Preliminary Modeling of the Eclipsing Binary Star GSC 05765-01271

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Abstract The authors discovered the eclipsing binary star system GSC 05765-01271 on August 19, 2015; here a preliminary model is presented. Lacking spectroscopic radial velocity data, period-based empirical relations have been used in order to constrain physical parameters as masses and radii. The effective temperature has been evaluated using color index (V–R) and spectral type estimated from a composite spectrum. These parameters were used as input to obtain a preliminary model of this binary system with BINARY MAKER 3 and PHOEBE software.

1. Introduction

Photometric observations to determine synodic rotational period of (9801) 1997 FX3 asteroid (Marchini *et al.* 2016) led us to discover the binary star system GSC 05765-01271 (Marullo *et al.* 2015). The discovery was made by Sara Marullo, an undergraduate student in Physics and Advanced Technologies at the DSFTA Department (Siena, Italy), and we thought it would be stimulating to go over the analysis of this system, aware of the important role played by eclipsing binary star systems in the knowledge of the universe. Eclipsing binaries are direct indicators of distance between galaxies; moreover, the analysis of the spatial distribution of these systems in an external galaxy gives an estimate of the size and the structure of the galaxy itself (Southworth 2012). Low mass eclipsing systems are an important subject because the vast majority of known extrasolar planets are hosted by low mass systems (Lopez-Morales 2007). Moreover, if radial velocities are known, it is possible to univocally determine masses and radii of eclipsing binaries.

2. Methods

2.1. Instrumentation

New filtered photometric data were acquired on October 11, 2015, using a 300-mm Maksutov-Cassegrain telescope equipped with a SBIG STL-6303E CCD camera and Custom Scientific Johnson-Cousins V and R filters at the Astronomical Observatory of the University of Siena, Italy. Exposures were taken in sequence with 4 minutes and 3 minutes, respectively, in V and R bands. All the images were calibrated with dark and flat-field frames. Differential aperture photometry was performed with MAXIM DL (Diffraction Limited 2012). V and R magnitudes were standardized using the method described by Dymock and Miles (2009) with selected reference stars from the CMC15 catalogue (Copenhagen Univ. Obs. 2013; Figure 1, Table 1).

In order to acquire the composite spectrum, we had a collaboration with Siding Spring Observatory, Australia (LCOGT network). The instruments used were a 2-m Ritchey-Chrétien telescope with e2v CCD42-10 and Andor Newton 9401 CCD cameras, on altazimuth mount. The spectrum was acquired on October 15, 2015, and reduced with the custom IRAF pipeline "floydsspec" (Valenti *et al.* 2013); an Hg-Ar lamp was used for wavelength calibration, and the white-dwarf Feige 110 was used for flux calibration. The wavelength coverage was 320–1000 nm. Spectrum inspection and analysis were made with VISUAL SPEC (Desnoux 2015) and ISIS (Buil 2015) software tools.

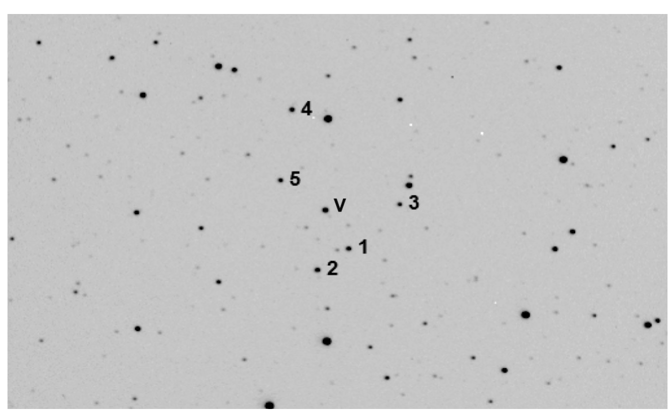

Figure 1. Star field with the binary star GSC 05765-01271 (V) and the reference stars used in differential photometry.

Table 1. Photometry.

Star	*CMC15 Designation*	*R.A. (J2000) h m s*	*Dec. (J2000) ° ′ ″*	*V*	*R*	*V–R*
GSC 05765–0127	204933.2–120851	20 49 33.3	–12 08 52	—	—	—
Reference 1	204930.4–121003	20 49 30.4	–12 10 03	13.661	13.280	0.381
Reference 2	204934.1–121044	20 49 34.1	–12 10 44	13.549	13.110	0.439
Reference 3	204924.5–120838	20 49 24.5	–12 08 38	14.147	13.743	0.404
Reference 4	204937.4–120543	20 49 37.4	–12 05 43	13.600	13.174	0.426
Reference 5	204938.6–120756	20 49 38.6	–12 07 56	13.936	13.523	0.413

2.2. Results

Period analysis gave an orbital period P = 0.382878 ± 0.00002 day with an epoch E = 2457254.5065 ± 0.0001 based on the first observed primary minimum (Papini *et al.* 2015). In the following we present the main results that led us to the preliminary model of this binary system.

2.2.1. Color index

Exposure times were a lot shorter than rotational period, so we assumed that taking an image with V filter and, immediately after it, another one in R-band was equivalent to taking them at the same time. This allowed us to measure the color index (V–R) = 0.37 ± 0.02, using the values of the magnitudes at the minima of the R and V light curves, determined with a 4th-order polynomial fit in PERANSO (Vanmunster 2007). The color index was dereddened using the NASA/IPAC Extragalactic Database—Coordinate Transformation and Galactic Extinction Calculator (NASA/IED 2015). This service gave us the total galactic visual extinction along the line of sight. At the object coordinates the service reports (Schlafly and Finkbeiner 2011), for Landolt bandpass, a color excess

$$E(B–V) = A_B – A_v = 0.174 – 0.132 = 0.042$$

and

$$E(V–R) = A_v – A_R = 0.132 – 0.104 = 0.028$$

Then, using experimental (V–R) color index and assuming an error of 0.02 for A_v and A_r as reported in Schlafly and Finkbeiner (2011), we derived the dereddened color index:

$$(V–R)_0 = (V–R) – E(V–R) = (0.37 – 0.03) \pm 0.03 = 0.34 \pm 0.03$$

where the error is evaluated as the quadratic sum of the uncertainties of the components (color index and color excess). This color index fits with spectral types G0/1V at effective temperature of ~5900 K (Mamajek 2016).

2.2.2. Spectrum Analysis

The reduced composite spectrum was dereddened applying a color excess E(B–V) = 0.042 (value obtained as shown in the previous section), by using the specific function implemented in the ISIS software tool. The resulting dereddened spectrum is close to an F8V type star (Figure 2) at an effective temperature of ~6100 K (Mamajek 2016).

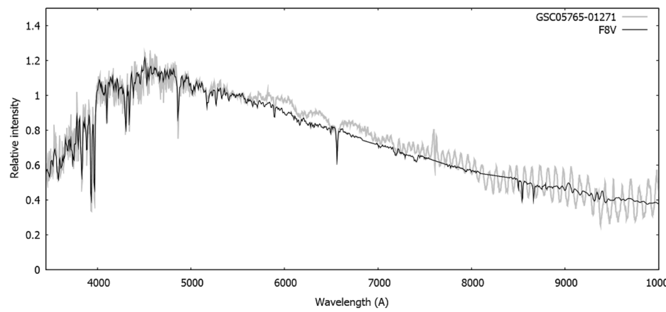

Figure 2. Comparison between GSC 05765-01271 dereddened spectrum and F8V synthetic spectrum.

2. 2. 3. Light curve modeling

Since radial velocities of this binary system weren't known, we used widely adopted empirical relations obtained by regression from the analysis of experimental data (including radial velocities) of several eclipsing binary systems.

Relations 4–5 reported in Gazeas and Stępień (2008) gave an estimate of the masses of the components. By applying Kepler's Third Law we estimated the semimajor axis. An estimate of radii was computed thanks to relations Eq. 8–9 in Gazeas and Stępień (2008).

In order to estimate temperatures, in agreement with previous works, we assumed the temperature of the hotter component equal to 6100 K and determined the other one with Bronstein's relation reported in Eq. 2 (Ivanov *et al.* 2010).

The distance of the system from Earth was figured out using

$$D = 10^{\{0,2\,(m_V – M_V + 5)\}} = 606 \text{ parsec},$$

where M_V = 3.81 was given by Eq. (3) in Gazeas and Stępień (2008) and m_V = 12.73 was derived by V-band maximum light (12.86 V) corrected for galactic extinction value A_V = 0.132.

We used these parameters as inputs in PHOEBE (Prša and Zwitter 2005), in addition to the following parameters: albedos (assumed 0.5 for both components—stars with convective envelopes, T < 7200 K); gravity darkening coefficients (assumed 0.32 for both components—convective envelopes, in agreement with Von Zeipel's Law); limb darkening coefficients (obtained by interpolating Van Hamme's tables).

We also assumed a low light scatter, because of the low magnitude of the system. Moreover, we interpreted the different depths of the minima in the light curve as due to different temperatures of the components; setting the lower temperature

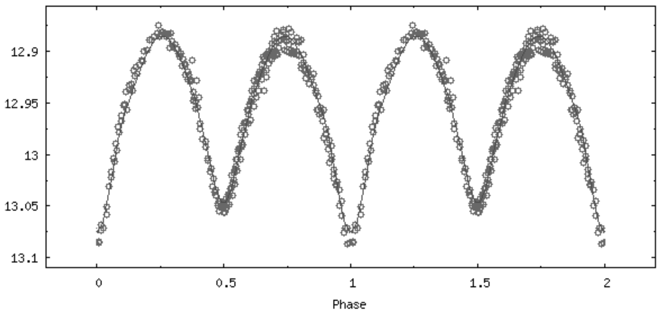

Figure 3. Fit of the light curve performed with PHOEBE.

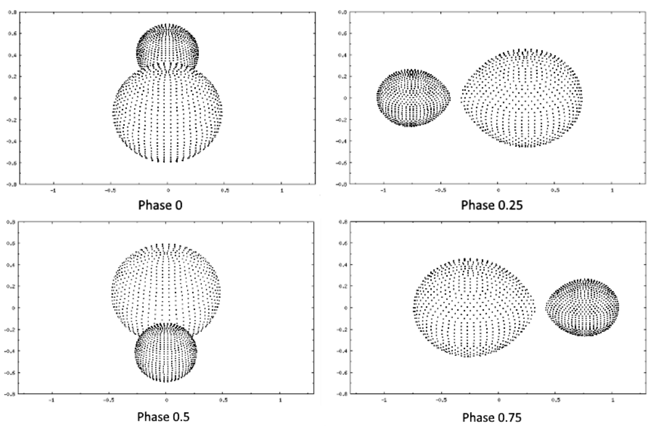

Figure 4. Graphical representation of the system (PHOEBE software).

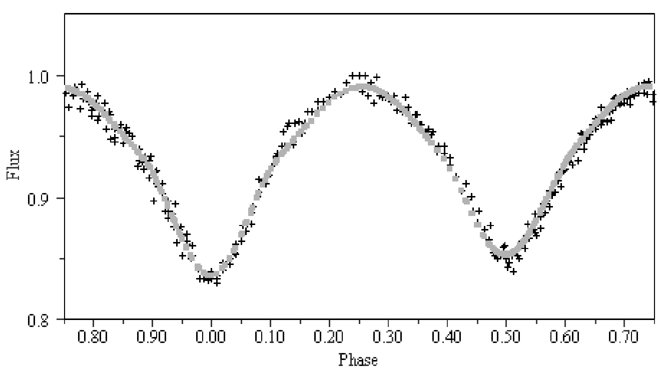

Figure 5. Fit of the light curve from BINARY MAKER 3.

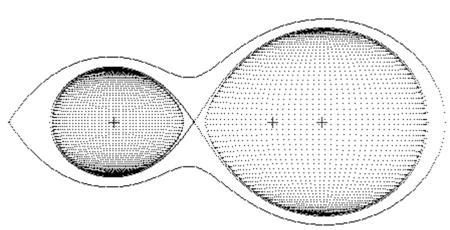

Figure 6. Equipotential curves (BINARY MAKER 3 tool).

for the more massive star was required in order to produce a good fit. The result of the fit is shown in Figure 3. In Figure 4 a possible graphic representation of the system is shown.

Moreover, an independent model of the system was realized using BINARY MAKER 3 (Bradstreet and Steelman 2002), starting from the mass ratio obtained by the empirical relations and adjusting the model parameters (q, T_1, i, Omega) in order to

Table 2. Results and comparison among PHOEBE, BINARY MAKER 3 and EMPIRICAL RELATIONS.

Parameter	*PHOEBE*	*BINARYMAKER3*	*EMPIRICAL REL.*
M_1	1.12 $M_\odot$	1.26 $M_\odot$	1.26 $M_\odot$
M2	0.36 $M_\odot$	0.40 $M_\odot$	0.40 $M_\odot$
q = (M_2 / M_1)	0.32	0.32	0.32
R_1	1.20 $R_\odot$	1.25 $R_\odot$	1.26 $R_\odot$
R_2	0.70 $R_\odot$	0.72 $R_\odot$	0.74 $R_\odot$
T_1	5832 K	5850 K	5855 K
T_2	6100 K	6100 K	6100 K
a (semi-major axis)	2.53 $R_\odot$	2.63 $R_\odot$	2.63 $R_\odot$
i (inclination)	57.1°	57.5°	——
x_1 (limb darkening coeff.)	0.50	0.50	——
x_2 (limb darkening coeff.)	0.49	0.50	——
Distance from Earth (1977 ly)	——	——	606 pc

minimize the sum square of the residual of the model fit. Fillout factors returned by BINARY MAKER 3 (–0.01 for both components) allowed us to classify better the system type: according to the initial classification, reported in Marullo *et al.* (2015), based only on period and light curve shape, the system should have been an EW-type member, but fillout factors clearly show that the system has to be considered as "near-contact." Fit of the light curve and equipotential curves are shown in Figure 5 and Figure 6, respectively.

Values obtained with PHOEBE, BINARY MAKER 3, and empirical relations are compared in Table 2.

3. Discussion

In this preliminary work, either the best fit obtained with PHOEBE or the best fit obtained with BINARY MAKER 3 minimizes the chi-squared, but we can't exclude that the proposed solutions are only local minima. However, the good agreement between empirical relations and the best fits supports the proposed analysis. A better way to proceed would be using the Wilson-Devinney code implemented in PHOEBE only as a likelihood function for a Bayesian model. A noise model of the data would need to be added to the likelihood function. With the aid of a MCMC (Markov chain Monte Carlo) sampler, it would then be possible to correctly search the best possible solution to the problem.

4. Conclusions

We think this work supports the claim that even with limited instrumentation it is possible to do quite complete binary system analysis. In this case, the object is also faint and there wasn't any support from historical records. A more accurate model (including spectral types) could be obtained with high-resolution spectroscopy and analysis of disentangled spectra of the two components. We want to remark that the present work, a little contribution to the astrophysical knowledge, was made possible thanks to the great deal of effort made in Observational

Astrophysics by astrophysicists like Gazeas, Stepień, and Bronstein during many years of hard work. The widely adopted empirical relations used in this work are recognized as good starting points in the process of modeling an eclipsing binary star system.

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