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Photometric analysis of the neglected eclipsing binary system DL Cygni*

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Abstract. DL Cygni is a poorly studied early-type eclipsing binary system. In this paper we present new Kron–Cousins VR light curves obtained at Baja Astronomical Observatory in 1998. A detailed photometric analysis based on these observations was carried out by the use of the most recent version of the Wilson–Devinney (WD) code. It is found that the system is likely a strongly interacting semidetached one. We explain the irregularities of the light curves with the presence of circumstellar matter. Different solutions are presented according to the supposed positions of the circumstellar medium. We suspect that the system consists of an asynchronously rotating main-sequence primary spinned up by the infalling gas of the mass losing evolved secondary component. A period study was also carried out. The period seems to be longer than some decades ago. Due to the lack of spectroscopic information we can give only a very uncertain estimation on the absolute parameters of the binary.

One of our initial comparison stars GSC 3595–0816 is suspected to be variable.

Key words: stars: binaries: eclipsing – stars: individual: DL Cyg – stars: fundamental parameters – techniques: photometric

1. Introduction

DL Cyg (BD $+47^\circ 3518$, SAO 51160) is an early-type eclipsing binary system discovered by Guthnick & Prager (1927). Early photographic light curves were published by Beyer (1929) and Zessewitsch (1930). The latter stated that the system shows continuous light variations. Kopal (1932) analysed Beyer's light curve. He obtained the first results for the fundamental parameters of the system. He classified the binary as a detached system, and found evidence for a small orbital eccentricity. The variable seems to be neglected afterwards for half a century. Then Koch et al. (1979) called for its observation. In 1975 Dworak calculated its parallax (Dworak 1975), while Brancewicz and Dworak (1980) tabulated physical parameters for the system in their catalogue. They also classified the system as a detached one.

The spectral classification of the system is uncertain. The SIMBAD database gives B3V without reference. The same data can be found in The Combined General Catalog of Variable Stars (GCVS) (Kholopov et al. 1998), while the Third Catalogue of Luminous Stars in the Northern Milky Way (Hardorp et al. 1964) contains OB^- classification also without any reference. On the other hand Brancewicz & Dworak (1980) give A3+A7 in the paper mentioned above.

The possibly non-zero eccentricity and the relatively large masses of the stars together with the lack of modern measurements stimulated us to observe this system as a possible apsidal motion candidate one. (That time we had not known Zessewitsch' work.)

We obtained nearly complete multicolour light curves, and analysed them with the newest version of the Wilson–Devinney code (Wilson 1998). The observations are described in Sect. 2, while the analysis is presented in Sect. 3. Our conclusions can be found in Sect. 4.

2. Observations

The measurements were carried out at Baja Astronomical Observatory with an SBIG ST-7 CCD camera and Kron–Cousins V,B,R filters attached to a 50 cm f/8.4 Ritchey-Chrètien telescope. The six brightest stars in the field of the camera were selected as comparison and check star candidates (Table 1). One of them, GSC 3595–0816 was found to be variable, and was dropped from further analysis. The others showed stable brightness and thus could be used as comparisons. We observed the system on 39 nights in total between August 10 – December 28, 1998. V and R filters were used primarily, but in the last few sessions filter B was also added for calibrational purposes. The exposure time varied between 20 and 60 seconds (half a minute being typical). (See Table 2 for a short observational log.) Tables 3a-c list the VBR data obtained as magnitude differences variable minus comparison in the observational system versus Heliocentric Julian Day. We reduced the data using IRAF CL scripts, written to meet local requirements, and relied heavily on the host IRAF tasks. The reduction of the frames included dark and flatfield correction, followed by the removal of cosmic ray

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* Tables 3a-c are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

Table 1. Data for DL Cygni, the comparison and the check stars

GSC ID	Type	RA (2000) (h)	 (m)	 (s)	Dec (2000) (°)	 (′)	 (″)	V (mag)	B–V (mag)	V–R (mag)
3595–1938[a]	var.	21	39	46	+48	32	24	$9^{\rm m}.22 \pm 0^{\rm m}.04$	$0^{\rm m}.23 \pm 0^{\rm m}.14$	$0^{\rm m}.02 \pm 0^{\rm m}.04$
3595–0200	comp.	21	39	41	+48	29	30	$11^{\rm m}.91 \pm 0^{\rm m}.02$	$1^{\rm m}.30 \pm 0^{\rm m}.10$	$0^{\rm m}.75 \pm 0^{\rm m}.02$
3595–0816[b]	cancelled	21	39	29	+48	31	54	$12^{\rm m}.42 \pm 0^{\rm m}.04$	$0^{\rm m}.24 \pm 0^{\rm m}.14$	$0^{\rm m}.04 \pm 0^{\rm m}.05$
3595–1276	check 1	21	39	44	+48	30	28	$13^{\rm m}.04 \pm 0^{\rm m}.05$	$0^{\rm m}.54 \pm 0^{\rm m}.15$	$0^{\rm m}.25 \pm 0^{\rm m}.05$
3595–0400	check 2	21	39	54	+48	32	18	$13^{\rm m}.11 \pm 0^{\rm m}.05$	$1^{\rm m}.15 \pm 0^{\rm m}.09$	$0^{\rm m}.68 \pm 0^{\rm m}.08$
	check 3	21	39	41	+48	30	04	$13^{\rm m}.53 \pm 0^{\rm m}.05$	$1^{\rm m}.26 \pm 0^{\rm m}.16$	$0^{\rm m}.73 \pm 0^{\rm m}.12$
	check 4	21	39	27	+48	32	11	$13^{\rm m}.53 \pm 0^{\rm m}.05$	$0^{\rm m}.30 \pm 0^{\rm m}.17$	$0^{\rm m}.11 \pm 0^{\rm m}.11$

[a] Photometry at phase 0.25

[b] Photometry on 16/17 November

Table 2. Observational log

Night		Phase	Filters	Observer	Night		Phase	Filters	Observer
Aug.	10/11	0.59–0.61	V,R	Borkovits	Oct.	4/5	0.96–0.98	V,R	Bíró
	11/12	0.75–0.82	V,R	Borkovits		11/12	0.37–0.41	V,R	Bíró
	12/13	0.96–1.03	V,R	Borkovits		13/14	0.78–0.86	V,R	Bíró
	13/14	0.17–0.23	V,R	Bíró		14/15	0.99–1.05	V,R	Borkovits
	14/15	0.39–0.44	V,R	Borkovits		16/17	0.43–0.48	V,R	Borkovits
	18/19	0.20–0.26	V,R	Borkovits		17/18	0.61–0.66	V,R	Borkovits
	23/24	0.26–0.31	V,R	Bíró		21/22	0.45–0.50	V,R	Borkovits
	25/26	0.66–0.72	V,R	Bíró		22/23	0.65–0.71	V,R	Bíró
	26/27	0.86–0.93	V,R	Borkovits		23/24	0.86–0.92	V,R	Borkovits
	30/31	0.70–0.73	V,R	Borkovits		26/27	0.48–0.54	V,R	Bíró
Sep.	1/2	0.12–0.14	V,R	Bíró	Nov.	5/6	0.54–0.58	V,R	Bíró
	8/9	0.55–0.61	V,R	Borkovits		6/7	0.75–0.77	V,B,R	Bíró
	9/10	0.76–0.83	V,R	Borkovits		7/8	0.96–1.01	V,B,R	Bíró
	14/15	0.80–0.86	V,R	Bíró		8/9	0.16–0.20	V,B,R	Bíró
	18/19	0.65–0.66	V,R	Borkovits		12/13	0.01–0.03	V,B,R	Bíró
	21/22	0.24–0.31	V,R	Borkovits		16/17	0.81–0.86	V,B,R	Borkovits
	22/23	0.45–0.52	V,R	Bíró		18/19	0.23–0.28	V,B,R	Borkovits
	24/25	0.89–0.93	V,R	Bíró	Dec.	28/29	0.51–0.52	V,B,R	Borkovits
	25/26	0.06–0.12	V,R	Borkovits					
	26/27	0.31–0.32	V,R	Bíró					
	30/Oct. 1	0.09–0.12	V,R	Borkovits					

events. Standard aperture photometry was then applied for the variable and the selected comparisons. Neighbour stars close to the variable forced us to use an aperture not larger than 9 arcseconds in diameter. For the transformation to the standard BVR system standard stars were observed from Landolt's (1983) list. Then again we used the `photcal` IRAF package to solve the following equations:

$$
\begin{aligned}
m_B &= B + b_1 + b_2 X_B + b_3(B-V)\\
m_V &= V + v_1 + v_2 X_V + v_3(B-V) \qquad (1)\\
m_R &= R + r_1 + r_2 X_R + r_3(V-R)
\end{aligned}
$$

where the m-s and the X-es stand for the instrumental magnitudes and airmasses for each bandpass (the other symbols being selfunderstanding). The coefficients can be seen in Table 4. While there was only a minor variation in the colour coefficients, the zero points varied strongly from night to night. As both standard stars and the variable were only observed on 26 October, that night's data was used to calculate the standard V and R magnitudes for the comparison and check stars (see Table 1). The standard magnitudes of the variable were calculated relative to GSC 3595–0200.

3. Light curve analysis

3.1. Period

To determine the period of DL Cyg we collected the minima times from the literature, and from our observations. Unfortunately we found only six earlier minima (Table 5). The first five minima are normal ones from seasonal light curves, with low level of reliability. The only fact that can be inferred from the O–C curve (Fig. 1) is that the period is possibly longer than that given in the GCVS (Kholopov et al. 1998).

First we constructed our light curves with the elements from the GCVS. When we obtained the best solution from the light curve synthesis, according to the case (a) model (see below) we fixed the other parameters, and made a least-squares fit for the best period and HJD0 data with the WD code, too. In this

Table 4. The instrumental coefficients. See Eq. 1 for details.

Coeff.	24 Apr 1998	24 Oct 1998	26 Oct 1998	17 Dec 1998
b1	6.187 ± 0.044	6.36 ± 0.12	–	5.645 ± 0.018
b2	0.490 ± 0.025	0.593 ± 0.061	–	0.836 ± 0.010
b3	−0.331 ± 0.015	−0.348 ± 0.022	–	−0.342 ± 0.010
v1	5.317 ± 0.029	5.529 ± 0.019	5.459 ± 0.010	–
v2	0.330 ± 0.014	0.359 ± 0.010	0.080 ± 0.005	–
v3	−0.015 ± 0.021	−0.040 ± 0.006	0.059 ± 0.010	–
r1	5.505 ± 0.012	5.534 ± 0.044	5.664 ± 0.010	5.38 ± 0.05
r2	0.253 ± 0.006	0.388 ± 0.022	0.069 ± 0.004	0.27 ± 0.03
r3	0.232 ± 0.010	0.178 ± 0.015	0.177 ± 0.012	1.43 ± 0.04

Table 5. Times of minima. (See text for details.)

HJD−2400000	Min	Type	Source
24775.597	pri.	seas.	1
25094.458	pri.	seas.	2
25123.390	pri.	seas.	1
25437.4	pri.	seas.	2
25524.314	pri.	seas.	1
44087.499	pri.	phot. el.	3
51038.485±0.002	pri.	CCD	4
51113.371±0.002	sec.	CCD	5

Sources: 1: Beyer (1929); 2: Zessewitsch (1930); 3: Diethelm (1979); 4: Borkovits & Bíró (1998); 5: this paper

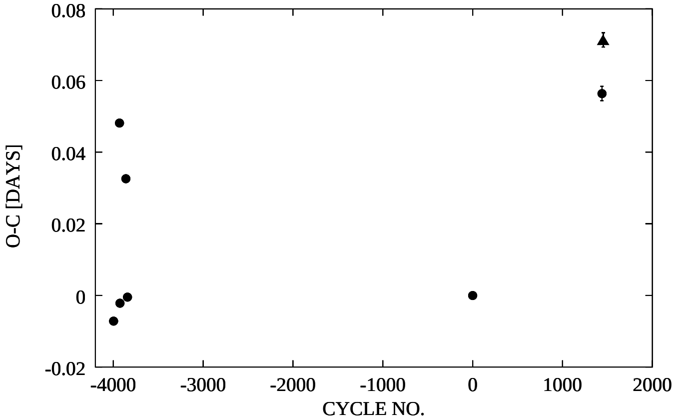

Fig. 1. The O–C diagram of DL Cyg. (The triangle notes the only one secondary minimum.)

way we got an unrealistic big difference in the orbital period (more than 2×10^{-4} days). Finally we calculated the following elements from the O–C curve by the least-squares method:

$$MinI(HJD) = 2451038.48865 + 4.830400415 \times E,$$

but as our observation were made in a short time interval this problem is insignificant from the point of view of light curve fits. (At the calculation we omitted the two very uncertain points of Zessewitsch 1930).

3.2. Light curve modelling

3.2.1. General considerations

Comparing our new light curves with Beyer's one (1929) it is evident that the 1998 curves show more significant ellipsoidal changes than the old one. Now the system corresponds to semidetached configuration. Moreover, it is obvious at the first glance that the curve is strongly asymmetric. There is a systematic difference between the brightness in the two quadratures (about 0.01 mag), and the curve seems to be depressed on the ingress to primary eclipse. (Although we gave 0.04 magnitude formal errors for the V and R brightnesses of the variable in Table 1, the greater part of these errors arise from the standard transformation, and the uncertainty of the original (relative) photometric data is much more less, thus this 0.01 magnitude difference is obviously relevant.) The missing or very small reflection effects at the first and last contacts are also remarkable. If the system really consists of early-type stars the presence of a dark spot can be disclosed. The possibility of a hot spot can also be excluded due to the behaviour of the V–R colour index (see Fig. 5), which clearly shows that the system is redder in the first (brighter) quadrature than in the second one. Moreover, before the first contact of the primary minimum the system becomes considerably hotter. (This is the opposite case of what we would expect if a hot spot were present on one of the stars.)

In our opinion the unusual behaviour of the light curves and the color index may be explained with circumstellar material in the system. This is why we used the current (November 1998) version of Wilson's eclipsing binary modelling program (Wilson 1998). This code already considers 'circumstellar light-attenuating regions', co-rotating with the system. In the present version these are taken to be spherical, and their only effect is the attenuation of starlight that passes through them (due to Thomson scattering, Rayleigh scattering and absorption). Moreover, properties of the circumstellar matter are not allowed to adjust. In the following subsection we give a phenomenological description only, then we examine the physical plausibility of such a solution.

3.2.2. The solution

As we already mentioned, the spectral classification is uncertain. We adopted the B3V classification for the primary star, so we fixed its temperature to $T_1 = 18,700\,\mathrm{K}$. Theoretical limb-darkening coefficients derived by Wade & Rucinski (1985) were adopted for both components. The assumed bolometric albedos and gravity-darkening exponents are appropriate for non-convective stellar exterior. After forming normal points we started the solution in MODE 5 of Wilson's code (in which the secondary exactly fills its Roche–lobe) simultaneously for the V and R bands, with seven free parameters: phase shift, inclination (i), temperature of the secondary (T_2), the primary's potential (Ω_1), mass ratio (q), and the monochromatic luminosity of the primary in V and R bands ($L_{V,R1}$).

At that first stage we were looking for an approximate solution without any distortion effect. After several runs we realized that there was a significant discrepancy between the depths of the two minima and the color indices. First we tried to solve this problem by adjusting the third light (l_3), but we got a notoriously negative value. This is why we could not find any reliable approximate solution without the circumstellar material.

As we did not have any a priori information about the circumstellar medium we examined three different configurations: (a) the secondary loses its mass via the L_2 Lagrangian point; (b) there is a mass-transfer between the two components; and lastly (c) we mixed the previous two.

In case (a) we obtained the approximate position and the size of the circumstellar 'cloud' projected onto the secondary star in the following way. We were looking for a 'solution' for the R curve with a dark spot on the secondary. After several runs we got a suprisingly good fit. (There was only a significant discrepancy before the first contact of the primary minimum due to the reflection effect. Of course this 'solution' was not valid for the V curve.) We got not only the (projected) geometry of the light-attenuating region, but also the nearly final parameters.

Then we 'put' the circumstellar material into the system. In that first model the cloud was of spherical shape in the orbital plane of the system, located at the distance of the L_2 point centered above the 207° longitude of the secondary star. (The longitude is measured counter-clockwise from the direction of the primary.) Finally, we found that an ellipsoidally-shaped, non-uniformly dense circumstellar medium gives a better solution.

In the purely mass-transfer case (b) we found only a weaker solution (e.g. the weighted sum of of the squares of the residuals [$\sum wr^2$] was significantly greater), while the case (c) fit is close to case (a). However, all the three solutions are so close to each other (almost undistinguishable) that we refrain from determining a rank between our models.

It is a well-known fact that the rapid phase of mass-transfer could spin up the gainer star. (For a short summary on the consequences of the fast rotation see Wilson (1994), and references therein.) When we allowed to adjust the F_1 rotational parameter in the models above we got physically unrealistic (negative) values in case (b), while in the (a) model this parameter differed only slightly from unity. In the third (c) model a high rotational ratio was obtained. This result forced us to try to obtain a double-contact configuration (MODE 6 in WD code) solution also. However, this gave only a weaker fit.

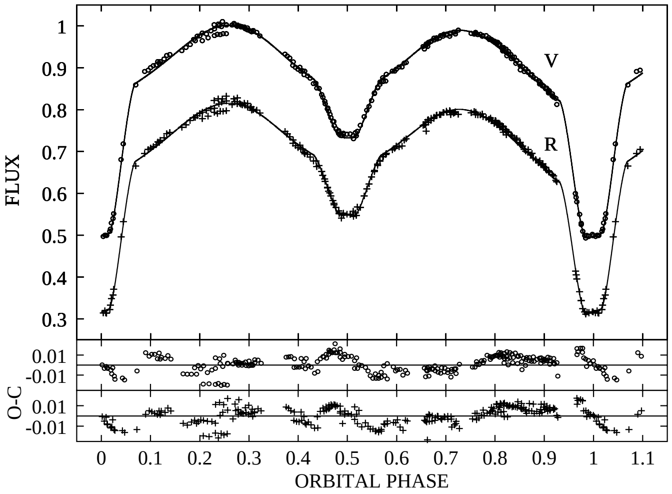

Fig. 2. Light curve of DL Cyg, fit and residuals in V and R bands, according to the case (a) solution. (An offset of -0.2 was applied at the R curve.)

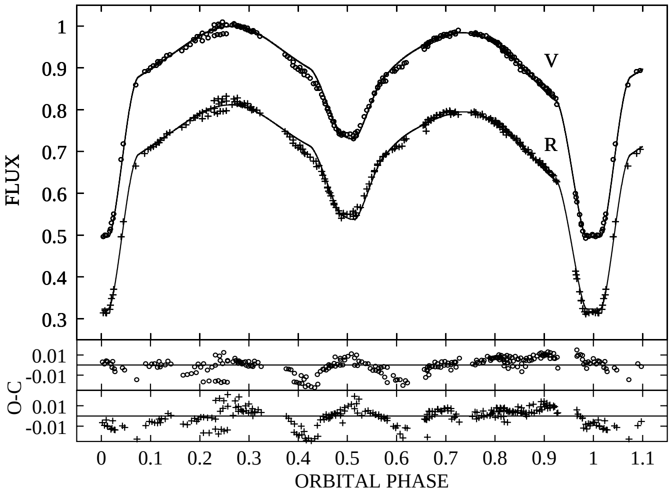

Fig. 3. The same as Fig. 2 but for case (b) solution

Our final results can be found in Table 6, the parameters of the circumstellar media in Table 7, while Figs. 2, 3, 4 show the observed and calculated light curves in V and R filters, together with the plots of the O–C residuals. Fig. 5 shows the observed and calculated V–R curves.

4. Discussion

Due to the lack of spectroscopic information our results are far from unique. Assuming a typical B3V primary with $m_1 = 7.60$ $\mathrm{M}_\odot$ we calculated the absolute dimensions and the related physical quantities of the system (Table 8). The size of the primary is in good agreement with a B3 main-sequence star. It is also obvious that the secondary is an evolved star. A B8-9III classification seems to be likely.

As the secondary fills its limiting lobe we calculated with zero eccentricity. At some iterational step we allowed to vary

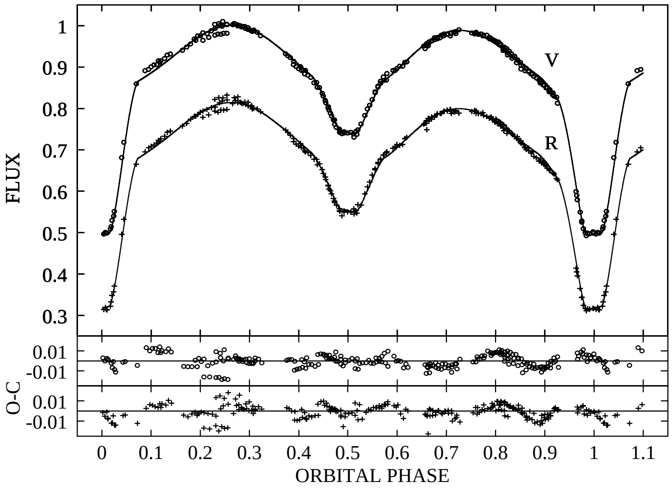

Fig. 4. The same as Fig. 2 but for case (c) solution

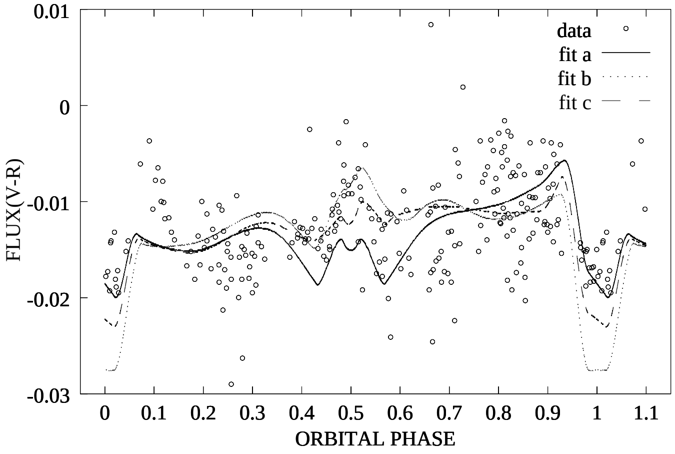

Fig. 5. The fits to the V–R color index

Table 6. Parameter values

Parameters	Model (a)	Model (b)	Model (c)
e	0.0	0.0	0.0
i	83.°95±0.°07	83.°84±0.°08	83.°08±0.°07
F_1	1.00	1.00	8.59±0.23
F_2	1.00	1.00	1.00
T_1	18700 K	18700 K	18700 K
T_2	11180±26 K	10654±29 K	10353±26 K
A_1	1.0	1.0	1.0
A_2	1.0	1.0	1.0
Ω_1	7.608±0.027	6.948±0.036	8.156±0.048
Ω_2	2.630	2.773	2.758
q	0.377±0.004	0.457±0.007	0.440±0.006
x_{1V}	0.280	0.280	0.280
x_{2V}	0.384	0.400	0.400
x_{1R}	0.220	0.220	0.220
x_{2R}	0.306	0.310	0.310
$L_1/(L_1+L_2)_V$	0.3411±0.0008	0.3918±0.0010	0.3787±0.0037
$L_1/(L_1+L_2)_R$	0.3268±0.0008	0.3743±0.0011	0.3600±0.0034
l_3	0.0	0.0	0.0
$\sum wr^2$	2.77625	3.88743	2.78309
r_1(pole)	0.1385±0.0005	0.1537±0.0009	0.1302±0.0008
r_1(point)	0.1390±0.0005	0.1545±0.0009	0.1562±0.0020
r_1(side)	0.1388±0.0005	0.1541±0.0009	0.1555±0.0019
r_1(back)	0.1390±0.0005	0.1544±0.0009	0.1560±0.0020
r_2(pole)	0.2788±0.0008	0.2911±0.0011	0.2903±0.0010
r_2(point)	0.4022±0.0086	0.4181±0.0114	0.4170±0.0102
r_2(side)	0.2906±0.0009	0.3037±0.0012	0.3028±0.0011
r_2(back)	0.3233±0.0009	0.3363±0.0012	0.3354±0.0011

Table 7. The parameters of the circumstellar medium. The origin of the right handed coordinate-frame is at the center of the primary. The x axis directed toward the secondary. Both the (x, y) coordinates, and r (the radius of the spherical-shape cloud) are in the unit of separation. The ρ means the mass density, in g/cm^{-3}.

Models	x	y	r	ρ
(a)	1.1533	0.4717	0.30	1.9×10^{-16}
	1.4717	0.1533	0.37	5.3×10^{-16}
(b)	0.2819	0.1026	0.14	4.6×10^{-15}
	0.0000	0.2500	0.08	4.6×10^{-15}
(c)	0.4963	0.0609	0.13	5.3×10^{-15}
	1.1533	0.4717	0.30	2.6×10^{-16}
	1.4885	0.0861	0.30	5.6×10^{-16}

the eccentricity, but we never got a value larger than some thousandths.

The presence of circumstellar matter in semidetached systems is not a suprising fact. (On the other hand, if the circumstellar gas really exists then the earlier models mentioned in the Introduction which attributed a detached configuration to the system might not be entirely valid.) The possible increase in the orbital period is in agreement with both the mass transfer from the lower mass secondary to the more massive primary and the mass loss from the system. As it was already mentioned in the previous section, ‘a certain amount of spin-up of the mass-accreting star should occur in the rapid phase of mass transfer’ (Wilson et al. 1985). The fast rotation forms the gainer star to lenticular-shape which produces a similar effect in its light distribution as a cool circumprimary gas in its equatorial plane (see eg. Wilson & Mukherjee 1988). This could be the reason why we could not make a clear distinction between our different fits described in the previous section. Moreover, we could not exclude the presence of an accretion disc around the primary, although according to the Lubow & Shu (1975) condition we could expect that due to the relatively large fractional radius of the primary component, the mass-transfering stream (if any) hits the gainer star directly. (See Table 2 in Lubow & Shu 1975, or Fig. 2 in Plavec 1989.)

It is very difficult to say anything about the evolutionary status of the DL Cyg system. If it really consists of a fast rotating primary then it might be in the rapid mass transfer phase, as this phenomenon should be damped quickly when mass transfer terminates. In that case the presence of the circumstellar gas not only between the two stars, but also above the back side of the secondary obtains a natural explanation as an indicator of the continuous mass loss from the binary.

Table 8. Absolute dimensions

Parameters	Model (a)	Model (b)	Model (c)
a ($R_\odot$)	26.2	26.6	26.6
m_1 ($M_\odot$)	7.54	7.52	7.55
m_2 ($M_\odot$)	2.84 ± 0.02	3.36 ± 0.05	3.32 ± 0.04
R_1 ($R_\odot$)	3.63	4.10	3.86
R_2 ($R_\odot$)	7.80	8.29	8.26
M_{bol1}	$-3.^{\mathrm{m}}11$	$-3.^{\mathrm{m}}38$	$-3.^{\mathrm{m}}25$
M_{bol2}	$-2.^{\mathrm{m}}54$	$-2.^{\mathrm{m}}46$	$-2.^{\mathrm{m}}33$
log g_1	4.20	4.09	4.14
log g_2	3.11	3.13	3.13

In the light of these facts and ambiguities, we can summarize what kind of observations are important in the future. We think this system might be an outstanding candidate for extended study. It shows deep, complete eclipses, and the secondary is bright and massive enough to be observed with reasonable ease not only photometrically, but spectroscopically too. (Amongst the rapidly rotating Algols tabulated in Van Hamme & Wilson 1990 perhaps only RW Monocerotis has the same lucky features.) Spectroscopic observations are needed to determine the spectral classification of the system, and to get an accurate mass-ratio. These observations could show evidence for mass transfer (emission lines with appropriate velocity behavior), and they could also indicate the asynchronous rotation. Furthermore, photometric observations are important for detecting any changes in the light curve. Monitoring of the times of minima is also necessary to determine the mass transfer and/or mass loss ratio.

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