COMMISSIONS 27 AND 42 OF THE IAU
INFORMATION BULLETIN ON VARIABLE STARS

Number 6081

Konkoly Observatory
Budapest
17 November 2013

HU ISSN 0374 – 0676

CU TAU – A TYPE-A OVERCONTACT ECLIPSING BINARY

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CU Tau (= TYC 1804-2416-1, RA = $3^{\mathrm{h}}47^{\mathrm{m}}36\overset{\mathrm{s}}{.}914$, Dec = $+25^\circ23'15''\!.86$ (2000)) was discovered to be variable by Binnendijk (1950) during a photometric survey of AH Tau. He provided a light curve and eclipse elements, including a period of 0.4126022 days. As for type, he was unable to distinguish between "the cluster type [RR Lyrae] or of the W Ursae Majoris type". He also quoted a spectral type of G0, from a W.P. Bidelman [reference not available], who also noted "fairly broad lines" possibly caused by rotation. Therefore, Binnendijk favoured the identification as EW. Since then, numerous authors have found times of minima, showing the period to be decreasing at a constant rate. (See later discussion.)

Yang & Liu (2004) obtained CCD light curves in B and V. They presented four new times of minima, but unfortunately missed the true period of 0.412541(1) days at that epoch (obtainable with data presented in their paper) and were not able to detect the period decrease. (They instead used a period of 0.41341521(11) days for all their phasing, and attributed the large scatter in their eclipse timing (ET) plot [a.k.a. O-C diagram] scatter as due to irregular variations.) They used the 1994 version of the Wilson-Devinney (Wilson & Devinney, 1971; Wilson, 1990) code to reach a photometric solution, and pronounced the system to be type A. [In type A systems, the more massive – and hence larger – star has the higher surface temperature, making the primary eclipse a transit.] Lacking spectroscopic data, they estimated the mass ratio q [=M2/M1] by the so-called "q-search" method. Although this has since been shown to be very questionable or even invalid for EW-type systems undergoing partial eclipses [see Terrell & Wilson, 2005], this system makes a total eclipse, so the method is valid. They noted a small (0.017 magnitude) difference in the height of the maxima (V only) – this is the O'Connell effect (Davidge and Milone, 1984) – and applied a small cool spot to obtain a fit. Their results are presented in Table 5, along with those of the present study.

Qian et al. (2005) also determined a set of light curves in B and V. Obtaining four new times of minima and gathering together all times of minima available to them, they derived the correct period of 0.412538(5) days and displayed an ET diagram clearly showing a period decrease over time. (They derived a rate of period change $\mathrm{d}P/\mathrm{d}t = -1.81(2)\times10^{-6}$ days/year.) They then went on to perform a Wilson-Devinney (WD) analysis (ibid) using photometric data alone. Unlike Yang and Liu (2004), they did not detect an O'Connell effect. Also lacking spectroscopic data, the performed a q-search to obtain a starting value for the mass ratio q. Their results are also presented in Table 5, along with those of the present study.

In view of the fact that the addition of radial velocity (RV) data (available to the author) allows the determination of fundamental parameters (such as mass, orbit size, stellar radii), it was decided to add this system to the author's programme.

The first task was to establish the proper elements (epoch, period) for phasing. All available elements were obtained (Nelson, 2013) and the ET plot of Fig. 1 obtained.

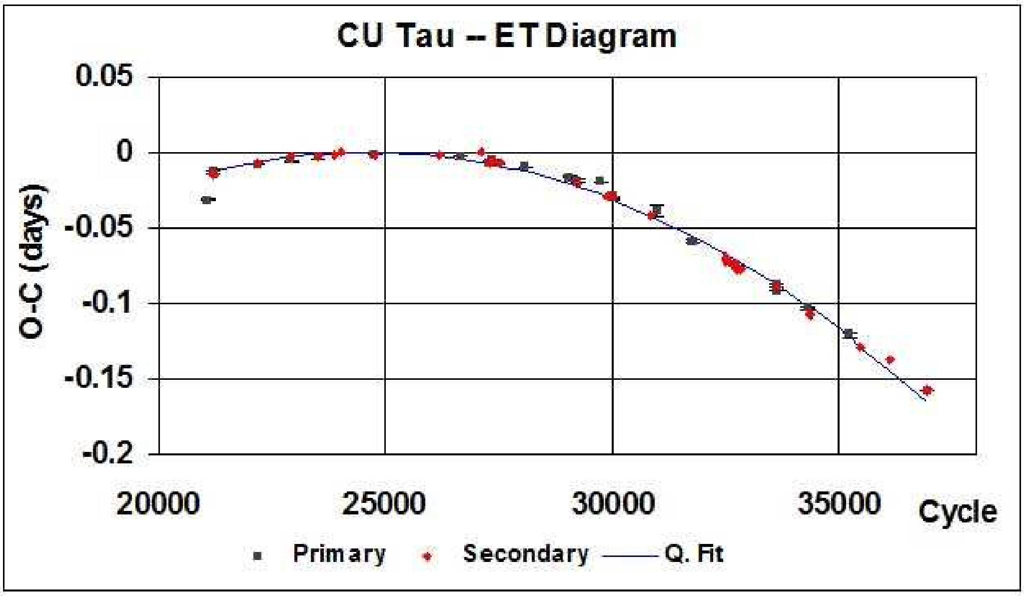


Figure 1. Eclipse timing diagram for CU Tau.

The least-squares best fit relation to fit the curve was found to be:

$$\mathrm{HJD\ (min\ I)} = 2440970.031(15) + 0.412518(1)\ \mathrm{E} - 1.09(2) \times 10^{-9}\ \mathrm{E}^2 \qquad (1)$$

The quadratic coefficient yields a rate of period change $\mathrm{d}P/\mathrm{d}t = -1.94(3) \times 10^{-6}$ days/year. Although the value of Qian et al. (2005) $[-1.81(2) \times 10^-6$ days/year] lies outside the ranges predicted by the statistical errors, the discrepancy is not thought to be significant since experience shows that the addition of a few extra times of minima can easily change the value of $\mathrm{d}P/\mathrm{d}t$ by this difference.

At the suggestion of an anonymous referee, the author also plotted in Fig. 2 the residuals from the above plot (in the sense observed - calculated by quadratic fit). It seems that there is some sort of quasi-periodic variation, but its cause is unclear. As is so often the case, future data may tell the tale.

In September of 2006, 2007, and September-October of 2010, the author took 6 medium resolution spectra at the DAO. The grating (#21181) was 1800 lines/mm, blazed at 5000 angströms and used in first order, reciprocal linear dispersion = 10 Å/mm, resolving power = 10,000. The cameras used were the SITe-5 for the first two sessions, and the SITe-2 for the last. The spectral range covered was from 5000 to 5260 angströms, approximately.

Since the period was shown to be varying over the interval in which the data were taken,

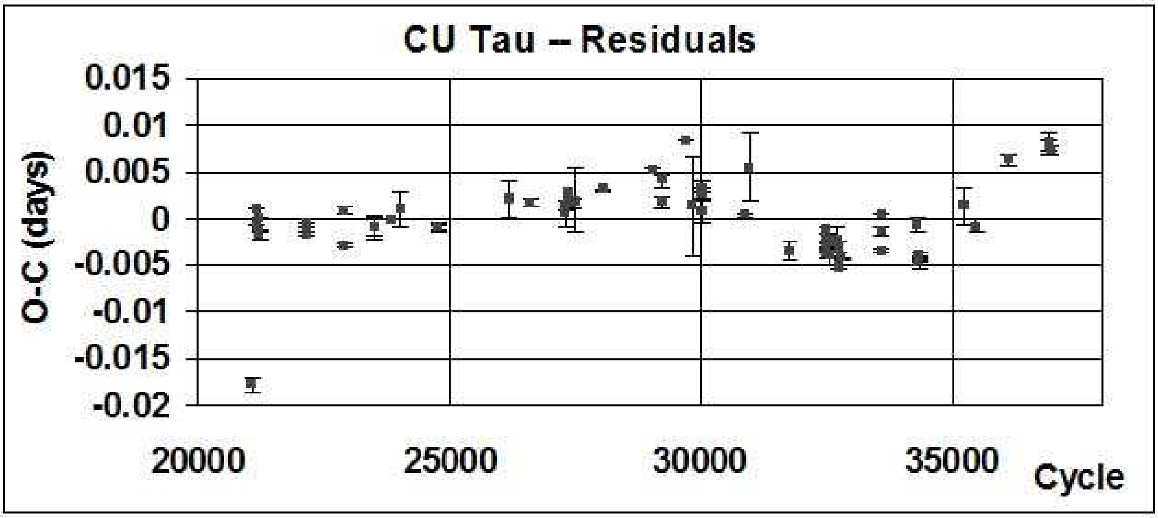


Figure 2. Residuals from quadratic best fit (Equation 1).

it was necessary to phase the data by using the current period, obtained by differentiating equation (1) getting:

$$P = \mathrm{d(HJD)/d}t = 0.412518 - 2.18 \times 10^{-9}\ \mathrm{E} \qquad (2)$$

The elements for each year were then:

Year	Epoch	Period (d)
2006	2454074.8901	0.412522
2007	2454406.5572	0.412520
2010	2455498.9036	0.412515

Table 1. Elements used for phasing RV data.

The author then used the Rucinski broadening functions (Rucinski, 2004) to obtain radial velocity (RV) curves (see Nelson, et al. (2006) and Nelson (2010) for details). A log of DAO observations and RV results is presented in Table 2. The results were corrected 7% up in this case to allow for the small phase smearing in the following way: the RVs were divided by the factor $f = (\sin X)/X$ [where $X = 2\pi t/P$ and t=exposure time, P=period]. For spherical stars, the correction is exact; in other cases, it can be shown to be close enough for any deviations to fall below observational errors. (This matter will be fully explored in a forthcoming paper.)

DAO Image #	Mid Time (HJD−2400000)	Exposure (sec)	Phase at Mid-exp	V1 (km/s)	V2 (km/s)
13090	53990.0188	3600	0.262	14.2	350.2
13227	54000.9571	3600	0.778	137.3	−191.1
11208	54367.0287	3600	0.178	43.8	318.2
17255	55468.9202	3600	0.316	25.9	320.3
17401	55474.8580	3600	0.709	114.4	−198.7
17492	55476.9685	3600	0.826	110.4	153.2

Table 2. Log of DAO observations.

In fitting two simple sine functions to the data, an overall rms deviation of 9.4 km/s was noted. These two best-fit functions yielded the following parameters:

$K_1 = 49.6 \pm 0.6$ km/s, $K_2 = 271.2 \pm 0.9$ km/s and $V_\gamma = 74.8 \pm 0.5$ km/s. Note that the latter high value is close to the threshold of 80 km/s that would classify the system as a high velocity star (Abell et al., 1991).

In October of 2012, the author took a total of 98 frames in V, 97 in R_c (Cousins) and 95 in the I_c (Cousins) band at his private observatory in Prince George, BC, Canada. (The telescope was a 33 cm f/4.5 Newtonian on a Paramount ME mount; the camera was an SBIG ST-10XME. Standard reductions were then applied. The comparison and check stars are listed in Table 3. The coordinates and magnitudes are from the Tycho Catalogue, Hog, et al., 2000.)

Type of target	GSC 1804-	R.A. J2000	Dec. J2000	V (Tycho) Mags	$B-V$ Mags
Variable	2416	03 47 36.911	+25 23 15.60	11.24	0.78
Comparison	2112	03 47 14.829	+25 22 17.94	11.22	1.22
Check	1922	03 47 46.731	+25 17 12.85	11.23	0.51

Table 3. Details of variable, comparison and check stars.

Here the elements for phasing, in accordance with equation (1), were:

$$\text{HJD (min I)} = 2456210.9102 + 0.412518\ \text{E} \qquad (3)$$

The author used the 2004 version of the Wilson-Devinney (WD) light curve and radial velocity analysis program with Kurucz atmospheres (Wilson and Devinney, 1971, Wilson, 1990, Kallrath, et al., 1998) as implemented in the Windows front-end software WDwint (Nelson, 2009) to analyze the data. To get started, a spectral type G0 (Binnendijk, 1950) was used. Interpolated tables from Cox (2000) gave $T_1 = 5940 \pm 114$ K and $\log g = 4.375 \pm 0.012$; an interpolation program by Terrell (1994, available from Nelson 2009) gave the Van Hamme (1993) limb darkening values; and finally, a logarithmic (LD=2) law for the extinction coefficients was selected, appropriate for temperatures < 8500 K (ibid.). (The stated error in T_1 corresponds to one spectral sub-class.)

From the GCVS 4 designation and from the shape of the light curve mode 3 (overcontact binary) mode was used. Convergence by the method of multiple subsets was reached in a small number of iterations. Convective envelopes for both stars were used, appropriate for cooler stars (hence values gravity exponent, $g = 0.32$ and albedo, $A = 0.500$ were used for each). Detailed reflections were eventually used, with $n_{\text{ref}} = 3$, but with little or no change. The limb darkening coefficients are listed below in Table 4.

Band	x1	x2	y1	y2
Bol	0.647	0.647	0.216	0.216
V	0.752	0.752	0.246	0.246
Rc	0.681	0.681	0.262	0.262
Ic	0.597	0.597	0.255	0.255

Table 4. Limb darkening values from Van Hamme (1993).

The model is presented in Table 5. Note that the quoted error in T_2 listed here, outputted by the WD program, refers to the error relative to T_1. This error, when added statistically to the error in T_1 quoted, yields an absolute error of 115 K for T_2 (see Table 6).

The light curve data and the fitted curves are depicted in Figure 3. The presence of third light was tested for, but found not to be significant.

WD- Quantity	This work Value	 error	Yang & Liu 2004* Value	 error	Qian, et al. 2005 Value	 error	 Unit
$q = M_2/M_1$	0.190	0.002	0.179	0.001	0.1770	0.0017	—
Temperature T_1	5940	[fixed]	5900	[fixed]	5900	[fixed]	K
Temperature T_2	5800	17	5851	6	5938	10	K
Potential $\Omega_1 = \Omega_2$	2.153	0.005	2.1237	0.0026	2.1176	0.0036	—
Inclination, i	76.0	0.4	74.04	0.16	73.95	0.26	degrees
Semi-maj. axis a	2.75	0.01	—	—	—	—	solar
V_γ	74.2	0.7	—	—	—	—	km/s
Phase shift	-0.0022	0.0003	—	—	—	—	—
$L_1/(L_1 + L_2)$ (B)	—	—	0.8205	0.0010	0.8123	0.0004	—
$L_1/(L_1 + L_2)$ (V)	0.8248	0.0004	0.8219	0.0011	0.8104	0.0005	—
$L_1/(L_1 + L_2)$ (R_c)	0.8224	0.0004	—	—	—	—	—
$L_1/(L_1 + L_2)$ (I_c)	0.8206	0.0004	—	—	—	—	—
r_1 (pole)	0.5042	0.0013	0.5092	0.0004	0.5102	0.0010	orb. rad.
r_1 (side)	0.5542	0.0020	0.5613	0.0006	0.5628	0.0016	orb. rad
r_1 (back)	0.5806	0.0026	0.5877	0.0006	0.5890	0.0021	orb. rad
r_2 (pole)	0.2442	0.0032	0.2420	0.0007	0.2412	0.0031	orb. rad
r_2 (side)	0.2562	0.0040	0.2541	0.0009	0.2533	0.0038	orb. rad
r_2 (back)	0.3054	0.0099	0.3058	0.0014	0.3053	0.0100	orb. rad
Fill factor	0.44	0.05	0.49	—	0.501	0.032	—
$\sum \omega_{res}^2$	0.0215	—	0.007263	—	0.00042	—	—

*Unspotted solution only

Table 5. Wilson-Devinney parameters.

The RVs are shown in Fig. 4. A three dimensional representation from Binary Maker 3 (Bradstreet, 1993) is shown in Fig. 5.

The WD output fundamental parameters and errors are listed in Table 6. Most of the errors are output or derived estimates from the WD routines. The fill factor $f = (\Omega^{\mathrm{I}} - \Omega)/(\Omega^{\mathrm{I}} - \Omega^{\mathrm{O}})$, where Ω is the modified Kopal potential of the system, Ω^{I} is that of the inner Lagrangian surface, and Ω^{O}, that of the outer Lagrangian surface, was also calculated.

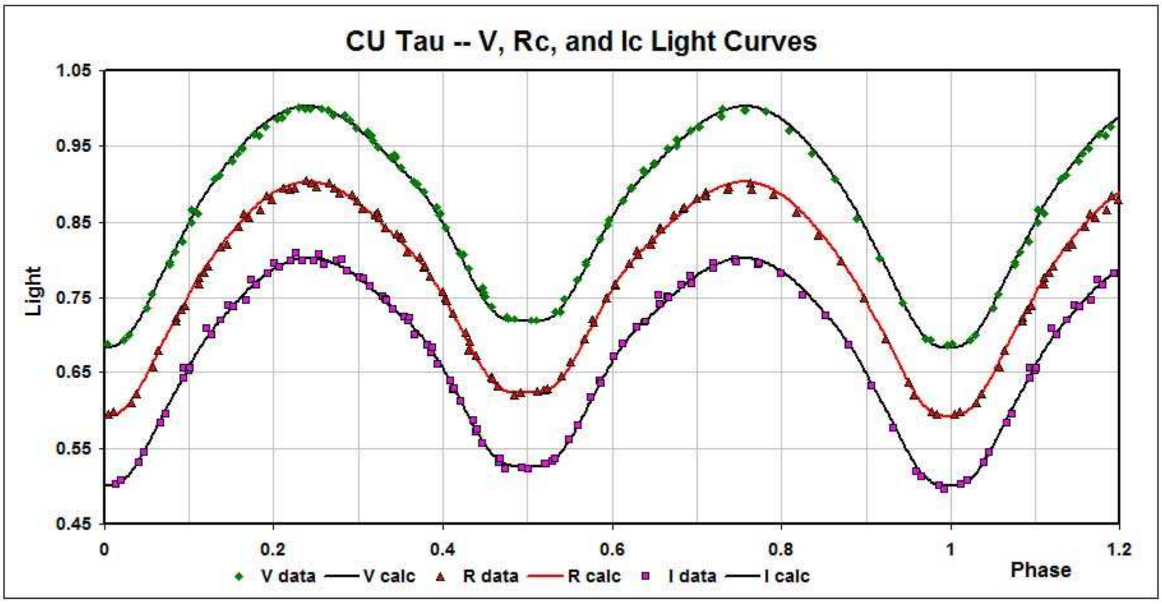


Figure 3. CU Tau: V, R_c, and I_c Light Curves – Data and WD fit.

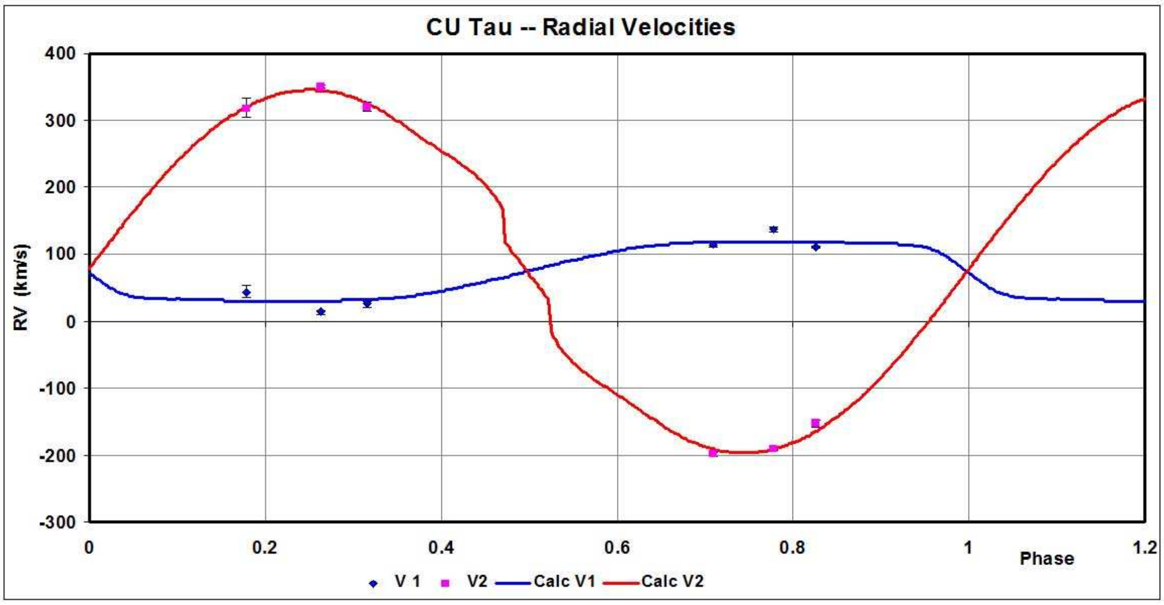
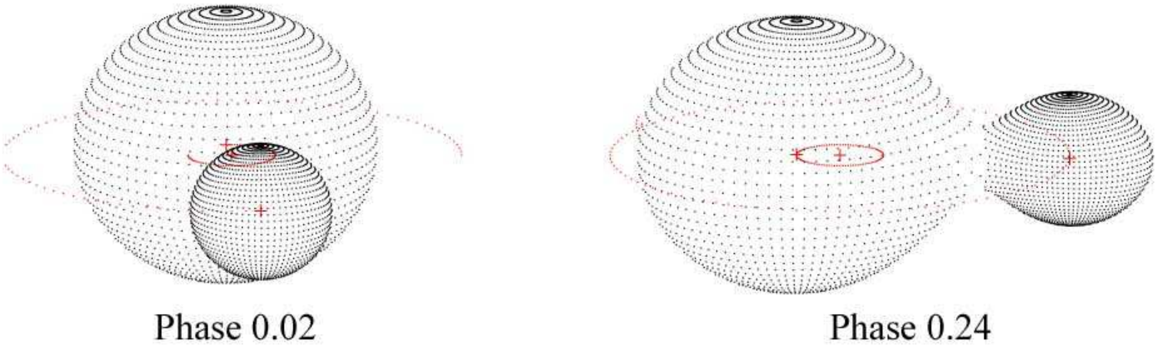


Figure 4. CU Tau: radial velocity curves – data and WD fit.



Phase 0.02

Phase 0.24

Figure 5. Binary Maker 3 representation of the system – at phases 0.02 and 0.74.

Quantity	Value	Error	unit
Temperature, T_1	5940	114	K
Temperature, T_2	5800	115	K
Mass, M_1	1.39	0.04	$M_\odot$
Mass, M_2	0.263	0.007	$M_\odot$
Radius, R_1	1.51	0.01	$R_\odot$
Radius, R_2	0.74	0.01	$R_\odot$
$\mathrm{M_{bol}}$, 1	3.78	0.02	mag
$\mathrm{M_{bol}}$, 2	5.42	0.02	mag
$\log g_1$	4.22	0.01	cgs
$\log g_2$	4.12	0.01	cgs
Luminosity, L_1	2.54	0.05	$L_\odot$
Luminosity, L_2	0.56	0.01	$L_\odot$
Distance, r	272	28	pc

Table 6. Fundamental parameters.

To determine the distance r, we proceeded as follows: first the WD routine gave the absolute bolometric magnitudes of each component, which were then converted to the absolute bolometric magnitude of both, getting $\mathrm{M_{bol}} = 3.56$. The bolometric correction, BC $= -0.106$, was taken from interpolated tables from Cox (2000). The absolute magnitude in the V passband was then $\mathrm{M}_V = \mathrm{M_{bol}} + \mathrm{BC} = 3.75$. The apparent magnitude in the V passband was $V = 11.37(4)$, taken from ensemble photometry of Tycho stars in the field (Hog et al., 2000). The colour excess, $E(B-V)$ was obtained from the $E(B-V)$ north galactic map (fits file) available from Schlegel et al. (2013). (The mapping formulas [galactic longitude, latitude > pixel column, row] were obtained from the original article by Schlegel et al. (1998), in Appendix C.) The images for the determination of the $E(B-V)$ values were obtained from Schlegel et al., 2013.) This gave $E(B-V) = 0.145$[1]. Galactic extinction was obtained from the usual relation $A_V = R \cdot E(B-V)$, using $R = 3.1$ for the reddening coefficient. Hence, distance $r = 272$ pc was calculated from the standard relation:

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[1] Note: Since the $E(B-V)$ values were obtained from full-sky far-infrared measurements, this means that the former apply to a light path from the observer all the way through the Galaxy (in the specified direction), and therefore represent an upper limit for the appropriate value for a star lying somewhat closer than the far edge. The error estimate in this quantity has been set to 50% of this value, and is then the largest contributor to the overall error in r.

$$r = 10^{0.2(V - \mathrm{M}_V - A_V + 5)} \text{ parsecs} \tag{4}$$

The errors were assigned as follows: $\delta V = 0.04$, $\delta \mathrm{M}_{\mathrm{bol},1} = \mathrm{M}_{\mathrm{bol},2} = 0.02$, $\delta \mathrm{BC}_1 = \delta \mathrm{BC}_2 = 0.015$ (the variation of 1.5 spectral sub-classes), $\delta E(B - V) = 0.07$, all in magnitudes, and $\delta R = 0.1$. Combining the errors rigorously yielded an estimated error in r of 28 pc.

In conclusion, the fundamental parameters of this system have been determined. Our derived parameters in Table 5 are reasonably close to those of Qian et al. (2005). However, our values may be expected to be more accurate since our value of the mass ratio $q = M_2/M_1$ is more tightly constrained by the radial velocity values rather than by photometric data alone. A strange discrepancy is the fact that Qian et al. (2005) obtain a value for $T_2 > T_1$ even though they label the system as A-type.

Also, Qian et al. (2005), lacking RV data, estimated the mass of the primary by the relation

$$M_1 = 0.391(59) + 1.96(17)P \tag{5}$$

getting $M_1 = 1.20 \pm 0.09\ M_\odot$ and $M_2 = 0.21 \pm 0.02\ M_\odot$. These values lie outside the error range of values in the present study suggesting that the error estimates in equation (5) are perhaps too small.

Acknowledgements: It is a pleasure to thank the staff members at the DAO (especially Dmitry Monin and Les Saddlemyer) for their usual splendid help and assistance.

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