Photometric study of the eclipsing binary EG Cep

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Abstract. New photoelectric B and V observations of EG Cep were taken and 11 new minima times were determined. They confirm the long-term increase of the orbital period. The light-curve analysis shows that the system is semi-detached. Mass transfer from the less to the more massive component is responsible for the observed orbital period increase. Variations in the transferred matter projected onto the surface of the components are responsible for the colour dependent variable shift of the minima. This effect, more pronounced in the secondary minima, explains also the disagreement of the limb-darkening coefficient of the secondary component with the theoretical value.

Key words: binaries - photometry

1. Introduction

EG Cep (BD +76°790, HD 194089, $V_{max} = 9.36$) was discovered by Strohmeier (1958) as an eclipsing binary with the following ephemeris: Min I = 2 426 929.458 + 0.5446202 E. The shape of the light-curve is typical of the β Lyr type with the depths of the primary and secondary minima $\Delta V_{\rm I} = 0.87$ mag and $\Delta V_{\rm II} = 0.29$ mag, respectively. Photoelectric light-curves were taken by Geyer (1961), Cochran (Wood, 1971), Van der Wal et al. (1972), Kaluzny & Semeniuk (1984)(K&S) and Erdem et al. (1993).

K&S found the value of interstellar extinction to EG Cep as E(B-V) = 0.035 and its distance $d = 120$ pc. They used the intrinsic colour index $(B\text{-}V)_0 = 0.197$ to derive the spectral type A7 of the primary component in disagreement with the spectral type of A3 given in the HD catalogue. Etzel & Olson (1993) determined the projected rotational velocity of this component as $v_1 \sin i =$

(146±20) km s^{-1}, measuring the half-width of the Mg 448.1 nm line using one spectrum only. Other spectroscopic observations of EG Cep were not published.

Photoelectric light-curves were analyzed by K&S using the Wilson & Devinney (1971)(W&D) method. The derived photometric mass ratio q = (0.45 - 0.50) led to the semi-detached configuration with the $M_1 \sim 1.8$ $M_\odot$ unevolved primary and evolved secondary. K&S also analyzed the *(O-C)* diagram and found continuous orbital period increase. They determined the quadratic term 8.2×10^{-11} d. Explanation of this term by the mass transfer from the secondary to the primary component leads to the mass transfer rate $\dot{M} = 10^{-7}$ $M_\odot y^{-1}$. Wolf & Diethelm (1992) determined the quadratic term as 7.82×10^{-11} d and noted that omitting the secondary minima, which they consider to be asymmetrical, two linear ephemeris are also suitable for the explanation of the *(O-C)* diagram. Erdem et al. (1993) found the quadratic term to be 4.73×10^{-11} d.

The aim of our paper is to present additional times of the minima of EG Cep, to discuss disagreement in the times of minima in the V and B passband and to determine a new ephemeris for the case of sudden and continuous period change, respectively.

2. New observations

The first set of our photoelectric observations of EG Cep was performed in 1983-84 using a multi-mode, nebular-stellar photometer attached to the 1.22 m Cassegrain reflector at the Kryonerion Astronomical Station (KAS) of the National Observatory of Athens, Greece. The B and V filters used closely conform to the international standard UBV system. The second set of observations in the B and V passbands was obtained in 1997 at the Skalnaté Pleso (SP) and Stará Lesná (SL) observatories of the Astronomical Institute of the Slovak Academy of Sciences. In both cases an 0.6 m Cassegrain telescope equipped with a single-channel pulse-counting photoelectric photometer was used.

In the case of the KAS observations, stars BD +75°737 (V = 9.5, sp. type A0) and BD +74°857 (V = 10.7, sp. type A2) served as the comparison and check star, respectively. In the case of the SP and SL observations, stars BD +76°791 (V = 9.2, sp. type K2) and BD +76°789 (V = 9.6, sp. type A0) were used.

Data reduction, the atmospheric extinction correction and transformation to the standard international system were carried out in the usual way.

3. Period change of EG Cep

Our observations led to the determination of 11 new times of minima. We have calculated the times of minima separately from B and V observations using Kwee & van Woerden's (1956) method (Table 1).

Table 1. New times of minimum light of EG Cep. The epochs were calculated according to Strohmeier's (1958) ephemeris.

Epoch	B		V		Obs.
	JD_{hel} 2 400 000+	σ [days]	JD_{hel} 2 400 000+	σ [days]	
34266	45591.44113	0.00003	45591.43957	0.00010	KAS
34268	45592.52767	0.00003	45592.52856	0.00034	KAS
34269.5	45593.34637	0.00014	45593.34689	0.00017	KAS
34914	45944.35676	0.00024	45944.35516	0.00028	KAS
34916	45945.44566	0.00012	45945.44395	0.00006	KAS
34919.5	45947.35141	0.00022	45947.34913	0.00010	KAS
43588	50668.41219	0.00021	50668.41180	0.00017	SL
43599	50674.40330	0.00028	50674.40337	0.00034	SP
43714.5	50737.31060	0.00060	50737.31000	0.00040	SL
43744	50753.37367	0.00039	50753.37436	0.00017	SL
43794	50780.60460	0.00070	50780.60473	0.00030	SP

To explore the period variations of EG Cep, we have collected in Table 2 all the times of minima available from the literature and have added our 11 times of minima (BV averages). Older times of minima based on photographic and visual observations were used by Hopp et al. (1983) to derive normal epochs (NE). The NE accuracy is comparable with the photoelectric times of minima. We have also included 6 NE, which we have calculated using Strohmeier's (1958) photographic times of minima. The times of minima in Table 2 were used to construct the *(O-C)* diagram (Fig. 1) applying the following ephemeris Min I = 2426929.4376 + 0.5446216 *E*.

The period change seen in the *(O-C)* diagram (Fig. 1) can be either:

1. Continuous increase. We obtained the following ephemeris:

$$\begin{array}{lllll} \text{Min I} = \mathrm{JD_{hel}}\ 2\,426\,929.4575 & + \ 0.54461943 & \times E & + \ 4.51\ 10^{-11} \times E^2. & \\ \qquad\qquad\qquad\qquad \pm 12 & \qquad \pm 10 & & \quad \pm 19 & (1) \end{array}$$

   The sum of squares of the residuals for the parabolic fit is 0.0004459 d^2. The total increase of the orbital period from onset of observations is $\Delta\ P/P = (7.25 \pm 0.30) \times 10^{-6}$.

2. The sudden period change around the year 1972. The minimum sum of squares of the residuals for the two linear fits occurs for the jump between $E = 26272$ and $E = 26751$. The ephemeris valid for $E < 26500$ was:

$$\begin{array}{lll} \text{Min I} = \mathrm{JD_{hel}}\ 2\,426\,929.4539 & + \ 0.54462069 & \times E, \\ \qquad\qquad\qquad\qquad \pm 14 & \qquad \pm 7 & \end{array} \qquad (2)$$

and for $E > 26500$:

$$\text{Min I} = \text{JD}_{\text{hel}}\ 2\,426\,929.3986 \underset{\pm 20}{} + \underset{\pm 6}{0.54462272} \times E. \tag{3}$$

The sum of squares of the residuals for the two linear fits is 0.0004318 d^2. Evidently the relative change of the period, caused by the jump, was $\Delta\ P/P = (3.72\pm0.17)\times10^{-6}$.

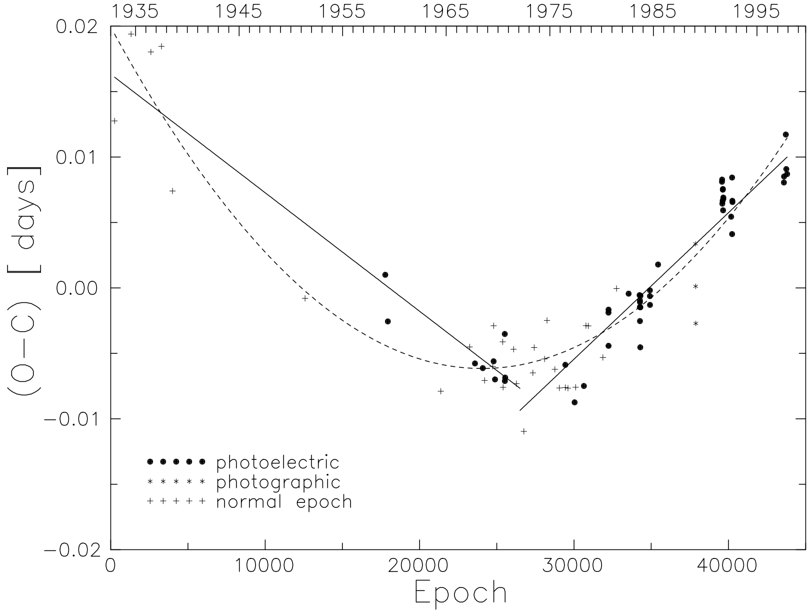

Figure 1. The *(O-C)* diagram for EG Cep

The larger value of the quadratic term in the parabolic ephemeris given by K&S and Wolf & Diethelm (1992) in comparison with the value published by Erdem et al. (1993) and our ephemeris (1) was due to the former two authors omitting Strohmeier's (1958) observations.

The times of the minimum light for $E < 26500$ yield the quadratic term $a = (0.29\pm0.13)\times10^{-10}$ d, which differs from $a' = (1.22\pm1.25)\times10^{-10}$ d found for $E > 26500$. If the period change were continuous, the quadratic term would be the same in both intervals. Moreover, the error of the quadratic term a' is larger than its value. The sum of squares of the residuals for the two linear fits is lower than for the parabolic fit. Therefore, the sudden period increase around the year 1972 seems to be more probable.

K&S noted that the time of the secondary minimum in the B light occurred in average 0.003 days later than in the V light. On the other hand, Erdem et al. (1993) did not observe any shift. To resolve the dilemma, we have gathered the

Table 2. The times of minima of EG Cep.

Epoch	JD$_{hel}$ 2 400 000+	Filt.	Ref.
246	27063.4273	NE	1
1314	27645.0898	NE	1
2604	28347.6503	NE	1
3283	28717.4488	NE	1
4003	29109.5653	NE	1
12582	33781.8658	NE	1
17781	36613.3553	BV	2
17941	36700.4912	BV	2
21373	38569.6272	NE	3
23244	39588.6176	NE	3
23585	39774.3323	V**	4
24092	40050.4551	V**	4
24210	40114.7195	NE	3
24739	40402.8254	NE	3
24794	40432.7827	NE	3
24795	40433.3246	V	4
24887	40483.4284	V	4
25388	40756.2867	NE	3
25410	40768.2649	NE	3
25513	40824.365	V	5
25522	40829.263	pe*	6
25542.5	40840.428	pe*	6
26081	41133.7089	NE	3
26272	41237.7290	NE	3
26751	41498.5991	NE	3
27336	41817.2072	NE	3
27422	41864.0466	NE	3
28092	42228.9422	NE	3
28257	42318.8077	NE	3
28763	42594.3825	NE	3
29051	42751.2321	NE	3
29434	42959.8222	NE	3
29437	42961.4578	V	7
29612	43056.7648	NE	3
30037.5	43288.5002	V	8
30104	43324.7187	NE	3
30641.5	43617.4529	V	9
30775	43690.1645	NE	3
30924	43771.3131	NE	3
31869	44285.9781	NE	3
32233.5	44484.4961	UBV	3
32235.5	44485.5830	BV	3
32237	44486.4025	UBV	3
32755	44768.5181	NE	3
33537	45194.4118	V	10
34246	45580.5484	BV	11
34260.5	45588.4445	BV	11
34266	45591.4403	BV	12
34268	45592.5281	BV	12
34269.5	45593.3466	BV	12
34291.5	45605.3247	BV	11
34293.5	45606.4170	BV	11
34299	45609.4133	BV	11
34914	45944.3560	BV	12
34916	45945.4448	BV	12
34919.5	45947.3503	BV	12
35443	46232.4628	V	13
37870	47554.261	pg	14
37872	47555.347	pg	14
37883	47561.335	pg	14
39576	48483.3902	BV	15
39587	48489.3812	BV	15
39598	48495.3702	BV	15
39622	48508.44134	B	16
39636.5	48516.3392	BV	15
39640.5	48518.51773	B	16
39649.5	48523.4177	BV	15
39666	48532.40483	B	16
39668	48533.49417	B	16
40176.5	48810.4328	BV	15
40233.5	48841.4749	BV	15
40237	48843.3854	BV	15
40250	48850.4637	BV	15
40259	48855.3652	BV	15
43588	50668.4120	BV	12
43599	50674.4033	BV	12
43714.5	50737.3103	BV	12
43744	50753.3740	BV	12
43794	50780.6047	BV	12

* - without filter, ** - filter not given in the original paper

References: 1 - Strohmeier (1958), 2 - Geyer (1961), 3 - Hopp et al. (1983), 4 - Ahnert (1975), 5 - Van der Wal et al. (1972), 6 - Kizilirmak & Pohl (1971), 7 - Pohl & Kizilirmak (1977), 8 - Ebersberger et al. (1978), 9 - Pohl & Gülmen (1981), 10 - Pohl et al. (1983), 11 - Kaluzny & Semeniuk (1984), 12 - this paper, 13 - Pohl et al. (1987), 14 - Wenzel (1989), 15 - Erdem et al. (1993), 16 - Wolf & Diethelm (1992) times of the minima published separately for the B and V light. The differences between the times of the minima in the B and V light given in Table 3 are plotted in Fig. 2.

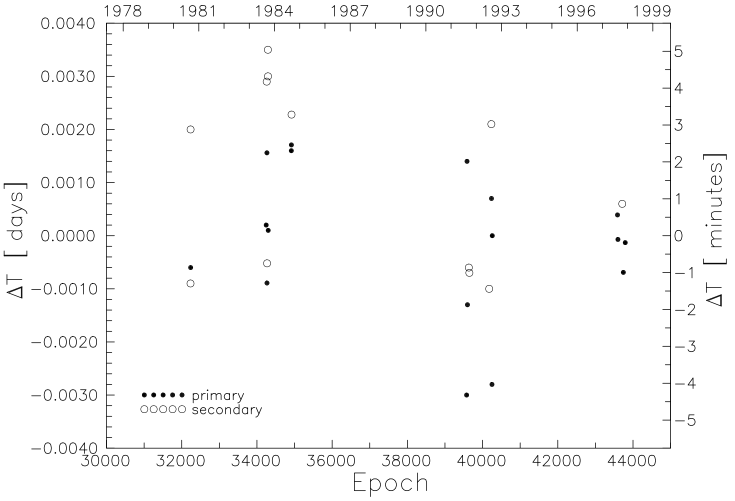

Figure 2. The differences between the times of minima in the B and V light.

It is apparent that the shifts between the times of minima in the B and V light are highly variable on the time scales of a few days. Their Fourier period analysis in the range of 1 - 10 days gave the best period 1.669 days.

Table 3. The time shifts between the minimum in B and V passband

Epoch	JD_{hel} 2 400 000+	ΔT_{B-V}	Ref.*
32233.5	44484.4957	-0.0009	3
32235.5	44485.5830	0.0020	3
32237	44486.4029	-0.0006	3
34246	45580.5484	0.0002	11
34260.5	45588.4445	0.0029	11
34266	45591.4403	0.00156	12
34268	45592.5281	-0.00089	12
34269.5	45593.3466	-0.00052	12
34291.5	45605.3247	0.0035	11
34293.5	45606.4170	0.0030	11
34299	45609.4133	0.0001	11
34914	45944.3560	0.00160	12
34916	45945.4448	0.00171	12
34919.5	45947.3503	0.00228	12
39576	48483.3902	-0.0030	15
39587	48489.3812	0.0014	15
39598	48495.3702	-0.0013	15
39636.5	48516.3392	-0.0006	15
39649.5	48523.4177	-0.0007	15
40176.5	48810.4328	-0.0010	15
40233.5	48841.4749	0.0021	15
40237	48843.3854	0.0007	15
40250	48850.4637	-0.0028	15
40259	48855.3652	0.0000	15
43588	50668.4120	0.00039	12
43599	50674.4033	-0.00007	12
43714.5	50737.3102	0.00060	12
43744	50753.3740	-0.00069	12
43794	50780.6047	-0.00013	12

* - like in Table 2

4. Light-curve analysis

Our observations in 1997 demonstrate that the light-curve of EG Cep was stable and symmetrical. As our observations did not cover the whole orbital period we have folded the light-curve around phase 0.5. The resulting B and V light-curves are displayed on Fig. 3.

As noted by K&S, the short phases of constant light are present in both minima. The B-V colour index exhibits (compared with B-V around maxima) a 0.05 mag increase and 0.03 mag decrease in the primary and secondary minimum, respectively. These behaviour is caused by the temperature difference between the components.

The observations shown in Fig. 3 were used to compute 94 normal points in each passband using the method of running parabolae (Andronov, 1997). We have assigned the same weight to each normal point. The W&D code was employed to determine the photometric elements of the system. As the first approximation we have used the photometric elements of EG Cep computed by K&S for $q = 0.45$ in mode 2, which is appropriate for detached configuration. In all cases, black-body radiation of both components was assumed and $T_1 = 7800$ K was accepted (K&S). The differential correction code was run until the corrections to the input parameters were lower than their errors. The luminosity of the secondary component was not minimized - it was computed automatically after every program run. Since the detached model led to non-physical solutions, we had to fix the surface potential of the secondary component Ω_2 on the inner critical surface. We have solved the light-curves for two cases: (i) inclination i, the polar temperature of the secondary T_2, the surface equipotential of the primary Ω_1 and mass ratio q were optimized, all other elements were fixed, (ii) the optimization of limb-darkening coefficients x_1 and x_2 was added to the previous case. The best photometric elements for both cases are given in Table 4. The elements of EG Cep do not fit the light-curve properly (see Fig. 4). The most problematic is fitting the descending and ascending branches of the secondary minimum in the V passband. A similar behaviour can also be clearly seen in Fig. 3 of K&S.

The fit for the V light is somewhat better in the second case with the limb-darkening coefficients not fixed. While the limb-darkening coefficient of the primary component in the V light is in good agreement with the expected value (e.g., Grygar et al., 1972), its value for the secondary component is abnormally low. The problem with the inexact fitting of the secondary minimum branches in the V passband is probably caused by the uneven distribution of temperature on the facing hemisphere of the secondary component. The surface brightness of the secondary component around the L_1 point must be lower than expected from normal limb and gravitational darkening, suggesting the presence of a dark spot(s) or/and matter projected on the secondary component. Short-term variations of the shifts of minima in the B and V passbands are in favour of variations in the mass transfer. We have also tried to relax the third light, which came out

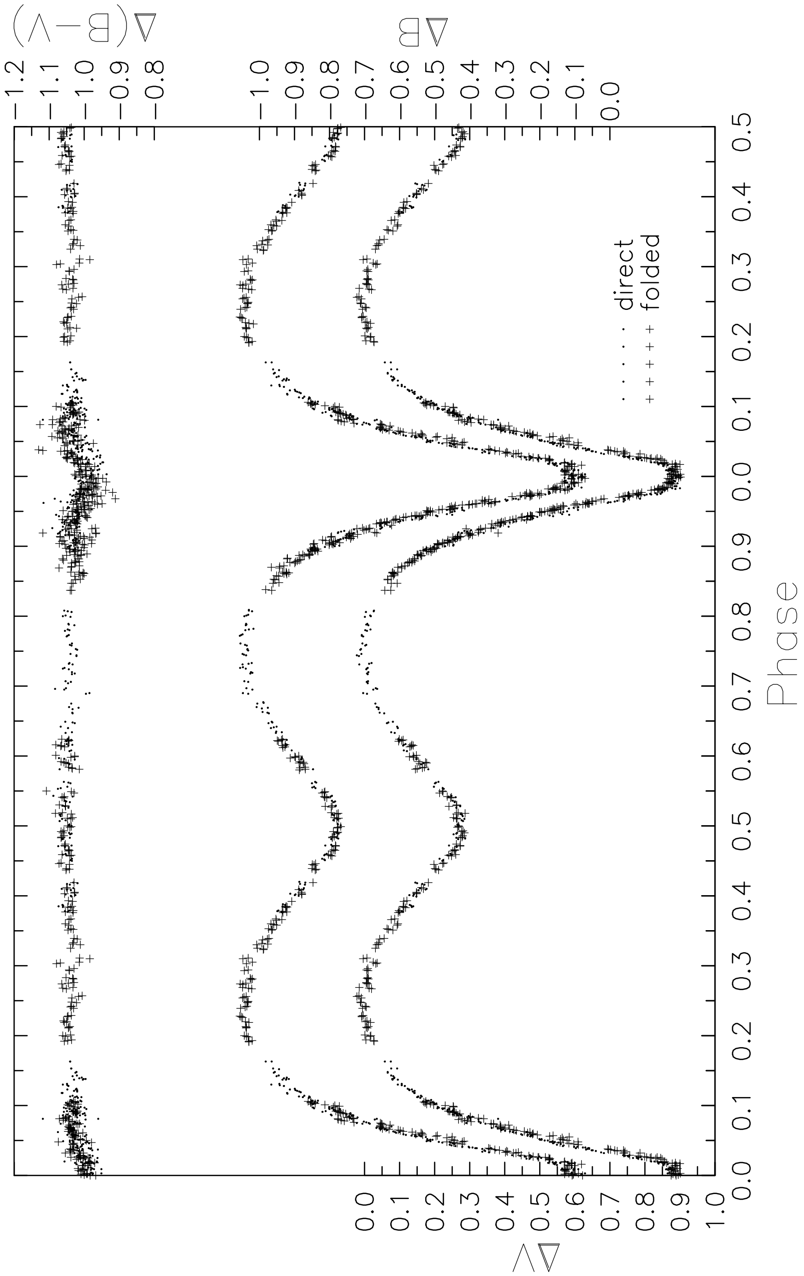

Figure 3. B and V light-curves from all our observations performed at the Stará Lesná and Skalnaté Pleso observatories.

Table 4. Photometric elements of EG Cep for a semi-detached configuration

Parameter		1		2	
			σ		σ
i [°]		86.1	0.08	86.0	0.25
q		0.468	0.002	0.470	0.003
T_2 [K]		5000	13	4988	13
Ω_1		2.8551	0.0047	2.8582	0.0061
Ω_2		2.8137	-	2.8176	-
L_1	B	0.9531	0.0001	0.9536	0.0001
	V	0.9281	0.0001	0.9288	0.0001
L_2	B	0.0469	-	0.0464	-
	V	0.0719	-	0.0712	-
x_1	B	0.680	-	0.658	0.0058
	V	0.550	-	0.602	0.0070
x_2	B	0.950	-	0.989	0.0897
	V	0.850	-	0.222	0.1256
Σ (O–C)^2	B	0.0193	-	0.0177	-
	V	0.0257	-	0.0210	-

slightly negative in both passbands. The corresponding fits, however, were not better than in the previous cases. Schematic model of the semi-detached system EG Cep is given in Fig. 5.

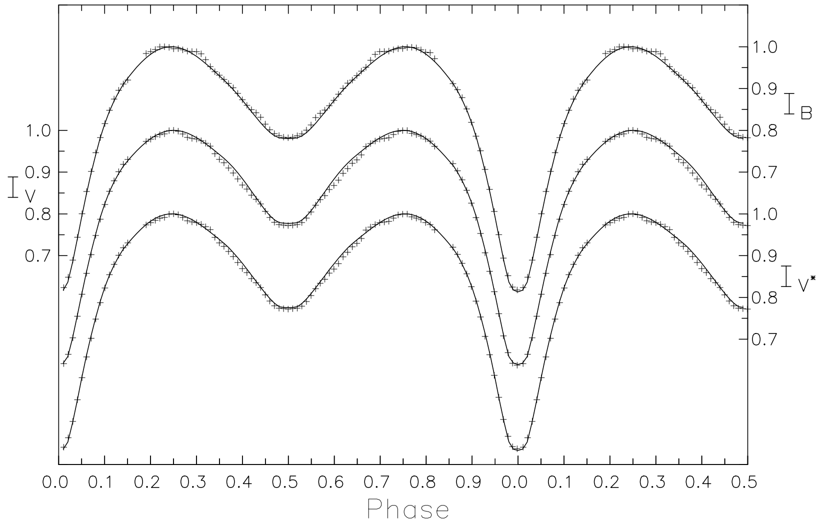

Figure 4. B and V light-curves and fits corresponding to the first solution (top). Fit of the V light-curve corresponding to the second solution (bottom).

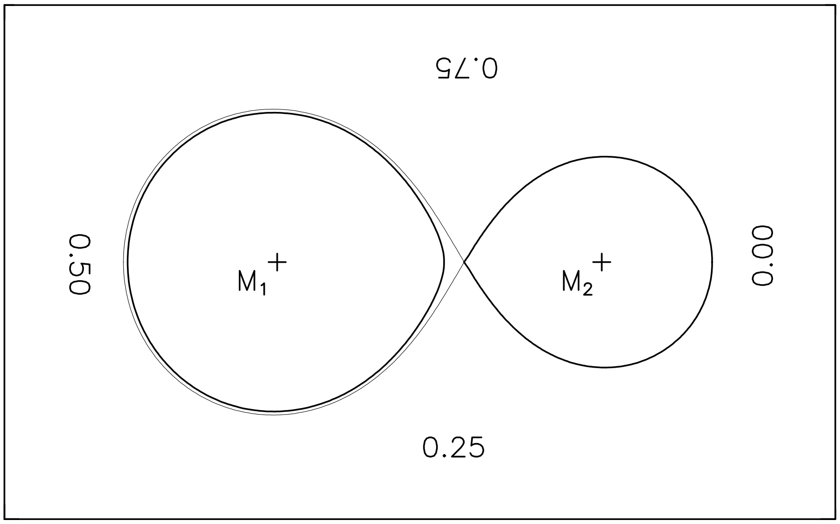

Figure 5. Schematic model of EG Cep

5. Discussion and conclusions

Our analysis of the *(O-C)* diagram showed that the sudden period change (around the year 1972) is more probable than the continuous one. Straightforward explanation of the sudden period increase is a mass transfer from the less massive to the more massive component. The relative change of the period caused by the mass transfer can be expressed as:

$$\frac{\Delta P}{P} = \frac{\Delta m}{m}\frac{3(1-q^2)}{q}. \tag{4}$$

Using $q = 0.47$ and the approximate mass of the primary component of EG Cep $M_1 = 1.8$ $M_\odot$ (K&S), the total mass transferred from the less to more massive component during the period jump came out as $\Delta m = 2\times10^{-6}$ $M_\odot$. Such large quantity of matter would surely affect the light-curve of the system. Unfortunately, there are no photoelectric observations of EG Cep at the time of the period jump.

A very interesting feature of the *(O-C)* diagram (Fig. 1) is the large scatter of the *(O-C)* residuals after removing the best fit. The secondary minima exhibit larger scatter than the primary. These results, together with the scatter and variations in the difference between the minima times in the B and V passband (Fig. 2) suggest the presence of the matter in the vicinity of L_1. The disagreement of the limb-darkening coefficient of the secondary component with the theoretical value can be explained by the projection of this matter on the surface of the secondary component. This intermittent presence of the transferred matter supports the continuous period change. In such a case the mass transfer rate $\Delta m = 5.9\times10^{-8}$ $\mathrm{M}_\odot$ y^{-1} is necessary.

The rotational velocity of the primary component, determined by Etzel & Olson (1992) as $v_1 \sin i = (146\pm20)$ km s^{-1}, allowed us to check the mass of the primary component and mass ratio. Since the primary component is close to the inner critical surface, it is reasonable to assume its synchronous rotation. If r_1 is the mean fractional radius of the primary component, derived from its surface potential Ω_1 and mass ratio q, we can easily derive the photometric rotational velocity as:

$$v_1 = r_1 \left[\frac{2\pi G M_1(1+q)}{P}\right]^{1/3} . \tag{5}$$

For $M_1 = 1.8$ $\mathrm{M}_\odot$, $r_1 = 0.437$ and $q = 0.47$ we will get $v_1 = 157$ km s^{-1}, in agreement (within the range of errors) with the value determined by Etzel & Olson from spectroscopy.

Even if we were able to determine the mass ratio precisely, spectroscopic observations would be very helpful in determining the masses of the components reliably, and for good spectral classification.

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