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THE ABSOLUTE DIMENSIONS OF CU Sge

NELSON, ROBERT H.[1,2]; TERRELL, D.[3]; GROSS, JOHN[4]

[1] 1393 Garvin Street, Prince George, BC, Canada, V2M 3Z1 email: b-o-b.nelson@shaw.ca [remove dashes]

[2] Guest investigator, Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics, National Research Council of Canada

[3] Dept. of Space Studies, Southwest Research Institute, 1050 Walnut St., Suite 300, Boulder, CO, USA, 80302

[4] Sonoita Research Observatory, Sonoita, AZ

CU Sge (= 2MASS J19242969+1629592), RA = $19^{h}24^{m}29\overset{s}{.}69$, Dec = $+16°29'59\overset{''}{.}3$ (2000.0) was discovered to be variable by Hoffmeister (1935) who supplied a finder chart and magnitude range but no period. Kurochkin (1949) seems to have determined a period but no other details are available. Numerous authors have determined times of minima (Nelson, 2010a) but no light curve is available and no analysis has been published.

During September of 2005 RHN took 11 spectra (10 Å/mm reciprocal dispersion, resolving power 10,000) at the Dominion Astrophysical Observatory (DAO) in Victoria, British Columbia, Canada; he then used the Rucinski broadening functions (Rucinski, 2004) to obtain radial velocity (RV) curves (see Nelson et al., 2006 for details). The spectral range was 5000-5263 Angstroms and the reciprocal dispersion, 10 Angstroms/mm. A log of DAO observations and RV results are presented in Table 1.

Table 1. Radial velocity observations of CU Sge.

DAO Image #	Mid Time (HJD-2400000)	Exposure (sec)	Phase at Mid-exp	V1 (km/s)	V2 (km/s)
9718	53634.7178	1736	0.143	−123.82	76.79
9722	53634.7616	3600	0.198	−131.61	117.00
9756	53635.6816	1492	0.360	−132.40	69.72
9759	53635.7161	3600	0.404	−122.11	30.88
9818	53636.6919	3600	0.636	−79.46	−295.36
9855	53637.6939	3600	0.902	−79.73	−224.73
9889	53638.7776	3600	0.271	−133.70	124.47
9891	53638.8463	3600	0.358	−131.06	72.66
9918	53639.8418	3600	0.615	−91.93	−278.26
9942	53640.7241	1812	0.730	−72.47	−332.59
9948	53640.8389	3600	0.875	−78.54	−275.80

Photometric data were obtained at the Sonoita Research Observatory (SRO) in September and October of 2006 with the 0.35m robotic telescope and SBIG STL-1001E CCD camera. The differential observations with respect to TYC 1600-439 to were made with

BVI_C filters and no variability in the comparison star greater than 0.01m was detected with respect to the check star TYC 1600-451. Table 2 gives the details of the variable, comparison and check stars.

VR_CI_C data were also obtained at the Sylvester Robotic Observatory (SyRO) in Prince George, BC, Canada. (See Nelson, 2010b for more details.)

Table 2. Details of the variable, comparison and check stars.

Star	Tycho ID	R.A. (2000)	Dec. (2000)	V	$B-V$
Variable	1600-1581	19:24:29.691	+16:29:59.293	11.2-11.9	0.51
Comparison	1600-0439	19:24:43.560	+16:30:01.169	11.10	0.35
Check	1600-0451	19:25:08.603	+16:44:28.145	10.03	0.34

The simultaneous light and radial velocity curve analysis was done by PHOEBE (Prsa and Zwitter, 2005), based on the Wilson-Devinney (WD) program (Wilson and Devinney, 1971; Wilson, 1979; Wilson, 1990) with weights for the individual curves determined by their scatter. The mean surface temperature of the primary star was fixed at a value of $T1 = 6650$ K based on the F5 spectral type (SIMBAD, no reference given), using the tables from Cox (2000).

Since the primary is in the transition region between stars that have convective envelopes and those that have radiative envelopes, we investigated solutions for both cases. The fits were noticeably better, especially in the shoulders of the eclipses for the convective case, and theoretical values for the bolometric albedo and gravity darkening appropriate for convective envelopes were assumed for both stars in our final solution. Similar results were found by Nelson et al. (1995) for V728 Her.

The initial solution attempts were made assuming a detached configuration (WD mode 2) but the corrections for the secondary star's surface potential consistently pushed it past the Roche lobe, so a semi-detached configuration (WD mode 5) was used. The parameters adjusted were the orbital semi-major axis (a), gamma velocity (V_γ), inclination (i), secondary mean surface temperature (T2), primary modified surface potential ($\Omega 1$), mass ratio (q) and primary wavelength-dependent luminosities (L1). We also used heliocentric Julian day as the independent variable and solved for the linear ephemeris parameters:

$$\text{JD Hel Min I} = 2452500.1332(7) + 0.7916754(4)\text{E}$$

Our initial attempts to fit the light curves were unsatisfactory due to a poor fit in the secondary eclipse. The theoretical curve, using the Van Hamme (1993) limb darkening coefficients and either the square root or logarithmic law, was insufficiently deep, so we decided to try adjusting the limb darkening coefficients. Since WD cannot adjust both coefficients of a non-linear limb darkening law, we used the linear law for these tests. The fit was noticeably improved, as shown in Figure 1. The final values for the limb darkening coefficients were substantially smaller than the theoretical values. For instance, the adjusted value for the B light curve was 0.14 ± 0.06 whereas the theoretical value from the Van Hamme (1993) tables is 0.79. An interesting difference was found in the adjusted values for the V curve obtained at SRO and the one obtained at Prince George. The SRO value is 0.16 ± 0.05 and the Prince George value was 0.26 ± 0.05. The other passband in common between the two observatories, I_C, did not show a significant difference, both being 0.11 ± 0.04. The V-band luminosity ratios in Table 3 also show differences. The two photometric datasets were obtained about a year apart, so it is unclear whether these differences are instrumental or a result of some time-dependent phenomenon of the

Table 3. Parameters from the final simultaneous light-velocity curve solution. The luminosity ratios marked with an asterisk, the values are from the 2005 SRO data while the others are for the 2006 SyRO data.

Quantity	Value	Error	Quantity	Value	Error
T1 (K)	6650	fixed	a ($R_\odot$)	4.14	0.09
T2 (K)	5483	18	V_γ (km sec^{-1})	-103	2
Ω1	3.089	0.005	r1 (pole)	0.3369	0.0006
q = M2/M1	0.127	0.001	r1 (point)	0.3485	0.0007
i (deg)	88.4	0.4	r1 (side)	0.3446	0.0007
L1/(L1+L2) (B)	0.858	0.001	r1 (back)	0.3469	0.0007
L1/(L1+L2) (V)	0.828*	0.001	r2 (pole)	0.2042	0.0006
continued	0.833	0.002	—	—	—
L1/(L1+L2) (R_C)	0.817	0.002	r2 (side)	0.2123	0.0006
L1/(L1+L2) (I_C)	0.798*	0.001	r2 (back)	0.2438	0.0006
continued	0.799	0.002	—	—	—
HJD0	52500.1332	0.0007	P (days)	0.7916754	0.0000004

system. The primary eclipse showed no fitting problems, so we used the theoretical limb darkening coefficients for the primary star.

A plot of the light curves and computed fits are shown in Figure 2 and the radial velocities and fits are shown in Figure 3. A three dimensional representation from Binary Maker 3 (Bradstreet, 1993) is shown in Figure 4. The absolute dimensions are listed in Table 4. The primary has a mass consistent with an F5 main sequence star, and a radius that indicates moderate evolution. The secondary is clearly an evolved object and the semidetached configuration is a clue that large-scale mass transfer has taken place.

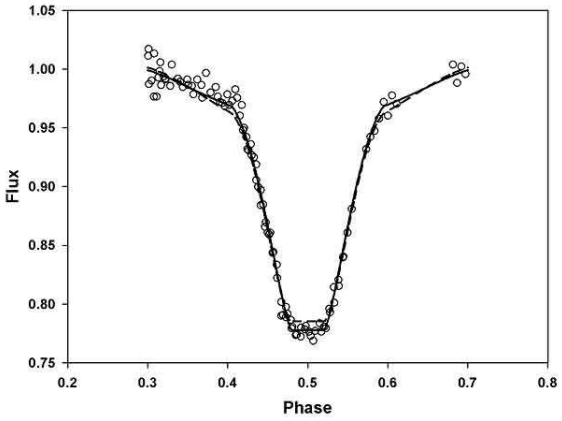

Figure 1. The secondary eclipse in I_C showing the poor fit with a logarithmic limb darkening law and theoretical limb darkening coefficients (dashed curve) for the secondary star, and the improved fit using a linear cosine law with an adjusted limb darkening coefficient (solid curve).

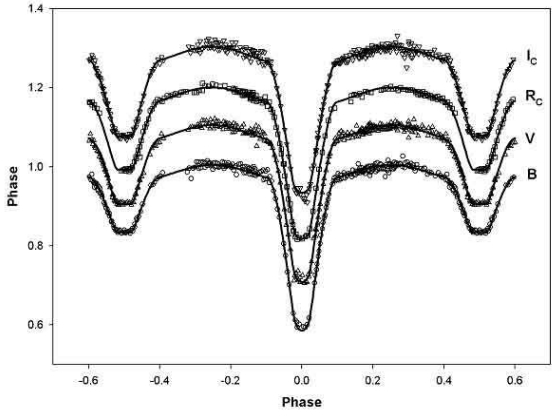

Figure 2. The observed light curves and fit using the linear limb darkening law with adjusted coefficients for the secondary star.

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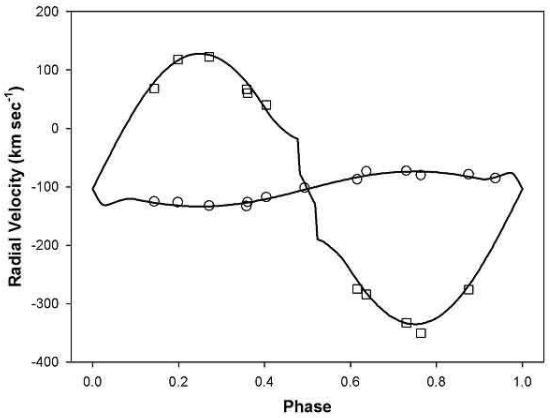

Figure 3. The radial velocity curves and the computed fit.

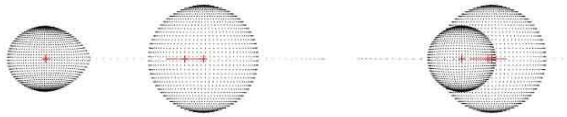

Figure 4. Binary Maker 3 representation of the system – at phases 0.75 and 0.97.

Table 4. Absolute dimensions for CU Sge.

Parameter	Star 1	Star 2
Mass ($M_\odot$)	1.36±0.09	0.17±0.01
Radius ($R_\odot$)	1.42±0.03	0.92±0.02
M bol	3.4±0.1	5.2±0.1
Log g (cgs)	4.26±0.03	3.75±0.03

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