A Photometric Study of the Contact Binary System FU Draconis

Ronald H. Kaitchuck
Robert L. Hill
Department of Physics and Astronomy, Ball State University, Muncie, IN 47304

Alexander Patrick Corn
Daleville High School, Daleville, IN 47334
Student participant, 2004 Research and Engineering Apprenticeship Program

Joshua Gevirtz
Central High School, Muncie, IN 47302
Student participant, 2004 Research and Engineering Apprenticeship Program

Kara L. Levell
Daleville High School, Daleville, IN 47334
Student participant, 2004 Research and Engineering Apprenticeship Program

Theanamous Leviatha Valenti
Southside High School, Muncie, IN 47302
Student participant, 2004 Research and Engineering Apprenticeship Program

Received March 28, 2006; revised January 23, 2007; accepted January 23, 2007

Abstract This paper reports new four-filter CCD observations of the contact binary FU Dra. The Wilson and Devinney model was used to simultaneously fit these light curves and published radial velocity data. The stellar masses, sizes, and densities were calculated. Five additional models involving dark spots, hot spots, and accretion heating were considered as explanations for the light curve asymmetry known as the "O'Connell effect" in FU Dra. No conclusive spot model choice could be made but the Liu and Yang model for accretion heating is an unlikely explanation for the O'Connell effect in FU Dra.

1. Introduction

FU Dra is a W UMa-type contact binary first discovered by the Hipparcos satellite and designated HIP 76272. There have been very few studies of this binary. Ruciński *et al.* (2000) found it to be a double-line spectroscopic binary with a mass ratio of 0.25 ± 0.03. They determined it to be a member of the W-type subgroup, i.e., the smaller, hotter star is occulted at primary minimum. Vaňko *et al.* (2001) obtained *B* and *V* photometry. They noted a flat bottom to the primary eclipse light curve that confirmed the W-type subclass. These authors applied the Wilson and Devinney (WD) model (Wilson and Devinney 1971; Wilson 1990) to obtain the first light curve solution for FU Dra.

2. Observations

We obtained new four-filter observations of FU Dra with the Ball State University 0.4-meter telescope and an SBIG ST-10 CCD camera on June 24, 26, and 27, 2004 (UT). The observations were 30-second exposures with Johnson-Cousins *BVRI* filters. The images were bias-subtracted, dark-subtracted, and flat-field corrected using IRAF. Differential aperture photometry was done with the CCDPHOT tool of the CCDIR software package (Henden *et al.* 1994; Leiker 1996). GSC 04 118-01726 was used as the primary comparison star. A field star (R.A. 15^h 36^m 04.38^s, Dec. +62° 16' 22.4" (2000)) was a used as a check star. Given the small angular separation of the variable and comparison star extinction corrections were not made. There were 254 observations in *B*, 211 in *V*, 259 in *R*, and 260 in *I*. The typical errors of single differential magnitudes were 0.011 (*B*), 0.005 (*V*), 0.003 (*R*), and 0.003 (*I*). Figure 1 shows the instrumental differential light curve for each filter with the solution of Vaňko *et al.* for comparison. These light curves show the flat-bottom primary eclipse reported by Vaňko *et al.* and an asymmetry in that the light level at phase 0.75 (max II) is different from that at phase 0.25 (max I). This asymmetry, often called the "O'Connell effect" has been reported in many contact binaries. The Vaňko *et al.* light curve solution is also too deep at primary minimum. At least some of the differences between the Vaňko *et al.* light curve solution and our observations are due to real changes in the light curve over time (see below). Our dataset will be web-archived and available through the AAVSO ftp site at: ftp://ftp.aavso.org/public/datasets/jkaitr342b.txt, jkaitr342v.txt, jkaitr342r.txt, and jkaitr342i.txt.

3. Period Study

Vaňko *et al.* (2001) did a period study based on twelve available times of minimum light. They determined an ephemeris for primary minimum as

$$\text{Min I} = 2450866.2770 + 0.30671686\,E$$
$$\pm\, 0.0003 \;\pm\, 0.00000009$$

Given that the O–C values didn't exceed 0.003 day they concluded that the period was stable. Table 1 contains those earlier times of minimum combined with recently published values and those determined from our observations. The later values were determined by a least-squares fit of a parabola to the ingress and egress phases of the eclipse. Figure 2 is the O–C diagram for these observations using the light elements of Vaňko *et al.*

The linear arrangements of points after E = 6000 suggests a fairly abrupt period change occurred about JD = 2452716. This portion of the O–C diagram is enlarged in Figure 3. A weighted linear fit to just these points yields the following light elements.

$$\text{Min I} = 2450866.265 + 0.3067190\,E$$
$$\pm\, 0.001 \;\pm\, 0.0000002$$

This is a more appropriate set of light elements for observations after JD 2452716.

4. Light Curve Analysis

The observations presented in this paper were analyzed with the WD model as implemented by PHOEBE (Prša and Zwitter 2005). PHOEBE is a computer program that allows efficient utilization of the WD model through a graphical menu-driven interface. PHOEBE also provides several numerical enhancements to the WD program. Our light curve analysis differs from that of Vaňko *et al.* (2001) in that we have observations in four filters rather than two, and instead of adopting the mass ratio it was determined by simultaneously fitting the light curves and the radial velocity data of Ruciński *et al.* (2000). Like Vaňko *et al.* we fixed the temperature of the primary (the star of higher mass and luminosity) at 5,800 K to match the observed spectral type.

The WD model applied to our *BVRI* light curves are shown in Figure 4. Consistent with the expected convective atmosphere, the gravity brightening coefficients were set at $g_1 = g_2 = 0.32$ (Lucy 1967) and the bolometric albedos at $A_1 = A_2 = 0.5$ (Ruciński 1969). It has been common practice when studying contact binaries to assume the limb darkening coefficients are the same for both stars. Given that the stars in a contact binary can have significantly different temperatures, WD 2003 (used in PHOEBE) allows the limb darkening of the stars to differ. A square root limb darkening law was used with coefficients obtained by interpolating in the tables by Van Hamme (1993). In PHOEBE these values are adjusted (as necessary) with each fitting iteration.

Table 2 summarizes the results of the WD modeling. We considered models with and without star spots. The main difference between the parameters of our unspotted model and those of Vaňko *et al.* is that the secondary star is about 70 K cooler. Figure 4 shows our unspotted light curve model fitted to the observations. As expected, the model light curve is too high at max I and too low at max II. A symmetric light curve will split the difference between the heights of the two maxima. The depth of primary eclipse matches the observations well except in the *B* filter where the model is too deep. Attempts to correct this with the addition of third light resulted in poorer fits in the other filters and/or unphysical values for third light parameters.

Table 3 contains masses and radii determined using the spectroscopic parameters from Ruciński *et al.* (2000) and the inclination from our unspotted WD model.

5. Star-spot models

In order to improve the fit to the light curve, we investigated star-spot models to correct for the O'Connell effect. There are two ambiguities that must be considered. First, is max II lower because of dark spots visible at phase 0.75 or is max I higher due to bright spots on the opposite hemisphere visible at phase 0.25? Secondly, are the spots on the primary or secondary star? Our approach was to assume a single spot in four models: a dark spot on the primary star, a dark spot on the secondary star, a bright spot on the primary star, and a bright spot on the secondary star.

The first attempt placed a single dark spot on the primary star near stellar longitude of 180°. Spot longitude is measured counter-clockwise from the L_1 point. See Figure 6a for a picture of this model.The spot parameters in the WD model are longitude, latitude, spot radius, and temperature factor (T_{spot} / T_{star}). The theoretical light curves were very insensitive to the spot latitude so it was fixed to the equator (90° in the WD formalism). We were never able to get the three remaining spot parameters to converge simultaneously. Instead, the stellar parameters were initially held fixed and longitude, spot radius, and spot temperature factor were individually allowed to converge. These parameters were then fixed and the stellar parameters were allowed to converge to new values. The fit to max I is improved, while the system parameters changed only slightly and the fit residuals are slightly smaller (see Table 2).

For the second model, a dark spot was added to the secondary star near a longitude of 270° (see Figure 6b). The fitting procedure was the same. Table 2 gives the resulting system parameters and Figure 5 shows the resulting light curves. In Figure 5 the improvements to the fits are most apparent at max I. The fit residuals are lowest of any model considered in this paper.

For the third model a bright spot was placed on the primary star near longitude 270° (see Figure 6c). This is a location that is geometrically opposite of the dark spot in the first spot model. The parameters for this model are found in Table 2. The fit residuals indicate that this model is the poorest match to the data, even worse than the unspotted model.

The fourth model placed a bright spot on the secondary star near longitude 90° (see Figure 6d). Table 2 shows the results. The fit residuals are better than the previous model but slightly worse than the unspotted model.

6. Discussion

Differences in the height of max I and max II are seen in many binary star light curves. O'Connell (1951) made one of the earliest studies of this phenomenon. More recently (Davidge and Milone 1984) refined the correlations between the O'Connell effect and system parameters. Star-spot models, like those presented here, have been one possible explanation for the O'Connell effect. Other explanations have included absorption by gas streams (O'Connell 1951), atmospheric circulation (Zhou and Leung 1990), and hot spots due to stream impacts (Shaw 1994). Because of our inability to converge spot parameters simultaneously with the stellar parameters it is impossible to claim the spot parameters are well established. The fact that four different spot models can produce fits that are only slightly different raises the question of the uniqueness of spot models. For FU Dra, at least, it is difficult to claim that star spots are the correct explanation for the O'Connell effect.

Recently, Liu and Yang (2003) have proposed another explanation for the O'Connell effect. In their model the stars are moving through circumbinary material. As each star orbits, this material impacts the leading side of the stars and elevates their temperatures. This produces a brightness asymmetry between the leading and trailing sides of each star. Combined with the difference in the stellar sizes, this asymmetry produces a difference in the light curves at the two quadratures. While this accretion model may account for the difference between max I and max II, the question remains as to how the rest of the light curve will be affected by the asymmetry of the stars. This can be tested with the WD model by placing a large bright spot on the leading side of each star. For each star a spot was placed on the equator and near longitude 270°. The spot radii were held fixed at a radius of 80° (because the regions near the limb are not expected to be as bright) while the spot longitude and temperature factor were simultaneously allowed to converge for each spot. The spot parameters were then held fixed and the other light curve parameters were allowed to converge. The results are shown in Table 2. The quality of the light curve fit was formally better than either bright-spot model but not as good as either dark-spot model. Based on this analysis the Liu-Yang model can not be excluded by this test. However, over the years between our observations and those by Vaňko *et al.* the O'Connell effect in FU Dra has changed. In their observations max II is brighter (by 0.02 mag); in our observations max I is brighter (by 0.02 mag). Clearly the Liu and Yang model cannot account for this.

7. Conclusions

This study has produced an improved light curve analysis of FU Dra. This analysis has been combined with published radial velocity data to give absolute system parameters. We have also explored three possible models (dark spots, bright spots, and accretion-heated stars) to explain the O'Connell effect in this system. The O'Connell effect in FU Dra is small and these models produce light curves that are only subtly different. Based on the fit residuals the best model is a dark spot on the secondary star (Figure 6c). However, the possibility of another explanation for the O'Connell effect can not be excluded. The Liu and Yang model for accretion heating is an unlikely explanation for the O'Connell effect in FU Dra.

8. Acknowledgements

The students in this project were supported by the 2004 Research and Engineering Apprenticeship Program of the New Hampshire Academy of Applied Sciences, grant W911NF-04-1-0226 with the U.S. Army Research Office. We also thank the referee for constructive comments.

References

Bakis, V., Bakis, H., Erdem, A., Cicek, C., Demircan, O., and Budding, E. 2003, *Inf. Bull. Var. Stars, No. 5464*.
Bradstreet, D. H. 2005, *BINARY MAKER 3.0*, Contact Software, Norristown, PA.
Davidge, T. J., and Milone, E. F. 1984, *Astrophys. J.*, **55**, 571.
Drózdz, M., and Ogloza, W. 2005, *Inf. Bull. Var. Stars, No. 5623.*
Henden, A. H., Kaitchuck, R. H., and Truax, R. 1994, CCDIR, Unified Software Systems, Flagstaff, AZ.
Leiker, S. 1996, *CCD Astron.*, **3**, 27.
Liu, Q. -Y., and Yang, Y. -L. 2003, *Chinese Astron. Astrophys.*, **3**, 142.
Lucy, L. B. 1967, *Z. Astrophys.*, **65**, 89.
O'Connell, D. J. K. 1951, *Publ. Riverview College Obs.*, **2**, 85.
Prša, A., and Zwitter, T. 2005, *Astrophys. J.*, **628**, 426.
Ruciński, S. M. 1969, *Acta Astron.*, **19**, 245.
Ruciński, S. M., Lu, W., and Mochnacki, S. W. 2000, *Astron. J.*, **120**, 1133.
Shaw, J. S. 1994, *Mem. Soc. Astron. Italiana*, **65**, 95.
van Hamme, W. 1993, *Astron. J.*, **106**, 2096.
Wilson, R. E. 1990, *Astrophys. J.*, **356**, 613.
Wilson, R. E., and Devinney, E. J. 1971, *Astrophys. J.*, **166**, 605.
Vaňko, M., Pribulla, T., Chochol, D., Parimucha, S., Kim, C. H., Lee, J. W., and Han, J. Y. 2001, *Contr. Astron. Obs. Skalnaté Pleso*, **31**, 129.
Zejda, M. 2004, *Inf. Bull. Var. Stars, No. 5583.*
Zhou, D. Q., and Leung, K. -C. 1990, *Astrophys. J.*, **355**, 271.

Table 1. Times of minima of FU Dra.

HJD+2400000	*Min.*	*E*	*(O–C)*	*Reference*
52002.5086	II	3704.5	–0.0010	Zejda, 2004
52023.5219	I	3773	0.00219	Zejda, 2004
52062.4734	I	3900	0.0006	Zejda, 2004
52039.4701	I	3825	0.0011	Zejda, 2004
52730.5016	I	6078	–0.0005	Zejda, 2004
52983.5459	I	6903	0.0024	Zejda, 2004
52983.393	II	6902.5	0.003	Zejda, 2004
52770.3762	I	6208	0.0009	Bakis, *et al.* 2003
52862.3919	I	6508	0.0016	Bakis, *et al.* 2003
52333.4576	II	4783.5	0.0005	Drózdz and Ogloza 2005
52338.519	I	4800	0.001	Drózdz and Ogloza 2005
52347.4142	I	4829	0.0015	Drózdz and Ogloza 2005
52347.5678	II	4829.5	0.0017	Drózdz and Ogloza 2005
51925.6761	I	3454	–0.0009	Vaňko, *et al.*, 2001
51925.6756	I	3454	–0.0014	Vaňko, *et al.*, 2001
51927.671	II	3460.5	0.0003	Vaňko, *et al.*, 2001
51927.6701	II	3460.5	–0.0006	Vaňko, *et al.*, 2001
51952.514	II	3541.5	–0.001	Vaňko, *et al.*, 2001
51952.5134	II	3541.5	–0.0014	Vaňko, *et al.*, 2001
51952.6665	I	3542	–0.0016	Vaňko, *et al.*, 2001
51952.6679	I	3542	–0.0002	Vaňko, *et al.*, 2001
51999.4407	II	3694.5	–0.0017	Vaňko, *et al.*, 2001
51999.4402	II	3694.5	–0.0022	Vaňko, *et al.*, 2001
52085.4777	I	3975	0.0012	Vaňko, *et al.*, 2001
52086.3984	I	3978	0.0017	Vaňko, *et al.*, 2001
52088.3913	II	3984.5	0.0010	Vaňko, *et al.*, 2001
53180.7669	I	7546	0.00445	This paper *V* filter
53180.7669	I	7546	0.0045	This paper *R* filter
53180.7671	I	7546	0.0047	This paper *I* filter
53182.6072	I	7552	0.0045	This paper *V* filter
53182.6071	I	7552	0.0044	This paper *R* filter
53182.6067	I	7552	0.0040	This paper *I* filter
53182.7601	II	7552.5	0.0040	This paper *V* filter
53182.7604	II	7552.5	0.0043	This paper *R* filter
53182.7601	II	7552.5	0.0040	This paper *I* filter
53183.6811	II	7555.5	0.0049	This paper *V* filter
53183.6811	II	7555.5	0.0049	This paper *R* filter

Note: (O–C) is calculated from Min. I = 2450866.2270 + 0.30671686 E.

Table 2. Photometric solutions for FU Dra.

Parameter	*No Spots*	*Primary Dark Spot*	*Secondary Dark Spot*	*Primary Bright Spot*	*Secondary Bright Spot*	*Accretion Heating*
i°	78.99(24)	78.99(24)	78.99(24)	77.99(25)	77.99(24)	77.59(19)
q	0.249(2)	0.249(2)	0.249(2)	0.249(2)	0.249(2)	0.249(2)
Ω	2.3170(56)	2.3143(55)	2.3127(55)	2.3255(53)	2.3225(55)	2.3083(54)
T_1 [K][a]	5800	5800	5800	5800	5800	5800
T_2 [K]	6060(7)	6068(6)	6054(6)	6092(7)	6078(7)	6047(7)
$A_1 = A_2$	0.50	0.50	0.50	0.50	0.50	0.50
$g_1 = g_2$	0.32	0.32	0.32	0.32	0.32	0.32
$[L_1/(L_1+L_2)]_B$	0.7243(3)	0.7220(2)	0.7240(2)	0.7200(2)	0.7220(2)	0.7252(2)
$[L_1/(L_1+L_2)]_V$	0.7382(2)	0.7365(2)	0.7378(2)	0.7356(2)	0.7369(2)	0.7385(2)
$[L_1/(L_1+L_2)]_R$	0.7444(2)	0.7428(2)	0.7438(2)	0.7425(2)	0.7435(2)	0.7443(2)
$[L_1/(L_1+L_2)]_I$	0.7491(3)	0.7478(2)	0.7486(2)	0.7479(3)	0.7487(3)	0.7491(2)
$r_{1\,(pole)}$	0.478(1)	0.478(1)	0.479(1)	0.476(1)	0.476(1)	0.480(1)
$r_{1\,(side)}$	0.519(1)	0.520(1)	0.520(1)	0.516(1)	0.517(1)	0.521(1)
$r_{1\,(back)}$	0.545(2)	0.546(1)	0.547(1)	0.542(1)	0.543(1)	0.549(1)
$r_{2\,(pole)}$	0.256(3)	0.257(3)	0.257(3)	0.254(3)	0.255(3)	0.258(3)
$r_{2\,(side)}$	0.267(4)	0.260(3)	0.269(3)	0.265(3)	0.266(3)	0.270(4)
$r_{2\,(back)}$	0.308(7)	0.309(7)	0.310(7)	0.303(6)	0.305(6)	0.312(7)
Fill-out	0.216(36)	0.233(35)	0.243(35)	0.162(35)	0.181(35)	0.289(35)
Spot Lat.[a]		90°	90°	90°	90°	P: 90° S: 90°
Spot Long.		86.6°	273°	257°	98.0°	P: 247° S: 240°
Spot Radius		10.4°	16.7°	8.3°	22.0°	P[a]: 80° S[a]: 80°
T_{spot}/T_{star}		0.94	0.89	1.13	1.05	P: 1.0089 S: 1.0132
$\Sigma(wr^2)$	0.003768	0.003619	0.003545	0.004080	0.003839	0.003633

Note: a = adopted.

Table 3. Absolute Parameters for FU Dra.

Parameter	*Value*
M_1 [$M_\odot$]	1.17 ± 0.03
M_2 [$M_\odot$]	0.29 ± 0.01
a [$R_\odot$]	2.169 ± 0.022
R_1 [$R_\odot$]	1.12 ± 0.03
R_2 [$R_\odot$]	0.60 ± 0.01
log g_1 [cm s^{-2}]	4.41
log g_2 [cm s^{-2}]	4.34
ρ_1 [g cm^{-3}]	1.18
ρ_2 [g cm^{-3}]	1.87

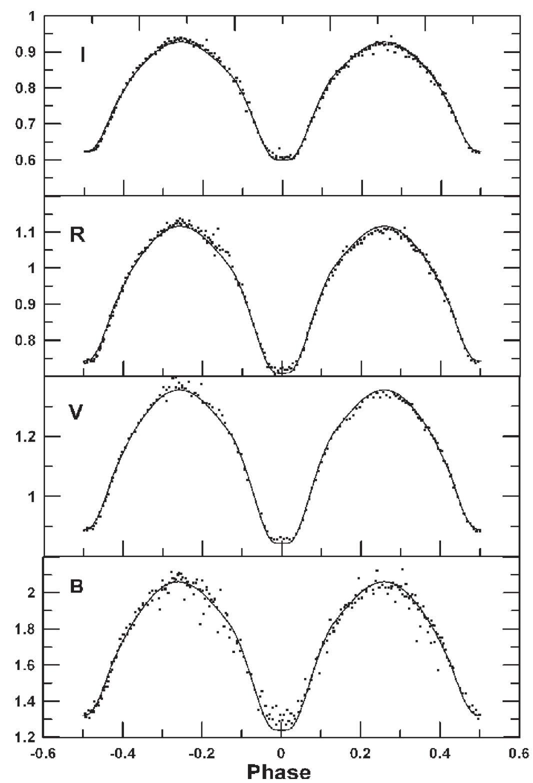

Figure 1. The *B*, *V*, *R*, and *I* observations of FU Dra compared to the light curve solution of Vaňko *et al.* (2001).

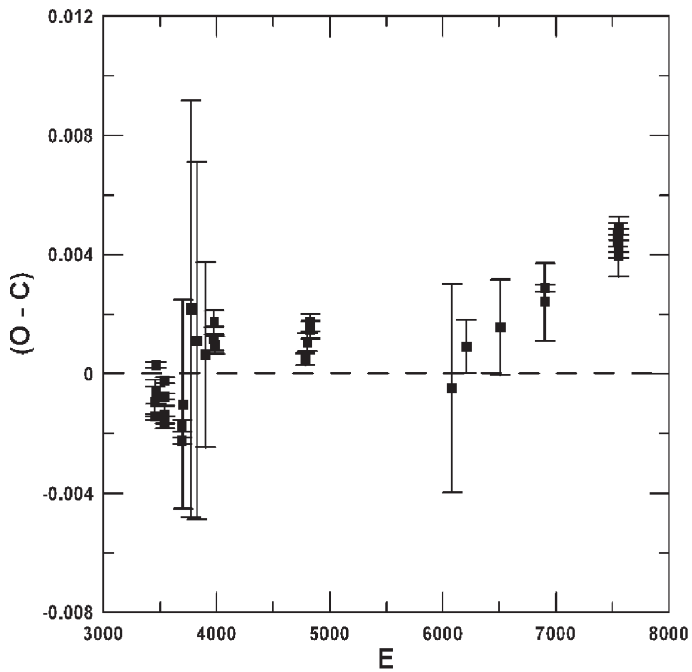

Figure 2. The difference between the observed and computed times of minimum light of FU Dra using the light elements of Vaňko *et al.* (2001).

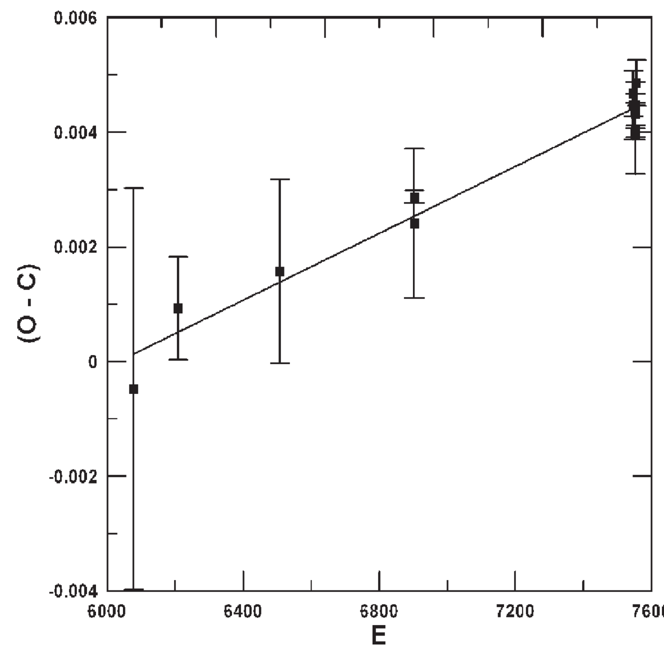

Figure 3. An enlargement of Figure 2 showing the O–C values after epoch 6000 with a linear least squares fit.

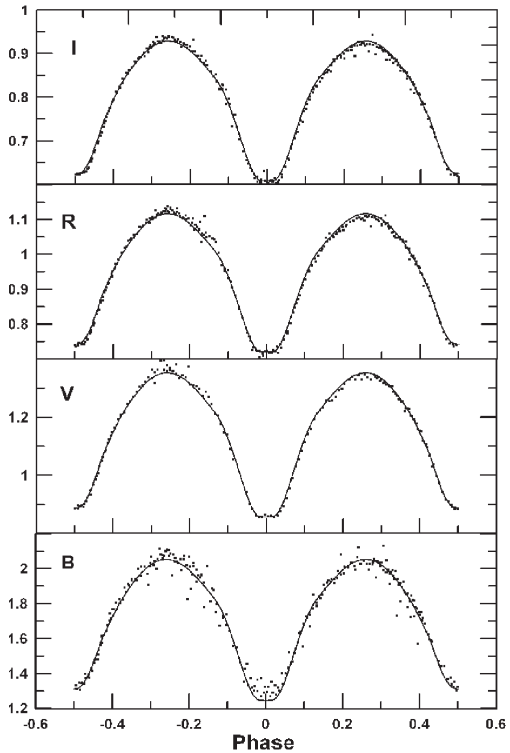

Figure 4. A comparison of the observations of FU Dra with a new WD solution for unspotted stars.

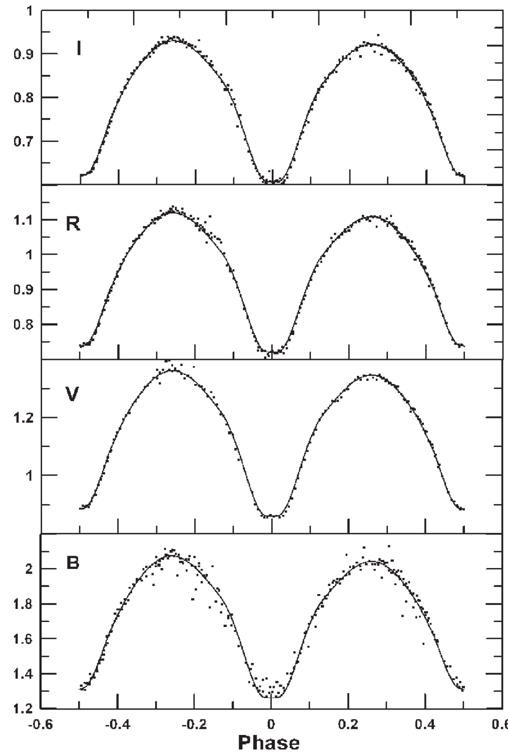

Figure 5. A comparison of the observations of FU Dra with a model that includes a dark spot on the secondary star.

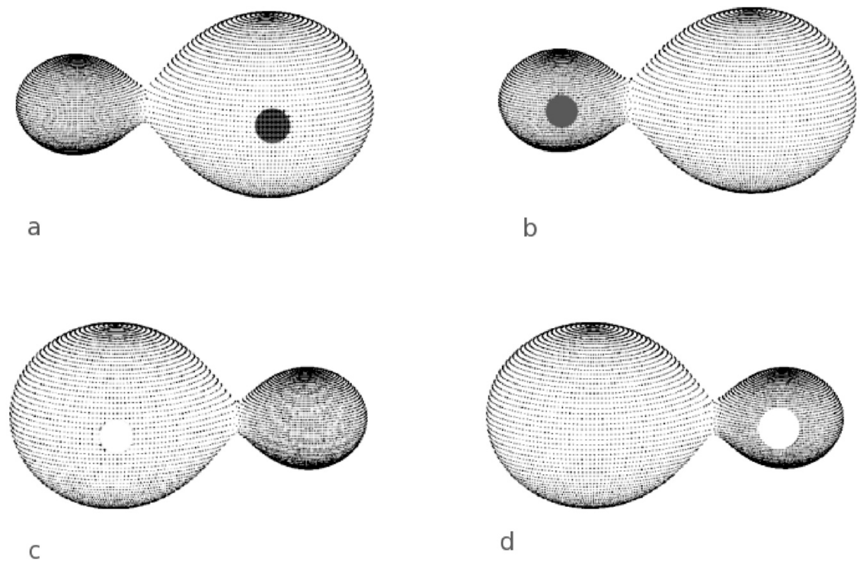

Figure 6. A graphical representation of the four spotted models: (a) a dark spot on the primary star, (b) a dark spot on the secondary star, (c) a bright spot on the primary star, and (d) a bright spot on the secondary star. These images were produced with BINARY MAKER 3.0 (Bradstreet 2005).