Physical parameters of components in close binary systems: II

by

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ABSTRACT

We present the absolute parameters of components for five contact binary systems: AB And, GZ And, AO Cam, DN Cam and DK Cyg. The results are based on solutions of new multicolor light curves as well as new radial velocity curves from the DDO radial velocity program. All five systems have a contact configuration with low (5-13%) to intermediate (30-33%) overfilling factors.

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

1. Introduction

This paper is the second in a series presenting absolute and geometrical parameters of components in close binary systems from the sample defined by Kreiner et al. (2003) (hereafter Paper I). The project, its motivations and the scientific background were described in greater details in Paper I.

The results for the first four systems have been published in Paper I, in this work we show results for the next five systems: AB And, GZ And, AO Cam, DN Cam and DK Cyg. For all of them we recently gathered new, multicolor light curves which are combined here with the DDO spectroscopic data, to derive in a uniform way as accurate absolute parameters as possible.

The paper discusses the available literature data in Section 2. The new photometric observations are presented in Section 3. The combined models are presented in Section 4, while the conclusions are given in Section 5.

2. The targets

2.1. AB Andromedae

Variability of AB And (BD $+36^{\circ}5017$, HIP=114508, V= 9.77^m) was first noticed by Guthnick and Prager (1927a). Struve et al. (1950) derived its spectral type of G5. Oosterhoff (1950) was the first to suggest a probable existence of a third component in this system. Bell et al. (1984) summarized the solutions of the light curve available at that time; the authors derived inclination of about $i = 85^{\circ}$ and the mass ratio, $q \approx 0.55$. The first simultaneous spectroscopic and photometric analysis was done by Hrivnak (1990). He used his new spectroscopic observations and photometric data published by previous observers. Demircan et al. (1994) published new photometric curves of this system. They reported the light curve changes between seasons with varying depths of the minima as well as different heights of light maxima. The newest spectroscopic determination based on the DDO data Pych et al. (2004) resulted in $q_{sp} = 0.560 \pm 0.007$.

2.2. GZ Andromedae

Brigtness changes of GZ And (HIP=10270, V= 10.89^m), a member of the trapezium system ADS 1693A, were visually observed by Espin (1908), however, it was uncertain which component, A or B, showed the light variations. The variability of the brightest (A) component was established by Strand after analysis of photographic plates obtained by Christy and Jasties (Walker (1973)). The first UBV light curves, typical of the W UMa type variability, were obtained by Walker (1973). These light curves showed night-to-night variations in the maxima and minima. In 1984 GZ And was also observed in the UBV filters by Liu et al. (1987). The period of GZ And is decreasing; moreover, sinusoidal variations (with the periodicity of 5.3 years) in the O-C diagram were discovered by Walker (1991), who concluded that a third body is present in the system. On the other hand, Lu and Rucinski (1999) analyzed the spectra of GZ And but they were unable to find any spectroscopic evidence for a third star in this system. The first photometric solution with the W-D model was published by Yang and Liu (2003). GZ And was investigated by Abt and Corbally (2000) in the work concerning the maximum age of the trapezium-type systems, and by Chambliss (1992) in the work dealing with the binaries in the multiple stellar systems.

2.3. AO Camelopardalis

The variability of AO Cam (BD $+52^{\circ}826$, V= 9.50^m) was discovered by Hoffmeister (1966). The photoelectric UBV observations were published by Milone et al. (1982). They estimated the spectral type to be G5 and published the first light curve solution. Evans et al. (1984,1985) obtained new BV light curves and computed a model of AO Cam. Reanalyzing the above data, Barone et al. (1993) classified AO Cam as a W-type contact system with the filling factor of 10% and a temperature difference between the components of about 300 K. Barone et al. (1993) noticed that the asymmetries in the light curve due to the presence of spots are of little relevance. The results derived by these authors gave contradictory results: the crucial mass ratio parameter was determined to

Table 1: Observational log

object	observatory	dates
AB And	Mt. Suhora	18/19,19/20 Sep 2003
GZ And	Fort Skała	16/17, 17/18 Nov 2001
AO Cam	Skibotn	20/21 Jan 2004
DN Cam	Skibotn	4/5, 5/6 Jan 2003
DK Cyg	Mt. Suhora	11/12 Aug; 5/6, 15/16, 20/21 Sep 2003

be close to about 0.75 (Milone et al. (1982), Barone et al. (1993)) while Evans et al. (1984,1985) found q_{phot}=1.3. Recently, Rucinski et al. (2000) performed spectroscopic observations of the star. They assigned AO Cam the spectral type of G0V, confirmed it to be a W-subtype, and found the spectroscopic mass ratio to be $q_{sp}=2.42 \pm 0.01$.

2.4. DN Camelopardalis

DN Cam (BD +72°233, HIP=21913, V= $8^m.36$) was discovered by the Hipparcos satellite mission (ESA (1997)). Rucinski et al. (2001) published the first spectroscopic analysis indicating the mass ratio $q=0.421\pm0.006$. They classified it to be a contact system of a W-subtype and estimated the spectral type at F2V. Vanko and Pribulla (2001) obtained the first ground-based photometry data. Based on the solution obtained with the W-D code, the W-subtype of the system was confirmed and system parameters determined.

2.5. DK Cygni

DK Cyg (BD +33°4304, HIP=106574, V= 10.38^m) was found to be variable by Guthnick and Prager (1927b). They obtained a photographic light curve and classified it as a W UMa-type system. Binnendijk (1964) published photometric light curves in two bands. Mochnacki and Doughty (1972) estimated the spectral type of DK Cyg to be between F0 and F2. Awadalla (1994) obtained UBV light curves and indicated the largest, at that time, brightness difference between the primary and the secondary maximum. The first spectroscopic observations done by Rucinski and Lu (1999) gave the mass ratio equal to 0.325, the spectral type of A8V and classified it as an A-subtype contact system. A detailed discussion of period changes was presented by Wolf et al. (2000). They concluded that the period is increasing. Such a long-term increase is usually explained by the mass transfer between the components. Wolf et al. (2000) obtained the value of the mass transfer rate of about $2.86{\cdot}10^{-8}$ M_{Sun}/year.

3. Photometric observations

AB And and DK Cyg were observed at the Mt.Suhora Observatory using the tree-channel photometer attached to the 60-cm Cassegrain telescope through the wide-band BVR filters.

The observations of DN Cam and AO Cam were collected at Skibotn Observatory, University of Tromsø. The Observatory is equipped with a CCD camera attached to the

Table 2: Linear elements used for phasing observations

star	reference epoch (HJD)	period (days)
AB And	2452500.0578	0.33189213
GZ And	2445985.8550	0.30500298
AO Cam	2452500.1060	0.32990441
DN Cam	2452499.9168	0.4983092
DK Cyg	2452500.2059	0.47069442

50-cm Cassegrain telescope; the V, R and I filters were used. The observations of GZ And were gathered at the Astronomical Observatory, Jagiellonian University (Fort Skała). The 50 cm telescope equipped with a Photometrics CCD camera and a set of wide-band filters were used. The new light curve was obtained through the B, V and I filters. The dates of observations for all objects analyzed in this paper are given in Tab. 1.

The O-C analyses for all systems of our sample were made and linear elements describing the most recent times of the primary minima were determined in order to phase our new data. The ephemerides are given in Tab. 2. The linear elements for all programme stars are being updated as soon as new times of minima become available (Kreiner (2004)) and can be found at the web address: http://www.as.wsp.krakow.pl.

4. The light curve modeling

The method we used for derivations of parameters of components is essentially the same as that described in Paper I. However, we decided to modify our approach in finding the combined photometric/spectroscopic solution. In Paper I, we assumed the spectroscopic data K_1 and K_2 and the resulting mass-ratio $q_{sp}=K_2/K_1$ as fixed and not modifiable through the whole solution process. We feel that this was not accurate enough as the values of the semi-amplitudes K_i had been obtained in the DDO spectroscopic studies by simple sine-curve fits to the radial velocity data. While this approach provided a reasonable approximate to q_{sp}, the proximity effects were not modeled correctly.

With this paper, we start a new approach based on iterative solutions, with alternating modeling of spectroscopic and photometric data. As can be argued, the Wilson-Devinney code (W-D) (Wilson (1993)) permits derivation of combined solutions by applying different relative weights to the spectroscopic and photometric data. However, we have found that – in general – the final results strongly depend on how the relative weights are selected. In contrast, by alternating the spectroscopic and photometric solutions, we retain freedom of keeping some desirable properties of solution, with a full control of parameters which we know are more accurately determinable than the other. This applies particularly to the mass ratio which we invariably keep at the spectroscopic value, with the only condition that this value takes into account the modeled proximity effects, i.e. that the deviations of the radial velocity curves from the sine curves are correctly accounted for. We assume that, as has been proven many times, the photometric data contain little or no information on the value of q, but that the photometry can be of use in a proper modeling of the radial velocity data through accounting for all proximity effects.

Thus, the iterative solution goes through the following steps:

Table 3: Results derived from the light curve modelling

parameter	AB And	GZ And	AO Cam	DN Cam	DK Cyg
overfilling factor	5%	8%	12%	33%	30%
phase shift	0.0018±0.0002	0.0006±0.0004	-0.0010±0.0004	0.0023±0.0004	0.0035±0.0003
i (degrees)	85.8±0.4	87.0±1.0	76.0±0.3	73.1±0.4	82.5±0.7
T_1(K)	*5500	*6200	*5900	*6700	*7500
T_2(K)	5140 ±10	5810±25	5590±33	6530 ±23	6700 ±64
Ω_1	4.856±0.004	5.011±0.012	5.565±0.012	5.319±0.027	2.401±0.007
Ω_2	**4.856	**5.011	**5.565	**5.319	**2.401
$\mathrm{q_{corr}(m_2/m_1)}$	*1.751	*1.880	*2.300	*2.260	*0.306
L_1^s (B)	5.594 ±0.032				9.437±0.140
L_1^s (V)	5.491 ±0.028	5.135±0.054	4.457 ±0.076	4.102±0.038	9.578±0.138
L_1^s (R)	5.364 ±0.025	5.022±0.046	4.375 ±0.066	4.049±0.033	9.659±0.128
L_1^s (I)		4.834±0.038	4.301 ±0.054	4.052±0.030	
L_2^s (B)	**6.448				**2.064
L_2^s (V)	**6.638	**6.858	**7.487	**7.524	**2.275
L_2^s (R)	**6.761	**6.992	**7.589	**7.514	**2.428
L_2^s (I)		**7.071	**7.728	**7.564	
$\mathrm{l_3^s}$ (B)					0.073±0.010
$\mathrm{l_3^s}$ (V)					0.043±0.011
$\mathrm{l_3^s}$ (R)					0.021±0.010
r_1 ^{pole}	0.3139±0.0003	0.3108 ±0.0011	0.2976±0.0010	0.3161±0.0025	0.4708±0.0015
r_2 ^{pole}	0.4067±0.0003	0.4150 ±0.0011	0.4342±0.0009	0.4487±0.0023	0.2804±0.0017
r_1 ^{side}	0.3285±0.0004	0.3255 ±0.0013	0.3117±0.0012	0.3341±0.0031	0.5107±0.0022
r_2 ^{side}	0.4316±0.0004	0.4415 ±0.0014	0.4645±0.0012	0.4843±0.0032	0.2948±0.0021
r_1 ^{back}	0.3630±0.0006	0.3619 ±0.0021	0.3506±0.0020	0.3901±0.0062	0.5420±0.0028
r_2 ^{back}	0.4617±0.0006	0.4722 ±0.0018	0.4950±0.0016	0.5227±0.0044	0.3445±0.0041

$*$ - 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.

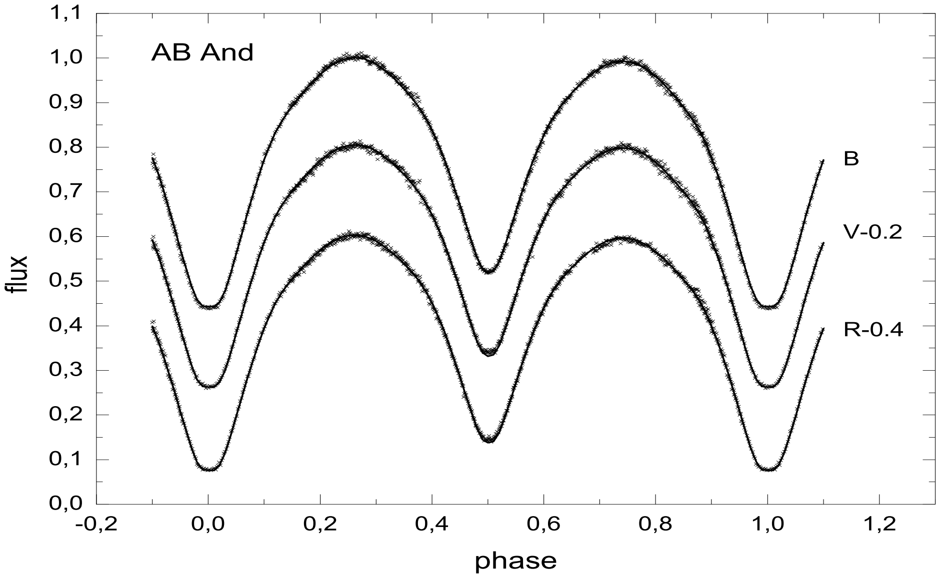

Figure 1: Comparison between theoretical and observed light curves of AB And (BVR filters). Individual observations are shown by dots and theoretical curves by lines.

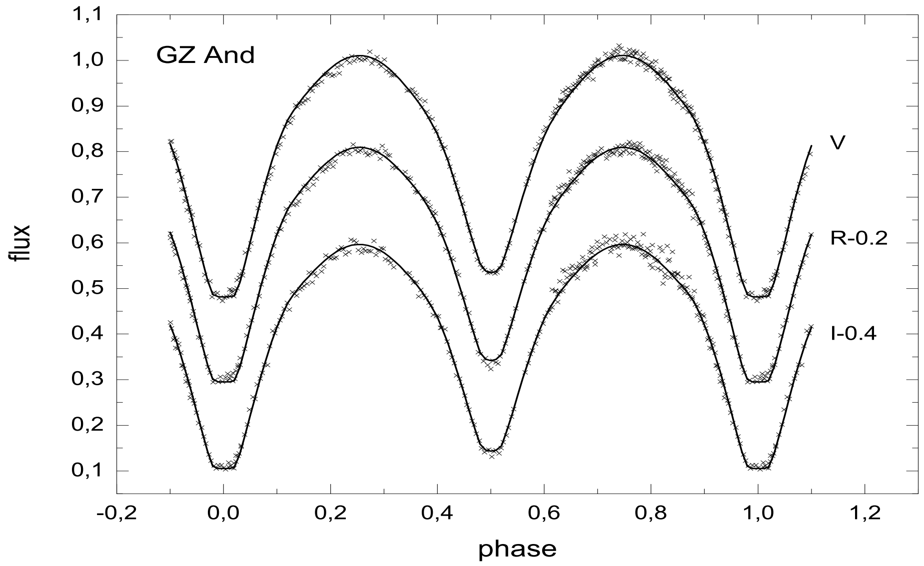

Figure 2: Comparison between theoretical and observed light curves of GZ And (VRI filters). Individual observations are shown by dots and theoretical curves by lines.

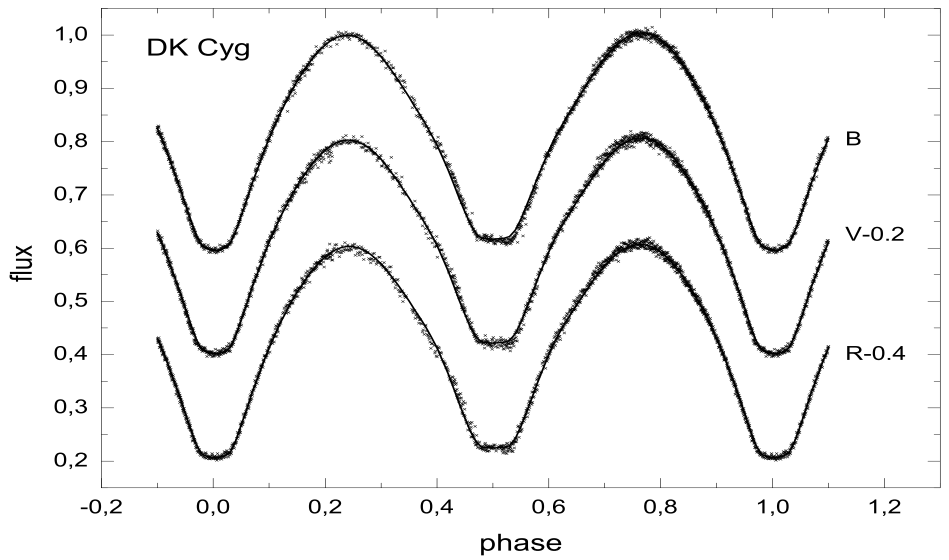

Figure 3: Comparison between theoretical and observed light curves of DK Cyg (BVR filters). Individual observations are shown by dots while lines represent the theoretical light curves.

1. The photometric solution. We take the spectroscopic mass ratio q_{sp} as determined from sine fits and derive the best fit to the photometric light curves using the Wilson-Devinney code. If the system is in contact configuration, the following parameters are treated as free ones: the inclination, the temperature of the secondary component, the potential, and the luminosities of the primary component (as defined in the W-D code) in the respective spectral bands. Also, if there is any hint about the existence of a third light, it is also included. In the latter case, the Monte Carlo method (Zola et al. (1997)) is applied ; otherwise, when the light curves are not complicated, the differential correction method is used.

2. The spectroscopic solution. The parameters relevant to the orbit, the mass-centre separation, A (which implicitly absorbs the orbital semi - amplitudes K_i), the centre of mass velocity, V_γ, the phase shift and the mass ratio (q_{corr}), are derived at this stage. If a significant difference between q_{sp} and q_{corr} occurs at this stage, we go back to Step 1.

3. With the new, corrected mass ratio fixed (q_{corr}), the search for the best fit to the photometric light curve is performed using the Monte Carlo search method.

We note that the temperature of one component is kept fixed at the value corresponding to the respective spectral type. We used the temperature versus the spectral type calibration of Harmanec (1998). Also, if there is an O'Connell effect visible in the light curve, both Step 1 and Step 2 require application of the MC method. In such a situation, a spot is introduced on the surface of one of the components (adding four more free pa-

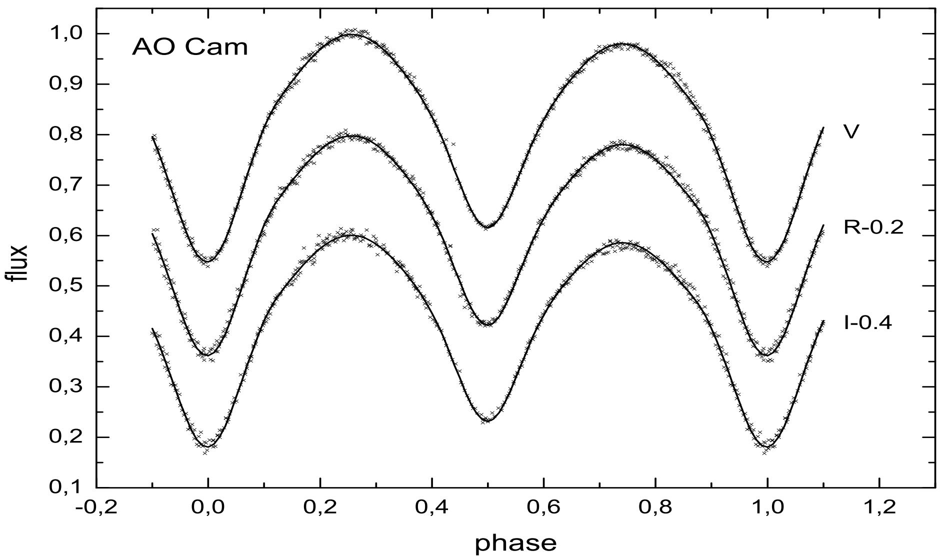

Figure 4: Comparison between theoretical and observed light curves of AO Cam (VRI filters). Individual observations are shown by dots and theoretical curves by lines.

rameters). The same method is used, if there is a third light in the system as the third light is heavily correlated with other parameters. The root square limb darkening law is adopted with the darkening coefficients taken from Diaz-Cordoves et al. (1995). The gravity darkening coefficients are assumed to be 1.0 and 0.32, while albedos are set to 1.0 and 0.50, respectively for radiative and convective envelopes, in accord with the effective temperatures of stars and the theoretically expected values. The Monte Carlo approach does not require setting of the starting values for the parameters. It is only necessary to assume ranges for each adjusted parameter, wide enough to ensure that the global solution lies within those limits.

We set the range between 50 and 90 degrees for the inclination of each system. The range from 1 to 12.6 is assumed for the luminosity of the primary component, while that for phase shift from -0.02 to 0.02. The ranges for the temperature of the secondary component are assumed according to the primary temperature: (4500 - 6000 K) for AB And, (5000 - 7000 K) for GZ And and AO Cam, (5500 - 7200 K) for DN Cam and (6000 - 8000 K) for DK Cyg. The ranges for potentials are set from (3.5 - 6.0) for AB And, GZ And and DN Cam, (4.0 - 7.0) for AO Cam and (1.5 - 4.0) for DK Cyg.

In case of an observed O'Connell effect (AB And, AO Cam and DK Cyg) a dark spot is included in the model and the whole stellar surface is searched for the spot location. The convergence is obtained for all five systems and the resulting parameters are shown in Table 3. The adjusted parameters are given with errors. The plots of observed and theoretical light curves are shown in Figs. 1 - 5, for AB And, GZ And, AO Cam, DN Cam and DK Cyg, respectively.

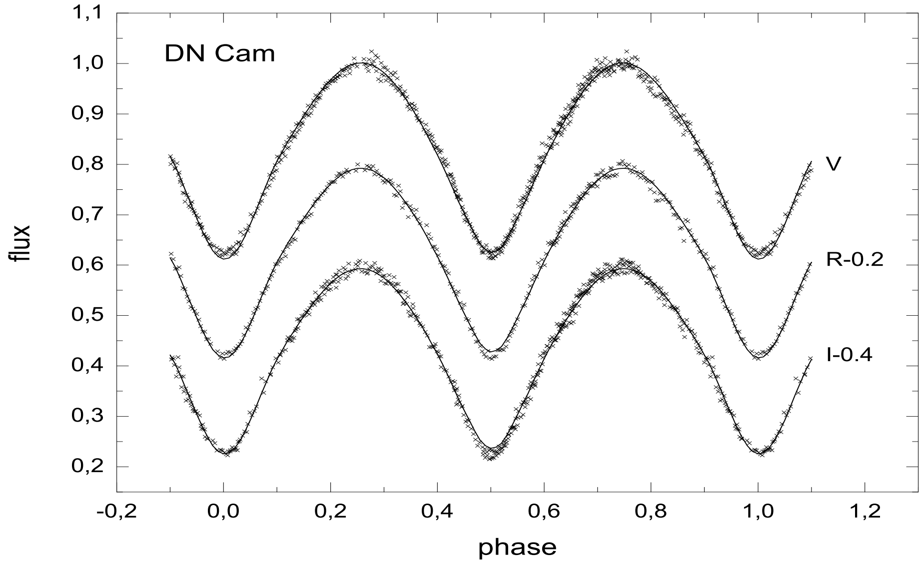

Figure 5: Comparison between theoretical and observed light curves of DN Cam (VRI filters). Individual observations are shown by dots and theoretical curves by lines.

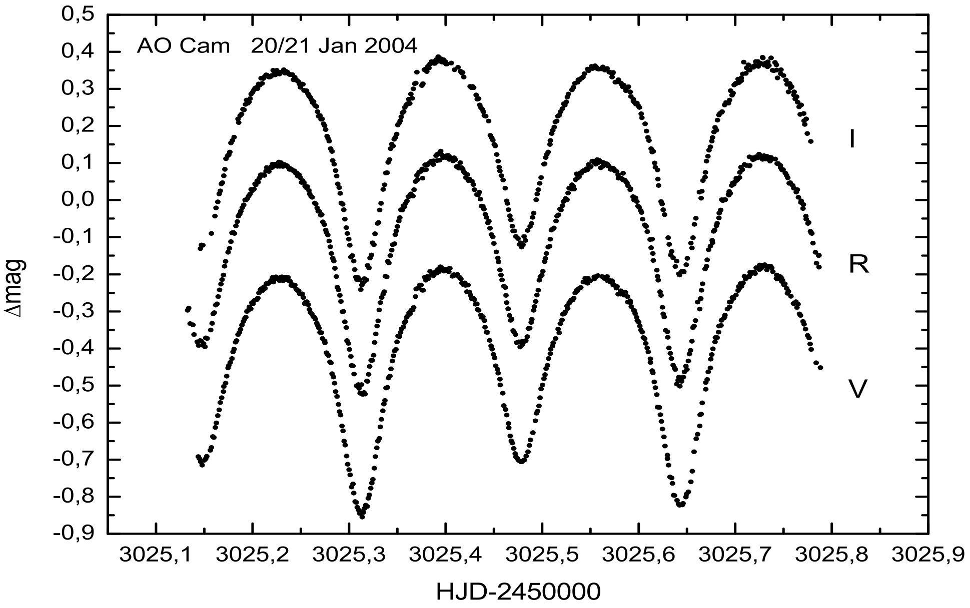

Figure 6: New, VRI observations of AO Cam taken during a long polar night.

Table 4: Absolute parameters (in solar units) of the systems studied in this paper and these in Paper I (bottom part)

system	$\mathcal{M}_1$	$\mathcal{M}_2$	R_1	R_2
AB And	0.595±0.005	1.042±0.006	0.780±0.002	1.025±0.003
GZ And	0.593±0.015	1.115±0.018	0.741±0.007	1.005±0.009
AO Cam	0.486±0.005	1.119±0.007	0.732±0.004	1.092±0.005
DN Cam	0.818±0.015	1.849±0.021	1.224±0.013	1.775±0.016
DK Cyg	1.741±0.056	0.533±0.033	1.708±0.018	0.986±0.012
SW Lyn	2.082±0.067	0.980±0.048	1.882±0.019	1.252±0.014
QW Gem	0.413±0.009	1.262±0.017	0.726±0.008	1.239±0.011
AP Leo	1.359±0.040	0.416±0.024	1.433±0.013	0.809±0.008
V2150 Cyg	2.233±0.098	1.798±0.080	1.946±0.013	1.756±0.012

5. Discussion

In this paper we present solutions of light curves by means of the W-D code supplemented by a Monte Carlo search method as well as the resulting absolute and geometrical parameters for the next five systems from the sample of contact and close binary systems defined in Paper I: AB And, GZ And, AO Cam, DN Cam and DK Cyg. All these systems have light curves with relatively high amplitude of ligh variations (GZ And and DK Cyg show even a flat-bottom minima). The light curves show practically no disturbances, except from a small O'Connell effect. Our results show that all the systems studied in this paper are contact binaries with low or intermediate overfilling factors (5-33%).

Satisfactory agreement between theoretical and observed light curves of GZ And and DN Cam was possible within a Roche model, without adding any spots or a third light parameter. Our new light curves of AB And, AO Cam and DK Cyg show clear, though small (not exceeding 0.02^m) differences between the hights of the maxima. In order to remove this asymmetry it was necessary to introduce a cool spot in the computations. For AO Cam and DK Cyg a better fit was achieved for a spot placed on the surface of the more luminous component, while in the case of AB And a spot appears to be located on the less luminous component. The theoretical light curves corresponding to the best fit for DK Cyg, even with a dark spot, did not match the observed depth of the minima. Therefore, a third light was added as a free parameter for this system and the resulting fit perfectly matches the observations. The third light contribution is moderate, the largest amount turned out to be in the B filter (7% contribution to the total light) and almost negligible in the longer wavelengths. Rucinski and Lu (1999) did not find any spectroscopic evidence for the existence of a third star in the system. The only evidence for a star bound to the system might be the O-C diagram (Kreiner (2001) showing variations which may be interpreted as sinusoidal; however, only one cycle is covered up to date, so that this evidence remains weak. The need for inclusion of a third light into the model may be also due to faint stars present in the 30" aperture used during the observations of DK Cyg, which is located in a rather crowded field.

Barone et al. (1993) found no or negligible spot activity in AO Cam. Our new observations (almost two consecutive cycles gathered during one night at Skibotn Observatory, displayed in Fig. 6) show clearly a difference in the heights of the maxima. Furthermore, the shape of the light curve (see Figs. 3 and 6, near the phases 0.7-0.9) changes even from one cycle to another, a clear evidence of intrinsic variability, usually explained by spot activity.

Finally, the absolute parameters of components were calculated making use of the spectroscopic results and parameters derived from the light curve modelling. They are presented in Table 4. We also present the absolute parameters for four systems studied in Paper I, recomputed to account for proximity effects. The errors in Tables 3 and 4 correspond to the 90% confidence level, and they have been computed in the way described in detail in Paper I.

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REFERENCES

Abt H.A., and Corbally C.J. 2000, ApJ, **541** 841.
Awadalla N.S. 1994, A&A, **289**, 137.
Barone F., di Fiore L., Milano L., and Russo G. 1993, ApJ, **407**, 237.
Bell S.A., Hilditch R.W., and King D.J. 1984, MNRAS, **208**, 123.
Binnendijk L. 1964, AJ **69**, 157.
Chambliss C.R. 1992, PASP, **104**, 663.
Demircan O., Derman E., Akalin A., Selam S., and Muyesseroglu Z. 1994, A&AS, **106**, 373.
Dias-Cordoves J., Claret A., and Gimenez A. 1995, A&AS, **110**, 329.
ESA 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200, Noordwijk.
Espin T.E. 1908, JRASC **2**, 248.
Evans E.E., Grossoehme D.H., and Moyer E.J. 1984, IBVS, 2497.
Evans E.E., Grossoehme D.H., and Moyer E.J. 1985, PASP, **97**, 648.
Guthnick P., and Prager R. 1927a, Kleinere Veröff. Berlin-Babelsberg, **4**, 16.
Guthnick P., and Prager R. 1927b, Astron. Nachr., **229**, 445.
Harmanec P. 1988, Bull. Astron. Inst. Czechosl, **39**, 329.
Hoffmeister C. 1966, AN, **289**, 1.
Hrivnak B.J. 1990, BAAS, **22**, 129.
Kreiner J.M., Rucinski S.M., Zola S., et al. 2003, A&A, **412**, 465.
Kreiner J.M., Kim C.H., and Nha I.S. 2001, An Atlas of O-C Diagrams of Eclipsing Binary Stars, Krakow Pedagogical University Press.
Kreiner J.M. 2004, AcA, submitted
Liu X,. Jing Y., and Huisong T. 1987, IBVS, 3080.
Lu W., and Rucinski S. M. 1999, AJ, **118**, 515.
Milone E.F., Piggott D.H., and Morris S.L. 1982, JRASC, **76**, 90.
Mochnacki S.W., and Doughty N.A. 1972, MNRAS, **156**, 243.
Oosterhoff P. Th. 1950, BAN, **11**, 217.

Pych W., Rucinski S.M., DeBond H., et al. 2004, AJ, **127**, 1712.
Rucinski S.M., and Lu W. 1999, AJ, **118**, 2451.
Rucinski S.M., Lu W., and Mochnacki S.W. 2000, AJ, **120**, 1133.
Rucinski S.M., Lu W., Mochnacki S.W., et al. 2001, AJ, **122**, 1974.
Struve O., Horak H.G., Canavaggia R., et al. 1950, AJ, **111**, 658.
Vanko M., and Pribulla T. 2001, IBVS, 5200.
Walker R.L. 1973, IBVS, 855.
Walker R.L. 1991, BAAS, **23**, 881.
Wilson R.E., 1993, Documentation of Eclipsing Binary Computer Model.
Wolf M., Molik P., Hornoch K., and Sarounova L. 2000, A&AS, **147**, 243.
Yang Y., and Liu Q. 2003, A&A, **401**, 631.
Zola S., Kolonko M., Szczech M. 1997, A&A, **324**, 1010.