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THE DETACHED SOLAR-TYPE BINARY CV Boo

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CV Boo (= BD +37°2641 = GSC 2570-0843) was discovered to be a possible eclipsing binary by Peniche et al. (1985) during a study of the Delta Scuti star YZ Boo. Busch (1985) made a study of 515 Sonneberg Sky Patrol Plates, determined 27 times of minima, and derived a period of 0.8469935 days. He also confirmed it as an eclipsing type and classified it as EA. Since then, numerous other workers have derived accurate times of minima, refining the period (see Nelson, 2004). The following elements were used for phasing:

$$\text{JD Hel Min I} = 52723.3207 + 0.8469938\ \text{E}$$

Popper (2000) did a spectroscopic study of four late F – K main sequence eclipsing binaries, deriving a radial velocity (RV) solution for CV Boo.

In the present study, photometric observations were carried out in 2003 March – June at the Sylvester Robotic Observatory in the V and I_c bands; 229 and 246 values in V and I_c were obtained, respectively. Images were reduced in the usual way with MIRA, by Axiom Research (for Windows; this platform was used throughout the study). (See Nelson 2002a for more details.) Comparison stars are listed in Table 1; the magnitudes are from the Tycho catalogue (ESA 1997).

Table 1. Positions and magnitudes

Star	GSC 2570-	RA (hh.mmss)	Dec (dd.mmss)	V	$B-V$
CV Boo	0843	15.2619	36.5853	10.75	0.73
Comp	0869	15.2707	36.5927	10.55	0.74
Check	0511	15.2652	36.5632	10.26	1.41

Twelve high-resolution (10 Å/mm) spectra were taken in 2003-2004 at the Dominion Astrophysical Observatory (DAO) in Victoria, British Columbia. (The spectral range was 4888-5150 Å). A log of observations and the derived heliocentric radial velocities (RVs) are presented in Table 2 and a list of IAU Standard Radial Velocity Stars (Roberts & Boksenberg, 1986) from which the CV Boo RVs were derived is given in Table 3.

Initial reductions of images (bias and cosmic ray removal) were preformed by MIRA. Intermediate reductions (overscan removal, setting apertures, fitting background, summation of counts, reduction to 1 dimension, calibration from Fe-Ar arc spectra, and finally dispersion correction) were performed by 'Ravere', software developed by the author. Final determination of radial velocities was performed by 'Broad', also software developed by the author that uses the Rucinski broadening functions (Rucinski, 2004). As expected, there was some scatter in the values for a given CV Boo spectrum from the various RV standard spectra. The mean and standard deviation were taken and those values lying outside twice the sample standard deviation were rejected. In this way, the standard deviations for each RV determination averaged 3.5 km/s; the rms deviation from the best-fit WD radial velocities was 14.3 km/s.

Table 2. Log of DAO observations and RV results

DAO Image #	Start time (HJD-240000)	Exposure (sec)	Phase at mid-exp	(km/s) V1	(km/s) V2
2487	52778.9382	3000	0.685	108.5	−133.2
4032	52807.7819	3600	0.743	136.6	−153.7
0773	53097.8980	3600	0.268	−138.9	118.2
0849	53098.7776	3600	0.306	−130.7	129.7
0879	53099.9480	3600	0.688	114.7	−143.2
0882	53099.9989	3600	0.748	137.3	−144.5
0918	53101.8284	3600	0.908	92.7	−75.1
0945	53103.7373	3600	0.162	−137.3	108.2
0983	53104.7261	3600	0.329	−117.8	120.7
0996	53104.9305	3600	0.571	65.34	−65.5
1044	53105.9844	3600	0.815	120.1	−134.3
1094	53107.9154	3600	0.095	−82.4	74.9

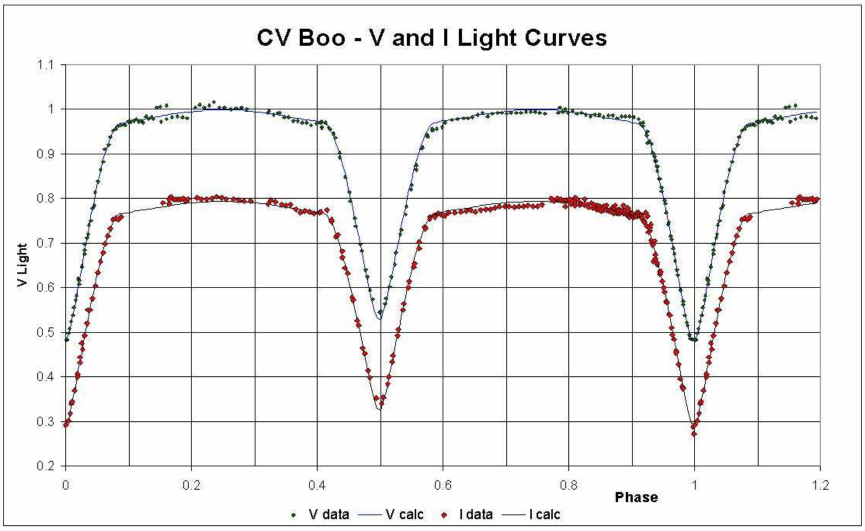

Figure 1.

In order to estimate the surface temperatures, T_1 and T_2, the following analysis is used: Simple double sine wave fitting of the radial velocity curves gives $K_1 \sim 138$ km/s and $K_2 \sim 140$ km/s, giving a spectroscopic mass ratio $q = M_2/M_1 = 0.986$. The speed in the relative orbit (assumed circular with inclination close to 90 degrees) is V = 278 km/s giving an orbital radius $R = VP/2\pi = 0.0215$ AU, where P = period = 0.847 days = 0.002164 years. Kepler's third law (as modified by Newton) gives the total mass $M_{tot} = R^3/P^2 = 1.885$ solar masses. Using the above value for the mass ratio gives $M_1 = 0.95$ and $M_2 = 0.94$ solar masses respectively. Allen (1973) then gives the spectral types as G3 and G4, leading to temperatures of 5784 and 5696 K (Flower, 1996), and log g values of 4.444 and 4.450 (cgs) respectively. Limb darkening values were found from van Hamme's tables (van Hamme, 1993). These values were used throughout the subsequent modelling; they agreed with the values from the best-fit model.

The photometric and RV data were analyzed by the Wilson-Devinney (WD) light curve analysis program (Wilson and Devinney, 1971, Wilson, 1990), using an interface program written by the author (see Nelson, et al., 2002b). The general appearance of the curve suggested a detached binary; hence mode 2 was chosen. Convective envelopes (appropriate for solar-type stars) were supposed, giving albedos $A_1 = A_2 = 0.5$ and gravity exponents $g_1 = g_2 = 0.32$.

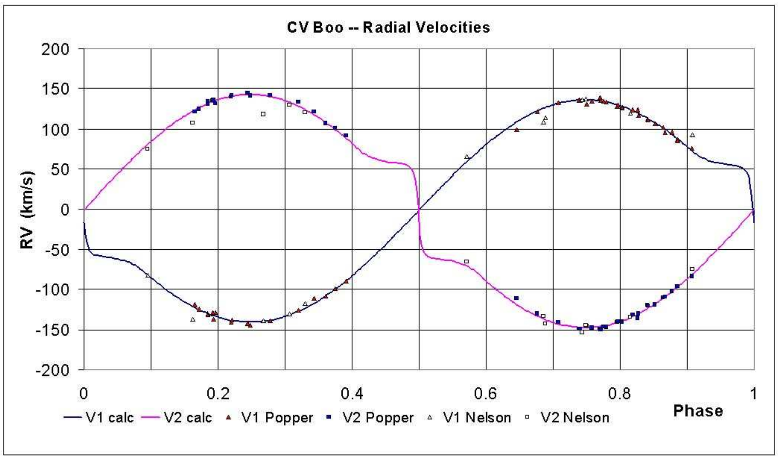

Figure 2.

Table 3. IAU standard RV stars used

Star HD -	RA (hh.mmss)	Dec (dd.mmss)	Sp. Type	V (mags)	RV (km/s)
76932	08.5844	−16.0759	F7-8 IV-V	5.80	119.2
89449	10.1946	+19.2806	F6 IV	4.78	6.3
102870	11.5041	+01.4555	F8 V	3.59	4.3
122693	14.0252	+24.3343	F8 V	8.11	−5.5
126053	14.2315	+01.1434	G1 V	6.25	−19.3
140913	15.4508	+28.2811	G0 V	8.06	−20
144579	16.0457	+39.0923	G8 V	6.66	−59.5
149803	16.3554	+29.4444	F7 V	8.58	−7.5
154417	17.0517	+00.4225	F9 V	6.00	−16.8
184467	19.3109	+58.3513	K1 V	6.60	11.2
184499	19.3327	+33.1205	G0 V	6.62	−166.1
187691	19.5102	+10.2458	F8 V	5.12	0

Table 4. Solution parameters

Quantity	Value		Error	Quantity	Value	Error
	Star 1	Star 2				
F	1.000	1.000	[fixed]	L1/(L1+L2) (V)	0.525	0.006
g	0.320	0.320	[fixed]	L1/(L1+L2) (I)	0.517	0.006
A	0.500	0.500	[fixed]	o	−0.0017	0.0001
x (bol)	0.186	0.207	[fixed]	e	0	0.0006
y (bol)	0.530	0.510	[fixed]	a (solar radii)	4.671	0.067
x (V)	0.246	0.283	[fixed]	V (km/s)	−0.033	0.016
y (V)	0.591	0.558	[fixed]	r1 (pole)	0.2562	0.0016
x (I)	0.055	0.086	[fixed]	r1 (point)	0.2699	0.0020
y (I)	0.632	0.606	[fixed]	r1 (side)	0.2606	0.0017
T1 (K)	5784	—	200	r1 (back)	0.2668	0.0019
T2 (K)	—	5639	6.9	r2 (pole)	0.2571	0.0021
	4.844	4.759	0.030	r2 (point)	0.2720	0.0027
f (fill factor)	−2.153	−1.992	0.050	r2 (side)	0.2617	0.0023
q = M2/M1	0.9708		0.0085	r2 (back)	0.2685	0.0025
i (deg)	87.89		0.13	res2	0.0139	0.00131

The square root (LD=3) limb darkening law was chosen, appropriate for infrared light curves (Bessell, 1979). Grid sizes were the same as in Nelson et al. (2002b). First black body radiation, later the atmosphere option of WD with Carbon and Gingerich atmospheres (Carbon & Gingerich, 1969) were used.

After a best-fit solution was found, third light was tested for and the predicted correction was less than the estimated error. Therefore third light may be ruled out. Similarly, quantities F_1 and F_2 (the ratios of axial to orbital rotation rates) were varied; however the corrections were again less than the errors, therefore values of unity (and hence synchronous rotation) may be assumed. A similar test was done against eccentricity e = 0 with the same null results. The final values are given in Table 4, the final light and radial velocity curves are plotted in Figures 1 and 2, and the derived fundamental values are summarized in Table 5 (where s.u. = "solar units").

It should be noted that the errors quoted in Tables 4 and 5 are formal (internal) errors provided by the WD program; actual errors may be several times those. With that caveat, the results are in essential agreement with Popper (2000). He has $q = M_2/M_1 = 0.9502(43)$ and, using the value of inclination obtained here, we get $M_1 = 1.056(6)$ and $M_2 = 1.003(7)$ where the figures in brackets are the errors in units of the last digit. His semi-major axis of the relative orbit is 4.7889(70) solar radii, also in essential agreement.

Table 5. Fundamental parameters

	Star 1	Star 2	Error
Spectral Type	G3	G4	—
Mass (s.u.)	0.97	0.94	0.03
Radius (s.u.)	1.22	1.23	0.01
Density (s.u.)	0.53	0.52	0.02
Log g	4.25	4.23	—
M bol (mag)	4.35	4.45	—
Mass ratio	0.9708		0.0084
Distance (pc)	235		—

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