Bull. Astron. Belgrade № 155 (1997), 55 – 62

UDC 524.387–54
Original scientific paper

ESTIMATION OF THE *SW Lac* PARAMETERS BASED ON THE LIGHT-CURVE ANALYSIS

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(Received: February 15, 1997)

SUMMARY: The paper is dedicated to the problem of the estimation of the orbital and physical parameters of short-period W UMa-type system *SW Lacertae* on the basis of the light-curves analysis. The main feature of its light curve is the different heights of the two successive maxima. This asymmetry and variations in the shape of *SW Lac* light curves may be attributed to the existence of active spot regions on some of the system's components. To test this hypothesis we analysed the light curves obtained in V and B filters (Niarchos, 1987). The problem is solved by applying the inverse-problem method (Djurašević, 1992b) in the framework of the Roche model with spots on the components (Djurašević, 1992a). The analysis shows that the system's components are in an overcontact configuration. The Roche model (with two dark-spot regions on the components) gives a good fit to the observations. Two different hypotheses on the spots' location (I - 1st spot on the primary and 2nd spot on the secondary; II - both spots on the secondary) fit the observations equally well. The basic parameters of the system and of active spot regions are estimated with both hypotheses.

1. INTRODUCTION

The eclipsing close binary (CB) star *SW Lac* is a short-period ($P = 0^d.32072$) W UMa-type system. Many light curves were obtained from photographic, visual and photoelectric observations. Photoelectric light curves of the system *SW Lac* were obtained by Rucinski (1968), Semeniuk (1971), Muthasam and Rakos (1974), Faulkner and Bookmyer (1980), Stepien (1980), Mikolajewska and Mikolajewski (1981), Leung *et al.* (1984), Lafta and Grainger (1985), Niarchos (1987), Eaton (1986), Han *et al.* (1988), Essam *et al.* (1992) and Jeong *et al.* (1994). The most striking feature of these light curves is their asymmetry arising from the unequal height of successive maxima. Leavitt (1918) reported that the range of light variations in the primary minimum is significant, while that of the secondary minimum was not detectable. Radial-velocity curves of *SW Lac* were observed by Struve (1949). He determined the observed spectroscopic mass ratio as $q_{sp} = 0.88$ or $m_2/m_1 = 1.14$. Disheng and Wenxian (1989) present their 1984 radial velocity observations. These observations gave a new spectroscopic mass ratio $q = m_2/m_1 = 1.255$. The spectral types of the system were classified as G3 + G3 by Wood *et al.* (1980).

The geometric elements of *SW Lac* derived by Lafta and Grainger (1985) and Niarchos (1987) indicate that the system is in a contact configuration with both components filling their Roche lobes. The analysis of their observations in the V and B filters is carried out by using Kopal's method of the Fourier analysis of the light curves. Leung *et al.* (1984)

and Binnendijk (1984), by using different methods of analysis of the light curves, find *SW Lac* to be an overcontact system. Jeong *et al.* (1994) used the IUE spectra of *SW Lac* for ultraviolet photometry and for a variation study of the chromospheric activity. This activity is indicated by the intensity variation of the Mg II emission line with orbital phase. The light curves are analysed by using the modified differential correction method of Wilson and Devinney (1971). The details concerning these procedures of light curve analysis can be found in the mentioned papers and the references therein.

The orbital period of this system is still decreasing after a period of constancy (Lafta and Grainger, 1985). The decrease of the orbital period may be a result of the mass transfer from the more massive component to the less massive one, or of a mass outflow from L_2 into space.

The significant asymmetry of the Niarchos' (1987) light curves can be explained by assuming the existence of active dark or hot spot regions on some of the system's components. For analysing the asymmetric light curves, deformed by the presence of spots on the components, a Roche model has been developed (Djurašević, 1992a), which is based on the principles originated in the Wilson and Devinney (1971) model.

For a successful application of the realized CB model in analysing the observed light curves, an efficient method, unifying the best properties of the gradient and the differential-corrections methods into a single algorithm (Djurašević, 1992b), is proposed. This method is realized by modifying the Marquardt (1963) algorithm. The inverse problem is solved in an iterative cycle of corrections to the model elements based on a nonlinear least-square method.

The interpretation of photometric observations is based on the choice of optimal model parameters yielding the best agreement between the observed light curve and the corresponding synthetic one. Some of these parameters can be determined *a priori* in an independent way, while the others are found by solving the inverse problem.

2. ANALYSIS

In this paper we present the analysis of light curves of *SW Lac* obtained in the V and B filters (Niarchos, 1987) based on the Roche model of a CB system with spots on the components (Djurašević, 1992a). The significant asymmetry of these light curves indicates a high level of activity in the system. On stars with convective envelopes, as in this case (spectral type G3), one can expect the presence of spots. Therefore, the hypothesis of spot activity appears justified. However, due to the mass and thermal-energy transfers between the components on the W UMa-type systems one can expect also the occurrence of regions with higher temperatures in the equatorial zone on the component towards which the transfer is directed.

A preliminary analysis of light curves shows that both components in this system fill their critical Roche lobes, therefore the tidal effects are expected to cause the synchronisation of rotational and orbital periods. We treated the gravity-darkening coefficients as free parameters in the solving of the inverse-problem. The linear limb-darkening coefficients are determined on the basis of the temperature of the components and of the stellar-surface gravity, according to the given spectral type, by using the polynomial proposed by Díaz-Cordovés *et al.* (1995). The temperature of the primary component T_1, was set at 5630 K based on the spectral type (G3). The temperature of the secondary (T_2) was adjusted. For the mass ratio the spectroscopic determination is the most reliable. For this reason, in the light curves analysis, the mass ratio is fixed at the spectroscopically estimated value - $q = m_2/m_1 = 1.255$ (Disheng and Wenxian, 1989).

The results of the light curve analysis for these systems highly depend on the chosen working hypothesis. The analysis shows that the system's components fill their critical Roche lobes, having approximately the same temperature. Several working hypotheses are considered concerning the nature and possible location of spots. The analysis shows that the Roche model with two dark-spot regions on the components gives a good fit to the observations. The quality of obtained fits is almost identical within two hypotheses: **I.** - 1^{st} spot on the primary and 2^{nd} spot on the secondary; **II.** - both spots on the secondary. For the temperature contrast of these spots with respect to the surrounding photosphere one assumes the value $A_s = T_s/T_2 = 0.65$. In both cases, for system's and for the spots' parameters, estimated by analysing the individual V and B light curves, one obtains relatively concordant solutions (Table 1.). The spots are located on high latitudes, near the star polar region, as could be expected for stars with rapid rotation (Schüssler and Solanski, 1992).

The quality of the obtained results can be presented graphically. Fig. 1 presents the results obtained under hypothesis **I.** It can be seen that model synthetic light curves (LCC) provide a good fit to the observations (LCO), and that the final residuals (O-C) have more or less random character. Although the model fits extremely well the individual light curves, it must be noted that there are some differences between orbit inclination estimations obtained in the analysis of the V and B filter observations (see Table 1). This discrepancy is characteristic also of the second hypothesis (**II**), with both spots situated on the secondary. The qualities of these results are presented by Fig. 2.

Through a specially developed programme (Djurašević, 1991) it is possible to present the view of the system in a selected orbital phase on the basis of the parameters obtained by solving the inverse-

Table 1.

Results of the analysis of the *SW Lac* light curves obtained by solving the inverse problem for the Roche model with two double spot hypotheses:
I. 1st spot on the primary and 2nd on the secondary;
II. both spots on the secondary.

Quantity	1st spot on the primary 2nd spot on the secondary **I.** V - filter	1st spot on the primary 2nd spot on the secondary **I.** B - filter	Both spots on the secondary **II.** V - filter	Both spots on the secondary **II.** B - filter
$\Sigma(O-C)^2$	0.1269	0.1403	0.1261	0.1395
θ_1	21.1 ±0.4	21.2 ±0.4	22.8 ±0.3	21.9 ±0.3
λ_1	89.4 ±2.8	89.5 ±2.7	88.3 ±1.8	87.1 ±1.8
φ_1	43.0 ±1.6	43.3 ±1.6	35.5 ±1.5	35.8 ±1.5
θ_2	11.8 ±0.9	12.6 ±0.8	32.1 ±0.8	33.9 ±0.8
λ_2	195 ±11	198 ±8	267 ±4.8	270 ±4.2
φ_2	61 ±5	59.6 ±5.3	79.4 ±0.7	81.3 ±0.6
F_1	1.000±0.003	1.000±0.004	1.000±0.003	1.000±0.003
F_2	1.000±0.003	1.000±0.003	1.000±0.003	1.000±0.003
T_2	5520 ±15	5520 ±12	5500 ±15	5510 ±12
i	79.6 ±0.2	81.6 ±0.2	79.6 ±0.2	81.3 ±0.2
β_1	0.20 ±0.01	0.194±0.008	0.24 ±0.008	0.24 ±0.007
β_2	0.35 ±0.01	0.350±0.008	0.35 ±0.01	0.35 ±0.008
u_1	0.67	0.75	0.67	0.75
u_2	0.68	0.75	0.68	0.75
Ω_1	4.154	4.154	4.154	4.154
Ω_2	4.154	4.154	4.154	4.154
R_1	0.337	0.337	0.337	0.337
R_2	0.375	0.375	0.375	0.375

FIXED PARAMETERS:
$q = m_2/m_1 = 1.255$ - mass ratio of the components,
$T_1 = 6200K$ - temperature of the primary,
$A_s = T_s/T_1 = 0.65$ - spots temperature coefficients,
$f_1 = f_2 = 1.00$ - nonsynchronous rotation coefficients of the components.

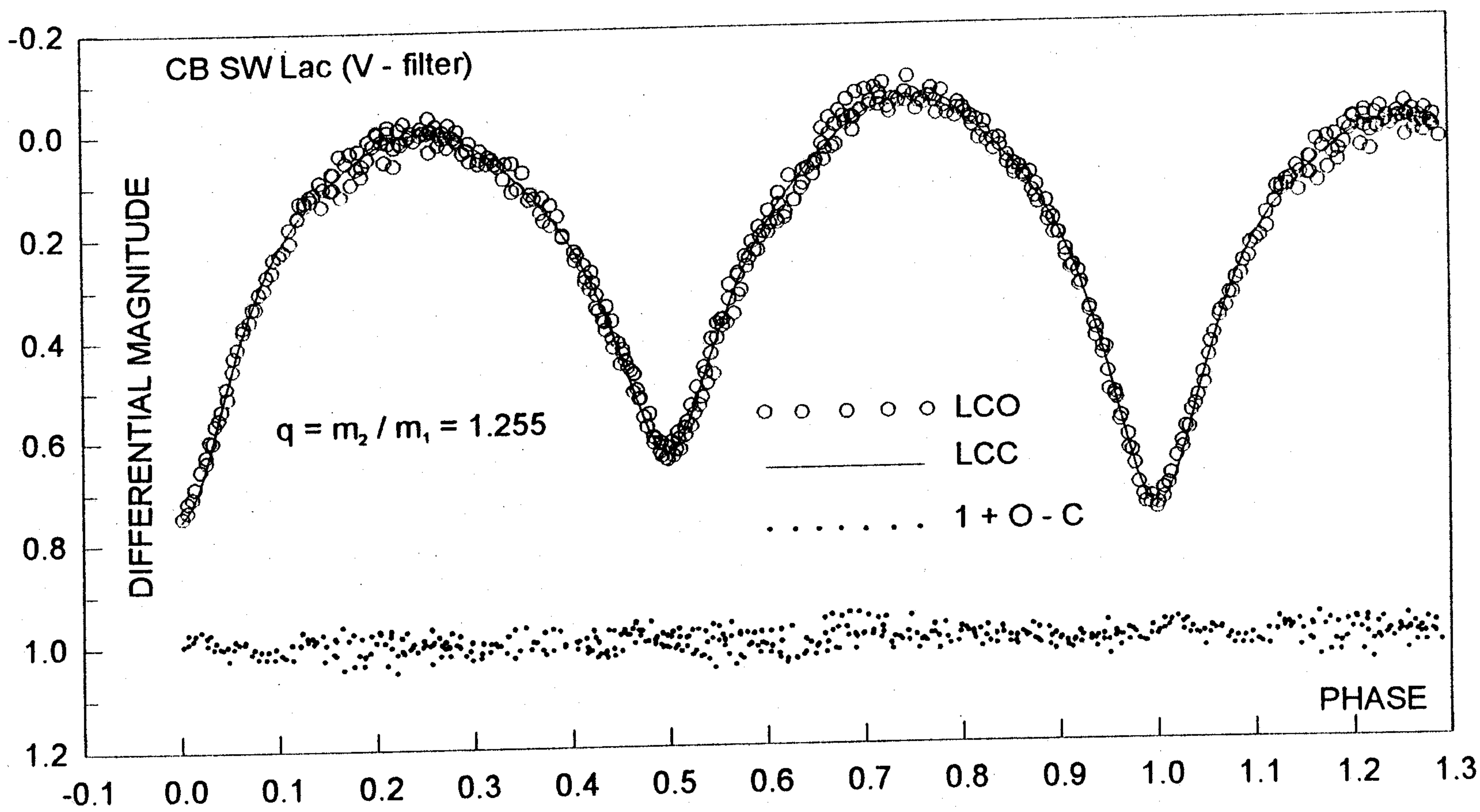
Note: $\Sigma(O-C)^2$ - final sum of squares of residuals between observed (LCO) and synthetic (LCC) light curves, $\theta_{1,2}$ - spots angular dimensions, $\lambda_{1,2}$ - spots longitude and $\varphi_{1,2}$ - spots latitude (all in arc degrees), $F_{1,2}$ - filling coeficients for critical Roche lobes of the primary and secondary, T_2 - temperature of the secondary, i - orbit inclination (in arc degrees), $\beta_{1,2}$ - gravity-darkening coefficients of the components, $u_{1,2}$ - limb-darkening coefficients of the components, $\Omega_{1,2}$ - dimensionless surface potentials of the primary and secondary and $R_{1,2}$ - polar radii of the components in units of the distance between the component centres.

problem. Fig. 3. gives the view of the system for both spot-location hypotheses: (Top - **I.** 1st spot on the primary and 2nd on the secondary; Bottom - **II.** both spots on the secondary).

3. DISCUSSION AND CONCLUSION

The obtained results show that the system components fill their critical Roche lobes, having approximately the same temperature. The system is in the overcontact configuration, which is implied by somewhat higher values of gravity-darkening coefficients. The used model does not predict an overcontact configuration which is compensated by increasing the gravity-darkening coefficients. The overcontact configuration is possible since the approximate equality of the temperatures of main-sequence stars with different masses can be explained through the exchange of thermal energy.

Lafta and Grainger (1985) show that the orbital period of the system decreases. Jointly with the prominent asymmetry of the light curves this can indicate a mass transfer from the more massive component towards the less massive one. As a consequence



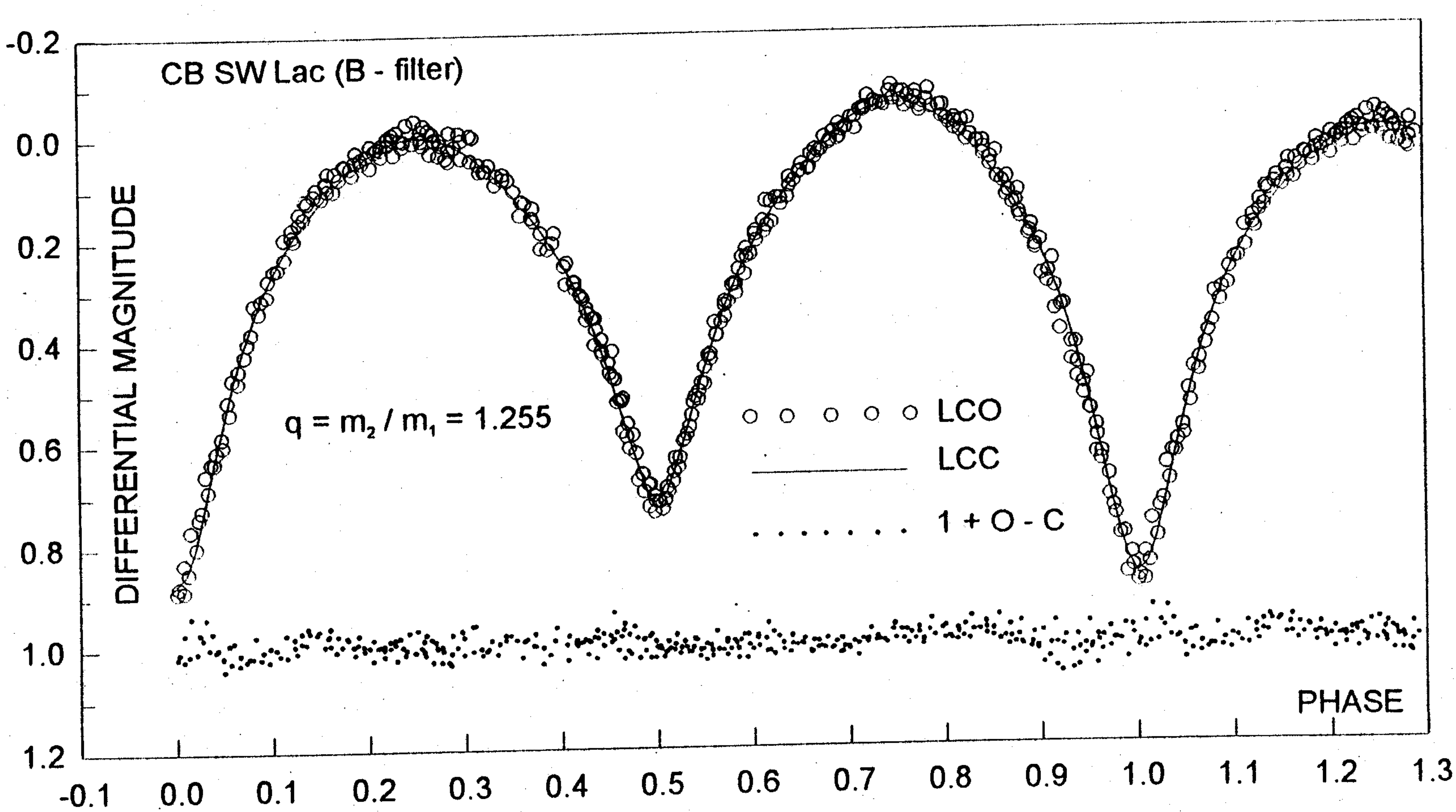
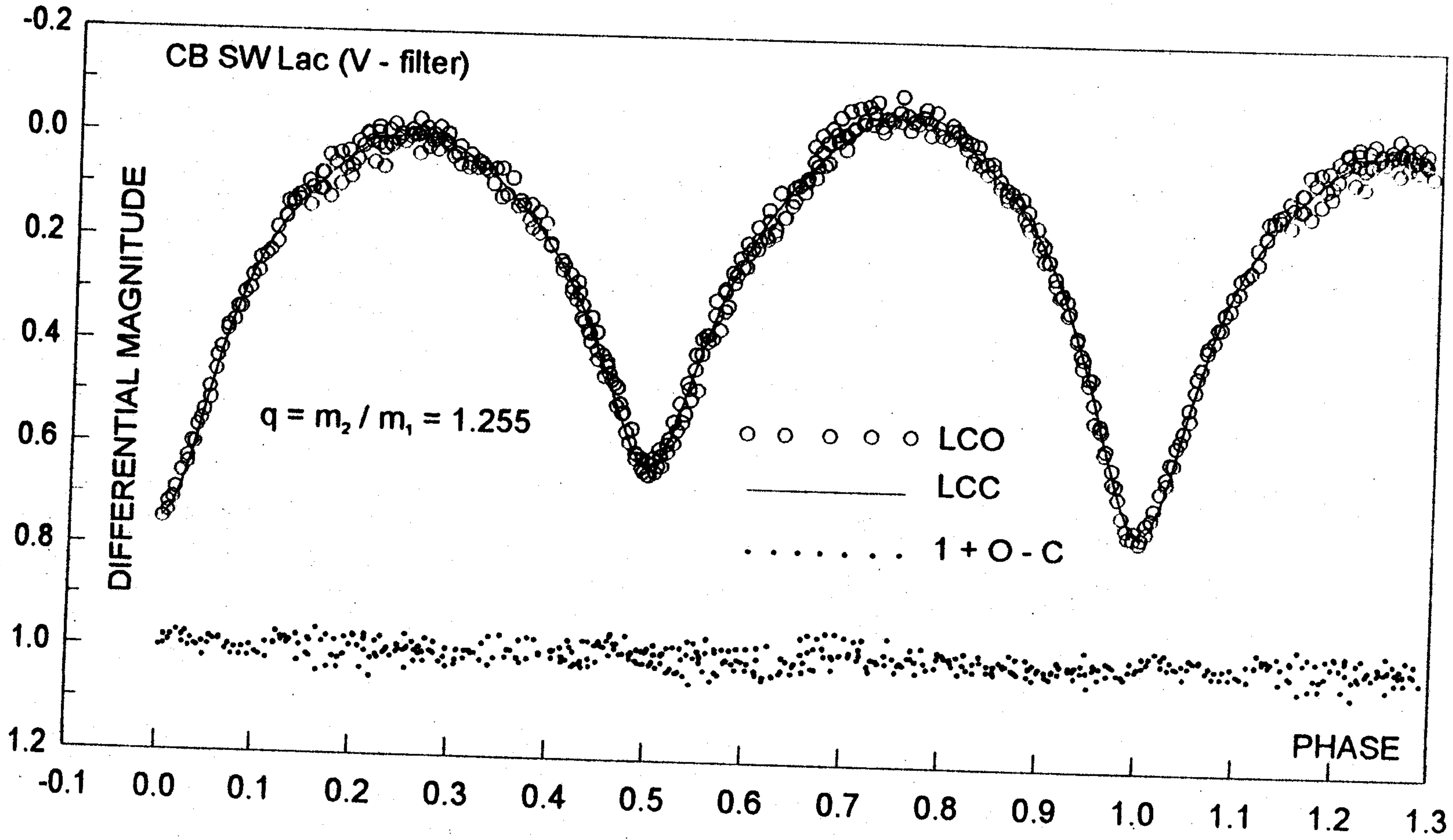


Fig. 1. Observed (LCO) and final synthetic (LCC) light curves with final residuals (O-C) obtained by solving the inverse problem of active CB *SW Lac*.
Hypothesis - **I.** 1st spot on the primary and 2nd on the secondary.
Top - V-filter; Bottom - B-filter



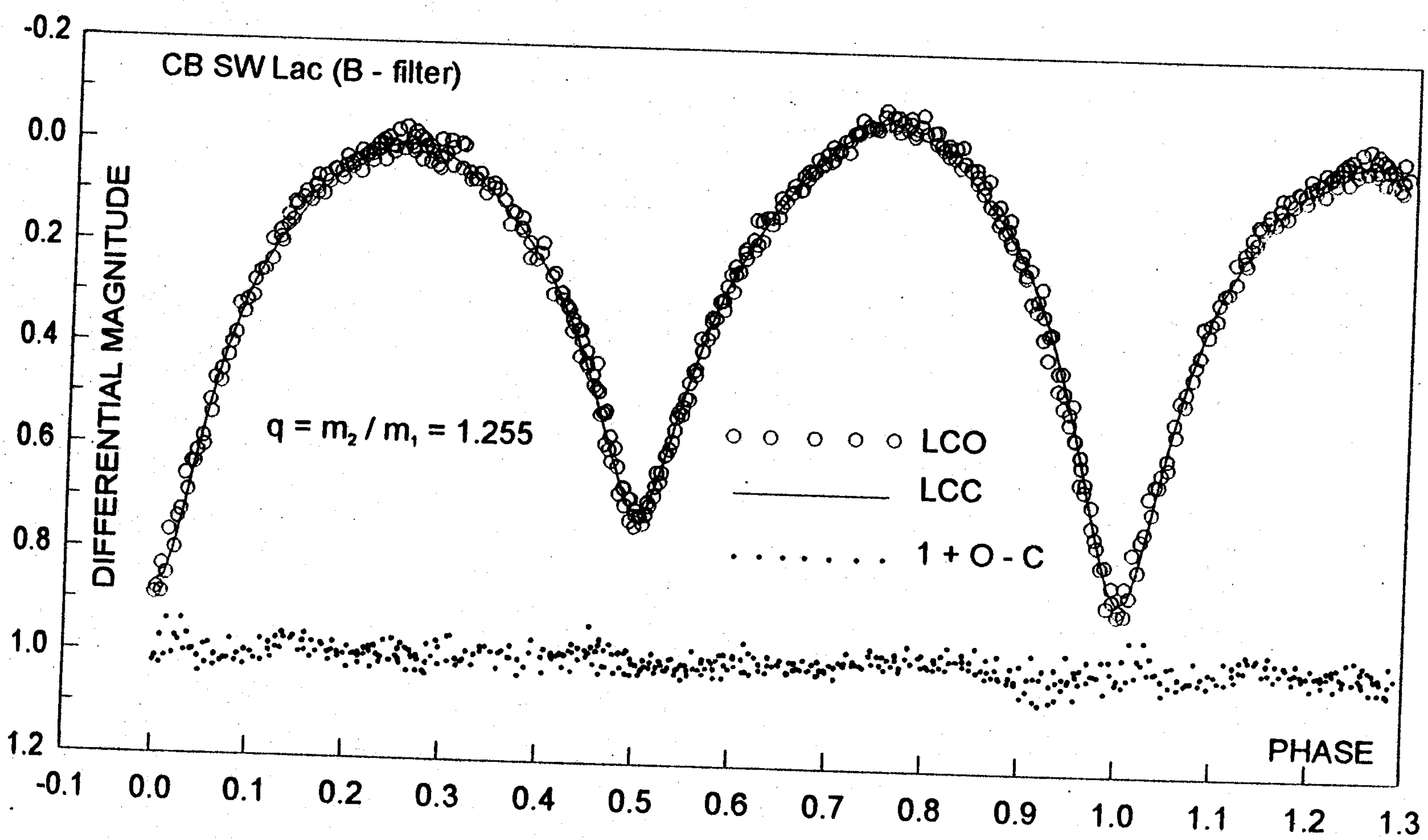


Fig. 2. Observed (LCO) and final synthetic (LCC) light curves with final residuals (O-C) obtained by solving the inverse problem of active CB *SW Lac*.
Hypothesis - **II.** both spots on the secondary.
Top - V-filter; Bottom - B-filter

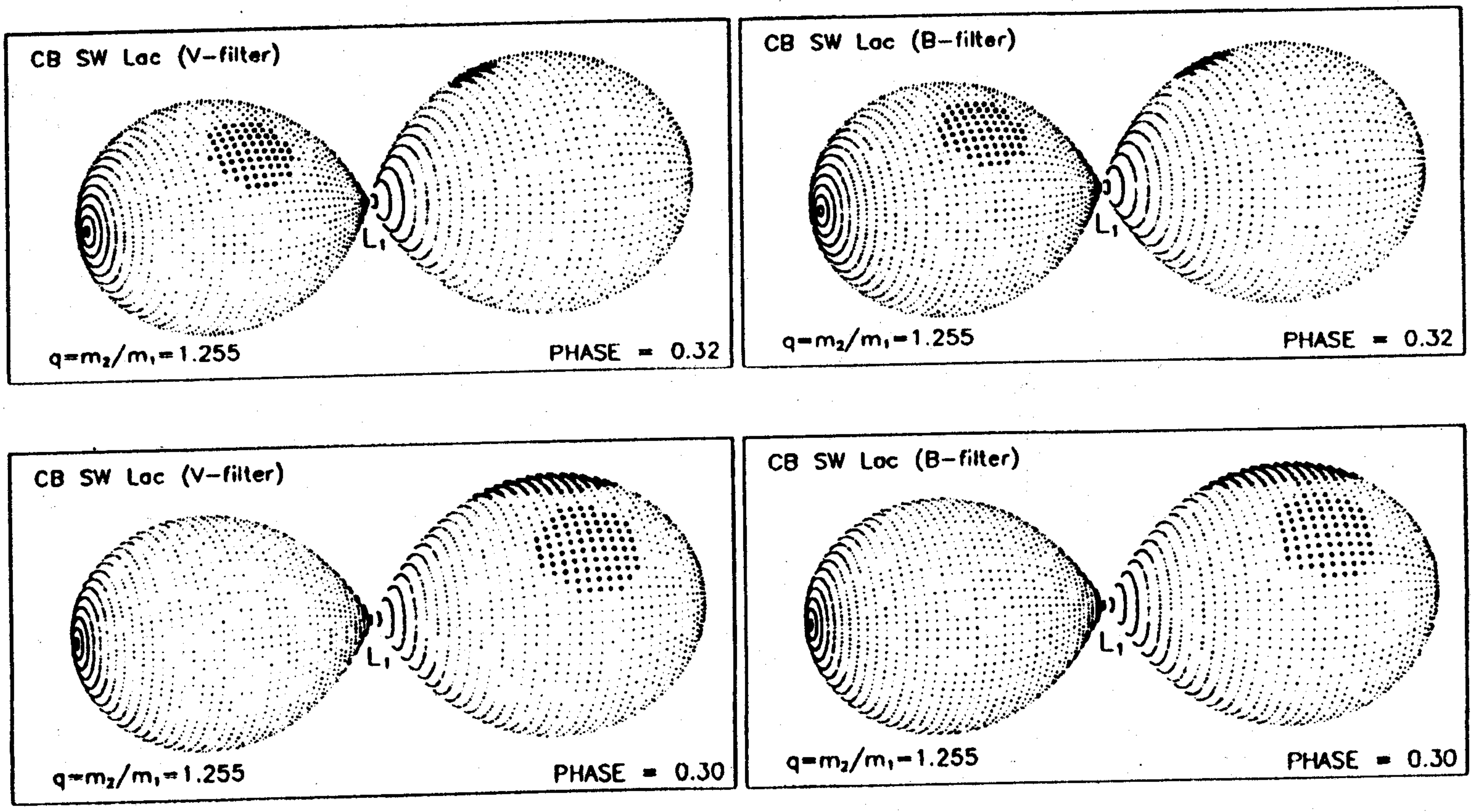


Fig. 3. The view of the CB *SW Lac* with parameters obtained by solving the inverse problem.
Top - Hypothesis **I.** 1^{st} spot on the primary and 2^{nd} on the secondary;
Bottom - Hypothesis **II.** both spots on the secondary.
Right - V-filter; Left - B-filter

a bright-spot region may arise in the equatorial zone of the star towards which the transfer is directed. Because of this, together with the hypothesis concerning the RS CVn activity type, we looked for a possible explanation of the observed deformation on the light curves in the framework of this mechanism of active-region formation. Within this hypothesis the analysis of the light curves (Niarchos, 1987) yields mutually well consistent parameters of the system and of the active regions in the B and V filters. Approximate equality of the temperatures for components in a physical contact suggests the exchange of thermal energy that is in favour of the latter hypothesis. However, by this hypothesis it is difficult to explain the seasonal variations in the form of the light curves indicating significant changes of the active-region longitude.

All light curves published since 1961 were collected by Jeong *et al.* (1994) aiming to investigate the variations of maxima heights beyond the eclipses. According to the form of the light curves the observations are classified into three groups. Group 1 has max II (orbital phase = 0.75) brighter than max I (orbital phase = 0.25). Group 2 refers to symmetric light curves. Group 3 has max II fainter than max I. These variations in the form of the light curves show no systematic changes over a long-term interval. The duration of the changing interval seems to be shorter than a season. From IUE spectra the analysis of these authors shows that the chromospheric activity is correlated with the light-curve variation and depends on the orbital phase. All this indicates that the hot-spot hypothesis should be rejected and the variations in the form of the *SW Lac* light curves should be interpreted as due to starspots resulting from the chromospheric activity of a late-type star.

The analysis of the light curves presented in this paper enables the estimation of parameters for *SW Lac* and for the active regions. It is shown that a Roche model with two spots hypothesis fits the observational material successfully. With spot hypothesis seasonal change of the depth of the primary minimum should be more pronounced than that of the secondary minimum, as a consenquence of the eclipse geometry. Some earlier studies (Leavitt, 1918) indicated exactly this kind of seasonal change of the light curves. This could be an argument in favour of the hypothesis of spot location on the secondary.

The system is in an overcontact configuration. The model applied for analysing the light curves involves certain idealisations. The real situation in the system can be significantly more complex than the solutions obtained here. In addition to the activity with dark spots on the components there are phenomena indicating a matter exchange between the components. A probable superposition of these effects results in complicated variations of the light-curve form. The *SW Lac* system should be continuously under observation in order to provide a photometric data base for analysing these variations over short and long time intervals. Such a material can be very important in the analysis of essentials of the activity in the system.

Acknowledgements – This work is a part of the project "Astrometrical, Astrodynamical and Astrophysical Researches", supported by Ministry of Science and Technology of Serbia.

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ПРОЦЕНА ПАРАМЕТАРА *SW Lac* НА ОСНОВУ АНАЛИЗЕ КРИВИХ СЈАЈА

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УДК 524.387–54
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У раду се на основу анализе кривих сјаја процењују орбитални и физички параметри краткопериодичног тесног двојног система *SW Lacertae*. Главна карактеристика кривих сјаја овог система типа W UMa је различита висина сукцесивних максимума. Ова асиметрија и промена форме кривих сјаја *SW Lac* може се објаснити присуством активних региона са пегама на некој од компонената система. У циљу тестирања ове хипотезе у раду анализирамо криве сјаја (Niarchos, 1987) добијене у V и B филтеру. Проблем се решава применом методе обрнутог задатка (Djurašević, 1992b) у оквиру Роше модела са пегама на компонентама (Djurašević, 1992a). Анализа показује да систему одговара оверконтакт конфигурација. Роше модел (са две тамне пеге на компоненетама) добро фитује посматрања при две различите хипотезе о локацији пега. Прва хипотеза подразумева по једну пегу на примару и секундару, док друга третира случај са две пеге на секундарној компоненети. Основни параметри система и пега су процењени при обе хипотезе.