Physical parameters of components in close binary systems: III

by

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ABSTRACT

The paper presents combined spectroscopic and photometric orbital solutions for five close binary systems: V402 Aur, SX Crv, V829 Her, VZ Lib and V753 Mon. The photometric data consists of new complete, multicolor light curves, while the spectroscopy has been recently obtained within the radial velocity programme at the David Dunlap Observatory. For one target, SX Crv, new spectroscopic data were obtained using the 6.5 m Magellan telescope. A contact configuration was found through light curve modelling for all targets except V753 Mon. Our solution for V753 Mon resulted in a semidetached configuration with the slightly less massive component filling its Roche lobe.

Key words: binaries: eclipsing–binaries: close–binaries: contact–stars: fundamental parameters

1. Introduction

In this paper we present the absolute and geometric parameters for five more systems from the sample defined by Kreiner et al. (2003), hereafter Paper I. The solutions are based on the combined spectroscopic data from the DDO program (Pych et al. (2004) and references to previous papers therein) and new multicolor light curves obtained recently. The project was described in greater detail in Paper I, along with the procedure used for the derivation of parameters, with a subsequent modification presented in Baran et al. (2004) (Paper II). In addition to gathering new photometric data, we also obtained new radial velocity curves for the most interesting object in our sample, SX Crv for which a very low spectroscopic mass ratio was recently obtained (q_{sp}=0.07) (Rucinski et al. (2001)).

A description of the targets analyzed in this work is presented in the next section. New photometric data, as well as new spectroscopic observations of SX Crv with the Magellan telescope, are described in Section 3, while the procedure used to derive the absolute parameters of components from the light curve modeling is outlined in Section 4. The results are briefly discussed in the last Section.

2. Targets

The variability of V402 Aur (BD+31^{o}0849, HIP=23433, V=8.95^m) was found by Oja (1991) and the UBV light curve was published 3 years later by Oja (1994). A spectroscopic study of this target was performed by Pych et al. (2004). A new spectral type of F2V was assigned, somewhat later than that from the HD catalogue (F0) and the mass ratio was determined to be 0.201$\pm$0.006. A new ephemeris for this system was given by Pribulla et al. (2002), with a period of 0.6034992^d for this system.

SX Crv (BD-18^{o}3437, HIP=61825, V_{max}=8.99^m) was found to be variable by Sanwal et al. (1974). They reported this star to be a contact type system with minima depths of 0.20^m and 0.18^m and a period of about 0.32 days. After rectification of the light curve they concluded that with such shallow minima the variability must be mainly due to ellipticity effects. Additional, night-to-night intrinsic varability was also observed. New photometric observations were performed by Scaltriti & Busso (1984). They confirmed changes in the light curves on consecutive nights, which were especially evident during the minima. They also pointed out that substantial period change may be occuring as indicated by large deviations in the O-C diagram. First results from spectroscopic observations were published by Rucinski et al. (2001). A surprisingly low mass ratio was determined (q=0.066$\pm$0.003, mass function=0.861$\pm$0.028) and a new spectral type (F6/7V) was estimated.

V829 Her (GSC 02597-00679, V=10.28^m) was discovered as an X-ray source by the Einstein Observatory. Fleming et al. (1989) suspected it to be a W UMa-type system, this classification was confirmed by Robb (1989) and a period of 0.358^d was obtained. The first spectroscopic orbit was obtained by Lu & Rucinski (1999). They classified it to be a W-type contact system with the mass ratio q=0.408$\pm$0.008. The masses of the components were found to be M_1=1.46 and M_2=0.60 (solar masses). The first multicolor (BVR) light curve was published by Erdem & Ozkardes (2004). They found no asymmetry in the light curve and also concluded that V829 Her is a W-type contact system.

The variability of VZ Lib (GSC06184-00156, HIP76050, V_{max}=10.36^m) has been known for a long time, since the work by Tsesevitch (1954). The only available UBV light curve was published by Claria & Lapasset (1981). The depths of the primary and secondary minima in the V band are 0.5^m and 0.4^m, respectively. Claria & Lapasset's light curve also revealed small intrinsic night-to-night variations. The results of the spectroscopic study by Lu & Rucinski (1999) revealed the existence of a spectroscopic companion (possibly even a binary system) of about 0.2 brightness of the contact binary. The mass ratio was determined to be 0.237$\pm$0.068, while the spectral type classified as G0.

V753 Mon (BD-03^{o}1780, HIP=34684, V_{max}=8.34^m) was discovered to be variable by the Hipparcos mission. The large error of the Olsen's (1994) photometric measurements in the Stromgren system could had been taken as an indication of variability before the Hipparcos mission. Spectroscopic data were obtained by Rucinski et al. (2000) and, as the result, the mass ratio q=0.97$\pm$0.009 was derived and the spectral type estimated to be A8V, in disagreement with the B-V color (0.34). This may suggest a considerable reddening ($E_{(B-V)}$ of about 0.12). The summed amplitudes of radial velocity curves gave the total mass of the system $(M_1+M_2)\sin^3 i$= 2.930$\pm$0.006.

3. New observations

3.1. Photometry

As mentioned in Paper I, the goal of this project is to collect the light curve of each object at only one observatory to avoid problems with combining data taken at different sites and with instruments. Additionally, we attempted to complete the light curves in as short a time as possible to minimize intrinsic variations, for example due to spot variability.

The light curve of V402 Aur was obtained with the 40 cm reflector of the University of Athens Observatory, Greece. An SBIG ST-8 CCD was used with a set of wide band BVRI filters. GSC 2388 320 was chosen as the comparison star while GSC 2388 480 as the check star. The data were gathered during four nights: 14/15, 15/16 and 28/29 January, and 8/9 February 2003.

V829 Her was observed with the 50 cm telescope at the Astronomical Observatory of the Jagiellonian University with the Photometrics S300 CCD camera through the BVRI set of wide band filters. The observations were taken on the following nights: 7/8, 8/9 and 9/10 May 2002, 25/26 April and 6/7 May 2003. GSC 2597382 was chosen as the comparison star and GSC 2597415 as the check star.

Four color (BVRI) light curves of SX Crv and VZ Lib were obtained at the South African Astronomical Observatory (SAAO) at Sutherland. Observations of SX Crv were taken with the 75 cm telescope using the single channel UCT photometer equipped with the RCA31034A PMT. The complete light curve was taken during four nights: 21/22, 25/26, 26/27 and 30/31 March 2003. Observations of VZ Lib were gathered with the 50 cm telescope and a one channel photometer equipped with the R943-02 GaAs PMT. The complete light curve was achieved during the following nights: 26/27, 27/28, 28/29 Mar and 31 Mar/1 Apr 2003. We used SAO157438 as the comparison star for SX Crv while HD137885 for VZ Lib.

A new light curve of V753 Mon was gathered through the BVRI filters at the Mt. Suhora Observatory using the two channel photometer and the 60 cm telescope. A more detailed equipment description can be found in Kreiner et al. (1993). Observations were obtained over 6 nights: 9/10, 11/12, 15/16 and 16/17 Jan, 5/6 and 15/16 Feb 2002. HD55187 was used as the comparison star. The data were cross-calibrated for differential channel amplification and corrected for differential extinction using the mean extinction coefficients for the observatory.

All data were left in the instrumental system, however for the light curve modelling we recalculated magnitude differences between the target and comparison stars into flux units. The observations were phased using the time of the most recently observed primary minimum as the reference epoch, with a linear ephemeris for each target system and the period usually taken from Kreiner et al. (2001). This catalogue is available on-line at the following address: *http://www.as.ap.krakow.pl/o-c/index.php3*. The reference epochs and periods we used are listed in Table 1.

3.2. Spectroscopy

Spectroscopic observations of SX Crv were obtained with the The Magellan Inamori Kyocera Echelle (MIKE) attached to the Baade 6.5 m telescope (Magellan 1) at the Las Campanas Observatory, Chile during three nights between 2003 February 14 and February 16. The observations were taken with a 0.35" slit, and the spectral resolution was about 2 km s^{-1}. We obtained a total of 40 spectra with exposure times of 600 seconds. Bias subtraction and flat-field correction were done using standard IRAF[1] procedures. The

[1]IRAF is distributed by the National Optical Astronomical Observatories, operated by the Association

Table 1: Linear elements used for phasing observations

star	reference epoch (JD_{hel})	period (days)
V402 Aur	2452499.9646	0.60349915
SX Crv	2452724.3831	0.3165992
V829 Her	2452403.4590	0.35815039
VZ Lib	2452727.4047	0.3582580
V753 Mon	2452284.5530	0.677049

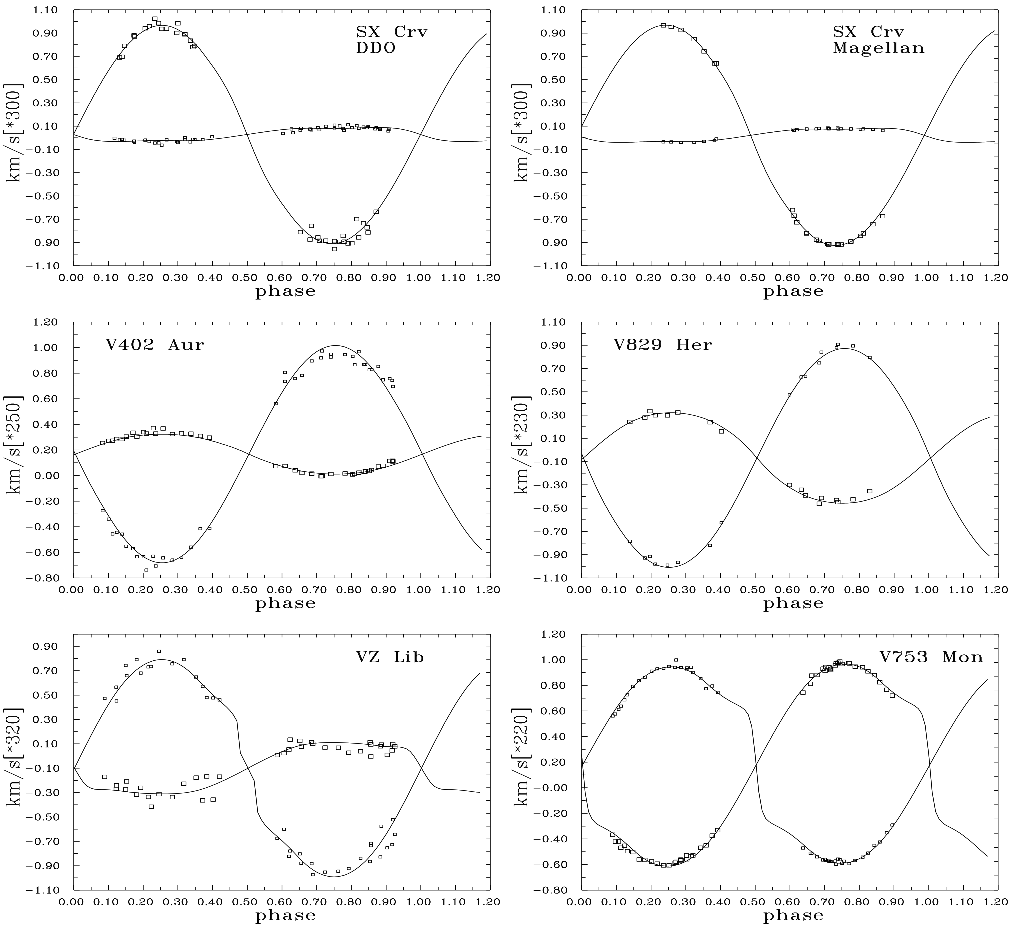

Figure 1: Comparison between theoretical and observed radial velocity curves for five systems analyzed in this paper. The DDO observations are shown by squares while lines represent the theoretical RV curves.

cosmic ray traces were removed using the software by Pych (2004). The spectra were extracted using procedures from the IRAF package *noao.imred.echelle.* Because our target was very bright, we skipped the procedure of complete rectification of the spectra and the background signal was not subtracted. The final spectra were binned to a resolution of 5.0 km s^{-1}. On each night spectra of the star HD 48938 (Sp. G2 V) were obtained and used as the template for the velocity measurements. Radial velocities of the components were measured using an IDL implementation of the broadening function technique (Rucinski (2002)).

4. Light curve modelling

The method used for deriving global parameters was described in detail in Paper I. However, in order to better account for the proximity effects we decided to redetermine the mass ratio for each system using the procedure outlined in Paper II. In this way, our solution still relies only on the spectroscopic mass ratio which we consider to be more reliable (at least for close systems without total eclipses) than a mass ratio obtained from light curve modeling alone. We believe that such an approach allows derivation of the physical parameters in the most reliable way, avoiding the danger of getting spurious values. The new fits to the radial velocity curves are shown in Fig. 1.

In order to obtain the physical parameters, we used the model built into the Wilson-Devinney code (W-D) (Wilson (1973), Wilson (1979), Wilson (1993)) but we applied a Monte Carlo search method. The search for the best fit was done in the following way: a search array of size of either 1000 (for systems without spots) or 2000 elements (systems with spots and/or a third star) was first filled with randomly generated parameters in chosen ranges. Each element of the array consists of the whole set of parameters needed to generate a theoretical light curve. Next, after each trial, the element with the largest χ^2 was replaced with a new one, if the fit was better (as measured by the χ^2). The whole procedure was repeated until convergence was achieved, *i.e.* the difference between elements with largest and smallest χ^2 values in the search array was small.

In our computations the theoretical values of the gravity darkening coefficients were used. The limb darkening coefficients were adopted as functions of the temperature and wavelength from Díaz-Cordovés et al. (1995) and Claret et al. (1995) tables. Also the theoretical values for albedo were assumed: 0.50 and 1.0 for convective and radiative envelopes, respectively.

4.1. V402 Aur

The light curve of this system (Fig. 2) is featureless and lacks any indication of eclipses. Therefore, due to the low inclination, the light curve solution must be somewhat less reliable. In the absence of any asymmetries, we derived the solution without assuming any spot or a third light in the system. The temperature of the primary was fixed at 6700 K (spectral type F2V), while the mass ratio at q_{corr}=5.008. The following search ranges were assumed: 30-90 degrees (for inclination), 5000-7200 K (the secondary temperature), 7.0-11.0 (potentials), 0.1-10 (for luminosity of the primary component). Additionally, the phase shift parameter was also adjusted. The final results are presented in Table 2 and a comparison between observed and synthetic light curves is shown in Fig. 2. All of the adjusted parameters have been given together with their errors.

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Table 2: Results derived from the light curve modelling

parameter	V402 Aur	SX Crv	V829 Her	VZ Lib	V753 Mon
configuration	contact	contact	contact	contact	semi-detached
filling factor	3%	27%	20%	13%	
phase shift	-0.0094±0.0005	-0.0143±0.0010	0.0025±0.0004	-0.0030±0.0004	0.0006±0.0002
i (degrees)	52.65±0.21	61.21±0.30	56.91±0.20	80.30±0.45	75.30±0.13
T_1(K)	* 6700	* 6340	* 5900	* 5920	* 7500
T_2(K)	6775±31	6160±32	5380±21	6030±21	7620±20
Ω_1	9.154±0.001	1.877±0.002	5.548±0.0060	2.344± 0.004	3.972±0.016
Ω_2	**9.154	**1.877	**5.548	**2.344	3.703±0.003
$q_{corr}(m_2/m_1)$	*5.008	*0.0787	*2.300	*0.255	*0.971
L_1^s (B)	2.092±0.038	10.855±0.038	4.892±0.057	9.436±0.065	5.168±0.053
L_1^s (V)	2.147±0.028	10.884±0.035	4.774±0.051	9.126±0.107	5.269±0.051
L_1^s (R)	2.153±0.024	10.832±0.032	4.685±0.045	8.990±0.103	5.244±0.048
L_1^s (I)	2.172±0.023	10.817±0.028	4.496±0.035	9.158±0.094	5.367±0.047
L_2^s (B)	** 9.535	** 1.017	** 6.676	** 3.031	** 6.663
L_2^s (V)	** 9.662	** 1.036	** 6.897	** 2.895	** 6.747
L_2^s (R)	** 9.641	** 1.048	** 7.095	** 2.820	** 6.664
L_2^s (I)	** 9.702	** 1.075	** 3.745	** 2.817	** 6.735
l_3 (B)	* 0.0	* 0.0	* 0.0	0.011±0.005	* 0.0
l_3 (V)	* 0.0	* 0.0	* 0.0	0.043±0.009	* 0.0
l_3 (R)	* 0.0	* 0.0	* 0.0	0.059±0.009	* 0.0
l_3 (I)	* 0.0	* 0.0	* 0.0	0.041±0.009	* 0.0
r_1 ^{pole}	0.2338±0.0001	0.5530±0.0007	0.2990±0.0003	0.4732±0.0009	0.3279±0.0002
r_2 ^{pole}	0.4881±0.0001	0.1818±0.0009	0.4355±0.0003	0.2545±0.0010	0.3536±0.0004
r_1 ^{point}					0.3797±0.0003
r_2 ^{point}					0.4911±0.0085
r_1 ^{side}	0.2433 ±0.0002	0.6251±0.0012	0.3134±0.0001	0.5122±0.0012	0.3402±0.0002
r_2 ^{side}	0.5312 ±0.0002	0.1897±0.0011	0.4663±0.0001	0.2655±0.0011	0.3713±0.0005
r_1 ^{back}	0.2765 ±0.0001	0.6427±0.0013	0.3535±0.0002	0.5378±0.0015	0.3595±0.0002
r_2 ^{back}	0.5541 ±0.0001	0.1818±0.0010	0.4974±0.0002	0.3022±0.0020	0.4022±0.0006

$*$ - not adjusted, $**$ - computed, L_1^s, L_2^s: W-D program input values
the subscripts 1 and 2 refer to the star being eclipsed at primary and secondary minimum, respectively.

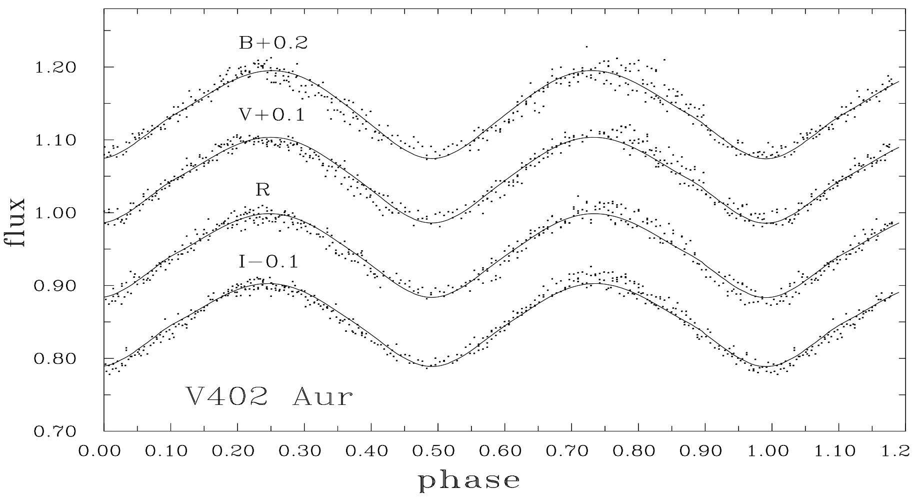

Figure 2: Comparison between theoretical and observed light curves of V402 Aur (BVRI filters). Individual observations are shown by squares while lines represent the theoretical light curves.

4.2. SX Crv

The inspection of the times of minima of SX Crv revealed a large scatter in the O-C diagram, previously also reported by Scaltriti & Busso (1984). A reasonable description of the O-C behaviour was found only with a decreasing period of SX Crv:

$$JD_{prim} = 2441017.4558(15) + 0.31663845(16)\times E - 4.572(43)^{-10}\times E^2$$

The above quadratic ephemeris was calculated using 14 times of the primary and 19 times of the secondary minima. The period of the linear ephemeris which gives the smallest residuals for the most current minima is P=0.3165992 days and this value was used for calculation of phases for this star.

Our new light curves (Fig. 3) show a very large O'Connell effect of about 0.06^{m}, practically independently of the filter. Additionally, night-to-night secular variations much larger than the expected observational errors are also visible.

For this interesting system we obtained new, more accurate spectroscopic observations and decided to redetermine the mass ratio, which was then fixed during further computations. The mass ratio as obtained from the new radial velocity curve is q_{corr}=0.0715. T he new result is more reliable as it is based on the new, more accurate observations and accounts for the proximity effects distorting the radial velocity of the more massive component from the sine curve (see Fig. 1, upper panel). The temperature of the primary was set to 6340 K as corresponding to its spectral type (F6/7 V, Rucinski et al. (2001)). We assumed the following ranges for the free parameters: a phase shift between -0.04 and 0.04, an inclination between 50 and 90 degrees, temperature of the secondary between 4500 K and 6500 K, potentials of the components between 1.6 and 2.5 and the luminosity of primary between 5 and 13. Due to very large O'Connell effect, spot(s) on the surface of the primary were added. The temperature factor range was set from 0.5 to 2.5 and the whole primary surface was searched for the location of possible spots. It was assumed that there is no third light in this system. We continued the computations until the difference between the best and the worst elements in the search array was less

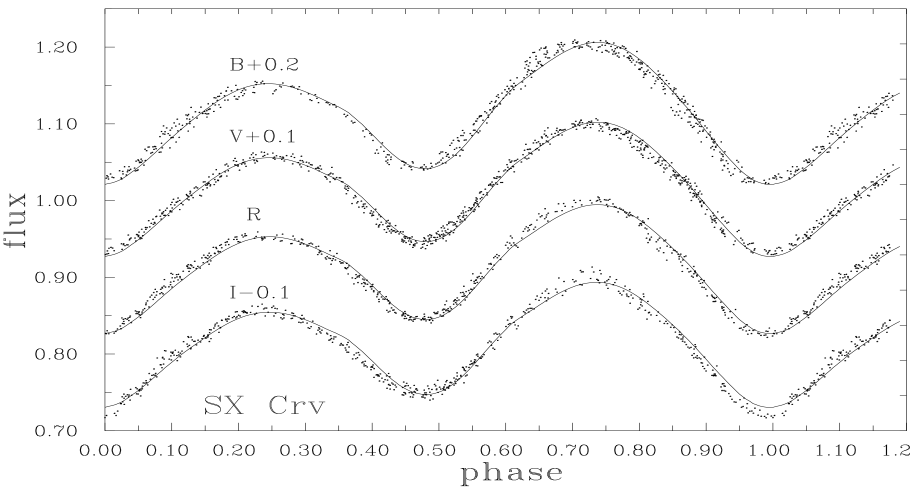

Figure 3: Comparison between theoretical and observed light curves of SX Crv (BVRI filters). Individual observations are shown by squares and theoretical curves by lines.

than 1 percent. The results are presented in Table 2 and comparison between observed and synthetic light curves is shown in Fig. 3.

4.3. V829 Her

There is a trace of an O'Connell effect in our light curve of V829 Her and we made a solution assuming there is a dark spot on the surface of the primary component. During the computations we set the temperature of the primary to be 5900 K (spectral type F5) and fixed the mass ratio at q_{corr}=2.3. We searched for the best solution in the following ranges: 30-90 degrees (inclination), 4500-6500 K (temperature of the secondary), 4.5-7.0 (potentials) and 1-12.5 (luminosity of the primary). The phase shift was an additional free parameter. In our solution we assumed there is no third light in this system.

The system parameters resulting from the best fit are presented in Table 2 while our best fit to observations is shown in Fig. 4.

4.4. VZ Lib

The light curve of VZ Lib (Fig. 5) shows a flat bottom secondary eclipse, however, there is also a pronounced O'Connell effect (the second maximum is lower by about 0.02^{m} - 0.03^{m} than that at phase 0.25), and it is necessary to introduce spot(s) to get rid of this asymmetry. Furthermore, evidence was found for a third component in the system (Lu et al. (2001)), which further complicates the light curve solution. On the other hand, VZ Lib has well defined eclipses so the solution of the light curve is better constrained. For this star we assumed the temperature of the primary to be 5920 K according to its spectral G0V type and fixed the mass ratio at q_{corr}=0.255. We searched for the best solution in the following ranges of parameters: inclination (50-90 degrees), temperature of the secondary (4500 - 6500 K), potentials (1.51 - 4.0) and the luminosity (4.0 - 13.0). Additionally, the phase shift parameter was adjusted and the range for the third light was set between 0.0 and 0.40. The whole surface of the primary star was searched for the location of a cool spot. The parameters giving the best fit are presented in Table 2. The theoretical versus

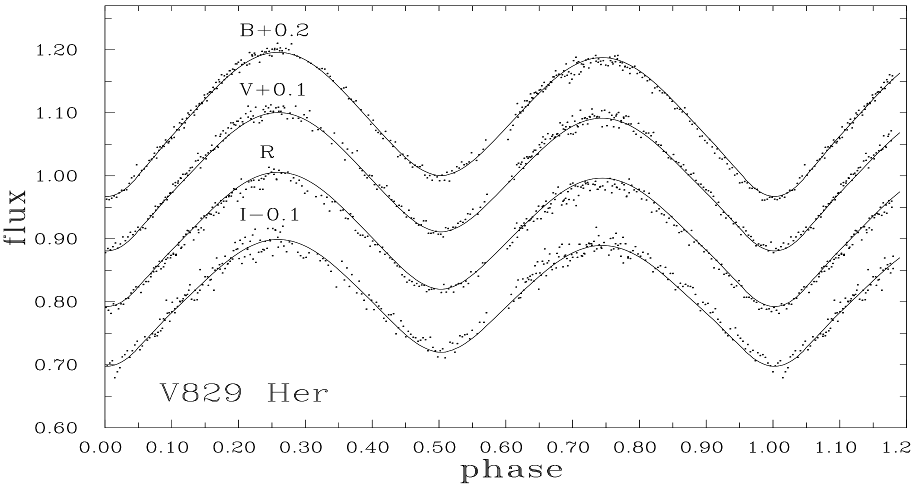

Figure 4: Comparison between theoretical and observed light curves of V829 Her (BVRI filters). Individual observations are shown by squares while lines represent the theoretical light curves.

observed light curves are shown in Fig. 5.

4.5. V753 Mon

The minima in the light curve of V753 Mon (Fig. 6) have almost exactly the same depth indicating very similar temperatures of the components. As the reference epoch we took the one listed in Tab. 1. Such phasing gives a slightly deeper (0.01^{m}) minimum at phase 0, especially well seen in the B filter. Our phases are shifted by almost half a period against those calculated with the JD_{prim} assumed by Rucinski et al. (2000). Moreover, the beginning and end of eclipses are clearly visible in the light curve which may suggest a non-contact configuration for this system. One can also notice an asymmetry near the phases 0.1-0.2.

In our computations we fixed the mass ratio q_{corr}=0.971 and the temperature of the primary T_{eff}=7500 K according to the spectral type from Rucinski et al. (2000). The ranges for the free parameters were set as follows: inclination was searched between 60 and 90 degrees, the secondary temperature between 6500 and 8000 K, while the potentials between 3.0 and 5.0. The range for the primary luminosity we assummed to be between 2-10 and the third light was set to 0.

The results are presented in Table 2 (system parameters), while the comparison between observations and theoretical light curve for the best fit achieved is shown in Fig. 6.

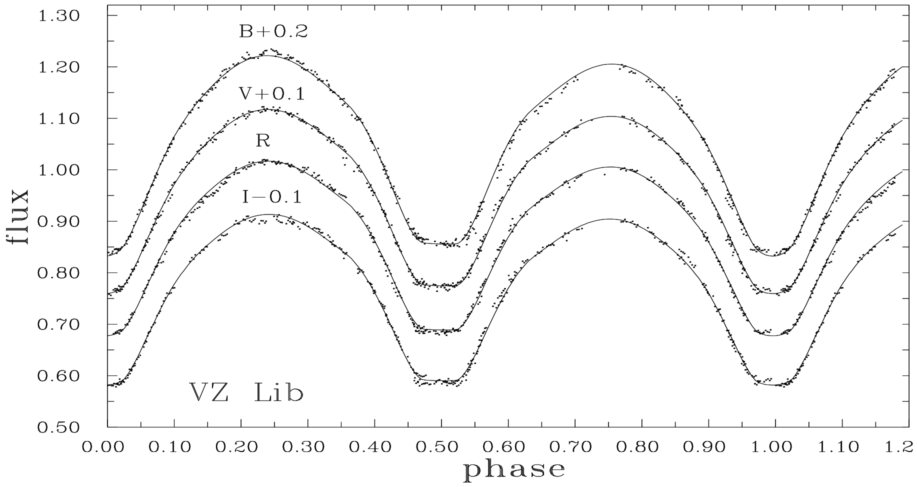

Figure 5: Comparison between theoretical and observed light curves of VZ Lib (BVRI filters). Individual observations are shown by squares and theoretical curves by lines.

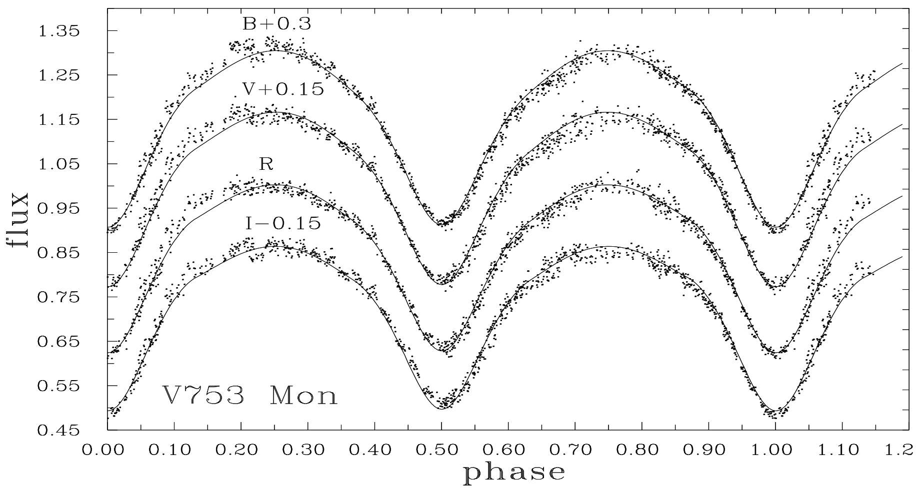

Figure 6: Comparison between theoretical and observed light curves of V753 Mon (BVRI filters). Individual observations are shown by squares and theoretical curves by lines.

5. Discussion

We present results of the combined photometric/spectroscopic solution of another set of five systems from the sample defined in Paper I. The solutions utilize new photometric data obtained through an international collaboration and the availability of new, homogeneous spectroscopic data from the David Dunlap Observatory. For SX Crv, the most interesting object in our sample, we collected new spectroscopic observations and redetermined a new mass ratio. Of particular importance in our solutions are the corrected for proximity effects spectroscopic values of the mass ratio $q_{\rm sp}$ which were kept fixed in the light curve analysis, thus helping to improve the quality of our final combined solutions.

Two systems studied in this paper, V402 Aur and V829 Her, show uncomplicated, if featureless light curves: we found no significant O'Connell effect, neither any trace of a companion was detected from the spectroscopic observations. Therefore, the solutions were obtained relatively quickly and the fits are very good. However, both these systems turned out to exhibit only grazing eclipses (inclination 52° and 57° for V402 Aur and V829 Her, respectively) and we expect that the uncertainty of parameters may be larger than those shown in this paper, due to lack of information present when deep eclipses are observed.

We found it most difficult to obtain a good and unique fit for SX Crv despite of the new very accurate spectroscopic observations and having the multicolor light curve gathered only within few days. It turned out that a model with a single spot cannot reproduce the observed light curve. Therefore, two spots were placed on the surface of the primary and three possibilities were considered. Firstly, we considered solutions with two cool spots, secondly, with two hot spots and, thirdly, we set the temperature factor of the spots between 0.5 and 2.0. In the latter case the code converged with one cool and one hot spot differing by about 160 degrees in the stellar longitude. The best fit was obtained for two spots, one hotter and one cooler than the surrounding stellar surface, with a reasonable reseblance of the theoretical light curve to the observed one. A contact configuration, with an intermediate overfilling factor (27%) was found. However, the fit is still not perfect especially in the I filter where the theoretical light curve in the primary minimum is too shallow (see Fig. 3). One should consider our results on SX Crv as the first step in understanding the nature of this unique object. Further study is necessary, both observational and theoretical, before final conclusions are drawn on its properties and an evolutionary status.

For VZ Lib we found a discrepancy between the amount of third light determined from spectroscopy ($L_3/(L_1L_2$=0.20, Lu et al. (2001)) and that derived from light curve modelling (maximum value about 0.06 in the R filter). We re-examined the DDO data and a somewhat smaller amount was obtained: 0.12±0.01, however, the discrepancy still exists. Unless the mass ratio is higher we cannot offer any explanation for this discrepancy at this time.

V753 Mon, which we initially thought to be very interesting due to its mass ratio very close to unity (q=0.971), which is a property not observed for contact binaries, turned out to be a semidetached system, with the secondary component almost filling its Roche lobe. We are pretty confident about the configuration found despite the larger scatter in the observational data, which is due to a lower air mass than that for the other observed targets. A mass ratio so close to unity is also unique. This means that this system is as compact as it can be and has been caught exactly at the stage of the closest orbit in its semidetached evolution.

The absolute parameters of the components for the five systems analysed in this paper which result from the best fits are given in Table 3. The errors shown in Table 1 and

Table 3: Absolute parameters of the studied systems (in solar units)

system	$\mathcal{M}_1$	$\mathcal{M}_2$	R_1	R_2
V402 Aur	1.638±0.048	0.327±0.023	1.997±0.019	0.915±0.008
SX Crv	1.246±0.040	0.098±0.013	1.347±0.012	0.409±0.004
V829 Her	0.856±0.022	0.372±0.014	1.058±0.009	0.711±0.006
VZ Lib	1.480±0.068	0.378±0.034	1.335±0.022	0.692±0.012
V753 Mon	1.528±0.020	1.482±0.020	1.738±0.007	1.592±0.006

subsequently used for calculating the errors of the absolute parameters were obtained from Monte Carlo computations and correspond to a 90 percent confidence level.

We postpone a discussion of the properties of these stars in a broader astrophysical context to a later paper which will summarize the results when accurate absolute parameters are determined for a few dozen binary systems.

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