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AN ANALYSIS OF THE LIGHT CURVES OF THE CLOSE BINARY *ST Ind*

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SUMMARY: The paper is dedicated to the problem of the determination of the orbital and physical parameters of active CB *ST Ind* based on the interpretation of photometric observations (Walter *et al.*, 1989). The analysis of these asymmetric light curves is done by applying the inverse-problem method (Djurašević, 1992b) in the framework of the CB model with spots on the components (Djurašević, 1992a). Several working hypotheses are considered. The analysis of the light curves reveals that Roche model with a single dark spot gives a good fit to the observations. The quality of obtained results is practically the same within two different hypotheses: I. - spot on the primary; II. - spot on the secondary, yielding the system in an overcontact configuration. The basic parameters of the system and of the active spot region are estimated.

1. INTRODUCTION

ST Ind is a W UMa-type short-period ($P = 0^d.401888$) CB system. Its light curves are characterised by approximately equal depths of minima and unequal heights of successive maxima. This asymmetry can be explained by assuming the existence of an active dark or hot spot region on one of the system's components. A rough spectral classification of G type for *ST Ind* can be inferred from the value of the colour index at the maxima ($B - V = 0.5$, Walter *et al.*, 1989). For stars with convective envelopes like the present ones one can expect the occurrence of spots. Therefore, the hypothesis involving an RS CVn-type activity seems justified. However, for W UMa systems due to the exchange of mass and thermal energy between the components increased-temperature regions may arise in the equatorial zone of the cooler secondary towards which this transfer is directed.

The light-curve analysis, presented in Walter *et al.* (1989), shows that a model without active regions cannot yield a good fit to the observations. The characteristic asymmetry of light curves has been attributed to the dark region near the pole of the primary. Within the applied model and the method for analysing the light curves it has been impossible to obtain particular parameters of the active region. Also, it proved that the amplitude of the light-curve depression has a variation period of about 80 days, which is explained by a modulation of the spot visibility due to a possible precession of the primary's rotation axis. The task has been solved assuming equal temperatures of the components. This assumption seems problematic and it may be the source of errors in the estimating of the system's basic parameters.

Therefore, our decision was to re-examine these light curves by applying the inverse-problem method (Djurašević, 1992b). For the analysis of the asymmetric light curves deformed by the presence of spots on the components a model (Djurašević, 1992a) has been developed, which is based on the principles originated in Wilson and Devinney (1971). The shapes of the components correspond to the equipotentials in the Roche model, so that the critical Roche lobes can be filled up to an arbitrary degree. For a given mass ratio of the components and the nonsynchronicity parameters the shape and the size of stars in a CB are unequivocally determined by the filling coefficients of the critical lobes. In a spherical coordinate system the surfaces of the components are divided into a large number of elementary cells, whose intensity and angular distribution of black-body radiation are determined by the star's temperature, limb-darkening, gravity-darkening and by the effect of reflection in the system.

The active regions are approximated by circular spots characterised by the temperature contrast of the spot with respect to the surrounding photosphere ($A_S \doteq T_S/T_*$), by the angular size of the spot (θ), by the longitude (λ) and by the latitude (φ) of the spot centre. The presence of spots (dark or hot) enables us to explain the asymmetry and depressions on the light curves of an active CB.

2. ANALYSIS

In this paper an analysis of B and V light curves (Walter *et al.*, 1989) for *ST Ind* is performed on the basis of the model of a CB with spots on its components (Djurašević, 1992a) where the inverse-problem method (Djurašević, 1992 b) is applied. This method is based on the modified Marquardt (1963) algorithm.

A preliminary analysis of the light curves has proved that both components in this system fill their critical Roche lobes. Therefore, the tidal effects are expected to cause the synchronisation between the rotational and orbital periods. By solving the inverse problem one estimates the basic parameters of the system and those of the active spot regions (longitudes, latitudes and spot size).

In the applied Roche model of CB system maximal dimensions of the components are defined by critical Roche lobes which are in the contact in the Lagrangian equilibrium point L_1. If we treat the gravity darkening coefficients $\beta_{1,2}$ as free parameters in the solving of the inverse-problem, then the model can be applied with success to the fitting of light curves of an overcontact configuration CB system. Namely, the increase of the coefficients $\beta_{1,2}$ beyond the values characteristic for stars with convective envelopes has similar effect on the light curves as does an overcontact configuration. For their initial values $\beta_{1,2} = 0.08$ are assumed. Lucy (1967) and Osaki (1970) regard this value as justified one for stars with convective envelopes.

In the programme, which solves the inverse problem, the linear limb-darkening coefficients are determined on the basis of the components' temperature 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 T_1 was set at 6200 K based on the colour index of the system $(B-V) = 0.5$ (Walter *et al.*, 1989). In our analysis of the light curves we rejected the assumption of the equality of the componenets' temperature which is used by mentioned authors. Namely, this assumption must reflect itself in the estimating of the CB system's parameters. Instead, at solving the inverse-problem, the temperature of the secondary is treated as a free parameter.

According to the preliminary analysis (Djurašević, 1996) the single-spot model, with the spot (with temperature contrast $A_s = T_s/T_1 = 0.65$) is on the primary, provides a good fit to the observations yielding mutually concordant solutions for the B and V light curves. This suggests that the hypothesis may be accepted as realistic. Detailed examination of the light curves reveals that another hypothesis of a spot on the secondary may be considered as equivalent to the first one. The quality of the results obtained under both hypotheses is almost identical. The analysed observational material cannot give the final answer as to which of the components the spot is situated on. Therefore, the results obtained under both hypotheses are treated as equally right. The results of the light curve analysis for the B and V filter are presented in Table 1.

The quality of the obtained results can be presented graphically. Figs. 1. and 2. present the fits of the observed light curves (LCO) by synthetic model curves (LCC) and the final residuals (O-C). It is quite clear from these graphs that under both working hypotheses (**I.** - spot on the primary; **II.** - spot on the secondary) synthetic light curves fit very well the observations. The residuals between observed and synthetic light curves are of a random character and within limits of the observational accuracy.

A programme (Djurašević, 1991), specially developed for the graphical presentation of the results by using the system's parameters obtained in the light curve analysis, enables presenting the view on the system at an arbitrary orbital phase. Fig. 3 gives the view on the system *ST Ind* at the orbital phase 0.30 according to the results in Table 1. The Figure presents the individual solutions for V and B light curves under both working hypotheses.

3. DISCUSSION AND CONCLUSION

The examination of the obtained results shows that the spot is situated on high latitudes. This conclusion does not depend on the adopted working hypothesis. Since CB *ST Ind* is a short-period system ($P = 0^d.401888$), the appearing of the spot near the star polar region is not surprising. Namely, as Schüssler and Solanski (1992) have demonstrated, the dynamo mechanism in rapid rotators causes the formation of spots on high latitudes, which is due to the important role of the Coriolis force in the rapid rotation. It coerces the magnetic flux tubes to move from the deep convective-zone layers almost parallel to the rotation axis and consequently the formation of spots on high latitudes becomes necessary.

Table 1.

Results of the analysis of the *ST Ind* light curves obtained by solving the inverse problem for the Roche model with two single spot location hypotheses:
I. - spot on the primary; **II.** - spot on the secondary.

Quantity	Spot on the primary **I.** V - filter	Spot on the primary **I.** B - filter		Spot on the secondary **II.** V - filter	Spot on the secondary **II.** B - filter
$\Sigma(O-C)^2$	0.001678	0.001378		0.001687	0.001368
θ	10.3 ±0.4	11.7 ±0.3		17.2 ±0.6	17.9 ±0.4
λ	113 ±5.9	114 ±2.1		106 ±4.9	108 ±3.9
φ	71.1 ±1.5	69.9 ±0.8		67.9 ±1.5	65.3 ±1.3
F_1	1.000±0.001	1.000±0.001		1.000±0.001	1.000±0.001
F_2	1.000±0.001	1.000±0.001		1.000±0.002	1.000±0.001
T_2	6060 ±10	6060 ±10		6040 ±10	6060 ±10
i	74.4 ±0.07	74.3 ±0.06		74.5 ±0.07	74.4 ±0.06
q	0.331±0.003	0.331±0.002		0.331±0.003	0.332±0.002
β_1	0.273±0.004	0.246±0.003		0.279±0.004	0.246±0.003
β_2	0.185±0.007	0.171±0.005		0.177±0.007	0.173±0.005
u_1	0.64	0.72		0.64	0.72
u_2	0.65	0.72		0.65	0.72
Ω_1	2.535	2.534		2.535	2.537
Ω_2	2.534	2.534		2.535	2.537
R_1	0.448	0.448		0.448	0.448
R_2	0.268	0.268		0.268	0.269

FIXED PARAMETERS:

$T_1 = 6200K$ - temperature of the primary,
$A_s = T_s/T_1 = 0.65$ - spot temperature coefficient,
$A_1 = A_2 = 0.5$ - albedo coefficients of the components,
$f_1 = f_2 = 1.00$ - nonsynchronous rotation coefficients of the components.

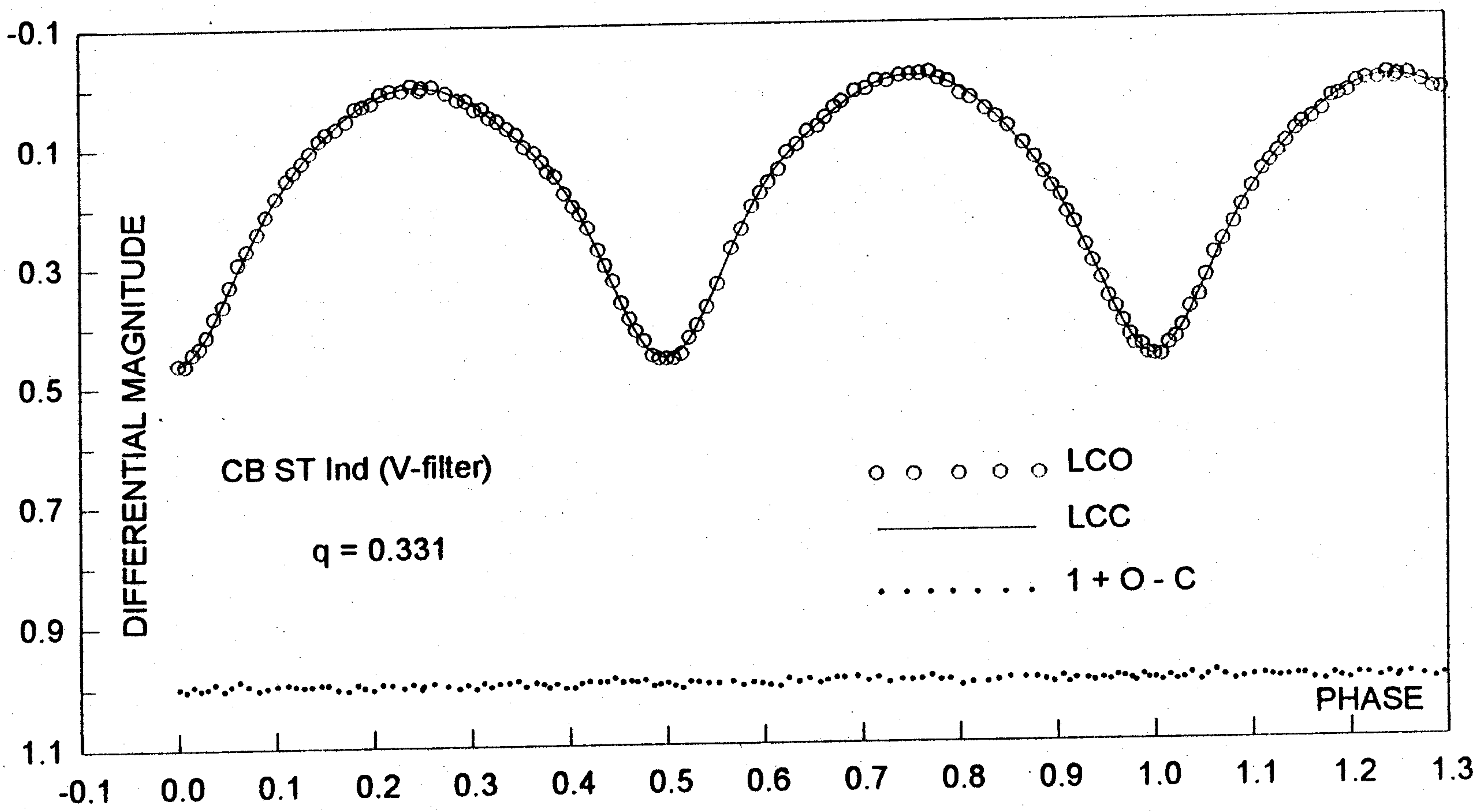
Note: $\Sigma(O-C)^2$ - **final sum of squares of residuals between observed (LCO) and synthetic (LCC) light curves, θ - spot angular dimensions, λ - spot longitude and φ - spot latitude (all in arc degrees), $F_{1,2}$ - filling coeficients for critical Roche lobes of the primary and secondary, T_2 - temperature of the secondary, i - orbit inclination (in arc degrees), $q = m_2/m_1$ - mass ratio of the components, $\beta_{1,2}$ - 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.**

The obtained solutions suggest that the components of the system fill their critical Roche lobes and have approximately the same temperatures. The estimated values of gravity darkening coefficients (see Table 1.) are beyond the values expected for the stars with convective envelopes. This indicates that the system components are in the overcontact configuration.

The system's stars are in a physical contact near the Lagrangian equilibrium point L_1. It has been shown by Lucy (1967, 1968a, 1968b) that during the contact of the adiabatic parts of two convective envelopes the thermal-energy exchange is necessary. This effect could explain the approximately equal temperatures of the components for different masses.

Due to the thermal-energy exchange a region of enhanced luminosity could be formed on the cooler secondary. However, such a model cannot offer a good fit to the observations and the expected agreement of the results for the B and V light curves.

The parameters of CB *ST Ind* obtained here are to some degree discordant with the estimates presented in Walter *et al.* (1989). In the present authors' opinion this is a consequence of the application of different models and methods of light-curve analysing. The approximation concerning the mutual temperature equality of the components applied by Walter *et al.* (1989) is reflected in the estimate of the free parameters of the model. In our opinion this is the main reason for mentioned differences in the estimating of the *ST Ind* CB system's parameters.



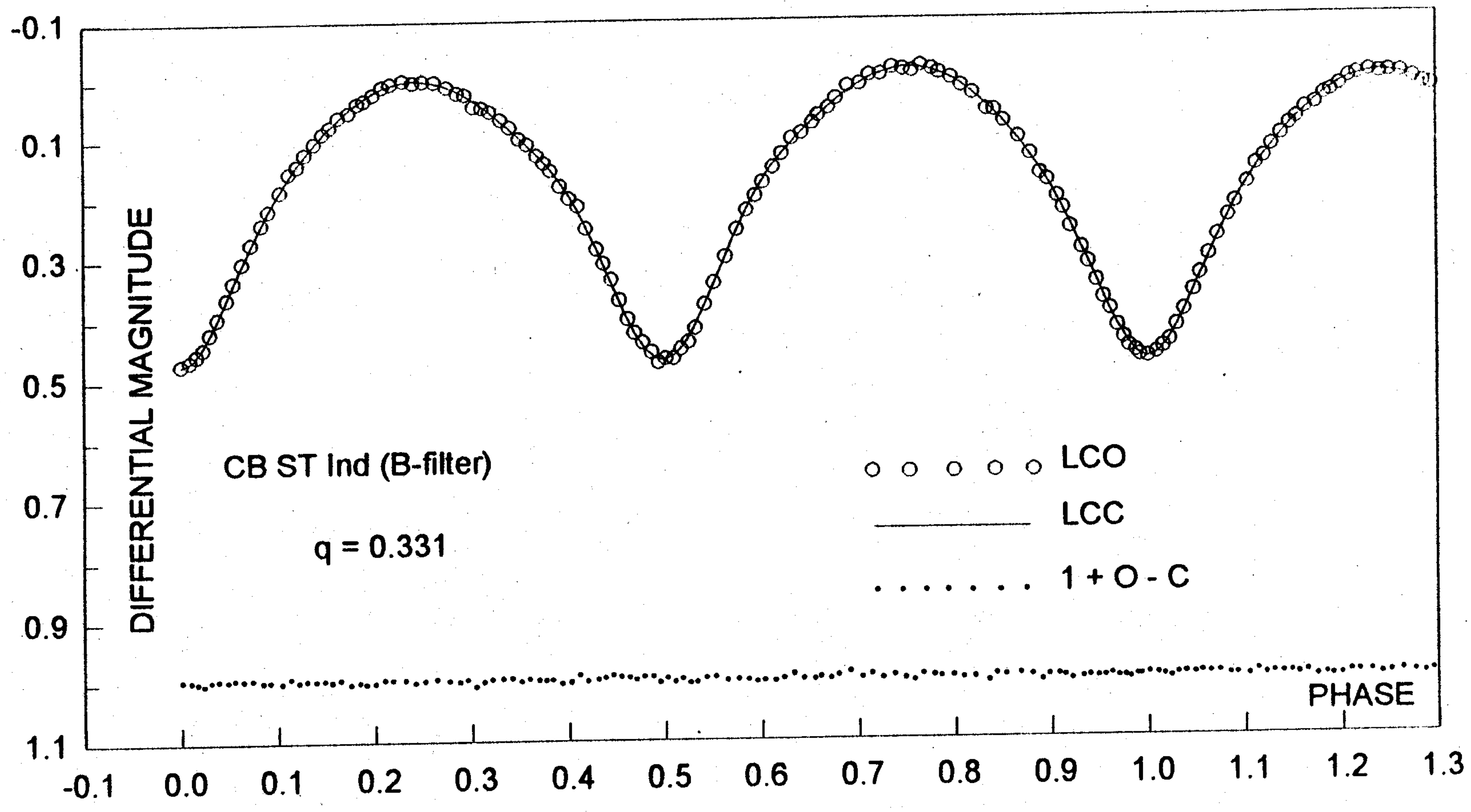


Fig. 1. Observed (LCO) and final synthetic (LCC) light curves with final residuals (O-C) obtained by solving the inverse problem of active CB *ST Ind.*
Hypothesis **I.** - spot on the primary.

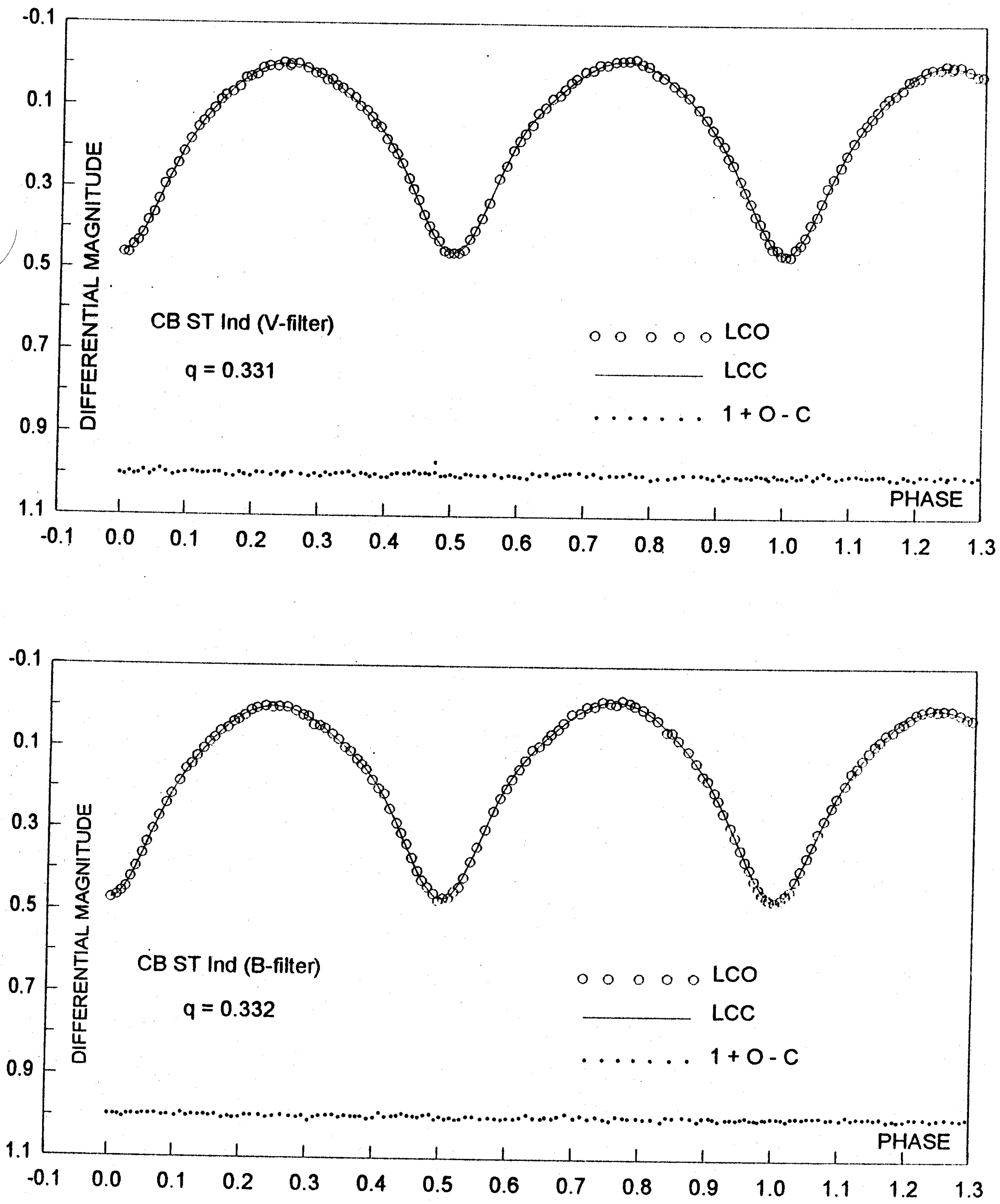


Fig. 2. Observed (LCO) and final synthetic (LCC) light curves with final O-C obtained by solving the inverse problem of active CB *ST Ind*.
Hypothesis II. spot on the secondary.

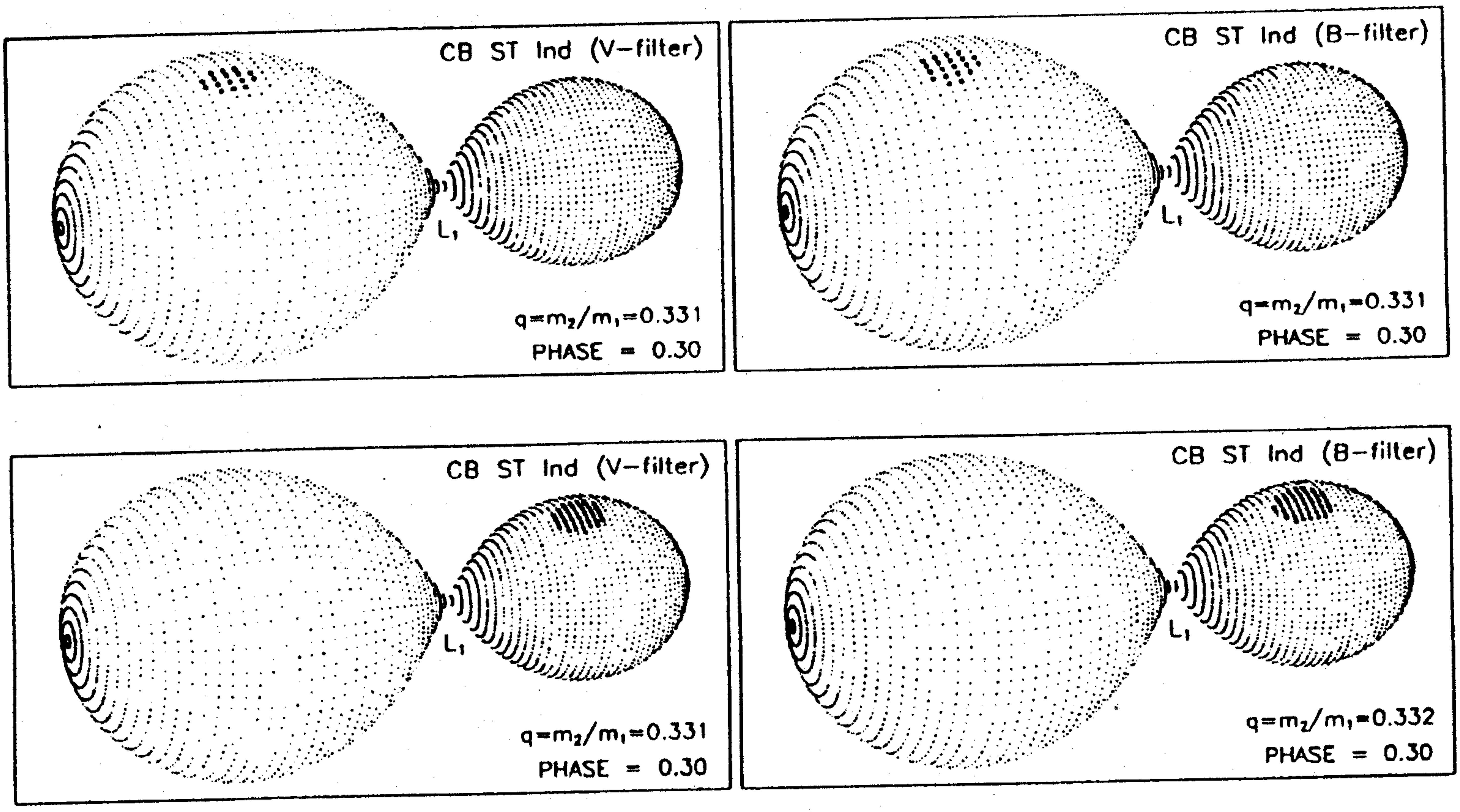


Fig. 3. The view of the CB *ST Ind* with parameters obtained by solving the inverse problem.
Top: Hypothesis **I.** - spot on the primary;
Bottom: Hypothesis **II.** - spot on the secondary.

The assumption that the rotation axis of the primary has precession, applied in the paper by Walter *et al.* (1989), in the present authors' opinion is premature. The changes of the amplitude depression caused by a spot can be interpreted through the changes of its position and size, due to both the change of the activity level and the possible differential-rotation effect. However, a definitive judgement can be reached only on the basis of a long observational series furnishing well - defined light curves.

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АНАЛИЗА КРИВИХ СЈАЈА ТЕСНОГ ДВОЈНОГ СИСТЕМА *ST Ind*

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Оригинални научни рад

Рад је посвећен проблему одређивања орбиталних и физичких параметара активног тесног двојног система *ST Ind* на основу анализе фотометријских посматрања (Walter *et al.*, 1989). Анализа ових асиметричних кривих сјаја је извршена применом методе инверзног проблема (Djurašević, 1992b) у оквиру модела тесног двојног система са пегама на компонентама (Djurašević, 1992a). Разматрано је неколико радних хипотеза. Анализа кривих сјаја показује да Роше модел са једном тамном пегом добро фитује посматрања. Квалитет добијених решења је практично исти при две различите хипотезе: **I.** - пега на примару; **II.** - пега на секундару. При обе хипотезе су процењени основни параметри система и пеге.