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A Binary Star Light Curve and Model of TYC 3670-588-1 From Professional-Amateur Collaboration

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Running Title: A Binary Star Light Curve and Model of TYC 3670-588-1

Abstract

We present the orbital light curve and model system parameters of a newly discovered eclipsing binary star in the constellation of Perseus.

Our professional-amateur astronomy collaboration between Arkansas Tech University (ATU), the Central Arkansas Astronomy Society (CAAS) and Whispering Pine Observatory, produced photometry in two wavelengths (Johnson V and R) in order to model the system for fundamental parameters with a binary modeling code.

We determined that this binary system contains two F-type stars orbiting each other with a short orbital period and having the following characteristics for the two components: mass ratio ($q \sim 0.92$), temperatures ($T_1 \sim 7170$ K, $T_2 \sim 7350$ K), sizes ($R_1 \sim 1.7 R_{\text{sun}}$, $R_2 \sim 2.4 R_{\text{sun}}$), orbital inclination ($i \sim 77^\circ$), and stellar separation ($a \sim 8.3 R_{\text{sun}}$).

The ephemeris for physical observations and primary mid-eclipse orbital phasing from the period in days is (HJD 2456488.885 + 1.292467 x N).

Introduction

This star, TYC 3670-588-1 (=NSVS 1748687, =AAVSO 000-BKF-917, =2MASS J01323010+5414055, =SDSS J013230.11+541405.5), had observations from the Northern Sky Variability Survey, NSVS (Wozniak et al 2004), the Sloan Digital Sky Survey, and the 2MASS survey, but was otherwise unremarkable within their errors and temporal sampling. It was discovered as having deep eclipses by Bruce McMath at the CAAS River Ridge Observatory after an unsuccessful attempt to use it as a constant comparison for the variable star IS Perseus that is found nearby.

The goal of this research was to photometrically observe this newly discovered binary at multiple

wavelengths and model the system in order to obtain the fundamental stellar parameters for each component star. Observations of binary stars still represent the most dependable and accurate way of determining individual stellar characteristics of stars such as temperature, size and mass.

Observations and Methods

Photometric observations, carried out at both the CAAS River Ridge Observatory (RRO) near Bigelow, and at Whispering Pine Observatory (WPO) near Jasper, are listed in Table 1. The CAAS-RRO system consists of an 0.3m SCT and an SBIG ST-10 CCD camera with standard Johnson V and R filters. The ATU-WPO system consists of an 0.3m SCT with f6.3 focal reducer and an SBIG ST-9 CCD camera with standard Sloan g and r filters.

All image frames were calibrated in a standard way (Warner 2006) utilizing dark frames for removing CCD thermal noise, digitizing and readout noise errors and dome flat fields for removing CCD pixel sensitivity variances. Aperture photometry was then done on the calibrated star field images to extract differential magnitudes using a set of non-variable comparison stars using standard astronomy algorithms incorporated into Cmunwin (Hroch 1998, Motl 2014). This software in short 1) converts images to FITS if necessary, 2) flat-fields and dark subtracts if desired, 3) processes to find stellar targets and photometrically measures them utilizing algorithms of DAOPHOT (Stetson 1987), 4) target lists pattern matched to identify stars in each image via the algorithm of Groth (1986), and 5) variable, comparison and check stars selected to generate differential photometry and light curves.

Table 1. Observation log for TYC3670-588-1 photometry.

Civil Date	JD-2450000.	Observatory	Filter
2013-AUG-27/28	6532	ATU-WPO	g
2013-AUG-28/29	6533	CAAS-RRO	V
		ATU-WPO	r
2013-AUG-29/30	6534	ATU-WPO	g
2013-AUG-30/31	6535	ATU-WPO	r
2013-AUG-31/01	6536	CAAS-RRO	V
		ATU-WPO	g
2013-SEP-02/03	6538	ATU-WPO	r
2013-SEP-03/04	6539	ATU-WPO	g
2013-SEP-04/05	6540	ATU-WPO	r
2013-SEP-05/06	6541	CAAS-RRO	V
		ATU-WPO	g
2013-SEP-06/07	6542	ATU-WPO	r
2013-SEP-07/08	6543	CAAS-RRO	V
		ATU-WPO	g
2013-SEP-08/09	6544	CAAS-RRO	V
2013-SEP-09/10	6545	CAAS-RRO	V
		ATU-WPO	r
2013-SEP-10/11	6546	CAAS-RRO	V
		ATU-WPO	g
2013-SEP-11/12	6547	CAAS-RRO	V
		ATU-WPO	r
2013-SEP-12/13	6548		V
2013-SEP-13/14	6549	CAAS-RRO	V
		ATU-WPO	g
2013-SEP-14/15	6550	ATU-WPO	r
2013-SEP-16/17	6552	CAAS-RRO	V
2013-SEP-17/18	6553	CAAS-RRO	V
2013-SEP-21/22	6557	CAAS-RRO	V
2013-OCT-06/07	6572	CAAS-RRO	V
2013-NOV-18/19	6615	CAAS-RRO	R
2013-NOV-19/20	6616	CAAS-RRO	R
2013-NOV-28/29	6625	CAAS-RRO	R

Results and Discussion

The resulting light curves, phased on the ephemeris, are shown in Figure 1. In general, the error bars are small, on the order of the size of the data points in the plot (~ 0.005 - 0.01 mag). There were some marginal nights with cirrus clouds, where the scatter is larger (i.e. V filter data near phase 0.6, R filter data near phase 0.9), but not used for fitting. Any well sampled eclipses that were captured, were analyzed to obtain the times of minima using the tried and true method of Kwee and van Woerden (1956). Four primary and five secondary eclipses were observed at several different wavelengths. The mid-eclipse times of minima are listed in Table 2.

Figure 1. Orbital light curve at four wavelengths for TYC 3670-588-1 from CAAS-RRO and ATU-WPO. Observations in each filter have been arbitrarily offset in the vertical axis for clarity.

Table 2. Times of Primary and Secondary Mid-eclipse Minima.

HJD	Error	Cycle	Filter
2456536.707104	0.000403	37	g
2456536.708618	0.000301	37	V
2456541.876961	0.000123	41	V
2456541.877568	0.000209	41	g
2456550.923729	0.000236	48	r
2456572.896862	0.000210	65	V
2456534.766400	0.000190	35.5	g
2456539.935631	0.000230	39.5	g
2456543.815484	0.000205	42.5	g
2456547.691140	0.000151	45.5	r
2456552.861351	0.000174	49.5	V

The light curves were then examined to determine rough initial parameters for the system to facilitate full scale modeling. Using the colors both inside and out of eclipses as well as the eclipse depths and durations, suggested two similar F-type dwarf stars with a moderate orbital inclination.

We then took the initial parameters for such a binary system as a starting point and utilized a standard binary star code (Wilson and Devinney 1971) to compute models using the interface and scripting software PHOEBE (Prsa and Zwitter 2005) as a front end that can facilitate simultaneous fitting of up to 30 separate system parameters to the multicolor light curve data (see <http://phoebe-project.org>). Since PHOEBE does not yet recognize the newer Sloan filter band-passes, only the Johnson V and R data were used for the model fit.

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The model parameters for the best fit solution are found in Table 3. The model parameters that were allowed to vary and then solved for by least squares are indicated in the table with their errors in (). The other physical parameters for the system were either set as fixed or calculated from the final best fit solution.

Table 3. Model Parameters for TYC3670-58801. An “*” indicates parameters that were allowed to vary and solved for in the least squares fitting process.

T0	Epoch (HJD-2456488.)	2456488.885
P	Orbital period (days)	1.292467
q	*Mass ratio (M_2/M_1)	0.92 (0.02)
i	*Orbital inclination (degrees)	77 (1)
a	*Orbital separation (R_{sun})	8.3 (1.2)
T1	*Star 1 effective temperature (K)	7175 (40)
T2	*Star 2 effective temperature (K)	7350 (40)
R1	*Star 1 radius (R_{sun})	1.72 (0.2)
R2	*Star 2 radius (R_{sun})	2.41 (0.3)
M1	Star 1 mass (M_{sun})	2.44
M2	Star 2 mass (M_{sun})	2.25
γ	*Center of Mass Velocity (km/s)	73 (17)
Ω_1	*Star 1 surface potential	5.75 (0.6)
Ω_2	*Star 2 surface potential	4.29 (0.55)
g1	Star 1 gravity brightening	0.32
g2	Star 2 gravity brightening	0.32
x1V	*Star 1 limb darkening (V filter)	0.487 (.015)
x2V	*Star 2 limb darkening (V filter)	0.489 (.015)
x1R	*Star 1 limb darkening (R filter)	0.389 (.015)
x2R	*Star 2 limb darkening (R filter)	0.389 (.015)
log g ₁	Star 1 surface gravity	4.35
log g ₂	Star 2 surface gravity	4.02

Figure 2 displays an example of the model goodness of fit versus the V filter light curve data. Data points in the figure are the observations (flux versus phase) and the WD-PHOEBE solution is the solid line. Also, in the bottom panels, are representations of the binary system model as seen from outside the binary orbit (Earth viewpoint) during the corresponding orbital phases.

These system model parameters are consistent with a binary containing two F-type stars, with spectral types of roughly F0 V + F0 V. Spectroscopic observations would help solidify this classification as well as tie down the individual masses via observation of radial velocities obtained from spectra lines of one or both stars.

Figure 2. Observed V filter light curve data (points) and best fit model (line) with corresponding binary system model in panels displayed at various orbital phases (i.e. 0.0, 0.25, 0.5, 0.75).

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