Characterizing Quadruple Eclipsing Binary Systems Through Combined TESS Photometry and Speckle Imaging During Eclipses (SIDE) Observations

Undergraduate Senior Thesis by:

Gabriel N. Hartwell

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Supervisor: Steven R. Majewski, Chair of the UVa Astronomy Department
Co-Supervisor: James W. Davidson, UVa Astronomy Department

ABSTRACT

Eclipsing binary stars (EBs) have long been valued as important tools in establishing fundamental properties and relationships in stellar astrophysics. With the discovery of systems with multiple families of eclipses, the importance of EBs extends to the study of hierarchical, multiple star systems. The primary objective of this thesis is to analyze several TESS-identified quadruple eclipsing binaries (QEBs) using both space and ground-based photometry, as well as high resolution speckle imaging obtained with the Differential Speckle Survey Instrument, DSSI [Horch et al., 2009] on the Astrophysical Research Consortium 3.5-meter telescope at Apache Point Observatory (APO) in Sunspot, NM with the goal of ascertaining detailed architectures of these hierarchal, multiple star systems. This is the first systematic application of Speckle Imaging During Eclipse (SIDE) applied to eclipsing binary starts. All systems discussed in this thesis were identified from photometric data obtained with NASA's Transiting Exoplanet Survey Satellite (TESS) by Kostov et al. [2022] and Kostov et al. [2024], whose work is essential to the creation of this thesis. The first aspect of the present analysis attempts to verify the times of current eclipses for each system using ground-based photometry collected with the 0.5-meter Astrophysical Research Consortium Small Aperture Telescope (ARCSAT) based at APO, and the 0.6-meter Rapid Response Robotic Telescope (RRRT) at Fan Mountain Observatory in Covesville, VA. These verifications are necessary to ensure that eclipse timings remain accurate after originally observed with TESS. After the original observations by TESS several years ago, both because the original derivations of some eclipse periods and durations had non-negligible errors, and because some systems were identified by Kostov et al. as showing evidence of eclipse timing variations (ETVs), predicted eclipse times could have shifted since the original observations. Due to these factors, further verification is necessary to ensure that our predicted eclipse times are still correct. The second portion of our analysis

uses diffraction-limited speckle imaging to resolve the QEBs into two subcomponents, to measure the photometric difference between these two components, and, most uniquely, to make these measurements both in and out of eclipses. By monitoring the changes in photometric difference during eclipses we show that it is possible to gain further insights into the architectures of the QEB systems, making it possible to determine which speckle-resolved source can be associated with which family of eclipses. The usage of high-resolution speckle imaging to analyze TESS-identified QEb candidates is currently in its infancy, and the results described will be among the first published analysis of these systems using this method. Ultimately, the goal of this analysis is to determine whether both binary pairs of the TESS-identified QEB reside in one of the speckle-resolved subcomponents or if each of the resolved subcomponents contains one of the EB pairs.

ACKNOWLEDGEMENTS

Contents

Chapter 1

Introduction

This thesis will present combined photometric and high resolution speckle imaging analysis of four QEB systems, whose ephemerides are obtained from the analysis of photometry from the Transiting Exoplanet Survey Satellite (TESS) published by Kostov et al. [2022, 2024], who did a systematic search for quadruple and sextuple eclipsing binaries within the TESS database. Eclipsing binaries (EBs) are binary systems with a known orbital inclination to the line-of-sight close to 90 degrees. The observed eclipses give us key information about the binary orbit such as period and eccentricity, as well as other stelar properties such as radii, surface temperature, and masses. Quadruple eclipsing binaries (QEBs) consist of two binary pairs orbiting a common barycenter, with both binary pairs exhibiting families of eclipses. Eclipsing binaries with multiple eclipse families are exceedingly rare and are only just now being found in numbers by the Kostov et al. analysis of TESS photometry. Studying these systems is important in our understanding of how close proximity hierarchal systems dynamically change over time, some of which may be undergoing mass transfer and stellar mergers [Tokovinin et al., 2024].

The systems studied in this thesis are all QEBs, which have at least two eclipsing binary pairs. The terminology we use to refer to each subcomponent of the binary pair is the same as described in Kostov et al. [2022, 2024]. Each QEB has a primary and secondary eclipsing binary pair, denoted with A and B. The primary binary pair is the sub-system with the shorter period identified by their eclipses in the photometry, while the secondary is the system with the longer period. Each sub-system has a primary and secondary eclipse as well, denoted with

α and β. These systems are labeled with both a Gaia ID from their observation with NASA's Gaia mission, as well as a TESS Input Catalog (TIC) number associated with the observations made with TESS. Precision photometry from these systems can help construct a rough picture of system architecture, with the light curves obtained showing detailed information about each sub component's period and relative makeup. These data tell us the period of the system, as well as the duration and depth of each eclipse to very low uncertainty. Using Keplerian mechanics, we can calculate the separation between each star in the binary pair, but more detailed measurements are required to obtain the separation between the subcomponents.

The systems cataloged in Kostov et al. [2022, 2024] provide detailed information about time and duration of eclipse, as well as the time at mid-eclipse of the first measured eclipse from TESS, denoted as t_0. Some of the cataloged systems exhibit evidence of eclipse timing variations (ETVs), caused by an unseen higher order object perturbing the orbit of the main QEB system [Borkovits et al., 2015]. The systems analyzed for this thesis did not exhibit any noticeable ETVs in the time frame analyzed by Kostov et al. [2022, 2024], so any variation in predicted contemporary timings are more likely the result of measurement error in the original TESS measurements. To determine the timings of eclipses for new observations, e.g., for speckle imaging, we take the original ephemerides and propagate an integer number of sub-system periods in the future. If the measured period or duration values are slightly off, this prediction will shift further from the correct time the further ahead one propagates. Section 2.1 describes the process of using ground-based photometry to verify eclipse timings, as well as more recent TESS data where available.

All systems observed with TESS or with ground based photometry do not have enough resolution to resolve the source into smaller components. To get the resolution required, high resolution speckle imaging is needed. The brighter resolved object in speckle imaging is referred to as the primary, while the dimmer

object is referred to as the secondary. If a system is able to be resolved into two subcomponents, we can measure the difference in magnitude (Δ mag) between the two at different points during an eclipse, a process we call Speckle Imaging During Eclipse (SIDE), discussed in section 2.2. Section 2.3 discusses how the trend that the magnitude difference takes will tell us which speckle resolved sub-system was undergoing an eclipse, and combined with the photometric data we can determine which QEB subsystem was in eclipse during that time. It is important to note that the sub-systems resolved with speckle are not analogous to the sub-systems of the binary pair, and just share a very similar naming convention. If the magnitude difference between the speckle-resolved sources increases while in eclipse, this indicates that the secondary resolved system is in eclipse, while the primary system is in eclipse if the difference decreases. This change alone does not verify weather or not the primary and secondary resolved objects in speckle are the same as the primary and secondary sub-systems of the QEB. Further observations of the other system's eclipse is needed.

Chapter 3 describes the results from data reduction of three QEBs using high resolution speckle photometry and TESS photometry to determine the system architecture of one binary pair in each QEB.

Chapter 2

Data and Background

2.1 Photometric Analysis of QEBs

NASA's TESS mission, launched in 2018, has spent the last six years imaging thousands of targets, collecting high quality photometric data. Space-based photometry is invaluable for several reasons; Space telescopes are not limited by atmospheric effects or any earth-based weather, and they are also not beholden to earth's day/night cycle. If a potential eclipsing binary target has long periods, or very long eclipse duration, it is very difficult to image a full eclipse on earth. TESS, however, can sit on a single target for multiple days and construct a very detailed picture of the system's phase. Figure 2.1 shows a full observation block of TIC 278465736, spanning a full month.
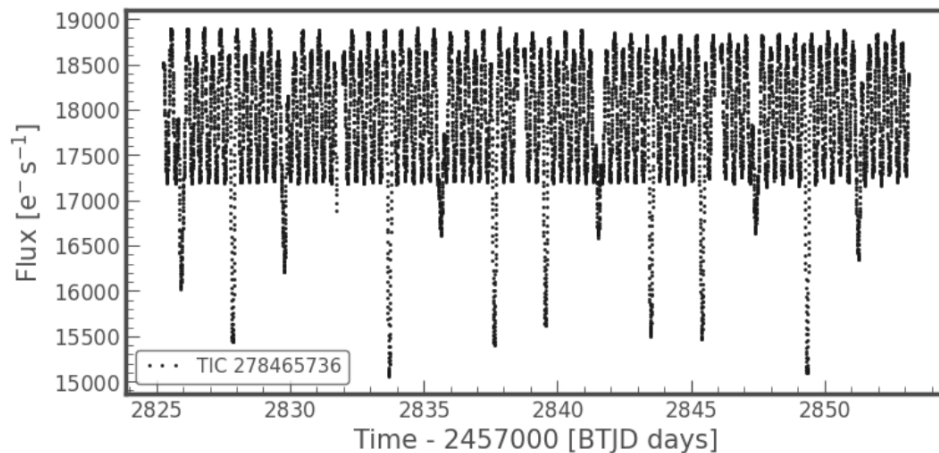

Figure 2.1: TESS Observation of TIC 278465736. The light curve of the source reflects oscillations due to two families of eclipses, of periods 0.61421 and 3.90630 days. Also obvious are occasions when there are double eclipses, leading to deeper than normal dimming.

Nominally, using the TESS light curves themselves it should be possible to extrapolate forward to any particular time to determine the expected eclipse state of the TIC. However, much of these data are sufficiently outdated that the accumulated errors are significant, so that it is necessary to have an independent verification that the timings of the eclipses have not shifted. The best way to do this is to re-image the systems of interest with ground-based photometry. Ideally one would obtain light curve data of the TIC at the same time the speckle data are taken to ensure there is no doubt that the eclipse timings are accurate for the observation date. However, sometimes this is not possible, so the next best thing is to verify that the older TESS ephemeridea are still valid close to the time of the speckle observations.
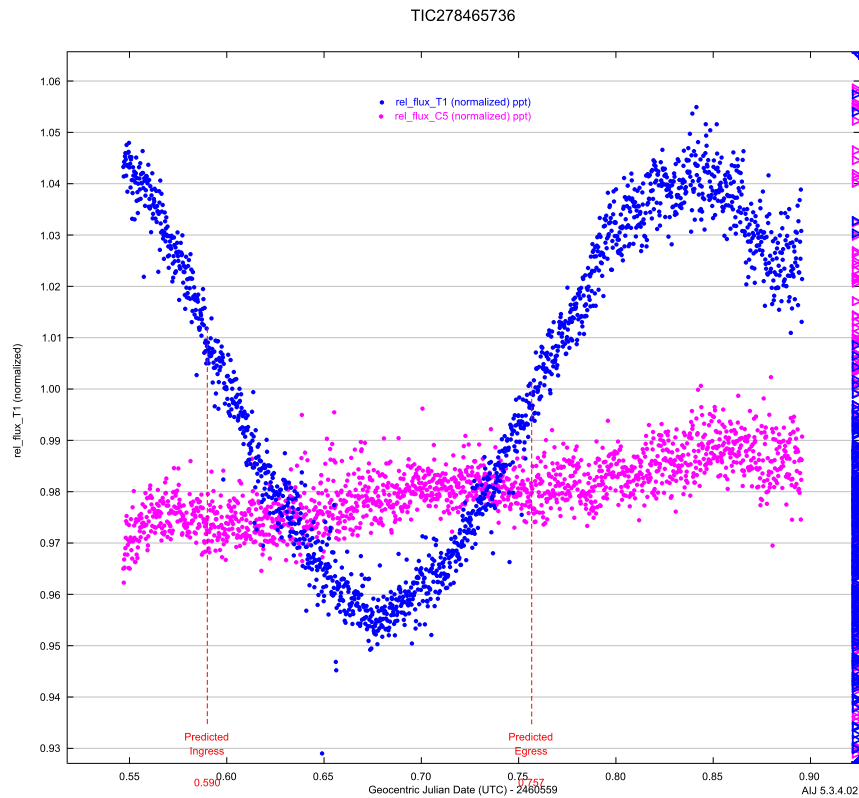

Figure 2.2: TIC 278465736 Aα eclipse observed on UT 2024 September 6, with the RRRT. The y-axis shows relative flux, compared with non-variable reference stars in the same field. A value of 1 is the normalized value. Note that this system often has a relative flux higher than 1, this is due to the ellipsoidal variation causing the system to appear brighter (explained in Section 2.4) The x-axis shows time in UT. The blue points denote the flux values of the eclipsing binary, while the magenta points show the reference flux of one of the non-variable stars.
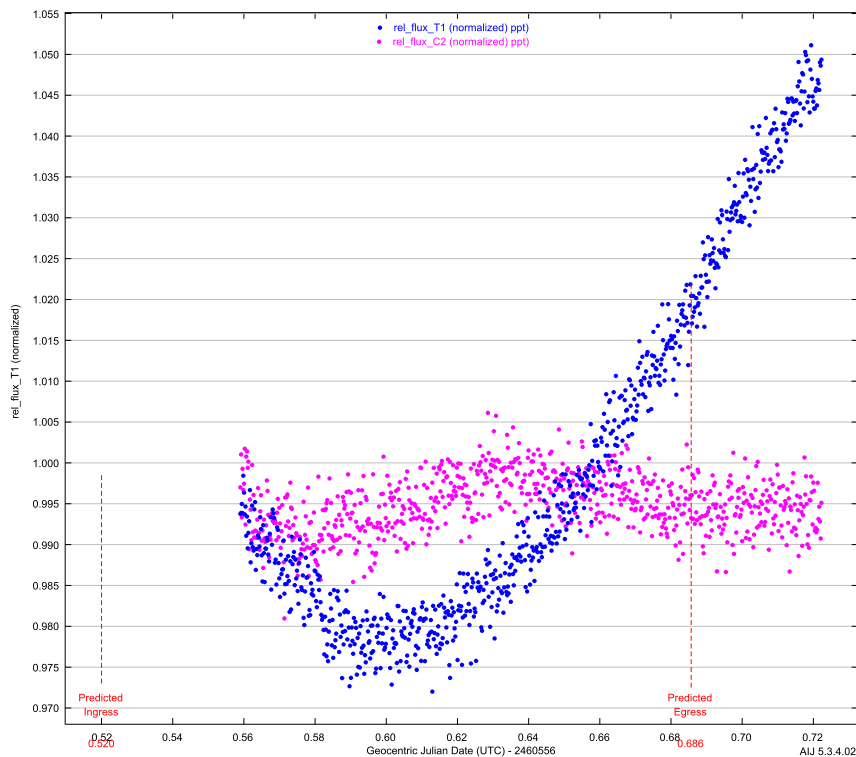
Figure 2.3: Same as Figure 2.2, but on UT 2024 September 3.

Figures 2.2 and 2.3 show ground-based photometry taken with the RRRT of the TIC 278465736 Aα eclipse. The dotted red lines are the predicted ingress and egress of the eclipse, obtained by using the original TESS measurements propagated into the future to determine if they are still correct. The pink dots on both plots are a representative reference star. To obtain a light curve of an eclipsing binary, we photometrically gauge its relative brightness against a set of non-variable reference stars in the same field-of-view view of an electronic detector (e.g., CCD or CMOS) over a long time series of images. In the examples shown in Figures 2.2 and 2.3, it is clear that the predicted times for the respective eclipses are still consistent with what is observed, based on how well they line up with the data. Out of the three systems described with speckle imaging in this thesis, two have ground-based photometric verification of their eclipses.

Figure 2.4 shows the Aα eclipse of TIC 470710327. This photometry is not as definitive as the ones above because less than half of an entire eclipse was captured, and the data were fairly noisy. The noise in the image is caused by a
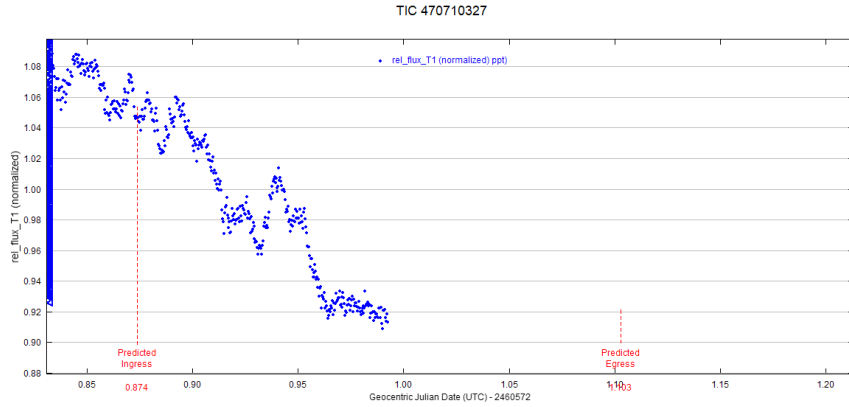
Figure 2.4:   Same as 2.2, but for TIC 470710327 observed on UT 2024 September 19.

focus issue with the telescope, which caused the stellar images to change their sizes relative to the fixed aperture size, so that the fraction of starlight captured varied slightly over time.

Where ground-based photometry is unavailable, it is still possible to verify eclipse timings. TESS often re-observes the same targets multiple times, so you can take the most recent data and verify using that. Using the known period of a sub-system you can extrapolate the curve over to any date. To verify whether or not eclipse timings have shifted, we compare the period-shifted light curves from different TESS data sets of the same target to see if they have shifted. Using one or both of these timing verifications, all QEBs described in this thesis observed during an eclipse with speckle imaging are verified to actually be undergoing the predicted eclipse.

2.2   High Resolution Speckle Imaging

Photometry, both from TESS and followup ground-based, can provide very useful information about the makeup of these QEBs, but to fully survey these systems we need a method with much better resolution. Using typical optical imaging techniques, all of these QEBs will appear as a single point source. To determine the separation between the component binary pairs, higher resolution is required. Speckle imaging uses blocks of many very short exposure observations

to resolve a target below the seeing limit caused by atmospheric disturbances. When viewing an object through a distorted medium, like earth's atmosphere, the effective resolution of a telescope is limited due to multiple, random deviations of the wave fronts by the layers of air of different temperatures and densities, which are corrugated and mixed by churning currents like the jet stream and convection. However, at any instant, for a point source, the phase screen presented by this intervening, churned-up atmosphere admits many diffraction-limited images of that point source. A quick snapshot therefore captures many, randomly placed, diffraction-limited images. In principle, if one could "collect" those speckles and somehow lay them on top of one another, one could "build up" a diffraction-limited image over time. Unfortunately, due to the quick motion of the overlying atmosphere over the telescope, the pattern of speckles quickly changes over time. However, the technique of speckle imaging uses techniques of Fourier de-convolution and image reconstruction to exploit the diffraction-limited information content available in many thousands of short images taken of a source to create images free of the distorting effects of the atmosphere [Bates, 1982] Using speckle imaging obtained with DSSI on the ARC 3.5-m telescope, we achieve nominally diffraction-limited imaging to about 0.04 arc seconds.

2.3 Combined Speckle Imaging and Photometric Analysis

If speckle imaging can be applied to a QEB to resolve it down into at least two subcomponents, we have made the first step into ascertaining the hierarchy of the QEB architecture. The next step is to measure the angular separation, position angle, and photometric difference between the two subcomponents. The next question is whether these separated subcomponents correspond to a separation of eclipsing binary pairs A and B, or whether the A and B pairs still reside, unresolved, within one of the speckle-separated subcomponents and the other subcomponents is unrelated to A and B — that is, either another part of the system hierarchy (system C, implying at least a quintuple star system), or an

unrelated background/foreground star that just happens to be along the same line-of-sight. To determine if the speckle-resolved subcomponents correspond to the subcomponents of the QEB (A and B), we use the light curves from TESS photometry and compare those data graphically with the speckle photometry. If subcomponents are resolved with speckle, the difference in magnitude between the resolved components can be measured at different points throughout an eclipse using SIDE observations. During an eclipse of one of the QEB sub-systems, the binary pair in eclipse will dim relative to the other. If the difference in magnitude (Δ mag) between the speckle subcomponents decreases as an eclipse occurs, that eclipsing binary resides in the speckle-resolved primary. This is because the primary sub-system in a speckle-resolved image is the brighter of the two. If the brighter system undergoes an eclipse, the Δ mag will decrease as the brighter sub-system dims. Conversely, if the Δ mag increases as an eclipse occurs, it follows that the subcomponent of the QEB undergoing an eclipse resides in the speckle secondary.

The photometric results from speckle yield three possible system architectures of the QEB, visualized in figure 2.5. At TESS resolution, the QEBs are unresolved, and multiplicity is detected through TESS light curves. Referring to figure 2.5, cases A and B illustrate system architectures where the QEB fully resides in one of the speckle-resolved subcomponents, where the other component is either a foreground/background star, or another star in the system. Case C is the classic "double-double", where each speckle-resolved subcomponent is one of the binary pairs of the QEB.

It is only possible to fully characterize a QEB if both eclipse families are measured. If we see a decreasing magnitude difference for one eclipse, we can only say that that subcomponent of the QEB is in the speckle-resolved primary, but until the other binary pair is observed during eclipse, we cannot determine whether or not the entire QEB is in the speckle primary (Case A), or if each component of the QEB is in a different speckle component (Case C). If we see an
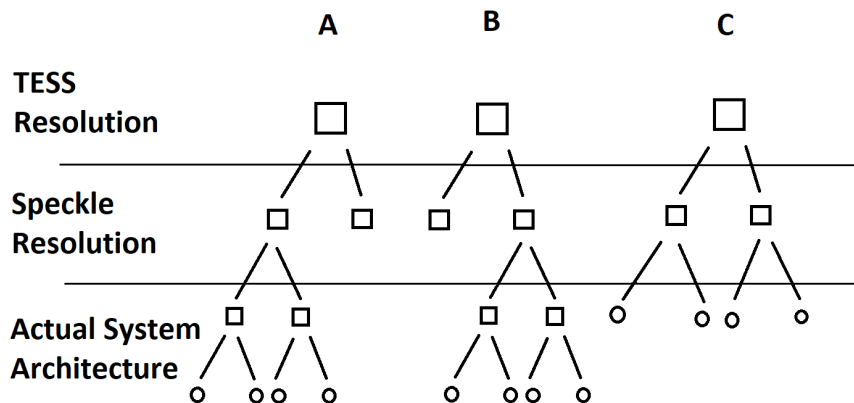
Figure 2.5:   Possible multiplicity architectures of a speckle-resolved QEB.

increase in magnitude of one eclipse, by similar logic we can only determine that that QEB is either Case B or Case C. The objective of this thesis is to determine which speckle-resolved subcomponent corresponds to the binary pair measured with speckle. Presented are speckle photometry data of one binary pair for three QEBs.

This thesis presents three QEBs that have been imaged with the DSSI instrument using the ARC 3.5-m telescope at APO. DSSI uses a dichroic to simultaneously measure the target with two filters, 690 nm and 880 nm. Table 2.1 shows the results used to plot each Δ mag point on the plots shown in Chapter 3. Each observation block of 1000 exposures with DSSI takes around five to ten measurements, which are then averaged to produce each point. The table will show the average Δ mag for each filter and observation block with associated uncertainties, as well as the median time in UT the observations in each block were taken. If "N/A" is entered in the error column, there is only one observation for that block.

2.4   Ellipsoidal Variations and Blended Eclipses

Several sub-systems in this thesis exhibit evidence of ellipsoidal variation. When two stars in a binary pair are very close together, they deform from a spherical shape to an elongated football shape as the mutual gravity pulls each star to the common barycenter, which changes the amount of light received with photome-

try. This is because when the stars are deformed, their surface luminosity and cross-sectional area changes, resulting in a sinusoidal variation in relative flux as observed from earth [Morris, 1985]. Figure 2.6 shows an example of this from the TESS curve of TIC 278465736. The smaller amplitude curves show the eclipses of the A system, and due to ellipsoidal variation of this system, the A system is functionally never out of eclipse.
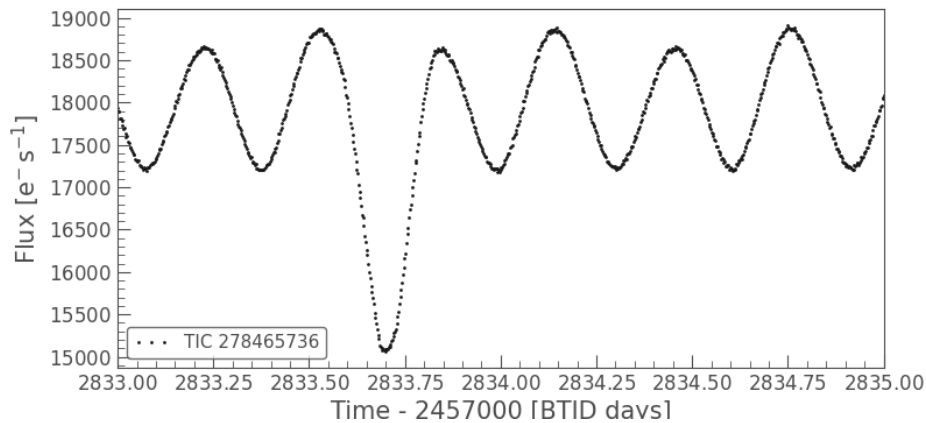

Figure 2.6: TESS Observation of TIC 278465736 showing ellipsoidal variation. The shorter depth eclipses show the A binary pair in eclipse, while the deeper eclipse is an eclipse of the B system.

This interference caused both by ellipsoidal variation and the short period of this system impacts the observed eclipses from the B system. We call this interference a blended eclipse. Because the A system is always oscillating in flux, any eclipse observed from the B system has components of the A system's change. For this particular system, the periods of the A and B sub-system are sometimes in phase, and sometimes not. This phase overlap impacts the depth of a B eclipse depending on what portion of the A eclipse occurs during the B eclipse.

Table 2.1: Speckle Imaging Data

TIC ID	UT Date(mm/dd/yy)	Time	Filter (nm)	Gain	avg. Δ mag	Error
367448265	9/29/2022	10:46	692	100	2.95	N/A
367448265	9/29/2022	10:46	880	100	2.64	N/A
367448265	3/9/2023	2:31	692	100	2.99	N/A
367448265	3/9/2023	2:31	880	100	2.64	N/A
367448265	9/4/2023	11:43	692	100	3.02	N/A
367448265	9/4/2023	11:43	880	100	2.71	N/A
367448265	2/24/2024	2:40	692	200	3.71	0.04
367448265	2/24/2024	2:40	880	200	3.37	0.03
367448265	2/24/2024	5:20	692	300	3.04	0.01
367448265	2/24/2024	5:20	880	300	2.71	0.01
367448265	11/15/2024	4:20	692	300	3.085	0.02
367448265	11/15/2024	4:20	880	300	2.753	0.01
367448265	11/15/2024	5:45	692	200	3.4	0.02
367448265	11/15/2024	5:45	880	200	2.99	0.03
367448265	11/15/2024	6:40	692	300	3.673	0.02
367448265	11/15/2024	6:40	880	300	3.28	0.01
367448265	11/15/2024	8:07	692	200	3.101	0.02
367448265	11/15/2024	8:07	880	200	2.72	0.01
367448265	11/15/2024	9:52	692	50	3	0.02
367448265	11/15/2024	9:52	880	50	2.69	0.01
367448265	11/15/2024	11:32	692	100	3.596	0.03
367448265	11/15/2024	11:32	880	100	3.32	0.05
278465736	5/28/2024	7:13	692	300	1.21	0.01
278465736	5/28/2024	7:13	880	300	1.06	0.02
278465736	5/28/2024	9:03	692	300	1.03	0.02
278465736	5/28/2024	9:03	880	300	0.91	0.03
278465736	5/28/2024	10:30	692	300	0.94	0.03
278465736	5/28/2024	10:30	880	300	0.78	0.02
470710327	10/19/2023	2:36	692	300	1.163	0.01
470710327	10/19/2023	2:36	880	300	1.109	0.006
470710327	10/19/2023	4:32	692	300	1.172	0.01
470710327	10/19/2023	4:32	880	300	1.122	0.01
470710327	10/19/2023	6:30	692	300	1.216	0.01
470710327	10/19/2023	6:30	880	300	1.157	0.02
470710327	10/20/2023	1:59	692	300	1.221	0.01
470710327	10/20/2023	1:59	880	300	1.157	0.01
470710327	10/20/2023	5:19	692	300	1.067	0.004
470710327	10/20/2023	5:19	880	300	1.03	0.008
470710327	10/20/2023	6:49	692	300	1.091	0.006
470710327	10/20/2023	6:49	880	300	1.084	0.01
470710327	10/20/2023	8:47	692	300	1.154	0.006
470710327	10/20/2023	8:47	880	300	1.117	0.003

Chapter 3

Results and Analysis

In this section we present the results of our analysis of the photometric differences obtained from speckle imaging during an eclipse of one EB pair in three TIC QEBs. The following plots show Δ mag and relative flux vs. time of three QEBs. For two out of the three systems, we have two independent measurements taken on different nights showcasing the same trend. Most of the observations listed were taken while one or both of the QEB subcomponents were eclipsing. If the timings for each eclipse have been verified by either newer TESS data or followup photometry, we know which sub-system (A or B) was undergoing an eclipse during the SIDE observations. Analyzing the relationship between Δ mag and relative flux of the eclipse will help us determine the related part of the system architecture by discovering how the QEB subcomponents compare with the speckle-resolved subcomponents. Currently, we only have data for one of the eclipses of each system, meaning we can only definitively assign that eclipse family to a speckle-resolved subcomponent. We need speckle imaging of the other binary pair eclipse to determine whether or not the second pair resides in the same speckle-resolved component, or if it is the other speckle component. Until it is known where all of the parts of the QEB lie, it is not possible to put an upper limit on the linear dimensions of the QEB and therefore understand how compact and susceptible to dynamical evolution and self-interaction the QEB is.

3.1   TIC 367448265

For this system, we have two separate observations of the A binary pair in eclipse, as well as older baseline points of the system out of eclipse. Figure 3.1 shows one

of the two plots we have for this system. The circular points with error bars are each observation block during eclipse taken on UT 2024 February 24, while the points marked with a star are previous observations of this system out of eclipse. These data strongly suggest there is an inverse relationship between Δ mag and eclipse depth. However, because there were only two observations made during an eclipse, there is not enough information to definitively assign this eclipse to the speckle-resolved secondary.
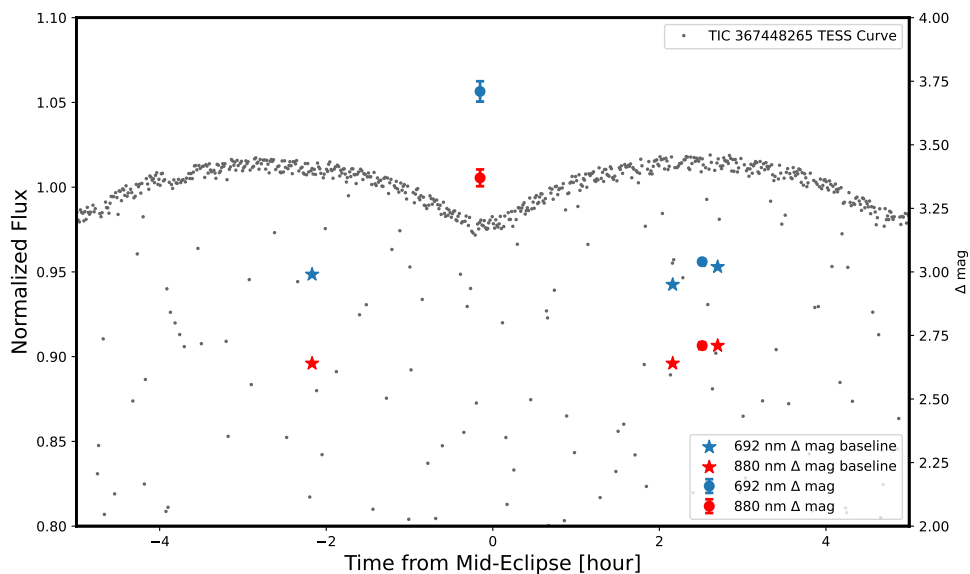

Figure 3.1: Δ mag vs. time for the TIC 367448265 Aα eclipse. The circular points are observation blocks taken on UT 2024 February 24 with associated errors (some error bars may be too small to see visually), while the star points are previous baseline observations taken on UT 2022 September 29, UT 2023 March 3, and UT 2023 September 4 of the system out of eclipse. The left-hand y-axis is normalized flux, where a value of 1 is seen when neither binary pair is in eclipse. The right-hand y-axis shows the difference in magnitude between the speckle-resolved subcomponents. Both axes are plotted against time from mid-eclipse, where zero is the middle of the eclipse. Note that some points of the TESS light curve do not line up nicely with the rest of the curve. This is an effect of period folding, where those points are artifacts of other eclipses that remain when the curve is folded.

To get a full characterization of this eclipse, we imaged it again with speckle on UT 2024 November 15. We took data before the Aα eclipse, and took additional data as the eclipse progressed. Due to the very short period of the A sub-system, we were able to get speckle data during the middle of the Aβ as well, which is shown by the points on the extreme right of the plot. Figure 3.2 shows these data
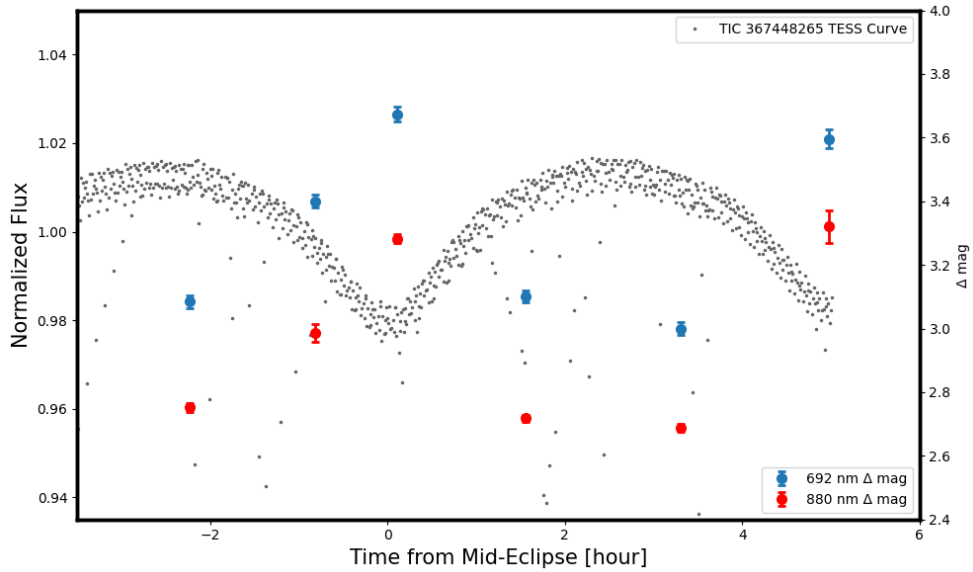
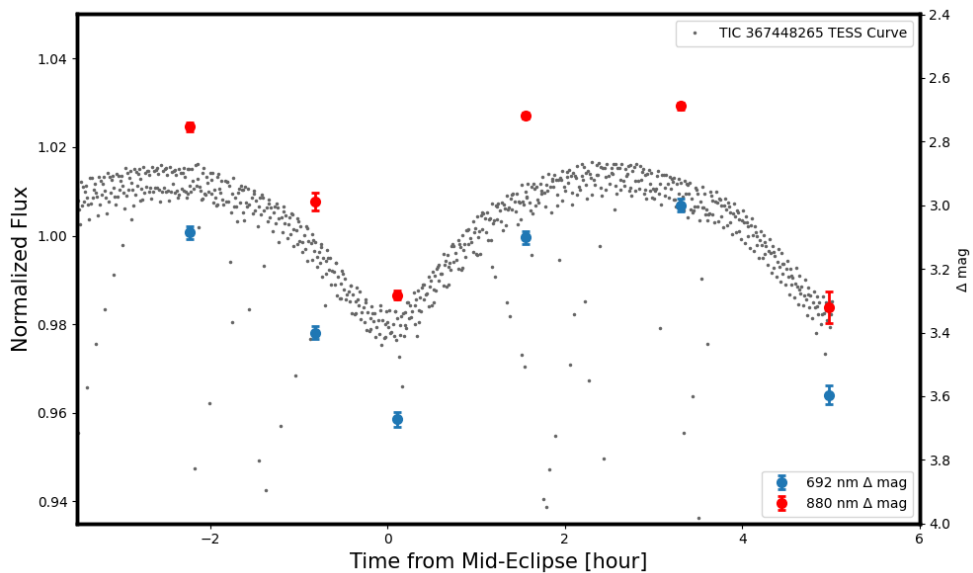Figure 3.2: Same as Figure 3.1, but all points are taken on UT 2024 November 15.

Figure 3.3: Same as Figure 3.2, but y-axis is inverted.

plotted against eclipse depth. With these data, the inverse correlation is clear, but it is difficult to interpret visually if the points logically follow the light curve.

In Figure 3.3, the y-axis is inverted to show better the trends of Δ mag, which follow the light curve well. These data clearly indicate that the magnitude difference between the speckle-resolved subcomponents increases as the eclipse occurs. With combined results, we can say with high confidence that the A sub-system of TIC 367448265 resides in the dimmer speckle-resolved component.

3.2 TIC 278465736

TIC 278465736 is a very interesting system for several reasons. First, this system exhibits very high ellipsoidal variation due to it's A system being so tightly bound. Second, the A subsystem has a very short period of 0.61421 days, meaning that there is an eclipse roughly every seven hours. Additionally, the eclipse has a duration of four hours, so the A subsystem is functionally never out of eclipse. This means that any eclipse observed of the B system will be heavily blended. We have gathered speckle data for both the A and B subsystems while in eclipse, however, the data for the B eclipse has yet to be fully analyzed, so the data discussed here will be solely for the A sub-system. Figure 3.4 shows our plot of speckle data with TESS photometry from SIDE observations taken on UT 2024 May 28.
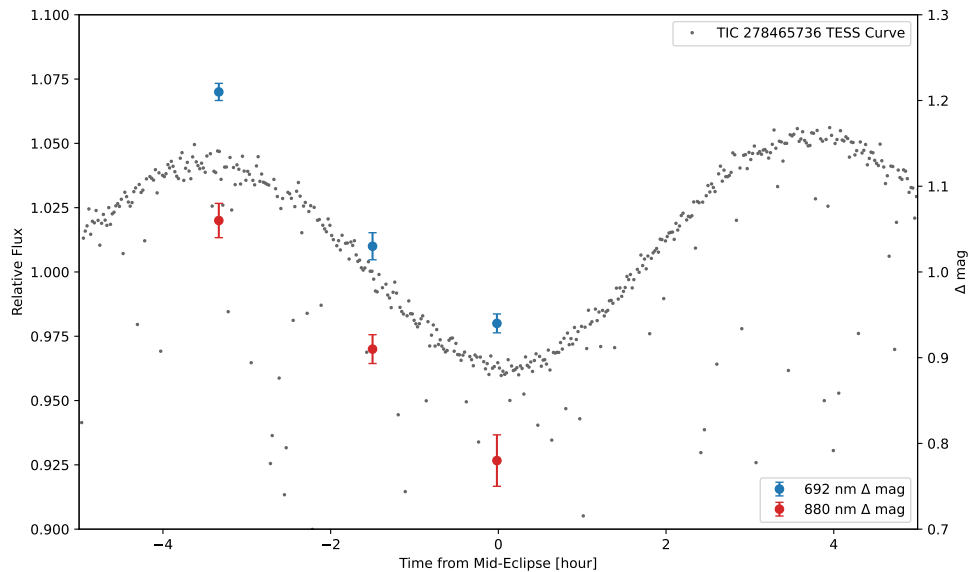

Figure 3.4:   Same as Figure 3.2, but for TIC 278465736 observed on UT 2024 May 28.

This plot clearly shows a direct relationship between Δ mag and eclipse depth. Using these data, we can confidently conclude that the A sub-system of the QEB corresponds to the brighter speckle-resolved primary. Due to the high ellipsoidal variation and blended eclipses, this system is interesting to study. Obtaining data for the B eclipse has proved challenging because it is impossible to isolate only

the B eclipse due to the A subsystem's short period.

3.3 TIC 470710327

For this system, we have two nights of SIDE observations of the Bα eclipse. These data are characterized and plotted in Majewski et al. (2025, in preparation). This comparison is useful because it plots the speckle data over the phase-folded TESS light curve, whereas in the upcoming paper, the data were plotted over a light curve from followup ground-based photometry. Figure 3.5 shows the speckle/photometry plot for SIDE observations taken on UT 2023 October 19, while Figure 3.6 shows the plot of speckle data from UT 2023 October 20 of the same eclipse.

These data clearly show a direct relationship between Δ mag and eclipse depth. With the large amount of data points, as well as different nights of observation, we can confidently state that the B sub-system of TIC 470710327 resides in the brighter speckle-resolved primary.
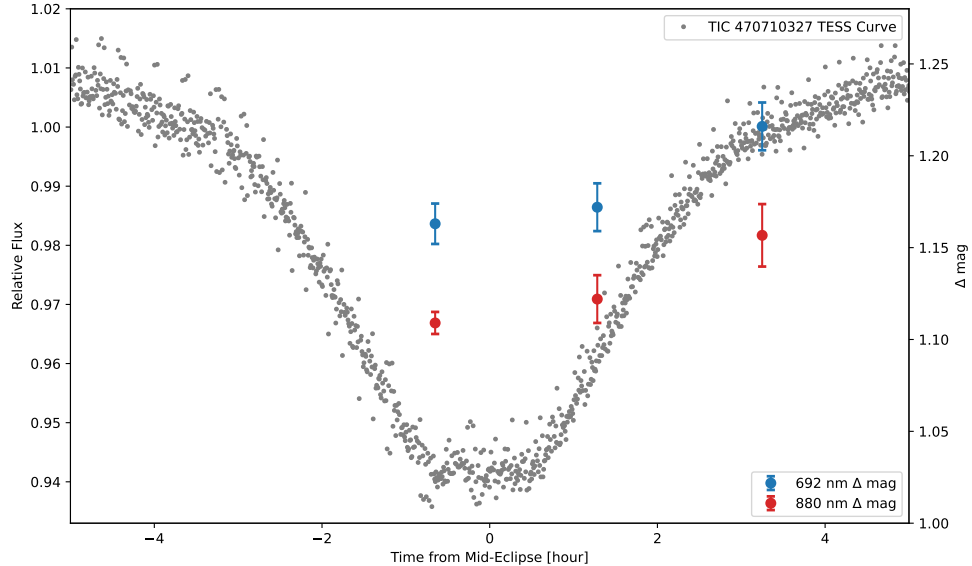

Figure 3.5: Same as Figure 3.2, but for TIC 470710327 observed on UT 2023 October 19. Note that the middle points were taken in poor conditions and are upper limits. This was the first attempt at dedicated SIDE observations, and the quality of the data are noticeably poorer than the other examples in this thesis.
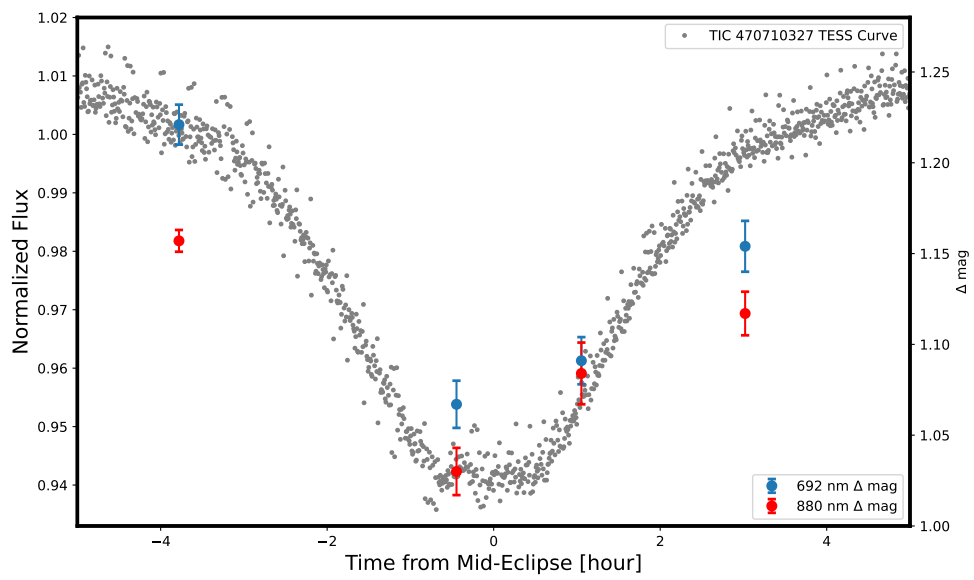
Figure 3.6: Same as Figure 3.5, but observed on UT 2023 October 20.

Chapter 4

Conclusion

4.1 Discussion

Quadruple eclipsing binaries are very intriguing systems for astrophysical research. Understanding their architecture can help us further our understanding of how tightly bound high-mass systems interact and and change dynamically over time.

The combined use of space quality photometric monitoring data and high resolution speckle imaging is a pioneering method in a full characterization of these systems. Using both methods of observations combined, we can accurately describe and model the architecture of these systems. This thesis presents the first systematic application of speckle imaging during eclipse applied to eclipsing binaries, and, specifically to the problem of assigning eclipse families to specific speckle imaging resolved sub components in quadruple eclipsing binaries discovered in TESS light curve data.

4.2 Future Plans

The overall goal of this project is to image all QEBs from Kostov et al. [2022, 2024] with contemporaneous photometry and speckle imaging. The Majewski collaboration is currently working to analyze the Kostov et al. [2022] catalog of QEBs. The author will work in conjunction with this collaboration in an attempt to fully characterize the Kostov et al. [2024] catalog of QEBs.

Many of these systems are highly complex, exhibiting eclipse timing variations, ellipsoidal variations, and blended eclipses. For these more complex systems,

further and more rigorous observation is needed. Future observations will revisit the QEBs discussed in this thesis to collect data during the eclipse of the other binary pair in order to fully characterize system architecture. We also plan to use the larger aperture Gemini telescope to get a smaller diffraction limit, enabling us to resolve more compact systems. With Gemini's 8-m telescopes, we could achieve a factor of 2x higher resolution. We are also using the Potsdam Echelle Polarimetric and Spectroscopic Instrument, PEPSI [Strassmeier et al., 2015] on the Large Binocular Telescope (LBT) to measure radial velocities and ascertain the motions of the stars in a QEB. We can use the radial velocities to solve Kepler's third law to determine the mass of the stars in the QEB. In addition to future observations, we can use the data obtained from imaging to model the system architecture. If we are successful in our efforts to observe and calculate the separation between the two binary pairs, we can begin modeling the system architecture and study how these systems self-interact, which could include mass transfer leading to Type 1a supernovae, cataclysmic variables, and many other astrophysical phenomena.

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