Physical parameters of close binary systems: VI

by

K.D. Gazeas[1], P.G. Niarchos[1], S. Zola[2,3], J.M. Kreiner[3], S.M. Rucinski[4]

[1] Department of Astrophysics, Astronomy and Mechanics, University of Athens, Panepistimiopolis, GR-15784 Zografos, Athens, Greece
e-mail: pniarcho@cc.uoa.gr

[2] Astronomical Observatory of the Jagiellonian University, ul. Orla 171, 30-244 Cracow, Poland
email: sfzola@cyf-kr.edu.pl

[3] Mt. Suhora Observatory of the Pedagogical University, ul. Podchorążych 2, 30-084 Cracow, Poland
email: sfkreine@cyf-kr.edu.pl

[4] David Dunlap Observatory, University of Toronto, P.O. Box 360, Richmond Hill, Ontario, Canada L4C 4Y6
email: rucinski@astro.utoronto.ca

ABSTRACT

New high-quality CCD photometric light curves for the W UMa-type systems V410 Aur, CK Boo, FP Boo, V921 Her, ET Leo, XZ Leo, V839 Oph, V2357 Oph, AQ Psc and VY Sex are presented. The new multicolor light curves, combined with the spectroscopic data recently obtained at David Dunlap Observatory, are analyzed with the Wilson-Devinney code to yield the physical parameters (masses, radii and luminosities) of the components. Our models for all ten systems resulted in a contact configuration. Four binaries (V921 Her, XZ Leo, V2357 Oph and VY Sex) have low, while two (V410 Aur and CK Boo) have high fillout factors. FP Boo, ET Leo, V839 Oph and AQ Psc have medium values of the fillout factor. Three of the systems (FP Boo, V921 Her and XZ Leo) have very bright primaries as a result of their high temperatures and large radii.

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

1. Introduction

In this paper we present the combined multicolor photometric and spectroscopic study of ten contact systems from the sample defined by Kreiner et al. (2003). The systems selected to be studied are: V410 Aur, CK Boo, FP Boo, V921 Her, ET Leo, XZ Leo, V839 Oph, V2357 Oph, AQ Psc and VY Sex. The targets 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 (Rucinski et al. 2005 and references therein).

Details of the project and the procedure used to derive the parameters were given in Kreiner et al. 2003 (Paper I) and in Baran et al. 2004 (Paper II). The selected systems are analysed with the same methods and techniques, as those in Zola et al. 2004 (Paper III), Gazeas et al. 2005a (Paper IV) and Zola et al. 2005 (Paper V). Remarks on individual systems are given in Section 2, while Section 3 contains the log of the new photometric observations and description of the instruments used. Section 4 outlines the procedure and method used to analyze the photometric and spectroscopic data, and to compute the absolute parameters of the components. A discussion of the results for each system is given in the last section. The theoretical light curves are compared with the observed ones and the assumptions made to explain better the observations, such as the existence of a third body in a system or magnetic activity of the components, are also discussed.

2. Remarks on the individual systems

2.1. V410 Aur

The eclipsing binary V410 Aur (BD +34° 934, HIP 23337, V = 10.33^m) was discovered by Hipparcos satellite mission (ESA, 1997). It has a typical light curve of a W UMa-type binary with total eclipses at the secondary minimum. There are limited observations of this system, such as those obtained by Dvorak (2005), who gave a time of minimum. V410 Aur is a spectroscopicaly triple system with a third component having relative brightness of $L_3/(L_1+L_2)=0.26 \pm 0.01$. Rucinski et al. (2003) calculated the mass ratio q_{sp}=0.144 ± 0.013 and classified the system as an A-subtype G0/2V contact binary. Yang et al. (2005) observed this binary and calculated its absolute photometric parameters. They also determined the mass ratio photometrically, giving the value of q_{ph}=0.1428 and found a filling factor of 52.4%. Finally, they suggested that the system undergoes mass transfer from the less massive component to the more massive one.

2.2. CK Boo

The eclipsing binary CK Boo (BD +9° 2916, HIP 71319, V = 9.09^m) was discovered by Bond (1975). The light variability was determined to be typical of a W UMa-type binary. Krzesinski et al. (1991) gave a solution with low inclination and partial eclipses. Rucinski and Lu (1999) calculated the mass ratio of this A-subtype contact binary $q_{sp} = 0.111 \pm 0.052$ and the spectral type F7/8V. Aslan and Derman (1986) presented an extended research of CK Boo based on observations obtained between 1976 and 1982. They noticed intrinsic light curve variations, mostly seen in the primary minimum, as well as variations of the color of the system. Qian and Liu (2000) published a list of minina of CK Boo and discussed a possible connection between the variation of light curve and the change of the orbital period. The most recent study of CK Boo was published by Kalci and Derman (2005). They performed light curve modelling using new BVR light curves. Due to well pronounced O'Connell effect a model with a cool spot on the surface of the larger component was adopted. Combined their results with spectroscopic data by Rucinski and Lu (1999) the authors derived the absolute parameters of the components.

2.3. FP Boo

FP Boo (BD +43° 2523, HIP 76970, V = 10.20^m) was discovered by the Hipparcos satellite mission. These data were analyzed by Selam (2004) who obtained the photometric mass ratio of the system to be $q_{ph} = 0.1$, which is in good agreement with the spectroscopic one ($q_{sp} = 0.106 \pm 0.005$) derived by Rucinski et al. (2005). The small mass ratio of the system and the large radial velocities may indicate a high inclination system with total eclipses, similar to the contact binary AW UMa.

2.4. V921 Her

The light variability of the eclipsing binary V921 Her (BD +47° 2388, HIP 82344, V = 9.49^m) was also discovered by the Hipparcos mission. It has a relatively long period (P=0.877 days), rare for a contact binary. V921 Her has a low amplitude of light variation and small RV values, indicating a low inclination orbit. Rucinski et al. (2003) determined the mass ratio $q_{sp} = 0.226 \pm 0.005$ and classified the system as an A-subtype A7IV contact binary.

2.5. ET Leo

ET Leo (BD +18° 2374, HIP 51677, V = 9.60^m) is another Hipparcos satellite photometric discovery. A new ephemeris, spectral type (G5) and V-light curve are given by Gomez-Forrellad et al. (1999). The system has very shallow eclipses of equal depth, and unequal maxima (O'Connel effect). Duerbeck (1997) included this system in his list of contact binaries with low amplitude light variation. Observations of ET Leo show that it undergoes marginal eclipses. Recently, Tanriverdi et al. (2004) obtained new photoelectric B and V light curves and obtained a photometric solution of the system. It turned out to be a W-subtype contact binary with q_{sp}=0.342 $\pm$ 0.005 and a spectral type of G8V assigned by Rucinski et al. (2002).

2.6. XZ Leo

The eclipsing binary XZ Leo (BD +17° 2165, HIP 49204, V = 10.29^m) was discovered by Hoffmeister (1934). Niarchos et al. (1994) gave the first times of minima, ephemeris and the physical parameters of the system. They noticed that the light curves were better approximated by introducing hot spots on both components near the neck region of the common envelope, to interpret the observed light curve asymmetries. The mass ratio, calculated by Rucinski and Lu (1999), is q_{sp} = 0.348 $\pm$ 0.029, far away from the photometric one determined in previous studies. Its spectral type is A8/F0V and it belongs to the A-subtype of contact binaries.

2.7. V839 Oph

The light variability of V839 Oph (BD +9° 3584, HIP 88946, V = 9.04^m) was discovered by Rigollet (1947). Several investigations followed, such as those made by Binnendijk (1960), Niarchos (1989), Akalin and Derman (1997). Radial velocity and light curves analysis of the star was made by Pazhouhesh and Edalati (2003). They obtained new physical parameters of V839 Oph. Wolf et al. (1996) analyzed in detail the O-C diagram and tried to explain period changes in terms of conservative mass transfer or magnetic activity of the system or even a possible third body orbiting the binary. According to Rucinski and Lu (1999) the system is an A-subtype contact binary with q_{sp}=0.305 $\pm$ 0.024 and a spectral type of F7V.

2.8. V2357 Oph

V2357 Oph (GSC 979:339, HIP 82967, V = 10.51^m) was discovered by the Hipparcos mission. It was initially classified as a pulsating variable and the Hipparcos ephemeris refers to the times of maxima. Rucinski et al. (2003) calculated an accurate mass ratio from their radial velocities observations. They found that q_{sp} = 0.231 $\pm$ 0.010 and estimated its spectral type as G5V. Assuming that the Hipparcos ephemeris is correct, Rucinski et al. (2003) classified the system as an A-subtype contact binary.

2.9. AQ Psc

The eclipsing binary AQ Psc (BD +6° 203, HIP 6307, V = 8.66^m) was discovered by Sarma & Radhakrishnan (1982). For this A-subtype contact binary very few observations exist, providing only times of minima and a good linear ephemeris of the system. Lu and Rucinski (1999) calculated the spectroscopic mass ratio of the system and found the value of q_{sp} = 0.226 $\pm$ 0.002. They classified it as a contact binary of F8V spectral type.

2.10. VY Sex

The eclipsing binary VY Sex (BD −1° 2452, HD 93917, V = 9.01^m) was recently discovered by Lasala-Garcia (2001) from a small, private observatory. It is one of the rare cases that, according to its brightness, it remained undetected for a long time. Rucinski et al. (2003) calculated the mass ratio of the system and found the value of q_{sp} = 0.313 $\pm$ 0.005. They classified it as a W-subtype contact binary of F9.5V spectral type.

3. Photometric observations

The observations of eight targets: V410 Aur, CK Boo, FP Boo, V921 Her, ET Leo, XZ Leo, V839 Oph and VY Sex were obtained at the University of Athens Observatory, Athens, Greece. The instruments used were the 0.40 m Cassegrain reflector and a ST-8 CCD camera. The CCD camera uses a Kodak KAF-1600 CCD chip, cooled by a two-stage Peltier element, which provides

Table 1: Log of observations

System	Observatory	Dates
V410 Aur	Univ. of Athens Obs.	21, 22, 26, 29 Nov; 11, 12, 13, 20 Dec 2004; 4 Jan 2005
CK Boo	Univ. of Athens Obs.	19, 20, 21, 23 Feb 2005
FP Boo	Univ. of Athens Obs.	3, 5, 6, 9, 16, 17, 18 March; 15, 16 May 2005
V921 Her	Univ. of Athens Obs.	11, 12, 13, 14, 25, 26, 27, 31 Aug; 5, 7, 8, 11, 13, 15 Sep 2004
ET Leo	Univ. of Athens Obs.	25 Mar 2003
XZ Leo	Univ. of Athens Obs.	29, 31 Jan; 15, 18, 29 Feb 2004
V839 Oph	Univ. of Athens Obs.	26, 27, 28 May; 5, 9, 11 Jun; 6, 7, 8 Jul 2004
V2357 Oph	Kryoneri Astr. Station	10, 11, 12 March 2005
AQ Psc	Kryoneri Astr. Station	24 Nov; 20 Dec 2003
VY Sex	Univ. of Athens Obs.	8, 9, 10, 11 May 2005

a CCD working temperature of $-30\,^{\circ}$C below ambient. The CCD chip has 1536×1024 useful pixels of 9x9 microns, covering an area of 15×10 arcmin, or 22×15 if a focal reducer is used. The CCD camera is equipped with a set of U, B, V, R and I Bessell filters.

V2357 Oph and AQ Psc were observed at the Kryoneri Astronomical Station of the National Observatory of Athens, Greece. The 1.22 m Cassegrain reflector and a Photometrics CH250 CCD camera were used. The CCD camera uses a Class I, SI502 CCD chip, cooled by a three-stage Peltier element and traditional chilled water cooling that provides a stable CCD working temperature of $-40\,^{\circ}$C. The CCD chip has 512×512 useful pixels of 24×24 microns, covering an area of 2.5×2.5 arcmin. The CCD camera is equipped with a set U, B, V, R and I Bessell filters. The log of observations for all objects analyzed in this paper is given in Table 1.

One of the aims of this project is to obtain a complete light curve of each object at only one observatory to avoid the procedure of combining data taken at different sites and with different instruments. Therefore, each target has been observed with the same instrument and under the same configuration. In addition, the need to minimize intrinsic variations we attempted to complete the light curves in as short as possible time.

All data were left in the instrumental system. However, 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, which is available on-line at: *http://www.as.ap.krakow.pl/ephem*. Table 2 lists the reference epochs, as well as the periods used for phasing our new photometric observations.

4. Light curve modelling

The method used for the derivation of the physical parameters is described in detail in Paper I. The procedure described in Paper II aims to the re-determination of the mass ratio for each system, correcting it for proximity effects. In order to obtain the physical parameters of components, we used the Wilson-Devinney code (W-D) (Wilson & Devinney 1973; Wilson 1979, 1993) and applied the Monte Carlo algorithm as the search method. Adjustments have been made to the following parameters: phase shift, inclination, temperature of the secondary component, potential(s) and the luminosity of the primary star.

In our computations theoretical values of the gravity darkening and albedo coefficients were used. In the cases where a star has a radiative envelope (T>7200 K), we used the value of 1.0 for both coefficients, whereas in the case of convective envelopes (T<7200 K) we set the albedo

Table 2: Linear elements used for phasing the observations

System	reference epoch (HJD)	period (days)
V410 Aur	2452500.0033	0.36635614
CK Boo	2452500.0237	0.35515534
FP Boo	2452500.2796	0.64048195
V921 Her	2452500.0973	0.87737804
ET Leo	2452500.3582	0.34650349
XZ Leo	2452500.4192	0.48773790
V839 Oph	2452500.4447	0.40900491
V2357 Oph	2452500.0907	0.41556707
AQ Psc	2452500.3638	0.47561168
VY Sex	2452500.1065	0.44343192

Table 3: Searching ranges of the adjusted parameters (W-D program input values)

System	ϕ	i(deg)	T_2(K)	Ω_1=Ω_2	L_1
V410 Aur	-0.01-0.01	65-90	4500-7500	1.90-4.50	2-12.5
CK Boo	-0.01-0.01	35-90	4700-7700	1.90-4.50	1-12.5
FP Boo	-0.01-0.01	35-80	5500-8500	1.90-4.50	1-12.5
V921 Her	-0.01-0.01	65-90	6000-9500	1.90-4.50	2-12.5
ET Leo	-0.01-0.01	35-90	4000-7000	4.00-9.50	1-12.5
XZ Leo	-0.01-0.01	65-90	5500-8000	1.90-4.50	2-12.5
V839 Oph	-0.01-0.01	65-90	4500-7500	1.90-4.50	2-12.5
V2357 Oph	-0.01-0.01	35-80	4000-7000	5.90-9.50	1-12.5
AQ Psc	-0.01-0.01	65-90	4500-7500	1.90-4.50	2-12.5
VY Sex	-0.01-0.01	50-90	5000-7000	4.00-9.50	1-12.5

coefficient to 0.5 and the gravity darkening coefficient to 0.32. 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. The tables by Harmanec (1988) provided us with the effective temperature of the primary component, according to the spectral type obtained at DDO. Table 3 shows the searching ranges for all free parameters. In Tables 4 and 5 the results from the light curve modelling are given for all systems analyzed in this paper. For models with spots the resulting spots parameters are also presented.

In the cases of an obvious O'Connell effect, a spot was considered in our solution. In such cases, the whole surface of the brighter component was scanned for a possible spot location. The comparison between the resulting theoretical light curves and the observations is shown in Figs. 1-10. By combining the photometric solution with the spectroscopic results we calculated the absolute parameters of the two components, which are presented in Table 6. The listed errors correspond to the 90 percent confidence level.

Table 4: Results derived from the light curve modelling

parameter	V410 Aur	CK Boo	FP Boo	V921 Her	ET Leo
filling factor	72%	91%	38%	23%	55%
phase shift	0.9960 ±0.0006	0.9850 ±0.0004	0.9990 ±0.0003	0.9992 ±0.0002	0.0017 ±0.0004
i(deg)	80.6 ±1.0	63.7 ±0.3	68.8 ±0.2	68.1 ±0.1	36.6 ±0.3
T_1(K)	* 5890	* 6150	* 6980	* 7700	* 5500
T_2(K)	5983 ±22	6163 ±10	6456 ±14	7346 ±20	5112 ±28
$\Omega_1 = \Omega_2$	2.004 ±0.005	1.915 ±0.002	1.922 ±0.012	2.304 ±0.002	6.178 ±0.004
$q_{corr}(m_2/m_1)$	* 0.137	* 0.106	* 0.096	* 0.244	* 2.924
L_1 (B)	8.423 ±0.018	10.363 ±0.015	11.386 ±0.024		3.922 ±0.018
L_1 (V)	8.944 ±0.015	10.366 ±0.016	11.365 ±0.021	9.555 ±0.051	3.849 ±0.015
L_1 (R)	8.837 ±0.013	10.368 ±0.016	11.262 ±0.022	9.569 ±0.048	3.802 ±0.013
L_1 (I)	8.882 ±0.010	10.394 ±0.014	11.207 ±0.022	9.494 ±0.047	3.696 ±0.010
L_2 (B)	** 1.932	** 2.203	** 1.181		** 8.644
L_2 (V)	** 2.064	** 2.200	** 1.202	** 3.011	** 8.717
L_2 (R)	** 1.995	** 2.198	** 1.304	** 2.997	** 8.764
L_2 (I)	** 1.963	** 2.172	** 1.359	** 3.072	** 8.870
L_3 (B)	0.176 ±0.010	* 0	* 0		* 0
L_3 (V)	0.124 ±0.010	* 0	* 0	* 0	* 0
L_3 (R)	0.138 ±0.010	* 0	* 0	* 0	* 0
L_3 (I)	0.137 ±0.010	* 0	* 0	* 0	* 0
$r_1{}^{pole}$	0.5309 ±0.0012	0.5469 ±0.0012	0.5442 ±0.0002	0.4798 ±0.0002	0.2964 ±0.0012
$r_1{}^{side}$	0.5928 ±0.0020	0.6172 ±0.0020	0.6115 ±0.0003	0.5212 ±0.0003	0.3130 ±0.0015
$r_1{}^{back}$	0.6179 ±0.0024	0.6406 ±0.0024	0.6311 ±0.0004	0.5476 ±0.0004	0.3722 ±0.0034
$r_2{}^{pole}$	0.2286 ±0.0016	0.2157 ±0.0016	0.1958 ±0.0003	0.2551 ±0.0003	0.4690 ±0.0011
$r_2{}^{side}$	0.2408 ±0.0019	0.2277 ±0.0020	0.2048 ±0.0003	0.2666 ±0.0003	0.5094 ±0.0016
$r_2{}^{back}$	0.3043 ±0.0020	0.3030 ±0.0085	0.2469 ±0.0007	0.3069 ±0.0006	0.5450 ±0.0021
spot parameters					
co-latitude (deg)	97 ±2	126 ±2	—	—	74.4 ±4
longitude (deg)	306 ±2	84 ±2	—	—	41.5 ±2
radius (deg)	12.2 ±0.2	56.8 ±0.5	—	—	11.5 ±1
temp. factor	0.73 ±0.05	0.98 ±0.02	—	—	0.61 ±0.01

$*$ - 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 brighter component.

Table 5: Results derived from the light curve modelling

parameter	XZ Leo	V839 Oph	V2357 Oph	AQ Psc	VY Sex
filling factor	19%	53%	23%	44%	22%
phase shift	0.0007 ±0.0003	0.9996 ±0.0004	0.0016 ±0.0004	0.0013 ±0.0002	0.0005 ±0.0002
i(deg)	78.3 ±0.2	82.9 ±0.6	48.0 ±0.6	68.9 ±0.2	65.2 ±0.2
T_1(K)	* 7240	* 6250	* 5780	* 6100	* 5960
T_2(K)	6946 ±13	6349 ±25	5640 ±25	6124 ±15	5756 ±15
$\Omega_1 = \Omega_2$	2.506 ±0.005	2.357 ±0.002	8.223 ±0.002	2.244 ±0.005	6.706 ±0.005
$\mathrm{q_{corr}(m_2/m_1)}$	* 0.336	* 0.294	* 4.329	* 0.231	* 3.171
L_1 (B)	9.115 ±0.015	8.582 ±0.051	2.643 ±0.051	9.210 ±0.091	3.445 ±0.091
L_1 (V)	9.014 ±0.016	8.636 ±0.051	2.627 ±0.051	9.220 ±0.078	3.399 ±0.078
L_1 (R)	8.976 ±0.016	8.658 ±0.048	2.618 ±0.048	9.265 ±0.069	3.367 ±0.069
L_1 (I)	8.941 ±0.014	8.694 ±0.047	2.615 ±0.047	9.286 ±0.070	3.331 ±0.070
L_2 (B)	** 3.451	** 3.985	** 9.924	** 3.356	** 9.122
L_2 (V)	** 3.552	** 3.931	** 9.939	** 3.346	** 9.167
L_2 (R)	** 3.590	** 3.909	** 9.949	** 3.302	** 9.199
L_2 (I)	** 3.625	** 3.873	** 9.952	** 3.280	** 9.236
L_3 (B)	* 0	* 0	* 0	* 0	* 0
L_3 (V)	* 0	* 0	* 0	* 0	* 0
L_3 (R)	* 0	* 0	* 0	* 0	* 0
L_3 (I)	* 0	* 0	* 0	* 0	* 0
$r_1{}^{pole}$	0.4546 ±0.0003	0.4782 ±0.0001	0.2486 ±0.0010	0.4911 ±0.0005	0.2743 ±0.0010
$r_1{}^{side}$	0.4892 ±0.0004	0.5208 ±0.0001	0.2595 ±0.0012	0.5369 ±0.0006	0.2871 ±0.0011
$r_1{}^{back}$	0.5178 ±0.0005	0.5537 ±0.0002	0.2973 ±0.0022	0.5655 ±0.0009	0.3278±0.0020
$r_2{}^{pole}$	0.2778 ±0.0003	0.2825 ±0.0001	0.4817 ±0.0009	0.2595 ±0.0005	0.4610±0.0009
$r_2{}^{side}$	0.2906 ±0.0004	0.2977 ±0.0001	0.5234 ±0.0013	0.2725 ±0.0006	0.4974±0.0012
$r_2{}^{back}$	0.3298 ±0.0006	0.3546 ±0.0003	0.5486 ±0.0016	0.3229 ±0.0015	0.5260±0.0015
spot parameters					
co-latitude (deg)	—	—	50 ±2	—	94 ±2
longitude (deg)	—	—	59 ±2	—	281 ±2
radius (deg)	—	—	10 ±1	—	19 ±1
temp. factor	—	—	0.55 ±0.01	—	0.83 ±0.01

$*$ - 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 brighter component.

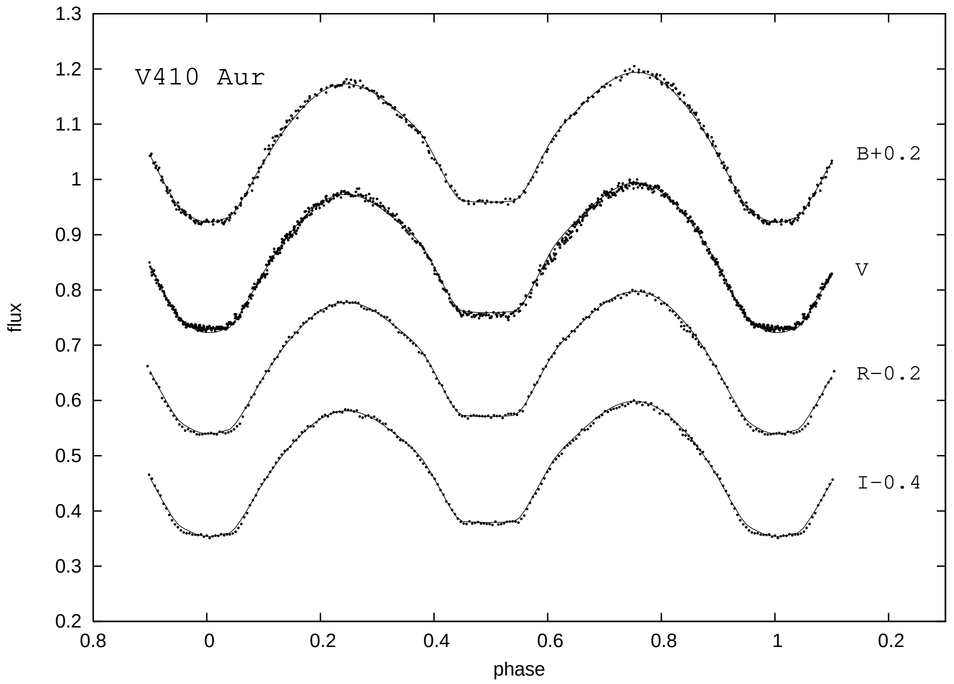

Figure 1: Comparison between theoretical and observed light curves of V410 Aur (BVRI filters). Individual observations are shown with dots and theoretical curves with solid lines.

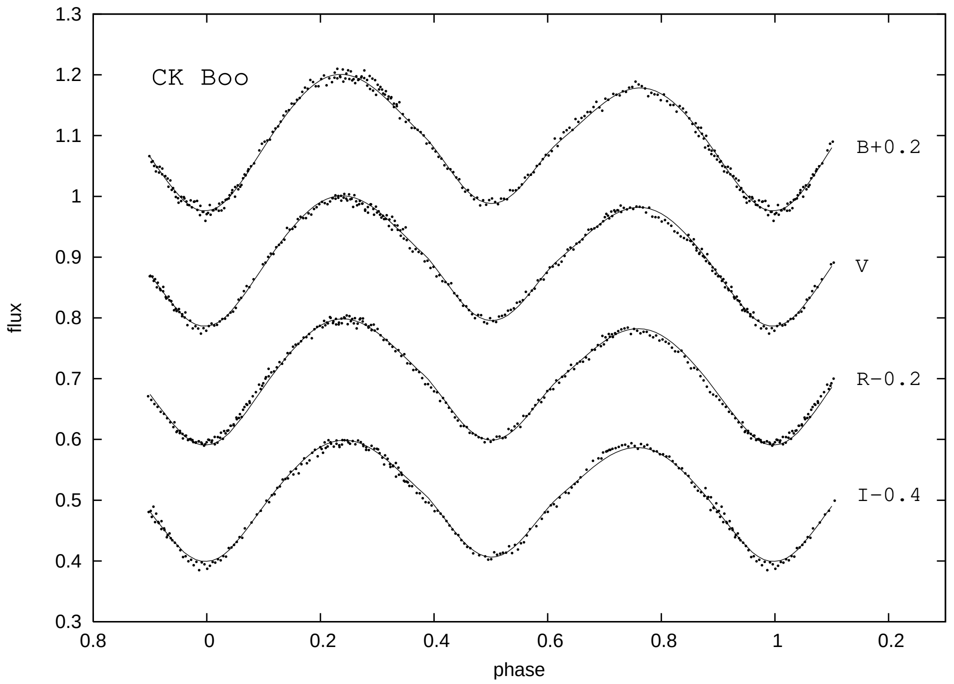

Figure 2: Comparison between theoretical and observed light curves of CK Boo (BVRI filters). Individual observations are shown with dots and theoretical curves with solid lines.

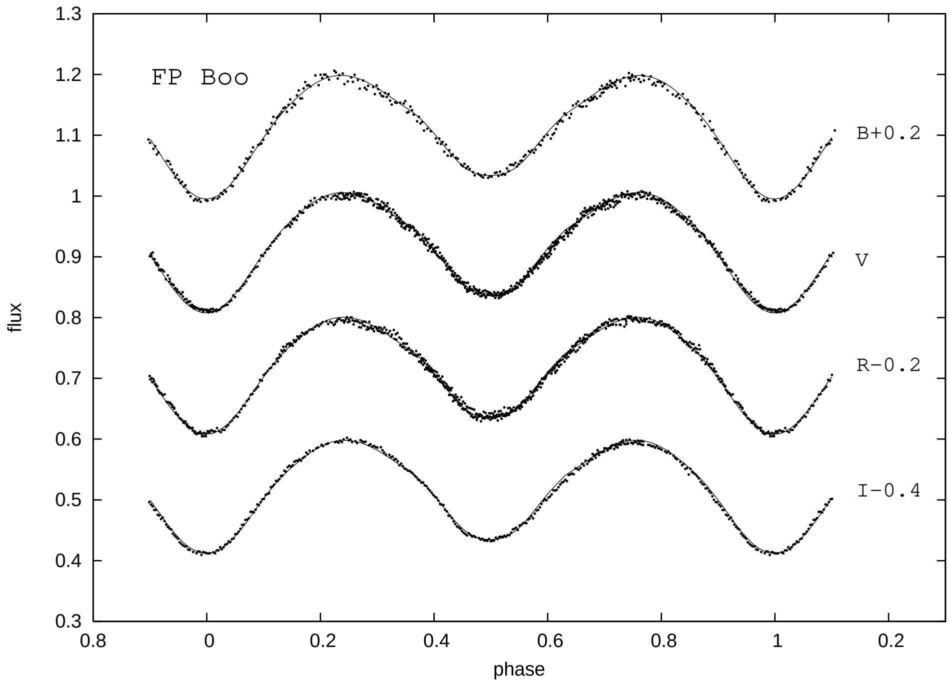

Figure 3: Comparison between theoretical and observed light curves of FP Boo (BVRI filters). Individual observations are shown with dots and theoretical curves with solid lines.

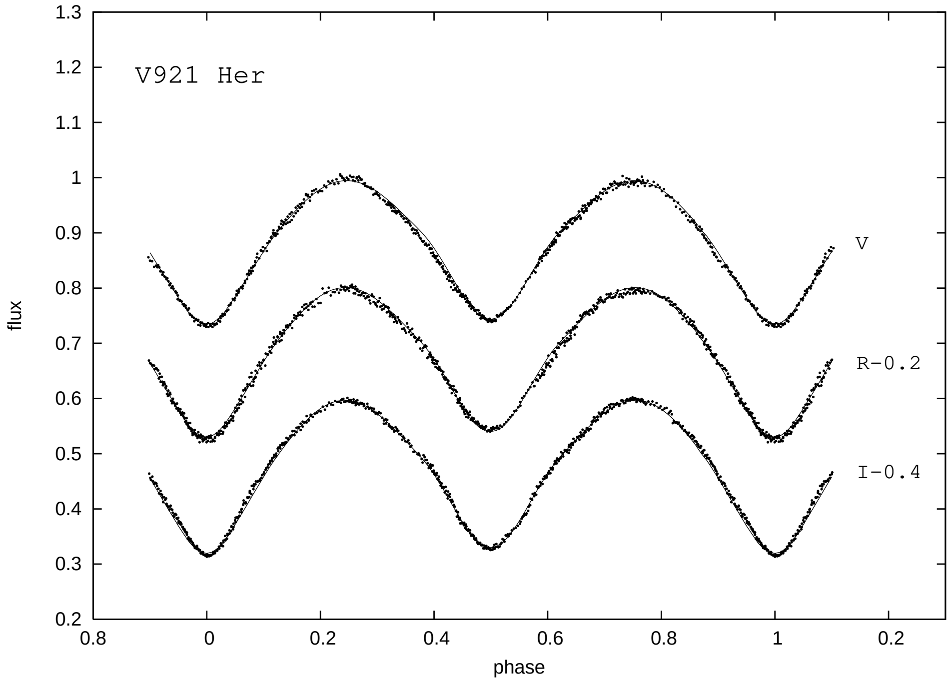

Figure 4: Comparison between theoretical and observed light curves of V921 Her (VRI filters). Individual observations are shown with dots and theoretical curves with solid lines.

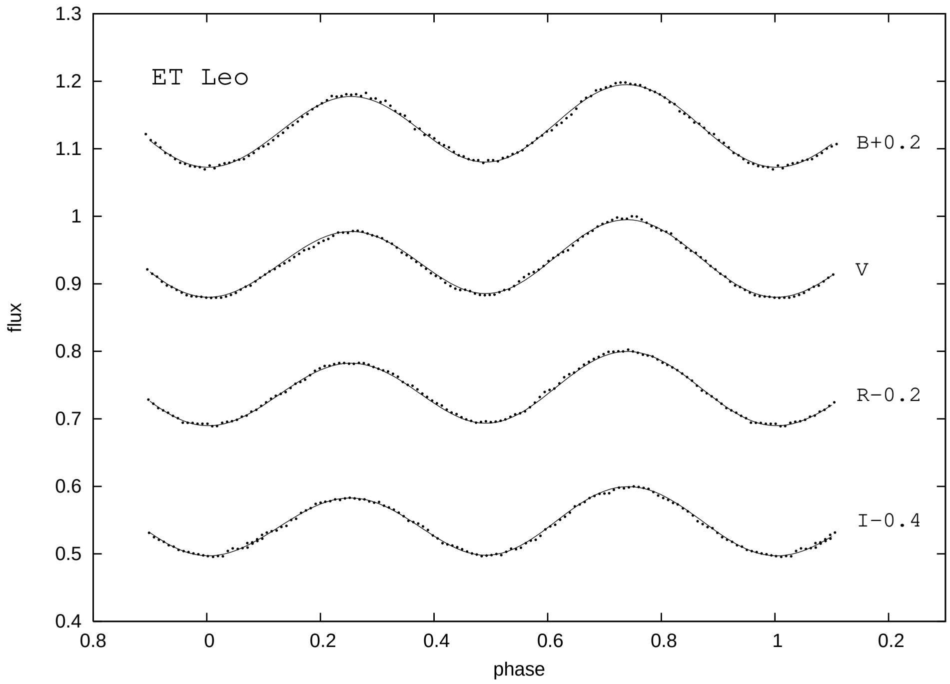

Figure 5: Comparison between theoretical and observed light curves of ET Leo (BVRI filters). Individual observations are shown with dots and theoretical curves with solid lines.

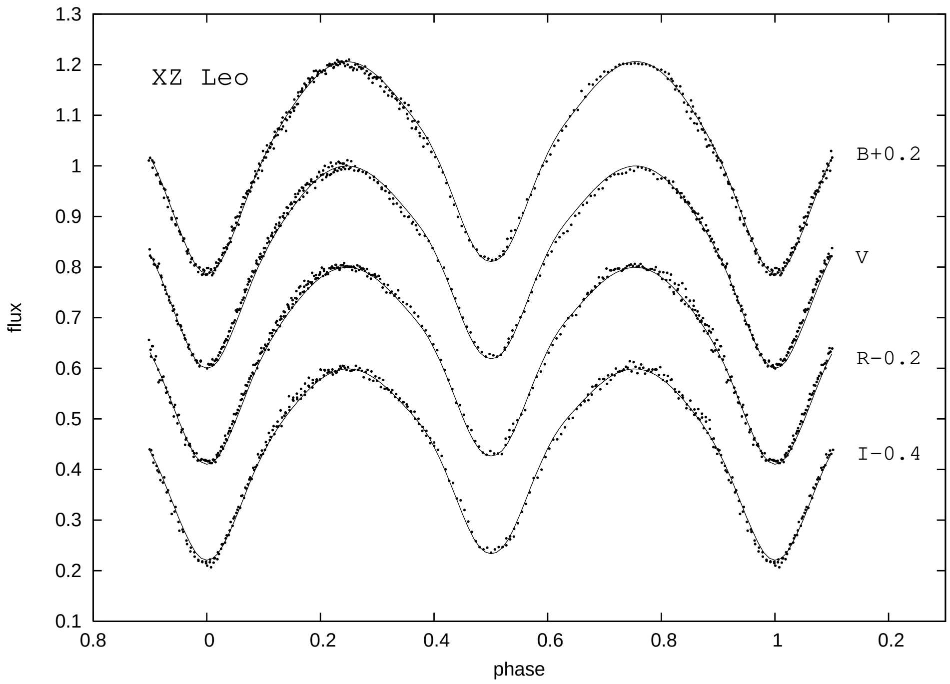

Figure 6: Comparison between theoretical and observed light curves of XZ Leo (BVRI filters). Individual observations are shown with dots and theoretical curves with solid lines.

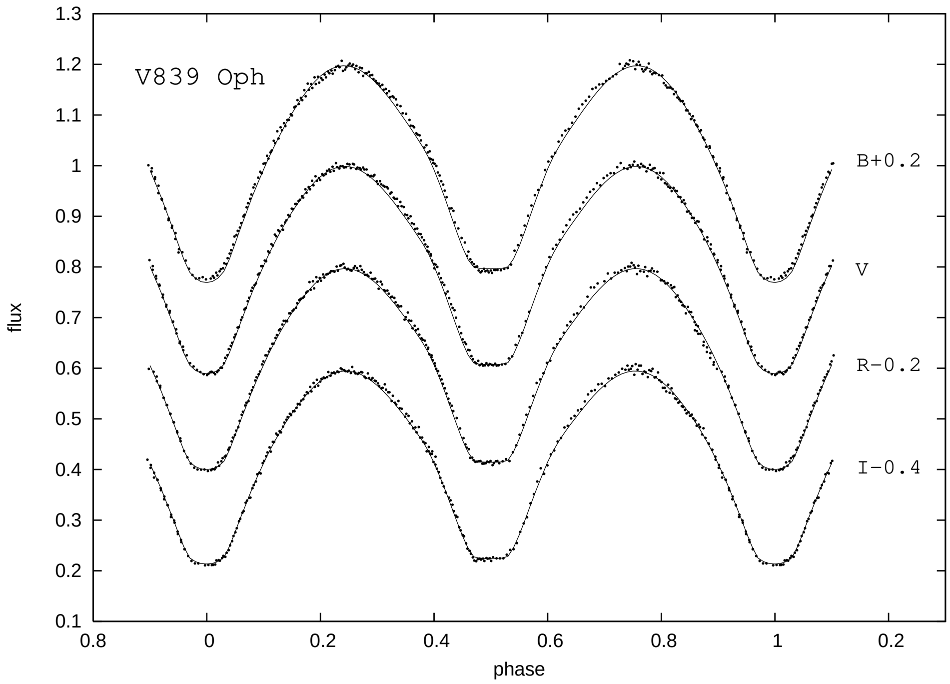

Figure 7: Comparison between theoretical and observed light curves of V839 Oph (BVRI filters). Individual observations are shown with dots and theoretical curves with solid lines.

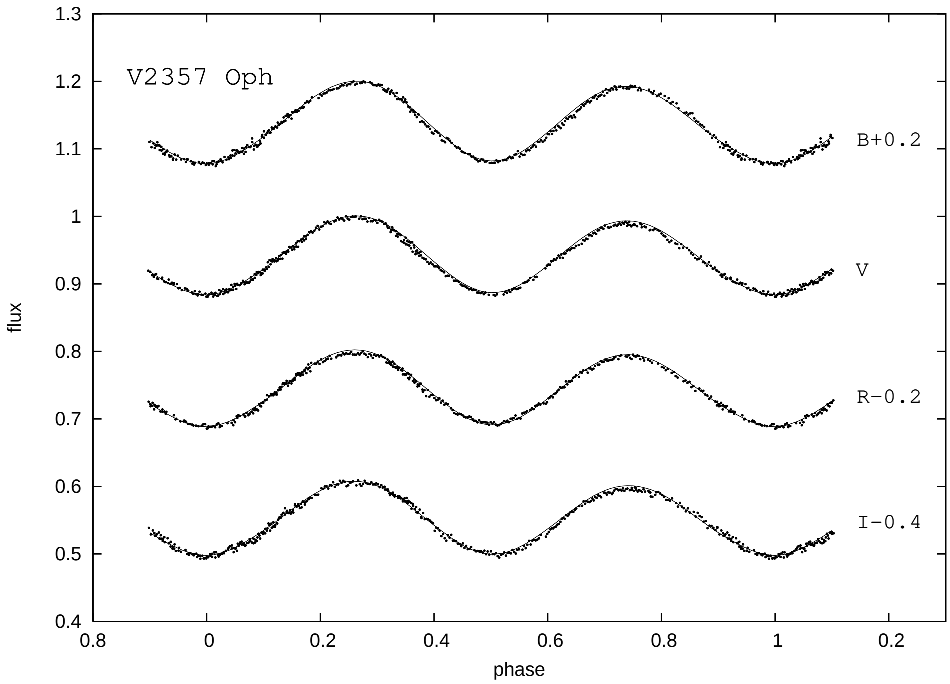

Figure 8: Comparison between theoretical and observed light curves of V2357 Oph (BVRI filters). Individual observations are shown with dots and theoretical curves with solid lines.

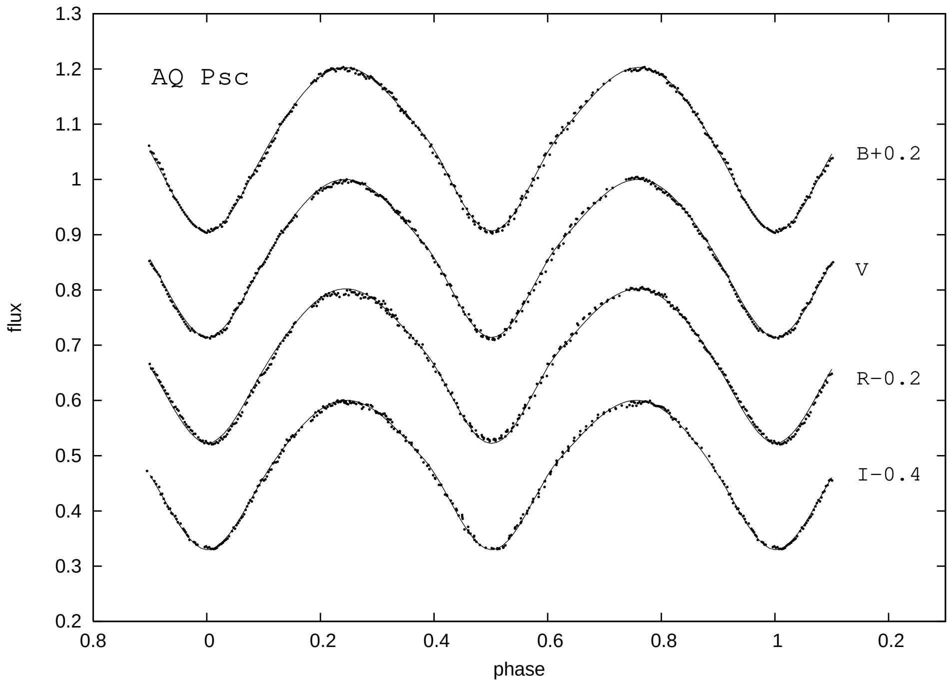

Figure 9: Comparison between theoretical and observed light curves of AQ Psc (BVRI filters). Individual observations are shown with dots and theoretical curves with solid lines.

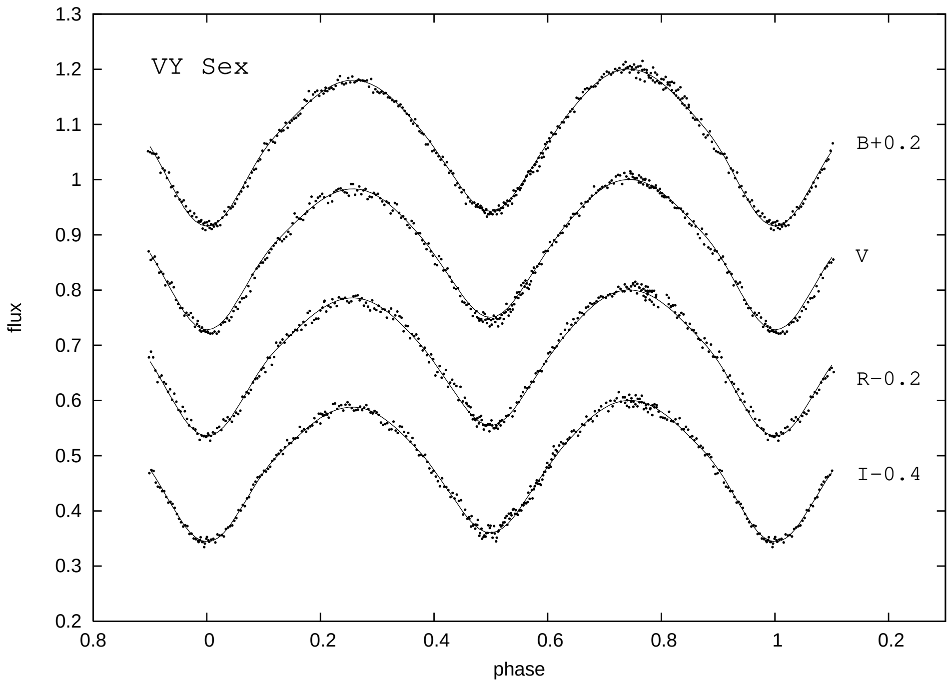

Figure 10: Comparison between theoretical and observed light curves of VY Sex (BVRI filters). Individual observations are shown with dots and theoretical curves with solid lines.

Table 6: Absolute parameters (in solar units) of the systems studied in the present paper. The standard errors are expressed in parenthesis, in units of last decimal places quoted

System	$\mathcal{M}_1$	$\mathcal{M}_2$	R_1	R_2	L_1	L_2
V410 Aur	1.270(61)	0.173(25)	1.442(26)	0.586(11)	2.227(46)	0.389(15)
CK Boo	1.442(24)	0.155(10)	1.521(10)	0.561(06)	2.924(20)	0.401(16)
FP Boo	1.614(52)	0.154(21)	2.310(25)	0.774(08)	11.193(99)	0.920(13)
V921 Her	2.068(49)	0.505(26)	2.752(21)	1.407(11)	23.526(87)	5.094(35)
ET Leo	0.542(12)	1.586(21)	0.835(07)	1.359(09)	0.564(08)	1.115(15)
XZ Leo	1.742(47)	0.586(27)	1.689(15)	1.004(09)	6.926(43)	2.073(20)
V839 Oph	1.572(31)	0.462(17)	1.528(10)	0.874(06)	3.148(20)	1.097(10)
V2357 Oph	0.288(09)	1.191(12)	0.689(09)	1.392(18)	0.468(11)	1.782(30)
AQ Psc	1.682(32)	0.389(17)	1.753(11)	0.890(05)	3.760(23)	0.984(08)
VY Sex	0.449(09)	1.423(16)	0.864(06)	1.497(08)	0.832(08)	2.174(22)

5. Discussion and Conclusions

We present the results of the combined photometric and spectroscopic solution for ten systems from the sample of close binary stars defined in Paper I (Kreiner et al. 2003). The solutions utilize new multicolor photometric data obtained through an international collaboration and results from homogeneous spectroscopic observations obtained within the David Dunlap Observatory Radial Velocity Program. We were able to derive the absolute physical parameters of components in contact systems with an accuracy of approximately $1\% - 2\%$. For half of the sytems analyzed in this paper spotted solutions are invoked to explain the observed asymmetries of their light curves.

The configuration of all ten systems is contact. We found that the system V410 Aur has a high degree of contact with fillout factor of 72%. V410 Aur was known to be a triple system from the time the spectroscopic observations were analyzed (Rucinski et al. 2003), where it was found that the third component contribution to the total light is about 26%. The third light, added to the model in our photometric solution, was derived to be about 15%. The difference between the two values of the third light contribution is significant. Spectroscopic detection of a third light can be a very sensitive tool in finding the presence of a third component. With special processing, third components as faint as 0.1% of the total light can be detected that way (D'Angelo et al. 2006). However, when the third component is moderately bright, the ratio $L_3/(L_1 + L_2)$ will be usually corrupted by the very different spectral continuum level for the heavily rotationally broadened and blended spectrum of the contact binary and of the slowly rotating third star. In fact, what we observe for contact binaries is really not a continuum, but a pseudo-continuum, sometimes by some 10 - 20% lower than the totally unavailable real continuum. Thus, we should expect that spectroscopic determinations of $L_3/(L_1 + L_2)$ may normally be exaggerated and that photometric values should be preferred as totally free of this effect. The highly inclined orbit of V410 Aur implies total eclipses and a flat secondary minimum is obvious. The light curve has a small O'Connell effect, and a spotted solution is given. No other peculiarities were found in this system.

CK Boo has also a high degree of contact with fillout factor of 91%. For this system we arrived at a higher fillout factor than the one derived by Kalci and Deman (2005). The light curve of this target exhibits a large O'Connell effect and a spotted solution was assumed with a cool spot on the primary star. The low inclination orbit produces a smooth light curve, and the spotted solution fits our observational data very well.

The lowest inclination (below 50 degrees) was found for V2357 Oph and ET Leo. The shape of the light curve of V2357 Oph due to inclination as low as 48 degrees shows a low amplitude of light variation. It has a small O'Connell effect and our spotted solution was done assuming existence of a cool spot on the primary component. According to the assumption made by Rucinski et al. (2003) this system belongs to the A-subclass. Our photometric observations show that the minima referred as secondary are deeper contrary to the assumption made by Rucinski et al. (2003). By phasing the light curves according to the deeper minimum, the system turns out to be a W-subtype contact binary and thus the mass ratio used in the modelling was reversed. Our solution gave a contact configuration with a fillout factor of 23%. Even lower inclination (i=37 degrees) was found for ET Leo. An O'Connell effect is visible as well. In our spotted solution, a relatively cool spot on the secondary component gave a reasonable fit to our observed light curves. Our solution gave a contact configuration with a fillout factor of 55%. However, for such a low orbital inclination this solution is of lower significance than for other systems.

V921 Her is an eclipsing binary which contains large and very bright components. There is no evidence of any spot activity on the surface of the two components and the light curve is smooth with deep minima and partial eclipses. Both components have rather high temperatures and a radiative envelope was assumed in the model. Our solution gave a low contact configuration with a fillout factor of 23%.

V839 Oph has almost total eclipses, a fact resulting from its highly inclined orbit (82.9 degrees). Continuous observations on 9 nights on May, June and July 2004 showed that the system undergoes a continuous brightening, which is obvious from the increased value of differential magnitudes of the light curves. Light curve variations were also noticed in the past by other investigators (Wolf, 1996 and Akalin & Derman, 1997), who gave an explanation based on the magnetic activity of the system. The brightening time rate gives information on the rearrangements of spots. What is important in such a case, is the overall brightening, even at eclipses, so that the whole system must get brighter. A similar case was also noticed by Rucinski & Paczynski (2002) for a system in the Galactic Bulge region. Our spotted solution resulted in a hot spot on the secondary component, close to the neck region, with temperature factor of 1.03, and a hot region on the primary, likely as a result of light reflected from the hot spot. The bright region around the neck can be regarded as an effect of mass/energy exchange between the components through the connecting neck of the common envelope (Van Hamme & Wilson, 1985). Although our solution may not be unique, it explains very well the observations. In the present analysis, only the unspotted set of data (three nights on May 2004) was used to derive the absolute parameters. The whole set of data of this interesting target is the subject of a more detailed study of its spot activity (Gazeas et al. 2005b). Our solution gave a contact configuration with a fillout factor of 53%.

FP Boo has no asymmetries in its light curve. Its relatively low amplitude is a result of the low inclination orbit. It has a very small mass ratio, large radial velocities and shows partial eclipses. The fillout factor derived from our solution is 38%.

The solution of the system VY Sex gave a contact configuration with a fillout factor of 22%. Its light curve exhibits a small O'Connell effect and our spotted solution gave a cool spot on the equatorial zone of the primary component.

XZ Leo and AQ Psc have no asymmetries in their light curves. They do not show any O'Connell effect and the eclipses are partial. We adopted solutions with unspotted surfaces and the derived results are quite satisfactory. The fillout factors found are 19% and 44% for XZ Leo and AQ Psc, respectively.

The results for the physical parameters, derived in the present study, will be used together with those obtained in the previous papers of this series (Papers I-V), as well as with those expected from the next papers of the W UMa Program (Kreiner et al. 2003), for a global study of the W UMa-type systems in a broad context of contact binary evolution.

Acknowledgements. This project was supported by the Polish National Committee grant No.2

P03D 006 22 and by the Special Account for Research Grants No 70/3/7187 (HRAKLEITOS) and 70/3/7382 (PYTHAGORAS) of the National and Kapodistrian University of Athens, Greece (for KG and PN). The project is co-financed within Op. Education by the ESF (European Social Fund) and National Resources. The research of SMR is supported by a grant from the Natural Sciences and Engineering Council of Canada. Support from SALT International Network grant No. 76/E-60/SPB/MSN/P-03/DWM 35/2005-2007 is also acknowledged.

REFERENCES

Akalin, A., and Derman, E. 1997, Astron. Astrophys. Suppl. Ser. **125**, 407.
Aslan, Z., and Derman, E. 1986, Astron. Astrophys. Suppl. Ser., **66**, 281.
Baran, A., Zola, S., Rucinski, S. M., Kreiner, J. M., Siwak, M., Drozdz, M., 2004, Acta Astron., **54**, 195 (Paper II).
Binnendijk, L. 1960, Astron. J., **65**, 79.
Bond, H.E. 1975, PASP, **87**, 877.
Claret, A., Díaz-Cordovés, J., Gimenez, A., 1995, Astron. Astrophys. Suppl. Ser., **114**, 247.
D'Angelo, C., van Kerkwijk, M. H., Rucinski S. M., 2006, Astron. J., submitted (astro-ph/0602139)
Díaz-Cordovés, J., Claret, A., Gimenez, A., 1995, Astron. Astrophys. Suppl. Ser., **110**, 329.
Duerbeck, H.W., 1997, IBVS 4513.
Dvorak, S.W. 2005, IBVS, 5603.
ESA, 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200, Noordwijk.
Gazeas, K. D., Baran, A., Niarchos, P., Zola, S., Kreiner, J. M., et al., 2005a, Acta Astron. **55**, 123 (Paper IV).
Gazeas, K.D., Niarchos, P.G., Gradoula, G.-P., 2005b, Proceedings of the International Conference on Conatct Binaries, 27-30 June 2005, Syros, Greece (in press)
Gomez-Forrellad, J.M., Garcia-Melendo, E., Guarro-Flo, J., Nomen-Torres, J., and Vidal-Sainz, J. 1999, IBVS, 4702.
Harmanec, P., 1988, Bull. Astron. Inst. Czechosl., **39**, 329
Hoffmeister, C. 1934, Astron. Nachr., **253**, 195.
Kalci, R., Derman, E., 2005, Astron. Nachr., **326**, 342.
Kreiner, J. M., Rucinski, S. M., Zola, S., Niarchos, P., Ogloza, W., et al., 2003, Astron. Astrophys., **412**, 465 (Paper I).
Kreiner, J.M., 2004, Acta Astron., **54**, 207.
Krzesinski, J., Mikolajewski, M., Pajdosz, G., and Zola, S. 1991, Astrophys. Space Sci. **184**, 37.
Lasala-Garcia, A. 2001, IBVS, 5075.
Lu, W., and Rucinski, S.M. 1999, Astron. J., **118**, 515.
Niarchos, P.G. 1989, Astrophys. Space Sci., **153**, 143.
Niarchos, P.G., Hoffmann, M., and Duerbeck, H.W. 1994, Astron. Astrophys., **292**, 494.
Pazhouhesh, R., and Edalati, M.T. 2003, Astrophys. Space Sci., **288**, 259.
Pych, W., Rucinski, S. M., DeBond, H., Thomson, J. R., Capobianco, C. C., et al., 2004, Astron. J., **127**, 1712
Qian, S., and Liu, Q. 2000, Astrophys. Space Sci., **271**, 331.
Rigollet, R. 1947, IAU Circ., 1013.
Rucinski, S.M., and Lu, W. 1999, Astron. J., **118**, 2451.
Rucinski, S.M., Lu, W., Capobianco, C.C., Mochnacki, S.W., Blake, R.M., et al., 2002, Astron. J., **124**, 1738.
Rucinski, S.M., Capobianco, C.C., Lu, W., DeBond, H., Thomson, J.R., et al., 2003, Astron. J., **125**, 3258.
Rucinski, S.M., Paczynski, B., 2002, IBVS 5321
Rucinski, S.M., Pych, W., Ogloza, W., DeBond, H., Thomson, J.R., Mochnacki, S.W., et al., 2005,

Astron. J., **130**, 767.
Sarma, M.B.K., and Radhakrishnan, K.R. 1982, IBVS 2073.
Selam, S.O. 2004, Astron. Astrophys., **416**, 1097
Tanriverdi, T., Senavci, H.V., Selam, S.O., and Albayrak, B. 2004, ASP Conf. Ser., **318**, 189.
van Hamme, W., Wilson, R.E. 1985, Astron. Astrophys., **125**, 25.
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.
Wolf, M., Satunova, L., and Molik, P., 1996, IBVS 4304.
Yang, Y.-G., Qian, S.-B., Zhu, L.-Y., 2005, Astron. J., **130**, 2252
Zola, S., Rucinski, S. M., Baran, A., Ogloza, W., Pych, W., et al., 2004, Acta Astron., **54**, 299 (Paper III).
Zola, S., Kreiner, J. M., Zakrzewski, B., Kjurkchieva, D. P., Marchev, D. V., et al., 2005, Acta Astron., **55**, 389 (Paper V).