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Research Article

An Extensive Photometric Investigation of the W UMa System DK Cyg

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DK Cyg ($P = 0.4707$) is a contact binary system that undergoes complete eclipses. All the published photoelectric data have been collected and utilized to reexamine and update the period behavior of the system. A significant period increase with rate of 12.590×10^{-11} days/cycle was calculated. New period and ephemeris have been calculated for the system. A long term photometric solution study was performed and a light curve elements were calculated. We investigated the evolutionary status of the system using theoretical evolutionary models.

1. Introduction

The eclipsing binary DK Cyg (BD +330 4304, 10.37–10.93 m_v) is a well known contact binary system with a period of about 0.4707 days. It was discovered as variable star earlier by Guthnick and Prager [1], so their epoch of intensive observations is very long. The earliest photographic light curve classified the system as a W Ursae Majoris type. Rucinski and Lu [2] carried out the first spectroscopic observations and estimated the mass ratio as $q = 0.325$ and classified the system as an A-subtype contact system with spectral type of A8V. Visual light curves were published by Piotrowski [3] and Tsesevitch [4] from Klepikova's observations.

First photoelectric observations for the system were carried out by Hinderer [5], while Binnendijk [6] observed the system photoelectrically in B- and V-bands and derived least squares orbital solution. The system DK Cyg was classified in the General Catalogue of Variable Stars as A7V [7], while Binnendijk [6] adopted it as A2. Mochnacki and Doughty [8] showed that the color index of the system judged its spectral type and found that the spectral type of the system is more likely to be about F0 to F2. Because the system DK Cyg is a summer object in the Northern hemisphere with 11.5-hour period and short durations of night, it is bound to remain ill-observed [9]. Only four complete light curves by Binnendijk [6], Paparo et al. [10], Awadalla [9], and Baran et al. [11] are published. Photoelectric observations and new times of minima have been carried out by many authors: Borkovits et al. [12], Sarounová and Wolf [13], Drozdz and Ogloza [14], Hübscher et al. [15], Dogru et al. [16], Hubscher et al. [17], Hubscher et al. [18], Erkan et al. [19], Diethelm [20], Dogru et al. [21], Simmons [22], Diethelm [23], and Diethelm [24].

In the present paper we are going to perform comprehensive photometric study for the system DK Cyg. The structures of the paper are as follows: Section 2 deals with the period change, Section 3 is devoted to the light curve modeling, and Section 4 presents the discussion and conclusion reached.

2. Period Change

Although the period variation of contact binary systems of the W UMa-type is a controversial issue of binary star astrophysics, the cause of the variations (long as well as short term) is still a mystery for a discussion of possible physical mechanisms [25]. Magnetic activity cycle is one of the main mechanisms that caused a period variation together with the mass exchange between the components of each system. Kaszas et al. [26] stated that the long term period variation may be interpreted by a perturbation of the third companion or surface activity of the system components.

Observations by Binnendijk [6] showed a change of the secondary minimum depth and a new linear light element was derived. Period study by Paparo et al. [10] showed that the orbital period of the system DK Cyg increases and the first parabolic light elements were calculated, which confirmed the light curve variability. Kiss et al. [25] updated the linear ephemeris of DK Cyg, while Awadalla [9] recalculated a new quadratic element for the system and confirmed the light curve variability suggested by Paparo et al. [10]. Wolf et al. [27] used a set of 101 published times of minimum covering the interval between 1926 and 2000 in order to update the quadratic element calculated by Awadalla [9]. They showed that the period increases by the rate 11.5×10^{-11} days/cycle. Borkovits et al. [28] follow the period behavior of the system using set of published minima from HJD 2424760 to HJD 2453302.

In this paper we studied the orbital period behavior of the system DK Cyg using the $(O - C)$ diagram based on more complete data set collected from the literatures and databases of BAV, AAVSO, and BBSAG observers. Part of our collected data set was given by Kreiner et al. [29]; unpublished Hipparcos observations and main part were downloaded from website (http://astro.sci.muni.cz/variables/ocgate/); Table 1 listed only those minima not listed on the mentioned websites. A total of 195 minima times were incorporated in our analysis covering about 86 years (66689 orbital revolutions) from 1927 to 2013. It is clear that our set of data added about 94 of new minima and increases the interval limit of the orbital period study about 13 years more than the data of Wolf et al. [27], which may give more accurate insight on the period behavior of the system. The different types of the collected minima (i.e., photographic, visual, photoelectric, and CCD) were weighted according to their type. The residual $(O - C)$'s were computed using Binnendijk [6] ephemeris (1) and represented in Figure 1. No distinction has been made between primary and secondary minima:

$$\text{Min } I = 2437999.5838 + 0.47069055 * E. \quad (1)$$

It can be seen from the figure that the behavior of the orbital period of the system DK Cyg shows a parabolic distribution which is generally interpreted by the transfer of mass from one component to the other of binary. Reasonable linear least squares fit of the data available improved the light elements given in (1) to

$$\text{Min } I = \underset{\pm 0.0192}{2437999.5961} + \underset{\pm 0.0243}{0^{d}.47069206} * E. \quad (2)$$

The linear element yields a new period of $P = 0^{d}.47069206$ days which is longer by 0.13 seconds with respect to the value given by Binnendijk [6]. Quadratic least squares fit gives

$$\text{Min } I = \underset{\pm 0.0192}{2437999.5803} + \underset{\pm 0.0237}{0^{d}.47069064} * E + \underset{\pm 2.5654 \times 10^{-12}}{6.284 \times 10^{-11}} \times E^{2}. \quad (3)$$

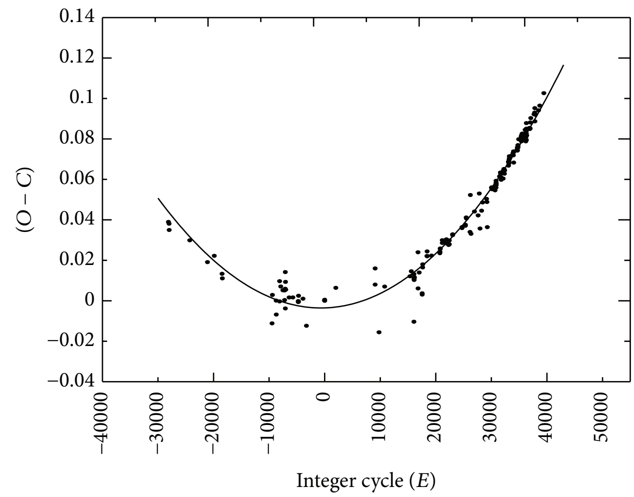

Figure 1: Period behavior of DK Cyg.

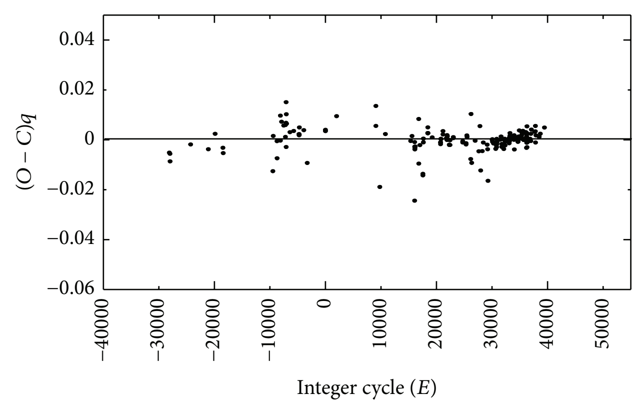

Figure 2: Calculated residuals from the quadratic ephemeris.

The rate of period increasing resulting from the quadratic elements (3) is $dP/dE = 12.568 \times 10^{-11}$ days/cycle or 9.746×10^{-8} days/year or 0.84 seconds/century. More future systematic and continuous photometric observations are needed to follow a continuous change in the orbital period of the system DK Cyg which may show a periodic behavior. The fourth column of Table 1 represents the quadratic residuals $(O - C)q$ calculated using the new element of (2) and represented in Figure 2. All published linear and quadratic elements together with that resulting from our calculations are listed in Table 2. It is noted from the table that the quadratic term resulting from our calculations has slightly higher value than that calculated by Awadalla [9], Wolf et al. [27], and Borkovits et al. [28]. This can be interpreted by the increasing of the set of minima in our study compared to the one they used (nearly double); also we covered an interval larger than the one they used.

3. Light Curve Modeling

Light curve modeling for the system DK Cyg by Mochnacki and Doughty [8] using Binnendijk [6] observations in V-band showed nonmatching between the theoretical curve and

Table 1: Times of minimum light for DK Cyg.

HJD	Method	E	$(O-C)$	$(O-C)q$	References	HJD	Method	E	$(O-C)$	$(O-C)q$	References
2434179.4690	Vis	−8116	0.00970	0.00971	1	2451749.4450	pe	29212	0.04885	−0.00370	3
2447758.4352	Pe	20733	0.02423	−0.00099	2	2451777.6740	ccd	29272	0.03642	−0.01636	5
2447790.4437	Pe	20801	0.02577	0.00037	2	2452163.6590	ccd	30092	0.05517	−0.00074	5
2447963.6620	Pe	21169	0.02995	0.00354	3	2452245.5592	ccd	30266	0.05521	−0.00137	5
2447963.8960	Pe	21169.5	0.02860	0.00220	3	2452253.5613	ccd	30283	0.05557	−0.00108	5
2448265.1380	Pe	21809.5	0.02865	0.00046	4	2452441.8384	ccd	30683	0.05645	−0.00176	5
2448265.1382	Pe	21809.5	0.02885	0.00066	4	2452512.4415	pe	30833	0.05597	−0.00284	7
2448272.1987	Pe	21824.5	0.02899	0.00076	4	2452525.6231	ccd	30861	0.05824	−0.00069	5
2448297.6160	Pe	21878.5	0.02900	0.00062	3	2452526.5644	ccd	30863	0.05816	−0.00078	5
2448302.7930	Pe	21889.5	0.02841	−0.00001	3	2452811.8062	ccd	31469	0.06148	0.00013	5
2448308.2078	Pe	21901	0.03027	0.00182	4	2453223.4286	ccd	32343.5	0.06500	−0.00006	8
2448308.2079	Pe	21901	0.03037	0.00192	4	2453228.3681	ccd	32354	0.06225	−0.00274	8
2448336.4491	Pe	21961	0.03013	0.00152	4	2453246.4950	ccd	32392.5	0.06756	0.00242	8
2449988.5840	ccd	25471	0.04120	0.00182	5	2453247.4346	ccd	32394.5	0.06578	0.00063	8
2450003.6456	ccd	25503	0.04070	0.00122	5	2453285.3260	ccd	32475	0.06659	0.00110	8
2450313.8240	ccd	26162	0.03403	−0.00765	5	2453286.2657	ccd	32477	0.06491	−0.00059	8
2450341.6130	ccd	26221	0.05229	0.01041	5	2453302.2672	ccd	32511	0.06293	−0.00271	8
2450397.6060	ccd	26340	0.03311	−0.00917	5	2454799.5505	ccd	35692	0.07959	0.00004	9
2450692.7400	ccd	26967	0.04414	−0.00030	5	2455043.8381	ccd	36211	0.07882	−0.00310	10
2451000.0990	pe	27620	0.04221	−0.00452	5	2455062.6680	ccd	36251	0.08107	−0.00105	11
2451095.6600	ccd	27823	0.05303	0.00557	5	2455088.5544	ccd	36306	0.07953	−0.00285	10
2451160.5980	ccd	27961	0.03573	−0.01222	5	2455810.6029	ccd	37840	0.08870	−0.00096	12
2451379.4820	pe	28426	0.04863	−0.00101	3						

(1) Szafraniec [30]; (2) Hubscher et al. [31]; (3) Wolf et al. [27]; (4) Hipparcos observations (unpublished); (5) Baldwin and Samolyk [32]; (6) Kiss et al. [25]; (7) Borkovits et al. [33]; (8) Borkovits et al. [28]; (9) Gerner [34]; (10) Menzies [35]; (11) Samolyk [36]; (12) Simmons [22].

Table 2: The light elements of DK Cyg.

JD	Period	Quadratic term	References
2437999.5838	0.470690550		Binnendijk [6]
2437999.5828	0.470690660	5.390×10^{-10}	Paparo et al. [10]
2437999.5825	0.470690730	5.760×10^{-11}	Awadalla [9]
2451000.0999	0.470692900		Kiss et al. [25]
2437999.5825	0.470690640	5.750×10^{-11}	Wolf et al. [27]
2451000.1031	0.470693909	5.862×10^{-11}	Borkovits et al. [28]
2437999.5961	0.470692060		Present work
2437999.5803	0.470690640	6.284×10^{-11}	Present work

the observations. The photometric mass ratio calculated from their accepted model was $q_{\text{ph}} = 0.33 \pm 0.02$, while the spectroscopic value estimated using radial velocity study by Rucinski and Lu [2] is $q_{\text{sp}} = 0.325 \pm 0.04$. Baran et al. [11] estimated an alternating model of spectroscopic and photometric data based on iterative solutions. Their model shows a better fit by introducing a cool spot on the surface of the more luminous component and adopted the third light as free parameter in the computations. On the other hand Rucinski and Lu [2] stated that they did not find any evidence for the existence of a third component in the system during their spectroscopic study. They refer the probability for the presence of a third star in the system to the $(O-C)$ diagram [29], which shows sinusoidal variation. This evidence is weak because only one cycle is covered up to date.

In the present work we used complete light curves published by Binnendijk [6], Paparo et al. [10], Awadalla [9], and Baran et al. [11] in V-band through a long term photometric solution study in order to estimate the physical parameters of the system and to follow its evolutionary status. The collected light curves showed a flat-bottom minima and O'Connell effect. Observations by Paparo et al. [10] and Awadalla [9] displayed some scattering specially at the two maxima of their light curves. Also the observed light curve

Table 3: Photometric solutions for DK Cyg.

Parameter	Binnendijk [6]	Paparo et al. [10]	Awadalla [9]	Baran et al. [11]
A	5500	5500	5500	5500
i (°)	80.59 ± 0.12	80.22 ± 0.21	80.83 ± 0.27	79.97 ± 0.06
$g_1 = g_2$	0.32	0.32	0.32	0.32
$A_1 = A_2$	0.5	0.5	0.5	0.5
q (M_2/M_1)	0.306*	0.306*	0.306*	0.306*
$\Omega_1 = \Omega_2$	2.4064 ± 0.002	2.4077 ± 0.005	2.3325 ± 0.004	2.3886 ± 0.001
Ω_{in}	2.4794	2.4794	2.4794	2.4794
Ω_{out}	2.2888	2.2888	2.2888	2.2888
T_1 (°K)	7500*	7500*	7500*	7500*
T_2 (°K)	6767 ± 4	6726 ± 7	6726 ± 9	6759 ± 2
r_1 pole	0.4696 ± 0.0007	0.4694 ± 0.0013	0.4861 ± 0.0014	0.4735 ± 0.0003
r_1 side	0.5091 ± 0.0010	0.5087 ± 0.0018	0.5328 ± 0.0021	0.5145 ± 0.0004
r_1 back	0.5400 ± 0.0013	0.5395 ± 0.0024	0.5716 ± 0.0029	0.5471 ± 0.0005
r_2 pole	0.2792 ± 0.0008	0.2789 ± 0.0014	0.2980 ± 0.0017	0.2835 ± 0.0003
r_2 side	0.2932 ± 0.0010	0.2929 ± 0.0017	0.3166 ± 0.0022	0.2985 ± 0.0004
r_2 back	0.3414 ± 0.0019	0.3407 ± 0.0034	0.3982 ± 0.0068	0.3522 ± 0.0008
Spot **A** of star **1**				
Colatitude	130*	130*	130*	130*
Longitude	180*	180*	180*	180*
Spot radius	33.61 ± 0.230	30.74 ± 0.437	27.23 ± 1.14	35.014 ± 0.09
Temp. factor	0.796 ± 0.003	0.840 ± 0.007	0.924 ± 0.01	0.819 ± 0.001
Spot **A** of star **2**				
Colatitude	120*	120*	120*	120*
Longitude	290*	290*	290*	290*
Spot radius	32.99 ± 3.60	29.42 ± 1.34	33.08 ± 1.24	29.44 ± 1.20
Temp. factor	1.01 ± 0.01	1.01 ± 0.01	1.17 ± 0.01	1.02 ± 0.002
$\sum(O-C)^2$	0.0229	0.02909	0.02458	0.0453

*Not adjusted.

by Awadalla [9] shows sudden increase in the light level at secondary minimum with respect to the other collected curves.

Photometric analysis for the studied light curves of the system DK Cyg was carried out using Mode 3 (overcontact) of WDint56a Package [43] based on the 2009 version of Wilson and Devinney (W-D) code with Kurucz model atmospheres [44–46]. The observed light curves were analyzed using all individual observations. Appropriate gravity darkening and bolometric albedo exponents were assumed for the convective envelope. We adopted $\mathbf{g_1} = \mathbf{g_2} = 0.32$ [47] and $\mathbf{A_1} = \mathbf{A_2} = 0.5$ [48]. Bolometric limb darkening values are adopted using the table of van Hamme [49]. Temperature of the primary star was adopted according to Baran et al. [11] model ($\mathbf{T_1} = \mathbf{7500}$°K).

The adjustable parameters are the mean temperature of the secondary component $\mathbf{T_2}$, orbital inclination **i**, and the potential of the two components $\mathbf{\Omega} = \mathbf{\Omega_1} = \mathbf{\Omega_2}$, while the spectroscopic mass ratio ($\mathbf{q_{sp}} = 0.306$) by Baran et al. [11] was fixed for all calculated models together with the primary star's temperature ($\mathbf{T_1}$).

We started modeling using as initial values the parameters of Baran et al. [11] solution based on cool spot on the luminous components and a third light as a free parameter. The used parameters show disagreement between the theoretical and observed light curves, except for Baran et al. observations. Regarding the conclusion of Rucinski and Lu [2], which stated a weak evidence of presence of a third component, we tried to construct a spotted model without the third light. We constructed a model including two spots; the first one is a cool spot located on surface of the more massive component, while the other is a hot spot located on the surface of the other component. The accepted model reveals good agreement between theoretical and observed light curves for all collected data. Table 3 lists the calculated parameters for the four light curves, while Figure 3 represented the theoretical light curves according to the accepted solution together with the reflected points in V-band. The $\sum(O-C)^2$ values in Table 3 are indicative of comparisons in future studies, since the number of observations and the accuracy are not the same in the four light curves. Absolute physical parameters for each component of the system DK Cyg were calculated based on the results of the radial velocity data of Baran et al. [11] and our new photometric solution for each light curve. The calculated parameters are listed in Table 3. The results show that the primary component is more massive and hotter than

Table 4: Absolute physical parameters for DK Cyg.

Parameter	Binnendijk [6]	Paparo et al. [10]	Awadalla [9]	Baran et al. [11]
$M_{1\odot}$	1.7363 ± 0.0709	1.7358 ± 0.0709	1.7679 ± 0.0722	1.7438 ± 0.0712
$M_{2\odot}$	0.5313 ± 0.0217	0.5312 ± 0.0217	0.5410 ± 0.0221	0.5336 ± 0.0218
$R_{1\odot}$	1.7037 ± 0.0696	1.7029 ± 0.0695	1.7635 ± 0.0720	1.7178 ± 0.0701
$R_{2\odot}$	1.0129 ± 0.0414	1.0118 ± 0.0413	1.0811 ± 0.0441	1.0285 ± 0.0420
$T_{1\odot}$	1.2980 ± 0.0530	1.2980 ± 0.0530	1.2980 ± 0.0530	1.2980 ± 0.053
$T_{2\odot}$	1.1712 ± 0.0478	1.1641 ± 0.0475	1.1641 ± 0.0475	1.1698 ± 0.0478
M_{1_bol}	2.4617 ± 0.1005	2.4627 ± 0.1005	2.3868 ± 0.0974	2.4438 ± 0.1000
M_{2_bol}	4.0375 ± 0.1648	4.0662 ± 0.1660	3.9224 ± 0.1601	4.0094 ± 0.1637
$L_{1\odot}$	8.2285 ± 0.3359	8.2208 ± 0.3356	8.8163 ± 0.3600	8.3653 ± 0.3415
$L_{2\odot}$	1.9276 ± 0.0787	1.8772 ± 0.0766	2.1431 ± 0.0875	1.9780 ± 0.0808

Note: subscripts 1 and 2 mean primary and secondary component, respectively.

Table 5: Physical parameters of the five A-type contact binaries.

Star name	Parameters						References
	$M_1(M_\odot)$	$M_2(M_\odot)$	$R_1(R_\odot)$	$R_2(R_\odot)$	$L_1(L_\odot)$	$L_2(L_\odot)$	
YY CrB	1.404	0.339	1.427	0.757	2.58	6.68	1
AW UMa	1.6	0.121	1.786	0.739	7.47	0.804	2
EQ Tau	1.214	0.541	1.136	0.787	1.31	0.6	3
RR Cen	1.82	0.38	2.1	1.05	8.89	2.2	4
V566 Oph	1.41	0.34	1.45	0.77	4.46	1.23	5

(1) Essam et al. [38], (2) Elkhateeb and Nouh [39], (3) Elkhateeb and Nouh [40], (4) Yang et al. [41], and (5) Degirmenci [42].

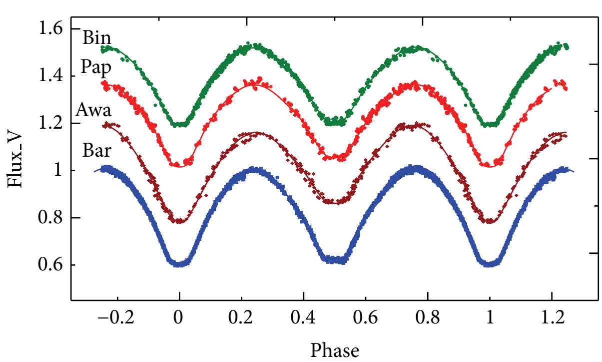

Figure 3: Observed and synthetic light curves of Binndijik [6] (Bin), Paparo et al. [10] (Pap), Awadalla [9] (Awa), and Baran et al. [11] (Bar), for the system DK Cyg.

the secondary component. A three-dimensional geometrical structure for the system DK Cyg is displayed in Figure 4 using the software Package Binary Maker 3.03 [50] based on the calculated parameters resulting from our models.

4. Discussion and Conclusion

Studying of the period behavior of the system DK Cyg based on all available published times of minima, covering 86 yr of observations including 195 times of light minima, shows a continuous period increase with the rate $dP/dE = 12.590 \times 10^{-11}$ days/cycle or 9.763×10^{-8} days/year or 0.84 seconds/century. New linear and quadratic elements were calculated using all available published data and yield a new period of $P = 0.47069203$ days. A long term photometric study was performed using published observations by Binnendijk [6], Paparo et al. [10], Awadalla [9], and Baran et al. [11]. More systematic and continuous photometric observations for the system DK Cyg are needed to confirm a continuous change in the period and follow its light curve variation.

One of the difficulties for W UMa binaries is to use stellar models of single stars to investigate the evolutionary status of these systems. However, using these theoretical models may give approximate view about the evolutionary status of the system.

We used the physical parameters listed in Table 4 to investigate the current evolutionary status of DK Cyg. In Figures 5 and 6, we plotted the components of DK Cygon on the mass-luminosity (M-L) and mass-radius (M-R) relations along with the evolutionary tracks computed by Girardi et al. [51] for both zero age main sequence stars (ZAMS) and terminal age main sequence stars (TAMS) with metallicity $z = 0.019$. As it is clear from the figures, the primary component of the system is located nearly on the ZAMS for both the M-L and M-R relations. The secondary component is above the TAMS track for M-L and the M-R relations. For the sake of comparison, we plotted sample of A-type contact binaries listed in Table 5. The components of DK Cyg have the same behavior of the selected A-type systems.

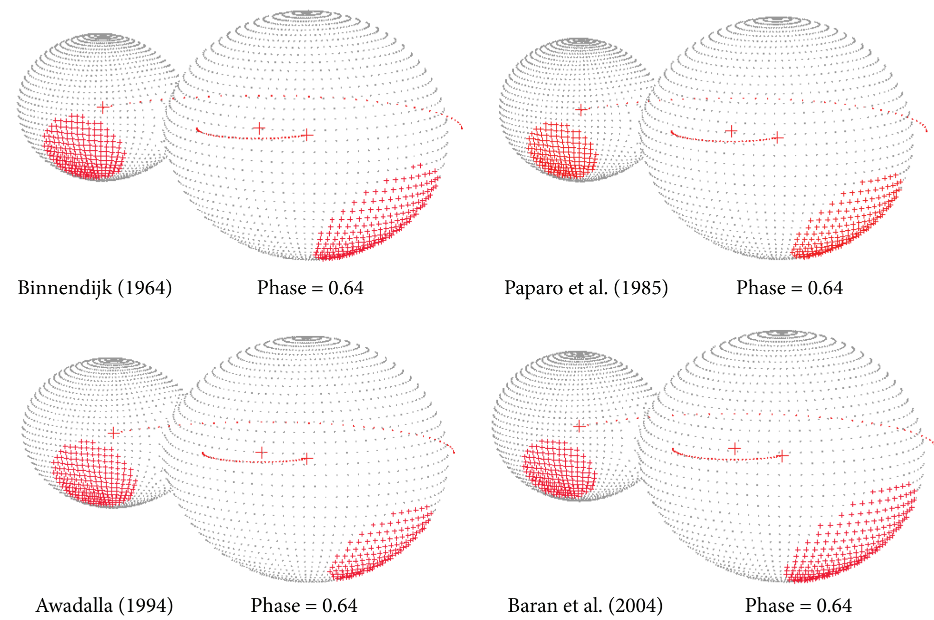

Figure 4: Three-dimensional models of the components of DK Cyg.

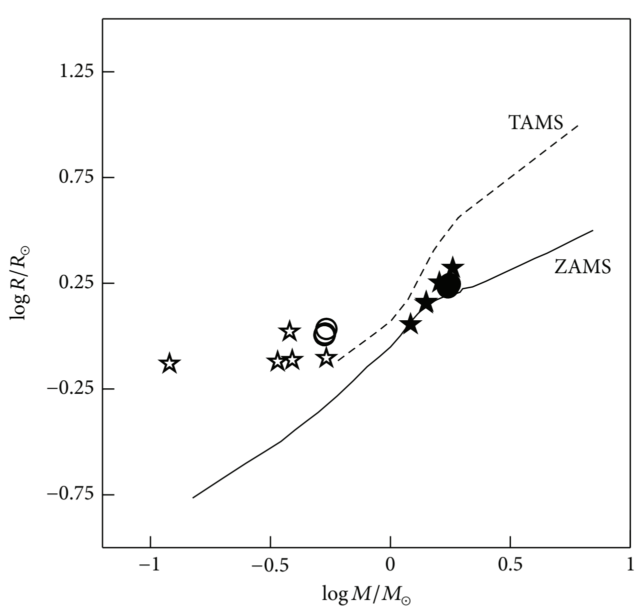

Figure 5: The position of the components of DK Cyg on the mass-radius diagram. The filled symbols denote the primary component and the open symbols represent the secondary component. The star symbols denote the sample of the selected A-type systems listed in Table 5.

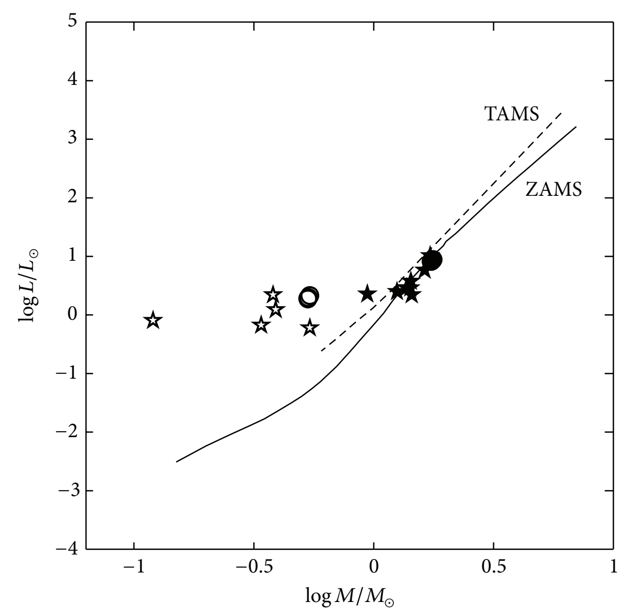

Figure 6: The position of the components of DK Cyg on the mass-luminosity diagram. The filled symbols denote the primary component and the open symbols represent the secondary component. The star symbols denote the sample of the selected A-type systems listed in Table 5.

The mass-effective temperature relation (M-T_{eff}) for intermediate and low mass stars [37] is displayed in Figure 7. The location of our mass and radius on the diagram revealed a good fit for the primary and poor fit for the secondary components. This gave the same behavior of the system on the mass-luminosity and mass-radius relations.

Conflict of Interests

The authors declare that they have no conflict of interests regarding the publication of this paper.

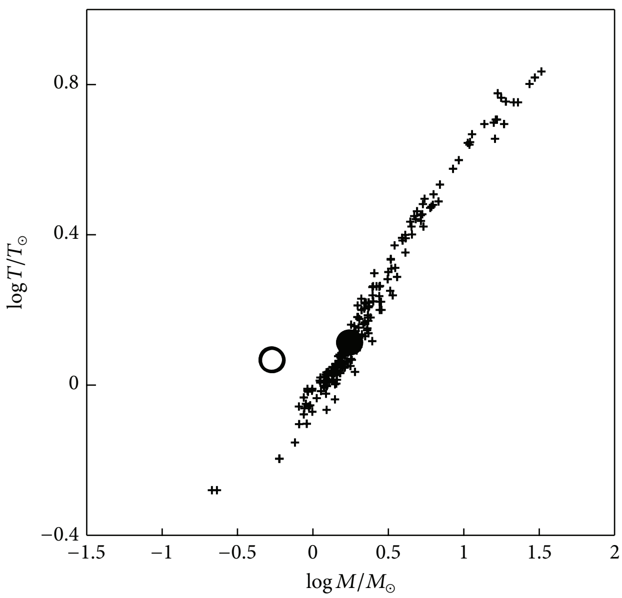

Figure 7: Position of the components of DK Cyg on the empirical mass-T_{eff} relation for low-intermediate mass stars by Malkov [37]. The filled symbols denote the primary component and the open symbols represent the secondary component.

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