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PHOTOMETRIC ANALYSIS AND EVIDENCE FOR A THIRD, DWARF COMPONENT IN THE FY Boo SYSTEM

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FY Boo [GSC 01999-00518, 2MASSJ13465180+2257140, ROTSE1 J134651.80+225714.7, $\alpha(2000) = 13^{\rm h}46^{\rm m}51\overset{\rm s}{.}81$, $\delta(2000) = +22^\circ57'13''\!.0$] was recently discovered by ROTSE I (Diethelm, 2001), and identified as an EW type variable with a period of 0.241168 d. This makes it one of the shortest period W UMa binaries known and an object of our continuing study of very short period binaries (e.g., Samec, Faulkner and Williams, 2004).

We took B, V, R, I light curves of the binary with the Lowell 31 inch reflector in Flagstaff with a CRYOTYGER cooled (−100°C) NASACAM and a 2K×2K chip and standard BVR_cI_c filters. The dates of the observations were 11-15, March, 2009. We undertook the observing run under the auspices of the National Undergraduate Observatory (NURO) and were granted observing time by the Lowell TAC. We used the Lowell program LOIS to take our observations. Our modeled light curves included 107 B, 109 V, 95 R and 98 I individual CCD observations. These observations were taken by Oliver, Samec and Faulkner. The photometric precision was ±0.008 in B, ±0.006 in V, and ±0.005 in R and I. They are given in Table I (IBVS^{e1} `5963-t1.txt`), in delta magnitudes, variable minus comparison star.

Our comparison star (C) was GSC 1999 0750 [$\alpha(2000) = 13^{\rm h}46^{\rm m}58\overset{\rm s}{.}583$, $\delta(2000) = +22^\circ56'47''\!.5$, TYCHO I $B-V = 0.666$]. The check star (K) was GSC 1999 0854 [$\alpha(2000) = 13^{\rm h}46^{\rm m}46\overset{\rm s}{.}152$, $\delta(2000) = +22^\circ54'41''\!.61$ TYCHO $B-V = 0.684$]. We include a finding chart of these stars including the variable (V) in Figure 7 (IBVS^e).

We determined six times of minimum light from our present observations. The minima were calculated using parabola fits. With their standard errors in parentheses, they include: HJDMin I = 2454901.9711(±0.0022) d, 2454902.9350(±0.0024) d, 2454904.8587(±0.0002) d, 2454905.8304(±0.0002) d and HJDMin II = 2454904.9774(±0.0007) d, 2454905.9491(±0.0002) d. From our timings and 43 others which are referenced in Table 2 (IBVS^e `5963-t2.txt`), we calculated the following precision linear ephemeris:

$$\text{HJD Min I} = 2454904.8660 \pm 0.0003 + 0.24115955 \pm 0.00000005\,\text{d} \times \text{E} \qquad (1)$$

[1]Available electronically through the IBVS website

Interestingly, our fit revealed the presence of a low amplitude sinusoid. The sinusoidal ephemeris is:

$$\text{HJD Min I} = 2454904.8691(\pm0.0002) + 0.2411596(\pm0.0000005) \times \text{E} \\ +0.00265(\pm0.00020) \cdot \sin[4.2(\pm0.1) \times 10^{-4} \times \text{E} - 6.07(\pm0.08)] \quad (2)$$

We believe this sinusoid is due to the light time effect of a third, orbiting component. The ephemeris gives an orbital period of 9.9±0.2 years for the third component. From the amplitude, we calculate an orbital radius of 0.61±0.05 AU in light travel time, assuming the orbital inclination of the third component is identical to that of the main binary. The third body has a mass ratio of 0.16±0.03 as compared to the FY Boo system. If the total mass of the eclipsing binary pair is 1 solar mass (K1V star; Cox, 2000) then the additional component has an estimated mass of 0.16 solar masses. This mass is that of an ∼M6 dwarf which is small, but comparable to the masses of the other two components (in the range of 0.2 to 0.8 solar masses).

The sinusoidal $O-C$ diagram is given in Figure 1. We also include the linear residuals from Equation 1 in the table.

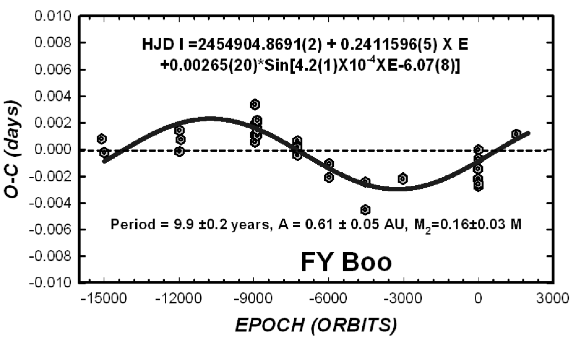

Figure 1. Sinusoidal $O-C$ residuals from Equation 2 revealing a third star orbiting the system.

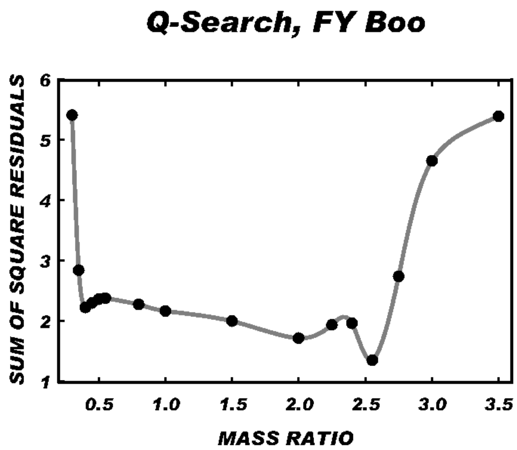

Figure 2. Chart of solution residuals of mass ratios extending from 0.3 to 3.5 minimizes near 2.5.

Our $UBVRI$ phased light curves, Phase versus Delta Magnitudes, in the sense of $V-C$, are given as Figures 8 and 9 (IBVS^e). The $BVRI$ curves are typical of a classic short period, solar-type contact system. The light curves show effects of night to night variability which forced us to use data for modeling from only two nights. Also, the maximum at phase 0.75 is about 0.1 mags higher than the one at phase 0.25. Thus, magnetic activity is strong in the system with either dark spots or hot spots predominating. Dips in the color curves at phase 0.0 and 0.5 indicate the system has achieved contact (as we view the cooler back parts of the contact Roche lobes). Broad eclipses at phase 0.0 indicate a brief total eclipse. This suggests that FY Boo is probably a W-Type W UMa binary (the hotter component is the less massive one).

Our B, V, R, I light curves were hand modeled with Binary Maker 3.0 (Bradstreet et al., 2002). Averaged values of parameters were then entered into the 2004 version of the Wilson Code (Wilson and Devinney, 1971 (WD); Wilson, 1990, 1994; Van Hamme and Wilson, 1998). From these we ran a full $BVRI$ simultaneous solution. Intermediate modeling iterations were done with PHOEBE (Prša and Zwitter 2005) which runs the same Wilson code in the background and makes it possible to view the light curve fit as the iterations progress. A mass ratio search covering regions from 0.3 to 3.5 was performed which indicated the value minimizes near ∼2.5. See Figure 2. Full synthetic light curve solutions follow. The temperature of the main component (4750K, K3V spectral type) which we used to model our light curves, was taken from a period-color relation from Battan, 1973 using the W UMa period. Recent 2MASS $B-V$, $V-R$, $J-H$ and $H-K$ average to K1±4 and affirms our choice. We computed both a Hot Spot and a Dark spot model. The Dark spot model has a slightly better sum of square residuals. Thus the choice of models is not conclusive. Either model is acceptable within the errors. The dark spot light curve solution is seen overlaying the normalized flux curves shown in Figures 3 and 4. The complete solutions are given as Table 3. Two phases of the Roche-lobe model of the binary for the dark spot solution are shown as Figures 5 and 6. Phase zero shows the total eclipse.

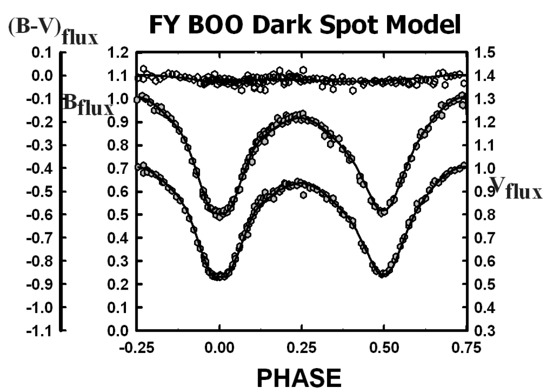

Figure 3. B, V synthetic light curve solutions overlaying the normalized flux curves.

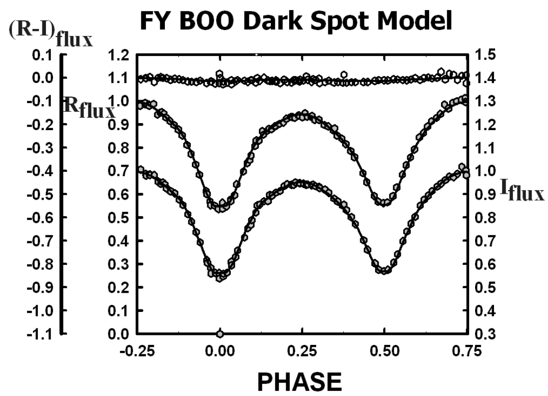

Figure 4. R, I synthetic light curve solutions overlaying the normalized flux curves.

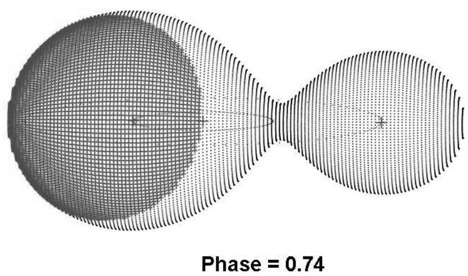

Figure 5. Roche Lobe surfaces from our $BVRI$ solution, phase 0.74.

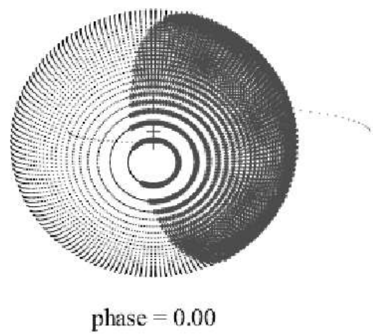

Figure 6. Roche Lobe surfaces from our $BVRI$ solution, phase 0.0 (the primary eclipse).

Our models show FY Boo is a W-type (the less massive component is the hotter) W UMa binary with a mass ratio of ~ 2.5. The system parameters from our model include a fill-out of 11%, a slight temperature difference of 200 K and an inclination of 82°. One large 68° radius magnetic region was modeled on the hotter companion with an average temperature of 0.96 times that of the photosphere. The T-Factors and spot radii indicate that this is a major *region* of spot activity rather than that of a single spot.

The solution gives a eclipse duration of $\sim$7 minutes. The shallow fill-out is quite normal for a W-type system. We believe that this results due to an early stage of contact. The fairly extreme mass ratio probably indicates that the components had nearly this value when they came in contact. We suspect that the mass ratio should progress to

TABLE 3. SYNTHETIC CURVE PARAMETERS FOR FY Boo

Parameters	Dark Spot Solution (Mode 3)	Hot Spot Solution (Mode 3)
l_B, l_V, l_R, l_I (nm)	440, 550, 640, 790	440, 550, 640, 790
xbol$_{1,2}$, ybol$_{1,2}$	0.619, 0.649, 0.190, 0.190	0.619, 0.649 0.190 0.190
x$_{1I,2I}$, y$_{1I,2I}$	0.626, 0.626, 0.226, 0.226	0.626, 0.626, 0.226, 0.226
x$_{1R,2R}$, y$_{1R,2R}$	0.711, 0.711, 0.223, 0.223	0.711, 0.711, 0.223, 0.223
x$_{1V,2V}$, y$_{1V,2V}$	0.780, 0.780, 0.192, 0.192	0.780, 0.780, 0.192, 0.192
x$_{1B,2B}$, y$_{1B,2B}$	0.848, 0.848, 0.087, 0.087	0.848, 0.848, 0.087, 0.087
g_1, g_2	0.32	0.32
A_1, A_2	0.5	0.5
Inclination (°)	82.4±0.3	82.2±0.4
T_1, T_2 (K)	4750(fixed), 4555 ±44*	4750(fixed), 4700.2 ±75*
$\Omega_1 = \Omega_2$	5.947±0.015	5.917±0.023
q (m2/m1)	2.55±0.01	2.517±0.022
Fill-outs: $F_1 = F_2$	11.0±2%	11.0±2%
$L1/(L1+L2)_I$	0.339±0.015	0.311±0.021
$L1/(L1+L2)_R$	0.346±0.018	0.312±0.025
$L1/(L1+L2)_V$	0.360±0.024	0.316±0.032
$L1/(L1+L2)_B$	0.376±0.032	0.319±0.041
JDo (days)	2454904.8652±0.0001	2454904.8647±0.0001
Period (days)	0.241141±0.000007	0.241141±0.00001
r_1, r_2 (pole)	0.286±0.001, 0.440±0.001	0.286±0.001, 0.437±0.002
r_1, r_2 (side)	0.299±0.001, 0.470±0.002	0.299±0.001, 0.467±0.002
r_1, r_2 (back)	0.336±0.003, 0.499±0.002	0.334±0.003, 0.496±0.003
Sum of square res	1.352	1.461

SPOT Parameters

Latitude (°)	78±26	78±38
Longitude (°)	241±5	67±7
Spot radius (°)	68±39	86±42
T-Factor	0.9562±0.0004	1.0368±0.0006

*All Errors are formal, here the error in T_2 is in relation to T_1. We expect errors to T_1 to be on the order of ∼250 K.

more extreme values in the future due to magnetic breaking. Breaking is due to the torque supplied by out flowing winds along ”stiff” magnetic field lines originating from this solar-type binary.

Should we be looking for eclipses of the third component? Our calculations show that the proposed dwarf orbiting at ~ 3.6 AU will never show any eclipses from an earth based observer.

We wish to thank Lowell Observatory for their allocation of observing time, and the AAS and the Arizona Space Grant for travel support for this observing run.

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