

LONG-TERM PHOTOMETRIC AND SPECTROSCOPIC OBSERVATIONS OF THE NEAR-CONTACT BINARY KR CYGNI¹

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RESUMEN

Presentamos curvas de luz en varios colores y velocidades radiales obtenidas a lo largo de cinco años para la binaria en cuasi-contacto KR Cyg. Obtenemos para las masas de las componentes $2.88 \pm 0.20 M_{\odot}$ y $1.26 \pm 0.07 M_{\odot}$, y para los radios $2.59 \pm 0.06 R_{\odot}$ y $1.80 \pm 0.04 R_{\odot}$. También investigamos las determinaciones empíricas del albedo y la temperatura efectiva de la estrella más fría y menos masiva de KR Cyg, y de otras dos binarias en cuasi-contacto similares, AK CMi y DO Cas. Los residuos entre los flujos observados y los calculados se atribuyen al efecto de la iluminación mutua, la cual calienta las capas superficiales de la estrella iluminada y hace que varíe no sólo el albedo bolométrico, sino también el coeficiente del ennegrecimiento al limbo y el exponente del abrillantamiento por gravedad. Los albedos efectivos son generalmente menores que los esperados para la envoltura de una estrella convectiva. Nuestros resultados son preliminares y especulativos.

ABSTRACT

We present the multi-color, five-year light curves and the radial velocities of the near-contact binary system KR Cyg. We derived the masses of the components as $2.88 \pm 0.20 M_{\odot}$ and $1.26 \pm 0.07 M_{\odot}$ and the radii as $2.59 \pm 0.06 R_{\odot}$ and $1.80 \pm 0.04 R_{\odot}$. We also searched for the empirical determination of albedo and effective temperature of the cooler, less massive star of KR Cyg, and of two similar near contact binaries AK CMi, and DO Cas. The residuals between the observed and computed fluxes are attributed to the effect of mutual illumination which heats the surface layers of the illuminated star and does vary not only its bolometric albedo but also its limb-darkening coefficient and gravity-brightening exponent. The effective albedos are generally smaller than that expected from an envelope of convective star. These results are preliminary and speculative.

Key Words: binaries: close — binaries: eclipsing — binaries: general — binaries: spectroscopic — stars: individual (KR Cyg, AK CMi, DO Cas)

1. INTRODUCTION

The light variability of KR Cyg (HD 333645, $V = 9^m.19$) was discovered by Schneller (1931a,b, 1932). The light curves obtained by photographic observations were published by Nekrasova (1945) and Wachmann (1948) and the visual observations by Lassovzsky (1936), Gaposchkin (1953) and Tsesevich (1954). Both visual and photographic observations showed that the light variations were originated

from the eclipses. The light curves were very similar to those of Algol-type binaries. The first photo-electric observations were made by Vetesnik (1965). He obtained blue and yellow light curves of the system. The passbands used in the observations were very similar to those Johnson's B and V filters. A preliminary solution of the light curves led him to the conclusion that the system consists of a B9 and an F5 main-sequence stars. He classified the system as a β Lyrae type by visual inspection of the light curves. He also called attention to some peculiarities in the course of the light curve. Later on, Vetes-

¹Based on observations collected at TÜBİTAK National Observatory (Antalya, Turkey).

nik's two-color light curves were analysed by Wilson & Rafert (1980) using a contemporary method, i.e. the Wilson-Devinney code (Wilson & Devinney 1971), henceforth WD. The main difference between the two solutions is the primary star radius, which is fifteen per cent larger in the latter than that found in the former analysis. In addition, Wilson & Rafert (1980) used an effective temperature for the primary star corresponding to a B7 star. The observations at the primary minimum of Vetesnik's light curves were re-analysed by Al-Naimiy et al. (1985) using the Fourier technique in the frequency domain. They find that, contrary to the older estimates, the more massive star has smaller radius than the less massive companion.

Sipahi & Gulmen (2004) published three-color photometric observations and the resultant light curves of KR Cyg. The light curves were analysed individually and simultaneously by the WD code. They determined the photometric mass-ratio to be 0.43 and suggested that the cooler, less massive component was nearly filling its corresponding Roche lobe. Recently, one of us (Sipahi 2012) collected all available times of light minimum and studied the orbital period of the system. She arrived at the result that the differences between the times of observed and calculated (O-C) minima show a periodic oscillation with an amplitude of 0.001 days and a period of about 76 years. This periodic change was attributed to a hypothetical third component.

Shaw (1990) defined a group of close binary stars named near-contact binaries (NCB) in which both components fill or nearly fill their critical Roche lobes. KR Cyg is included in the list of NCBs. According to his definition the stars of the near-contact binaries are near enough to each other to have strong proximity effects like W UMa type systems but are not in contact. As it is known, mass and energy exchange are occurring among the components in contact systems. This energy exchange results in both components reaching nearly the same effective temperature. The main difference between the near-contact and contact binaries is the non-existence of energy exchange through the neck of material connecting the components in the near-contact systems. The non-existence of energy exchange in the case of NCB allows a large temperature difference between the components. Some NCBs show photometric asymmetries such that the system is brighter at the first quarter than that at the second one. This asymmetry is attributed to the primary star having one hemisphere, facing at phase about 0.25, hotter than that at phase 0.75, or due to some material ob-

TABLE 1
THE COORDINATES, APPARENT VISUAL
MAGNITUDES AND THE SPECTRAL TYPES
OF THE STARS OBSERVED

Star	Alpha	Delta	V (mag)	Sp
KR Cyg	20 09 06	30 33 01	9.23	A0V
HD 191398	20 08 39	30 20 15	9.01	A0V
HD 333664	20 09 18	30 13 39	9.58	A0

scuring the surface of the primary, visible at phase 0.75. Therefore the NCBs are assumed to be lying in key evolutionary states of close binary systems. Shaw (1994) updated the list of NCBs in which over 130 systems are given. He proposes that the NCBs are precursors of the A-type W UMa contact binaries.

The main aim of this study is to analyse the 1999 and 2000 *BVR*, and 2003, 2004, and 2005 *UBVR* light curves and the first radial velocities obtained by us. We derive the absolute physical parameters of the components and discuss light curve peculiarities by taking into account the mutual irradiation and therefore the changes of the value of the albedo of the irradiated star for four passbands.

2. OBSERVATIONS

2.1. Photometric observations

The observations were made with the High-Speed Three-Channel Photometer attached to the 48 cm Cassegrain telescope at Ege University Observatory. HD 191398 and HD 333664, respectively, are taken as the comparison and check stars. These stars are of nearly the same apparent magnitude and spectral type as the variable star. Moreover, they are located very close to the variable on the plane of the sky which makes the effect of the atmospheric extinction on the differential magnitudes almost negligible. In Table 1 the coordinates, apparent visual magnitudes and spectral types of the variable and the comparison stars are given. The observations were made using the *BVR* passbands in 1999 and 2000, and the *UBVR* passbands in 2003, 2004 and 2005. Though the comparison star is so close to the variable, the differential magnitudes, in the sense variable minus comparison, are corrected for atmospheric extinction. The nightly extinction coefficients were derived from the observations of the comparison stars in each passband.

2.2. Spectroscopic observations

Optical spectroscopic observations of KR Cyg were obtained with the Turkish Faint Object Spec-

trograph Camera (TFOSC) attached to the 1.5 m telescope on 4 nights (July–August, 2011) under good seeing conditions². The wavelength coverage of each spectrum was 4000–9000 Å in 12 orders, with a resolving power of $\lambda/\Delta\lambda$ 7,000 at 6563 Å and an average signal-to-noise ratio (S/N) of ~ 120 . We also obtained a high S/N spectrum of α Lyr (A0 V) and HD 27962 to use as templates in derivation of the radial velocities (Nidever et al. 2002).

The electronic bias was removed from each image and we used the ‘creject’ option for cosmic ray removal. Thus, the resulting spectra were largely cleaned from cosmic rays. The echelle spectra were extracted and wavelength calibrated by using a Fe–Ar lamp source with the help of the IRAF ECHELLE (Tonry & Davis 1979) package.

The stability of the instrument was checked by cross correlating the spectra of the standard star against each other using the FXCOR task in IRAF. The standard deviation of the differences between the velocities measured using FXCOR and the velocities in Nidever et al. (2002) was about 1.1 km s^{-1} .

3. ANALYSES

3.1. Radial velocities

To derive the radial velocities for the components of binary system, the four TFOSC spectra of the eclipsing binary, obtained near the quadratures, were cross-correlated against the spectrum of α Lyr on an order-by-order basis using the FXCOR package in IRAF. The majority of the spectra showed two distinct cross-correlation peaks in the quadrature, one for each component of the binary. Thus, both peaks were fitted independently in the quadrature with a Gaussian profile to measure the velocity and errors of the individual components. If the two peaks appeared blended, a double Gaussian was applied to the combined profile using *de-blend* function in the task. For each of the four observations we then determined a weighted-average radial velocity for each star from all orders without significant contamination by telluric absorption features. Here we used as weights the inverse of the variance of the radial velocity measurements in each order, as reported by FXCOR.

We adopted a two-Gaussian fit algorithm to resolve cross-correlation peaks near the first and second quadratures when spectral lines were visible separately. Figure 1 shows examples of cross-correlations obtained by using the largest FWHM at nearly first and second quadratures. The two

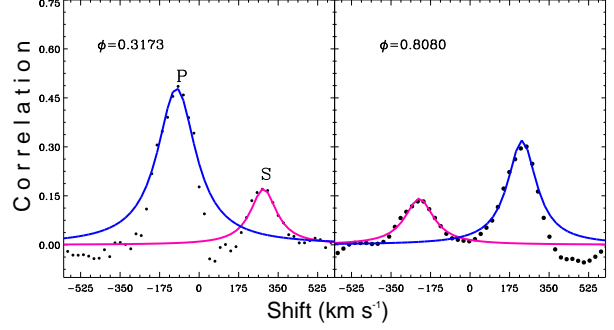


Fig. 1. Sample of CCFs between KR Cyg and the RV template spectrum around first and second quadrature. The color figure can be viewed online.

TABLE 2

HELIOCENTRIC RADIAL VELOCITIES OF KR CYGNI¹

HJD 2400000+	Phase	Star 1		Star 2	
		V_p	σ	V_s	σ
55751.36069	0.8080	73.1	11.8	−290.8	11.3
55796.38592	0.0826	−92.3	7.8	77.7	11.2
55835.36321	0.2013	−150.4	6.8	188.3	9.5
55835.46128	0.3173	−144.6	9.9	184.1	9.9

¹The columns give the heliocentric Julian date, the orbital phase, the radial velocities of the two components with the corresponding standard deviations.

peaks correspond to each component of KR Cyg. The stronger peaks in each CCF correspond to the more luminous component which has a larger weight in the observed spectrum.

The heliocentric RVs for the primary (V_p) and the secondary (V_s) components are listed in Table 2, along with the dates of observation and the corresponding orbital phases computed with the new ephemeris given by Sipahi (2012). The velocities in this table have been corrected to the heliocentric reference system by adopting a radial velocity of 9.5 km s^{-1} for the template star α Lyr. The RVs listed in Table 2 are the weighted averages of the values obtained from the cross-correlation of orders #4#, #5#, #6# and #7# of the target spectra with the corresponding order of the standard star spectrum. The weight $W_i = 1/\sigma_i^2$ has been given to each measurement. The standard errors of the weighted means have been calculated on the basis of the errors (σ_i) in the RV values for each order according to the usual formula (e.g., Topping 1972). The σ_i values are computed by FXCOR according to the fitted peak height, as described by Tonry & Davis

²Further details on the telescope and the spectrograph can be found at <http://www.tug.tubitak.gov.tr>.

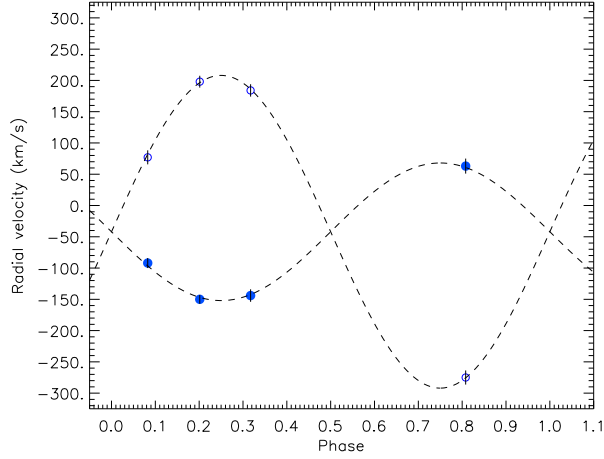


Fig. 2. Radial velocities of the components.

(1979).

The measured radial velocities of both stars are plotted in Figure 2 against the orbital phase. First we analysed the radial velocities for the initial orbital parameters. We used the orbital period held fixed and computed the eccentricity of the orbit, systemic velocity and semi-amplitudes of the RVs. The results of the analysis are as follows: $e = 0.001 \pm 0.001$, i.e. formally consistent with a circular orbit as expected, $\gamma = -43 \pm 3 \text{ km s}^{-1}$, $K_1 = 110 \pm 4 \text{ km s}^{-1}$, and $K_2 = 251 \pm 7 \text{ km s}^{-1}$. Using these values we estimate the projected orbital semi-major axis and mass ratio as: $a \sin i = 6.028 \pm 0.127 R_\odot$ and $q = M_2/M_1 = 0.438 \pm 0.017$.

3.2. Effective temperature of the primary star

The spectral type of a star can be derived from the multi-color photometry and spectroscopy, or both. Unfortunately, *UBV* measurements of the system are not available. Therefore we observed the system with *UBV* standard stars on some nights and obtained the standard apparent visual magnitude and colors at mid-secondary eclipse as: $V = 9.231 \pm 5$, $U - B = 0.101 \pm 15$, and $B - V = 0.156 \pm 7 \text{ mag}$. The Q -parameter of the Johnson's wide-band photometry, defined as $Q = (U - B) - 0.72(B - V)$ (Johnson & Morgan 1953), is independent of interstellar reddening for early type stars. Using the observed $(U - B)$ and $(B - V)$ colors at secondary eclipse we calculated the Q -parameter as -0.011 for the hotter star. Then, we estimated the intrinsic color of $(B - V)_0 = -0.021 \text{ mag}$ from the tables given by Hovhannessian (2004). Since the light contribution of the secondary component does not exceed a few hundredths of magnitudes in the B and V passbands its contribution to the $B - V$ color at maximum light

may be ignored. This intrinsic color corresponds to an $A0 \pm 1$ main-sequence star. The average effective temperature deduced from the calibrations of Bohm-Vitense (1981), de Jager & Nieuwenhuijzen (1987), Flower (1996) and Drilling & Landolt (2000) is about 9810 K. The spectral-type uncertainty leads to an uncertainty of about 150 K in the effective temperature of the primary star. The difference between the observed and intrinsic $B - V$ color, i.e. the interstellar reddening, is about 0.177 mag.

KR Cyg was observed by Hilditch & Hill (1975) in the intermediate-band photometric system. One of their observations falls into the primary eclipse. Excluding this observation we calculated the colors of $u - b = 1.555 \pm 0.011$, $b - y = 0.111 \pm 0.010$ and $c = 0.970 \pm 0.022 \text{ mag}$. Taking $E(b - y) = 0.73E(B - V)$ we computed the intrinsic color of $(b - y)_0 = -0.018 \pm 0.010 \text{ mag}$ which corresponds to an A0 star. The infra-red magnitudes $J = 9.278 \pm 0.022$, $H = 9.169 \pm 0.022$ and $K = 9.098 \pm 0.018$ are given in the 2MASS catalog (Cutri et al. 2003). The infrared colors are calculated as $J - H = 0.109 \pm 0.031$ and $H - K = 0.071 \pm 0.028$ which correspond to a reddened B9 ± 2 star. The spectral type of the primary star obtained from both intermediate and infrared photometric systems is consistent with what we derived from the *UBV* photometry.

3.3. Analyses of the light curves

As we stated in § 2.1 we have multi-color light curves of KR Cyg obtained with the same instrumentation. We used the recent version of the eclipsing binary light curve modelling algorithm of Wilson & Devinney (1971) (with updates), as implemented in the PHOEBE code of Prša & Zwitter (2005). The code needs some input parameters, such as the effective temperature of the hotter star and the mass-ratio of the system. These two parameters are the key parameters for the solution which should be estimated before beginning the light curve modelling. The effective temperature of the hotter star, eclipsed in the primary minimum, has been estimated using the photometric indices as $9810 \pm 150 \text{ K}$. The mass ratio, $q = M_2/M_1$, is very important parameter in the light curve analysis, because the WD code is based on Roche geometry which is sensitive to this quantity. A mass ratio of 0.438 ± 0.017 determined from the radial velocities was kept fixed. A preliminary estimate for the effective temperature of the cooler component was made using the depths of the eclipses.

The logarithmic limb-darkening coefficients, x_1 and x_2 , and bolometric limb-darkening coefficients, x_{bol} and y_{bol} , were determined from tables by van

TABLE 3

FITTED PARAMETERS FOR THE FIVE-YEAR MULTI-COLOR LIGHT CURVES OF KR CYG

Parameter	<i>U</i>	<i>B</i>	<i>V</i>	<i>R</i>
λ (Å)	3500	4300	5500	6700
N_{obs}	1752	2825	2804	2825
x_1	0.620	0.714	0.611	0.773
x_2	0.871	0.844	0.773	0.682
g_1	1.0	1.0	1.0	1.0
g_2	0.32	0.32	0.32	0.32
A_1	1.0	1.0	1.0	1.0
A_2	0.5	0.5	0.5	0.5
T_1 (K)	9810	9810	9810	9810
$q=M_2/M_1$	0.438	0.438	0.438	0.438
$L_1/(L_{1+2})$	0.9791 ± 0.0005	0.9727 ± 0.0004	0.9467 ± 0.0005	0.9179 ± 0.0006
$i(^{\circ})$	87.00 ± 0.02			
T_2 (K)	5580 ± 10			
Ω_1	2.8645 ± 0.0012			
Ω_2	2.8111 ± 0.0008			
r_1	0.4297 ± 0.0002			
r_2	0.2989 ± 0.0002			
χ^2	1.821			

Hamme (1993) for the primary and secondary components, respectively, taking into account the effective temperatures and the wavelengths of the observations. Standard values of bolometric albedos (Ruciński 1973), and the gravity-darkening coefficients (Lucy 1967) for radiative and convective envelopes were used. The rotational velocities of the components are assumed to be synchronous with the orbital one. The adjustable parameters in the light curves fitting were the orbital inclination i , the surface potentials Ω_1 and Ω_2 , the effective temperature of the secondary T_2 , and the luminosity of the primary star L_1 .

Using a trial-and-error method, we obtained a preliminary set of parameters which represent the observed $UBVR$ light curves. The code was set in Mode-2, a detached configuration, with coupling between luminosity and effective temperature and no constraints on the potentials. We used a simple reflection treatment as MREF=1 and NREF=1 at the beginning of the iterations.

The iterations were carried out automatically until convergence, and a solution was defined as the set of parameters for which the differential corrections were smaller than the probable errors. After a few iterations, convergence was obtained. The final results

of the five-year multi-color light curves' simultaneous analysis of KR Cyg are listed in Table 3. r_1 and r_2 in this table are the mean fractional radii of the hotter and cooler components, respectively. The uncertainties assigned to the adjusted parameters are the internal errors provided directly by the Wilson-Devinney code. We also ran models for KR Cyg in mode Mode-5, the secondary component filling its Roche lobe, in Mode-4, the primary filling its Roche lobe and in Mode-3, both components filling their Roche lobes. Convergence was obtained in Modes-4 and 3 but with larger sum of squared residuals. The absolute parameters of the stars are obtained and presented in Table 4.

The computed light curves (continuous line) are compared with the observations in four passbands in Figure 3. While there is a satisfactory fit between observed and computed lights for the U passband the binary model does not represent the observed light curves successfully in the B , V , and R passbands. The residuals, in the sense observed minus calculated, are plotted in Figure 4 for a better visibility. The differences between the model and the observed light curves are clearly seen at both maxima in three passbands and particularly at the secondary eclipse in the B and R passbands. As pointed out by Shaw

TABLE 4
ABSOLUTE PARAMETERS OF KR CYG

Parameter	Primary	Secondary
a (R_{\odot})		6.04 ± 0.13
V_{γ} (km s^{-1})		-43 ± 5
q		0.438 ± 0.017
Mass (M_{\odot})	2.876 ± 0.198	1.261 ± 0.074
Radius (R_{\odot})	2.594 ± 0.055	1.804 ± 0.038
$\log g$ (cgs)	4.069 ± 0.012	4.026 ± 0.012
T_{eff} (K)	9810 ± 150	5580 ± 150
$(v \sin i)_{\text{obs}}$ (km s^{-1})	141 ± 7	108 ± 9
$(v \sin i)_{\text{calc.}}$ (km s^{-1})	155 ± 3	108 ± 2
$\log (L/L_{\odot})$	1.750 ± 0.032	0.454 ± 0.050
d (pc)		411 ± 12
U, B, V (mag)	9.488 ± 0.014	$9.387 \pm 0.005, 9.231 \pm 0.005$
J, H, K_s (mag)	7.159 ± 0.018	$7.221 \pm 0.027, 7.249 \pm 0.027$

(1990) all of the NCBs do not show the O’Connell effect, one maximum is higher than the other. If a NCB shows an asymmetry in the light curve, the first maximum is brighter than the second maximum. This difference is generally attributed to the secondary component, in which the visible surface at phase 0.25 is brighter than the other half. While the asymmetries reach to 5% of the total light, the secondary components in these systems contribute less than 5% of the system’s total light. Therefore, it is suggested that the visible hemispheres of the hotter components at the orbital phase of 0.75 are either cooler or obscured by a cool material.

In the case of KR Cyg the light curve is almost symmetric in all passbands. At phases of about 0.15 and 0.85 the observed fluxes are larger than those computed in the BVR passbands. In contrast, the observed fluxes are smaller than those computed at the secondary eclipse in the B, V and R passbands. The components in the NCBs are nearly touching each other but their photospheres are not in physical contact. A gaseous stream and an energy exchange between the stars may be excluded.

3.4. Search for the empirical derivation of the albedo

The values of the local emergent bolometric flux and energy balance in a distorted star are significantly dependent upon the assumed values of the gravity darkening exponent and the bolometric albedo (Rafert & Twigg 1980). The reflection effect is used to describe the mutual irradiation of the fac-

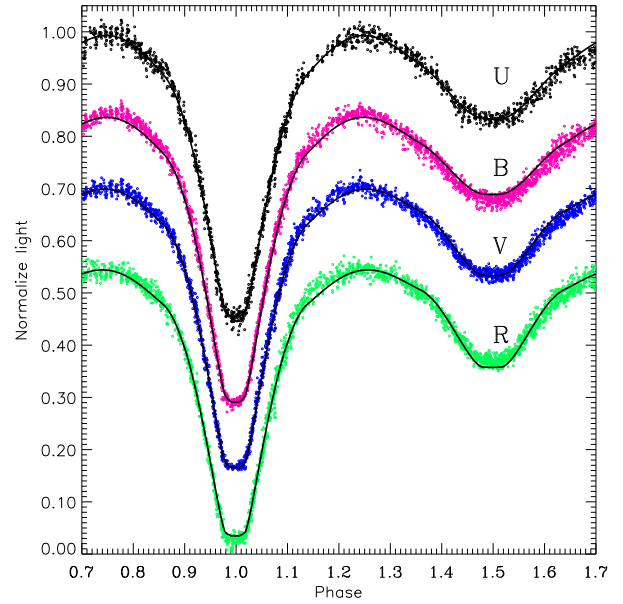


Fig. 3. The observed five-year $UBVR$ flux scale light curves and computed light curves for KR Cyg. The color figure can be viewed online.

ing hemispheres of the components in a close binary system. For stars of intermediate temperatures of about 10000 K the incoming radiation is almost completely absorbed by atoms and ions in the irradiated atmosphere, which alters the temperature structure and causes an increased emergent flux. For stars of convective envelopes half of the incoming radiation

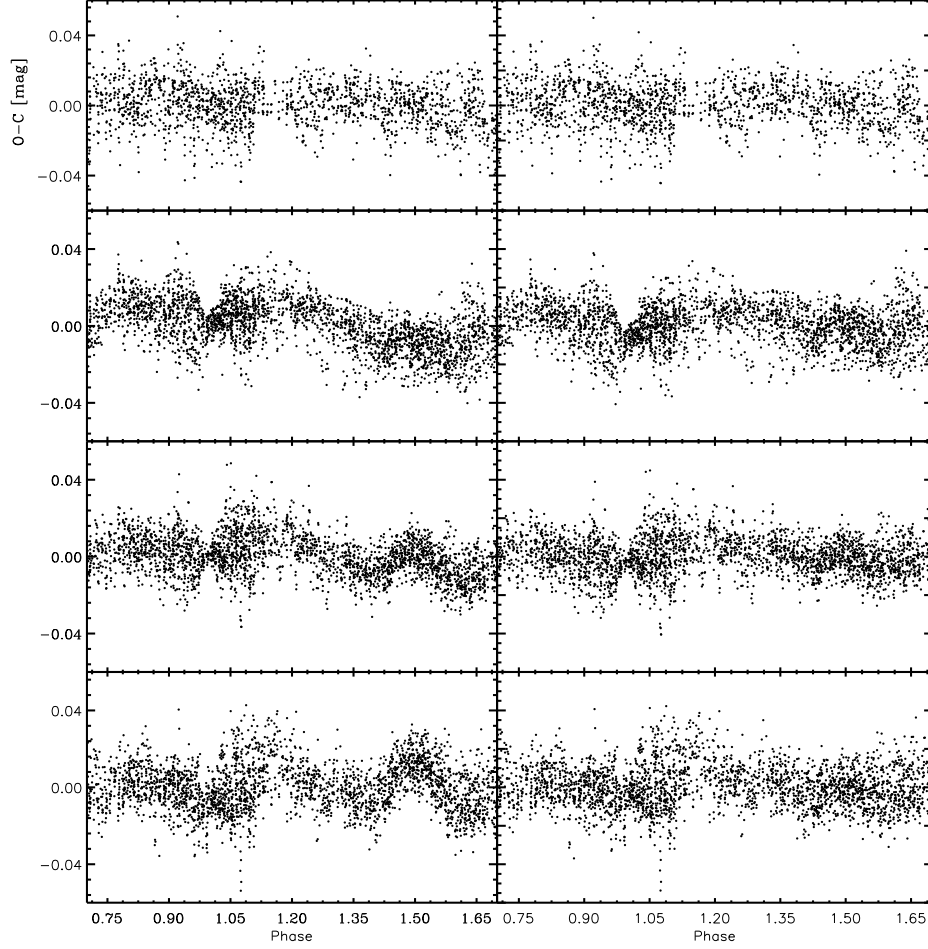


Fig. 4. Residuals, in light units, for the two solutions of KR Cyg's $UBVR$ light curves from top to bottom: $A_2 = 0.5$ (fixed, left panels) and A_2 is an adjustable parameter (right panels).

is converted to bulk motions of the atmosphere gases (Ruciński 1969). The theoretical value of bolometric albedo is assumed to be about 0.5 for the stars having convective atmospheres. Furthermore, Vaz & Nordlund (1985) calculated bolometric reflection albedo for a particular reflecting main-sequence star with a temperature of 4500 K and presented the results as a function of angle of incidence and relative incident flux. As pointed out by Cranmer (1993) the effect of mutual irradiation will be strongest on the line-of-centers points of the stars in a close binary system. The stars themselves iterate this effect between one another, e.g., hotter star heats up the cooler that in turn affects the illumination back on the hotter star, and so on. The facing hemispheres of both components are heated up by multiple scattering processes.

Therefore we attempted to estimate the values of g_2 and A_2 from analyses of well-defined multi-color

light curves of the system. The WD code allows us to make parallel solutions by solving any number of subsets of adjustable parameters in the same computer run. By adopting the theoretical values of the less sensitive parameters of limb-darkening coefficients, gravity-darkening exponents and the limb-darkening coefficients we derived the basic set of parameters i , Ω_1 , Ω_2 , L_1 , L_2 and T_2 from the analyses of multi-color light curves. The components of the system KR Cyg are nearly contact, they rotate faster than 100 km s^{-1} , and have a large temperature difference of about 4200 K. Therefore, the gravity-darkening exponent and the bolometric albedo for the components are expected to be different from the non-rotating and gravitationally undistorted stars. In the second step, we take the gravity-darkening exponent, effective temperature, luminosity and effective albedo for the cooler component as adjustable parameters in the analysis of the U , B , V , and R

TABLE 5
CALCULATED EFFECTIVE ALBEDOS AND EFFECTIVE TEMPERATURES
FOR THE COOLER COMPONENTS OF KR CYG, AK CMI AND DO CAS

Star	Parameter	U	B	V	R
KR Cyg	A_2	0.435 ± 0.023	0.225 ± 0.016	0.241 ± 0.012	0.304 ± 0.012
KR Cyg	T_2	5600 ± 27	5985 ± 14	5653 ± 12	5336 ± 12
KR Cyg	L_2	0.022	0.041	0.057	0.070
AK CMi	A_2	0.457 ± 0.041	0.132 ± 0.038	0.219 ± 0.028	—
AK CMi	T_2	5658 ± 60	5880 ± 45	5677 ± 32	—
DO Cas	A_2	0.275 ± 0.158	0.377 ± 0.127	0.333 ± 0.089	—
DO Cas	T_2	5441 ± 147	5615 ± 105	5427 ± 74	—

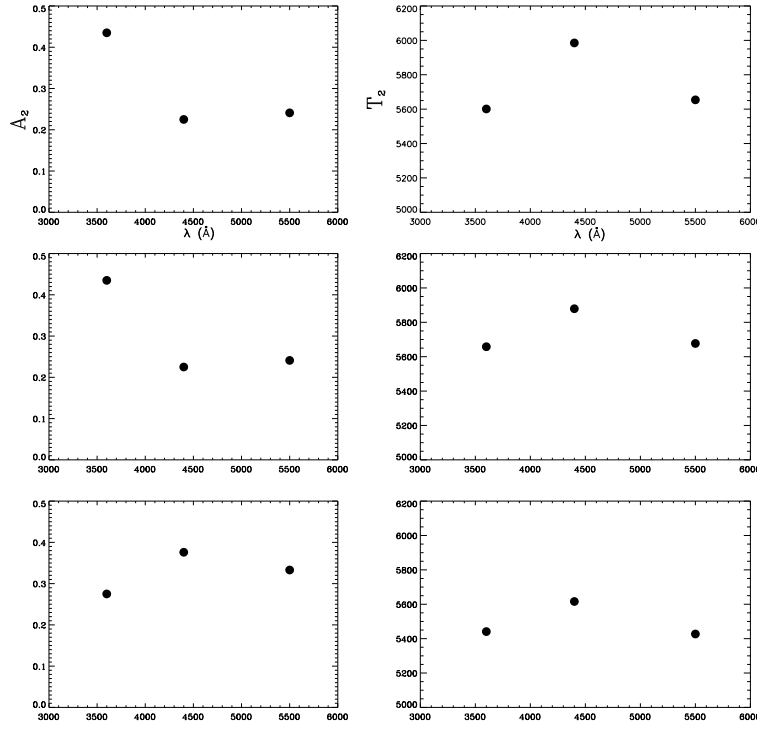


Fig. 5. The empirical values of the effective albedos (left panels) and temperatures (right panels) are plotted against the wavelengths for the cooler components of KR Cyg (top panels), AK CMi (middle panels) and DO Cas (bottom panels).

light curves separately. A few iterations indicate that there is no significant deviation in the gravity-darkening exponent between the theoretical and calculated values. The iterations are carried on excluding the gravity-darkening. After a few iterations convergence is attained. The computed values of A_2 , and T_2 are given with their standard deviations in Table 5. The computed L_2 values are also presented. Following the formulation given by Cranmer (1993) and Claret (2001) we connect the bolometric albedo

with the intrinsic and incident flux by

$$\sigma T_h^4 = \sigma T_{\text{eff}}^4 + F_{\text{incident}}, \quad (1)$$

$$A_{F_r} = \sigma T_h^4 - T_{\text{eff}}^4, \quad (2)$$

where T_{eff} is the effective temperature of the star without external flux, T_h is the effective temperature after irradiation, F_r is the external radial flux and A is the bolometric albedo. The external flux

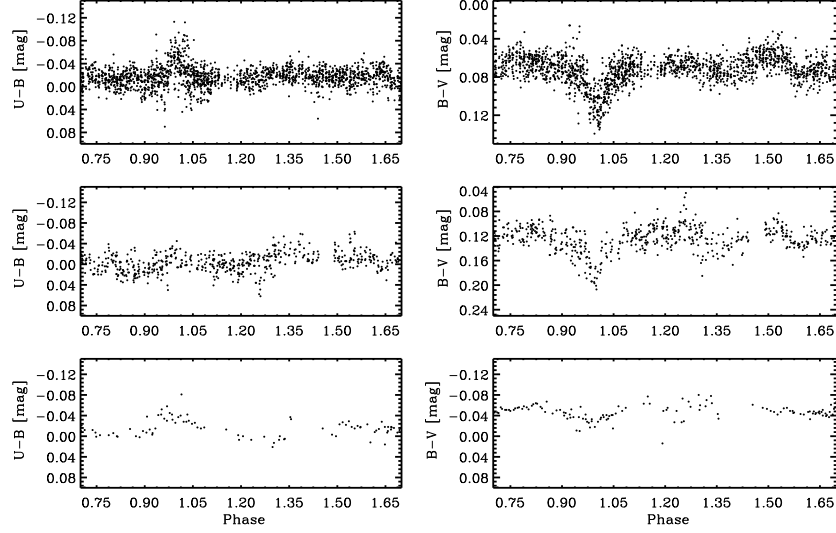


Fig. 6. The $U - B$ and $B - V$ colors against the orbital phase for KR Cyg (top panels), AK CMi (middle panels) and DO Cas (bottom panels).

F_r is dependent on apparent radius, effective temperature of the irradiating star, and on the cosine of the angle of incidence. The amount $(1-A)F_r$ is absorbed and the atmosphere of the irradiated star re-emits this excess energy later. Moreover, Kirbiyik & Smith (1976) and Kirbiyik (1982) proposed that not only the irradiated hemisphere of the star is heated in close binaries. The horizontal fluxes resulting from the incident radiation field can cause large circular currents over the irradiated stellar surfaces and may penetrate into the non-directly irradiated hemisphere. As a result the irradiated star would increase its temperature and luminosity. The values given in Table 5 confirm this theoretical prediction. The empirically derived values of A_2 , and T_2 from the light curves are plotted versus the wavelengths of the observations in Figure 5. The derived values of A_2 are systematically smaller than their theoretical values of about 0.5. Moreover, the deviations appear to be depended upon wavelength. The largest deviation occurs at about $\lambda 4350$. While the albedo gets smaller the effective temperature of the illuminated star increases. The computed value of the albedo in the U -passband is close to the theoretically expected value for convective envelopes. The light contribution of the secondary star to the total light is too low for this passband. The influence of the mutual illumination in close binary systems is not only seen on the bolometric albedos but also in other properties of the stars such as limb-darkening coefficients and gravity-darkening exponents. The reflection effect has a strong influence on limb-darkening coefficients,

as already noticed by Vaz & Nordlund (1985), Nordlund & Vaz (1990), Claret & Giménez (1990). Later, the effect of illumination on the limb-darkening coefficients was studied numerically by Alencar & Vaz (1999) using the Uppsala Model Atmosphere code in convective line-blanketed atmospheres. Their results show that the limb-darkening coefficients of illuminated atmospheres are significantly different from the non-illuminated ones. They concluded that the limb-darkening coefficients vary depending on the characteristics of external illumination such as the incidence angle, the amount of infalling flux, the temperature of the illuminating star. In addition, Alencar, Vaz, & Nordlund (1999) showed that external illumination changes the gravity-brightening exponent of an illuminated star. They proposed that the contact and semi-detached eclipsing binary systems should be better represented by illuminated atmospheres, since their components are closer to each other. Their numerical calculations showed that the external illumination increases the values of the gravity-brightening exponent roughly in proportion to the amount of the incident flux. The classical value of 0.32 for the convective atmospheres may be too small for binary systems with close components.

We also solved the UBV light curves of AK CMi, a similar system to KR Cyg, obtained by Samec et al. (1998). They estimated an effective temperature of 8510 K for the hotter star. We derived a value of 10150 K using the UBV measurements of the system at four orbital phases, at maxima and in mid-eclipses. Applying the same procedure as in KR Cyg

we obtained A_2 , and T_2 for the cooler component. They are listed in Table 5 and plotted in the middle panel of Figure 5. Though the uncertainties are slightly larger, both astrophysical parameters indicate very similar variations as in the cooler component of KR Cyg. DO Cas is also a NCB and its UBV light curves were published by Oh & Ahn (1992). We derived an effective temperature for the hotter star of 8700 K using the intermediate-band measurements by Hilditch & Hill (1975) and the $BVJHK$ magnitudes given in the SIMBAD database. Initial parameters were adopted from Siwak, Zola, & Koziel-Wierzbowska (2010) who obtained spectroscopic mass-ratio and modelled the BV light curves. Their analysis resulted in a near-contact configuration. Applying the same procedure we derive A_2 and T_2 for the irradiated star of DO Cas. The results are given in Table 5 and plotted in the bottom panels of Figure 5. The uncertainties of the parameters are very large, and originate from the large scatters in the observational data; the effective albedos are smaller than the expected value of 0.5.

In Figure 6 we plot the observed $U-B$ and $B-V$ colors for the systems KR Cyg, AK CMi and DO Cas. The bluer color especially in the $U-B$ just in and around primary eclipse is clearly seen. About 50 per cent of the apparent disk of the hotter component of KR Cyg is obscured by the cooler star in mid-primary eclipse. We therefore, suggest that multiple scattering of the light between the components of close binaries with large temperature differences results in bluer color, especially during annular eclipse.

4. CONCLUSIONS

We obtained the five-year $UBVR$ light curves and the radial velocities of the near-contact binary KR Cyg. Analysing the multi-color data and measured radial velocities we obtained, for the first time, the absolute parameters of the components. Comparison of the components' radii with the corresponding Roche lobes indicates that the system appears to be in near-contact but not in contact. Combining the results of light-and radial-velocity analyses we obtained the absolute physical parameters of the system. Both components are located on the main-sequence of the Hertzsprung-Russell diagram. Systematic behaviour of the residuals between the observed and fitted light curves is attributed to the effect of the mutual heating of the components, mainly in the case of the cooler star of this near-contact system. Analyses indicate that the effective albedo and the effective temperature of the irradiated star are significantly altered. The empirically

derived value of the albedo is smaller than that expected for a convective star. While the albedo gets smaller the effective temperature increases. We also analyzed the UBV data, taken from literature, for the systems AK CMi and DO Cas. The changes of albedos versus the wavelength are very similar for AK CMi and KR Cyg. It should be noted that the results related to the albedos are preliminary and speculative. The analysis of eclipsing binary light curves involves a large number of parameters. The bolometric albedos, limb-darkening coefficients, and gravity-brightening exponents are mostly kept fixed at the theoretical values. Nevertheless, external illumination is significant in close eclipsing binary systems, because it heats the surface layers of the illuminated star, thus altering its physical properties.

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