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Light Curve analysis of WASP0845+53

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ABSTRACT

EL CVn is a prototype of a binary system that consists of an A/F-type main sequence star and a proto-helium White Dwarf. Analyzing EL CVn type binary stars can give insights into formation of low mass white dwarf in great detail. The Wide Angle Search for Planets (WASP) survey was used to discover these objects. Here we study one of the EL CVn type binary stars, WASP0845+53, in the Harris R-filter using the mont4k instrument on the Kuiper 61" telescope. The light curve analysis is done to find the orbital parameters of the system and the luminosity ratio of the stars. We present the probable Roche lobe values for any EL CVn-type binary system with an orbital period similar to our target. The Roche lobe is found to be bigger than the pre-He-WD suggesting a detached binary system.

INTRODUCTION

Wide Angle Search for Planets (WASP) is an international collaboration to find exoplanets using transit surveys. The instrument detected around seven million stars with V magnitude ranging from 8 to 13 (Maxted et al. 2014). The majority of star systems in the sky are binary systems. Eclipsing binary star systems are useful for studying the properties, interactions, and evolution of different types of stars. By analyzing the light curves of these systems, we can obtain valuable information about stellar properties, such as mass, effective temperature, relative radius, and Roche lobe shape. Combining it with spectroscopic analysis can lead to exploring a wider range of properties such as radial velocity and stellar composition.

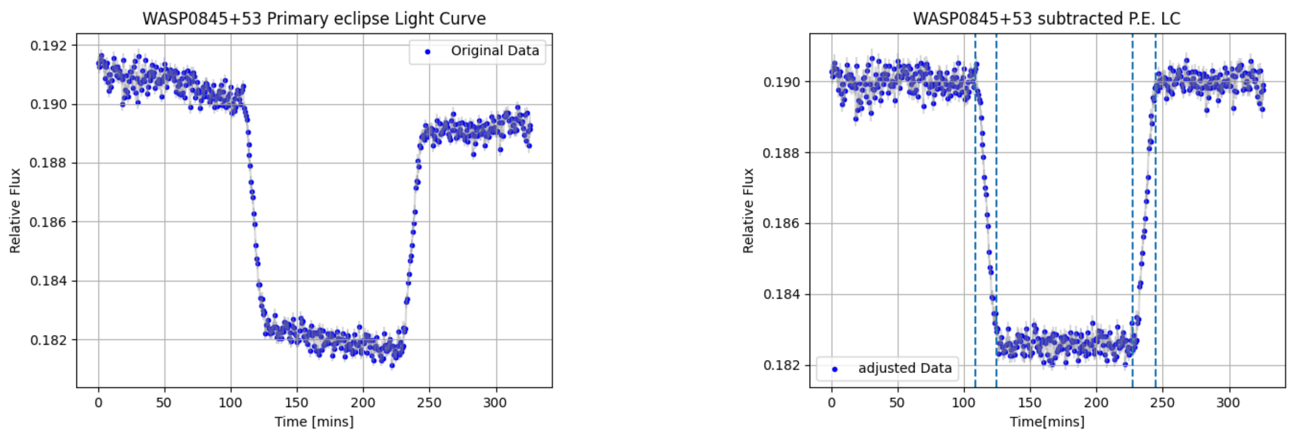
Amongst the binaries identified in the WASP data, Maxted et al. (2014) discovered 17 systems of binaries where the primary star is a main sequence A-star and the secondary star is a pre-Helium white dwarf. The A-type star (presumed to be a blue straggler) quenched its companion star of hydrogen during its first giant branch evolution phase. This caused the secondary to drift towards the helium white dwarf cooling phase in its evolutionary track. EL CVn is a prototype of this type of binary system (Maxted et al. 2014). Studying EL CVn-type binaries is of specific importance because it gives insights into the formation and evolution of low-mass white dwarfs (LMWD). Previous studies on EL CVn binaries have been conducted with low signal-to-noise ratio, single filters, sparsely sampled data, or a combination of these three limitations. Hence, it is important to analyze these eclipsing binary systems using different filters, with high signal-to-noise ratios.

We observe the primary eclipse of one of the 17 binaries from Maxted et al. (2014), 1SWASPJ084558.78+530209.8, in the R band filter using the Mont4k instrument on the Kuiper 61" telescope. 1SWASPJ084558.78+530209.8 (hereafter WASP0845+53) has an A-type primary star and pre-He White Dwarf secondary star of the effective temperature of 8000K ± 400 and 15,000K ± 1800, respectively (Maxted et al. 2014). In this report, the light curve analysis of WASP0845+53 is discussed. We utilized the light curve and information from Maxted et al. (2014) to determine relative flux change, star radii, orbital parameters, and the Roche lobe radii of this binary stellar system.

OBSERVATION AND DATA REDUCTION

WASP

WASP0845+53 was initially observed as part of the WASP program. The program used instruments with a wide field of view covering $\sim 482\ deg^2$ with an angular scale of $13.7''\ pixel^{-1}$ (Pollacco et al. 2006). The program automatically converted the data collected to light curves. The method of the candidate selection is mentioned in Maxted et al. (2014). They specifically looked for a light curve in the WASP archive which is associated with a binary system with



(a) Light curve

(b) Light curve after systematic error subtraction

Figure 1. Light curve adjusted to exclude systematic errors. *Left:* Light curve made by doing differential photometry using AstroimageJ. *Right:* Adjusting the light curve for its systematic errors.

inclination $\sim 90°$. Such light curves have a flat transit line, and steep ingress and egress lines (Maxted et al. 2014). They use transit detection models to find a close match to the type of light curve they were looking for.

Kuiper 61″ telescope

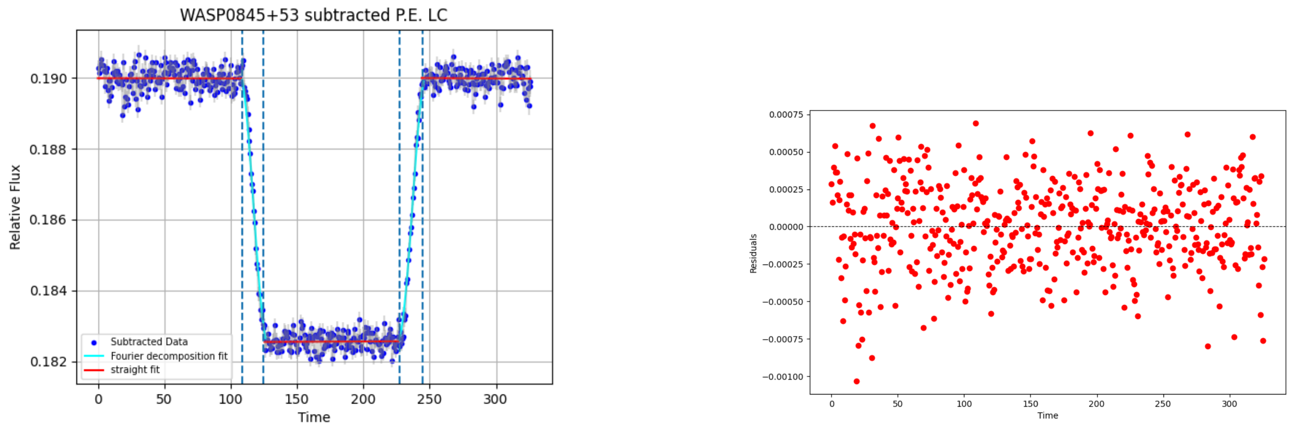
Observation for WASP0845+53 in Harris-R filter was made in the Kuiper 61″ telescope located at Mount Bigelow in Tucson, Arizona. The telescope is equipped with a primary mirror with a diameter of 1.54 meters and a primary focal ratio of f/4. We used the “Montreal 4K” (Mont4k) CCD imager. It has a size of 4096×4097 pixels and an image scale of 0.14 arcsec/pixel. Its field of view is $580'' \times 580''$. The Mont4k camera possesses a gain of 3.1 electrons per analog-to-digital unit (e^-/ADU), a readout noise level of 5 electrons, and a dark current of 16.6 electrons per pixel per hour. 482 images were taken on the night of 2023 February 26 by Dr. Elizabeth Green for an exposure time of 30 seconds each. The seeing was reported to be poor and variable ranging from 2.2″ to 4.5″ with times where seeing conditions occasionally improved, but overall deteriorated significantly towards the end. The observations started at 03:29:59.334 UTC and ended at 08:55:56.858 UTC. We used 2 by 2 binning for CCD imaging. The extended fits images were already combined into a normalized FITS image by the script, “merge4k” used in the operating system in the telescope. The script subtracts the over-scan from the data taken by the two sides of the CCD before merging into one FITS image. The bad and zero columns in between the two halves of CCD are interpolated over. The Full Width at Half Maximum (FWHM) difference between the brightness of the reference stars was kept the same, varying by only 5% to 10%. Photometry was done on all 482 raw FITS files made from these observations.

Photometry

Differential photometry using the software AstroimageJ [1] was done to calculate the light curve of the binary. AstroimageJs CCD data processor was utilized to do the bias subtraction and flat fielding of all the images. The cosmic rays had already been removed manually after the observation was finished. We plate solve and add the World Coordinate System (WCS) to each image. We then do multi-aperture differential photometry. The object aperture radius for all images was estimated to be approximately 15 pixels by multiplying the average of the FWHM of the target and reference stars by 2.50. Using the multi-aperture tool the radius of the object aperture, the inner radius of the background annulus, and the outer radius of the background annulus were set to 15, 35, and 65 pixels, respectively.

The light curve made had lower values of relative flux as the time went on as shown in the figure 1(a). It was concluded as a systematic error and to fix this we fit a five-degree polynomial through the out-of-transit data points and then subtract that fit from the whole curve. This results in a more acceptable light curve shown in figure 1(b).

[1] https://www.astro.louisville.edu/software/astroimagej/



(a) Light curve fit.

(b) Residual plot of the fit.

Figure 2. *Top:* Fitting a straight line and Fourier series through the light curve by breaking it into regions. *Bottom:* The residual plot of the whole fit through the light curve.

For fitting we break the light curve into regions made by the vertical dashed lines shown in the figure 1(b). The region with the ingress and egress lines was fitted using Fourier decomposition (Dey et al. 2015). The Fourier series used for fitting was:

$$f(\phi) = f_0 + \sum_{i=1}^{n} (a_i \sin(2\pi i\phi) + b_i \cos(2\pi i\phi)) \tag{1}$$

where f_0 is the mean relative flux. ϕ is the time since the observation started. An iteration of n = 50 was used to get a good fit.

A linear regression model was used to fit the data for the regions that had a flatter trend. The fits worked quite well and can be seen in figure 2(a). We plotted the fit residual and observed no discernible pattern, indicating a good fit.

ANALYSIS AND RESULTS

After analyzing the light curve, we estimated that the eclipse lasted for 101 minutes. During this time, the pre-He WD is positioned completely behind the A-type star. The ingress and egress regions are estimated to take 16 minutes each. Let's assume the radius of the A-type star (hereafter A) is R_a and that of the pre-He WD (hereafter B) is R_b. Using simple geometry we can say:

$$\frac{2 \times R_b}{t} = \frac{2 \times R_a}{T + t} = \frac{2 \times \pi \times a}{P} \tag{2}$$

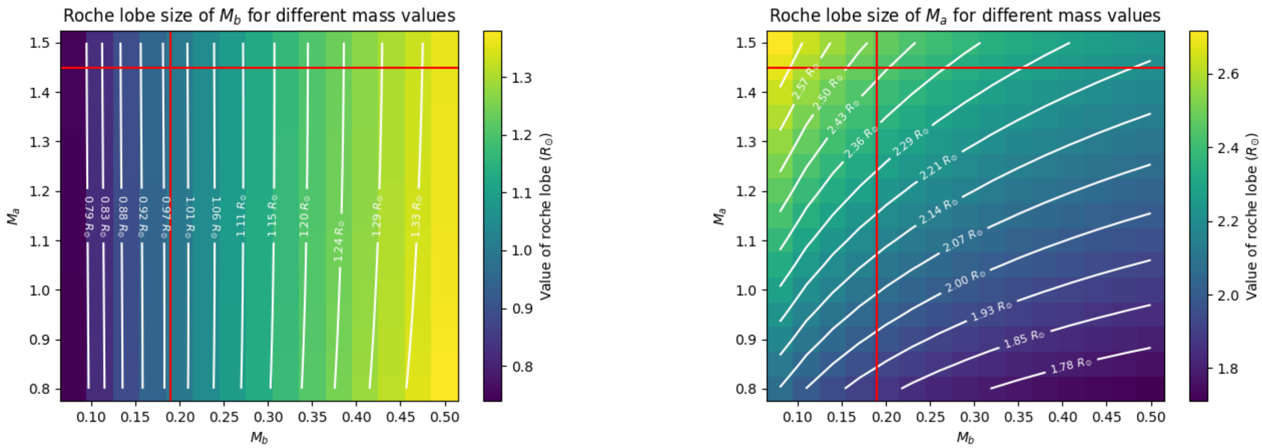
where a is the semi-major axis, P is the orbital period, T is 101 minutes and t is 16 minutes. For this, a circular orbit is assumed. Hence, B is revolving with constant angular velocity.

Using the value of $\frac{R_a}{a} = 0.303$ as given in Table 2 of Maxted et al. (2014), we find an orbital period of 0.842 days. Kepler's 3rd law (see equation 3) is used to calculate the semi-major axis. A range of masses is taken for both the stars. According to Chen et al. (2017), the probable mass range where most pre-He WD in EL CVn binary stars lie is from 0.17 to 0.21 $M_\odot$. The now A-type star must have been a lower-mass star that gained mass due to mass transfer (this is a common trait in these types of binaries). We note the most probable mass of a main sequence F0 type star is 1.6 $M_\odot$ [2]. Based on this information, a range of the masses of A and B stars is taken to lie between 0.8-1.5 $M_\odot$ and 0.1-0.5 $M_\odot$, respectively.

$$a = \left(\frac{M_t * G * P^2}{4 * \pi^2}\right)^{\frac{1}{3}} \tag{3}$$

Here M_t denotes the sum of the mass range of A and B. G is the gravitational constant. We use the range of the semi-major axis to calculate the radius of the Roche-lobe which can be found by equation 4 (Eggleton 1983).

[2] Appendix G, An Introduction to Modern Astrophysics Bradley W Carroll and Dale A Ostlie.



(a) roche lobe values for M_b

(b) roche lobe values for M_a

Figure 3. A color map of the Roche lobe values for different masses of Type-A star and pre-He WD. The white contour lines are the values of the Roche lobe. The red straight lines represent the mass values of the two stars in Maxted et al. (2014)

$$r_1 = a * \frac{(0.49q^{\frac{2}{3}})}{(0.6q^{\frac{2}{3}}) + \ln(1 + q^{\frac{1}{3}})} \tag{4}$$

Where r_1 is the Roche-lobe radii of star 1. q is the mass ratio $= M_1/M_2$. Figure 3(a) shows a color map of the Roche-lobe values for different masses for both of our stars. Since the Roche lobe values are constrained to the orbital period of WASP0845+53, this plot is unique to this binary star system, or other EL CVn binary stars with the same P. For $M_a = 1.45\ M_\odot$ and $M_b = 0.19\ M_\odot$ (Maxted et al. 2014) we get a r_b of 0.97 $R_\odot$ and r_a of 2.43 $R_\odot$.

The luminosity ratio of the stars is estimated using the equation (Dey et al. 2015):

$$\frac{L_b}{L_a} = (\frac{R_b}{R_a})^2 * (\frac{T_b}{T_a})^4 \tag{5}$$

Where L_b and L_a are the luminosity of stars A and B. T_b and T_a are the temperatures of stars B and A, from Maxted et al. (2014). We get a value of $\frac{L_b}{L_a} = 0.313$.

Name	M_a	M_b	P	a	R_a	R_b	r_b	r_a	L_b/L_a
WASP 0845+53	1.45	0.19	0.842	4.37	1.32	0.17	0.97	2.43	0.313

Table 1. Masses are units of $M_\odot$ taken from Maxted et al. (2014). The orbital period is in days. All the distances are in $R_\odot$

DISCUSSION AND FUTURE WORK.

An EL CVn type binary, WASP 0845+53, is analyzed in the Harris-R filter observed using the Kuiper 61" telescope. We fit its light curve and calculate its orbital parameters, Roche lobe, and luminosity ratio. Different possible values of the Roche lobe radii is found for a range of masses for the two stars. Using the mass of the two stars from previous studies, we could determine an explicit value for their Roche lobe. Table 1 has the results of the calculations.

Our value of the pre-He-WD Roche lobe is bigger than its radius which would suggest that they are now detached binaries. Our calculation of the Roche lobe confirms this binary system's evolution theory briefly mentioned in Maxted et al. (2014). The precursor of the now pre-He-WD must have been a red giant star which due to Roche lobe overflow lost a bit of its outer envelope to its companion, the main sequence F-type star. On gaining the mass, the F-type star must have gone up the mass ladder to become an A-type star (what we see now). The red giant left behind a hydrogen quenched, hot helium core which is not massive enough to start nuclear fusion. Considering the difference between the Roche lobe and radii of the pre-He-WD, the rate at which the red giant progenitor of WASP 0845+53 B lost its mass was much faster than the rate at which its Roche lobe decreased.

Our study of WASP 0845+53 gives a template for future Roche lobe estimation of EL CVn-type binaries with a similar orbital period to that used in this report. A spectral analysis of the pre-He-WD would yield what elements it constitutes. Knowing its radial velocity can help us understand the kinematics of such binaries with extremely short orbital periods (< 1 day). We believe due to this the mass transfer wasn't exactly conservative, this is also talked in Chen et al. (2017). With spectral data, we would like to estimate its current mass and radii of the stars more accurately and repeat the process in this report.

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