Optical Observation of a Contact Eclipsing Binary

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A W Ursae Majoris (W UMa) variable star with the identifier 1SWASP J074658.62+224448.5 (J074658) (Jiang et al., Yang et al.), a contact binary with a period of 5.28 hours, was observed using the Plaskett 1.8m telescope on the mornings of 2022-02-26 and 2022-03-04 for 340 minutes and 42.767 minutes, respectively. Exposure times of 60 seconds was used to take images during the observation periods that were then processed using the available DAO flats and darks from CADC. The cleaned images were then analyzed using aperture photometry, with apparent magnitude calculations made using calibration stars to produce a light curve. Without enough data from day 2, only the light curve for day 1 was plotted. Once these magnitudes were corrected and a fit was applied, the value for the maximum V magnitude from literature, 14.13, nearly fell within error to the measured value of 14.27 ± 0.08.

PACS numbers:

I. INTRODUCTION

Eclipsing binary star systems possess properties, such as periodic magnitude modulation, that make them excellent candidates for photometric measurements. photometric observation of binary stars allows for the construction of a light curve: a plot of the apparent magnitude of the source binary over time. Eclipsing binaries are tremendous candidates for light curve observation because they are systems with an orbital plane lying edge-on to the observer; if the individual stars are unresolved, this results in a periodic drop of observed magnitude, which is exhibited as dips in the light curve. Physical information, such as the inclination of the orbital plane, can be determined from these light curves. We hope to extract the masses of the stars, the luminosity, and distance to the chosen target eclipsing binary. The instrument used to collect data will be the 1.8-m Plaskett Telescope, which features an imaging camera with a field of view of 24' x 11' with normal 2-pixel binning of the 2K x 4K E2V-1 CCD ([1]).

II. DATA

The selected target is a variable star located within W Ursae Majoris (W UMa), designated 1SWASP J074658.62+224448.5, or J074658 for short [6, 7]. J074658 is a contact binary with a period of 5.28 hours, The data was taken on two separate morning observations using the Plaskett 1.8m telescope: the first occurred on the 26th of February 2022 and lasted 5 hours and 40 minutes. The second occurred on the 4th of March 2022 for 42 minutes and 46 seconds. Each raw image was created from a 60 second exposure. DAO flats, biases, and darks were available on the CADC public site, but only the darks and flats will be needed for image processing. The data was stored in "fits" files, which unfortunately did not contain any gain, readnoise, or unit data; this made it more difficult to accurately analyze, as will be touched on in the Methods section.

III. METHODS

First all frames had the top 45 rows of pixels trimmed from them. Then, the ten dark frames were combined to create a raw master dark. This was then subtracted from each of the 16 flat frames, which were then combined to make a master flat. These two files allow for processing of the science frames. The raw master dark is subtracted from each science frame, then each science frame is divided by the master flat. These processed images were then aligned using AstroImageJ using the target star J074658, as well as three calibration stars: GSC 01912-01105, GSC 01912-01015, and TYC 1912-1125-1. Out of 212 images from the first day of observation, only 120 processed images were aligned because the noise on the other frames made it difficult to properly align them.

The aligned images were then analyzed using the `photutils` package library, particularly the `make_source_mask`, `aperture_photometry`, `ApertureStats`, `CircularAperture` and `CircularAnnulus` packages. This allowed for circular apertures and annuli to be defined to subtract the background contributions from the target and calibration stars, as seen in figures 2 and 3. Here the dashed lines represent the outer radius of the annulus for which the mean will be calculated and subtracted across the interior aperture, to hopefully remove the background contribution.

Using `AperStats`, the means of the background annuli were taken, which were multiplied by the areas of the corresponding circular apertures and subtracted by the

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Object	RA	Dec.	V magnitude	Parallax (mas)	Period (hr)
1SWASP J074658.62+224448.5	07h 46m 58.64s	+22° 44′ 48.24″	14.13	2.74 ± 0.02	5.28

TABLE I: Parameters for J074658. Right ascension, declination, and parallax values are taken from Gaia's Early Data Release 3 [4]. The period is taken from [7], and V-band magnitude is taken from [3].

Object identifier(s)	RA	Dec.	V magnitude	Parallax (mas)
TYC 1912-1125-1	07h 46m 56.75s	+22° 47' 28.38"	12.00 ± 0.021	1.5002 ± 0.0129
GSC 01912-01105	07h 46m 48.40s	+22° 45′ 07.89″	14.69 ±0.08	0.9215 ± 0.0207
GSC 01912-01015	07h 46m 46.06s	+22° 44′ 46.76″	13.15 ± 0.11	1.8988 ± 0.0183

TABLE II: Parameters for J074658. Important values for the calibration stars. Right ascension, declination, and parallax values are taken from Gaia's Early Data Release 3 ([4]). V-band magnitudes for GSC 01912-01105 and GSC 01912-01015 are given by The fourth US Naval Observatory CCD Astrograph Catalog ([8]) and the magnitude for TYC 1912-1125-1 is given by the Tycho-2 Catalogue ([5]).

sum of the aperture contribution.

The actual magnitudes for the sources will be difficult to get, as one must convert from the counts. An additional correction is needed:

$$c = -2.5\log_{10}(C) \tag{1}$$

where C are the counts for a given object, after correction from background and summing over the aperture. Combining this with the relative magnitude equation:

$$m_1 - m_2 = -2.5\log_{10}\left(\frac{f_1}{f_2}\right) \tag{2}$$

an equation can be created to convert from counts to magnitude and calibrate with the selected calibration stars:

$$m_T = c_T + m_{cal,i} + 2.5\log_{10}(C_{cal,i}) \tag{3}$$

where c_T is the correction defined in equation 1, $m_{cal,i}$ is the apparent magnitude of calibration star i given in literature; $C_{cal,i}$ are the corrected aperture counts of calibration star i. This would give different magnitudes for each calibration star used, and thus different light curves. A final light curve can be plotted using the mean of $m_{cal,i} + 2.5\log_{10}(C_{cal,i})$ for all calibration stars, which should reduce the

Uncertainties are particularly difficult to account for in the calculation of the brightness, due to a lack of known gain and readnoise.

After gathering the light curve, an attempt can be made to calculate the luminosities of each star. Using the equation (from [2]:

$$I = \frac{A_{\text{Plaskett}}}{D^2}(F_1A_1 + F_2A_2) = \frac{A_{\text{Plaskett}}}{4\pi D^2}\left(\frac{L_1A_1}{R_1^2} + \frac{L_2A_2}{R_2^2}\right) \tag{4}$$

where A_{Plaskett} is the area of the Plaskett 1.8m telescope, D is the distance from the Earth to the binary, L_1 and L_2 are the luminosities of the two stars, R_1 and R_2 are the radii, and A_1 and A_2 are the amount of area of each star visible.

Since this is a contact binary system, we expect there to be two slightly different local minima and one maximum for the magnitude. The maximum represents where both stars are clearly visible in the line-of-sight, while each minima represents where one star is causing either a total or annular eclipse of the other star. Assuming star 1 is larger than star 2, such that a minimum magnitude occurs when $A_1 = \pi R_1^2$ and $A_2 = 0$, then the equation reduces to

$$I = \frac{A_{\text{Plaskett}}}{4D^2}L_1 = 10^{\frac{-V_{\min,1}}{2.5}} \tag{5}$$

where $V_{\min,1}$ refers to the magnitude at the point where star 1 eclipses star 2. Assuming that the warping of the spherical shapes of the stars due to contact is negligible, when $V = V_{\max}$, $A_1 = \pi R_1^2$ and $A_2 = \pi R_2^2$, suggesting

$$\frac{A_{\text{Plaskett}}}{4D^2}(L_1 + L_2) = 10^{\frac{-V_{\max}}{2.5}} \tag{6}$$

which, when combined with equation 5, gives an expression for L_2:

$$L_2 = \frac{4D^2\left(10^{\frac{-V_{\max}}{2.5}} - 10^{\frac{-V_{\min,1}}{2.5}}\right)}{A_{\text{Plaskett}}} \tag{7}$$

If values are achievable, it may be possible to extract masses as well, using the Mass-Luminosity Relation:

$$\left(\frac{L}{L_\odot}\right) \simeq 1.4\left(\frac{M}{M_\odot}\right)^{3.5} \quad (2M_\odot < M < 55M_\odot) \tag{8}$$

For these calculations, assuming a normal distribution of errors, the uncertainty of a function $z = f(x_1, x_2, ...x_n)$ with respect to the uncertainty of its variables, will be calculated using

$$(e_z)^2 = \sum_{i=1}^{n}\left(\frac{\partial f}{\partial x_i}e_i\right)^2 \tag{9}$$

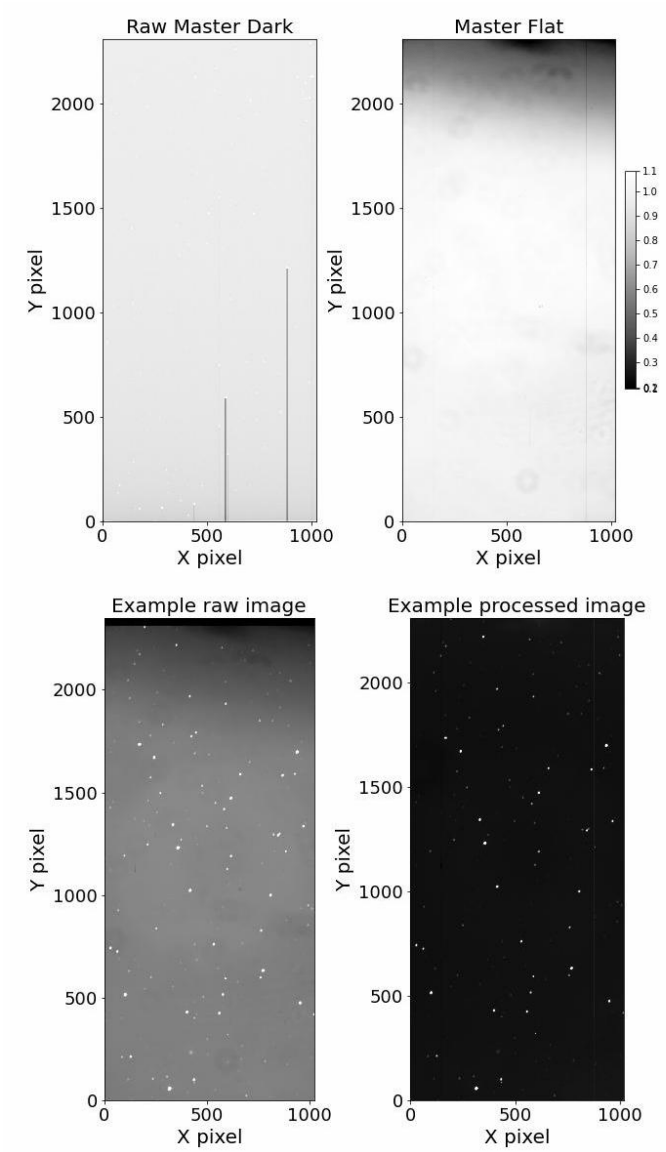

FIG. 1: An image of the raw master dark *(top left)*, the master flat *(top right)*, and a comparison between an initial example raw image *(bottom left)* vs after it had been processed *(bottom right)*. The units of brightness are not contained within the fits files, so "analog to digital units" are assumed.

IV. RESULTS

Unfortunately, the images gathered on the second day were not as sufficient for analysis as those gathered on the first day of observation. There were 212 exposures (120 used) completed on day 1, while day 2 completed only 38 exposures. First taking three light curves, one for each calibration star, we get very different results. Looking at figure 4, we can see that the curve whose maximum magnitude is closest to [3] is TYC 1912-1125-1, sitting in the middle between the high estimate of the GSC 01912-01015 correction and the low estimate of the GSC 01912-01105 correction:

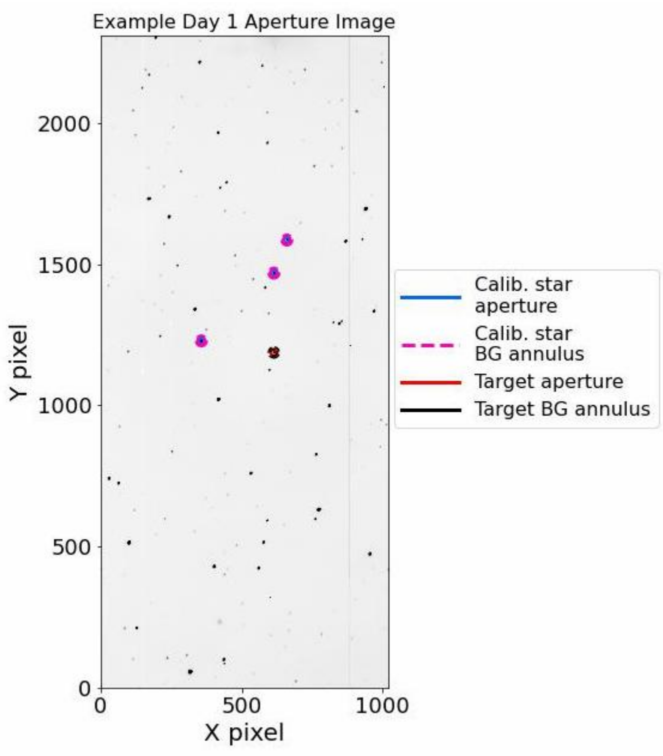

FIG. 2: An example image of the annulus and apertures used to isolate the source from the background contribution. This figure is not as clear as figure 3, but it does demonstrate where the target and selected calibration stars lie in the entirety of the frame.

Taking the mean of the corrections gives the light curve seen in figure 5. The results do not quite match those found in [3], but they are close; the maximum V magnitude of the mean-corrected light curve is 14.27 ∓ 0.08. Looking at figure 5, we can also spot orbit extrema. Unfortunately, due to the noise of the 92 other science frames from day 1, a complete period of 5.28 hours could not be plotted, and thus only two extrema are clearly seen. The shape of the light curve is remarkable; normally one would expect a near-constant magnitude interrupted by the trench-like drops caused by the eclipsing. This light curve appears nearly sinusoidal; this is most likely due to the two stars being in contact.

A Gaussian fit could be applied to both extrema, as seen in figures 6 and 7, to mixed results

An attempt was made at calculating the luminosities and masses. Unfortunately, the uncertainties are orders of magnitude larger than the calculated values, as can be seen in Table III.

One of the largest contributing factors to this was compounding the uncertainties. The constant value $K = \frac{A_{\text{Plaskett}}}{D^2}$ was frequently in the denominator of the equations used to calculate the values. Since it is a coefficient, it would survive the uncertainty calculation of Equation 9 and cause the error to skyrocket. One of many problems could have led to this result:

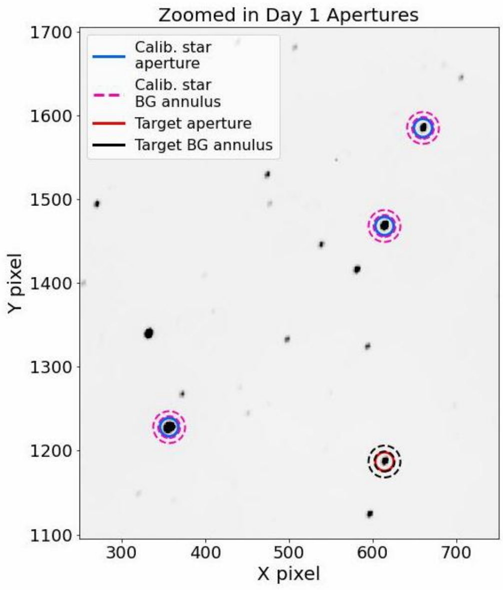

FIG. 3: A zoomed version of the example image of the annulus and apertures used to isolate the source from the background contribution. Here the annuli that will be used to calculate the background contribution within the apertures can clearly be seen.

Quantity	Value	Uncertainty
D (metres)	1.12615×10^{19}	0.00002×10^{19}
$K = \frac{A_{\text{Plaskett}}}{D^2}$	2.01×10^{-38}	8.02×10^{-43}
$V_{\text{min},1}$ (mag)	14.88	0.08
V_{max} (mag)	14.27	0.08
L_1 (W)	2.2×10^{32}	1.3×10^{43}
L_2 (W)	1.7×10^{32}	1.5×10^{43}
M_1 (kg)	8.0×10^{31}	1.3×10^{42}
M_2 (kg)	7.4×10^{31}	2×10^{42}

TABLE III: The results of attempting to calculate the luminosities and masses of the binary stars. Unfortunately, the constant K caused a massive increase in the compounding uncertainties when using Equation 9 to calculate them. as a result, some uncertainties are orders of magnitude larger than the values themselves.

1. Equation 4 is not applicable/inaccurate

2. The assumption that the errors are normally distributed is incorrect, and thus Equation 9 is inappropriate.

3. Several computational errors were made and not discovered.

More research is needed to determine what can be done to more accurately calculate the individual luminosities of the stars within the binary system J074658.

V. ACKNOWLEDGEMENTS

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- *This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France*

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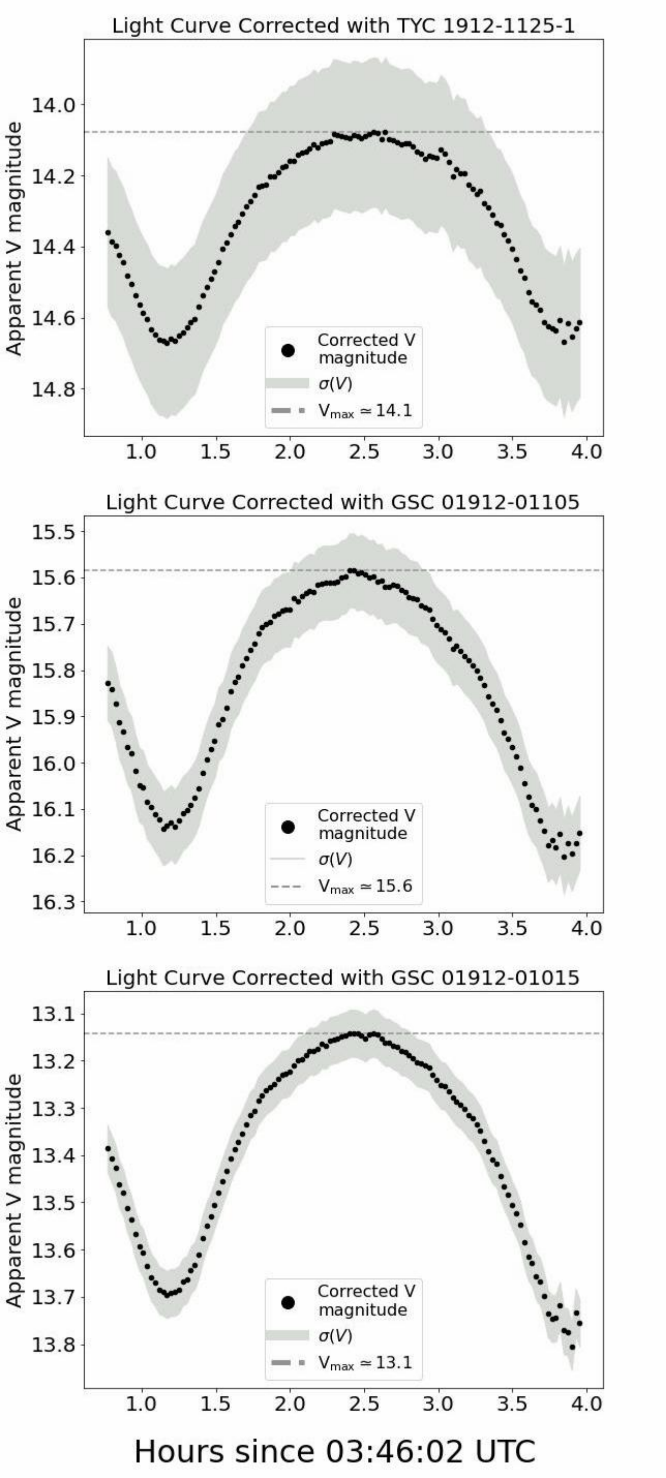

FIG. 4: Light curves for the binary, each corrected using a different calibration star, are shown. The uncertainty in this case is equal to the uncertainty of the V magnitude measurement for each respective calibration star.

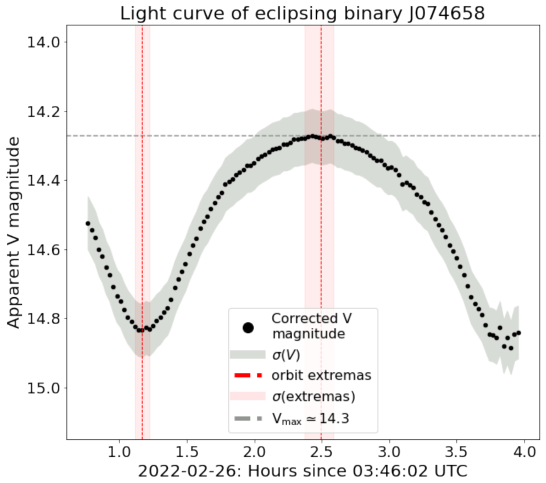

FIG. 5: a plot of the analyzed light curve for the target binary, with mean correction applied

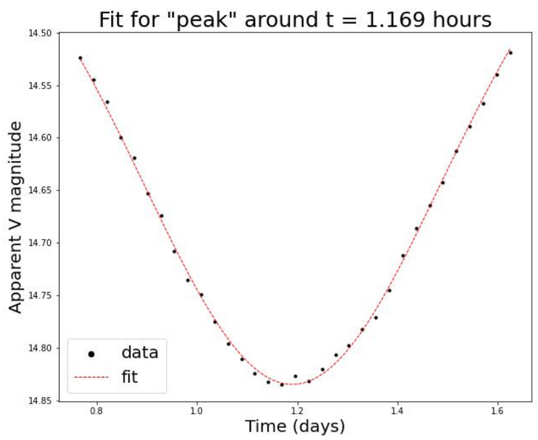

FIG. 6: A plot of a Gaussian curve fit of the leftmost ”peak” of the mean-corrected light curve.

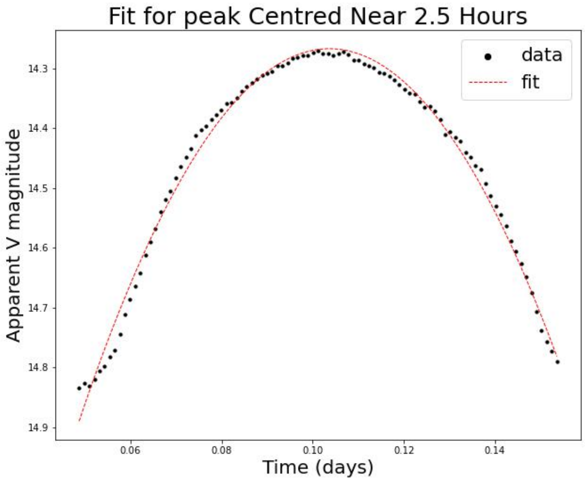

FIG. 7: A plot of a Gaussian curve fit of the second "peak" of the mean-corrected light curve. Notice that it does not fit as well as the first peak does.