Physical Parameters of Components in Close Binary Systems: IV

by

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ABSTRACT

The paper presents new geometric, photometric and absolute parameters, derived from combined spectroscopic and photometric solutions, for ten contact binary systems. The analysis shows that three systems (EF Boo, GM Dra and SW Lac) are of W-type with shallow to moderate contact. Seven systems (V417 Aql, AH Aur, YY CrB, UX Eri, DZ Psc, GR Vir and NN Vir) are of A-type in a deep contact configuration. For six systems (V417 Aql, YY CrB, GM Dra, UX Eri, SW Lac and GR Vir) a spot model is introduced to explain the O'Connell effect in their light curves. The photometric and geometric elements of the systems are combined with the spectroscopic data taken at David Dunlap Observatory to yield the absolute parameters of the components.

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

1. Introduction

In this paper we present the results of simultaneous light and radial velocity curve solutions, as well as the physical parameters for ten contact systems from the sample defined by Kreiner et al. (2003). The observed systems were selected according to the accurate multicolor photometric light curves, obtained recently from ground-based observations and the spectroscopic mass ratio, derived from the radial velocity curves from the DDO program (Pych et al. 2004 and references therein).

Details of the project and the procedure used to derive the parameters are given in Paper I (Kreiner et al. 2003), Paper II (Baran et al. 2004) and Paper III (Zola et al. 2004). A description of the targets analyzed in this work is presented in Section 2, while Section 3 describes the new photometric observations. The procedure and the method used for the analysis of photometric and spectroscopic data and for the derivation of the absolute parameters of components are outlined in Section 4. A discussion of the results for all systems is given in the last Section.

Table 1: Log of observations

System	Observatory	Dates
V417 Aql	Kryoneri Astr. Station	13, 14 Jul 2002
AH Aur	Univ. of Athens Obs.	4, 18 Dec 2003; 16, 23 Jan; 14, 17 Feb 2004
EF Boo	Mt. Suhora Obs.	14 Feb, 11, 17, 30 Apr, 1, 2 May 2002
YY CrB	Kryoneri Astr. Station	15, 16, 17 Jul 2002
GM Dra	Skibotn Obs.	19 Jan 2004
UX Eri	SAAO	5, 6, 7, 10 Nov 2003
SW Lac	Mt. Suhora Obs.	20, 21 Sep 2003
DZ Psc	Univ. of Athens Obs.	17, 23, 24 Sep; 2, 3, 4, 5, 9, 10 Oct 2001
GR Vir	SAAO	25, 27, 29, 30 Mar 2003
NN Vir	Univ. of Athens Obs.	26, 28 Mar; 2, 8, 9 Apr; 7 May; 1, 2, 4 Jun 2003

2. Remarks to Individual Systems

2.1. V417 Aquilae

The eclipsing binary V417 Aql (BD +52° 4202, HIP 96349, V = 10.67^m) was discovered by Hoffmeister (1935). Soloviev (1937a) classified it as a W UMa-type variable with a period of 0.37 days. Koch (1974) identified it as a strongly interacting solar-type binary system. Since then, various studies were published, giving times of minima and the O-C diagram. An analysis of observations in U, B and V filters was made by Samec et al. (1997), who derived the system parameters as well as the first model. The mass ratio was found spectroscopically to be $q = 0.362 \pm 0.007$ (Lu and Rucinski 1999). Other studies, such as the multicolor analysis made by Pribulla and Vaňko (2002), gave more accurate results for the physical parameters of the system. A detailed orbital period investigation, based on the analysis of all existing O-C values, was presented by Qian (2003). It was shown that the period change of the binary system is continuous, leading to the conclusion that V417 Aql is either a member of a triple system with an invisible companion or there is a strong magnetic activity in the system, a common feature for the solar-like components of close binaries.

2.2. AH Aurigae

The eclipsing binary AH Aur (BD +28° 1116, HIP 30618, V = 10.18^m) was discovered by Guthnick & Prager (1928). It was neglected after its discovery until Hinderer (1960) published its first photoelectric observations. The first spectroscopic study of the system was performed by Rucinski and Lu (1999), who gave a mass ratio $q = 0.169 \pm 0.059$ and a spectral type of F7V. Using this value of q, Vaňko et al. (2001) provided the first solution of the system, fitting the model to the B and V light curves, and found $i = 75.46^{\circ}$, $T_1 = 6215$ K (assumed) and $T_2 = 6141$ K.

2.3. EF Bootis

EF Boo (BD +51° 1929, HIP 71107, V = 9.45^m) was discovered by the Hipparcos satellite mission (ESA, 1997). The first spectroscopic observations of this system were carried out by Rucinski et al. (2001). They classified EF Boo as a W-type system with a F5V primary component and a late G secondary and obtained the mass ratio $q = 0.512 \pm 0.008$. UBV photoelectric observations of EF Boo were made by Samec et al. (1999), who derived a contact configuration with a mass ratio of 1.75 (= 1/0.571), temperature difference between the components of ≈ 100 K and a fill-out factor of 25%. Additionally, they noticed a spot activity and introduced a cool spot of radius 14° with a temperature factor of 0.76 on the cooler, more massive component to obtain a good fit to the observed light curves. Gothard et al. (2000) estimated the absolute dimensions of EF Boo and found that a contact configuration with a dark spot on either of the two components fits the observations

Table 2: Linear elements used for phasing observations

System	Reference Epoch (HJD)	Period (days)
V417 Aql	2452500.2995	0.3703133
AH Aur	2452500.3823	0.4941085
EF Boo	2452500.2254	0.4205144
YY CrB	2452500.1584	0.3765640
GM Dra	2452500.0493	0.3387475
UX Eri	2452500.0450	0.4452850
SW Lac	2452500.1435	0.3207158
DZ Psc	2452500.0850	0.3661283
GR Vir	2452500.2490	0.3469673
NN Vir	2452500.3046	0.4806867

equally well. Özdemir et al. (2001) noticed neither asymmetry nor O'Connell effect in the new light curves of EF Boo. Recently, Selam (2004) analyzed the Hipparcos data and re-determined the parameters of EF Boo. The photometric mass ratio q was found to be 0.45, the fill-out factor $f = 20\%$ and the orbital inclination $i = 77.5°$. Such a large range of the mass ratio determined from photometric light curves alone puts in question validity of using q_{ph} at all when q_{sp} is available.

2.4. YY Coronae Borealis

YY CrB (BD +38° 2706, HIP 77598, V = 8.69^m) was discovered by Hipparcos satellite mission (ESA 1997) and listed in 74^{th} special name-list of variable stars (Kazarovets et al. 1999). Several observations were made since its discovery, such as those made by Sipahi et al. (2000) and Erdem et al. (2001). An analysis of UBV observations by Pribulla and Vaňko (2002) gave a contact configuration for the system, with 63% fill-out factor and an inclination of 77°, but with a relatively poor fitting. There is no obvious indication for total eclipses, but the coverage of eclipses is relatively poor, so that it is possible that the minimum identified as the primary is not the deeper one. The mass ratio was found spectroscopically to be $q = 0.243 \pm 0.008$ and the spectral type F8V (Rucinski et al. 2000). Recently, Vaňko et al. (2004) obtained new photoelectric UBV light curves and presented absolute parameters of the system.

2.5. GM Draconis

GM Dra (BD +58° 1069, HIP 84837, V = 8.80^m) is another eclipsing binary discovered by Hipparcos satellite mission (ESA 1997). The first BVR ground-based photoelectric observations were carried out by Çiçek et al. (2001). They noticed a small O'Connell effect but only in the B band. Using Hipparcos photometric data, Selam (2004) found the following parameters: $q = 0.35$, $f = 0.4$ and $i = 57.5°$. Spectroscopic orbit of the system was determined by Rucinski et al. (2002). They obtained the mass ratio $q = 0.180 \pm 0.007$ and estimated the spectral type as F5V. GM Dra belongs to the W subtype class.

2.6. UX Eridani

Soloviev (1937b) discovered the variability of UX Eri (BD −7° 553, HIP 14699, V = 10.63^m). Binnendijk (1966) published the first B and V light curves and determined orbital elements. UX Eri was studied by Al-Naimiy et al. (1989) who obtained geometrical and physical elements of the system using the method of Fourier analysis of the light changes. According to their calculations $q = 0.422$ and $\Delta T = T_1 - T_2 = 190\,\mathrm{K}$. The spectroscopic observations of the star were carried out by Rucinski et al. (2000). They classified UX Eri as an A-subtype contact binary with a mass ratio equal to $q = 0.373 \pm 0.021$ and a spectral type of F9V.

2.7. *SW Lacertae*

SW Lac (BD +37° 4717, HIP 113052, V = 8.90^m) is one of the most often observed contact binaries. The variability of the star was found by Miss Ashall during an examination of photographic plates made at Harvard College Observatory (Leavitt 1918). Brownlee (1957) obtained the first photoelectric UBV light curves of SW Lac. He noticed peculiarities in the light curves of the star, that were changing from cycle to cycle. Many authors confirmed this behaviour (c.f. Rucinski 1968; Niarchos 1987). Zhai and Lu (1989) performed radial velocity observations and determined the mass ratio equal to $q = 0.797$. Hrivnak (1992) obtained the spectroscopic mass ratio equal to $q = 0.73 \pm 0.01$. Pribulla et al. (1999) published an extensive list of photoelectric minima. They analyzed the O–C diagram and concluded that period changes may occur due to the presence of third and fourth bodies with orbital periods of $P_3 = 23$ and $P_4 = 90$ years, respectively. From spectroscopic observations Hendry and Mochnacki (1998) found the late-type tertiary component in the system. Albayrak et al. (2004) obtained a set of orbital and physical parameters for the years 2001–2003. They concluded that the observed light-curve variations might be explained by the changes of spotted areas on the cooler component, which cover a significant part of the stellar surface. Recently, new spectroscopic observations were made by Rucinski (2004). He obtained a new value of the mass ratio, 0.777, and a spectral type of G5. The error of q_{sp} is relatively large in this case, 0.010. The scatter in data must be genuine and probably related to activity of this star.

2.8. *DZ Piscium (NSV 223)*

The variability of DZ Psc (GSC 1193-0972, BD +20°75, V = 10.86^m) was discovered by Strohmeier et al. (1956) and confirmed by Filatov (1957). Verrot and Van Cauteren (2000) obtained the first CCD light curve of DZ Psc. Spectral type of the system was determined as F7V and the mass ratio was found to be $q = 0.136 \pm 0.010$ by Rucinski et al. (2003).

2.9. *GR Virginis*

GR Vir (BD −6° 4068, HIP 72138, V = 8.00^m) was discovered by Strohmeier et al. (1965) and independently by Harris (1979). Cereda et al. (1988) and Halbedel (1988) carried out photoelectric B and V observations. Cereda et al. (1988) found cycle-to-cycle variations of the light curve and classified GR Vir as a possible A-subtype W UMa star with low mass ratio. The first spectroscopic observations of the system were carried out by Rucinski and Lu (1999). They estimated the spectral class of the star as F7V/F8V and derived the mass ratio $q = 0.122 \pm 0.044$. GR Vir has one of the smallest mass ratios among W UMa binaries. Recently, Qian and Yang (2004) published absolute parameters for GR Vir: $M_1 = 1.36M_\odot$, $M_2 = 0.17M_\odot$, $R_1 = 1.42R_\odot$ and $R_2 = 0.61R_\odot$. $L_1 = 2.87L_\odot$, $L_2 = 0.48L_\odot$. They found the oscillation of the orbital period caused by either an unseen tertiary component or by magnetic activity of the stars.

2.10. *NN Virginis*

The EW type active eclipsing binary star NN Vir (BD +06° 2869, HIP 70020, V = 7.64^m) was discovered by Hipparcos satellite mission (ESA 1997) and listed in 74^{th} special name-list of variable stars (Kazarovets et al. 1999). According to Woitas (1997) the system NN Vir was classified as a RR Lyrae variable, but, after verification made by several observers (Gomez-Forrellad & Garcia-Melendo 1997), it was decided that it is a W UMa-type eclipsing binary with a period of 0.48 days. Later on, Rucinski and Lu (1999) observed this system spectroscopically yielding mass ratio of $q = 0.491 \pm 0.011$ and spectral type of F0V/F1V. Recently, a photometric study of NN Vir was published by Djurašević et al. (2004).

3. Photometric observations

The observations of AH Aur, NN Vir and DZ Psc were made from the University of Athens Observatory with the 40-cm f/8 Cassegrain telescope and ST-8 CCD camera equipped with the Johnson-Cousins $\mathrm{UBV(RI)_C}$ filters.

The observations of YY CrB and V417 Aql were made with the 1.22-m Cassegrain reflector at the Kryoneri Astronomical Station of the National Observatory of Athens, Greece, and a Photometrics CH250 CCD camera equipped with a set of wide-band Johnson-Cousins $\mathrm{UBV(RI)_C}$ filters.

EF Boo was observed at the Mt. Suhora Observatory, using a two-channel photometer and the wide-band, Johnson-Cousins BVR filters, attached to the 60-cm Cassegrain telescope. SW Lac observations were also obtained at the Mt. Suhora Observatory using a three-channel photometer attached to the same telescope and wide-band BVR filters.

GM Dra was initially observed at Mt. Suhora Observatory, during May and June 2003. Although the photometric conditions during all nights were quite satisfactory and the star was observed high above the horizon, we noticed significant night-to-night variations in the UBVR light curves. Both the level of O'Connell effect and the shapes of both minima were variable, so that it was impossible to built a mean light curve for each filter. Due to the rapid changes in the light curves of the system, we re-observed it during two polar nights (15 and 19 Jan 2004) from the Skibotn Observatory (University of Tromsø, Norway). The observatory is equipped with a CCD camera attached to the 50-cm Cassegrain telescope and wide-band Johnson-Cousins BVRI filters. In these two separate data sets we also noticed significant changes in the shape of the minima and in the level of the O'Connell effect. Therefore we analysed only the second night, when the most complete and symmetric light curves were gathered.

Data for the systems UX Eri and GR Vir were collected at the South African Astronomical Observatory in Sutherland as these systems can be more conveniently and with higher accuracy observed from a southern-hemisphere observatory. UX Eri was observed with the 75-cm telescope and the UCT CCD photometer. The 50-cm telescope and the Modular Photometer were used to observe GR Vir. The wide-band BVRI filters were used in both instruments. The log of observations for all objects analyzed in this paper is given in Table 1.

The goal of this project, as mentioned in Paper I, is to obtain the light curve of each object at only one observatory to avoid problems with combining data taken at different sites and with different instruments. Therefore, observations of one target were made with the same instrument and the same detector/filters. Additionally, we tried to complete the light curves in as short as possible time to minimize intrinsic variations, i.e. due to spot activity.

All data were left in the instrumental system, but for the light curve modelling we transformed differential magnitudes into flux units. The observations were phased using linear ephemeris for all targets, taken from the Kreiner's (2004) catalogue. This catalogue is available on-line at the following address: *http://www.as.ap.krakow.pl/ephem.* The reference epochs and the periods we used for phasing our new photometric observations are listed in Table 2. Notice that in the case of GR Vir the GCVS catalogue gives a value of 0.42 d for its period, instead of 0.347 d.

4. Light Curve Modelling

The method used for deriving the physical parameters was described in Paper I. However, in order to better account for the proximity effects, we decided to re-determine the mass ratio for each system and correct it for the proximity effects, using the procedure described in detail in Paper II. In order to obtain the physical parameters, we used the Wilson-Devinney model (W-D) (Wilson and Devinney 1973; Wilson 1979, 1993), but we applied Monte Carlo algorithm as the search method.

In our computations theoretical values of the gravity darkening and albedo coefficients were used. We assumed 1.0 for both coefficients, if a star had a radiative envelope ($T > 7200\,\mathrm{K}$) and 0.5 (albedo coefficient) and 0.32 (gravity darkening coefficient) in the case of a convective envelope ($T < 7200\,\mathrm{K}$). The limb darkening coefficients were adopted as functions of the temperature and

Table 3: Results derived from the light curve modelling

Parameter	V417 Aql	AH Aur	EF Boo	YY CrB	GM Dra
Fill-out Factor	31%	75%	18%	23%	23%
Phase Shift	0.9899±0.0006	0.0053±0.0004	0.0016±0.0003	0.0026±0.0002	0.0021±0.0008
i [°]	89.2±1.0	76.1±0.3	75.7±0.2	79.5±0.1	62.6±0.6
T_1 [K]	* 5860	* 6200	* 6450	* 6100	* 6450
T_2 [K]	6066±22	6418±10	6425 ±14	6499±20	6306±58
$\Omega_1 = \Omega_2$	2.518±0.005	2.064±0.002	4.921±0.012	2.277±0.002	8.609±0.024
$q_{\rm corr}$ $[M_2/M_1]$	* 0.355	* 0.165	* 1.871	* 0.232	* 4.758
L_1 (B)	8.299±0.018	—	4.319 ±0.028	8.872±0.053	2.608±0.091
L_1 (V)	8.371±0.015	9.617±0.016	4.295 ±0.024	9.050±0.051	2.582±0.078
L_1 (R)	8.352±0.013	9.662±0.016	4.302 ±0.021	9.064±0.048	2.570±0.069
L_1 (I)	8.495±0.010	9.686±0.014	—	9.240±0.047	2.538±0.049
L_2 (B)	** 3.952	—	** 7.394	** 3.292	** 9.115
L_2 (V)	** 3.896	** 2.458	** 7.378	** 3.221	** 9.171
L_2 (R)	** 3.811	** 2.420	** 7.406	** 3.109	** 9.234
L_2 (I)	** 3.770	** 2.358	—	** 3.013	** 9.293
r_1 ^{pole}	0.4556±0.0010	0.5216±0.0005	0.3187±0.0012	0.4836±0.0007	0.2508±0.0014
r_2 ^{pole}	0.2876±0.0011	0.2446±0.0006	0.4219±0.0011	0.2516±0.0008	0.4964±0.0012
r_1 ^{side}	0.4912±0.0013	0.5797±0.0008	0.3350±0.0014	0.5261±0.0010	0.2631±0.0017
r_2 ^{side}	0.3018±0.0013	0.2583±0.0007	0.4505±0.0015	0.2630±0.0010	0.5437±0.0018
r_1 ^{back}	0.5224±0.0017	0.6077±0.0009	0.3770±0.0024	0.5521±0.0012	0.3112±0.0037
r_2 ^{back}	0.3463±0.0023	0.3271±0.0005	0.4846±0.0020	0.3034±0.0018	0.5708±0.0023
spot parameters					
co-latitude (deg)	* 90.0	—	—	35±12	69±13
longitude (deg)	307±2	—	—	26±3	275±5
radius (deg)	10.4±0.2	—	—	38±2	18.2±1.9
temp. factor	0.21±0.05	—	—	0.93±0.03	0.88±0.04

$*$ - assumed, $**$ - computed, L_1, L_2: W-D program input values – the subscripts 1 and 2 refer to the star being eclipsed at primary and secondary minimum, respectively.
Spot parameters refer to the larger and more massive component.

Table 4: Results derived from the light curve modelling

Parameter	UX Eri	SW Lac	DZ Psc	GR Vir	NN Vir
Fill-out factor	13%	30%	79%	93%	61%
Phase Shift	0.0075±0.0004	0.0051±0.0003	0.0018±0.0004	0.0050±0.0004	0.9998±0.0002
i [°]	75.3±0.3	79.8±0.2	80.5±0.5	81.9±0.6	66.6±0.2
T_1 [K]	* 6100	* 5800	* 6210	* 6150	* 6900
T_2 [K]	6340±28	5515 ±13	6187±12	6554 ±25	6925±15
$\Omega_1 = \Omega_2$	2.578±0.004	3.977±0.005	2.015±0.001	1.913±0.002	2.674±0.005
q_{corr} $[M_2/M_1]$	* 0.366	* 1.270	* 0.145	* 0.106	* 0.487
L_1 (B)	8.102±0.056	5.893±0.035	10.316±0.037	10.338±0.037	7.337±0.031
L_1 (V)	8.238±0.050	5.836±0.031	10.006±0.020	10.493±0.008	7.400±0.025
L_1 (R)	8.275±0.044	5.763±0.026	10.277±0.016	10.477±0.027	7.495±0.022
L_1 (I)	8.333±0.034	—	10.270±0.013	10.561±0.026	7.381±0.020
L_2 (B)	** 3.946	** 5.508	** 2.009	** 2.199	** 4.094
L_2 (V)	** 3.927	** 5.751	** 1.953	** 2.125	** 4.113
L_2 (R)	** 3.863	** 5.856	** 2.009	** 2.041	** 4.159
L_2 (I)	** 3.732	—	** 2.013	** 1.974	** 4.091
$r_1{}^{pole}$	0.4458±0.0008	0.3595±0.0006	0.5300±0.0002	0.5493±0.0006	0.4485±0.0009
$r_2{}^{pole}$	0.2820±0.0008	0.3990±0.0006	0.2356±0.0002	0.2168±0.0008	0.3316±0.0010
$r_1{}^{side}$	0.4782±0.0010	0.3809±0.0008	0.5918±0.0003	0.6212±0.0010	0.4852±0.0012
$r_2{}^{side}$	0.2947±0.0010	0.4253±0.0008	0.2488±0.0003	0.2292±0.0010	0.3523±0.0013
$r_1{}^{back}$	0.5066±0.0013	0.4281±0.0013	0.6184±0.0004	0.6450±0.0012	0.5292±0.0019
$r_2{}^{back}$	0.3320±0.0017	0.4679±0.0012	0.3217±0.0011	0.3169±0.0081	0.4182±0.0027
spot parameters					
co-latitude (deg)	145±34	107± 17	—	6±14	—
longitude (deg)	221±2	279±3	—	267±9	—
radius (deg)	90±5	17±3	—	22±3	—
temp. factor	0.92±0.01	0.72±0.10	—	0.40±0.16	—

$*$ - assumed, $**$ - computed, L_1, L_2: W-D program input values – the subscripts 1 and 2 refer to the star being eclipsed at primary and secondary minimum, respectively.
Spot parameters refer to the larger and more massive component.

Table 5: Search ranges of the adjusted parameters

System	i(deg)	T_2(K)	Ω_1=Ω_2	L_1
V417 Aql	65-90	4500-7600	2.30-3.80	6-12.5
AH Aur	60-90	5200-7000	1.80-2.70	8-12.5
EF Boo	70-90	5800-7000	4.00-6.00	2-8.0
YY CrB	55-90	5200-7000	2.00-3.50	7-12.5
GM Dra	60-90	6000-7000	7.70-10.0	1-3.5
UX Eri	60-90	5000-7000	2.00-3.50	5-12.5
SW Lac	70-90	4500-6500	3.50-5.00	3-8.50
DZ Psc	60-90	5200-6800	1.90-2.80	8-12.5
GR Vir	50-90	5000-6800	1.80-2.50	8-12.5
NN Vir	55-90	5500-7500	2.50-3.80	3-12.5

wavelength from Díaz-Cordovés et al. (1995) and Claret et al. (1995) tables. Effective temperature of the primary component was taken from the tables publsihed by Harmanec (1988) according to the spectral type obtained at the DDO. New values for the mass ratio for each of the above systems, corrected for the proximity effects, are listed in Tables 3 and 4, together with the parameters derived from the light curve modelling. In case of an obvious O'Connell effect, a spot was added in our solution and the whole surface of the brighter component was scanned for a possible spot location. The following parameters were adjusted: phase shift, inclination, the temperature of the secondary component, potential(s) and the luminosity of the primary. The search ranges for the above parameters are given in Table 5. The observational data are compared with the theoretical light curves in Figures 1-10. The absolute parameters of all systems analyzed in Papers I-IV and their errors are given in Table 6.

5. Discussion of Results

We present results of the combined photometric and spectroscopic solution of ten systems from the sample defined in Paper I. The solutions utilize new photometric data obtained through an international collaboration and new, homogeneous spectroscopic data from the David Dunlap Observatory.

Light curve of V417 Aql exhibits an O'Connell effect with the maximum around phase 0.75 being slightly brighter (Fig. 1). The spotted solution, resulting in a very cool spot in the equatorial zone of the primary component gave a reasonable fit to the observed light curves. We assumed in the analysis that there is no third light in the system. The asymmetries in the light curve may be by a solar-type magnetic activity of the components. Our solution indicates a contact configuration with a fill-out factor of 31%.

The light curve of EF Boo (Fig. 3) has an excess of light at phases 0.78-0.91. If this is not caused by some not fully reduced atmospheric effects, it could be attributed to some enhanced surface activity (e.g. due to flares), but it is difficult to define the activity type from our observations. We did not attempt to model this excess of light by assuming any spot model. Our solution gave a contact configuration with a fill-out factor of only 18%.

YY CrB is a contact binary with a fill-out factor of about 23%. The light curves show (Fig. 4) an O'Connell effect and the presence of a cool spot was assumed. Magnetic activity could be the reason of the above asymmetries. Our solution resulted in a large cool spot near the polar region of the primary.

GM Dra shows cycle-to-cycle variations. The light curve (Fig. 5) shows a significant O'Connell effect. Additionally, the difference in heights of the maxima and the shape of the light curve varies from one orbital cycle to another as we observed in two consecutive cycles made during a polar

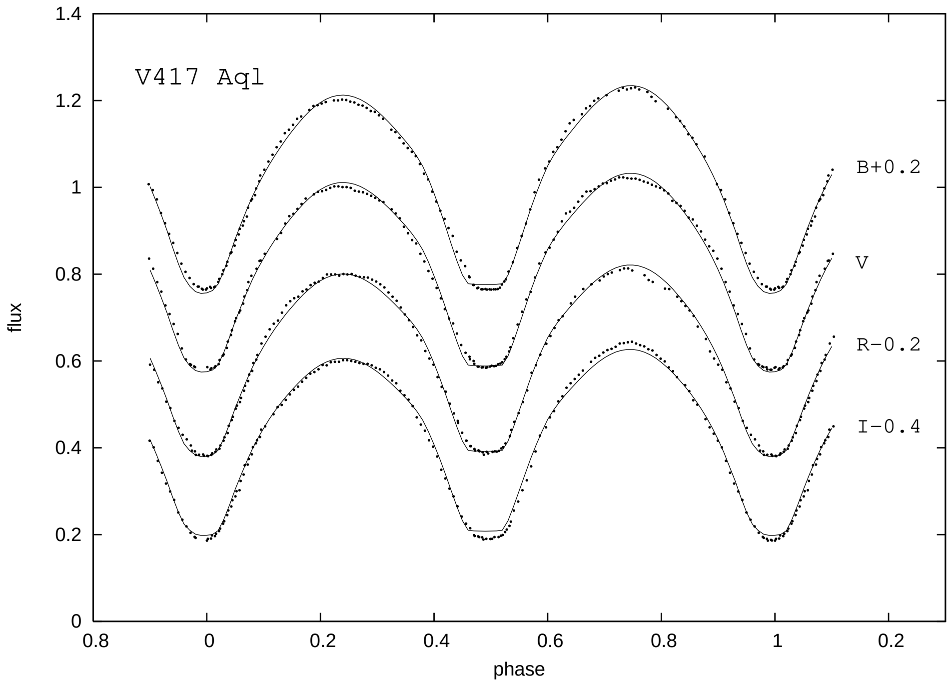

Figure 1: Comparison between theoretical and observed light curves of V417 Aql (BVRI filters). Individual observations are shown with dots and theoretical curves with solid lines.

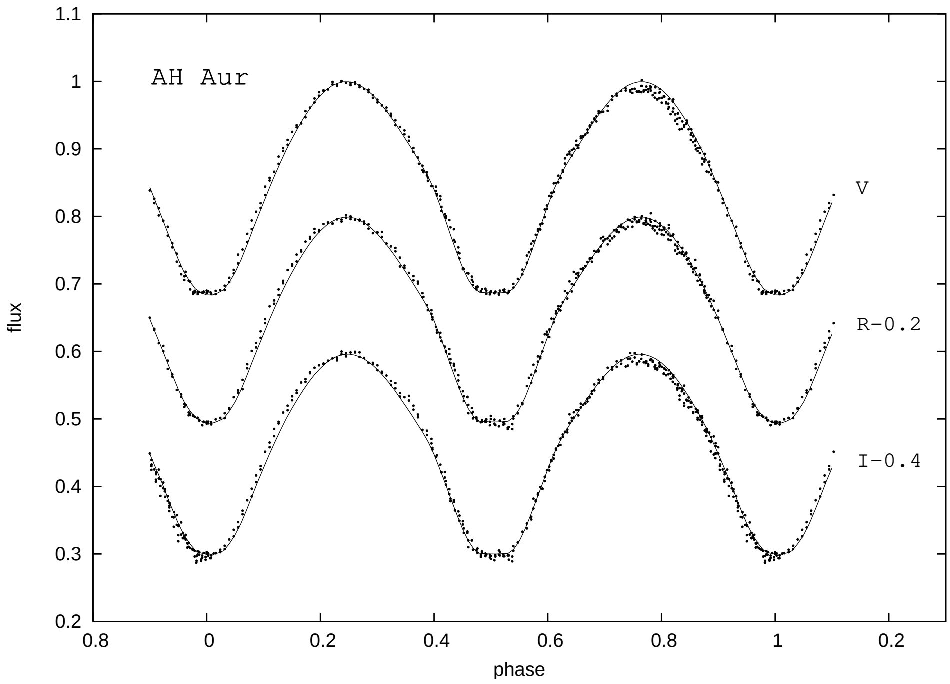

Figure 2: Comparison between theoretical and observed light curves of AH Aur (VRI filters). Individual observations are shown with dots and theoretical curves with solid lines.

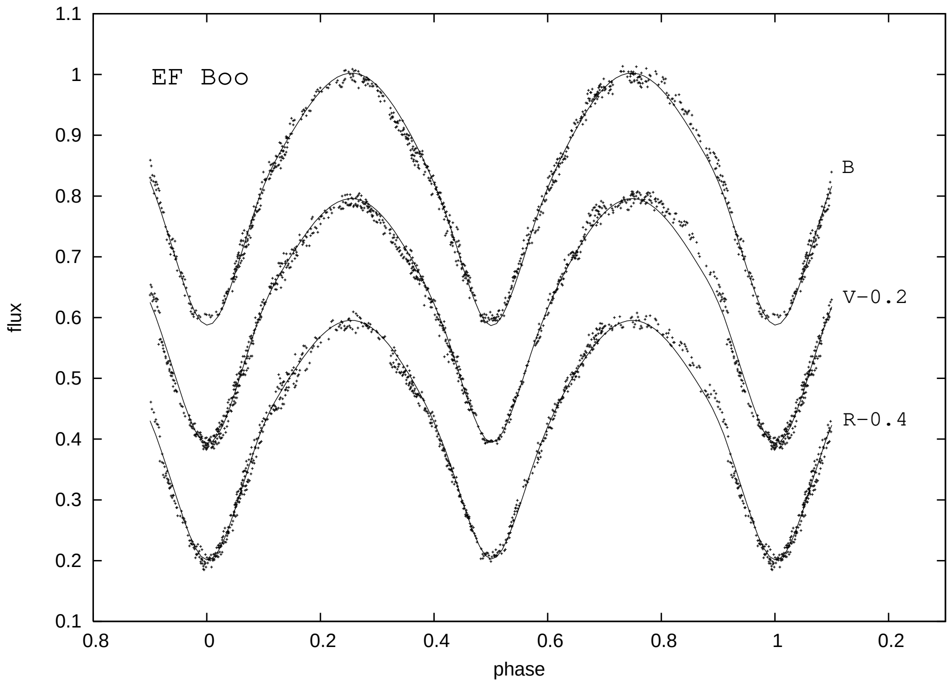

Figure 3: Comparison between theoretical and observed light curves of EF Boo (BVR filters). Individual observations are shown with dots and theoretical curves with solid lines.

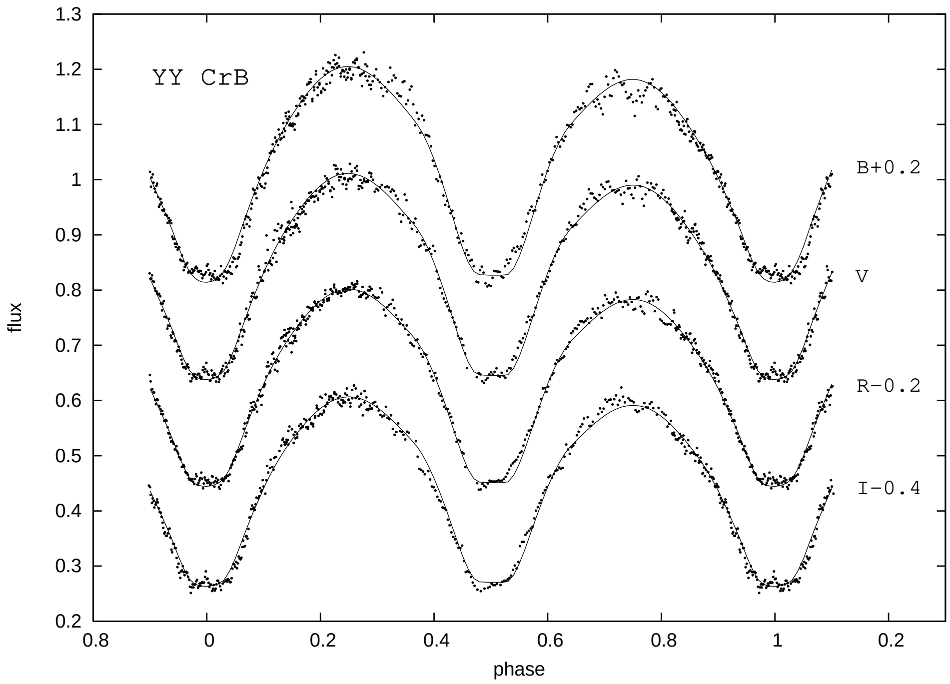

Figure 4: Comparison between theoretical and observed light curves of YY CrB (BVRI filters). Individual observations are shown with dots and theoretical curves with solid lines.

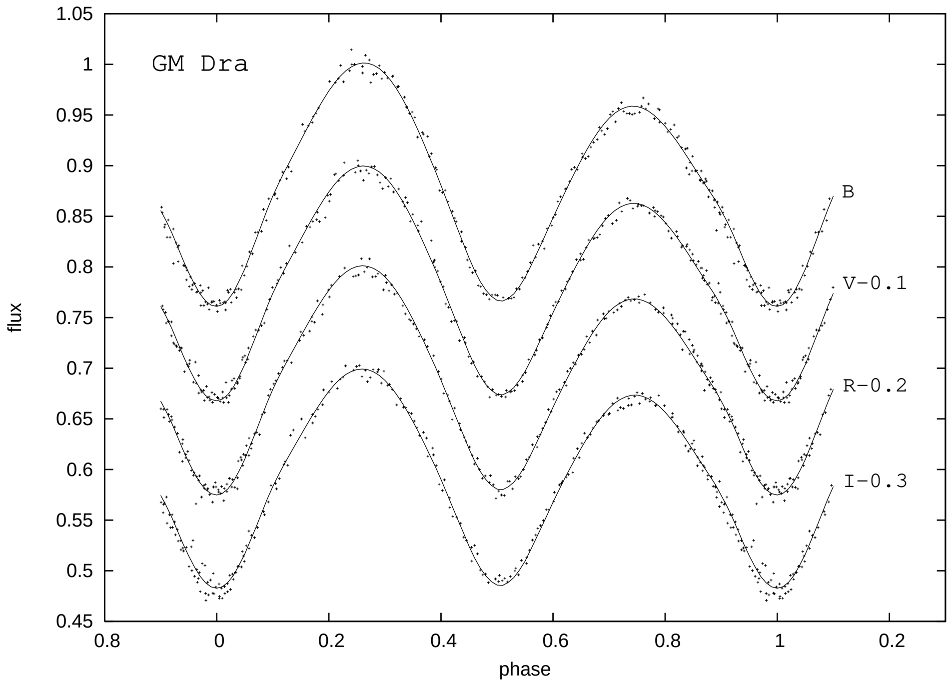

Figure 5: Comparison between theoretical and observed light curves of GM Dra (BVRI filters). Individual observations are shown with dots and theoretical curves with solid lines.

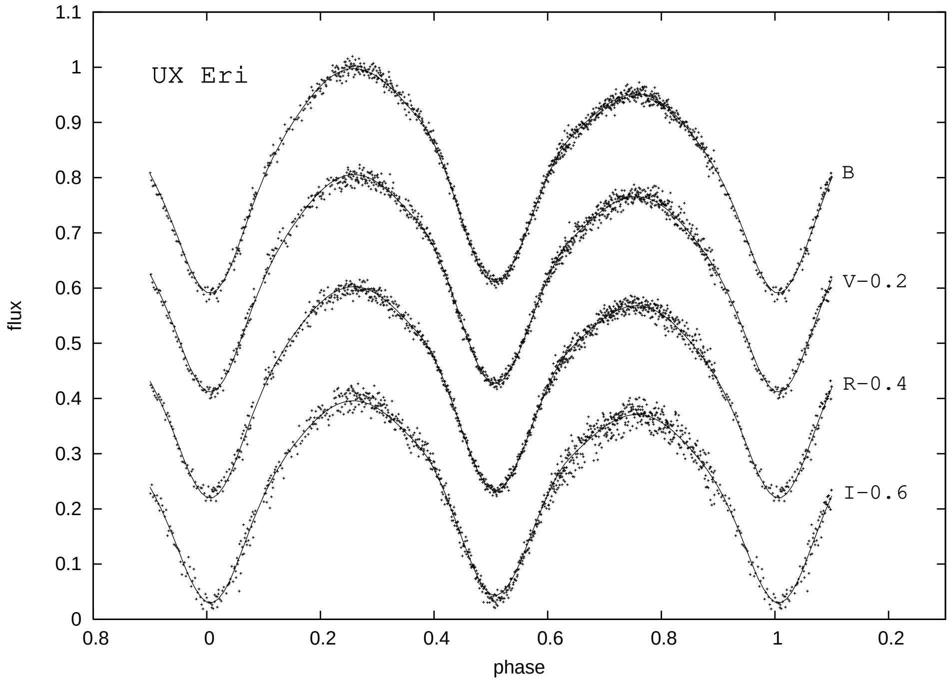

Figure 6: Comparison between theoretical and observed light curves of UX Eri (BVRI filters). Individual observations are shown with dots and theoretical curves with solid lines.

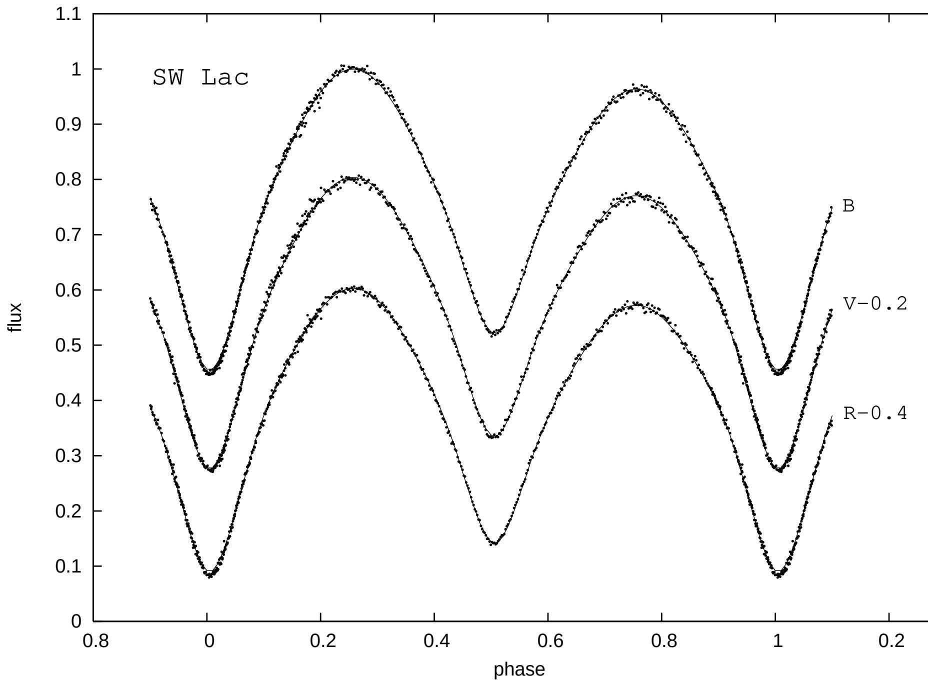

Figure 7: Comparison between theoretical and observed light curves of SW Lac (BVR filters). Individual observations are shown with dots and theoretical curves with solid lines.

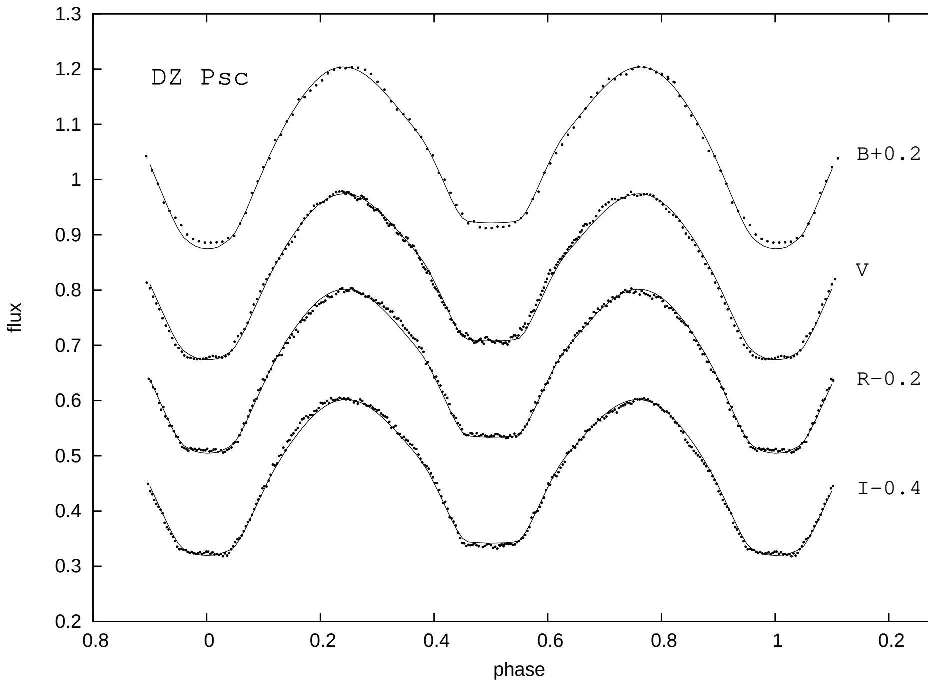

Figure 8: Comparison between theoretical and observed light curves of DZ Psc (BVRI filters). Individual observations are shown with dots and theoretical curves with solid lines.

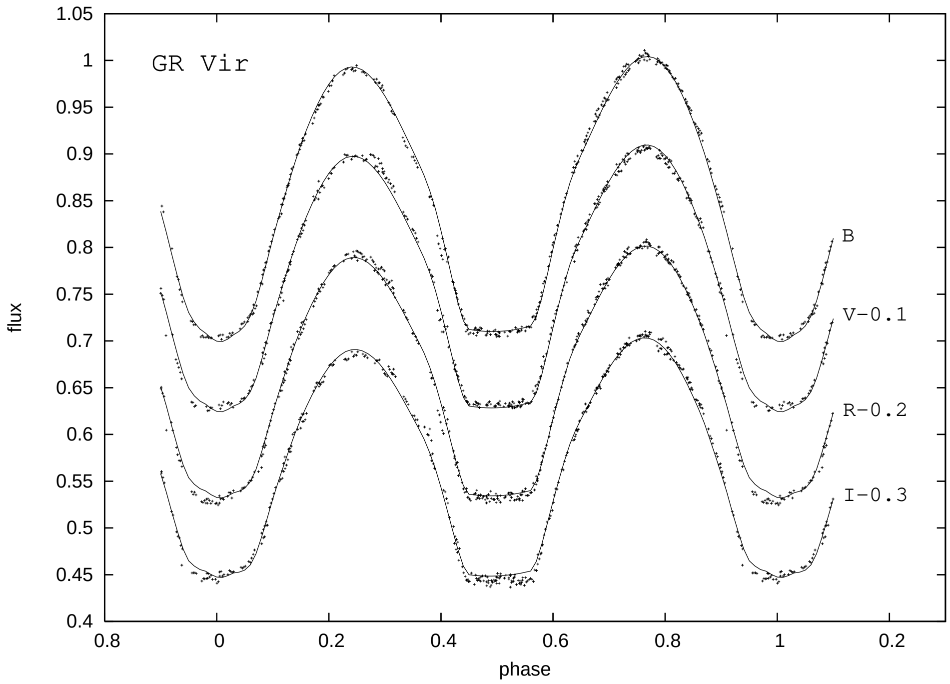

Figure 9: Comparison between theoretical and observed light curves of GR Vir (BVRI filters). Individual observations are shown with dots and theoretical curves with solid lines.

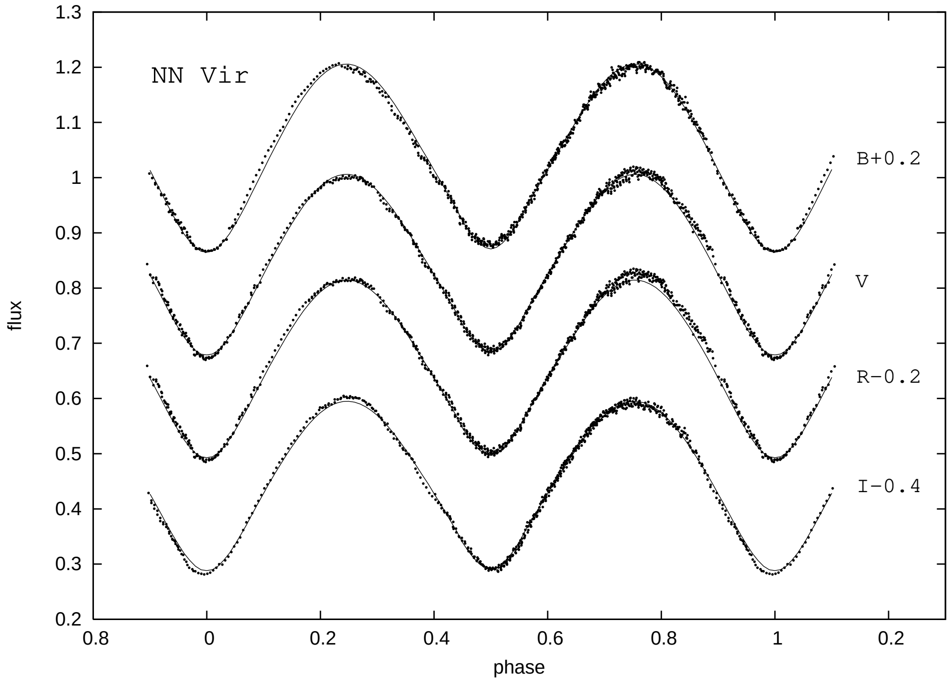

Figure 10: Comparison between theoretical and observed light curves of NN Vir (BVRI filters). Individual observations are shown with dots and theoretical curves with solid lines.

Table 6: Absolute parameters (in solar units) of the systems studied in Papers I-IV. The standard errors are expressed in parentheses, in units of last decimal places quoted

System	$\mathcal{M}_1$	$\mathcal{M}_2$	R_1	R_2	L_1	L_2	type
AB And	1.042(6)	0.595(5)	1.025(3)	0.780(2)	0.648(18)	0.492(3)	W
GZ And	1.115(18)	0.593(15)	1.005(9)	0.741(7)	1.017(54)	0.717(14)	W
V417 Aql	1.377(36)	0.498(22)	1.314(12)	0.808(8)	1.796(33)	0.777(41)	A
V402 Aur	1.638(48)	0.327(23)	1.997(19)	0.915(8)	7.425(211)	1.491(26)	W
AH Aur	1.674(48)	0.283(22)	1.897(18)	0.837(9)	4.729(90)	1.090(58)	A
EF Boo	1.547(35)	0.792(26)	1.431(11)	1.064(9)	3.084(67)	1.731(29)	W
AO Cam	1.119(7)	0.486(5)	1.092(5)	0.732(4)	1.029(69)	0.574(6)	W
DN Cam	1.849(21)	0.818(15)	1.775(16)	1.224(13)	5.062(134)	2.668(57)	W
YY CrB	1.393(25)	0.339(11)	1.385(9)	0.692(5)	2.347(31)	0.755(27)	A
SX Crv	1.246(40)	0.098(13)	1.347(12)	0.409(4)	2.590(46)	0.213(29)	A
V2150 Cyg	2.233(98)	1.798(80)	1.946(13)	1.756(12)	13.707(183)	10.721(277)	A
DK Cyg	1.741(56)	0.533(33)	1.708(18)	0.986(12)	8.157(172)	1.731(162)	A
GM Dra	1.213(41)	0.219(17)	1.252(14)	0.606(7)	2.190(172)	0.562(13)	W
UX Eri	1.430(30)	0.534(18)	1.468(11)	0.905(7)	2.637(40)	1.169(71)	A
QW Gem	1.262(17)	0.413(9)	1.239(11)	0.726(8)	1.633(39)	0.645(14)	W
V829 Her	0.856(22)	0.372(14)	1.058(9)	0.711(6)	0.829(42)	0.541(9)	W
SW Lac	1.240(24)	0.964(21)	1.090(7)	0.976(7)	0.971(29)	0.953(14)	W
AP Leo	1.359(40)	0.416(24)	1.433(13)	0.809(8)	2.596(47)	0.882(48)	A
VZ Lib	1.480(68)	0.378(34)	1.335(22)	0.692(12)	1.934(64)	0.559(36)	A
SW Lyn	1.716(55)	0.899(29)	1.762(36)	1.219(27)	5.528(224)	0.529(31)	near contact
V753 Mon	1.528(20)	1.482(20)	1.738(7)	1.592(6)	8.446(68)	7.551(112)	semi-detached
DZ Psc	1.352(57)	0.183(24)	1.469(21)	0.617(9)	2.836(81)	0.493(22)	A
GR Vir	1.376(26)	0.168(11)	1.490(10)	0.550(4)	2.806(38)	0.493(34)	A
NN Vir	1.730(24)	0.850(17)	1.717(8)	1.246(7)	5.905(55)	3.155(60)	A

Subscripts 1 refers to the larger and more massive star, while subscript 2 refers to the smaller and less massive star night. In our solution we had to add a spot and we placed it on the primary component. In consequence, we got a contact configuration with a fill-out factor of 23%.

An O'Connell effect is also pronounced for UX Eri (Fig. 6). In order to obtain a good fit, we assumed one cool spot on the surface of the primary. We obtained a convergence and but a huge spot, covering half of the surface of the primary component is required to get a good fit. UX Eri has a fill-out factor of only 13%, which is in the weakest contact out of all systems analyzed in this paper.

SW Lac has one of the biggest amplitudes of light variation. O'Connell effect is also present in the light curve (Fig. 7) and we added a spot on the larger and more massive component. We found that the system has a contact configuration with a fill-out factor of 30%.

Solution for GR Vir (Fig. 9) resulted in one big and very cool spot and another one which was small in size. For SW Lac we derived a deep contact configuration with a fill-out factor of 93%. For both SW Lac and GR Vir we made also solutions including a third light in the systems. The solutions converged at a small third light contribution to the total light of about 1% in case of SW Lac and about 2% for GR Vir, only slightly improving the fits and, finally, we decided to present the non-spotted solutions as involving smaller number of free parameters.

AH Aur, DZ Psc and NN Vir show no asymmetries in their light curves (Figs. 2, 8, and 10). We adopted solutions with unspotted surfaces and the fits to observations are quite satisfactory. These three targets have a contact configuration with large fill-out factors (75% for AH Aur, 79% for DZ Psc and 61% for NN Vir).

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REFERENCES

Albayrak, B., Djurašević, G., Erkapić, S., and Tanriverdi, T. 2004, Astron. Astroph., **420**, 1039.
Al-Naimiy, H.M.K., Jabbar, S.R., Fleyen, H.A., and Al-Razzaz, J.M. 1989, Astrophys. Space Sci., **159**, 279.
Baran, A., et al. 2004, Acta Astron., **54**, 195 (Paper II).
Binnendijk, L. 1966, Astron. J., **72**, 82.
Brownlee, R.R. 1957, Astrophys. J., **125**, 372.
Cereda, L., Misto, A., Niarchos, P. G., and Poretti, E. 1988, Astron. Astrophys. Suppl. Ser., **76**, 255.
Çiçek, at al. 2001, IBVS, 5144.
Claret, A., Díaz-Cordovés, J., and Gimenez, A. 1995, Astron. Astrophys. Suppl. Ser., **114**, 247.
Díaz-Cordovés, J., Claret, A., and Gimenez, A. 1995, Astron. Astrophys. Suppl. Ser., **110**, 329.
Djurašević, G., Albayrak, B., Tanriverdi, T., and Erkapic, S. 2004, Astron. Astrophys., **415**, 283.
Erdem, A., et al. 2001, IBVS, 5152.
ESA 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200, Noordwijk.
Filatov, G. S. 1957, Astron. Circ. USSR, **182**, 14.
Gomez-Forrellad, J.M., and Garcia-Melendo, E. 1997, IBVS, 4469.
Gothard, N.W., Van Hamme, W., and Samec, R.G. 2000, Bull. American Astron. Soc., **197**, 4803.
Gutnick, P., and Prager, R. 1928, Astr. Nach., **233**, 35.
Halbedel, E.M. 1988, IBVS, 3132.

Harmanec, P. 1988, Bull. Astron. Inst. Czechosl., **39**, 329.
Harris, A.W. 1979, IBVS, 1691.
Hendry, P. D., and Mochnacki, S.W. 1998, Astrophys. J., **504**, 978.
Hinderer, F. 1960, Journal des Observateurs, **43**, 161.
Hoffmeister, C. 1935, Astr. Nach., **255**, 403.
Hrivnak, B.J. 1992, Bull. American Astron. Soc., **24**, 686.
Kazarovets, A.V., et al. 1999, IBVS, 4659.
Koch, R. 1974, Astron. J., **79**, 34.
Kreiner, J.M., et al. 2003, Astron. Astrophys., **412**, 465 (Paper I).
Kreiner, J.M. 2004, Acta Astron., **54**, 207.
Leavitt, H.S. 1918, Harvard Circ., No 207.
Lu, W.X., and Rucinski, S.M. 1999, Astron. J., **188**, 515.
Niarchos, P.G. 1987, Astron. Astrophys. Suppl. Ser., **67**, 365.
Özdemir, S., et al. 2001, IBVS, 5033.
Pribulla, T., Chochol, D., and Parimucha, S. 1999, Contrib. Astron. Obs. Skalnaté Pleso, **29**, 111.
Pribulla, T., and Vaňko, M. 2002, Contrib. Astron. Obs. Skalnaté Pleso, **32**, 79.
Pych, W., et al. 2004, Astron. J., **127**, 1712
Qian, S. 2003, Astron. Astrophys., **400**, 649.
Qian, S.B., and Yang, Y.G. 2004, Astron. J., **128**, 2430.
Rucinski, S.M. 1968, Acta Astron., **18**, 49.
Rucinski, S.M., 2004, private communication
Rucinski, S.M., and Lu, W. 1999, Astron. J., **118**, 2451.
Rucinski, S.M., Lu, W., and Mochnacki, S.W. 2000, Astron. J., **120**, 1133.
Rucinski, S.M., Lu, W., Mochnacki, S.W., Ogloza, W., and Stachowski, G. 2001, Astron. J., **122**, 1974.
Rucinski, S.M., et al. 2002, Astron. J., **124**, 1738.
Rucinski, S.M., et al. 2003, Astron. J., **125**, 3258.
Samec, R.G., Pauley, B.R., and Carrigan, B.J. 1997, Astron. J., **113**, 401.
Samec, R.G., Tuttle, J.P., Brougher, J.A., Moore, J.E., and Faulkner, D.R. 1999, IBVS, 4811.
Selam, S.O. 2004, Astron. Astrophys., **416**, 1097.
Sipahi, E., Keskin, V., and Yasarşoy, B. 2000, IBVS, 4859.
Soloviev, A. 1937a, Tadjik Obs. Circ., **22**, 1.
Soloviev, A. 1937b, Tadjik Obs. Circ., **25**, 7.
Strohmeier, W., Kippenhahn, R., and Geyer, E. 1956, Kleine Veröff. Bamberg, 15.
Strohmeier, W., Knigge, R., and Ott, H. 1965, IBVS, 115.
Vaňko, M., et al. 2001, Contrib. Astron. Obs. Skalnaté Pleso, **31**, 129.
Vaňko, M., Parimucha, Š., Pribulla, T., and Chochol, D. 2004, Baltic Astronomy, **13**, 151.
Verrot, J.P., and Van Cauteren, P. 2000, IBVS, 4910.
Wilson, R.E., and Devinney, E.J. 1973, Astrophys. J., **182**, 539.
Wilson, R.E. 1979, Astrophys. J., **234**, 1054.
Wilson, R.E. 1993, Documentation of Eclipsing Binary Computer Model.
Woitas, J. 1997, IBVS, 4444.
Zhai, D., and Lu, W. 1989, Acta Astrophys. Sinica, **9**, 208.
Zola S., et al. 2004, Acta Astron., **54**, 299 (Paper III).