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Analysis of multicolour light curves of southern eclipsing binaries GW Car, V685 Cen, V742 Cen and V764 Sco

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Abstract. First multicolour photoelectric light curves of the southern early-type eclipsing binaries GW Car, V685 Cen, V742 Cen and V764 Sco were obtained in the years 1969, 1974, 1977-8 at the Leiden Southern Station using Walraven $VBLUW$ filters. New orbital periods 0.86446 days and 1.54263 days were found for V742 Cen and V764 Sco, respectively. The long-term orbital period decrease was detected in GW Car. Our light-curve analysis accomplished by Wilson-Devinney's code found an almost semi-detached configuration for GW Car and revealed that V685 Cen, V742 Cen and V764 Sco are detached systems.

Key words: eclipsing binaries – photometry – orbital elements

1. Introduction

In 1965-78 the second author (CJvH) initiated a program for obtaining multicolour photoelectric light curves of eclipsing variables observed in the southern hemisphere using the 0.9 m telescope of the Leiden Southern Station in South Africa. As a part of this program, the four-band Walraven $VBLU$ light curves of the eclipsing binaries V742 Cen and V764 Sco were obtained in 1974, V685 Cen in 1977-78 and GW Car in 1969, 1974 and 1977. In 1969, GW Car was also observed in the Walraven W band. The observations are published by van Houten et al. (2003). The detailed characteristics of the Walraven system can be found in Walraven & Walraven (1977). Brand & Wouterloot (1988) compared the Walraven colour indices with stellar atmospheres' models for O,B and A stars. Their calibration allows to determine effective temperature and surface gravity from Walraven intrinsic (dereddened) stellar colours. The aim of our paper is to analyze multicolour light curves of the binaries employing the revised version (Wilson, 1992) of Wilson-Devinney's (1971,1973) code (W&D).

2. Basic information and efemerides of GW Car, V685 Cen, V742 Cen and V764 Sco

2.1. Determination of minima times and their weights

The minima times of GW Car, V742 Cen and V764 Sco were determined from our observations (van Houten et al. 2003) using Kwee & van Woerden's (1956) method for each Walraven passband separately. These data were used to find the mean value of the minimum including its standard error σ. The weight of the minimum was calculated by a usual way as $1/\sigma^2$. Due to the bad coverege of minima by observations for V685 Cen, we used them only to find the normal epoch of the primary minimum.

We have determined the ephemeris from photoelectric minima times only in the case of GW Car, because they covered the interval of 12 years. For other stars we had to use also the published photographic minima times. We fitted these data by linear ephemeris and found the standard error and corresponding weight from the scatter of these data. Thereafter, we normalized the weights of photoelectric data setting the weights of photographic data $w = 1$. All minima times including their weights were used for determination of the ephemerides, valid in the intervals covered by observations.

2.2. Determination of T_{eff} from Walraven colour indices

The effective temperatures and corresponding spectral types of variables were determined from the Walraven dereddened $[B-U]$ and $[B-L]$ colour indices in quadratures derived from our observations (van Houten et al., 2003) using the calibration of Brand & Wouterloot (1988). They are listed in Table 1. All quantities are in the usual notation of the Walraven colour system: use of log$I$ instead of magnitudes. The $V-B$ colour determines the reddening, $B-U$ measures the Balmer jump, so it is a good temperature indicator for O and B stars, $B{-}L$ mainly depends on gravity. The last two parameters were dereddened using the formulae published by Brand & Wouterloot (1988).

2.3. GW Car

The eclipsing binary GW Car (HD 83475; sp. type B1 III (Garrison et al., 1977), B0.5 II (our paper); $m_{\mathrm{pg}}^{\mathrm{max}} = 9.55$ mag; $m_{\mathrm{pg}}^{\mathrm{min\ I}} = 10.1$ mag; $m_{\mathrm{pg}}^{\mathrm{min\ II}} = 9.9$ mag; $P = 1.12891$ days (Kholopov et al., 1985)) was discovered by O'Connell (1937). The photographic light curve was obtained and analyzed by O'Connell (1956). He concluded that the primary eclipse was a total occultation. He further suggested that the system may exhibit apsidal motion as a result of displacements of the secondary minima. Buckley (1984) found from the simultaneous solution of B, V, R light curves using the W&D code that the system is semidetached, with smaller and cooler secondary filling its Roche-lobe. On the other hand, his solution of V light curves by the WINK code provided a detached configuration

Table 1. The V colour, colour indices, intrinsic (dereddened) colour indices in Walraven system and corresponding $T_{\rm eff}$ for studied eclipsing binaries and their comparison stars

star	V	$V-B$	$B-L$	$[B-L]$	$B-U$	$[B-U]$	$U-W$	$T_{\rm eff}$
GW Car	-1.065	0.004	-0.011	-0.013	-0.012	-0.014	0.002	25 000
HD83502	-1.309	0.033	0.114	0.101	0.346	0.326	0.100	11 400
V685 Cen	-0.784	0.006	0.104	0.102	0.306	0.302	–	11 900
HD99415	-0.840	0.028	0.042	0.031	0.131	0.114	0.029	17 500
V742 Cen	-1.040	0.017	0.106	0.099	0.294	0.284	–	12 200
HD100119	-0.113	-0.022	0.073	0.081	0.304	0.317	0.056	11 300
V764 Sco	-0.702	0.117	0.215	0.169	0.453	0.381	–	10 300
HD162967	-0.657	-0.018	0.090	0.097	0.274	0.285	0.039	12 200

for the mass ratio $q = 0.72$. He also mentioned that a 0.06 decrease in q brings the secondary in contact with its inner critical surface.

All available minima times of GW Car are listed in Table 2. The weights of the photographic minima times were adopted from the work of O'Connell (1956) except for the minimum JD2433121.743, which was omitted from our further analysis. We calculated the weights od photoelectric minima using the procedure as described in the subsection 2.1., but we used for normalization of the photoelectric weights the mean photographic weight $w = 6$ instead of the weight equal one. Our analysis of the data showed considerable difference between the linear ephemerides found from the photografic and photoelectric minima times taken in 1935-1954 and 1969-81, respectively. Therefore, we used only the photoelectric minima times for determination of the light elements (by the least-squares method):

$$\begin{array}{llll} \mathrm{Min\ I} = \mathrm{HJD} & 2\,440316.8699 & +\ 1.12890795 & \times\ E \\ & \qquad\quad \pm 9 & \qquad\quad \pm 35 & \end{array} \tag{1}$$

The $O-C$ diagram of GW Car is presented in Fig. 1. The long-term variations in the displacement of the secondary minima with respect to the primary ones, which can indicate an apsidal motion, are clearly visible in the old photographic data. Hegedüs (1988) included eclipsing binary GW Car into a list of binaries with poorly proved or questionable apsidal motion. Our new photoelectric data are not sufficient to prove quoted orbital eccentricity $e = 0.025$ and discuss possible existence of an apsidal motion in the system. The $O-C$ diagram evidently indicates the long-term orbital period decrease as a consequence of the mass transfer/loss and/or the light-time effect due to the presence of a third body. More data are necessary to distinguish the cases.

2.4. V685 Cen

Eclipsing binary V685 Cen (HD 99218; sp. type B9 V (Lodén et al., 1976), B7.5 V (our paper); $m_{\rm pg}^{\rm max} = 9.4$ mag; $m_{\rm pg}^{\rm min\ I} = 9.8$ mag; $m_{\rm pg}^{\rm min\ II} = 9.5$ mag; $P =$

Table 2. Minima times of GW Car. Photographic minima times (with given weights) were published by O'Connell (1956), photoelectric minimum time in epoch 3880 by Buckley (1984). We added further 5 photoelectric minima times found from our observations. Their weights were calculated using the method described in text.

Epoch	HJD	w	Epoch	HJD	w	Epoch	HJD	w
	2 400 000+			2 400 000+			2 400 000+	
-11033	27861.617	8	-9829	29220.829	4	-6755.5	32690.540	8
-10990	27910.169	8	-9716.5	29347.813	3	-6617	32846.883	6
-10964.5	27938.949	12	-9699	29367.589	6	-6562	32908.994	7
-10935	27972.258	8	-9695.5	29371.535	6	-6398.5	33093.554	6
-10718	28217.231	8	-9245.5	29879.555	6	-6373.5	33121.743	0
-10634.5	28311.486	10	-9234.5	29891.958	2	-6134	33392.157	4
-10617	28331.249	6	-9079	30067.527	2	-5970	33577.299	5
-10424	28549.133	8	-8841	30336.197	5	-5867	33693.586	4
-10422	28551.386	9	-8582.5	30628.005	3	-5599.5	33995.559	4
-10361.5	28619.692	10	-8446.5	30781.547	4	-5256.5	34382.765	3
-10309	28678.956	7	-8432	30797.922	8	-5153.5	34499.066	3
-10304.5	28684.023	4	-8360	30879.201	6	-5076	34586.537	5
-10302	28686.855	9	-7620.5	31714.011	1	-4802.5	34895.310	3
-10268.5	28724.661	9	-7386	31978.763	6	0.5	40317.4362(3)	3550
-10061	28958.926	8	-7143.5	32252.525	8	7.5	40325.3366(6)	890
-10051	28970.211	5	-7087	32316.307	4	19	40338.3174(3)	3550
-10005.5	29021.574	4	-6815	32623.368	8	1651.5	42181.2595(5)	1280
-10003.5	29023.824	12	-6811	32627.889	8	2587	43237.3557(3)	3550
-9951	29083.104	5	-6770.5	32673.600	2	3880	44697.0326(2)	8000

1.19096 days (Kholopov et al., 1985)) was discovered by Uitterdijk, the first photographic light curve was obtained and period determined by van Houten (Uitterdijk & van Houten 1960). Their photographic minima times, together with the mean epoch, determined from our observations and published HIPPARCOS mean epoch (ESA, 1997) are listed in Table 3. The least-squares solution resulted in the light elements:

$$\begin{array}{lllll} \mathrm{Min\ I} = & \mathrm{HJD}\ \ 2\,443586.3313 & + & 1.19096085 & \times E \\ & \qquad\qquad \pm 13 & & \quad \pm 26 & \end{array} \tag{2}$$

2.5. V742 Cen

Eclipsing binary V742 Cen (HD 99628; sp. type B 7.5 V (our paper); $m_{\mathrm{pg}}^{\mathrm{max}}$ = 9.4 mag; $m_{\mathrm{pg}}^{\mathrm{min\ I}}$ = 10.2 mag; $m_{\mathrm{pg}}^{\mathrm{min\ II}}$ = 10.1 mag (Kholopov et al., 1985); P = 0.864456 days) was discovered by Strohmeier et al. (1965b), who found the light elements: Min I = 2438493.45 + 6.49 d $\times E$. Our photoelectric data revealed that the orbital period is much shorter. It is easy to find, using Tanner's (1948) formula, that the period 6.49 days is a one-day alias of the true orbital period 0.8644 days. The photographic minima times published by Strohmeier et al. (1965b) and photoelectric minima times, found from our data, are listed

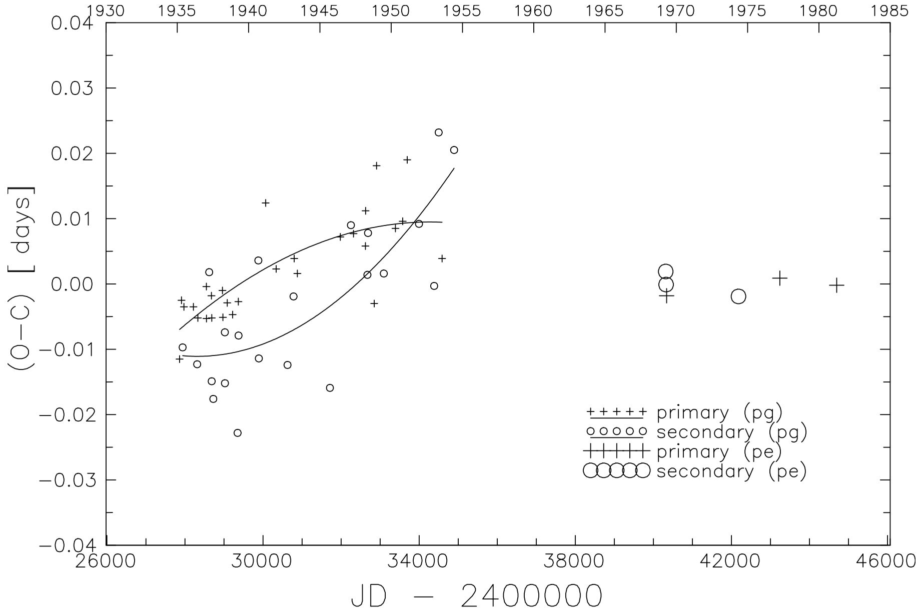

Figure 1. The $O-C$ diagram of GW Car using the ephemeris (1)

in Table 3. They were used to derive the new ephemeris by the least-squares method:

$$\begin{array}{llll} \text{Min I} = & \text{HJD} & 2\,442169.87349 & +\ 0.8644556 \ \times E \\ & & \pm 20 & \qquad \pm 18 \end{array} \quad (3)$$

2.6. V764 Sco

Eclipsing binary V764 Sco (HD 162985; sp. type B9.5 V (our paper); $m_{\mathrm{pg}}^{\mathrm{max}}$ = 8.5 mag; $m_{\mathrm{pg}}^{\mathrm{min\ I}}$ = 9.1 mag; $m_{\mathrm{pg}}^{\mathrm{min\ II}}$ = 9.0 mag; Kholopov et al. (1987); P = 1.5426 days) was discovered by Strohmeier et al. (1965a), who determined its period as 0.86875 days. Schöffel & Köhler (1965) corrected this period to 6.8084 days and published a light curve based on this period. Our photelectric observations revealed that the true orbital period of V764 Sco is 1.5426 days. The photographic minima times published by Schöffel & Köhler (1965) together with photoelectric minima times, determined from our observations, are listed in Table 3. They were used to derive the new ephemeris by the least-squares method:

$$\begin{array}{llll} \text{Min I} = & \text{HJD} & 2\,442192.46601 & +\ 1.5426320 \ \times E \\ & & \pm 19 & \qquad \pm 28 \end{array} \quad (4)$$

Table 3. Minima times and weights (w) of V685 Cen, V742 Cen and V764 Sco used for the least squares solutions. Standard errors of photoelectric minima times determined from our observations are given in parentheses. Their weights were calculated using the method described in text.

Epoch	HJD	O-C	w	Epoch	HJD	O-C	w
	2 400 000+				2 400 000+		
	V685 Cen			-3930	38772.548	-0.0149	1
-16516	23916.417	-0.0048	1	-3870	38824.444	0.0138	1
-16480	23959.281	-0.0154	1	-3783.5	38899.213	0.0073	1
-16475	23965.280	0.0288	1	-3780	38902.212	-0.0192	1
-16454	23990.238	-0.0234	1	0.5	42170.3064(3)	0.0007	4060
-16449	23996.206	-0.0102	1	7.5	42176.3572(5)	0.0003	1460
-16228	24259.445	0.0265	1	11	42179.3822(2)	-0.0003	9130
-16202	24290.360	-0.0235	1	29.5	42195.3732(3)	-0.0017	220
-16197	24296.346	0.0077	1		**V764 Sco**		
-15328	25331.278	-0.0053	1	-2566.5	38233.315	0.0140	1
-15311	25351.536	0.0064	1	-2549	38260.273	-0.0241	1
-14668	26117.305	-0.0125	1	-2544.5	38267.223	-0.0159	1
-12500	28699.363	0.0424	1	-2390	38505.577	0.0014	1
-12490	28711.225	-0.0052	1	-2374.5	38529.518	0.0316	1
-1249	28724.330	-0.0008	1	-2357	38556.468	-0.0144	1
0	43586.3295(52)	-0.0018	13	-2341.5	38580.388	-0.0052	1
4126	48500.2358(10)	0.0000	360	-2319.5	38614.305	-0.0261	1
	V742 Cen			-2315	38621.295	0.0220	1
-4256.5	38490.316	-0.0021	1	-2304	38638.218	-0.0239	1
-4253	38493.319	-0.0247	1	-2299.5	38645.224	0.0402	1
-4241.5	38503.306	0.0210	1	0	42192.4662(3)	0.0002	6000
-4226.5	38516.255	0.0032	1	4	42198.6357(7)	-0.0008	1100
-4223	38519.254	-0.0234	1	8.5	42205.5782(8)	-0.0002	840
-4211.5	38529.248	0.0294	1	15.5	42216.3768(3)	0.0000	6000

References for photographic minima ($w = 1$): V685 Cen - Uitterdijk & van Houten (1960), V742 Cen - Strohmeier et al. (1965b), V764 Sco - Schöffel & Köhler (1965). The last minimum of V685 Cen is the Hipparcos mean epoch (ESA, 1997).

3. Multicolour light-curve analysis

3.1. Determination of normal points and their weights

Our Walraven photoelectric observations of GW Car, V685 Cen and V742 Cen were published in van Houten et al. (2003). They were listed in their Tables 3,4,5 and 6. In the case of V764 Sco the number of individual observations in every passband reached 1094. Therefore, in their Table 7 there are presented 100 normal points in every passband in normalised intensities instead of original observations.

The procedure of calculation of normal points in intensities can be described as follows. The normal points in magnitudes were calculated as a mean value of brightness in an interval of the orbital phases $0.01P$. The standard deviation σ of the normal point is

$$\sigma_N = \frac{\sigma}{\sqrt{N}} \ , \tag{5}$$

where N is the number of observations in a given interval. The weight of the normal point w can be calculated as follows

$$w_N = \frac{1}{\sigma_N^2} = \frac{N}{\sigma^2} \ . \tag{6}$$

The differential magnitudes were transformed to intensities by the standard equation

$$I = 10^{-0.4m} \ . \tag{7}$$

These intensities were normalised to the intensity at brighter maximum (orbital phase 0.25 or 0.75). The weights in intensities were calculated as:

$$w_N^{int} = \left(\frac{2.5}{I \ln 10}\right)^2 w_N^{mag}. \tag{8}$$

3.2. Photometric elements

The normal points in intensities are suitable for the determination of photometric elements using the W&D method. In order to decrease the number of free parameters, we assumed $T_{\rm eff}$ determined in Section 2.2, a logaritmic limb-darkening law and theoretically predicted values of monochromatic and bolometric coefficients of limb-darkening given by van Hamme (1993), gravitational darkening and bolometric albedo appropriate for radiative envelopes given by Rucinski (1973). Synchronous rotation and zero eccentricity were assumed. Approximate atmosphere option was used. All light curves in the $VBLU$ (for GW Car also W) passbands were solved simultaneously. The differential corrections code was run until the output corrections were smaller than the standard errors σ of the elements. The differential corrections converged rather slowly. We had to perform up to 100 steps for one solution.

We have solved the light curves for several fixed values of mass ratio q. For a given system we have accepted the solution, where χ^2 reached the minimum (Figs. 2 and 3). The resulting photometric elements of all four systems with their standard errors are given in Table 4. The fits corresponding to these elements are shown in Figs. 4 - 7.

For V685 Cen we found that adopted temperature T = 11 900 K from Walraven colour indices is not appropriate to fit the observed light curves. Due to the large difference of temperatures of the primary and secondary component, the light-curve solution is quite sensitive to the temperature of the primary component. We have fixed several possible temperatures between 8 000 and 20 000 K in the light-curve solution and found the best fit for the temperature 16 000 K. The discrepancy is probably caused by the activity in the system detected as an occasional brightening in the U passbands.

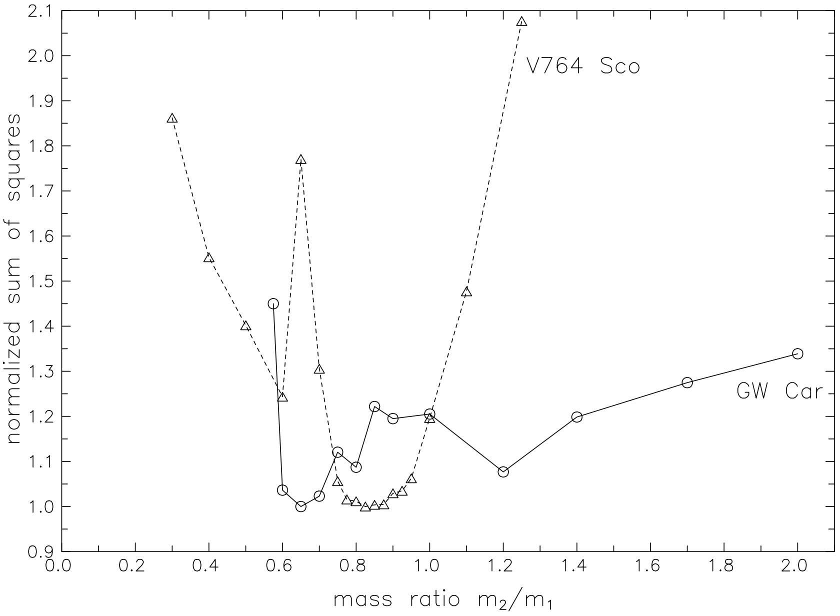

Figure 2. The χ^2 dependence on the mass ratio for GW Car and V764 Sco

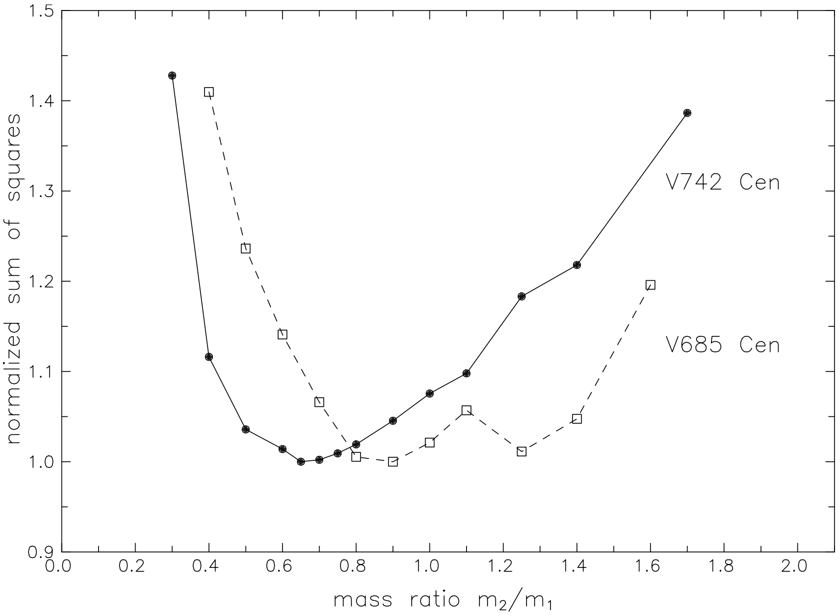

Figure 3. The χ^2 dependence on the mass ratio for V742 Cen and V685 Cen

Table 4. Photometric elements and their standard errors (in parantheses): i - inclination; $q = m_2/m_1$ - mass ratio; Ω_1, Ω_2 - surface potentials; r_1, r_2 - mean volume radii of the components; V_1, V_2, V_{inn} - volumes of the components and the corresponding Roche lobes; T_1, T_2 - polar temperatures; L_1, L_2 - luminosities of the components. $\sum w(O-C)^2$ is weighted sum of squares of residuals. Parameters not adjusted in the solution are denoted by a superscript "f".

Element		GW Car	V685 Cen	V742 Cen	V764 Sco
i		90^f	68.22(7)	83.62(9)	86.9(5)
q		0.65^f	0.90^f	0.65^f	0.825^f
Ω_1		3.2619(24)	3.950(9)	3.841(9)	4.002(4)
Ω_2		$3.1985(16)^f$	3.884(10)	3.583(10)	4.4735(24)
r_1		0.3980(4)	0.3361(11)	0.3194(10)	0.3217(4)
r_2		0.3336(3)	0.3258(13)	0.2752(12)	0.2465(2)
V_1/V_{inn}		86%	65%	45%	53%
V_2/V_{inn}		92%	68%	52%	31%
T_1 [K]		$25\ 000^f$	$16\ 000^f$	$12\ 200^f$	$10\ 300^f$
T_2 [K]		19 481(31)	10 300(42)	10 853(15)	9 826(13)
$L_1/(L_1+L_2)$	W	0.7330(8)	–	–	–
	U	0.7257(8)	0.8164(27)	0.6782(26)	0.6664(14)
	L	0.7001(8)	0.7482(28)	0.6498(27)	0.6701(10)
	B	0.6861(8)	0.7126(26)	0.6401(26)	0.6534(10)
	V	0.6823(8)	0.6960(26)	0.6355(26)	0.6472(9)
$\sum w(O-C)^2$		0.04107	0.07136	0.06113	0.71152

Our light-curve analysis revealed that all four binaries are detached systems. The determination of q for detached systems from the χ^2 dependence on the mass ratio is always problematic and can be in disagreement with the q found from spectroscopy. For GW Car, the mass ratio lower than 0.6 provides a semi-detached configuration with the smaller component filling its Roche lobe. On the other hand, the χ^2 reached minimum for the mass ratio $q = 0.65$, suggesting that the smaller component is detached from its Roche lobe. Therefore, we have classified GW Car as an almost semi-detached system. The spectroscopic mass ratio of GW Car is highly desirable to resolve the problem of configuration of the system.

4. Conclusions

Our Walraven $VBLUW$ light curves of GW Car are superior to all previously published photometric data. Their analysis found an almost semi-detached configuration of the binary. The long-term period change of the orbital period was detected indicating either the mass transfer/loss in the binary or the possible presence of a third body in the system.

Our Walraven $VBLU$ light curves of V685 Cen, V742 Cen and V764 Sco are the first photoelectric light curves of these binaries ever published. Our observations allowed to change erroneous orbital periods 6.49 and 6.8084 days

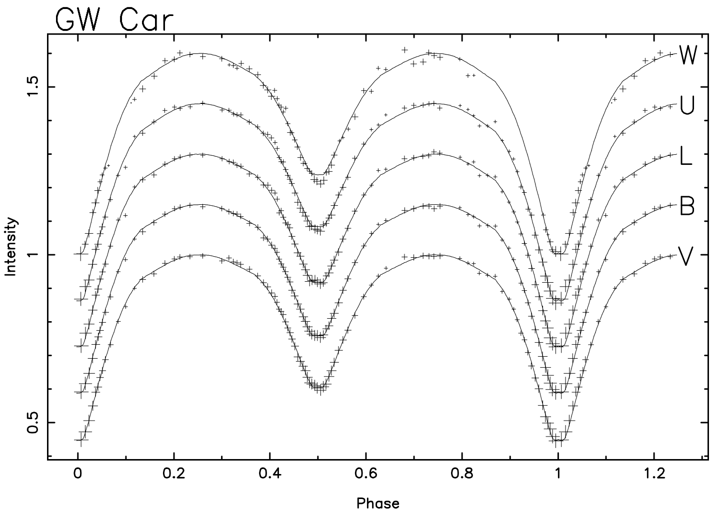

Figure 4. *VBLUW* observations (normal points in intensities) of GW Car and their best fits. The sizes of the normal points are proportional to their weights. The light curves and fits are shifted by 0.2 in intensities for a better illustration

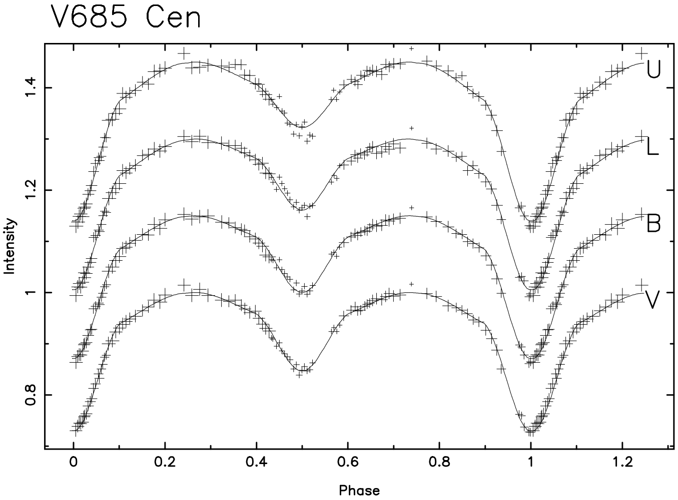

Figure 5. *VBLU* observations of V685 Cen and their best fits. The description of symbols is the same as in Fig. 4

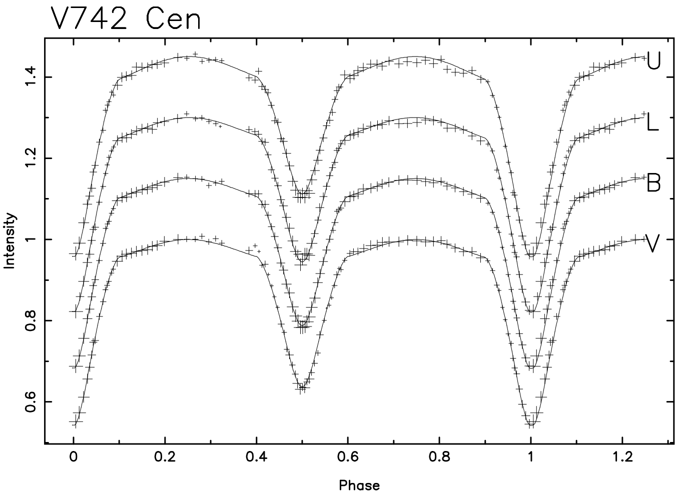

Figure 6. *VBLU* observations of V742 Cen and their best fits. The description of symbols is the same as in Fig. 4

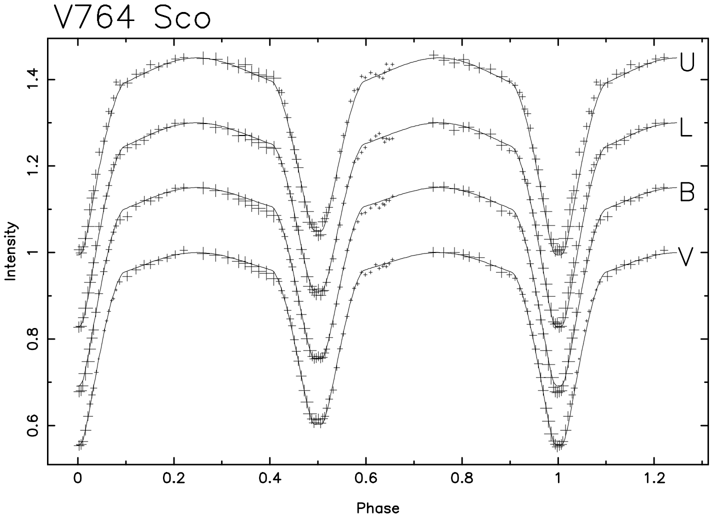

Figure 7. *VBLU* observations of V764 Sco and their best fits. The description of symbols is the same as in Fig. 4

of the binaries V742 Cen and V764 Sco to the true ones: 0.86446 and 1.54263 days, respectively. New ephemerides of the systems are given. The light curve analysis by the W&D code revealed the detached configuration of all three binaries.

The photometric elements found from the light curves are influenced by the fact that the mass ratios of the components were not yet determined spectroscopically.

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