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Defined Orbital Elements and Solution Parameters for Binary Star System ET Tau

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An abstract of
a thesis submitted to the Faculty of Emory College of Arts and Sciences
of Emory University in partial fulfillment
of the requirements of the degree of
Bachelor of Science with Honors

Department of Physics

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Abstract

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ET Tau is a semi-detached variable star system of combined visual magnitude of 8.8 with a period of around 5.996 days. The Wilson-Devinney program was used to solve the Emory University and Fernbank Science Center BV light curves simultaneously with single-line radial velocity measurements of the secondary star. The system has the secondary component filling its Roche Lobe. The resulting masses are M_1=16.43 M_{sun} and M_2=7.17 M_{sun} with mean radii R_1=5.77 R_{sun} and R_2=12.32 R_{sun}. Light curve parameters, radial velocity parameters, orbital elements, and absolute dimensions are presented in the paper. Observations were taken in the UBV filter sets for the Fernbank Science Center data from January 1983 – April 1986. Observations were taken in BVR filter sets for the Emory University Observatory data during Spring 2013. After varying all parameters, our data and theoretical solution suggests that period has remained constant between the Fernbank and Emory data over the course of 27 years.

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Chapter 1: Introduction to Eclipsing Binaries and Astronomical Quantities

Chapter 2: Light Curve Data, Fitting, and Stellar Modeling

Chapter 3: ET Tau Observations and Analysis

1. Introduction to Eclipsing Binaries and Astronomical Quantities

1.1 Eclipsing Binary Star Systems

A majority of star systems in the known universe come in pairs, which are known as binary star systems. These systems have two component stars revolving around a common center of mass known as the barycenter of the system.[4] These stars follow the regime of classical mechanics in their mutual orbit of this center of mass. Observation of the mechanics of our own solar system with only one star has advanced our knowledge of how objects orbit a center of mass. We can apply the rules that many physicists have provided to study the orbit of these interesting and prevalent binary star systems.

The analyses of binary stars systems provide one of the few methods by which the masses of stars can be directly calculated from observations. The stars revolve in a particular orbital plane, which can be angled in such a way that an observer sees one component of the system blocking some of the light coming from the other star. This observational phenomenon is known as an eclipse, and by observing eclipses we can apply our knowledge of mechanics, spectra, magnitudes, and distance to define many of the inherent parameters of these binary star systems.[4]

The distances that these stars are in relation to an observer make them appear as an unresolved point source. An observer can thus not directly resolve the image of each component star separately and must alter their approach to observation. Conceptually, the light that an observer receives on Earth should change as a component star orbits and blocks the light coming from the other component.[2] This allows an observer to take measurements on the brightness of the binary star system over time, which will provide a light curve for the system. This light curve along with spectral data is key in making direct and indirect assertions about the two components. A generic synthetic light curve developed in the Windows program Binary Maker 3 can be seen in Figure 1-1.[1]

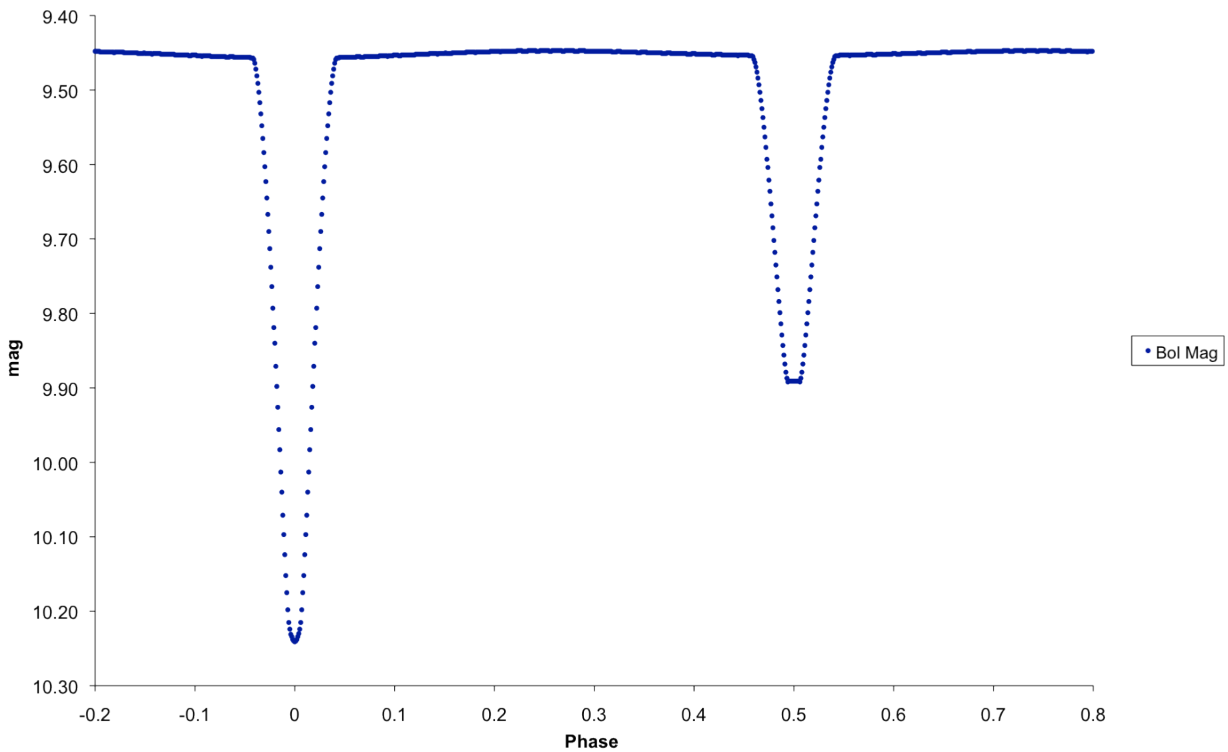

Figure 1: Synthetic Light Curve - Bolometric Magnitude vs. Phase (Partial Primary Eclipse and Total Secondary Eclipse)[1]

1.2 Parameters of the System

An eclipsing binary system can be defined by a set of parameters that refer to basic physical quantities such as radii, separation, color, and brightness that are inherent to the makeup of the system. These parameters affect various aspects of the light curve, and our intent is to model a system that fits best with our light curve data by varying many of these parameters that are not directly observable. We use quantities that have been determined from the light curve or spectra while varying other parameters that we have no way to directly measure. The period of the system is defined as the time it takes for a complete orbit of the system, generally measured from primary eclipse to primary eclipse in days. The period is related to the mass of each component along with the orbital separation of the two components center of masses. This quantity is seen in Kepler's third law as seen in Equation 1, and applies for any bound system.[2]

$$P^2 = \frac{4\pi^2}{G(M_1 + M_2)} a^3 \quad (1)$$

A second important parameter of the star system is the mass ratio. The mass ratio of a system refers to the mass of one component divided by the mass of the other component. Specifically for our treatment of binary star modeling, we will define the mass ratio as the mass of the secondary component over the mass of the primary component ($\frac{M_2}{M_1}$). This ratio is related to the respective semi-major axis of each components orbit by the following expression:[2]

$$\frac{M_2}{M_1} = \frac{a_1}{a_2} \quad (2)$$

Each star has a particular radius that can be related to the width of total eclipses in the light curve. Some stellar radii are not easily defined, as the tidal distortion from orbiting and the gravitational interaction with the other star can cause non-spherical components. At that point radius becomes a less important measure, and we instead use a related quantity, known as surface potential, that is more robust in these non-spherical shapes. The eclipse depths are related to the surface temperatures of each star, specifically by a ratio between the surface temperatures of the two component stars. The ratio of the primary and secondary eclipse depths are related to the temperature ratio via the Stefan-Boltzman law, namely that the luminosity is proportional to the fourth power of the surface temperature.[2, 4]

The inclination of the system is the angle at which the orbital plane is viewed by an observer. This inclination is defined as 90° if the system is viewed directly edge on and defined as 0° if the system is viewed face on. Lower inclinations will result in both the primary and secondary eclipse depths to become shallower, as the eclipses observed become progressively less complete. An example of both a total eclipse and partial eclipse can be found in Figure 1-2.[2]

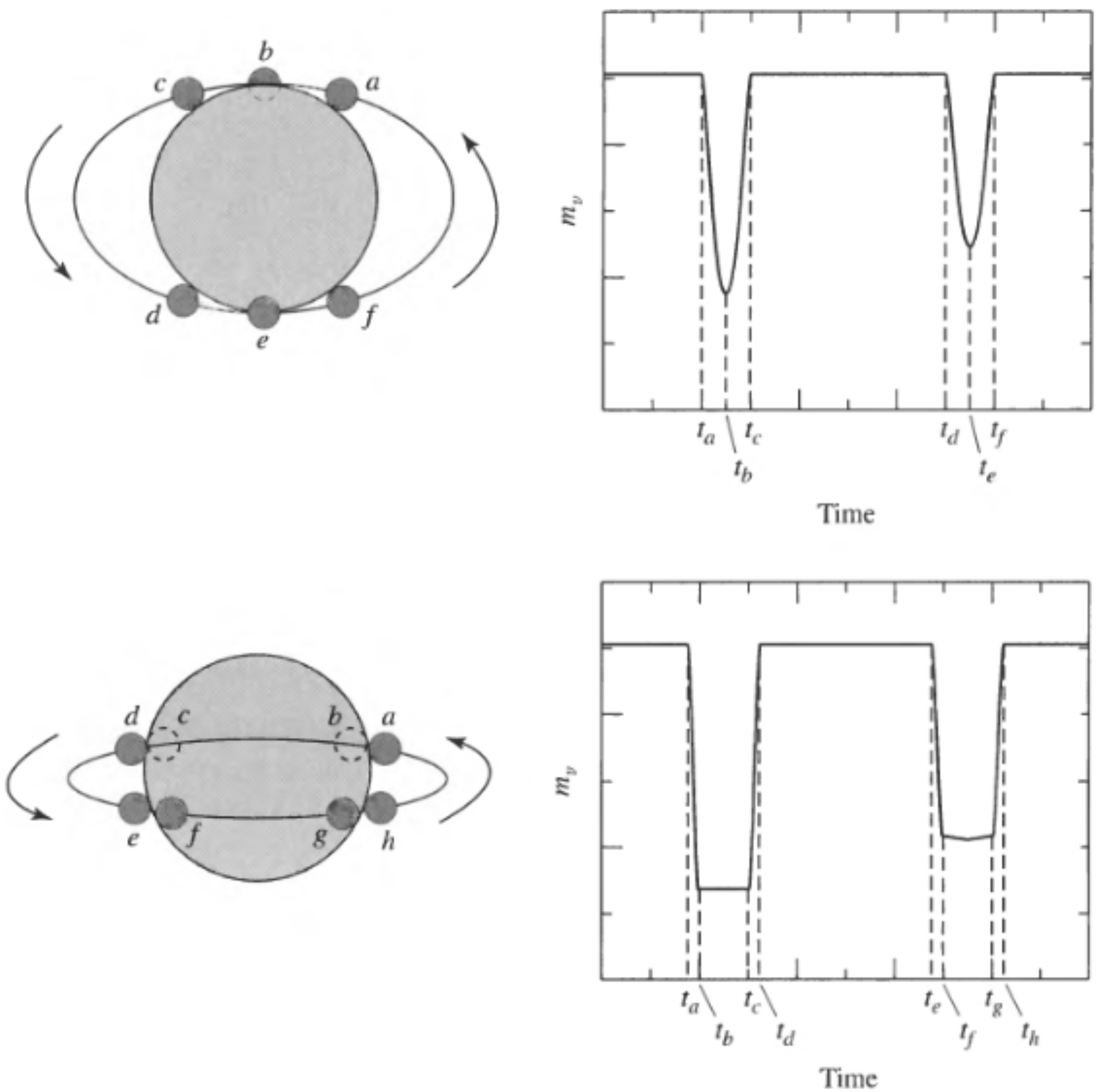

Figure 2: Partial Eclipse and Light Curve (top) Total Eclipse and Light Curve (bottom)[2]

Another parameter to consider in the mechanics of two orbiting bodies is the eccentricity of the orbit. Though many planet-star orbits have a more elliptical orbit and thus a larger eccentricity, most binary star systems have very circular orbits with close to zero eccentricity due to tidal synchronization. Often times the mass and radius parameters are represented as ratios with respect to the other component. The actual determination of mass and radius parameters (not simply as ratios) requires radial velocity measurements of the components that come from spectral data. These mass and radius parameters are often reported in terms of solar mass ($M_\odot$) and solar radii ($R_\odot$).

1.3 Naming Conventions and Classification

Variable stars were originally named using a convention starting with a capital letter R followed by a short hand representation of the constellation that the star was located within. Subsequent variable stars found would be designated alphabetically from R to Z. As soon as these letters had been exhausted then a second letter, again starting at R, would be placed behind the first. For the first variable star found in the constellation Taurus would be known as R Tau with subsequent names being S Tau, T Tau successively continuing on to Z Tau. Then cycling back to be called RR Tau, RS Tau, …, RZ Tau. When these letters were used up for naming variable stars, astronomers resorted to starting at the beginning of the alphabet with letter A followed by a second letter designation as well (AA, AB, AC, …, AZ). The letter J was skipped to reduce confusion with the letter I. After this naming convention reached its last two-letter designation of QZ, astronomers realized that the number of existing variable stars necessitated the formation of a new, numerical naming convention with many more potential combinations. These additional variables in a given constellation started with V-335 and sequentially increased from there.[2, 3]

The historical way of classifying binary star systems refers to the connection and interaction of the two components. This depends on whether a binary system is detached, semi-detached, or in contact. One can map the gravitational potential function of the system throughout space in the co-rotating frame. This map is based on the integral of gravitational force at different points in space for the system. Places where the gravitational force is zero are known as Lagrangian points. As this is the derivative of the potential, we know that these points in space are critical points of the potential function. These points are in stable equilibrium when an object that finds itself at this point will go back to equilibrium if slightly perturbed or in unstable equilibrium if an object will go away from equilibrium if slightly perturbed. Each star has a tear drop shaped boundary known as the Roche lobe of the star. This tear drop shape meets the point of the other star’s tear at an equilibrium point between the two stars, which is known as the first Lagrangian point (L1). The classification of the star system depends on where the stars mass is located with respect to its respective Roche lobe.

If both components are within their respective Roche lobes than the system is defined as a detached system, which means that each component is separate and there is no transfer of material from one star to the other as can be seen in the binary model of a detached system in Figure 1-3.

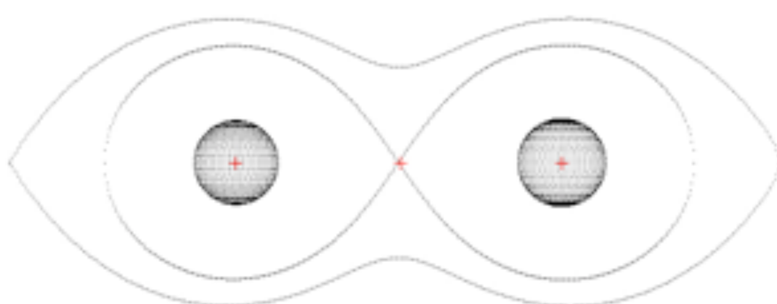

Figure 3: Detached Binary System Model from Binary Maker 3[1]

If just one star fills its respective Roche lobe then there will be mass transfer from that star to the other component via the inner Lagrangian point. This particular system is known as a semi-detached system and an example can be seen in Figure 1-4.

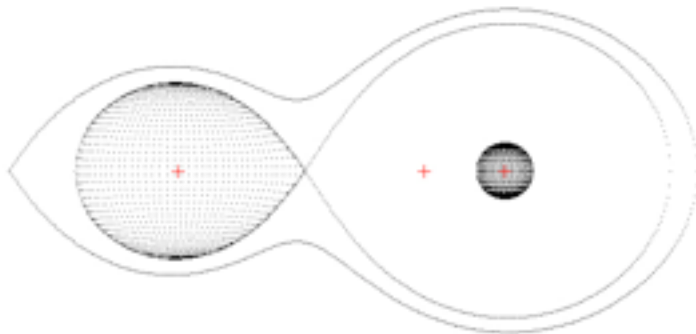

Figure 4: Semi-Detached Binary System Model from Binary Maker 3[1]

In the case where both stars either fill or extend outside their respective Roche lobes, then there is physical contact between the two stars, and they share a common outer envelope. This system is known as a contact system, and an example can be seen in Figure 1-5.

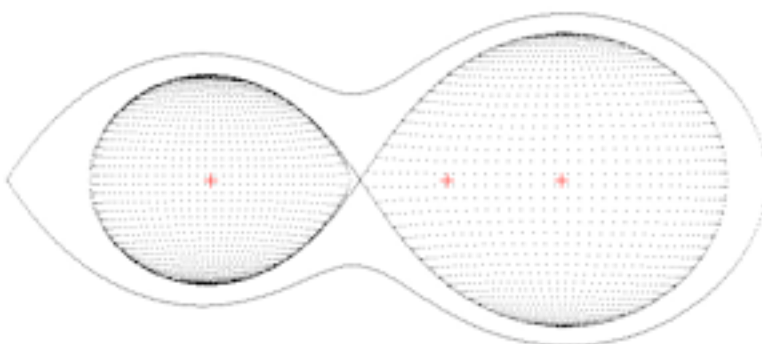

Figure 5: Contact Binary System Model from Binary Maker 3[1]

Further classification requires relating distinct systems to their most similar prototype systems, or the first discovered system similar to them. Some examples of prototype systems are that of W UMa, Algol, and Beta Lyrae.

1.4 How Do We Measure Brightness

Flux and magnitude are the two main ways that brightness can be represented for astronomical sources. Magnitude can be described in both apparent and absolute terms. As the name implies, apparent magnitude is the magnitude that we measure on Earth. Absolute magnitude is the magnitude of the star with consideration to a standard distance of 10 parsecs. Since light intensity falls off as a function of distance from the source, we can calculate the absolute magnitude if we take distance into account. Both varieties of magnitude are logarithmic in nature and in reverse order (a star with a lower magnitude is actually brighter than a star with a higher magnitude). This otherwise scale is calibrated by using the brightness of the star Vega as its zero point. To give an impression of what magnitudes the naked eye can see without consideration of light pollution is that of magnitude 6. Using the star Vega as the zero point causes stars that are brighter than Vega to have negative magnitudes.[2]

Flux is another scale system that is used in astronomy as a measure of brightness. This scale is linear with a maximum flux of 1 for a particular object, meaning that it is a relative measure. Stars will have different magnitudes and fluxes based on the range of light that is observed. This allows us to use filters that allow passage of selected wavelengths and collect color specific brightness information on stars. UBVRI is a commonly used optical system of filters that refers to the ultraviolet band (U), blue band (B), visual band (V), red band (R), and infrared band (I). Ideally an observer would be able to observe light curves in all bands to best determine the properties of the system, but in many cases logistical or technical limitations make this unnecessary or impossible.

1.5 Astronomical Timing and Heliocentric Julian Date Correction

The Julian Date (JD) is a measure of time that was created to make calculating the time differences between observations easier. This is because it is not based on the month, date, and year of the widely adopted Gregorian calendar. Instead this calendar is the amount of time in days that has elapsed since noon Universal Time (UT) on January 1st, 4713 BC.[2] Universal Time is the time that occurs based on the location of Greenwich, England. This calendar allows for direct subtraction to find the amount of time between two JDs in days without having to consider leap years and calendar oddities.

A more important timing measure for astronomy, however, is the Heliocentric Julian Date (HJD). This quantity takes into account the movement of the Earth around the sun as well as the sun's movement within the Milky Way galaxy. This correction is needed because the distance between the observer and a star can vary throughout the year from the Earth's orbit by up to 2 astronomical units (AU), and can vary as the solar system itself moves through space. An astronomical unit is a measurement that is based on the average distance of the Earth from the sun throughout its orbit. If we think in terms of light years, or more aptly at this scale light minutes, then this distance corresponds to around 8 light minutes. If the path between observer and star changes by about 16 light minutes at its two extremes then this will cause error in timing that will need to be accounted for when trying to correctly plot brightness vs. time. A diagram illustrating the concept of different path lengths at different locations in the Earth's orbit can be seen in Figure 1-6.[3]

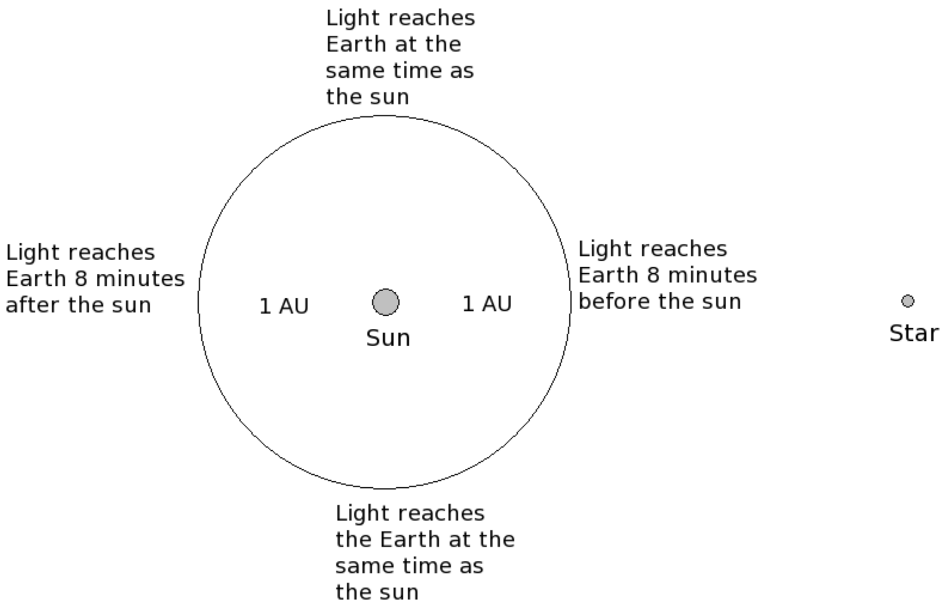

Figure 6: Heliocentric Julian Date Correction - Light Path Difference Along Earth's Orbit[3]

To correct for this error between different times of the year when observations take place, we must make the sun a stationary reference point. Based on our position in orbit, we can thus calculate the amount of time that must be added or subtracted to the Julian Date to correct for differences in path length. This addition or subtraction of time turns the recorded Geocentric Julian Date into Heliocentric Julian Date.

When plotting several nights of observation to construct a light curve we must use a determination of epoch and period of the system to find the phase at a particular observation time. Phase goes from the center of a primary eclipse starting at 0.0 progressing up to 1.0, which corresponds to the bottom of the primary eclipse as well. A primary star is defined as the hotter and more luminous component. This is likely to be the more massive and larger star, but this trend is not always true. When this primary star passes behind the secondary component, it results in a larger drop in brightness in the light curve, creating the primary eclipse. A secondary eclipse occurs when the secondary (cooler) component is eclipsed by the primary component. If there is a low eccentricity (e=0) for the system, then the secondary eclipse should line up to the bottom of the eclipse at a phase of 0.5. The parts of the light curve at a phase of .25 and .75 represent when neither component is eclipsing the other and we are thus seeing the combined light from both components. For a clearer picture of the phase plot, we often graph two full phases from 0.0 to 2.0 (another option is to plot from a phase of 0.8 to 0.8). This allows us to both start the phase diagram in the center of a primary eclipse and also be able to see an uninterrupted view of the primary eclipse on the same plot. Once the period of the data has been analyzed and the ephemeris has been found, subsequent observations can be analyzed and phased accordingly assuming there is not a period shift or apsidal motion due to the effect of eccentricity over time.

1.6 Stellar Spectra

An optical characteristic of prisms or gratings is that they can disperse light into its corresponding colors by interacting with light of different wavelengths in different ways. This can be used to disperse the spectrum of incident light from a source such as a star. We can use a spectrograph to measure the intensity of incident light as a function of wavelength. An example of the raw and analyzed spectra of sample B stars can be seen in Figure 1-7 and Figure 1-8 respectively.[7]

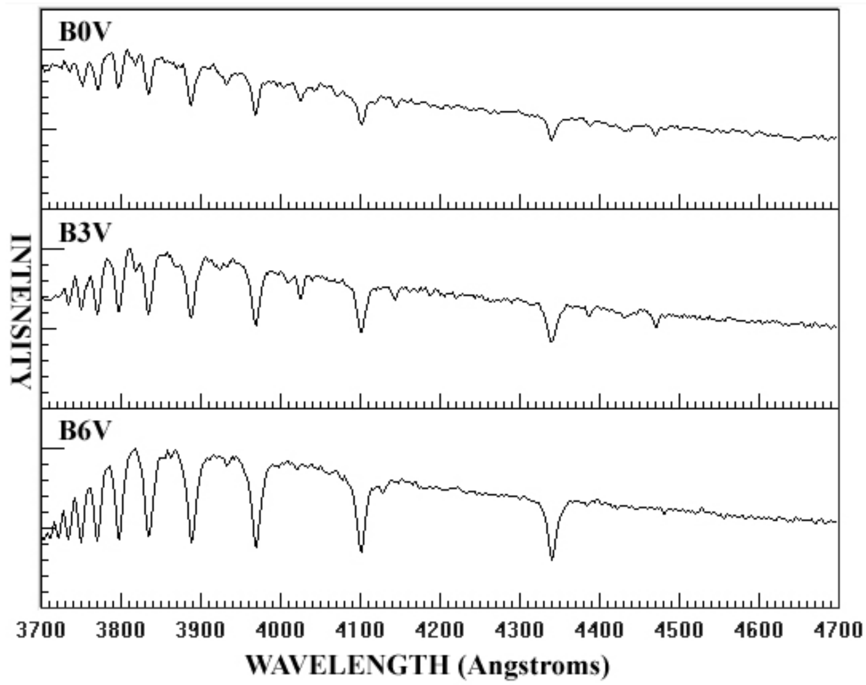

Figure 7: Raw Stellar Spectrum of B Type Stars as a function of Intensity vs. Wavelength[7]

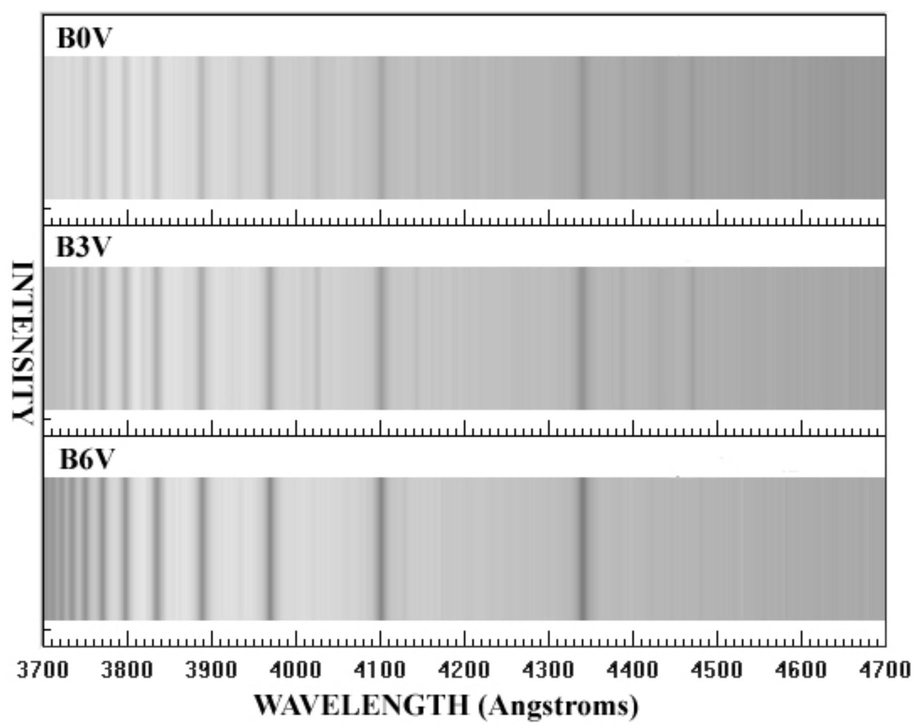

Figure 8: Processed Stellar Spectrum of B Type Stars as a function of Intensity vs. Wavelength[7]

Using these spectra to make determinations about the composition of a star is known as spectroscopy. Looking at the wavelength of peak emission from the spectrum we can use Wien's law to get an idea of the surface temperature of the stellar source. Composition information can be determined from the spectral lines that can be seen in the spectrum that correspond to the known excitation or absorption bands of particular chemical species in different ionization states. This information can give us an idea of the metallicity (percentage of elements with atomic weight greater than helium) of the star, as well as providing information on the chemical composition of the stellar atmosphere. We can look at the width of these spectral lines to get an impression of the atmospheric conditions such as density and surface gravitational potential. We can use this to discriminate between the spectral typing of the star and tell whether the star is a hydrogen-burning star, main-sequence star, helium-burning star, or a stellar remnant. The spectrum obtained of a binary star system includes the spectrum of both components overlaid on top of one another.

1.7 Radial Velocity Curves

Many times when looking at spectrum from a stellar object, an observer can see distinct shifts of expected spectral lines from their original location. This shift can move in one direction or the other in terms of a red and blue shift, or can broaden or narrow spectral lines. The spectrum gives a preliminary identification of the chemical composition of the trace elements and surface conditions of a stellar object. We can also look at the spectrum in regards to these shifts to determine radial velocities of one or both of the two components as they rotate around their center of mass. An example of a double line radial velocity plot where both components' radial velocities have been determined as a function of phase can be seen in Figure 1-9.

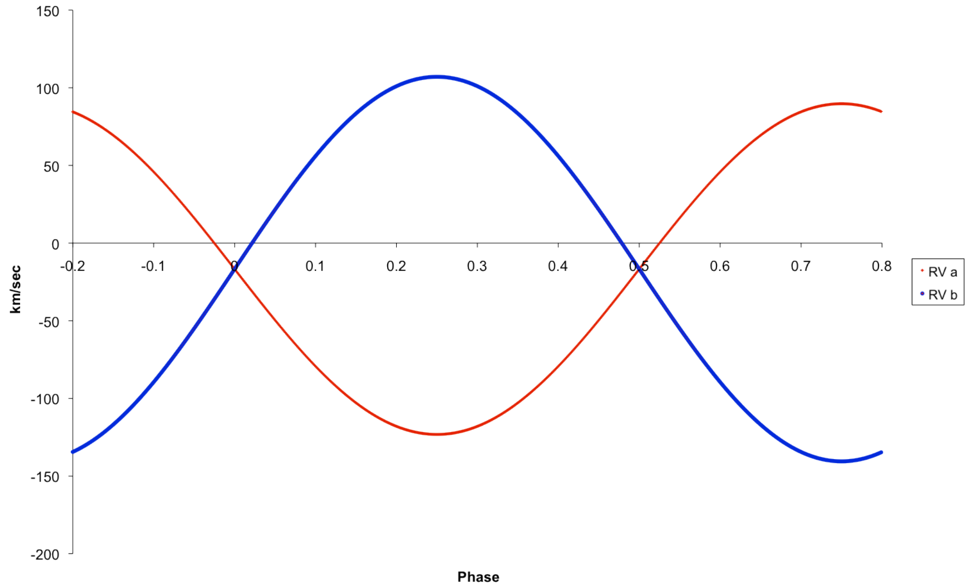

Figure 9: Synthetic Double-line Radial Velocity Plot vs. Phase[1]

An example of a single line radial velocity plot where only the radial velocities from one component are known can be seen in Figure 1-10.

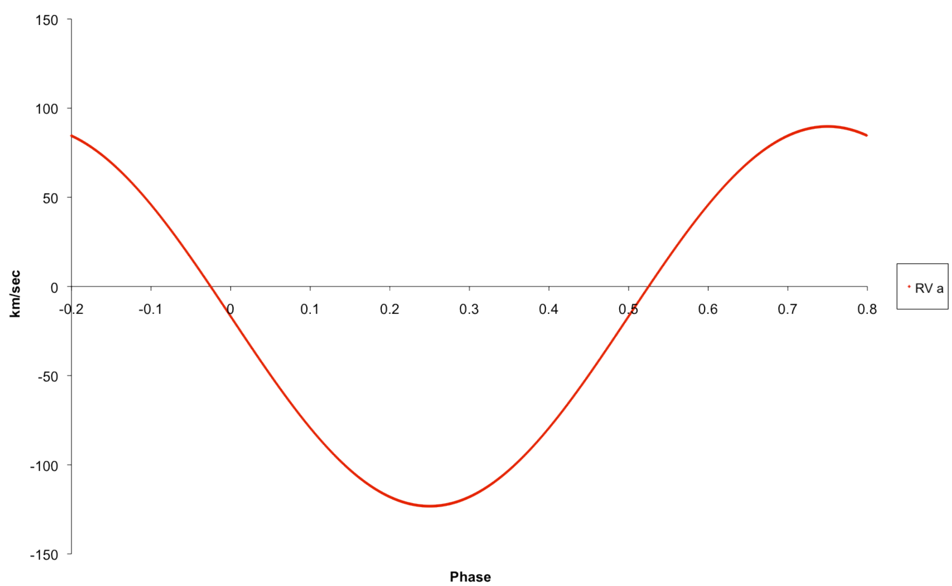

Figure 10: Synthetic Single-line Radial Velocity Plot vs. Phase[1]

These radial velocities are seen as a Doppler shift from a certain expectation of where a spectral line should be as opposed to what is actually observed. We can use this Doppler shift to determine the radial velocities at which the stars are orbiting. Since the stars can vary greatly in heavy element composition, size and mass, there can be significant differences in their orbital speeds that are detectable in the observed spectral shifts. Spectral data must be collected over different regions of the phase to get an accurate view of the radial velocities of both components. Ideal spectra obtained from a binary star system would include a red shift and a blue shift of certain spectral lines, as each component should be either moving away from us with the other moving towards us or vice versa. If a system is determined to be a binary star system, without two observable spectral shifts, then one of the components may be spinning very quickly so that the spectral lines would be Doppler broadened and blurred, thus becoming faint and undetectable. If the radial velocity of only one component can be determined, then we must use information of mass ratio by varying parameters to fit a theoretical curve over our observed light curve. If no spectral data is available for a system, then an educated inference of the photometric color can yield estimates of temperature. This estimate of temperature can then be used to find mass from known mass-temperature relations for particular types of stars.

1.8 Telescope Configuration and CCD Cameras

Telescopes are the main instrument of an astronomer when observing astronomical objects. Many different types of telescopes exist, which employ either refraction based light collection or reflection based collection methods. The type of telescope used in the study of the star system ET Tau was a 36 – inch diameter Cassegrain type telescope at the Fernbank Science Center Observatory. We also used the Mead refractor telescope attached to the side of the main telescope at the Emory University Observatory. The Mead was used to provide a larger field of view for reasons of providing a reference and check star for differential photometry. Greater apertures in telescopes allow for more light to be collected, yielding higher signal to noise ratios when investigating dimmer astronomical objects. Specifically for the Cassegrain type telescope, light first enters the telescope and reflects off a concave mirror known as the primary mirror. This mirror causes the light rays to converge toward a convex mirror at the top of the telescope known as the secondary mirror. This secondary mirror reflects the light back down to a hole located in the center of the primary mirror. This light is then either focused to an instrument such as a CCD chip of a research camera or an eyepiece depending on the setup. A ray diagram of a Cassegrain type telescope can be seen in Figure 1-11.[2]

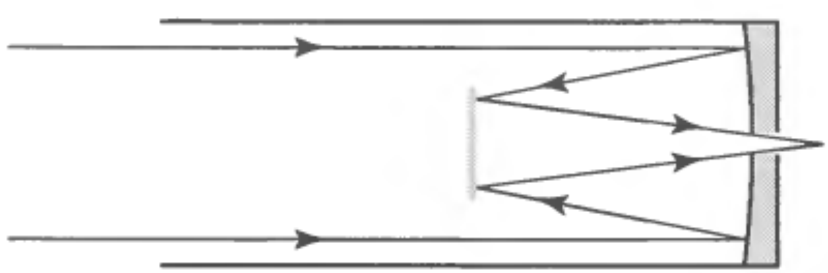

Figure 11: Ray Diagram of Cassegrain Type Telescope[2]

The Mead telescope uses a different methodology, focusing light by using refractory lenses. Light passes through an objective lens and the top of the telescope that then focuses to the bottom of the telescope and eventually to an eyepiece or CCD chip of a research camera. A ray diagram of a refractor type telescope can be seen in Figure 1-12.[2]

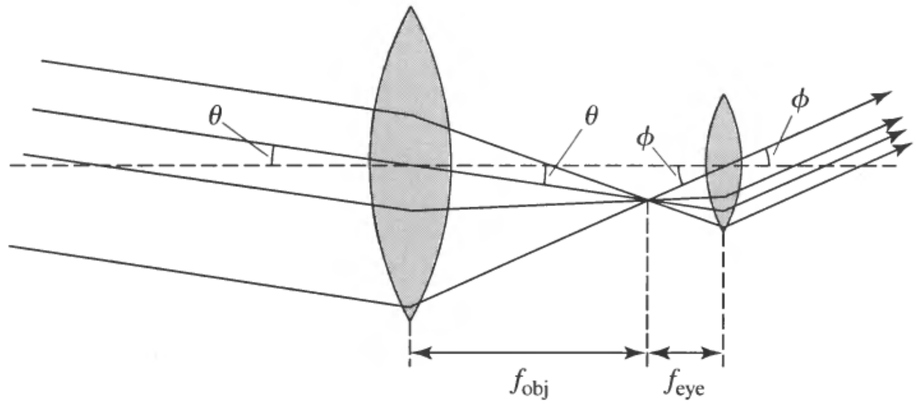

Figure 12: Ray Diagram of Refractor Type Telescope[2]

Prior to the digital age of astronomy, the primary mode of collecting information on stellar brightness came from the use of photomultiplier tubes. This has now been made much faster and more accurate through the use of charge coupled devices (CCD) cameras in the digital age. Comparing photomultiplier tubes with a CCD camera, we may consider the CCD as a chip that has every pixel acting as a photomultiplier tube. The premise of a CCD chip is that a chip, made of a semiconductor such as silicon, will release electrons after incident photons hit its active surface. These photons are thus "countable" by understanding how these collected charges and read-out voltages relate to the amount of incident photons. From 70-90% of incident photons in the visible range can eject a photoelectron depending on the CCD chip. In turn, this makes CCD cameras very sensitive, especially when compared to organic media like film or the human eye. During the time that the aperture of the camera is open, known as an exposure, electrons accumulate in the pixels of the chip. These charges are shifted vertically to a serial register, then shifted horizontally one pixel at a time into a charge to voltage converter. The resulting voltage is then converted to a number via an analog to digital converter, which can be seen as an image of the stellar field of view on a computer.

Three principle corrections are made to images from research grade CCD cameras including what is known as bias, dark, and flat corrections. These frames are known as calibration frames, compared with the stellar field of view frames, which are called the science frames. After every new exposure, the charge buildup that corresponds to the photon counting on each pixel is cleared to zero. Each pixel does not necessarily get entirely cleared of charge after being shifted for various chip specific reasons. We thus must take an average of several bias frames to subtract out of all our science frames to account for these errors. A bias refers to a “zero” second exposure, and measures the “biases” of the chips structure. Many research grade CCD cameras have the built in ability to cool the chip down to -30° C to reduce the dark current and the associated noise that the chip experiences. Though this reduces the noise, dark current from the chip and any stray light photons cause irregularities in the collected charge. To account for this we take an average of several dark frames to access these extra non-stellar photons. Dark current is a property of the CCD chip that is dependent on the time of exposure, as it is a current that represents charge per time. We take dark exposures that are with the aperture of the camera closed at the length of time of the longest exposure of the night. The dark frames are then applied to all images and scaled according to the different exposure times during the observation set or for different filters. The third source of error and artifacts in our images is accounted for by taking flats. Flats refer to illumination a flat field such as a screen with a source of light with a continuous emission spectrum. This flat frame takes care of pixels that do not have the same responsivity. A flat frame is also used to divide out artifacts in the images from dust that can be in the telescope between the aperture and camera.

1.9 Differential Photometry

As the night progresses, an observer uses a sensitive CCD camera and telescope array to take images of stellar objects of interest with roughly the same field of view. When employing the method of differential photometry, one must also include at least two more specific stellar objects, known as the check star and the reference star. As the name implies, the reference star is the star in the same field that is closest to the magnitude of our stellar object with the assumption that there is no variability in this reference. We use the reference star of a known literature (or independently measured) magnitude in the filters we are interested in, to directly compare with our object. This magnitude calibration also allows us to find how the brightness of our object changes in relation to this stellar comparison reference. The check star is another requirement that is meant to verify constancy or determine variability in our reference star. Ideally, this star should have no variability, thus any observed deviation from our assumption after analysis will show false variability of the system or of the reference star.

When looking at the field of view, one may notice that stars are not point sources. They instead seem to spread their light in roughly circular patterns among multiple pixels on the CCD chip. This occurs due to the imperfections of the focusing from either the mirrors or lenses of a telescope. This also occurs because of the variations in our atmosphere such as temperature differentials, moisture, and turbulence that causes an effect called scintillation. Focusing the telescope can aid in bringing these stellar objects more towards point sources, but without an adaptive optics array we cannot account much for the atmospheric variations. In some practical cases, we intentionally want the light of a brighter star to be counted by several pixels because of the limitations in linearity and well depth of the CCD chip, as we focus brighter objects onto fewer pixels. By letting the light be measured or averaged over several pixels, we are increasing the accuracy for these brighter stars.

When analyzing the data from these images, we must sum the intensity of all the pixels that measure light from our object of interest. The background of the night sky is also taken using an annulus in the analysis program around the aperture that encompasses the stellar object, and this background is subtracted from object to account for different times of night, as well as light pollution. You must use the same aperture, annulus, and gap width when looking at the check, reference, and object from any one night of observation. For different observation sets you may change these, but they will remain constant for their particular observation set.

Throughout the night the field of view we are observing will appear to be traversing the sky because of the rotation of the earth. This movement in position in the sky will affect the amount of atmosphere that we are looking through to observe this field, known as the air mass. Due to different extinction rates for each filter wavelength and absorption of the light through different amounts of air at different altitudes, the stars will become brighter or dimmer depending on the air mass at the time of observation. High clouds and atmospheric changes that occur with time will also cause variability in our brightness measurements from our objects of interest. The use of differential photometry and the practice of comparing the variable to a reference and a check star in the same field at the same time helps to account for these time-dependent, changing conditions. We are then able to use most of the data points from a night of observation, as well as compare them to other nights' data based on the use of the same reference star and check star.

The main program of processing and analysis of these observational images is known as Maxim DL. The program is able to specify an object, reference star with a settable magnitude, and a check star. Maxim DL will then go through all the similar images from the night and use relative positions to identify these stars in a majority of the images. Sometimes the star matching fails if significant drifting throughout the night occurs or there was a period of poor visibility images. If this occurs, one must then manually exclude these problem images or reselect the object, reference, and check. With this program the object is measured with respect to the reference star of published magnitude. The program performs differential photometry to provide a portion of the light curve for the object. Using this method with reasonably high signal to noise ratios from the original observational integration times, we can thus arrive with highly time resolved light curves with errors on the order of millimagnitudes.

2. Light Curve Data, Fitting, and Stellar Modeling

2.1 Overview of Modeling

The premise of modeling eclipsing binary stars is that given a certain set of basic system parameters there exists a unique solution of these parameters that will match the observed radial velocity and light curves. Light curves of multiple filters can be used to check that the modeled temperature distribution matches the data from different bandpasses. We can be reasonably confident that a solution found from a set of many varied parameters that matches the observed light curves as well as the experimental radial velocity curves will represent the physical quantities of the system. We must first use differential photometry to get raw light curve information in textual form based on JD and magnitude. The JD is corrected to HJD via the period analysis software and then phased appropriately after a value for the period has been determined.

2.2 Times of Minima

The time at which a light curve reaches a local minimum value is known as the time of minima. Minima are separated into two classes: primary minima and secondary minima depending on which component is being eclipsed. The primary minimum occurs when the less luminous component eclipses the more luminous component. A secondary minimum occurs when the more luminous component eclipses the less luminous component. As such there is a greater eclipse depth to a primary minima compared with a secondary minima. Period analysis software such as Peranso can take reduced photometric data and compute the times of minima for secondary and primary eclipses if those events have been observed in a data set. The method generally employed is the Kwee-van Worden method. Using this method one can find a period of the system being analyzed. This can either be a first baseline value for determining a novel ephemeris, or can serve as an update to a period if significant change has occurred.

2.3 O-C Diagram

A main way of either verifying the constancy of period or tracking period shifts in a star system is using an observed time of minimum minus calculated time of minimum diagram (O-C). This uses a standard ephemeris determined from previous observations to calculate a time of minimum that is closest to a newly observed minimum. Any deviation in period over the time between when the standard ephemeris was developed and when the new observation took place is seen in a non-zero O-C that is not accounted for by associated error. An O-C diagram is traditionally a plot of the observed minus calculated HJD for a minimum on the y-axis with the epoch, or number of orbits since the standard ephemeris, on the x-axis. Another commonly used measure of time on the x-axis is the Heliocentric Julian Date, which can be convenient when looking at O-C values from observers who use different standard ephemerides. From an O-C diagram, one can determine how or if the period changes over time.

2.4 Solutions of Varied Parameters

The solution model of a binary star system can involve the varying of many parameters. Some of these parameters can be solidified using spectroscopy or other methods to reduce the number and complexity of the parameters being altered to model a system. Even in the ideal case where many of the parameters are set with limits, the task of finding a suitable solution with the lowest residuals compared with the observed light curve can be difficult. The function that represents the solution of our model system can have many local minima throughout this multi-parameter space. The main way of calculating and finding these minima is known as differential corrections. This requires an initial starting point for all the parameters being varied. We can vary all the parameters at once, but in practice a more methodical and effective way is to reduce the system to varying one or two parameters concurrently. This process is limited by the starting value as the computing of the variation in the parameters has a limit in which it can calculate and compare new parameter values. As the parameters are varied, the program will look for unique local minima and return the values identified for the varied parameters and the updated values. As values are returned and updated, the solution should approach a local minima value and hopefully a suitable solution of the system. When the differential corrections program has been allowed to run varying all parameters with no updates and low residual values, we can be reasonably confident that the solution describes our binary system. This process is iteratively based thus it requires significant time and patience to accomplish with great accuracy. The parameters found using the differential corrections can then be applied to the light curve-plotting program and compared to our observed plots in the different filters. The theoretical plot should visually match the observed plots for all filters and radial velocity curves. We must also employ sound scientific analysis to our start points, and returned values to ensure that we do not allow parameters to vary to a point of being physically unreasonable.

2.5 Wilson-Devinney Code

The renowned code used by many different secondary applications and programs comes from the Wilson-Devinney code (W-D).[5] This code has been updated as the understanding of different aspects of eclipsing binary stars has evolved with time and the development of new modeling techniques. The code employed in the analysis of this thesis is the 2003 release with minor scripting changes made by Dr. James Sowell of the Physics Department of the Georgia Institute of Technology. The code in its current state can model all but the most extreme examples of eclipsing binary stars. The method by which it calculates variations in parameters is also limited to differential corrections, making the computation and modeling dependent on the time, set points, and perseverance of an apt user.[5] Another well-known program used by educators and students that applies this code is known as Binary Maker 3. This Windows based program allows for the modeling of simpler systems visually, but does not include any functionality for solving the many parameter functions.[1] The W-D code itself has a more robust, but less user-friendly plotting feature that can return many of the same image types as Binary Maker 3.

3. ET Tau Observations and Analysis

3.1 Background Information

ET Tau, [RA: 05 37 40.845, Dec: +27 16 16.60, 2000, V_{mag}≈8.8] is a short period system, (P=5.996 days).[6, 9] This system is classified as an Algol type binary. Previous spectral typing stated that the primary component was a B8. The technical difficulty associated with this period results from it mirroring an integer number of Earth days, which causes roughly every 6 days of observation to measure the same portion of the light curve. This also means that if all the observations occur in roughly the same amount of time that there will be gaps in the light curve. The period of this star thus gives the system more difficulty in providing a complete light curve for curve fitting analysis. The number of nights and amount of data taken at relatively distant times can aid in getting a more complete light curve of this star system. The star system has not been thoroughly studied, and the Emory University and Fernbank Science Center data is the most comprehensive view of the light curve to date.[9] The first available spectral data that has been taken on this system is in conjunction with this current project with Dr. Frank Fekel at Tennessee State University. The Fernbank data collected by Dr. Richard Williamon, now faculty of Emory University, contained a few crucial gaps in the light curves that were filled during observations taken at the Emory University Observatory. The unpublished 30+ nights of observation from Fernbank, 6 nights of observation at Emory University, newly taken spectral data, and advances in binary star modeling has made it possible to take another look at this interesting and technically difficult system. Additionally, there is a poorly sampled light curve available from ASAS data. The only other publication that directly addresses ET Tau is a study that involves analysis of the carbon spectral lines in type B eclipsing binary stars that stated that ET Tau illustrated expected amount of carbon.[8]

3.2 Observations

Observations of ET Tau were taken in the U, B, and V filters by Dr. Richard Williamon at the Fernbank Science Center using an EMI 6256s photomultiplier tube. The comparison star used in these 30+ nights worth of observations was GSC 1869-615 [B= 9.358,V= 9.207].[10] The check star used in these observations was GSC 1869-1487. These observations were taken between the dates January 1983-April 1986. Observations were taken in the B, V, and R filters by Charles Evavold at the Emory University Observatory using the 5" Mead refractor telescope with the SBIG ST-10XME CCD camera cooled to -20° C. The dates of observations were the nights of January 18^{th}-19^{th}, January 20^{th}-21^{st}, February 08^{th}-09^{th}, February 14^{th}-15^{th}, February 16^{th}-17^{th}, and February 17^{th}-18^{th} in 2013. Differential photometry was performed via Maxim DL software on the Emory data. The reference star used for differential photometry was GSC 1869-1171 [B= 9.251,V= 8.811,R= 8.520].[10] The check star used was GSC 1869-686. A finder chart that consists of an inverted color science frame taken at the Emory University Observatory can be found in Figure 3-13. The times of observation were HJD corrected using Peranso period analysis software.

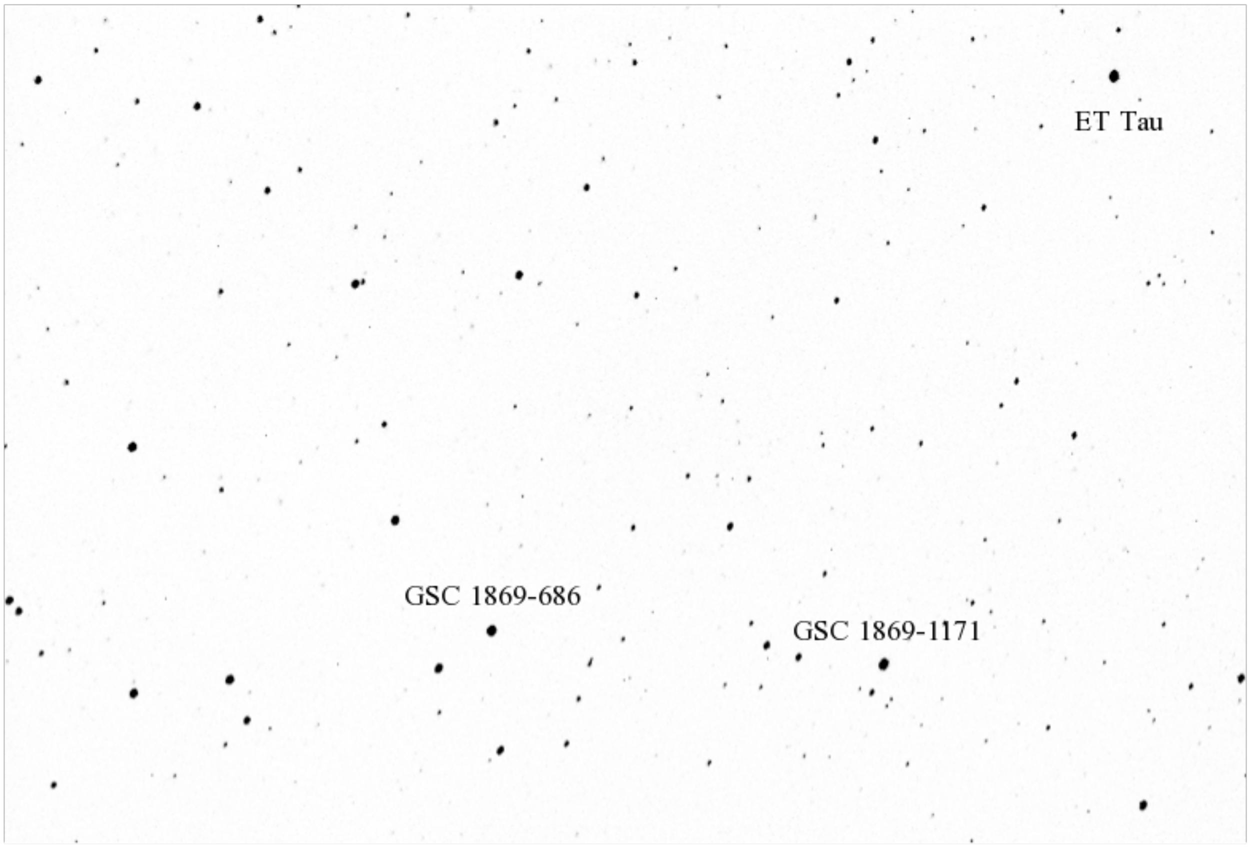

Figure 13: ET Tau Finder Chart

3.3 Light Curves and Model

The data taken at Fernbank Science center were compiled in the BV filters. The data taken at Emory University were also compiled in the BV filters. A nearly complete light curve in B and V was then constructed from the Fernbank and Emory data. These light curves were input into the W-D code at Georgia Institute of Technology by Charles Evavold under the direction of Dr. James Sowell. Through use of differential corrections and visual light curve fitting a theoretical solution to the system was obtained. The radial velocity data collected by Dr. Frank Fekel was also input into the W-D after a solution was found.

3.4 Results

The purpose of this thesis was to obtain a physically meaningful and plausible solution of parameters that match the observed light curves in different filters as well as the experimental radial velocity curves. Presented in the following figures and tables are the raw light curves, theoretical solutions, and a listing of our parameters used in finding this solution.

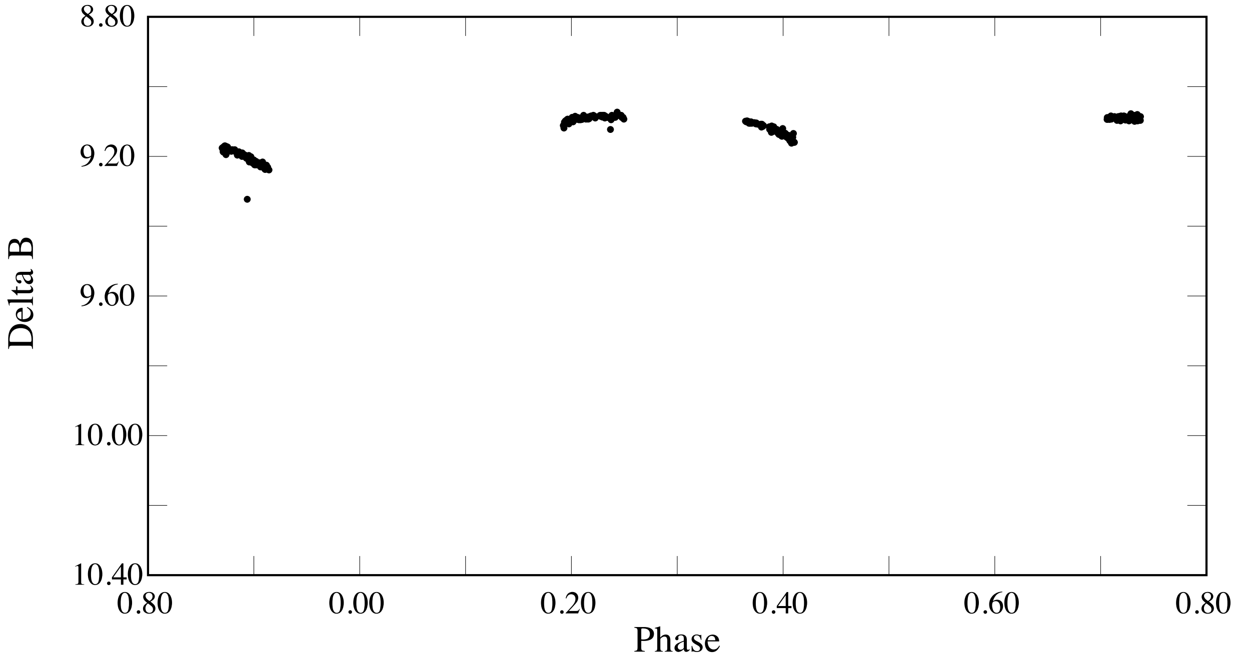

Figure 14: B Filter Emory University Observatory Data and Phased Light Curve

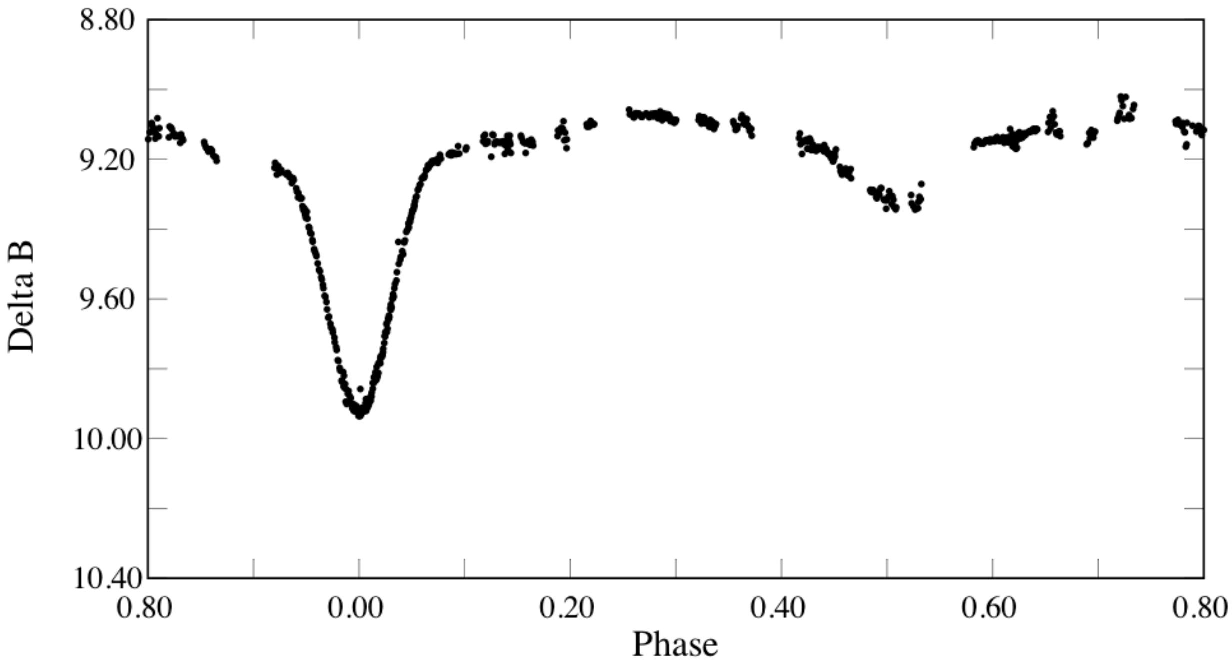

Figure 15: B Filter Fernbank Science Center Data and Phased Light Curve

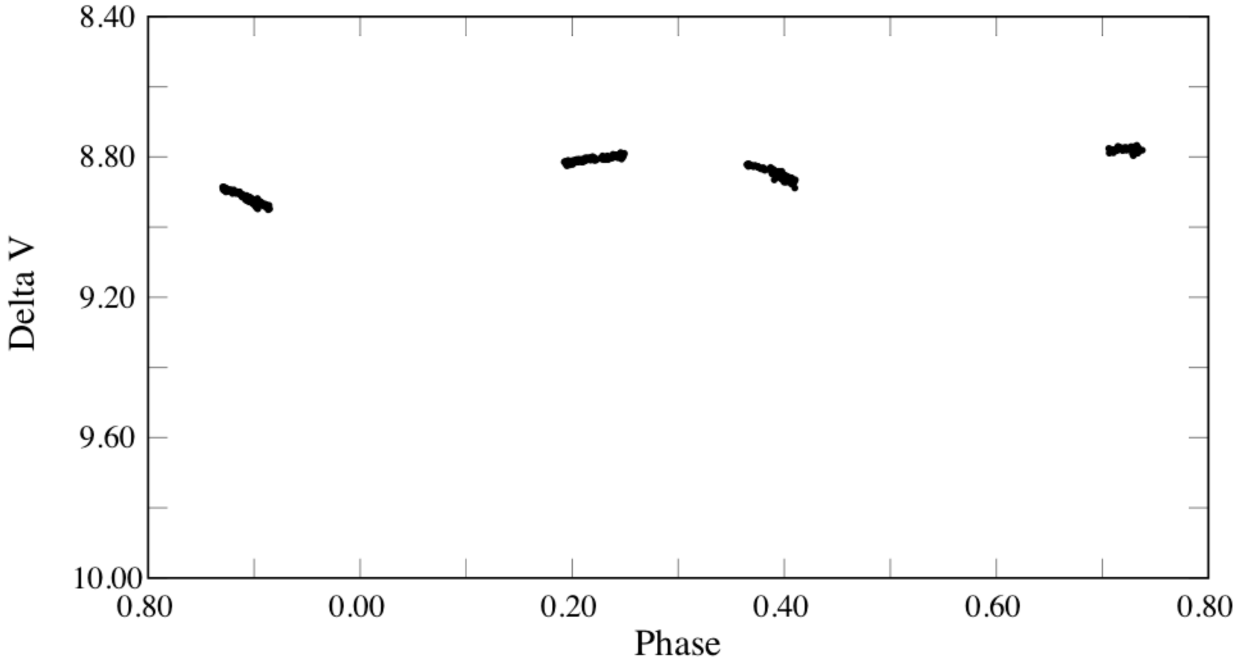

Figure 16: V Filter Emory University Observatory Data and Phased Light Curve

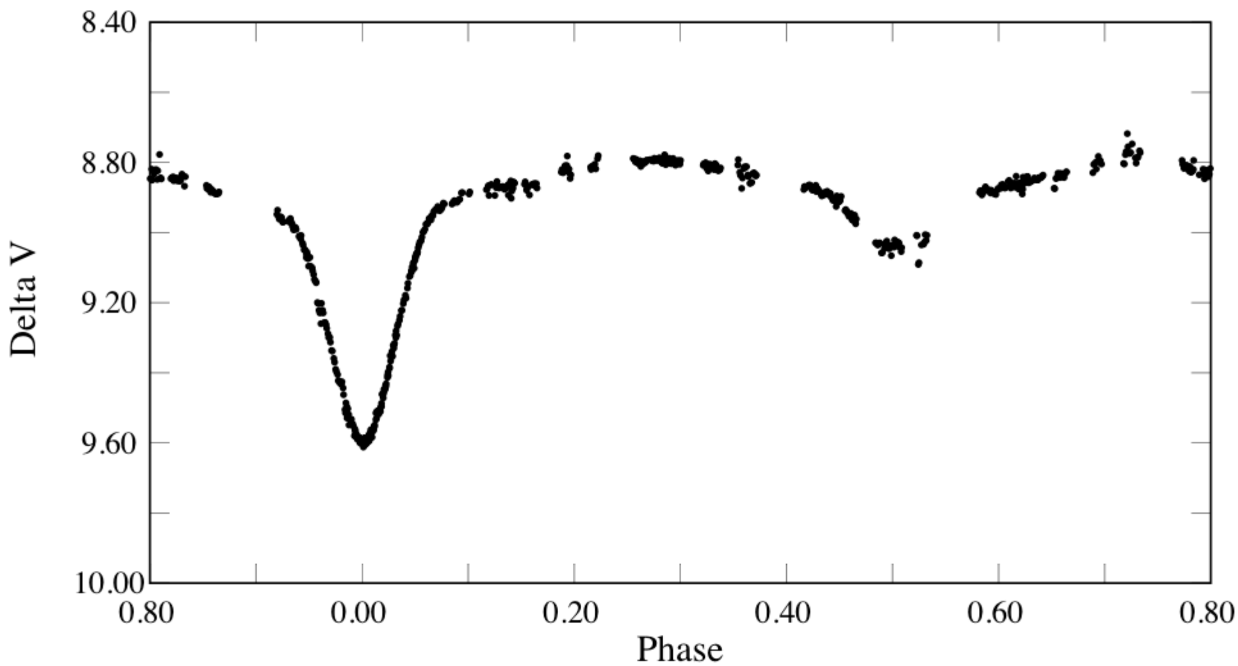

Figure 17: V Filter Fernbank Science Center Data and Phased Light Curve

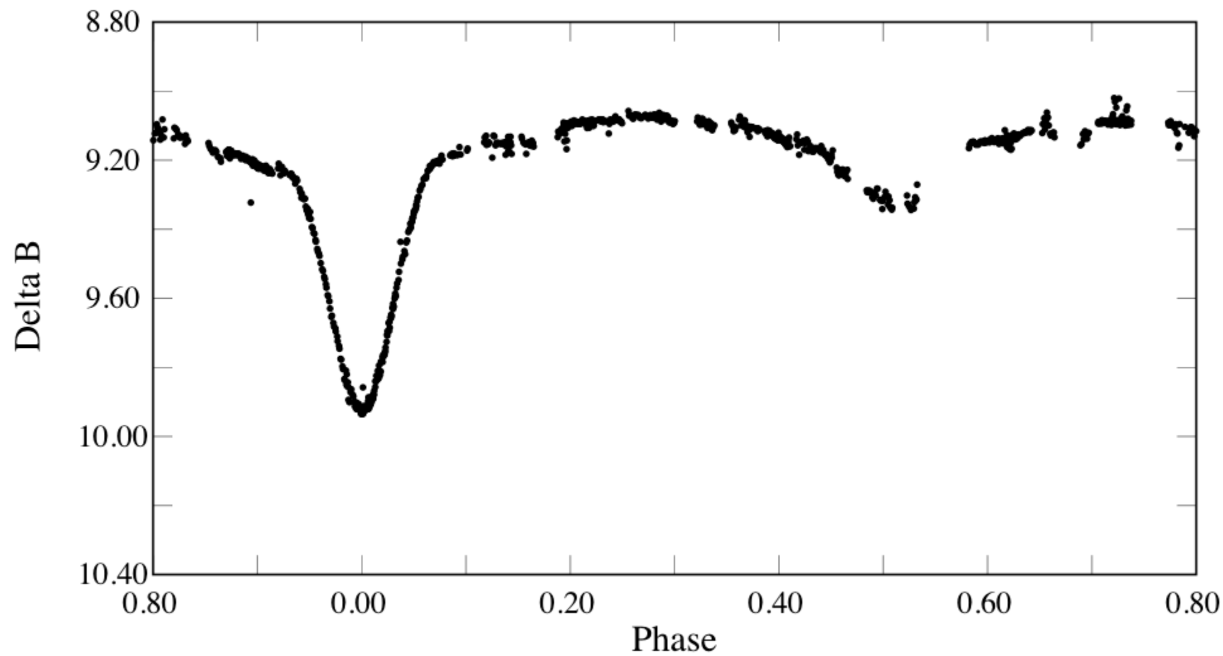

Figure 18: B Filter Combined Observation Sets Light Curve

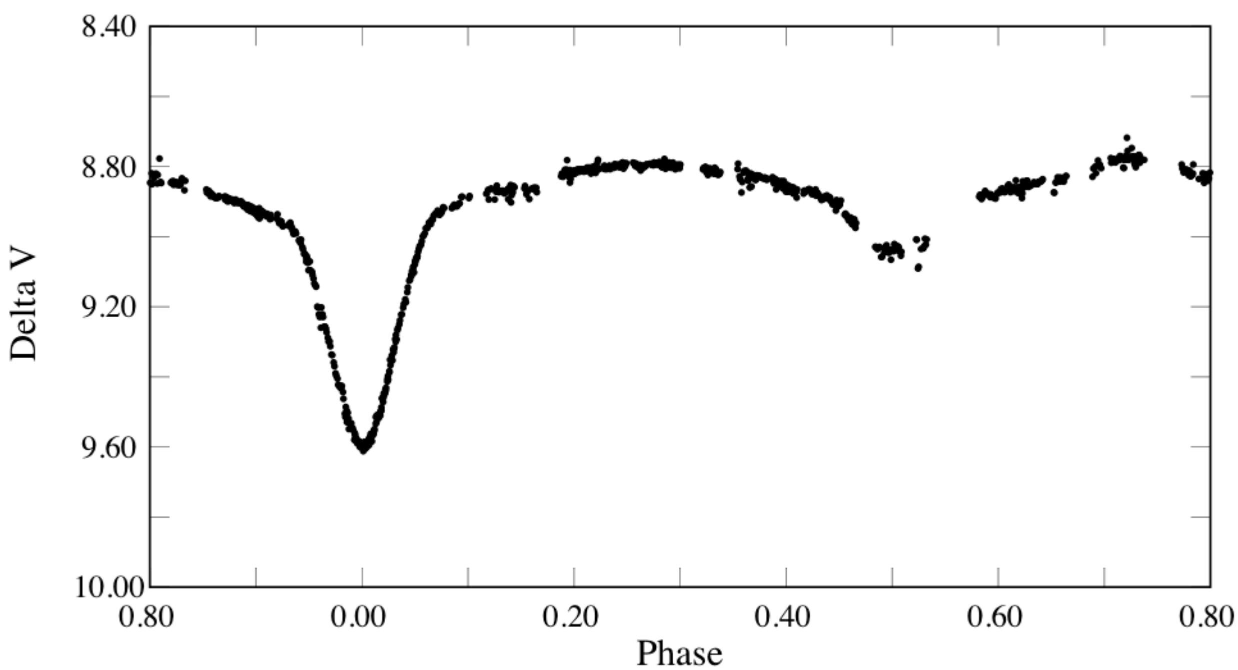

Figure 19: V Filter Combined Observation Sets Light Curve

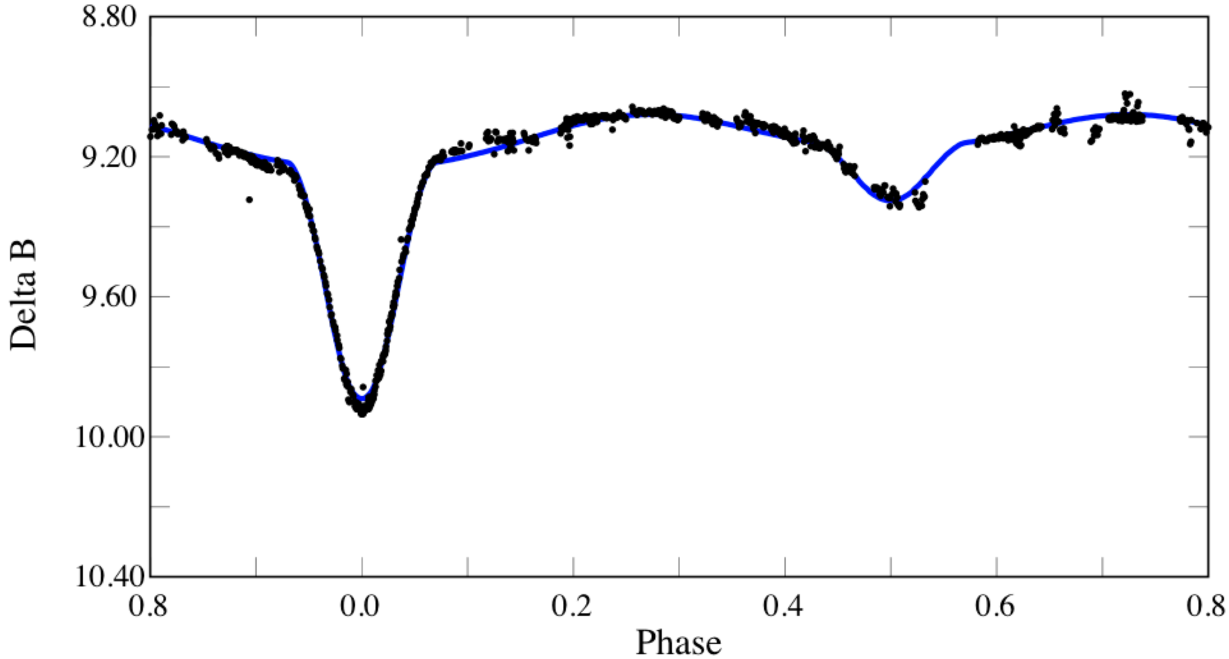

Figure 20: B Filter Combined Observational Sets Light Curve and Theoretical for ET Tau

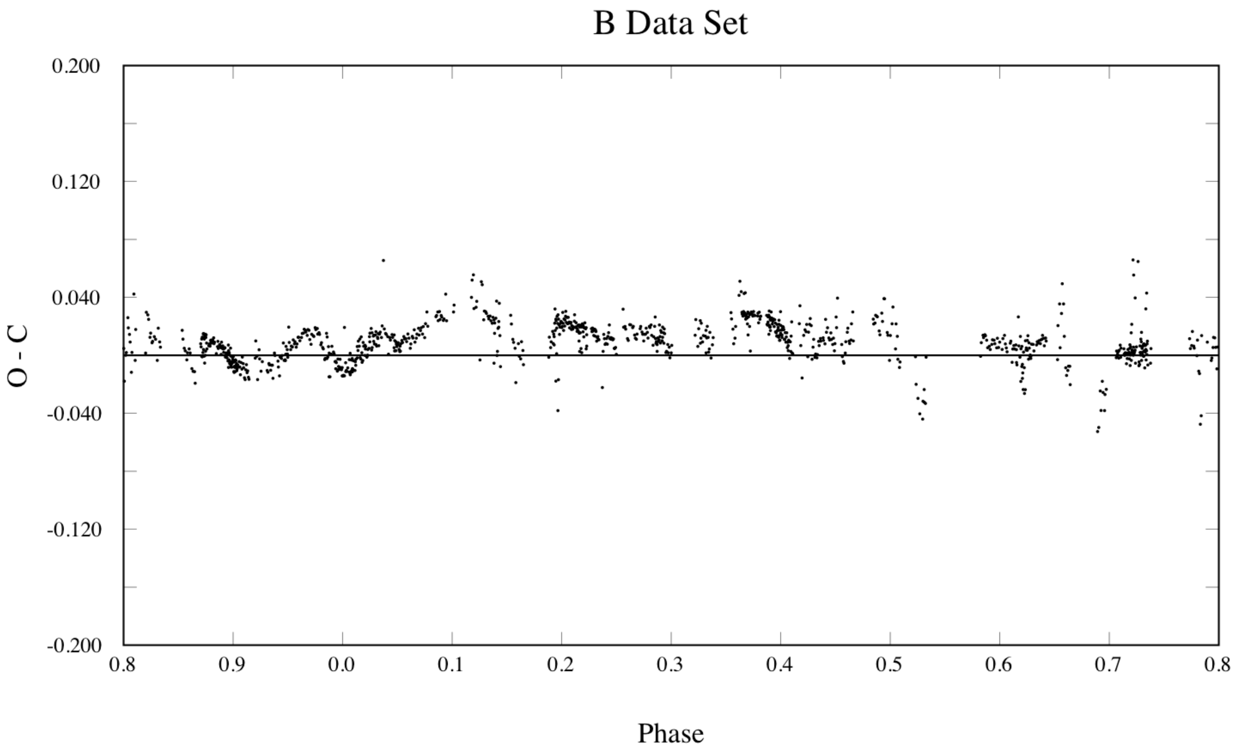

Figure 21: O-C Residuals with Phase for B Data

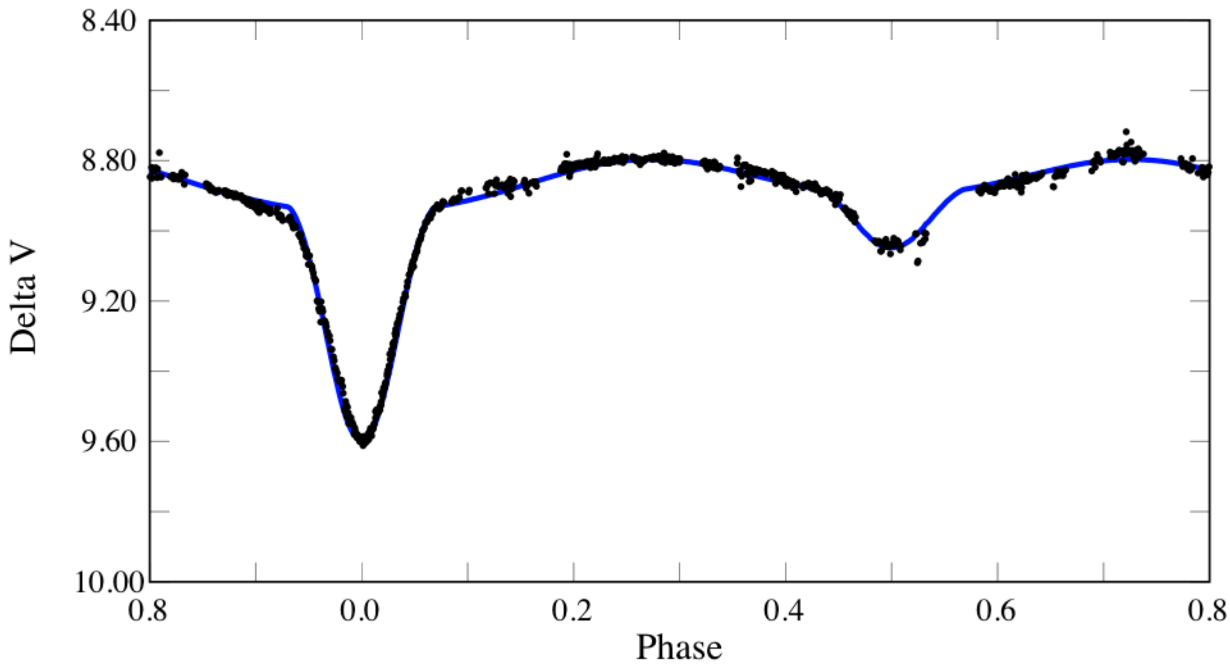

Figure 22: V Filter Combined Observational Sets Light Curve and Theoretical for ET Tau

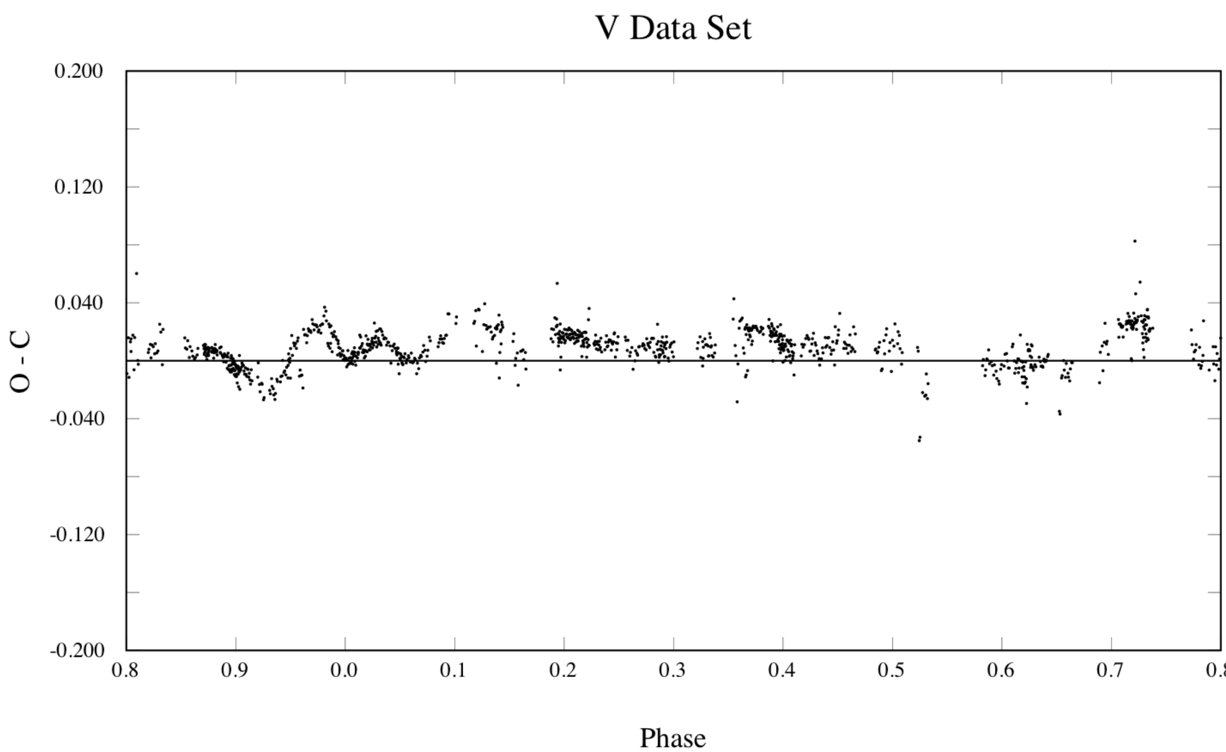

Figure 23: O-C Residuals with Phase for V Data

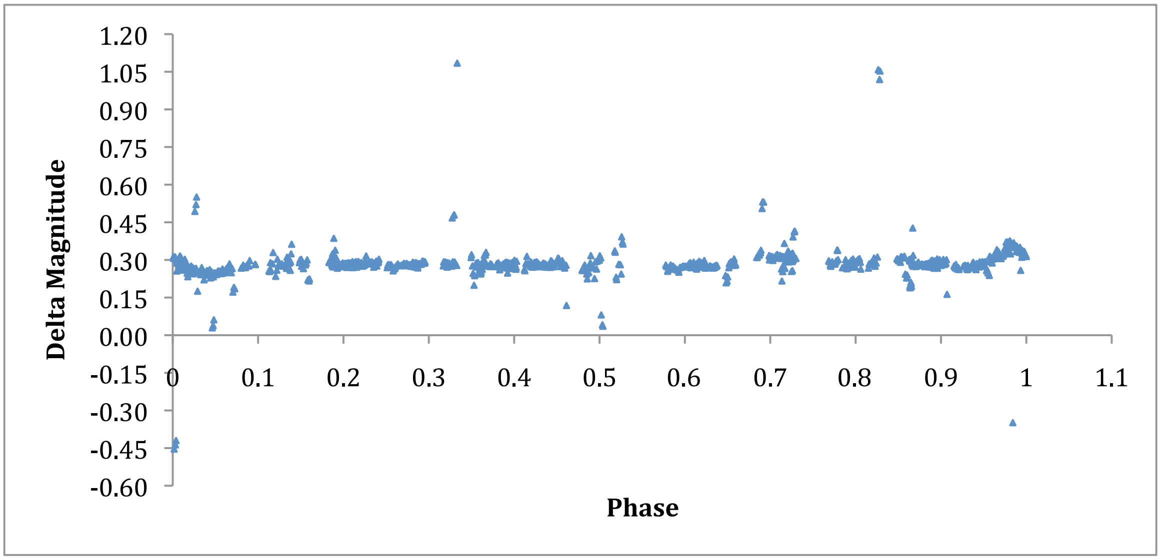

Figure 24: B-V Diagram vs. Phase

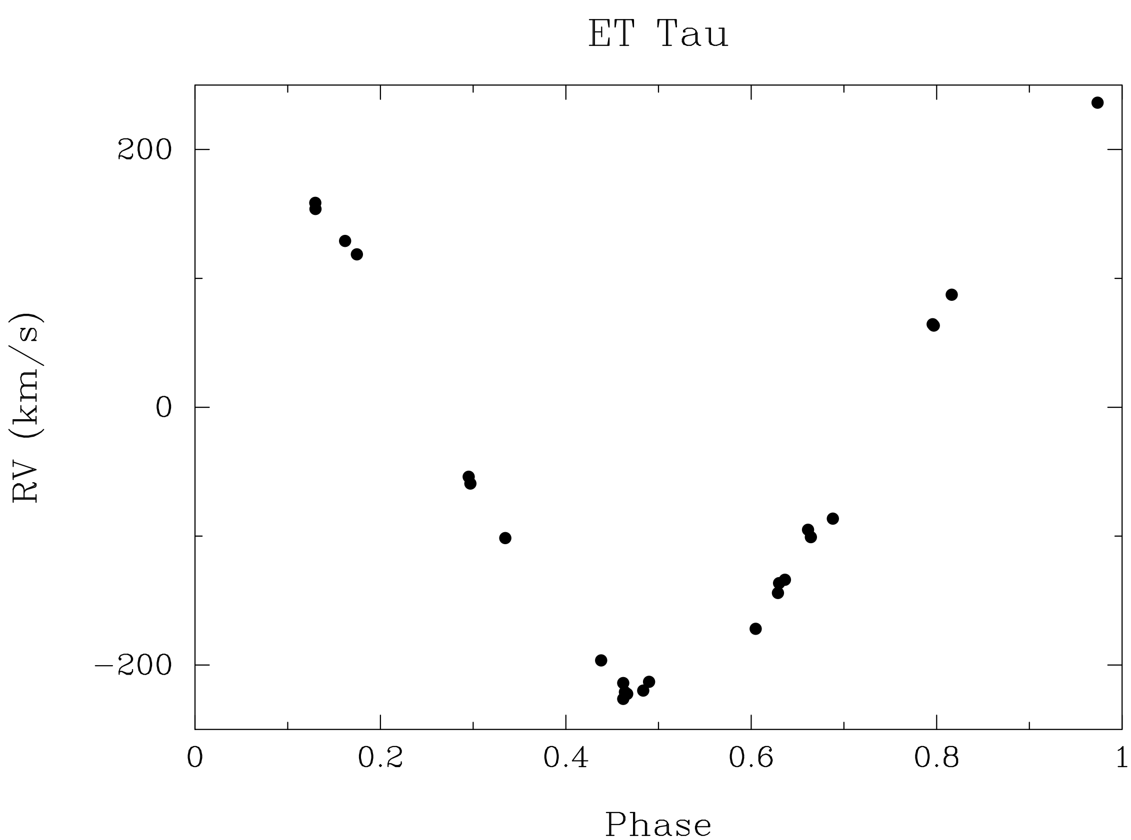

Figure 25: Single Line Radial Velocity Plot vs. Phase for the Secondary Component of ET Tau Binary System

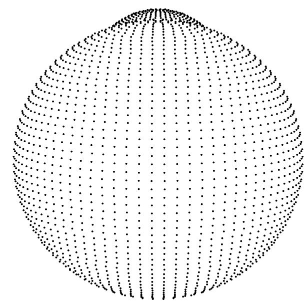

Figure 26: 0.00 Phase Model Solution for ET Tau

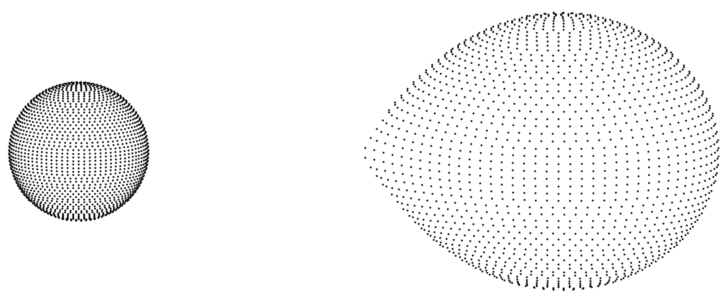

Figure 27: 0.25 Phase Model Solution for ET Tau

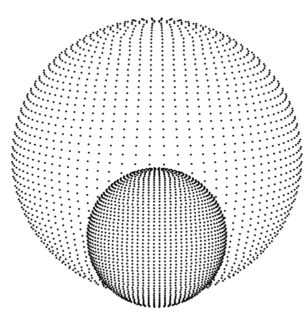

Figure 28: 0.50 Phase Model Solution for ET Tau

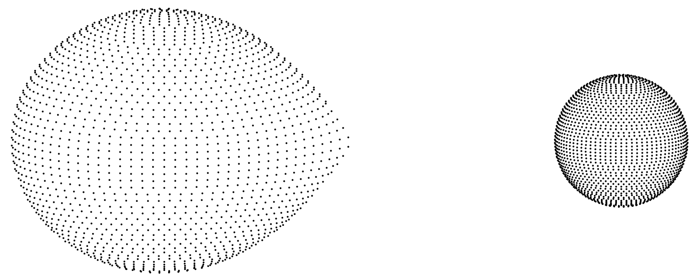

Figure 29: 0.75 Phase Model Solution for ET Tau

Table 1: Solution Parameters for Theoretical Light Curve

Parameter	Value
Inclination	80.46°
Mass Ratio (M_2/M_1)	0.436
Primary Temperature	23600 K
Secondary Temperature	11400 K
Surface Potential of Primary	7.340
Surface Potential of Secondary	2.900
V Band Relative Luminosity of Primary	5.06765
B Band Relative Luminosity of Primary	5.08325

Table 2: Orbital Elements of ET Tau Binary System

Orbital Elements	Value
Mass of Primary ($M_\odot$)	16.43
Mass of Secondary ($M_\odot$)	7.17
Mean Radius of Primary ($R_\odot$)	5.77
Mean Radius of Secondary ($R_\odot$)	12.32
Semi Major Axis ($R_\odot$)	39.80
Period (days)	5.996879
Epoch (HJD)	2429362.3715

Table 3: Spectral Typing Based on Spectra and Theoretical Temperature Solutions

System Component	Spectral Type
Primary	B1
Secondary	B8

3.5 Discussion

According to our initial period analysis of the Emory and Fernbank data, there has been no significant period change in the last 27 years between these times of observation. From our model of ET Tau found through the W-D differential corrections code at Georgia Institute of Technology, we have a model of a semidetached Algol binary system seen in Figures 26-29. Our solution provides a good fit for both the B and V filter light curves, as seen in Figure 20 and 22 respectively, and solidifies that our solution represents well the physical system of ET Tau. The good fit of the radial velocity curves with our solution also provides evidence that this solution matches the physical parameters of the system. The solution provided that the inclination of the system is 80.46° as seen in Table 1. The reported epoch and period used to phase all data together were respectively 2429362.3715 and 5.996879 days seen in Table 1. This is an update from the original analysis of the Fernbank data using an epoch and period of 2429362.3730 and 5.996879 days respectively. As we can see the epoch was only updated slightly, while the period used for solving the light curve remained the same. We have a surface potential of 7.340 for the primary component, and a surface of 2.900 for the secondary component seen in Table 1. The mass ratio was found to be 0.436 and can be seen in Table 1, where the mass ratio is the mass of the secondary component divided by that of the primary component. The primary component is thought to be a B1 type star with an effective surface temperature of 23600 K. The secondary component is thought to be a B8 type star with an effective surface temperature of 11400 K. This classification for the secondary component was confirmed with the spectral data obtained from Dr. Frank Fekel. The system is thought to have an eccentricity of zero based on the sine nature of the radial velocity plot in Figure 25, as well as the secondary eclipse occurring at a phase of 0.50. The system is thought to be two very hot B type stars and fits the classification of an Algol system. The primary component is thought to be rapidly rotating, thus blurring out its constituent spectral lines from the spectrum obtained by Dr. Frank Fekel at Tennessee State University. The B-V plot found in Figure 24 shows a trend of a fairly constant B-V magnitude throughout different phases. Since we know that we are seeing both components even during eclipse, we cannot use this diagram to tell definitively the spectral type of a single component. The fact that it is rather constant even through eclipse suggests that the components are of similar spectral types. The residual vs. phase plots in Figures 21 and 23 indicate that our theoretical solution fits well to the observed data, and thus we can conclude that the parameters that make up our theoretical solution likely describe the physical properties of binary star system ET Tau.

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