Precision Photometric Observations and Analysis of the Totally Eclipsing, Solar-Type Binary WISE J051352.5-170113

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Abstract CCD BVRI light curves of WISE J051352.5-170113 (GSC 5906 0087 = ASASSN-V J051352.59-170113.6) were taken on 21, 22, and 26, 27 January and 04 February 2021 at the Cerro Tololo InterAmerican Observatory, Chile, with the 0.6-m reflector, remotely. It is classified as a contact variable with a mean V magnitude of 11.77 and amplitude of V~0.4. Five times of minimum light were determined, with one from the literature, along with 7 times of low light. From our present observations, and one primary eclipse and four secondary eclipses, we determined linear and quadratic ephemerides. From our 20-year period study, the period is found to be increasing. This might be due to mass transfer to the more massive, primary component making the mass ratio more extreme ($q = M_2 / M_1$). A Wilson-Devinney Program analysis reveals that the system is a A-type (more massive component is the hottest) W UMa binary with a fairly extreme mass ratio, $q = 0.2987 \pm 0.0007$, $1/q = M_1 / M_2 = 3.35$). Its Roche Lobe fill-out is ~18.9%. One hot spot was needed in the solution. The temperature difference of the components is only ~32 K, making the system in good thermal contact. The inclination is high, 80°, resulting in a brief total secondary eclipse lasting about 15 minutes.

1. History and background

The variable star WISE J051352.5-170113 (GSC 5906 0087 = ASASSN-V J051352.59-170113.6) is found online in the ASAS-SN Catalog of Variable Stars: V. The ASAS-SN low precision light curve is given as Figure 1.

The information given in the catalog includes the alternate name WISE J051352.5-170113, Mean VMag 11.57, APASS Vmag = 11.656, Amplitude VMag = 0.54, and an ephemeris:

$$HJD = 2457767.55404\,d + 0.3418393 * E, \quad (1)$$

a J–K: 0.415, and parallax, 4.2518 mas., giving a distance of 235.2 pc. Gezer and Bozkurt (2016) solved the low precision ASASSN-V V light curve (Figure 1) with the PHOEBE software (Pršа and Zwitter 2005). This single curve has a precision of $\Delta V \sim 0.03$ mag. We simultaneously solved four light curves (B, V, R, I) with a much higher precision of ~0.004 mag. Their one color, low precision "solution" is given as Table 1; this, of course, bears little resemblance to our BVRI synthetic light curve solution. For instance, their inclination is 70.3° whereas our light curve solution gives 80.2 ± 0.2°, with a short total eclipse in the secondary. Such low precision light curves do not avail themselves of useful or accurate solutions.

From the ASAS curves (ASASSN-V J051352.59-170113.6) we were able to phase the data with Equation 1 and perform parabola fits to the primary and secondary minima to locate

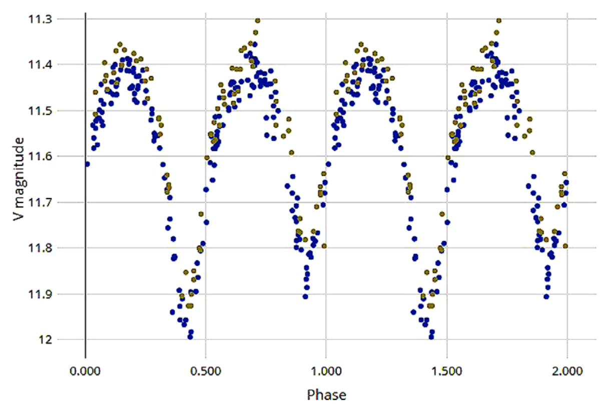

Figure 1. ASASSN-V J051352.59-170113.6, (low resolution) light curves (Pojmański 2002).

Table 1. Low Precision ASAS-SN Light Curve "Solution."

Parameter	*Prša Software Value*
I (°)	70.3
q (mass ratio)	0.52
T_1, T_2 (K)	5419, 5086
Ω (potential)	2.81
f (fill-out, %)	34
$L_{1v} / (L_{1v} + L_{2v})$	0.71
r_1 / a, r_2 / a	0.71. 0.46
HJD (T_o)	2,451,914.6192
Period (d)	0.34183617

seven times of "low light" within 0.001 phase of each minimum. We also included the ASAS HJD Min I in our period study.

This system was observed as a part of our professional collaborative studies of interacting binaries at Pisgah Astronomical Research Institute using data taken from CTIO observations.

The observations were taken by Caton. Reduction and analyses were done by Samec.

The 2020 BVRI light curves were taken at Cerro Tololo InterAmerican Observatory, on 21, 22, 26, 27 January, 3 and 4 February 2021 with a thermoelectrically cooled (–25° C) 1KX1K FLI camera and Bessell BVRI filters.

Individual observations included 179 in B, 180 in V, 188 in R, and 180 in I. The probable error of a single observation was 4 mmag in B, V, and R, and 3 mmag in I. The nightly C–K values stayed constant throughout the observing run, with a precision of about 1%. Exposure times varied from 45 s in B, to 20 s in V, and 15 s in R and I. To produce these images, nightly images were calibrated with 25 bias frames, at least five flat frames in each filter, and ten 300-second dark frames. A sample of the observations are given in Table 3 (The full table is available through the AAVSO ftp site as noted in the table).

2. Target stars

Figure 2 shows the variable (V), comparison (C), and check (K) stars. Details regarding these stars are given in Table 2.

3. Period determination

Five mean times (from BVRI data) of minimum light were calculated from our present observations, one primary and four secondary eclipses:

HJD I = 2459240.54968 ±0.00040

HJD II = 2459235.59483 ± 0.00042; 2459236.62057 ± 0.00079; 2459240.7216 ± 0.0015; 2459249.61244 ± 0.00086.

These minima were weighted as 1.0 in the period study. Another minimum was obtained from Gezer and Bozkurt (2016). In addition, seven times of minimum light were calculated from ASAS data and were weighted 0.1. These 13 minima gave us a period study with an interval of ~20.1 years. From these timings, two ephemerides have been calculated, a linear and a quadratic one:

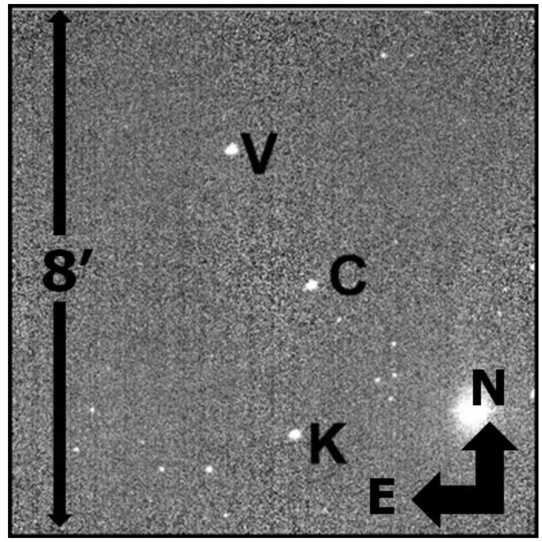

Figure 2. V magnitude finding chart, showing the variable star (V), comparison star (C), and check star (K).

$$\text{JD Hel Min I} = 2459240.55065 \pm 0.00066\,\text{d} + 0.341838117 \pm 0.000000078 \times E \quad (2)$$

$$\text{JD Hel Min I} = 2459240.55147 \pm 0.00030\,\text{d} + 0.34184041 \pm 0.00000023 \times E + 0.000000000108 \pm 0.000000000011 \times E2. \quad (3)$$

The initial ephemeris used to start the period study was:

$$\text{JD Hel Min I} = 2459240.54968 + 0.3418393 \times E. \quad (4)$$

The residuals of the period study are given in Table 4.

The current study covers a time interval of 20.1 years. It shows an orbital period that is increasing as shown in the O–C curve. This might be due to mass transfer to the more massive, primary component making the mass ratio more extreme.

Table 2. Photometric targets.

Star	*Name*	*R.A. (2000)* h m s	*Dec. (2000)* ° ′ ″	*V*	*J–K*	*Type*[2]
V (Variable) distance: 235.2 pc parallax: 4.2518 mas proper motion: α –22.76(4), δ –46.25(5)	WISE J051352.5-170113 GSC 5906 0087 2MASS J05135261-1701128 ASAS J051353-1701.2 Gaia DR2 2982692166728058880	05 13 52.6098618119[1]	–17 01 13.018190520[1]	11.359	0.415 ± 0.041	G7.5
C (Comparison)	GSC 5906 0601 3UC146-016767	05 13 46.0730[2]	–17 03 53.47[2]	12.25	0.36 ± 0.046	G2V
K (Check)	GSC 5906 0211 3UC255-052413	05 13 47.4780[2]	–17 06 49.807[2]	12.26	0.380 ± 0.046	G4V

[1] *ICRS (IAU 2013).* [2] *UCAC3 (Zacharias, N.,* et al. *2010).*

Table 3. Sample of first ten WISE J051352.5-170113 *B, V, R, I* observations.

ΔB	*HJD 2459200+*	ΔV	*HJD 2459200+*	ΔR	*HJD 2459200+*	ΔI	*HJD 2459200+*
–0.7010	35.5232	–0.8360	35.5184	–0.8680	35.5336	–0.9410	35.5221
–0.6730	35.5290	–0.7900	35.5246	–0.7660	35.5545	–0.9320	35.5268
–0.6490	35.5372	–0.8040	35.5319	–0.6650	35.5683	–0.8970	35.5349
–0.4810	35.5639	–0.7370	35.5394	–0.6180	35.5737	–0.8020	35.5592
–0.4110	35.5713	–0.6040	35.5670	–0.5740	35.5778	–0.7150	35.5696
–0.3630	35.5756	–0.5270	35.5728	–0.5320	35.5818	–0.6640	35.5744
–0.2690	35.5836	–0.4930	35.5770	–0.4940	35.5858	–0.6250	35.5784
–0.2430	35.5875	–0.4520	35.5810	–0.4750	35.5897	–0.5890	35.5824
–0.2060	35.5915	–0.4140	35.5849	–0.4580	35.5937	–0.5530	35.5863
–0.1890	35.5955	–0.3780	35.5889	–0.4590	35.5977	–0.5420	35.5903

Note: First ten data points of WISE J051352.5-170113 *B, V, R, I observations. The complete table is available through the AAVSO ftp site at ftp://ftp.aavso.org/public/datasets/3871-Samec-511-wisej051.txt (if necessary, copy and paste link into the address bar of a web browser).*

Table 4. Period study residuals, WISE J051352.5-170113.

	Epoch +2400000	*Cycle*	*Initial Residuals*	*Linear Residuals*	*Quadratic Residuals*	*Wt.*	*Ref.*
1	51914.6192	–21431.0	0.0276	0.0013	0.0000	1.0	2
2	56978.943	–6616.0	0.0021	–0.0067	0.0030	0.1	1
3	57004.919	–6540.0	–0.0017	–0.0104	–0.0008	0.1	1
4	57599.890	–4799.5	–0.0020	–0.0086	–0.0009	0.1	1
5	57724.662	–4434.5	–0.0013	–0.0075	–0.0003	0.1	1
6	57745.684	–4373.0	–0.0024	–0.0086	–0.0014	0.1	1
7	58010.781	–3597.5	–0.0018	–0.0070	–0.0010	0.1	1
8	58035.737	–3524.5	–0.0001	–0.0052	0.0007	0.1	1
9	59235.5949	–14.5	0.0019	0.0009	0.0001	1.0	3
10	59236.6206	–11.5	0.0020	0.0011	0.0003	1.0	3
11	59240.5497	0.0	0.0000	–0.0010	–0.0018	1.0	3
12	59240.7216	0.5	0.0010	0.0001	–0.0008	1.0	3
13	59249.6124	26.5	0.0040	0.0031	0.0022	1.0	3

References: (1) Shappee et al. *(2014), Kochanek* et al. *(2017); (2) Gezer and Bozkurt (2016); (3) present observations.*

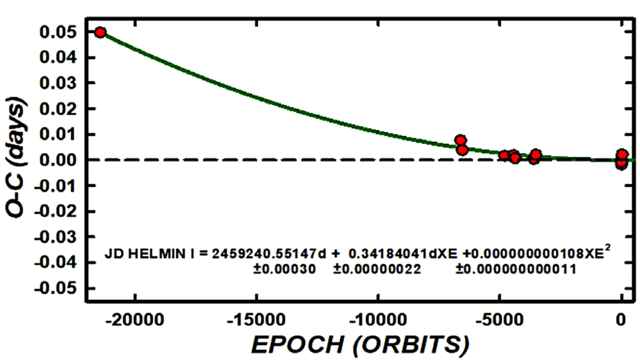

Figure 3. Quadratic period residuals, Equation 2.

The quadratic ephemeris yields a $dP/dt = 2.31 \times 10^{-7}$ d/yr, or a mass exchange rate of $dM/dt = 9.86 \times 10^{-8} M_\odot/d$, in a conservative scenario (the primary component is the gainer.) The phased light curves from Equation 2 are given in Figures 4 and 5.

4. Light curve characteristics

The curves are of good precision, averaging about 1% over the run. This variability is probably due to coronal action in this solar-type binary over the fourteen nights. The amplitude of the light curve varies from 0.581 to 0.506 mag. B to I. The O'Connell effect, an indicator of spot activity, was 0.017–0.040 mag, B to I, indicating some magnetic activity. The variation of the maximum in the primary maximum of the R and I curves is the effect of this activity. The difference in minima, 0.062 to 0.046 B to I, indicates overcontact light curves in good thermal contact. A time of zero secondary component flux in our BVRI light curve solutions reveals an eclipse that lasts 15 minutes. The phased light curve characteristics are given in Table 5.

5. Light curve solution

5.1. Temperature

The 2MASS, $J–K = 0.415 \pm 0.033$ for the binary star corresponds to $\sim$G7.5 ± 0.5, which yields a temperature of $\sim 5750 \pm 250$ K. Fast rotating binary stars of this type are noted for having strong magnetic activity, so the binary is of solar type with a convective atmosphere.

The BVRI curves were pre-modeled with Binary Maker 3.0 (Bradstreet and Steelman 2002), and fits were determined in all filter bands which were very stable. The solution was that of an overcontact eclipsing binary. The parameters were

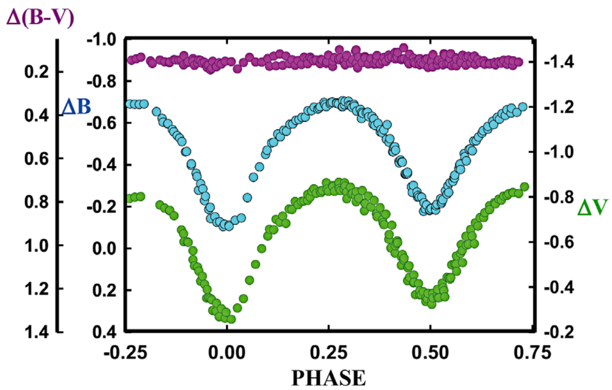

Figure 4. B, V mag light curves phased with Equation 2.

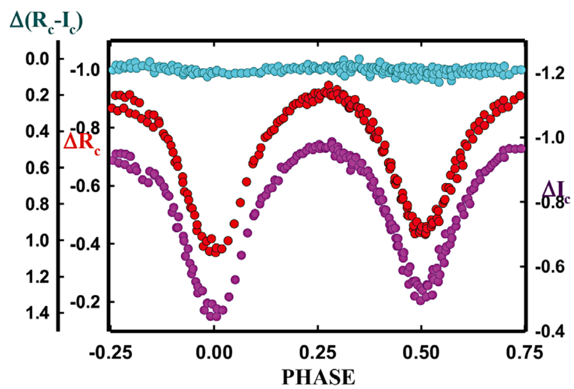

Figure 5. R, I mag light curves phased with Equation 2.

Table 5. Light Curve Characteristics, WISE J051352.5-170113.

Filter	*Phase Mag. Min I*	*±σ*	*Phase Mag. Max I*	*±σ*
	0.000		0.25	
B	–0.107	0.006	–0.693	0.004
V	–0.284	0.018	–0.842	0.015
R	–0.391	0.021	–0.918	0.005
I	–0.465	0.020	–0.968	0.003

Filter	*Phase Mag. Min II*	*±σ*	*Phase Mag. Max II*	*±σ*
	0.50	0.75		
B	–0.194	0.014	–0.688	0.004
V	–0.348	0.017	–0.796	0.015
R	–0.443	0.010	–0.911	0.005
I	–0.523	0.021	–0.945	0.003

Filter	*Min I– Max I*	*±σ*	*Max II– Max I*	*±σ*	*Min I– Min II*	*±σ*
B	0.586	0.010	0.005	0.005	0.087	0.020
V	0.558	0.033	0.046	0.046	0.063	0.035
R	0.527	0.026	0.007	0.007	0.053	0.031
I	0.503	0.023	0.023	0.023	0.057	0.041

Filter	*Min II– Max I*	*±σ*	*Min I– Max II*	*±σ*	*Min II– Max II*	*±σ*
B	0.499	0.018	0.581	0.010	0.494	0.018
V	0.495	0.032	0.512	0.033	0.449	0.032
R	0.475	0.015	0.520	0.026	0.468	0.015
I	0.446	0.023	0.480	0.023	0.423	0.023

Table 6. Synthetic Light Curve Solution of WISE J051352.5-170113.

Parameters	*Values*
$\lambda_B,\lambda_V,\lambda_R,\lambda_I$ (nm)	440, 550, 640, 790
g_1, g_2	0.32
A_1, A_2	0.5
Inclination (∞)	80.2±0.2[1]
T_1, T_2 (K)	5500, 5468±36
$\Omega_1=\Omega_2$	2.42820±0.00228
$q(m_1/m_2)$	0.29868±0.00074
Fill-outs: f(%)	18.9±0.2
$L_1/(L_1+L_2)_I$	0.7509±0.0102
$L_1/(L_1+L_2)_R$	0.7489±0.0098
$L_1/(L_1+L_2)_V$	0.7523±0.0133
$L_1/(L_1+L_2)_B$	0.7538±0.0085
JDo (days)	2459240.55082±0.00009
Period (days)	0. 341896±0.000008
Dimensions:	
r_1/a, r_2/a (pole)	0.463±0.002, 0.268±0.001
r_1/a, r_2/a (side)	0.5004±0.0024, 0.281±0.001
r_1/a, r_2/a (back)	0.528±0.003, 0.320±0.008
Spot, Primary Component	*Hot Spot Region*
Colatitude (°)	80.1±0.2
Longitude (°)	209.6±0.3
Radius (°)	12.57±0.20
T-Factor	1.119±0.003

[1] Note on Wilson (WD) program errors: The WD uncertainties are computed from the covariance matrix of the normal equations in the standard way. They are 1-σ uncertainties, which may strike some persons as too small, but they are standard error estimates—not peculiar to WD.

Table 7. Roche Lobe Dimensions.[1]

Radii	*Star 1*	*Star 2*
R_1, R_2 (pole, $R_\odot$)	1.0234±0.0039	0.5931±0.0027
R_1, R_2 (side, $R_\odot$)	1.1046±0.0027	0.6200±0.0006
R_1, R_2 (back, $R_\odot$)	1.1656±0.0050	0.7063±0.0005

[1] Using light curve solution units, a = 1, R's output of Wilson program, a is calculated for the Wilson program, the semi-major axis, using $a = 2.20762\ R_\odot$ from Kepler's law.

Table 8. WISEJ051352.5-170113 estimated system parameters (totally eclipsing).[1]

Parameter	*Star 1*	*Star 2*
Mean Radius ($R_\odot$)	1.098±0.004	0.640±0.0013
Mean density	1.020	1.556
Mass ($M_\odot$)	0.958	0.289
Log g	4.34	4.29

[1] The densities are in g/cm^3 Binary Maker, using calculated density from Roche Lobes by Bradstreet and Steelman (2002).

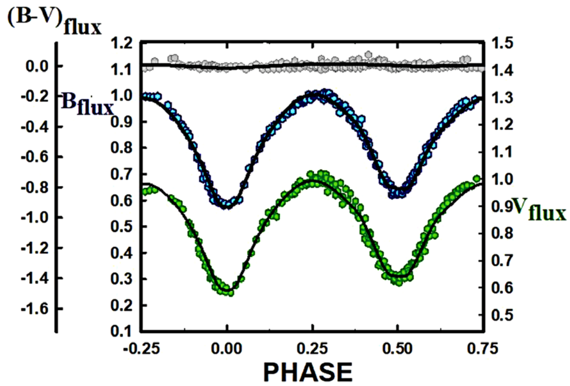

Figure 6. Figure 6. B, V light curve solution overlaying normalized flux light curves.

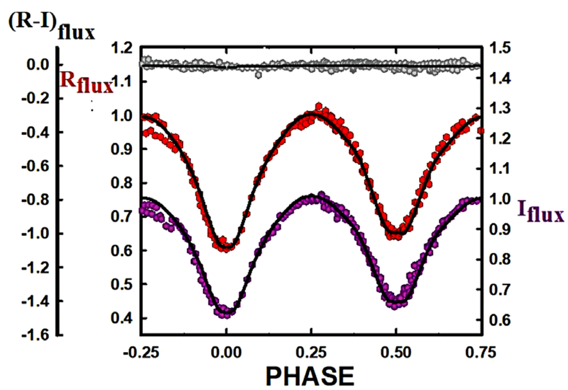

Figure 7. Figure 7. R, I light curve solution overlaying normalized flux light curves. The variability of the R and I light curves are probably due to magnetic activity.

then averaged (q = 0.30, fill-out = 30%, i = 80.5°, T_1 = 5750, with one 10° hot spot, T-FACT = 1.18) and input into a four-color simultaneous light curve calculation using the Wilson-Devinney Program (WD; Wilson and Devinney 1971; Wilson 1990, 1994, 2004; Van Hamme and Wilson 1998). The solution was computed in Mode 3 and converged to a solution. Convective parameters, g = 0.32, A = 0.5 were used. An eclipse duration of ~15 minutes was determined for the secondary eclipse from the light curve solution. The more massive component is the hottest one, making the system an A-type W UMa overcontact binary. We tried third light but that did not solve any fitting issues. The solution parameters are given in Table 6.

The estimated and absolute system parameters follow in Tables 7 and 8.

The surface geometry at quarter phases of the orbit is shown in Figure 8.

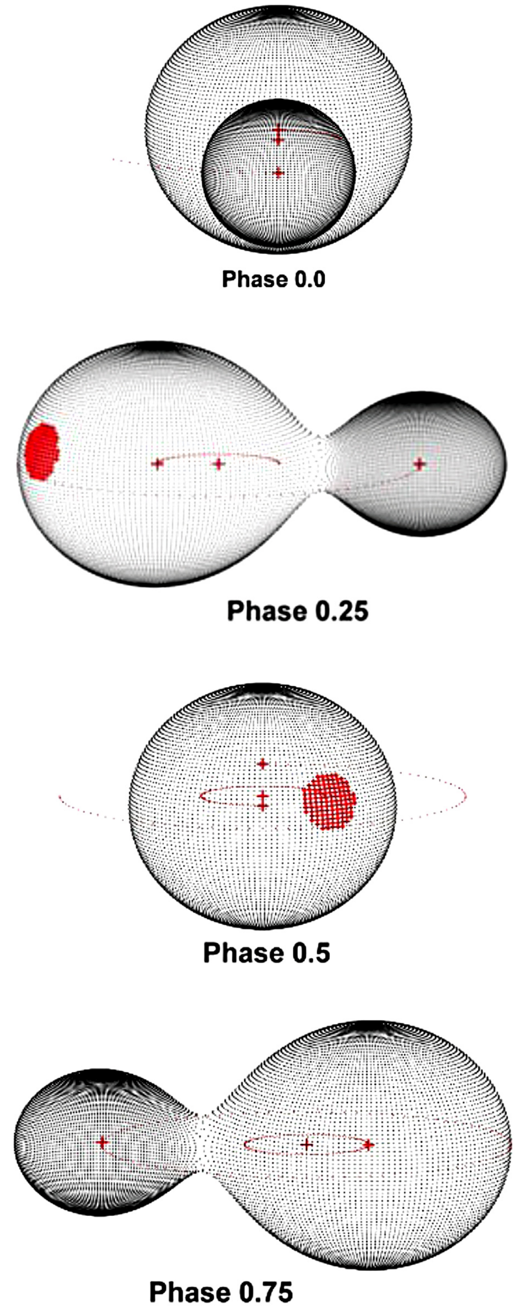

Figure 8. The surface geometry at quarter phases of the orbit

6. Discussion and conclusion

WISE J051352.5-170113 is a A-type, W UMa binary. Since the eclipses are total, the mass ratio, q = 0.30, is well determined with a fill-out of ~19%. The system has a component temperature difference of only ~32 K, and is in good thermal contact. One spot was needed in the final modeling. The inclination of ~80.2 degrees resulted in a time of constant light in the primary eclipse. Its photometric spectral type indicates a surface temperature of ~5500 K for the primary component, making it a solar-type binary. Such a main sequence star would have a mass of ~0.96 $M_\odot$ (G7.5V) and the secondary (from the solution's mass ratio) would have a mass of ~0.29 $M_\odot$, making it under-massive for its size. The temperature of the secondary component (~5468 K) of a main sequence star would make it of type G7.5V instead of M3.5V as indicated by its mass. This is probably due to substantial energy transfer between them. The period study of this binary indicates that it is increasing. This could be due to mass exchange with the flow toward the more massive component making the mass ratio more extreme.

7. Future work

Radial velocity curves are needed to obtain absolute (not relative) system parameters.

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