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TU Bootis: An ambiguous W Ursae Majoris system

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Abstract. — The W UMa system TU Boo has a period of 0.32438 days and a spectral type G3. We present here the first photometric analysis, based on photoelectric B and V light curves. The q-search method was used to find the preliminary range of the mass-ratio in order to search for the final solution. The unspotted solution was found by using the unperturbed part of the light curve and applying the DC program of the WD code. Spot models were computed, a one-spot model to explain the O'Connell effect (Max II fainter than Max I) by introducing a cool spot on the larger component, and a two-spot model to explain both the O'Connell effect and the small excess of light just after Max I by assuming, in addition, a bright region on the smaller component near the neck region of the common envelope. TU Boo is an A-type W UMa system with complete eclipses, the secondary minimum being an occultation. However, the derived physical parameters of the system and its light curve anomalies are more common for slightly evolved W-type systems.

Key words: stars: TU Boo — binaries: eclipsing — starspots

1. Introduction

Guthnick & Prager (1926) discovered W UMa type variability of the star Ox ph +36° 31142 on photographic plates. They derived the elements

$$\text{J.D.hel. (Min I)} = 2424609.332 + 0.32440 \cdot E.$$

Additional analyses were carried out by Parenago (1930) on Moscow plates, by Dragomiretskaya (1948), using Moscow plates and Tsesevich's observations, by Szafraniec (1952) from own visual observations, and by Tsesevich (1953).

The spectral type of TU Boo was determined as G3 in the Bergedorf spectral survey of the 115 northern selected areas (star 328 of SA 58; Schwassmann & van Rhijn 1947).

2. Observations

Photoelectric observations were carried out on 1982 March 26/27 and April 18/19 by M. Hoffmann at the 1.06 m telescope of Hoher List Observatory of Bonn University, using a two-channel photometer. The single observations and comparison star data are given in Hoffmann (1984), minimum times in Hoffmann (1983).

3. Period study

Minimum times of TU Boo have been recorded fairly regularly during its comparatively long observational history. Szafraniec (1952) gave an analysis of the early timings, but could not find an obvious period change. We have collected the early minimum timings, carried out mainly by Dragomiretskaya (1948) and Szafraniec (1952, as well as scattered data in Acta Astr. Ser. c, vols. 4 – 16, 1949-1966), a few timings by Whitney (1957) and Koch & Koch (1962), Hoffmann's (1983) photoelectric results, as well as recent monitoring by observers of the Swiss Astronomical Society (BBSAG Bulletins 22, 23, 25, 27, 28, 33, 36-38, 42, 43, 46-49, 51-55, 61, 65-67, 70-72, 75, 76, 80, 82-85, 87, 88, 91, 92, 94, 97, 98, 100-105). We have formed normal points from about 10 subsequent single O-C determinations, based on the light elements

$$\text{J.D.min. (hel.)} = 2433066.404 + 0.3242868 \cdot E\,.$$

The resulting O-C-diagram is shown in Fig. 1. A major period change occurred shortly after the epoch of our

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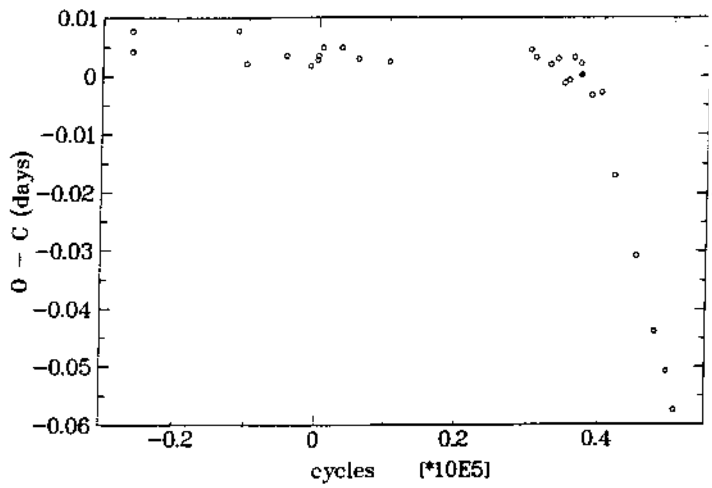

Fig. 1. (O-C) diagram of TU Boo. The dot indicates the average of the two photoelectrically determined minimum times by Hoffmann (1983), circles are average values based on 7 – 11 photographic or visual minima

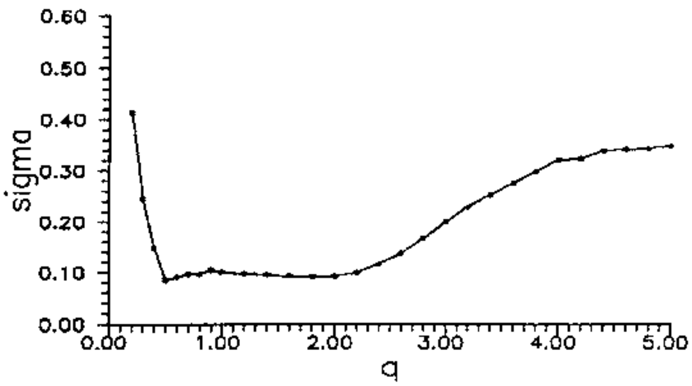

Fig. 2. The fit parameter $\Sigma(\mathrm{res})^2$ as a function of the mass-ratio q

photoelectric observations. We have fitted two straight lines through the data for epochs −26070 to 36970, and 38500 to 50729, respectively. The light elements in the corresponding intervals can be written as

$$\begin{aligned}\text{J.D.min. (hel.)} &= 2433066.4079 + 0.32428674 \cdot E \\ &\quad \pm 0.0004 \pm 0.00000002\end{aligned}$$

and

$$\begin{aligned}\text{J.D.min. (hel.)} &= 2433066.5817 + 0.32428217 \cdot E\,. \\ &\quad \pm 0.0084 \pm 0.00000019\end{aligned}$$

The intersection of the two lines at cycle 38110 indicates a period shortening of 0.413 s around JD 2445425, and the more recent minima are best described by the elements

$$\begin{aligned}\text{J.D.min. (hel.)} &= 2445425.3022 + 0.32428196 \cdot E\,. \\ &\quad \pm 0.0018 \pm 0.00000024\end{aligned}$$

4. Solution procedure

The light curve analysis of TU Boo is quite difficult for three reasons:
a) no spectroscopic mass-ratio is known,
b) the O'Connell-effect, although small, is different in the B and V light curves,
c) the light curve anomalies present in both B and V light curves do not appear at the same phase regions.

An inspection of the light curves reveals that brightness variations occur mainly around the two maxima. A relatively small radiation excess is seen in the V light curve in the phase interval $0.14 - 0.22$, and in both light curves in the phase interval $0.28 - 0.38$. An unusual light excess of extremely short duration is present in the B light curve in the phase interval $0.22 - 0.23$, which is totally absent in V light curve. The O'Connell-effect is observed in both light curves, but it is more pronounced in the V curve. $\mathrm{Max\,II} - \mathrm{Max\,I} = 0\overset{\mathrm{m}}{.}02$ in the B band and $\mathrm{Max\,II} - \mathrm{Max\,I} = 0\overset{\mathrm{m}}{.}04$ in the V band. The shape of the light curve in both colours indicates that a total eclipse occurs at secondary minimum. The difference between the two minima is about $\mathrm{Min\,I} - \mathrm{Min\,II} = 0\overset{\mathrm{m}}{.}102$ in B and $0\overset{\mathrm{m}}{.}075$ mag in V.

A photometric analysis of a system with so many anomalies in the light curve is quite difficult. The only favorable condition is the totality at secondary minimum, which allows a relatively accurate determination of the photometric mass-ratio. In modelling the light curves of systems exhibiting light curve anomalies and the O'Connell effect, the need to place hot and/or cool spots of solar type has been suggested by several investigators (e.g. Binnendijk 1960; Hilditch 1981; Linnell 1982; Van Hamme & Wilson 1985; Milone et al. 1987). Especially for late type systems with strong magnetic activity, the existence of large spots on their surface is suggested by the high angular momentum loss in very close and contact binaries (van't Veer & Maceroni 1988, 1989; Maceroni et al. 1990).

The lack of a spectroscopic mass ratio does not affect the photometric solution, however, it makes it more difficult. The completeness of the eclipses ensures that the photometric mass-ratio can be determined with high accuracy by the synthetic light curve technique (Wilson 1978). The photometric solution was carried out in the following way:

4.1. *Unspotted solution*

The modelling was carried out with the most recent (1993) version of the Wilson-Devinney (Wilson 1990) synthetic light curve code, which has the capability of automatically adjusting star spots. In order to reduce computational

Table 1. Normal points for TU Boo in intensity units

phase	l_B	n	phase	l_B	n	phase	l_V	n	phase	l_V	n
0.0068	0.4597	4	0.5167	0.5054	3	0.0075	0.4792	3	0.5147	0.5214	3
0.0226	0.4960	3	0.5317	0.5407	3	0.0218	0.5038	4	0.5310	0.5556	4
0.0324	0.5508	2	0.5468	0.5969	3	0.0371	0.5516	3	0.5483	0.5989	3
0.0542	0.6298	2	0.5599	0.6457	3	0.0542	0.6315	3	0.5624	0.6528	3
0.0641	0.6430	4	0.5744	0.7058	3	0.0684	0.6753	3	0.5769	0.7204	3
0.0825	0.7320	6	0.5930	0.7677	3	0.0803	0.7239	5	0.5942	0.7541	2
0.0957	0.7765	3	0.6075	0.8106	3	0.0978	0.7982	6	0.6070	0.7956	4
0.1125	0.8146	5	0.6198	0.8387	2	0.1139	0.8080	2	0.6213	0.8445	2
0.1285	0.8617	5	0.6390	0.8800	4	0.1274	0.8439	7	0.6386	0.8585	3
0.1413	0.8738	2	0.6537	0.8992	3	0.1436	0.9112	2	0.6537	0.8861	4
0.1579	0.9154	2	0.6676	0.9185	4	0.1594	0.9320	2	0.6691	0.9037	4
0.1722	0.9185	3	0.6838	0.9245	4	0.1747	0.9199	3	0.6838	0.9176	3
0.1872	0.9380	2	0.6989	0.9512	3	0.1887	0.9423	2	0.6985	0.9302	4
0.1993	0.9786	2	0.7121	0.9658	4	0.2023	0.9763	2	0.7136	0.9484	4
0.2196	1.0195	2	0.7267	0.9777	2	0.2174	0.9836	2	0.7290	0.9476	2
0.2334	1.0104	3	0.7414	0.9856	4	0.2309	0.9899	2	0.7429	0.9590	4
0.2467	0.9986	2	0.7568	0.9811	4	0.2480	1.0000	3	0.7566	0.9500	3
0.2625	0.9957	3	0.7711	0.9739	3	0.2618	0.9845	2	0.7719	0.9513	4
0.2806	0.9954	1	0.7870	0.9656	4	0.2806	0.9954	2	0.7862	0.9433	3
0.2926	0.9884	3	0.8013	0.9448	3	0.2919	0.9683	2	0.8016	0.9245	4
0.3084	0.9678	2	0.8167	0.9204	4	0.3067	0.9668	3	0.8163	0.9020	3
0.3242	0.9556	2	0.8314	0.9129	1	0.3232	0.9565	3	0.8324	0.8907	3
0.3370	0.9532	2	0.8468	0.8841	4	0.3438	0.9053	1	0.8469	0.8667	3
0.3498	0.8843	2	0.8635	0.8459	3	0.3536	0.8884	2	0.8610	0.8548	3
0.3669	0.8893	3	0.8765	0.8343	3	0.3689	0.8976	3	0.8765	0.7993	4
0.3835	0.8691	3	0.8911	0.8118	3	0.3837	0.8634	2	0.8908	0.7285	2
0.3950	0.8061	1	0.9071	0.7523	3	0.3920	0.8249	1	0.9066	0.7063	2
0.4116	0.7362	2	0.9217	0.7008	3	0.4121	0.7526	3	0.9213	0.6616	4
0.4271	0.6769	3	0.9371	0.6383	4	0.4251	0.6970	1	0.9373	0.6183	3
0.4431	0.6151	3	0.9496	0.5848	2	0.4423	0.6212	4	0.9493	0.5712	3
0.4584	0.5598	5	0.9684	0.5319	3	0.4581	0.5646	3	0.9709	0.5285	3
0.4708	0.5182	4	0.9838	0.4639	4	0.4679	0.5445	4	0.9834	0.4945	3
0.4891	0.5077	3	0.9940	0.4483	1	0.4795	0.5186	3	0.9947	0.4782	2
0.5054	0.5051	2				0.4977	0.5214	3			

time and to smooth the scatter in the maxima, normal points (67 in each colour) were formed from the individual observations. They are given in Table 1. Each normal point was weighted according to the number of observations on which it is based. The mean standard deviation for normal points in B and V are $0^{\mathrm{m}}.014$ and $0^{\mathrm{m}}.015$, respectively. Care has been taken to ensure a faithful resemblance of the normal points to the actual shape of the minima.

The subscripts 1 and 2 refer to the components eclipsed at primary and secondary minimum, respectively. Since the secondary minimum appears to be an occultation, the subscripts 1 and 2 refer to the larger (more massive and hotter) and smaller (less massive and cooler) component. Since no previous solution exists, we first compared the V light curve to those of our previously solved contact systems and to those given in the Contact Binary Light Curve Atlas of Anderson & Shu (1979). Based on these initial hints we made several runs with the LC program and, by trial and error, found the initial set of parameters to start the simulation with the DC program. Both programs (LC and DC) were used in mode 3, since the system, according to the shape of the light curve and its classification, belongs to the W UMa-type systems.

In deriving the unspotted photometric solution, the unperturbed parts of the light curves were used. In accordance to the light curve asymmetries mentioned above, the parts of the light curve between phases $0.65-0.85$ and $0.28-0.38$ were omitted. In the subsequent analysis, the following assumptions were made: a mean surface temperature $T_1 = 5800$ K according to the spectral type G3V; bolometric albedos $A_1 = A_2 = 0.5$ and gravity darkening coefficients $g_1 = g_2 = 0.32$ were assigned values typical for stars with convective envelopes; limb darkening coefficients $x_1 = x_2 = 0.78$ in B and $x_1 = x_2 = 0.65$ in V were taken from Al-Naimiy's (1978) tables; bolometric

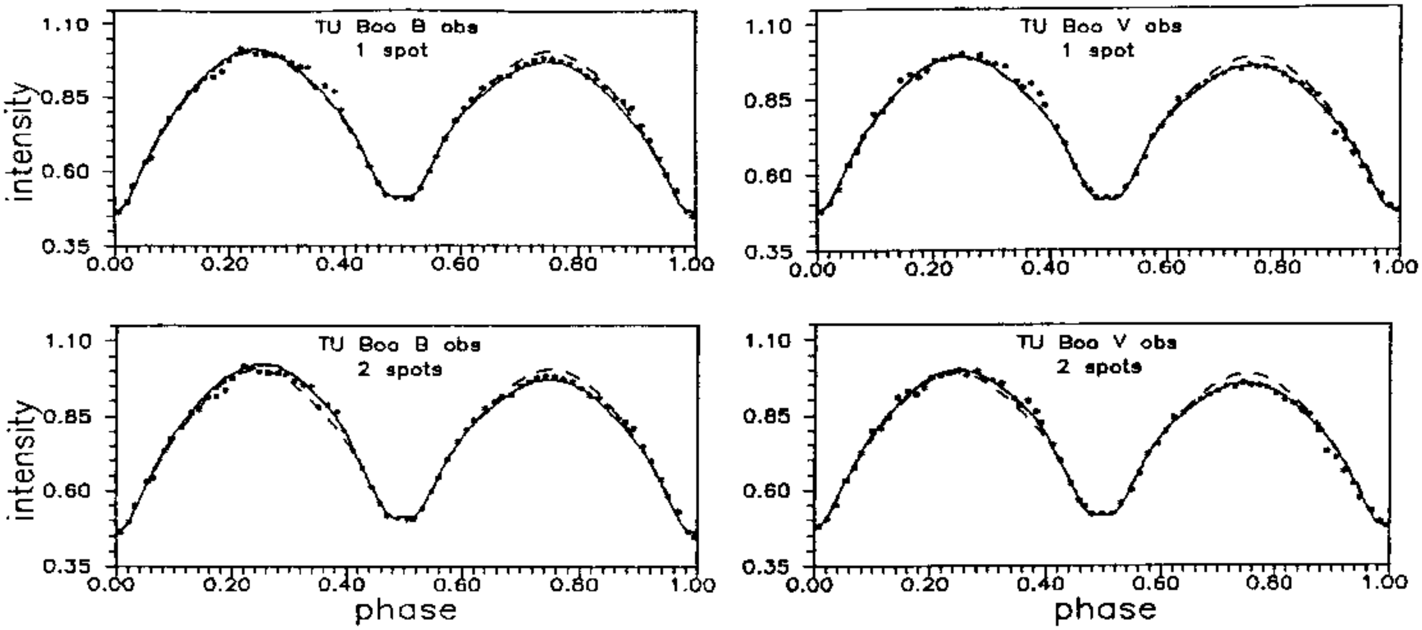

Fig. 3. Normal points and theoretical light curves of TU Boo. Left side: B-light curve. The dashed line always refers to the unspotted solution; the solid line to the 1-spot solution (upper plot) and to the 2-spot solution (lower plot). Right side: the same for the V light curve

linear limb darkening coefficients $x_1 = x_2 = 0.505$ were taken from Van Hamme (1993); third light was assumed to be $\ell_3 = 0.0$. Adjustable parameters were: the phase of conjunction ϕ_0, the inclination i, the temperature T_2, the nondimensional potential $\Omega_1 (= \Omega_2)$, the monochromatic luminosity L_1 and the mass-ratio $q = m_2/m_1$. The quantity ϕ_0 was adjusted only in the first few iterations, since it showed no tendency to vary significantly.

Since no spectroscopic mass-ratio of the system is known, a search for the solution was made with several fixed values for the mass-ratio q in the range $0.2 - 5.0$. For each assumed value of q, the result converged to a solution after several runs. In all stages of the present analysis a few more iterations were performed after the corrections to the adjustable parameters became smaller than their probable errors.

The sum $\Sigma(\text{res})^2$ of the weighted squares of the residuals for the corresponding values of q is shown in Fig. 2. The lowest value of $\Sigma(\text{res})^2$ occurs at $q = 0.50$, in whose vicinity a solution should be searched. The fact that (a) the shape of the light curve shows complete eclipses (occultation at secondary minimum), and (b) the $\Sigma - q$ diagram gives a minimum value of Σ around $q = 0.50$, indicates that TU Boo is of A-type and a final solution should be carried out under this assumption.

To obtain the final solution, we continued the analysis by applying the DC program of the WD code. We took as initial values of the adjusted parameters those found in the q-search procedure (corresponding to the lowest value of Σ in the $\Sigma - q$ diagram). q was treated as an additional free parameter. At this stage, the method of subsets (Wilson & Biermann 1976) was applied because of the strong correlation of the adjusted parameters. The solution converged to $q = 0.4981$, which is the final unspotted solution. The results are given in Table 2 and the corresponding theoretical light curves are shown as dashed lines in Fig. 3.

4.2. *Spotted solution*

An inspection of Fig. 3 shows that the theoretical light curves, computed from the unspotted solution, do not fit satisfactorily the observations (normal points). The disagreement is especially severe in the phase region around Max II, and it is more pronounced in the V light curve.

We started the spotted solution by assuming that the larger component of the system has a cool spot, of the same nature as solar magnetic spots (Mullan 1975), to explain the light loss around Max II. Several runs of the LC program, adjusting the spot parameters (except that of latitude), lead to a reasonable fit to the observations.

Once the preliminary spot parameters were specified, the DC program was used to derive the final solution. The parameters i, T_2, Ω_1, L_1 were varied, while the mass-ratio, for reasons of convergence, was fixed at the value found in the unspotted solution, since at this stage we tried to adjust also some of the spot parameters. The latitude was fixed at 90°, while longitude, spot radius and temperature factor, were allowed to vary. The method of subsets was employed again. The differential corrections were calculated until the corrections became smaller than their

Table 2. Light curve solutions of TU Boo

Parameter	unspotted solution	spotted (1 spot) solution	spotted (2 spots) solution
ϕ_0	0.9972 ± 0.0004	0.9972 ± 0.0004	0.9972 ± 0.0004
i (degrees)	87.514 ± 0.808	88.455 ± 0.946	88.097 ± 0.808
$g_1 (= g_2)$	0.32^*	0.32^*	0.32^*
T_1 (K)	5800^*	5800^*	5800^*
T_2 (K)	5787 ± 12	5815 ± 11	5805 ± 12
A_1 $(= A_2)$	0.5^*	0.5^*	0.5^*
Ω_1 $(= \Omega_2)$	2.7388 ± 0.0119	2.7459 ± 0.0046	2.7769 ± 0.0047
$q = m_2/m_1$	0.4981 ± 0.0067	0.4981^*	0.4981^*
$L_1/(L_1 + L_2)$ (B)	0.6476 ± 0.0042	0.6419 ± 0.0033	0.6481 ± 0.0029
$L_1/(L_1 + L_2)$ (V)	0.6471 ± 0.0039	0.6427 ± 0.0027	0.6483 ± 0.0023
x_1 $(= x_2)$ (B)	0.780^*	0.780^*	0.780^*
x_1 $(= x_2)$ (V)	0.650^*	0.650^*	0.650^*
x_1 $(= x_2)$ (bol)	0.505^*	0.505^*	0.505^*
% overcontact	44%	42%	32%
r_1 (pole)	0.4381 ± 0.0015	0.4368 ± 0.0008	0.4311 ± 0.0008
r_1 (side)	0.4713 ± 0.0019	0.4695 ± 0.0012	0.4619 ± 0.0011
r_1 (back)	0.5103 ± 0.0026	0.5077 ± 0.0016	0.4971 ± 0.0015
r_2 (pole)	0.3242 ± 0.0047	0.3228 ± 0.0009	0.3167 ± 0.0010
r_2 (side)	0.3426 ± 0.0060	0.3408 ± 0.0011	0.3334 ± 0.0011
r_2 (back)	0.3959 ± 0.0027	0.3926 ± 0.0021	0.3790 ± 0.0019
$\Sigma_(\mathrm{res})^2$	0.08492	0.05154	0.03943
$\mathcal{M}_1/\mathcal{M}_\odot$		0.97^*	0.97^*
$\mathcal{M}_2/\mathcal{M}_\odot$		0.48	0.48
$R_1/R_\odot$		1.06	1.05
$R_2/R_\odot$		0.79	0.78
ρ_1 (g cm^{-3})		1.13	1.18
ρ_2 (g cm^{-3})		1.35	1.45
$\log(L_1/L_\odot)$		0.06	0.05
$\log(L_2/L_\odot)$		-0.19	-0.21

*assumed

probable errors. The final results of the 1-spot solution are given in Table 2 and the theoretical light curves are shown as solid lines in Fig. 3, left side. The final parameters for the cool spot on component 1 are: latitude $b = 90°$, longitude $l = 78.°3 \pm 8.°0$, angular radius $r = 17.°1 \pm 11.°7$, temperature factor T.F. $= 0.857 \pm 0.011$.

A satisfactory fit was obtained, but an excess of light just after Max I remained, which cannot be approximated by the 1-spot model. To improve the fit in this part of the light curve, we introduced a bright region on the secondary near the neck region of the common envelope. Such a hot spot can be regarded as an effect of energy exchange between the components through the connecting neck of the common envelope (Van Hamme & Wilson 1985). Using the LC program, we obtained by trial and error a satisfactory fit. The DC program was used to adjust some of the parameters (longitude, angular radius and temperature factor) of both spots together with the parameters i, T_2, Ω_1 and L_1; however, no convergence could be obtained by adjusting both spots. Dr. Van Hamme (private communication) clarified that the problem arises from the adjustment of the hot spot, which is located near the neck region and has very little influence on the light curve. Thus we decided to adjust only the cool spot on the larger component, employing again the method of subsets. The differential corrections were computed until the corrections became smaller than their probable errors. The final results of the 2 spot-solution are given in Table 2 and the theoretical light curves are shown as solid lines in Fig. 3. The final parameters for the spot on component 1 are: latitude $b = 90°$, longitude $l = 69.°5 \pm 10.°1$, angular radius $r = 11.°5 \pm 6.°4$, temperature factor T.F. $= 0.848 \pm 0.028$, and for the spot on component 2: latitude $b = 90°$, longitude $l = 5°$, angular radius $r = 19°$ and temperature factor T.F. $= 1.25$. The O-C differences between the observed and calculated points for the unspotted and spotted solutions are shown in Fig. 4.

5. Discussion

In modelling the light curves of TU Boo, we invoked a cool spot on the larger component and a hot one on the smaller one. The cool spot is regarded to be of the same nature as

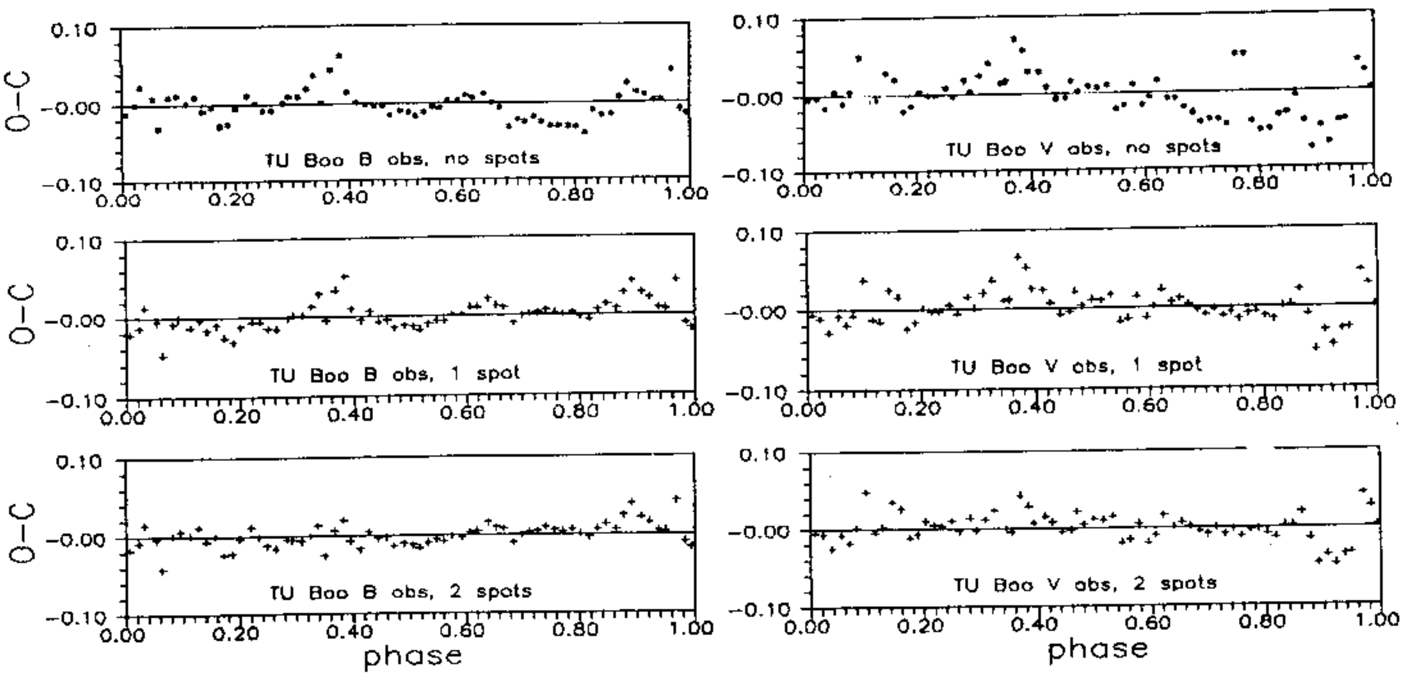

Fig. 4. The light curve (O-C) residuals for TU Boo in B band (left) and V band (right). Asterisks refer to unspotted solution (upper row); crosses refer to the 1-spot (middle row) and 2-spot (lower row) solutions

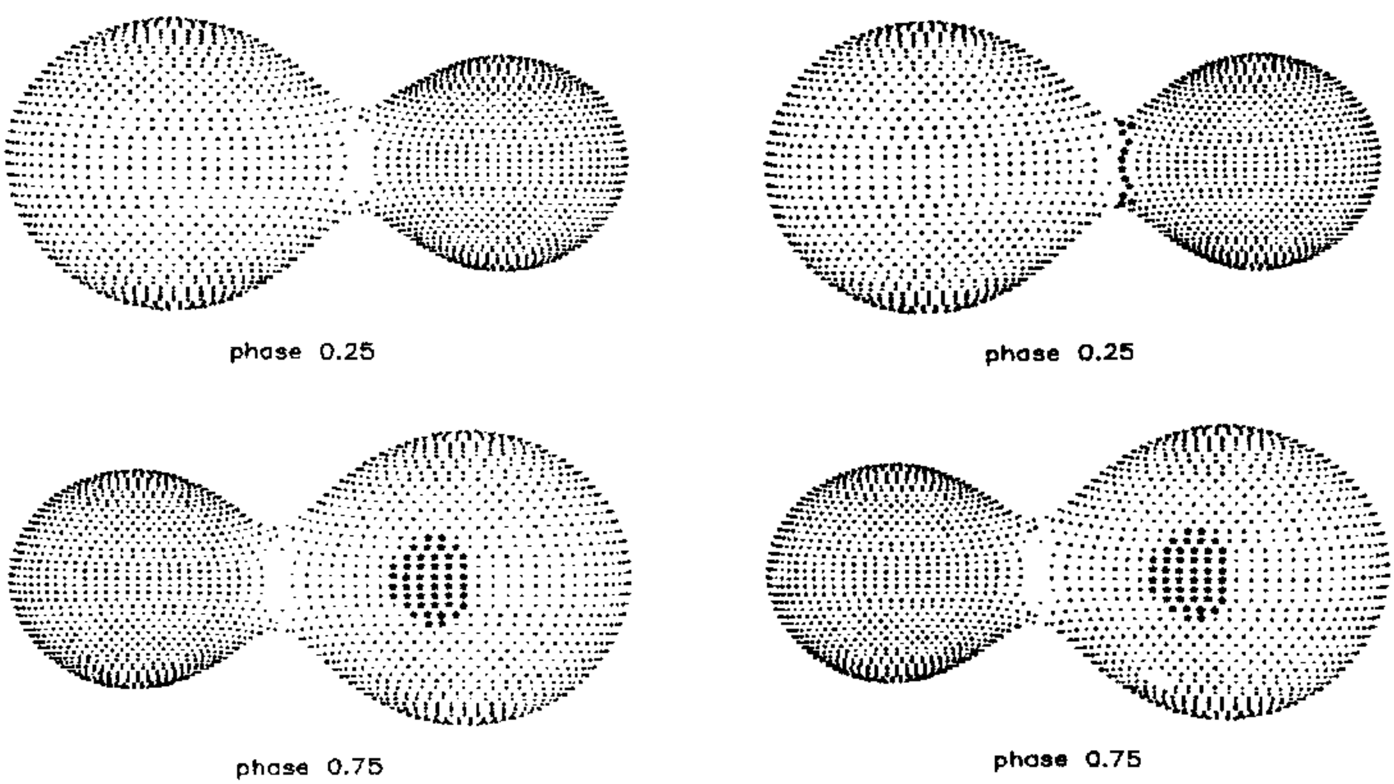

Fig. 5. Three-dimensional 1-spot (left) and 2-spot (right) models of TU Boo for phases 0.25 and 0.75

solar magnetic spots, while the hot region on the smaller component is produced as an effect of energy exchange between the two components through the connecting neck of the common envelope.

Such a spot model fits satisfactorily the observed light curves. It is clear from Fig. 4 that the O-C values of the 2-spot solution are much smaller than those of the unspotted one and certainly smaller than the O-C values of the 1-spot solution.

The depth of the common envelope, described by the degree of contact, was found from the 2-spot solution to be 32%, sufficient to equalize the temperatures of both components. As far as the uniqueness of our model is concerned, it should be stressed that solutions with different spot combinations may equally well fit the observations. It was pointed out by Maceroni et al. (1990) and Maceroni & van't Veer (1993) that this is a general problem of light curve fitting with spot models. Because of the non-uniqueness of such solutions, we tried to use the simplest possible model with a physical meaning. A three dimensional picture of the spotted models of TU Boo at phases 0.25 and 0.75 is shown in Fig. 5.

Although the only available information about TU Boo is based on the photometric analysis and its spectral type, it is interesting to speculate on the evolutionary status of the system. In order to do so, the absolute parameters of the system have to be evaluated. These parameters were computed by using standard relations, where we assumed a mass of the primary $\mathcal{M}_1 = 0.97\ \mathcal{M}_\odot$, a value typical for a main sequence star of spectral type G3. The parameters of the two final spotted solutions were used as input parameters to compute the absolute elements of TU Boo listed in Table 2. It should be noted that the absolute parameters of TU Boo derived from the two spotted solutions do not differ appreciably, so that the system configuration remains basically the same.

We use the absolute elements of the 2-spot solution to estimate the evolutionary status of TU Boo by means of the mass-radius (MR), mass-luminosity (ML) and HR diagrams of Hilditch et al. (1988). According to those authors, the mass-radius diagram is the principal indicator of the evolutionary state of the individual stars. In these diagrams, the primary component of TU Boo lies above the zero-age main sequence and close to the terminal-age main sequence, in a region where many W type primaries are found. The evolutionary state of the system can also be studied by means of the mean density ρ_1 of the more evolved primary component and the initial minimum period P_0. According to Mochnacki (1981) these two parameters provide the means to compare observations with theoretical models. The evolutionary state can be inferred from the relation between the above two parameters and a temperature index, like the corrected colour index $(B-V)_I$ of the primary component (calculated for the case of zero luminosity transfer to the secondary component). In the case of TU Boo we found $P_0 = 0.2435$ days and $(B-V)_I = 0.45$, and TU Boo falls onto the ZAMS in Mochnacki's (1981) Figs. 3 and 4.

The position of the primary component of TU Boo in the diagrams given by Hilditch et al. (1988) indicates that TU Boo is a slightly evolved system, while such a conclusion cannot be inferred from its position in Figs. 3 and 4 of Mochnacki (1981). The shape of the light curve clearly shows that the system undergoes complete eclipses with the secondary minimum being an occultation. Following Binnendijk (1970), TU Boo should be classified as an A-type contact W UMa system. Such systems, however, tend to be evolved and of earlier spectral type.

On the other hand, some physical characteristics of the system, such as: moderate mass-ratio, late spectral type, high density, short period and light curve anomalies are typical for W-type systems. It seems, therefore, that a problem of classification of TU Boo exists, as is the case for some other systems, e.g. RW PsA, W Crv and UV Lyn, which should be classified more correctly as W-type, although their primary minimum results unambiguously from a transit (Maceroni et al. 1985). TU Boo is another example for the ambiguity of the classification in W and A types according to the type of primary minimum.

The present analysis is based on photometry only. The A-type solution is successful in reproducing the observed light variations and it is quite consistent with the MR, ML and HR diagrams of Hilditch et al. (1988). We hope that new photoelectric and spectroscopic observations will provide the means to obtain a better picture of this interesting W UMa system.

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