	0.0016	I	R	0	–0.0022
	2455436.5359	0.0087	II	V	0.5	0.0076
	2455436.5350	0.0041	II	R	0.5	0.0067
	2455437.5619	0.0128	II	V	3.5	–0.0062
	2455437.5727	0.0015	II	R	3.5	0.0046
	2455438.4567	0.0021	I	V	6	0.0221
	2455438.4359	0.0019	I	R	6	0.0013
	2455444.3264	0.0018	I	R	23	–0.0004
V0566 Hya	2455576.3910	0.0005	I	V	–16	–0.0001
	2455576.3921	0.0007	II	V	–16	0.0010
	2455576.5537	0.0019	I	R	–15.5	0.0014
	2455576.5567	0.0002	II	R	–15.5	0.0044
	2455580.5789	0.0019	I	V	–3	–0.0038
V0666 Lac	2455441.3568	0.0008	I	R	0	0.0001
	2455441.3594	0.0006	I	B	0	0.0027
	2455448.4111	0.0012	I	R	16	–0.0094
	2455448.4187	0.0018	I	B	16	–0.0018
	2455450.3823	0.0006	II	R	20.5	–0.0250
	2455450.4273	0.0005	II	B	20.5	0.0201
	2455457.4779	0.0008	II	B	36.5	0.0068
	2455457.478	0.0008	II	R	36.5	0.0069

and (O–C), which are computed using Liakos and Niarchos ephemeris, as listed in Table 2.

The estimated (O–C) values for the studied systems are represented by a linear fit, as shown in Figure 3(a)–(c), to give a first impression of the period behaviour of the systems. Because the studied systems did not have a time of minima database from which to draw any conclusions about the potential variability in the system's period, the O–C curves generated in this research are used as a starting point for each system.

3 Photometric analysis

Fundamental stellar attributes and associated knowledge can be found mostly in light-curve modelling and radial velocity curves. Accurate physical properties can be derived from the analysis of the eclipsing binaries' physical characteristics, which can be used to track the evolution of the stars. Orbital solutions and light-curve modelling for the systems under study were performed using a synthetic light curve and a differential corrections software (Windows interface version) based on WD code (Wilson *et al.* 2020). The photometric light curves of the studied systems in all observable bands were analysed using this code, which was based on Kurucz's (1993) model atmosphere. Using the (B–V)

colour index for each system listed in SIMBAD (<http://simbad.u-strasbg.fr/simbad/>), the initial value for the temperature of the primary star (T_1) of each system was calculated using Tokunaga's (2000) (B–V) temperature relation.

The observed light curves for each band were examined individually. The logarithmic law for the extinction coefficients from Van Hamme (1993) was used to adopt and interpolate the bolometric limb darkening coefficients. In a late spectral type, gravity darkening and bolometric albedo were considered in accordance with the exponents suitable for convective envelopes ($T_{\text{eff}} < 7,500$ K). The albedo values $A_1 = A_2 = 0.5$ (Rucinski 1969) and $g_1 = g_2 = 0.32$ (Lucy 1967) were adopted. The spectroscopic observations (radial velocity measurements) are usually considered a primary source for determining the mass ratio (q), but since the studied systems were recently discovered and do not have any such observations, the q search method was used to adopt the mass ratio's starting value. The test solutions in this method were performed by a series of assumed mass ratios (q) with values ranging from 0.10 to 0.90, utilizing the adopted mode for each system. For each assumed q , a convergent solution has been found, and the sum of the squared deviations for each value of q is plotted in Figure 4(a)–(c) for all systems under study. The computed minima of $\Sigma(\text{O–C})^2$ for each system's initial values of q are employed in the modelling process. Through the photometric solution, the following adjustable absolute parameters are employed: the orbital inclination (i), the mass ratio (q), the temperature of the primary component (T_1) and secondary one (T_2), the surface potentials of the stars (Ω_1 and Ω_2), and the monochromatic luminosity of the primary star (L_1). The relative brightness of the secondary star was calculated from stellar atmosphere models. The WD code was run in Mode 4 (semi-detached mode) on the systems V0566 Hya and V0666 Lac and in Mode 2 (detached mode) on the system V0487 Lac, and the best matching between the observed and synthetic curves was achieved after several runs for all models. Orbital solutions for the system V0487 Lac based on Liakos and Niarchos and Gaia 3rd data release observations reveal somewhat different absolute parameters, which can be attributed to the quality difference between ground-based and satellite observations and the light curve gaps of Gaia 3rd data release observations.

Table 4 lists the accepted solutions for the three systems, while Figures 5(a) and (b) and 6(a) and (b) depict their constructed theoretical light curves. According to the estimated parameters from the used models, all primary components of the systems are hotter than secondary components. The spectral types of system components were adopted based on the parameters of the accepted orbital solutions (Popper 1980). Figure 7(a)–(c) depicts the

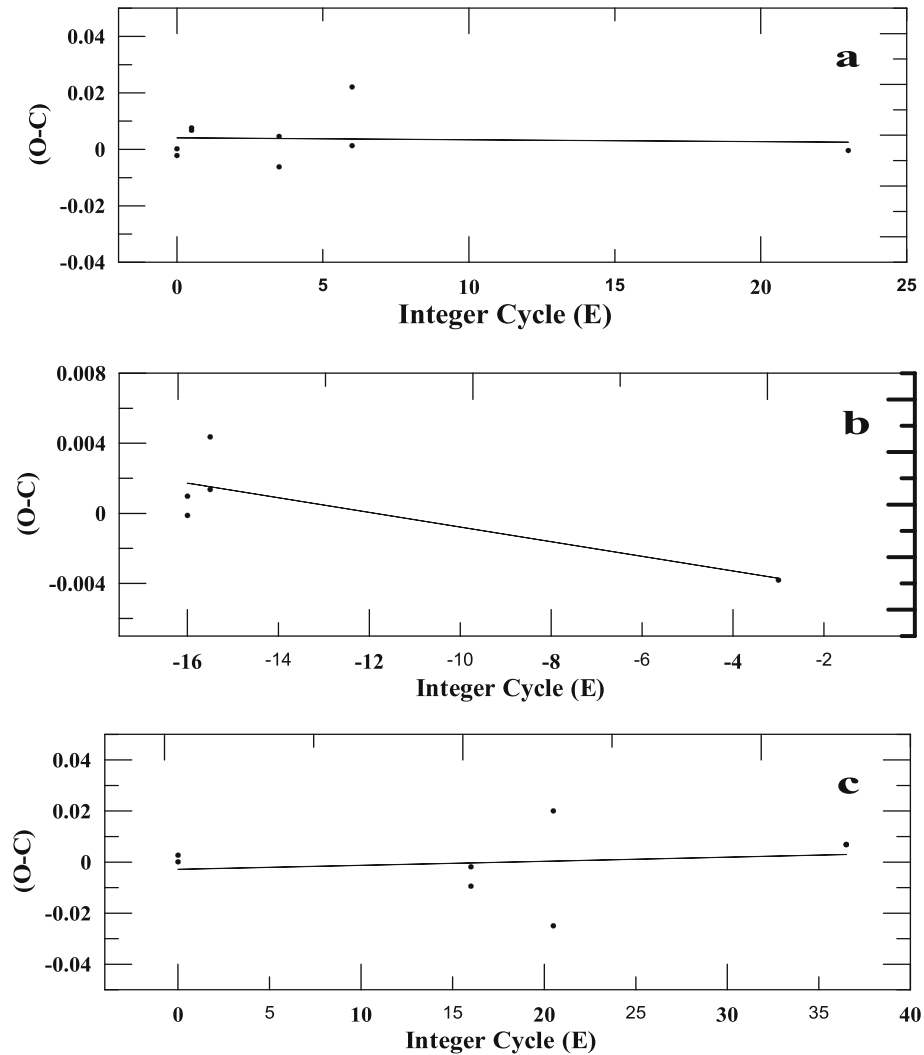


Figure 3: Period behaviour of the systems: (a) V0487 Lac, (b) V0566 Hya, and (c) V0666 Lac.

geometric structure of the studied systems based on the calculated parameters from the adopted models using the software Package Binary Maker 3.03 (Bradstreet and Steelman 2002). Due to the lack of spectroscopic observations (radial velocity measurements) of the studied systems, we estimated the absolute physical parameters for the components of each system using Harmanec's (1988) empirical effective temperature–mass ($T_{\text{eff}}-M$) relation. The calculated parameters reveal that the primary components in each system are massive and hotter than the secondary ones. The distance ($d = 10^{(m - M_v + 5)/5}$) was calculated using the photometric and absolute properties of each system, where m and M_v are the apparent and absolute magnitudes, respectively. Table 5 shows all of the calculated physical parameters.

As the studied systems did not have any previous distance calculations using ground-based observations to compare with our results, the approximate distance to the systems was calculated using the trigonometric parallaxes released by the Gaia 3rd data release. A distance difference of 9%–11% for the systems V0566 Hya and V0666 Lac, respectively, while 38% and 29% for the system V0487 Lac than our estimated values using Liakos & Niarchos data and Gaia photometric data, respectively. This can be attributed to the fact that our calculations based on ground-based observations and our estimation of the mean system colour index and interstellar reddening can be a little bit inaccurate because we do not know the phase at which the measurements were made, so we cannot be sure that they refer to the maximum light.

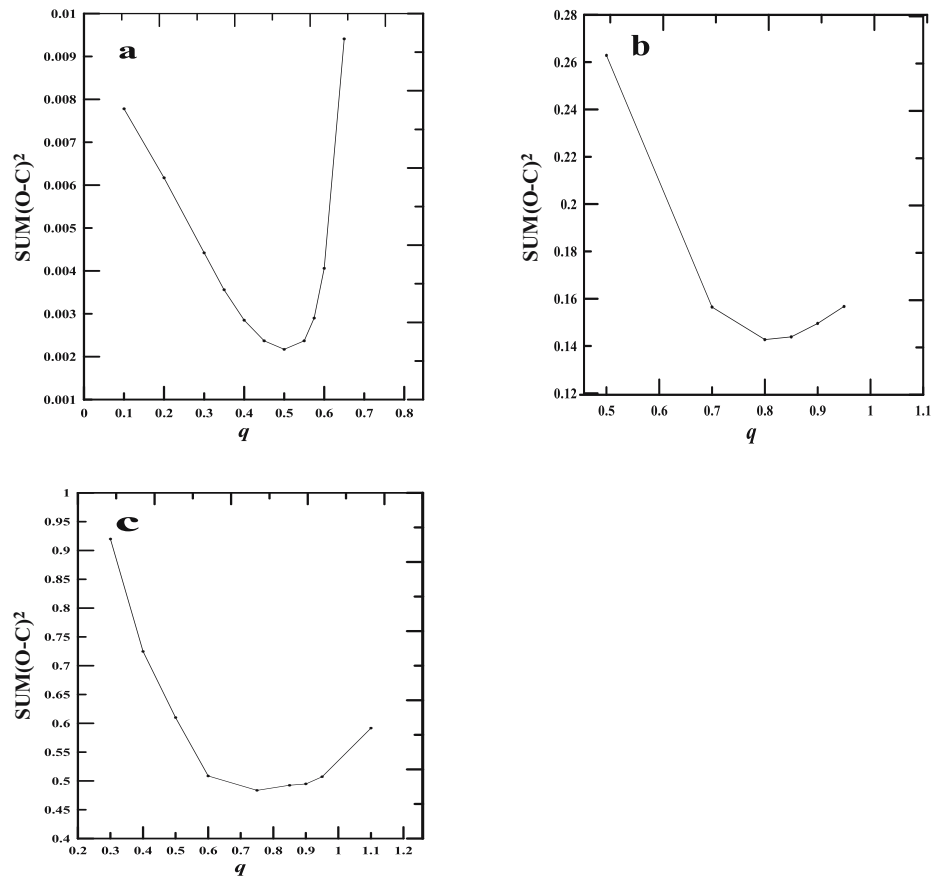


Figure 4: q -search of the binary systems: (a) V0487 Lac, (b) V0566 Hya, and (c) V0666 Lac.

Table 4: Orbital solution parameters for the systems V0487 Lac, V0566 Hya, and V0666 Lac

Parameter	V0487 Lac		V0566 Hya	V0666-Lac
	Liakos and Niarchos	Gaia data		
i ($^\circ$)	51.91 ± 1.68	78.01 ± 0.54	78.11 ± 0.44	76.29 ± 0.33
$g_1 = g_2$	0.32	0.32	0.32	0.32
$A_1 = A_2$	0.5	0.5	0.5	0.5
q (M_2/M_1)	0.4804 ± 0.0033	0.6455 ± 0.0085	0.9055 ± 0.0108	0.8374 ± 0.0078
Ω_1	3.8219 ± 0.0173	3.2994 ± 0.0179	3.5946	3.4804
Ω_2	$\pm 0.02463.4960$	3.2197 ± 0.0190	3.7013 ± 0.0130	3.6410 ± 0.0169
T_1 (K)	$5,051 \pm 13$	$5,269 \pm 51$	$5,331 \pm 65$	$6,332 \pm 82$
T_2 (K)	$4,296 \pm 7$	$4,989 \pm 10$	$4,742 \pm 26$	$4,759 \pm 17$
Ω_{in}	2.8378	3.1461	3.5946	3.4804
Ω_{out}	2.5499	2.7717	3.0946	3.0123
r_1 pole	0.2975 ± 0.0053	0.3712 ± 0.0130	0.0041 ± 0.3644	0.3710 ± 0.0043
r_1 side	0.3036 ± 0.0058	0.3886 ± 0.0158	0.3833 ± 0.0046	0.3906 ± 0.0048
r_1 back	0.3090 ± 0.0062	0.4101 ± 0.0202	0.4139 ± 0.0044	0.4209 ± 0.0046
r_2 pole	0.2127 ± 0.0048	0.3093 ± 0.0155	0.3347 ± 0.0124	0.3211 ± 0.0122
r_2 side	0.2160 ± 0.0051	0.3219 ± 0.0184	0.3491 ± 0.0149	0.3338 ± 0.0144
r_2 back	0.2225 ± 0.0058	0.3485 ± 0.0265	0.3744 ± 0.0207	0.3565 ± 0.0197
$\sum (\text{O}-\text{C})^2$	0.00174	0.01147	0.1493	0.4982

Table 5: Absolute physical parameters for the systems V0487 Lac, V0566 Hya, and V0666 Lac

Element	Star name			
	V0487 Lac		V0566 Hya	V0666 Lac
	Liakos and Niarchos	Gaia 3rd data release		
$M_1(M_\odot)$	0.8610 ± 0.0352	0.9370 ± 0.0383	0.9584 ± 0.0391	1.2934 ± 0.0528
$M_2(M_\odot)$	0.4136 ± 0.0169	0.6048 ± 0.0247	0.8678 ± 0.0354	1.0831 ± 0.0442
$R_1(R_\odot)$	0.9575 ± 0.0391	1.0351 ± 0.0423	1.0568 ± 0.0431	1.3794 ± 0.0563
$R_2(R_\odot)$	0.6761 ± 0.0267	0.9351 ± 0.0382	0.8442 ± 0.0345	0.8505 ± 0.0347
$T_1(T_\odot)$	0.8742 ± 0.0357	0.9119 ± 0.0372	0.9226 ± 0.0377	1.0959 ± 0.0447
$T_2(T_\odot)$	0.7435 ± 0.0304	0.8635 ± 0.0353	0.8207 ± 0.0335	0.8236 ± 0.0336
$L_1(L_\odot)$	0.5347 ± 0.0218	0.7399 ± 0.0302	0.8082 ± 0.0330	2.7405 ± 0.1119
$L_2(L_\odot)$	0.1395 ± 0.0057	0.4854 ± 0.0198	0.3229 ± 0.0132	0.3324 ± 0.0136
M_{bol_1}	5.4298 ± 0.2217	5.0771 ± 0.2073	4.9812 ± 0.2034	3.6554 ± 0.1492
M_{bol_2}	6.8886 ± 0.2812	5.5349 ± 0.2260	5.9774 ± 0.2440	5.9458 ± 0.2427
M_{V_1}	5.8422 ± 0.2385	5.3993 ± 0.2204	5.2813 ± 0.2156	3.7576 ± 0.1534
M_{V_2}	7.8071 ± 0.3187	5.9766 ± 0.2440	6.5555 ± 0.2676	6.5134 ± 0.2659
Sp. Type	(K1) ¹ , (K6) ²	(G9) ¹ , (K1) ²	(G8) ¹ , (K3) ²	(F7) ¹ , (K2) ²
Distance (pc)	391 ± 15.96	460 ± 18.78	$1,207 \pm 49.28$	$1,243 \pm 50.75$

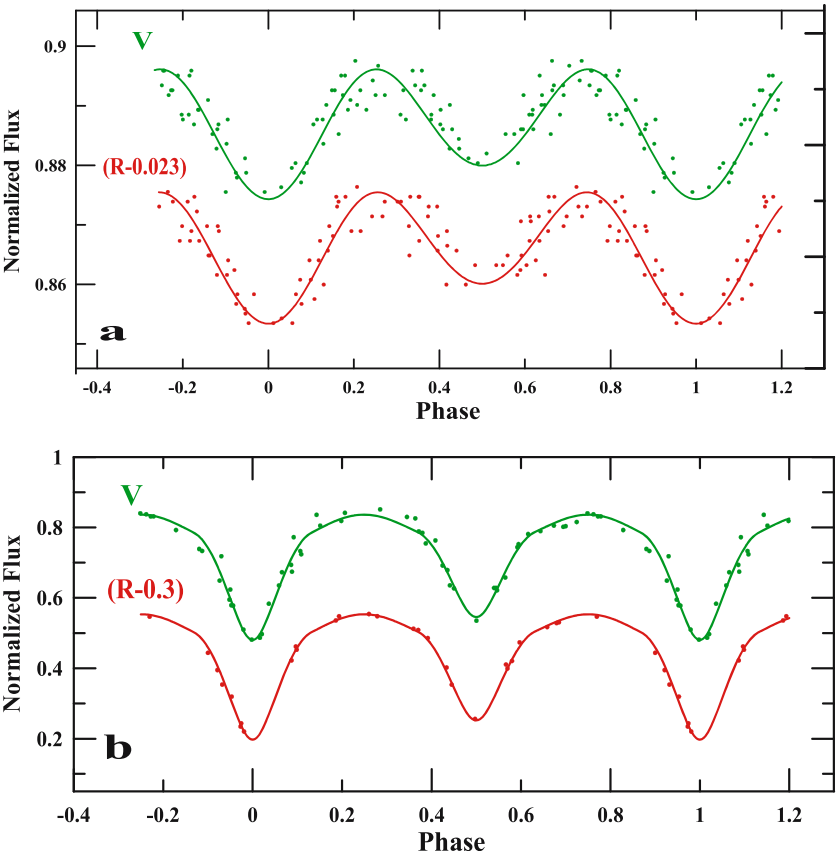


Figure 5: Light curve solution for the system V0487 Lac: Synthetic (solid lines) and observed (dotted lines), using (a) Liakos and Niarchos data, (b) Gaia 3rd data release.

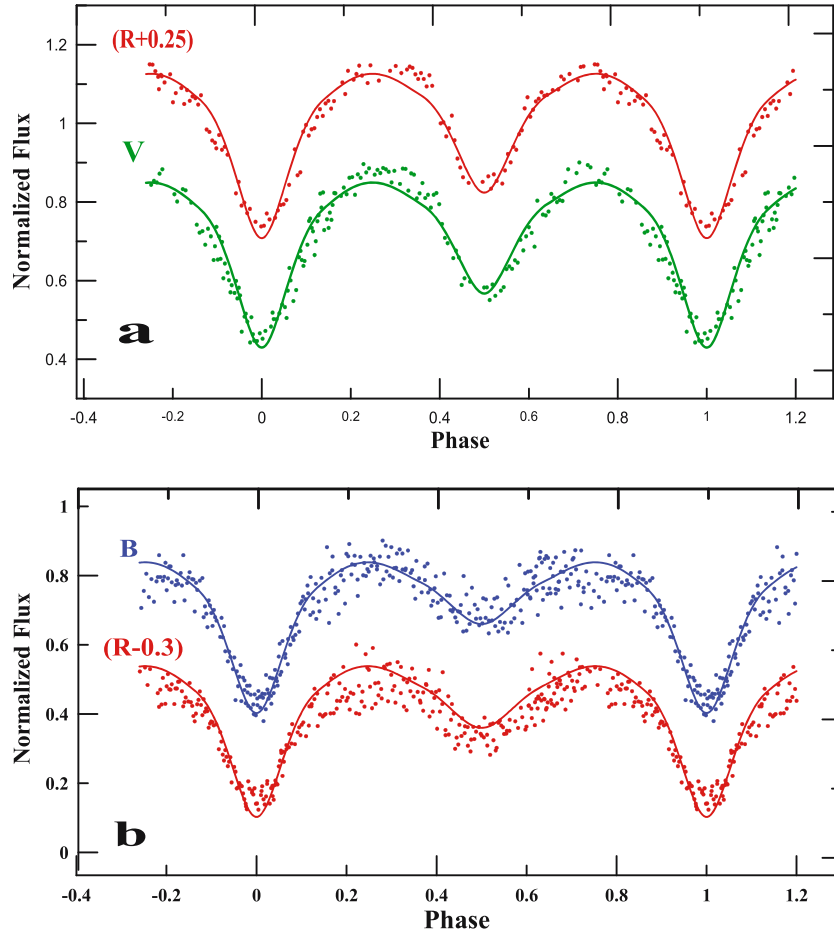


Figure 6: Light curve solution, Synthetic (solid lines) and observed (dotted lines), for the systems: (a) V0566 Hya, (b) V0666 Lac.

4 Evolutionary state of the systems

The evolutionary status of the studied systems was investigated by means of the estimated physical parameters listed in Table 5. Figure 8(a) and (b) shows the positions of the studied systems' components on the mass–luminosity (M – L) and mass–radius (M – R) relationships, as well as the evolutionary tracks computed by Girardi *et al.* (2000) for both zero-age main sequence stars (ZAMS) and terminal-age main sequence stars with metallicity $z = 0.019$. The figures showed that the primary and secondary components (S_1 and S_2) of all studied systems are located near the ZAMS for the M – R relation; therefore, all the components of the systems appear to be main-sequence stars. The luminosity of the secondary component of the system V0487 Lac is higher than expected from the ZAMS mass, which Lucy (1973) attributed to energy transfer from primary to secondary *via* the common convective envelope. Using the non-rotated evolutionary models of Ekstrom *et al.* (2012) in the range 0.7 – $2.0 M_{\odot}$ at solar metallicity $z = 0.014$, we located all the components of the systems on the effective

temperature–luminosity (T_{eff} – L) curves to test the agreement between the masses derived from the orbital solutions and those for the stellar models, as shown in Figure 9. We used the tracks for the masses appropriate to those of the orbital solutions. With the exception of the secondary component of the system, V0487 Lac, all the components display fair fit.

Figure 10 illustrates the mass–effective temperature relation (M – T_{eff}) for intermediate and low-mass stars (Malkov 2007). A good fit was shown for all of the studied systems' component locations on the (M – T_{eff}) diagram, with the exception of the secondary component (S_2) of the system V0487 Lac. The behaviour of the secondary component of the system V0487 Lac in Figure 8 is similar to how it behaves in Figure 6(a) and (b) in the M – L and M – R diagrams. We attributed this, as Lucy (1973) suggested, to an energy transfer from this system's primary to secondary components through the common convective envelope.

The estimated parameters listed in Tables 4 and 5, together with the positions of the components (S_1 and S_2)

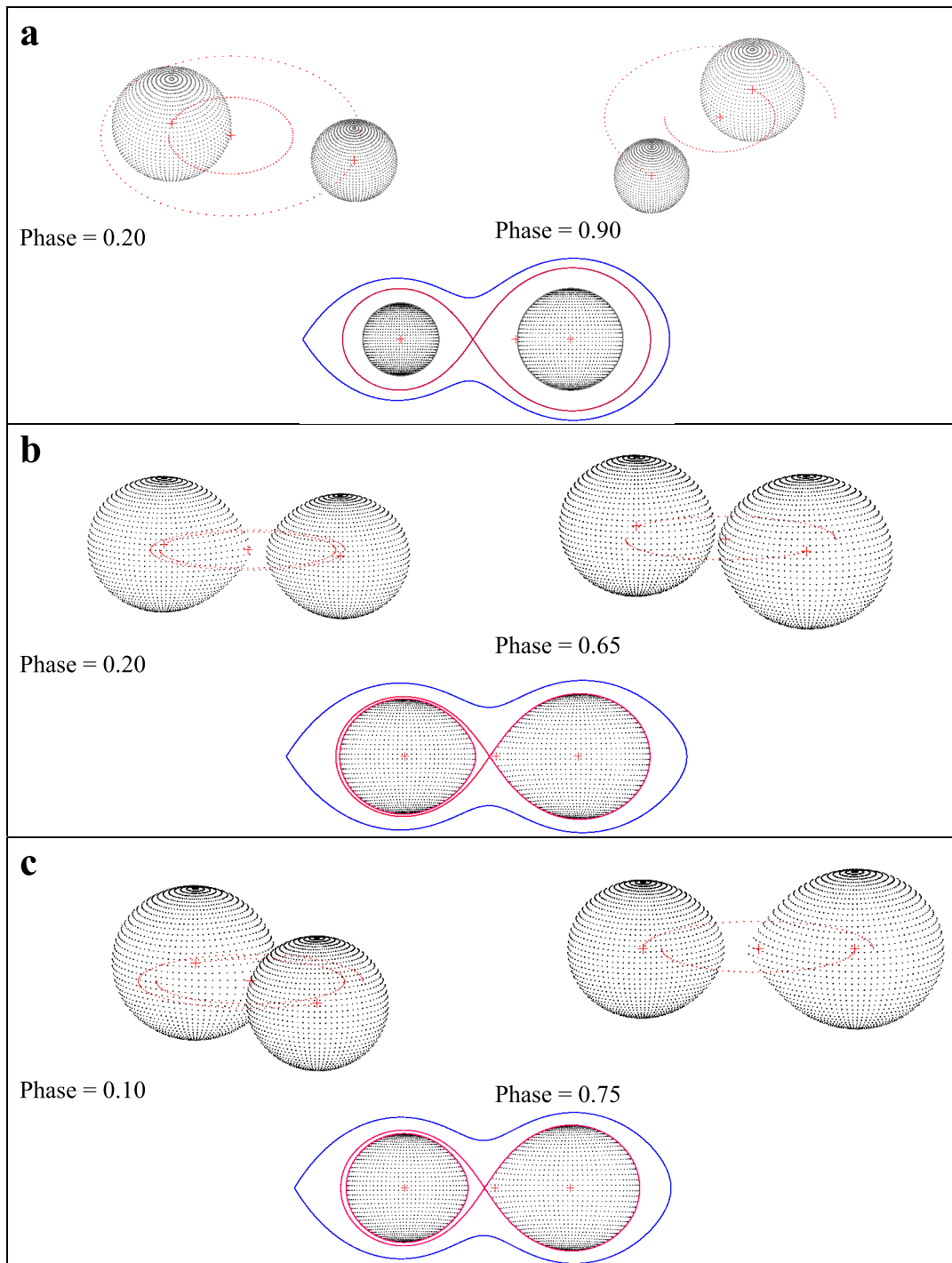


Figure 7: Three-dimensional structure of the binary systems: (a) V0487 Lac, (b) V0566 Hya, and (c) V0666 Lac.

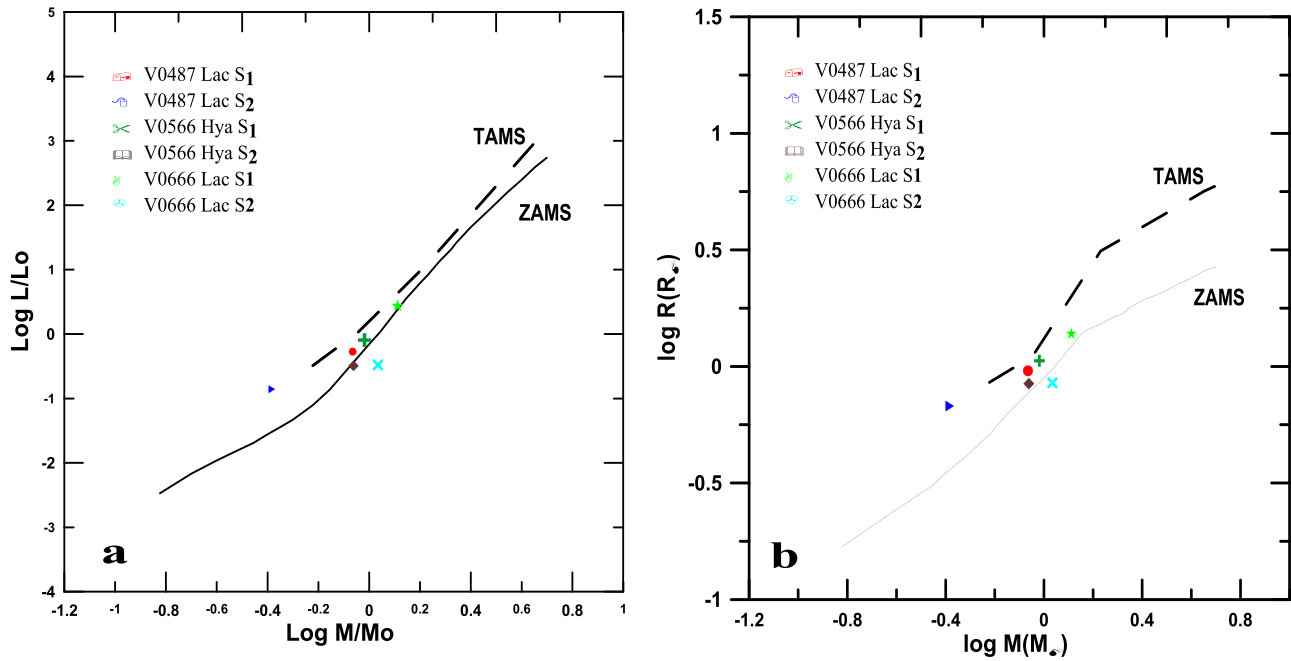


Figure 8: Positions of the components (S₁ and S₂) of the systems V0487 Lac, V0566 Hya, and V0666 Lac on the theoretical: (a) mass–luminosity diagram and (b) mass–radius diagram of Girardi *et al.* (2000).

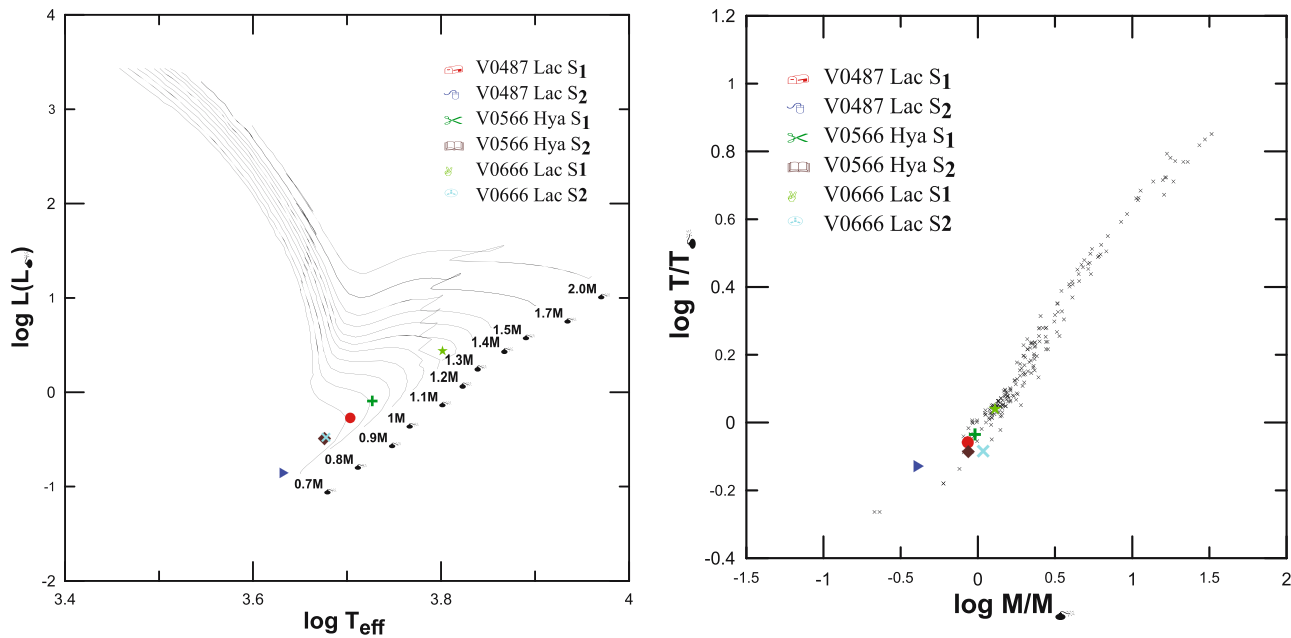


Figure 9: Positions of the components (S₁ and S₂) of the systems V0487 Lac, V0566 Hya, and V0666 Lac on the $T_{\text{eff}}-L$ diagram of Ekstrom *et al.* (2012).

of the studied systems on the $M-T_{\text{eff}}$ diagram by Malkov (2007) (Figure 10), confirmed that the systems V0487 Lac and V0566 Hya are of WUMa type, while the results for the system V0666 Lac indicated that the classification of the

Figure 10: Positions of the components (S₁ and S₂) of the systems V0487 Lac, V0566 Hya, and V0666 Lac on $M-T_{\text{eff}}$ diagram by Malkov (2007).

system as Beta Lyrae needs to be reviewed because the system period, adopted spectral type (late type), and component masses indicate that the system belongs to the WUMa class. Spectroscopic observations of the studied systems are needed to confirm their type of variability.

5 Discussion and conclusion

We presented a holistic photometric study involving the evolutionary state of the systems V0487 Lac, V0666 Lac (both discovered in 2010), and V0566 Hya (discovered in 2011). Their light curves were observed in the period from July 2010 to March 2011. The first O–C diagrams were created, and new times of minima were calculated for all the systems. According to the first orbital solutions for the systems, all primary components are hotter and more massive than secondary ones. As well as adopting their component's spectral type, the distance to each system was calculated. The behaviour of the studied systems with regard to $M-R$ and $M-L$ relations has been examined by exploring their evolutionary state. With the exception of the secondary component of the system V0487 Lac, the locations of the components of the studied systems on the $M-R$ and $M-L$ diagrams show a good fit to the ZAMS track. The components of all systems lie in their expected positions when located on the $T_{\text{eff}}-L$ and $M-T_{\text{eff}}$ diagrams, except for a minor deviation in the case of the secondary component of the system V0487 Lac. As a result, we conclude that the luminosity of the secondary component of the system V0487 Lac appears to have a higher temperature and luminosity than that predicted by the four relations, which is attributed to energy transfer from the primary to the secondary through the common convective envelope, as suggested by Lucy (1973). Since the systems under study have never been studied before and lack any historical data or prior research, we view our findings as preliminary. All three new variables presented in this study need more photometric and spectroscopic observations with different filters to determine their spectral characteristics, confirm their variability type, and follow their orbital period behaviour.

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Author contributions: M.A. wrote and edited the manuscript; M.E. carried out the calculations and modelling.

Conflict of interest: The authors state that there is no conflict of interest.

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