MODELING OF ECLIPSING BINARY CANDIDATES IN THE
NORTHERN SKY VARIABILITY SURVEY

A THESIS
SUBMITTED TO THE GRADUATE SCHOOL
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FOR THE DEGREE
MASTER OF SCIENCE
BY
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BALL STATE UNIVERSITY
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Abstract

THESIS:  Modeling of Eclipsing Binary Candidates in the Northern Sky Variability Survey

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DEGREE:  Master of Science

COLLEGE:  Sciences and Humanities

DATE:  December 2014

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In this thesis, I detail the methods I have used to reduce and analyze the data I have collected on two eclipsing binary systems from the Northern Sky Variability Survey:  NSVS 7322420 and NSVS 5726288.  These systems have not had any follow-up studies performed on them other than classification as potential eclipsing binary systems.  I present the data that I have collected as well as the results of my analysis of the data.  My analysis indicates that both systems are β Lyrae type eclipsing binaries.
I: Introduction

Binary systems form one of the greatest wells of knowledge for our understanding of stars. While observing solitary stars does provide insight to several characteristics of stars, observing binary systems offers a much richer selection of characteristics to study. Most importantly, Kepler’s Third Law allows the direct determination of the stellar mass of the system, something that is impossible to determine for a solitary star. Historically, this is what allowed astronomers to understand the relationship between stellar mass and characteristics such as the evolutionary state, temperature, and lifespan of the star (Kallrath & Milone 1999, pg. 2).

An important subclass of binaries is the eclipsing binary system, wherein one stellar component periodically eclipses the other. Eclipsing binary systems allow the determination of several characteristics that are otherwise difficult or impossible to determine without resolving the stellar components. These characteristics include the orbital inclination of the system as well as the shapes and radii of the component stars (Kallrath & Milone 1999, pg. 6-7). Due to the importance of eclipsing binaries, several models have been published to describe these systems, as described in Kallrath & Milone (1999). I have selected the Wilson-Devinney model (Wilson & Devinney 1971).

I.1: Eclipsing Binary Systems

Eclipsing binaries are a type of variable star. Variable stars exhibit changes in their apparent magnitude over time. The changes have a variety of causes and can be either periodic or non-periodic. In eclipsing binary systems, the orbital plane of the system is aligned such that
one of the stellar components passes in front of the other as seen from Earth. These periodic eclipses are what cause the variability of the system.

One way of classifying these systems is to use the concept of the Roche lobe. The Roche lobe is an example of a Roche surface, an equipotential surface wherein the combined rotational and gravitational forces are constant. The Roche lobe is the Roche surface that passes through the first Lagrangian point, the unique point between the stars where the gravitational and centrifugal forces exerted by each star are equal (Kallrath & Milone 1999, pg. 11). This equality means that there is no net force at that point in the rotating reference frame. A diagram illustrating the Roche lobe and first Lagrangian point is shown in Figure I-1. Binary systems can be broadly classified based on whether their component stars fill their Roche lobe or not, leading to three separate types of systems:

I. Detached system: Neither component fills their Roche lobe and therefore there is no mass transfer in the system.

II. Semi-detached system: One component exactly fills its Roche lobe, leading to mass transfer from the component filling its Roche lobe to its companion through the first Lagrangian point.

III. Over-contact system: Both components exceed their Roche lobe and are in physical contact with each other.
While these classifications are theoretically important, astronomers more commonly classify them by studying their light curve. A light curve, which is obtained by observing the system over a period of time, shows how the system’s brightness changes during the course of their orbit. The shape of the light curve is dependent on the characteristics of the system components, a fact which forms the basis of photometric modeling. Systems can be broadly separated into three different categories based on their light curves, examples of which are shown in Figure I-2:

---

1 Source: http://www.wallentinsen.com/binary/Ch1_Introduction.htm
I. Algol type: Their light curves are flat topped, with minimal variation outside of eclipse. The eclipses are sharp, well-defined, and of unequal depth, indicating that the stars do not have the same temperature. They are typically detached or semi-detached systems.

II. β Lyrae type: Their light curves change smoothly and continuously. The eclipses are broad and their boundaries poorly defined, but they are of unequal depth, indicating that the stars do not have the same temperature. They can be detached, semi-detached, or over-contact systems.

III. W Ursae Majoris type: Their light curves change smoothly and continuously. The eclipses are broad, poorly defined, and of nearly equal depth, indicating that the stars have nearly the same temperature. They are typically over-contact systems.

Figure I-2²: Sample light curves of the three eclipsing binary types.

² Source: http://www.vs-compas.belastro.net/bulletin/issue/2/p6
I.2:  Northern Sky Variability Survey

The Northern Sky Variability Survey, or NSVS, was a comprehensive survey of the northern sky conducted to record stellar variations of faint objects (Woźniak et al. 2004). The survey, which was conducted between April 1, 1999 and March 30, 2000 at Los Alamos National Laboratory, imaged 14 million objects north of declination -38° with magnitudes between 8 and 15.5. There were typically a few hundred measurements taken for each object, creating a strong base set for searching for variability. The telescopes used in the survey were small, which limited photometric precision, but the precision was great enough to allow for the identification of variable stars.

Due to the enormous volume of data, many systems in the NSVS have not had follow up studies performed, but there has been some work cataloguing systems based on the NSVS data set itself. One such example is the work done by Hoffman et al. (2008), who identified 409 candidate Algol and β Lyrae systems in the NSVS. It is from these candidates that I chose my two targets: NSVS 7322420 (henceforth Target A) and NSVS 5726288 (henceforth Target B). I chose these targets because of their favorable position in the sky at the time I began my observations as well as the fact that they were relatively bright compared to other candidates I looked at. Some relevant information about each target is provided in Tables I-1 and I-2; the Johnson B and V magnitudes are from by Kharchenko & Roeser (2009) while the rest of the information is from Hoffman et al. (2008).
### Table I-1: Select properties of Target A.

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<td>Orbital Period (d)</td>
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### Table I-2: Select properties of Target B.

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\(^3\) Time of minimum light
II: Observations

Observations of my targets were carried out between March, 2013 and October, 2014 (exact UT dates are listed in table II-1). These observations were performed at two sites: the Ball State University Observatory (BSUO) and Kitt Peak National Observatory (KPNO). Images were taken in four different filters: Bessel B (blue), Bessel V (visual or green), Bessel R (red), and Bessel I (infrared). There was a brief period in late April, 2013 in which data was not taken in the B filter due to tracking issues. These tracking issues were more pronounced in the longer duration exposures used with observing with the B filter. Phased light curves of the data I have taken on my targets are shown in Figures II-1 and II-2.

II.1: Ball State University Observatory

The Ball State University Observatory is located on the campus of Ball State University in Muncie, Indiana. While light pollution from the city affects the quality of data, the site proved suitable for my research.

The instrument I used was a 16” diameter Meade LX200, which was outfitted with a STXL-6303E CCD camera. The telescope was controlled using the computer program The Sky 6, which allowed us to move the telescope to any point in the sky using a real-time virtual representation of the sky. The camera was controlled with MaxIm DL Pro 5. Both of these programs were controlled by a master program, CCDAutoPilot 5, which also allowed a sequence of exposures to be set up.
Initially, the images were binned 1x1, which is to say that each pixel was individually read out. The exposure lengths during this time span were 120, 60, 40, and 60 seconds for the B, V, R, and I filters, respectively. Beginning in the middle of June, 2013, I began binning the images 2x2, which is to say that four pixels are grouped together into a single pixel chunk and read out. This increased the S/N ratio for a given exposure length and therefore reduced the exposure lengths to 60, 40, 30, and 40 seconds. I did this primarily to increase the temporal resolution of the observations by reducing the exposure length and readout time of the chip.

II.2: Kitt Peak National Observatory

Kitt Peak National Observatory is located approximately fifty miles southwest of Tucson, Arizona. Due to its remote location, there is little light pollution to interfere with astronomical observing.

The instrument I used was the 0.9-meter telescope owned by the SARA (Southeastern Association for Research in Astronomy) Consortium, of which Ball State University is a member. The telescope is outfitted with a CCD camera custom built by Astronomical Research Cameras, Inc. (ARC) as well as an Eschelle spectrograph also built by ARC. The computer program used to control the telescope were custom made by Astronomical Consultants & Equipment Inc. for use with the SARA telescope. The program moves the telescope and dome in sync and allows for setting up observing sequences.

The images were binned 2x2 for all nights of observation from this site with exposure lengths of 35, 20, 15, and 20 seconds for the B, V, R, and I filters, respectively. In addition, an
attempt was made using the spectrograph on Target A with an exposure length of an hour. The target was too faint, and the resultant image showed no hint of spectrographic features.

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<td>A</td>
</tr>
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<td>BSUO</td>
<td>A</td>
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<td>4/4/13</td>
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<td>4/5/13</td>
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</tr>
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</table>

Table II-1: A list of dates of observation along with the location and target of the observations.
Figure II-1: Phased light curves for B-, V-, R-, and I-band data on Target A. Error bars are plotted for all data points with phase between −0.5 and 0.5, but on this scale they are negligible. The vertical axis shows the differential magnitude in the given band, while the horizontal axis shows the orbital phase of the system. This data is only the subset of data taken from November 29, 2013 to January 29, 2014 for reasons that will be explained in section VI-1.
Figure II-2: Phased light curves for B-, V-, R-, and I-band data on Target B. Error bars are plotted for all data points with phase between −0.5 and 0.5. The vertical axis shows the differential magnitude in the given band, while the horizontal axis shows the orbital phase of the system. This plot includes all data I have taken on Target B.
III: Data Reduction and Analysis

In order to model my targets, I first had to reduce and analyze the data produced by my observations. The reduction process was performed in the Image Reduction and Analysis Facility\(^4\), or IRAF, which is freeware developed and distributed by the National Optical Astronomical Observatory specifically for image reduction. The reduction process served to create uniform images that were suitable to perform photometry. This was done by using flat field, dark, bias, and fringe correction images to reduce the number of defects created by imperfections in the observation process. I will describe this process in detail in the following sections.

Once the reduction process was completed, I used the software Astronomical Image Processing for Windows\(^5\), or AIP4Win, to perform photometry on my images and produce a light curve. I then performed heliocentric correction (see section III.7) and converted the data to be a function of system phase (see section III.7), allowing me to combine observations from separate nights into one set of data. It was this final set of data that I then used in the modeling process. I also used other programs to analyze other aspects of the data I collected; these programs will be covered at the end of this section.

III.1: Overscan and Image Trimming

The overscan region of a CCD chip is a region on the output images that do not correspond to a physical location on the chip. Rather, the region is generated by clocking the

\(^4\) http://iraf.noao.edu/  
\(^5\) http://www.willbell.com/aip4win/aip.htm
output device after the image has been read out, essentially reading out a subset of pixels a
second time after they had been depleted of charge by the first readout (Howell 2006, pg. 53).
The pixels in this region can then be used to assist bias correction by giving a representative
average of the bias level for that particular image. Bias frames (described in the next section) are
still needed to correct for patterns in the bias level that the overscan region cannot account for.

The CCD used on the SARA telescope had an overscan region programmed into the
device, but some issues with the device clocking made it infeasible to use this capability. It was
still necessary to trim the overscan region off of my images as they were not a usable region of
the image. In order to determine what the overscan region on the output image was, I used the
IRAF command implot. An implot of an image displays the analog-to-digital unit (ADU) count
of all the columns in a given row or all the rows in a given column in that image. The overscan
region can be identified as the region in which the counts drop from high-level region containing
both the bias level and the sky background to a low-level region containing only the bias level.
Other artifacts such as unusable columns or rows can be identified in this manner as well,
allowing the complete determination of the usable area on the image.

Once the region has been determined, the information must be added into the image
header so that it can be used by IRAF. This is done using the command hedit, or header edit.
The usable region is entered in the format \([x1:x2,y1:y2]\) into the header field trimsec. For my
images, I found the usable region to be columns 3 to 997 and rows 2 to 1024. I therefore inserted
the value \([3:997,2:1024]\) into the header file. With this field now present in the header, the
subsequent steps would automatically trim the images as needed during execution.
III.2: Zero Correction

The bias is a positive offset value added to each image in order to prevent a negative value in the output image (Howell 2006, pg. 52). The overscan region can assist with zero correction by determining the average bias level, which can vary throughout an observing session. However, there are also pixel-by-pixel variations that the overscan region cannot account for, and in order for full zero correction, it is necessary to take bias exposures.

A bias exposure is a zero second exposure, which is to say that the unexposed chip is simply read out (Howell 2006, pg. 53). Since there is no exposure, the ADU values read from the chip are due only to the bias offset and the pixel-by-pixel variation in the offset. The bias offset is an additive effect (Massey 1997, pg. 2), meaning that these values can be subtracted from the exposures, effectively eliminating the bias offset from them.

I took approximately thirty to sixty bias exposures each observing session in order to obtain a representative average. To combine these separate images into a single master image, I used the command zerocombine, which averaged all images with the image type “zero” together. The zerocombine command ignores the highest valued image for each pixel with the settings I chose, which reduces the chance of a cosmic ray interfering with my images (Massey 1997, pg. 12). The master image created from this procedure (a sample of which is displayed in Figure III-1) was subtracted on a pixel-by-pixel basis from all remaining images using ccdproc.
III.3: Dark Correction

Dark current is the current generated by thermal fluctuations in the CCD chip. This current is strongly dependent on CCD temperature, necessitating the cooling of the CCD to minimize its effect on the data (Howell 2006, pg. 47). It is impossible to completely eliminate the dark current as the thermal fluctuations are present in any system above absolute zero. The detector at KPNO was operated at a low enough temperature that the dark current was negligible; however, the detector at the Ball State University Observatory had a non-negligible dark current that required dark correction. In order to perform dark correction, I needed to take dark exposures during my observing sessions.
Dark exposures are long duration exposures performed while the shutter is closed, ensuring that the only signal is due to a combination of the dark current and the bias offset. With the bias signal removed, all remaining counts were due to the dark current, which allowed these counts to be subtracted from later images. To ensure that phenomena such as cosmic rays do not affect the final images, multiple images are taken and then combined with a median filter. The duration of the exposures are equal to that of the longest duration exposures of that session. The master dark image is linearly scaled to the exposure length of each image during processing.

I typically took six dark exposures each session, three at the beginning of the session and three more at the end. To combine these separate images into a single master image, I used the command darkcombine, which combined all images with the image type “dark” together. As with the bias images, the highest valued image for each pixel is ignored. The master image created from this procedure (a sample of which is displayed in Figure III-2) was subtracted from all remaining images using ccdproc.
A CCD chip is not a perfect device, and therefore the gain and sensitivity differ from pixel to pixel. In addition, artifacts such as out-of-focus dust on the filter can cause further variation across the image. These variations are multiplicative in nature and must be divided out of each image in order to obtain usable photometry from the image. To make this correction, it is necessary to take flat field exposures (Howell 2006, pg. 67).

Flat field exposures require bright and uniform illumination of the CCD chip in order to emphasize the defects in the image. One method to accomplish this is to project a bright light onto a flat screen located in the dome and then take exposures of the screen, a process known as
*dome flats*. Another method is to take exposures of the twilight sky, a process known as *sky flats*. For my research, I utilized the latter approach.

In order to obtain suitable flats, the exposures had to have enough counts to ensure a high signal-to-noise ratio while being short enough in duration so as not to infringe on observing time. These two requirements can be simultaneously satisfied by exposing during a short period immediately following sunset or immediately preceding sunrise. This period, only a few minutes in length, is therefore one of the most crucial periods of an observing session.

I typically took between three and ten sky flats per filter each observing run. While continuing to track, I shifted the telescope between each exposure in order to move the background star field, allowing me to remove the stars using a median filter. To combine these separate images into a single master image, I used the command flatcombine to make a master flat image for each filter from the flats taken during that session; such a master flat image is shown in Figure III-3. Each remaining exposure in a given filter would then be divided by the appropriate master flat image using ccdproc. This division is scaled according to the mean ADU counts of the image being corrected and the mean ADU counts in the master flat image.
Figure III-3: Sample master flat image, B filter.

III.5: Fringe Correction

Fringing is the name for a pattern of fringes caused by interference between reflected light waves within the CCD (Howell 2006, pg. 83). These reflections occur due to the fact that silicon is nearly transparent to infrared radiation, and so reflections occur in the interface between air and the chip. The light waves produced by these reflections then interfere constructively and destructively with each other, causing the characteristic fringing pattern to appear in the final image. This pattern causes the image to be non-uniform, so it must be corrected. The effect is most prominent in longer wavelengths, particularly affecting the infrared region. The radiation that causes the fringing primarily comes from forbidden OH transitions in
Earth’s upper atmosphere (Howell 2006, pg. 85) rather than from an extraterrestrial source, which causes the intensity of the fringing pattern to vary during the night.

The fringing pattern for a given CCD is constant for a given wavelength (Howell 2006, pg. 84), so only a single correction image is needed for a given device and filter. To create this correction image, I exposed the night sky for a duration of 100 seconds before shifting the telescope and taking another exposure. I repeated this process over three separate observing sessions and combined the best images using the command imcombine, which used a median filter to remove the stars and leave only the fringing pattern. To make this combined image into one suitable for removing the effects of fringing, I used the command mkfringe.

The mkfringe command removes the sky background average so as to leave only the fringing pattern. The background average is determined using a particular smoothing algorithm known as the “boxcar” average. This algorithm uses a variably sized box that averages all the values inside the box and subtracts it from the center pixel. The box is smallest at the edge of the image, which allows for a better representative average at these points, and is largest near the center of the image, which allows for large scale smoothing that better captures the fringing pattern. A sigma clipping algorithm detects and excludes any pixels that are a specified number of standard deviations above or below the background average from the smoothing algorithm, allowing the fringing pattern to remain. Therefore, the final image contains only the fringing pattern. This master fringe correction image (shown in Figure III-4) is then subtracted during the reduction process from each exposure taken in that filter (IRAF help file). This subtraction is scaled according to the exposure length of the image being corrected and the images used to create the master fringe correction image.
III.6: Data Reduction

The final step is to reduce the object images. This is done using the command ccdproc, which, for each object image, trims the image, subtracts the master bias and dark images, divides by the appropriate flat image, and subtracts the fringe correction image if applicable. This produces images with a flat, uniform background that is suitable to perform photometry.
III.7: Photometry

Photometry is the process of determining the luminous flux of an object and if and how it varies with time (Howell 2006, pg. 102). If the flux is found to vary, then each measurement of flux can be plotted against the time the measurement was taken in a plot called the light curve. The light curve is a rich source of information on an astronomical target, and for the purposes of my research it was the end goal of performing photometry.

There are various methods and programs that can be used to produce a light curve. The program that I used is called the Astronomical Image Processing for Windows, or AIP4Win for short, which is a licensed software designed for performing photometry. The method that I used was differential aperture photometry, which is a combination of two separate techniques: aperture photometry and differential photometry. The first technique is used to determine the flux of an object while the second technique allows for a more consistent determination of the flux for reasons explained below.

Aperture photometry uses three concentric rings or apertures. The innermost ring is the region that contains the variable source, and the analog device unit (ADU) counts in this region are summed up and stored. The region between the innermost and middle ring is ignored by the program so as to exclude excess light from the source. The middle and outermost rings define the sky region, in which a per-pixel average for the sky background is calculated and then subtracted from the counts in the inner region. This leaves only the counts from the source, which is used as the flux for the variable.

Differential photometry compares the counts from the variable to one or more comparison stars in the same field of view. Calculating the difference in flux between the
variable star and a comparison star provides a more consistent measurement than only calculating the flux of the variable because, while the flux from each object will vary due to weather conditions and the amount of air the light has to pass through to reach the detector, the difference in the flux between two objects should remain constant, excepting any intrinsic variability in the objects. This is because the objects are located close to each other in the sky and should therefore be similarly affected by conditions that affect the flux. This assumes that the objects are in fact close to each other in the sky, an assumption that holds for my observations. I selected two comparison stars for each of my targets.

Once the apertures are selected, the program is set into motion. The aperture photometry sums the counts from the variable and each comparison star. The differential photometry compares the counts from the variable to the counts of the first comparison on an image-by-image basis, outputting the difference in their counts as a magnitude, which is a measure of the flux of an object. It also compares the counts of the first comparison star with the counts of the second comparison star in order to determine that neither are variable. While it is possible that both stars are variable, it is exceedingly unlikely that they would have the amplitude, frequency, and phase necessary to perfectly cancel the variability, and so this is a satisfactory method to determine that the stars are not variable. The information that I am interested in is the differential magnitude of my variable with the first comparison, the error in this magnitude, and the Julian date of the observation, which is read from the image header.

The final step is to convert the data to heliocentric Julian date. This heliocentric correction takes into account the position of Earth in its orbit and how this affects light travel time from the source to the instrument (Henden & Kaitchuck 1982, pg. 113-114). In order to make this correction, I used a program written to perform this task (Ronald Kaitchuck, private
This program simultaneously converts the data to be a function of phase. This is done by providing a time of minimum light as well as the period of the system, both of which are found by means I will describe in the next few sections. The program then finds the fractional part of the difference between the HJD of the given time of minimum light and the time of observation, and then divides this difference by the period of the system. If the HJD of the observation is less than the given time of minimum light, this fraction is subtracted from unity. The value obtained is then added to the UT at the time of observation divided by the period of the system in hours, giving the phase at the time of observation (Henden & Kaitchuck 1982, pg. 263). With this finished, modeling using the Wilson-Devinney code can begin.

III.8: Period Search

I used the output from AIP4Win in the period search program Peranso\(^6\). Peranso is a shareware program that combines several different period analysis methods into a graphical user interface. Peranso imports photometric data and allows the user to run a period analysis using any of several methods included with the program. It then displays the results graphically, using the most significant found period to convert all the data into a phased curve. The user can manipulate the period to see how the phased curve changes with the period.

For my targets, I used the analysis of variance, or ANOVA, method to determine periodicity. The ANOVA method, as described by Schwarzenberg-Czerny (1996), uses periodic orthogonal polynomials to fit a period to the observations, then uses the analysis of variance statistic to determine how well the period fits the observations.

---

\(^6\) http://www.peranso.com/
Once the data is imported and the ANOVA method selected, the next step is to define the shortest and longest periods to try as well as the resolution, which defines the step size. The program will then test all periods in that range with a step size given by the equation:

\[
\text{Step} = \frac{P_{\text{long}} - P_{\text{short}}}{\text{Resolution}}
\]  

(III.1)

The program then graphically displays the significance of these tested periods, allowing the user to select the most significant period. The user may open another window that displays the phased light curve for the selected period, allowing the user to qualitatively see how well the observations fit a particular period. The program gives the period as well as the error associated with the period.

### III.9: Other Tools

I used several other tools to supplement my data analysis and assist in the modeling process. Many of these tools were primarily aimed at determining the effective temperature of my targets, as I had no access to spectroscopic data that would allow me to directly determine that information. In addition, one of the tools allowed me to determine the time of minimum light from my data, which allowed me to correctly set my data such that the deepest point of primary eclipse occurred at phase zero.

The first tool was written to determine the time of minimum light for an observation as well as the error associated with that measurement (Robert Berrington, private communication, 2014). He based his program on the technique presented by Kwee and van Woerden (1956), which I shall briefly describe. From the observed data points, one point \((T_1)\) is chosen as the estimated time of minimum light. An interval of time \(\Delta t\) is then chosen, and all points in the
interval \((T_1, T_1 + \Delta t)\) are reflected across \(T_1\) to coincide with the points on the interval \((T_1, T_1 - \Delta t)\). The difference between each pair of points is then computed, as is the sum of the squares of the difference, \(s(T_1)\). This process is repeated to find \(s(T_1 + \Delta t/2)\) and \(s(T_1 - \Delta t/2)\). Then a new function \(s(T)\) is defined:

\[
s(T) = aT^2 + bT + c
\]  \(\text{(III.2)}\)

The constants \(a\), \(b\), and \(c\) are computed using \(s(T_1)\), \(s(T_1 + \Delta t/2)\), and \(s(T_1 - \Delta t/2)\). The minimum value of the function is found by taking the derivative of the function \(s(T)\) with respect to \(T\), setting the derivative equal to zero, and solving for \(T\). This \(T\) is the time of minimum light that the user is looking for, and the uncertainty in the result is given by:

\[
\sigma_{T_0}^2 = \frac{4ac - b^2}{4a^2(Z - 1)}
\]  \(\text{(III.3)}\)

where \(Z\) is the maximum number of independent pairs of observed points. Dr. Berrington’s program displays the data graphically, allowing the user to select \(T_1\) based upon the shape of the light curve. Once \(T_1\) and \(\Delta t\) are selected, the program calculates the time of minimum light and associated error.

The next tool was written to determine the \((B - V)\) color index of the selected star (Robert Berrington, private communication, 2014). To accomplish this, the program reads in a modified version of the AIP4Win output file that includes only the heliocentric Julian date of the observation, the differential magnitude of the system, and the error in the magnitude. From this data, the user inputs given values for the apparent magnitude of the comparison star determined from the literature, which is then added to each observed data point to give the apparent magnitude of the object at the HJD of observation; the error in the observation is added in quadrature to the error given for the measurement of the comparison star. The program then compares data taken in two different filters, which in the case of my research was the B and V filters. Since the observations in the B and V filters did not occur simultaneously, the
observational values from the B filter are linearly interpolated to coincide with the values for the V filter. The difference between the interpolated B data and observed V data are then displayed as a function of phase, giving the user the \((B - V)\) values as a function of phase. For my research, I used the \((B - V)\) value at phase 0.5 to determine the temperature of the primary component and the value at phase 0.0 to give a starting value for the temperature of the secondary component. The eclipses in my systems do not appear to be total eclipses, meaning that light from the secondary star is present during primary eclipse. As a result, the \((B - V)\) index at phase 0.0 is an average of the two stars weighted by the surface area visible for each star, and therefore the value at this phase is only an approximation of the \((B - V)\) index for the primary component. The error in this measurement is found by adding in quadrature the given errors for the B and V magnitudes of the comparison star with the average error in the differential magnitude for the B and V data output by AIP4Win.

Before converting the \((B - V)\) color index into an effective temperature value, I first had to account for interstellar reddening. Interstellar reddening is caused by absorption of short wavelength radiation by dust particles that exist in interstellar space. This absorption serves to increase the \((B - V)\) color index by removing blue light. The amount of dust varies based upon where in the sky observations are being carried out, so in order to make the correction, I used research conducted by Schlafly and Finkbeiner (2011) to give me the estimated correction for interstellar reddening at my target coordinates. Once the correction had been made, I used a source\(^7\) that allowed me to convert the \((B - V)\) color index of my target into an effective temperature based upon the research of Flower (1996). The error in this measurement is found by adding and subtracting the error in the \((B - V)\) index to the actual \((B - V)\) index, converting these values to temperature, and subtracting the average of these from the assumed temperature.

\(^7\) http://www.uni.edu/morgans/stars/b_v.html
IV: Modeling

A model is a set of mathematical and physical relations that relate a set of physical parameters with an observed light curve. Modeling, then, is the process of using a model to determine the characteristics of a system by using the observations of that system. There are two concepts associated with this: the direct problem, in which a set of input parameters is used to create a light curve, and the inverse problem, in which a light curve is used to derive a set of parameters. The inverse problem is more pertinent to my research, but I will briefly discuss the direct problem as well.

IV.1: The Direct Problem

The direct problem deals with taking a set of parameters \( x \) and from it generate an observable curve \( O \) (Kallrath & Milone 1999, pg. 51). An observable is an orbital phase dependent quantity such as flux or radial velocity. Observables can be plotted against phase to create an observable curve, e.g. a light curve. Solving the direct problem is a necessary step in solving the inverse problem, as if the model cannot generate a realistic light curve, its underlying assumptions are questionable at best. Any realistic model that can solve the direct problem has three fundamental components:

I. The geometry of the system. This includes the orbital inclination and eccentricity as well as the sizes and shapes of the stellar components.

II. The stellar radiative properties. This includes effects such as gravity brightening, limb darkening, and effects from the stellar atmosphere.
III. The flux as seen by the observer. This takes into account the eclipses as well as environmental effects such as circumstellar material.

For a more in-depth mathematical formulation of the direct problem, I would refer the reader to chapter 3 of Kallrath & Milone (1999). For this thesis, it is sufficient to state that, using reasonable models for the components listed above, it is possible to create an observable curve when given a set of parameters to generate it. This observable curve can be plotted alongside the curve generated from observational data as a comparison, allowing the modeler to visually check that the parameters given from the inverse problem compare reasonably to the observed data.

IV.2: The Inverse Problem

The inverse problem deals with taking an observable curve $O$ and from it generate a set of parameters $x$. The problem can be solved by performing a least-squares fit between the observed and calculated observable curves (Kallrath & Milone 1999, pg. 137) with the objective of minimizing the deviation between the two. The best fit to the data occurs when the deviation is minimal, and it can then be inferred that the parameters that produce the best fit are representative of the parameters of the binary system being studied. It is in this way that we can determine the parameters of an eclipsing binary system by studying the light curve of the system.

Mathematically, the observable curve $O$ is a set of $n$ elements of the form $(t, o)$, with $t$ serving as the independent variable time and $o$ serving as the associated observable (Kallrath & Milone 1999, pg. 49). The observable $o$ is itself a function of $t$ and the parameter vector $x$ (Kallrath & Milone 1999, pg. 51). Solving the inverse problem involves varying $x$ such that the
variance between the calculated observable curve $O_{\text{cal}}$ and the observed curve $O_{\text{obs}}$ is minimized (Kallrath & Milone 1999, pg. 139). The objective of the process is to achieve a global minimum $x^*$ of the variance. This global minimum is then assumed to reflect the actual parameters of the system under study.

For an astronomer, the parameter vector $x$ includes all relevant information of the system, including orbital inclination, eccentricity, and stellar temperature. In order for a full determination of system characteristics a full light curve and a radial velocity curve for both components are required. The reason for this is that, without radial velocity data, it is impossible to determine the absolute masses of the components, and hence only relative quantities can be determined. Without a light curve, the inclination of the system cannot be determined, and so the mass of each component cannot be found.
V: Wilson-Devinney Model and PHOEBE

Numerous models have been produced in an attempt to better characterize eclipsing binary systems. The first such model was the Russell-Merrill model published in 1952. This and other early models contained many simplifying assumptions, most notably that the component stars were spherical or ellipsoidal in shape (Kallrath & Milone 1999, pg. 186). The simplicity of these models was a major asset in which the models were introduced since ellipsoidal geometry is much easier computationally to work with. Unfortunately, these assumptions only hold for widely separated components, and as a consequence these early models often failed to provide reasonable results for semi-detached and over-contact binaries (Kallrath & Milone 1999, pg. 16).

More sophisticated models began to be produced in the early 1970s. These models, aided by the increasing availability of computers, were based on using Roche geometry instead of the ellipsoidal geometry of earlier models. This geometry, while more difficult to work with, is much more realistic in systems where the stars are distorted. In addition, models began to use a least-squares fit to determine the parameters of the light curves, which provided a more rigorous mathematical basis for the models. One of the first models of this new generation was the Wilson-Devinney model (Kallrath & Milone 1999, pg. 17).

V.1: The Wilson-Devinney Model

The Wilson-Devinney model was introduced in 1971 by Robert Wilson and Edward Devinney. The model is “identical [to] the classical Roche model for close binaries in
synchronous rotation.” (Wilson & Devinney 1971) Where it differed from previous models was the inclusion of an iterative least-squares analysis that was aimed at solving the heretofore intractable inverse problem.

Since its inception, the Wilson-Devinney model has been modified to incorporate many parameters. The parameters most pertinent to my research include:

- Orbital inclination: The inclination of the system’s orbit relative to the plane of the sky. An inclination of 90° would indicate that the geometric centers of the components would coincide during eclipse while an inclination of 0° would indicate that we are viewing the system from directly above or below the poles of the components.

- Mass ratio: The ratio of the masses of the stellar components, defined as the secondary component’s mass divided by the primary’s.

- Luminosity: The total energy radiated from the component stars per unit time.

- Effective temperature: The temperature of an ideal blackbody that has the same radius and luminosity as the stellar component.

- Surface potential: The modified Kopal potential that defines the surface, and therefore the size and shape, of the component.

- Surface albedo: The ratio of radiated energy to incident energy.

- Gravity brightening: Variation in local surface brightness caused by oblateness and tidal distortion.

- Limb darkening: Variation of the observed flux across the component’s surface due to the light’s passage through a greater stellar atmospheric mass at the edge of the disk.
V.2: PHOEBE

PHOEBE\(^8\) (Prša & Zwitter 2005), or PHysics Of Eclipsing BinariEs, is a graphical user interface program that is based upon the Wilson-Devinney program. It was released by Andrej Prša in 2002 with the intent of providing a free, open-source graphical interface for the Wilson-Devinney code. The program was run on the Ball State CCN cluster, which was accessed using a remote desktop connection.

The first step in using PHOEBE is importing the photometric data. The optical filter the data was taken in is specified at this point, which allows for the determination of the surface temperature of the components. Once the data has been imported, the user chooses the particular model constraints to apply to the data. These constraints are built into the Wilson-Devinney code and constrain certain parameters to simplify the modeling process. Determining which system of constraints to use is typically done by inspecting the light curve, which often indicates the type of system being modeled. For Target A, I chose for the final model the semi-detached system in which the primary component fills its Roche lobe. The only constraint this option imposes is that the potential of the primary component is set equal to the potential of its Roche lobe (Kallrath & Milone 1999, pg. 206). For Target B, I chose the unconstrained system, which imposes no constraints on the solution.

With those tasks completed, the modeling process may begin. The luminosities of the components are the first parameter to be adjusted as this creates the first synthetic light curve. Beyond this, the modeling process involves adjusting the various parameters of the system incrementally, either together or individually. The user may at any point plot the synthetic light curve against the observed data to compare how well the model fits. To gain a more rigorous

\(^8\) http://phoebe-project.org/1.0/
understanding of how well the model fits, the user may also plot the residuals, which is the difference between the synthetic and observed light curves. Once the synthetic and observed light curves fit acceptably well to the user, the values of the parameters for the model are recorded. The error in the values can be found from the output files from PHOEBE.
VI: Results

VI.1: NSVS 7322420

The modeling process for Target A was problematic. The reason for this difficulty is twofold. First, the structure of the light curve is changing in that the observed differential magnitude at a given phase can be significantly different in data taken several months apart. This forced me to use only the data I took from November 29, 2013 to January 29, 2014, as the changing light curve made it impossible to combine all of the data into one set in any usable fashion. Second, the light curve itself has several peculiarities that make the system more difficult to model. The maxima between eclipses are of unequal height, a feature that is known as the O’Connell effect (Milone 1969) and which is typically explained by a hot or cool spot on the surface of one of the components (Wilsey & Beaky 2009). In addition, the secondary eclipse features an abrupt jump in the light curve that indicates a sharply defined surface being occulted. The most likely explanation for this feature is an accretion disk around one of the components (Ronald Kaitchuck, private communication, 2014) which, taken together with the O’Connell effect and the period shift, indicates that mass is being transferred from one component to the other. The Wilson-Devinney code, and by extension PHOEBE, is unable to model an accretion disk, making it difficult to find a solution to the inverse problem.

My primary and secondary comparison stars have the designation of TYC 1936-1001-1 and TYC 1936-113-1, respectively. For my primary comparison star, the magnitudes given by Kharchenko & Roeser (2009) are $M_B = 11.395 \pm 0.086$ and $M_V = 10.800 \pm 0.081$. For my secondary comparison star, the magnitudes given by the same reference are $M_B = 12.477 \pm 0.296$.
and $M_V = 11.173 \pm 0.105$. Using the $(B - V)$ program discussed in section III-9, I determined that the $(B - V)$ index of my system was approximately 0.80 during primary eclipse and 0.75 during secondary eclipse, as shown in Figure VI-1; the uncertainty of these measurements is 0.12. Schlafly and Finkbeiner (2011) estimated a $E(B - V)$ of 0.03 at my target coordinates, which resulted in a $(B - V)$ color index of $0.72 \pm 0.12$ during the secondary eclipse of my system. This indicated a primary effective temperature of $5,500 \pm 360$ K, which I held fixed during the modeling process. Due to this assumed temperature, I assumed a convective envelope for both the primary and secondary components, which allowed me to fix the gravity brightening and surface albedo parameters to their theoretical values.
Figure VI-1: \((B - V)\) color curve for Target A. The apparent V-band magnitude is plotted in the top panel, while the \((B - V)\) color curve is plotted in the lower panel. Error bars are not plotted.

I produced multiple models for this system, and while some models fit certain phases better than other models, none of the models adequately fit the observed data for all phases. The models varied widely in many of their parameters; for instance, one model that fit the maxima
very well had an inclination of 67° and a mass ratio of 2.03, while another model that fit the shapes of the eclipse minima very well had an inclination of 90° and a mass ratio of 0.37. One consistent feature of every model is that both components fill or nearly fill their Roche lobe, making the system a near contact binary. The models also tend to give similar temperatures for the secondary component. For the purposes of this thesis, I am reporting the two best models I have produced. These models indicate an early to middle G primary component and a late K to early M secondary component. Both models also have a single hot spot located on the secondary component. Each component is heavily distorted by the other, which causes both stars to appear tear-drop shaped which in turn produces a continuously changing light curve typical of a β Lyrae type eclipsing binary. A full summary of the results of the model is given in Table VI-1, three dimensional figures of the models are given in Figures VI-2 and VI-4, Roche lobe diagrams are shown in Figures VI-3 and VI-5, and plots of the models versus the observed data are given in Figures VI-6, VI-7, VI-8, and VI-9.
<p>| | | |</p>
<table>
<thead>
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<td></td>
</tr>
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<td>Orbital Period (d, J2014)</td>
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<tr>
<td>Orbital Inclination (°)</td>
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<td>89.67 ± 0.07</td>
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</tr>
<tr>
<td>$T_{\text{eff}}$ of Secondary Component (K)</td>
<td>3,944 ± 8</td>
<td>3,934 ± 15</td>
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<td>Surface Potential of Secondary Component</td>
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<td>2.6303 ± 0.0112</td>
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<tr>
<td>Mass Ratio</td>
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<td>2456674.944067 ± 0.000100</td>
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</tbody>
</table>

Table VI-1: Results of the modeling process and analysis for Target A. The results for model one are listed in the middle column while the results for model two are listed in the rightmost column; results listed in the full-width columns are common to both models.
Figure VI-2: Three dimensional figure of model one for Target A. The phase of the system in this figure is 0.25, with the primary component on the left and the secondary component on the right. The red markers on the left and red represent the center of each star while the red marker in the center represents the center of mass of the binary system.

Figure VI-3: Roche lobe diagram of model one for Target A. The Roche lobe of each component meets in the center at the first Lagrangian point. Note that the primary component fills its Roche lobe while the secondary component nearly does so. The outer line is irrelevant.
Figure VI-4: Three dimensional figure of model two for Target A. The phase of the system in this figure is 0.25, with the primary component on the left and the secondary component on the right. The red markers on the left and red represent the center of each star while the red marker in the center represents the center of mass of the binary system.

Figure VI-5: Roche lobe diagram of model two for Target A. The Roche lobe of each component meets in the center at the first Lagrangian point. Note that the primary component fills its Roche lobe while the secondary component nearly does so. The outer line is irrelevant.
Figure VI-6: Observed B data for Target A plotted against synthetic light curves. The top panel plots the normalized fluxes of the observed and synthetic light curves against the phase of the system. Model one is indicated by the solid red curve and model two is indicated by the dashed red curve. The residuals for model one (black) and model two (grey) are shown in the bottom panel.
Figure VI-7: Observed V data for Target A plotted against synthetic light curves. The top panel plots the normalized fluxes of the observed and synthetic light curves against the phase of the system. Model one is indicated by the solid red curve and model two is indicated by the dashed red curve. The residuals for model one (black) and model two (grey) are shown in the bottom panel.
Figure VI-8: Observed R data for Target A plotted against synthetic light curves. The top panel plots the normalized fluxes of the observed and synthetic light curves against the phase of the system. Model one is indicated by the solid red curve and model two is indicated by the dashed red curve. The residuals for model one (black) and model two (grey) are shown in the bottom panel.
Figure VI-9: Observed I data for Target A plotted against synthetic light curves. The top panel plots the normalized fluxes of the observed and synthetic light curves against the phase of the system. Model one is indicated by the solid red curve and model two is indicated by the dashed red curve. The residuals for model one (black) and model two (grey) are shown in the bottom panel.
VI.2: NSVS 5726288

Unlike with Target A, the modeling process for Target B was relatively straightforward. One reason for this was the fact that the light curve of Target B does not appear to be changing, which allowed me to use all the data I had collected rather than a subset of it. In addition, the light curve for Target B is significantly less complex than the light curve of Target A, displaying neither the O’Connell effect nor any indication of an accretion disk. As a result, PHOEBE was able to converge to a solution with little trouble.

Shortly after I began collecting data on Target B, I noticed a discrepancy in the light curve: the data, when plotted as a function of phase, showed both the primary and secondary minima occurring at phase zero. The cause of this discrepancy was due to the fact that the period given for the system by Hoffman, et al. (2008) was incorrect. Using my data, I determined that the true period of the system is approximately 0.85621 days as opposed to 0.59935 days as given by Hoffman, et al. (2008). It is worth mentioning that the 0.59935 day period is almost exactly seven-tenths of the true period, indicating that the published period is an alias of the true period caused by poor temporal coverage of the system. My analysis of the NSVS data\(^9\) shows that the 0.59935 day period is in fact the most significant period when using the NSVS data alone. I have since further refined the period of Target B.

My primary and secondary comparison stars have the designation of BD+43 3570 and TYC 3163-221-1, respectively. For my primary comparison star, the magnitudes given by Kharchenko & Roeser (2009) are \( M_B = 11.142 \pm 0.057 \) and \( M_V = 10.902 \pm 0.072 \). For my secondary comparison star, the magnitudes given by the same reference are \( M_B = 11.250 \pm 0.061 \) and \( M_V = 10.975 \pm 0.074 \). I determined that the \((B - V)\) index of my system was approximately

\(^9\) http://skydot.lanl.gov/nsvs/star.php?num=5726288
0.40 during primary eclipse and 0.33 during secondary eclipse, as shown in Figure VI-10; the uncertainty of these measurements is 0.09. Schlafly and Finkbeiner (2011) estimated a $E(B - V)$ of 1.55 at my target coordinates, which resulted in a $(B - V)$ color index of $-1.22 \pm 0.09$ during the secondary eclipse of my system. Such a $(B - V)$ index gives a non-physical value for the effective temperature, which forced me to use another rationale to determine the color index of my system. The reason for such a large correction is due to the fact that the system lies in the plane of the Milky Way, which is an area heavily obscured by dust. With no way to determine the distance to my target and therefore no way to determine the interstellar reddening, I made the physically unrealistic assumption of no interstellar reddening and used the raw color index of my target during secondary eclipse: $0.33 \pm 0.09$. This indicated a primary effective temperature of $7,000 \pm 450$ K, which I held fixed during the modeling process. Due to this assumed temperature, I assumed a convective envelope for both the primary and secondary components.
Figure VI-10: \((B - V)\) color curve for Target B. The apparent V-band magnitude is plotted in the top panel, while the \((B - V)\) color curve is plotted in the lower panel. Error bars are not plotted.

The modeling process produced a model that agreed very well with the observed data; the typical scatter in the residuals was around two percent of the total flux and appeared to be primarily observational in nature, which is to say that there is no discernible pattern in the
residuals. The model indicates a detached system with an early F primary component of 7,000 K and an early G secondary component of approximately 5,700 K. These temperatures are lower bounds, as correcting for interstellar reddening will decrease the \((B - V)\) index of the system which will result in a higher effective temperature. Each component is slightly distorted by the gravity of the other component, causing a continuously changing light curve typical of a β Lyrae type eclipsing binary. A full summary of the results of the model is given in Table VI-2, a three dimensional figure of the model is given in Figure VI-11, a Roche lobe diagram is shown in Figure VI-12, and plots of the models versus the observed data are given in Figures VI-13, VI-14, VI-15, and VI-16.

<table>
<thead>
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<tbody>
<tr>
<td>Orbital Inclination (°)</td>
<td>77.19 ± 0.03</td>
</tr>
<tr>
<td>(T_{\text{eff}}) of Primary Component (K, fixed)</td>
<td>7,000 ± 450</td>
</tr>
<tr>
<td>(T_{\text{eff}}) of Secondary Component (K)</td>
<td>5,747 ± 30</td>
</tr>
<tr>
<td>Surface Potential of Primary Component</td>
<td>3.5582 ± 0.0049</td>
</tr>
<tr>
<td>Surface Potential of Secondary Component</td>
<td>3.6456 ± 0.0066</td>
</tr>
<tr>
<td>Mass Ratio</td>
<td>0.8003 ± 0.0025</td>
</tr>
<tr>
<td>Magnitude Difference (M₂ – M₁)</td>
<td>1.1813</td>
</tr>
<tr>
<td>(T_{\text{min}}) (HJD)</td>
<td>2456457.738889 ± 0.000178</td>
</tr>
<tr>
<td>(T_{\text{min}}) (HJD)</td>
<td>2456922.677753 ± 0.000231</td>
</tr>
<tr>
<td>(T_{\text{min}}) (HJD)</td>
<td>2456945.796265 ± 0.000127</td>
</tr>
</tbody>
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Table VI-2: Results of the modeling process and analysis for Target B.
Figure VI-11: Three dimensional figure of the model for Target B. The phase of the system in this figure is 0.25, with the primary component on the left and the secondary component on the right. The red markers on the left and red represent the center of each star while the red marker in the center represents the center of mass of the binary system.

Figure VI-12: Roche lobe diagram of the model for Target B. The Roche lobe of each component meets in the center at the first Lagrangian point. Note that neither component fills its Roche lobe and there is only minimal tidal distortion. The outer line is irrelevant.
Figure VI-13: Observed B data for Target B plotted against the synthetic light curve. The top panel plots the normalized fluxes of the observed and synthetic light curves against the phase of the system. The residuals for the model are shown in the bottom panel.
Figure VI-14: Observed V data for Target B plotted against the synthetic light curve. The top panel plots the normalized fluxes of the observed and synthetic light curves against the phase of the system. The residuals for the model are shown in the bottom panel.
Figure VI-15: Observed R data for Target B plotted against the synthetic light curve. The top panel plots the normalized fluxes of the observed and synthetic light curves against the phase of the system. The residuals for the model are shown in the bottom panel.
Figure VI-16: Observed I data for Target B plotted against the synthetic light curve. The top panel plots the normalized fluxes of the observed and synthetic light curves against the phase of the system. The residuals for the model are shown in the bottom panel.
VII: Conclusion

Binary stars form part of the basis of our understanding of the nature of stars. They have allowed us to characterize how mass relates to evolution, spectral class, and lifespan of a star. Eclipsing binaries in particular are important as they allow full determination of a star’s characteristics. The continued study of these systems is therefore a vital and fruitful endeavor to help our understanding of the characteristics of stars.

For this thesis, I have studied two such systems in hopes of coming to a better understanding of how to analyze and interpret the data I have collected. The data reduction and analysis comprised the bulk of the time spent on this project, exceeding the time spent observing or writing. The data reduction process is where I have given the most in-depth explanation, due primarily to the importance of the process in other areas of astronomical research. I have also summarized the modeling process in general and the Wilson-Devinney model in particular, especially in regards to how they relate to my research.

My analysis of the two systems indicates that both are β Lyrae type eclipsing binary systems. Of these two systems, one is a fairly typical eclipsing binary with a well-behaved and consistent light curve. The model produced for this system indicates a moderately inclined detached binary system with two similarly massed components. The other system has many peculiar features that warrant further study, such as a rapidly changing light curve, a pronounced O’Connell effect, and some indications of an accretion disk. What little consistency the models provide indicates a near-contact semi-detached system with component stars of significantly different mass.
The most important next step to study these systems would be to obtain spectroscopic data. This would allow the determination of the effective temperature and spectral type of the components as well as the masses via radial velocity analysis. Unfortunately, the faintness of my systems makes it difficult to obtain usable spectra on any of the instruments available to me, making the future study of these systems uncertain.
VIII: Acknowledgements

I would like to thank Dr. Ronald Kaitchuck for his invaluable guidance, knowledge, assistance, and friendship over the eight years that I have attended Ball State. Without him to guide me, this project would never have begun, much less finished. I would like to thank Dr. Robert Berrington for his support in the data collection aspect of this project as well as for his invaluable support in understanding and completing the data analysis aspect. I would like to thank Dr. David Grosnick for his assistance in understanding the uncertainty calculations performed as part of this thesis. I would like to thank the Indiana Space Grant Consortium for funding my research and therefore allowing me to be more secure with my future at Ball State. I would like to thank my good friend Monique Gabb, who gave me moral support and a platform to bounce ideas off of. Finally, I would like to thank my parents, Jan and Steve Knote, who have continuously supported my decisions and who have been available when I have needed support the most.
References


6. Kharchenko, N. V., Roeser, S., 2009, yCat, 1280, 0


