A MODEL FOR A CONTACT ECLIPSING BINARY SYSTEM IN THE FIELD OF KOI 1152

by

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ABSTRACT

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An unanticipated result of researching transiting planet candidates from the Kepler spacecraft mission was the discovery of several variable objects in the fields of some of the targets. One particular object, which it was determined had not been previously documented, had a light curve that indicated it was a contact eclipsing binary star system. We found that this object has a period of about 0.3462 days. We worked to find a model that best fit our observed data of this system. Our results indicate that the two stellar components have similar temperatures, one around 6240 Kelvin, and the other is about 110-130 K warmer. The mass ratio is about 4.5, and the system is nearly edge-on relative to the plane of the sky. We emphasize the inconclusive nature of our results as other models may also be valid and more data is needed to confirm the binary nature of this system.

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1. Introduction

1.1 Background

When we view a clear night sky, the distant stars look to be hundreds of isolated points of light. Our own solar system contains only one star, with the nearest stellar neighbor more than four light years away. But it turns out that our Sun is an anomaly. It is estimated that more than half of the stars in our galaxy are members of multiple star systems, consisting of two or more stars orbiting around each other. A system with just two stars is called a binary system. Studying binary systems can yield fundamental stellar parameters, such as mass, that can't be found from single stars alone, so these objects are very valuable to astronomy.

Astronomers often study celestial phenomena by studying an object's light curve. This is a plot that shows how the object's magnitude, or brightness, varies over time. When a binary system is oriented such that the stars' orbital plane is edge-on as seen from Earth, the two stars will pass in front of, or eclipse, each other. This produces periodic decreases in the amount of light that reaches Earth from the system, and thus there are corresponding drops in the light curve. The stars are so far away that even through a telescope, the individual stars in a binary system cannot be resolved visually and appear as a single point of light. A light curve, however, contains valuable information and can be used to find such parameters as the period of the orbit and the relative brightness of the two binary components. A basic eclipsing binary and its resulting light curve are shown in Figure 1.

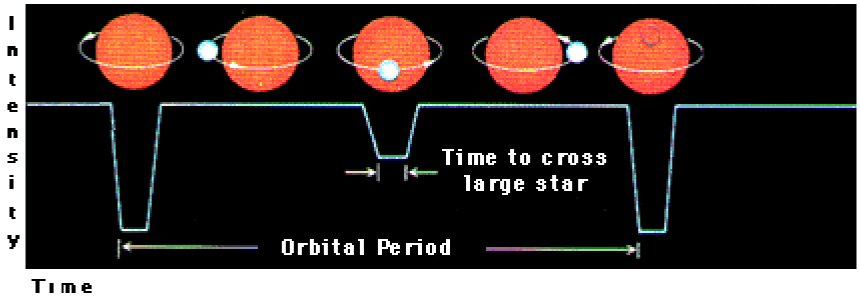

Figure 1. An eclipsing binary system and its resulting light curve, showing the brightness of the system (y-axis) over time (x-axis). Each drop in light corresponds to an eclipse. The depth of the eclipse depends on the temperature of the blocked star. Hotter, bluer stars produce greater drops in the brightness of the system, regardless of the radii of the stars. Image from http://imagine.gsfc.nasa.gov/YBA/HTCas-size/binary-model.html.

The orbital period is easily found by measuring how long it takes the system to complete one cycle. It is determined by the stars' masses and orbital separation as shown in Newton's version of Kepler's third law:

$$P^2 = 4\pi^2 a^3/G(M_1+M_2).$$

P is the orbital period, a is the separation, M_1 and M_2 are the masses of the components, and G is the universal gravitational constant. The width of an eclipse in a light curve indicates how long it takes one star to cross the face of the other, and from this information and knowing the period, the relative radii of the two stars can be determined. A star's radius is usually correlated with its mass, but this relation is often broken in binary systems due to tidal forces between the two stars or the transfer of mass from one component to another (Coughlin 2007).

The eclipse depths are determined by the relative temperatures of the two stars. Each star emits a spectrum of light, a range of colors all across the electromagnetic spectrum, but not every wavelength is emitted in the same amount. A star's color is determined by the wavelength of light at which the star gives off the most energy, and this in turn is directly related to its surface temperature. Hotter stars appear bluer and cooler stars appear redder. In addition, hotter stars give off more energy per unit surface area at all wavelengths than cooler stars do. This is seen in the Stefan-Boltzmann law,

$$F = \sigma T^4,$$

where F is the energy output per unit surface area, T is the temperature, and σ is a constant. In eclipsing binary systems, this means that the greater eclipse depth occurs when the bluer star is blocked by the redder one. It also means that comparing the two depths can give the stars' relative temperatures.

The shape of a light curve can also indicate the presence of starspots, analogous to sunspots on the Sun. These are regions of strong magnetic activity that are cooler and thus dimmer than the rest of a star's surface. Starspots are often included in models of eclipsing binaries to account for asymmetries in the light curve (Coughlin 2007).

Eclipsing binaries are classified based on how close the two components are relative to their radii, and thus can be considered detached, semi-detached, or in contact. Each star in a binary system is surrounded by an imaginary teardrop-shaped boundary called a Roche lobe (see Figure 2). On this boundary, there is zero net force from the two stars. If each star is within its Roche lobe, the system is considered detached – the stars are physically separate from each other. If one of the components is large enough to fill its lobe, matter will flow onto the other star through the point where the two Roche lobes meet, called the inner Lagrangian point L1. This type of system is referred to as semi-detached. If both stars fill their Roche lobes, material flows between them and the system is known as a contact binary because the stars are actually in physical contact and share a common outer envelope (Coughlin 2007).

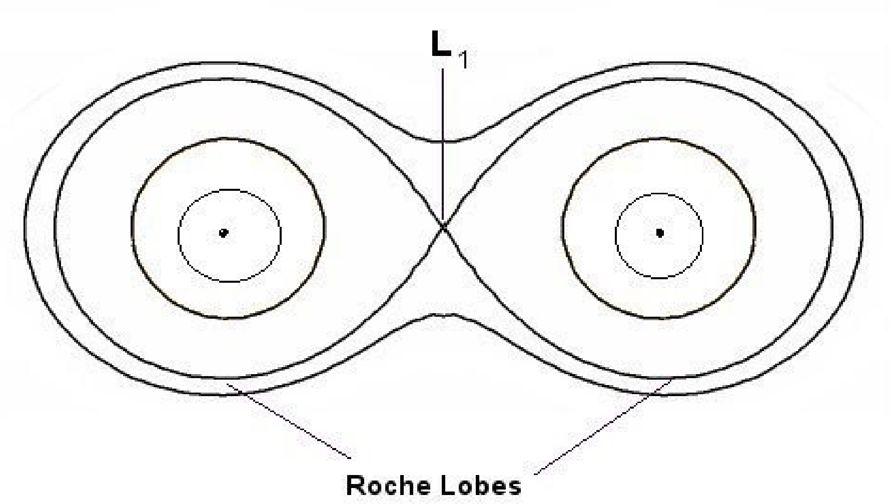

Figure 2. The Roche lobes and inner Lagrangian point L1 of a binary system. Image from http://ericfdiaz.wordpress.com/dispelling-a-common-misconception-about-novae/.

1.2 The Kepler Mission and the Discovery of A New Contact Binary

For several years, the Kepler space telescope monitored thousands of stars in an area of the sky near the constellation Cygnus. Its goal was to look for changes in brightness of these stars that could be indicative of a planet passing in front of the star and blocking some of its light. Many hundreds of exoplanet candidates have been discovered using this method. These need to be followed up with ground-based observations to confirm the existence of a planet or mark the candidate as a false positive. With so much more amassed data than Kepler scientists could hope to sort through within a reasonable time, the information has been released to the public to allow any astronomers to follow up on these Kepler Objects of Interest, or KOIs.

Astronomers from Brigham Young University (BYU) used the 0.9-meter optical telescope at the university's West Mountain Observatory to obtain data on several KOIs in 2011 and 2012. The images were calibrated and analyzed using various packages and scripts within a computer program called IRAF (Image Reduction and Analysis Facility). After correcting for sources of noise inherent in the telescope system, these programs perform aperture photometry on each image frame. These processes will be explained in greater detail in a later section; for now, suffice it to say that the result of aperture photometry is the magnitude of a star. The magnitude is found for the target star as well as for an ensemble of other theoretically stable stars in the same field. The target star's magnitude is compared to the average magnitude of the ensemble stars in order to cancel out sources of noise that affect the whole field of view, such as thin clouds; this is called the star's differential magnitude. For this method to be effective, the ensemble stars need to be rather stable; otherwise, they introduce variabilities into the light curve of the target that are not actually intrinsic to the target star.

It was while checking for the stability of the ensemble stars in the field of a transiting planet candidate, KOI 1152, that researchers at BYU found one star to be highly variable. It was determined that this star had not previously been documented as such, and based on the shape of the light curve, it was initially thought that it was an intrinsically variable star called a Delta Scuti variable, a type of star that physically changes in size and brightness. A portion of the light curve is shown in Figure 3. The y-axis is the object's differential magnitude, and the x-axis marks the time in Heliocentric Julian Days (HJD). Note that the scale on the y-axis increases going downward. This is because the magnitude scale is backwards, such that a lower number indicates a brighter star. The Julian Date is the number of days that have passed since January 1, 4713 BC at noon in Greenwich England, while the heliocentric correction accounts for the Earth's movement about the Sun which varies the distance, and thus light travel time, between Earth and a star over the course of a year (Coughlin 2007). More data was taken on this object and through closer inspection of the light curve, the researchers realized that it more closely resembled the curve of a contact eclipsing binary system. The symmetry of the rises and falls as well as the brief flattening out of the minima suggest the occurrence of eclipses. In addition, the fact that the maxima are not flat lines indicates the contact nature of the system.

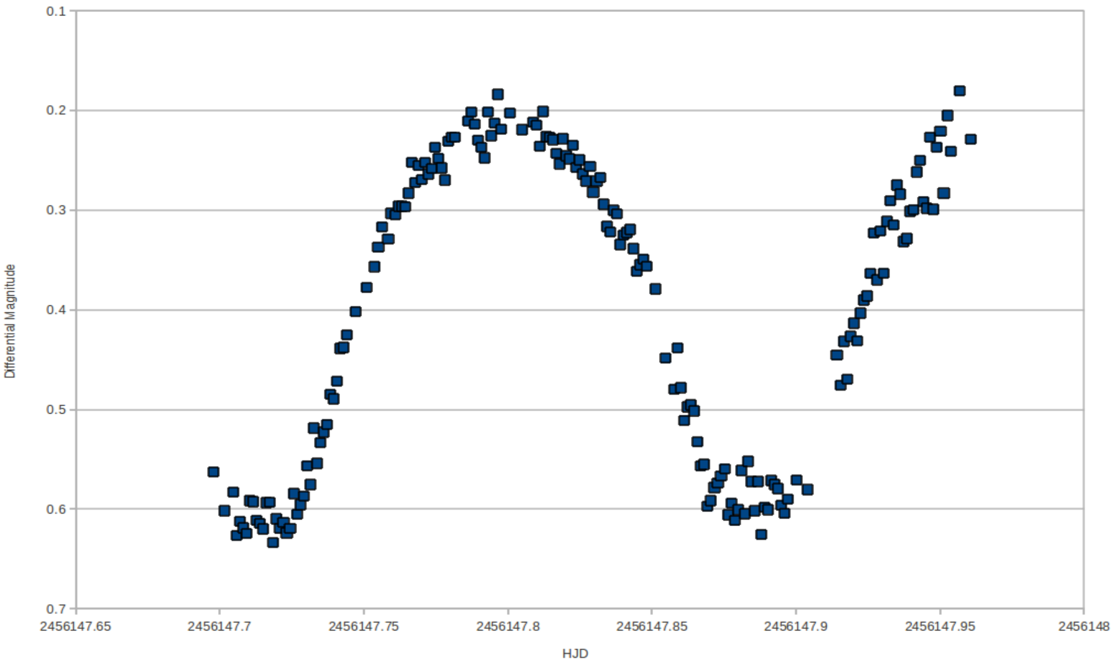

Figure 3. A portion of the light curve of the contact eclipsing binary candidate. This is data taken throughout a single night and spans about six hours. Examination of this light curve indicated that the object was likely an eclipsing binary instead of an intrinsically variable star.

This thesis gives a model for the system, which will be referred to as 1152EB hereafter in this work. But this isn't the only variable object found near a KOI; some target fields that we have studied have several variable stars that may not be documented yet. We submit that Kepler fields as well as other exoplanet surveys provide rich opportunities not only for studying possible exoplanets, but also for discovering other unknown interesting variable objects.

2. Observations and Processing

2.1 Telescopes

The majority of telescopes in use today consist of a system of curved mirrors that direct incoming light onto a detector. Telescopes can be thought of as light buckets: the larger the mirror diameter, the more light it can collect and the more powerful the telescope.

Most telescopes use a charge-coupled device, or CCD, as a detector. A CCD camera can be pictured as a grid of tiny wells, called pixels, that collect incoming photons. When a photon enters a well, it knocks loose an electron from a layer of silicon on the CCD, which is recognized by the detector as a count. Obviously, the brighter a star is, the more photons reach the CCD and the more counts will be detected. And the longer the detector is exposed to the sky (i.e. the longer the integration time), the more photons will be received from a star. A pixel can only handle so many counts, though, and above this limit, the well starts to “overflow” into nearby pixels. When this occurs for a star, it is said to be saturated. Hence, care is taken not to overexpose an object of interest. On the other hand, the integration time should be long enough to produce a good signal-to-noise ratio, or S/N. The CCD also collects photons from other sources like the background sky. The S/N is the ratio of the signal detected from the target to the background noise in the image. In addition, images are usually taken in a filter, which allows only light within a certain wavelength range to reach the CCD. The most common filters in the visible light range are U (ultraviolet), B (blue), V (yellow-green), R (red), and I (infrared) of the Johnson/Cousins system.

We obtained data on our contact eclipsing binary candidate using BYU's 0.9-m optical telescope at West Mountain Observatory on eleven nights in 2011, 2012, and 2013. The CCD on this instrument is a 3056 x 3056 array of 12 μm pixels. It has a plate scale of 0.49 arcseconds per pixel, meaning that the total angular area of the sky that can be imaged is 25.2 arcminutes by 25.2 arcminutes. For comparison, the angular size of the full moon in the sky is about 30 arcminutes across. Data were taken in the B, V, R, and I filters of the standard Johnson/Cousins filter system. In our analysis, we used 872 images in V, with integration times ranging from 30 seconds to 90 seconds; 186 images in I, which were exposed for between 45 seconds and 60 seconds; 136 frames in B which were exposed for 120 seconds; and 134 frames in R, with exposure times of 90 seconds.

2.2 Data Reduction

A CCD image is subject to three main sources of noise from the system electronics: readout bias, thermal noise, and varying sensitivity across the detector. Each of these is corrected with a certain kind of calibration frame. When an exposure concludes, the pixels are read out, essentially emptied of their electrons which are measured and used to create an image. This process, however, introduces readout noise to the detector so that there is some level of bias (Coughlin 2007). This offset is accounted for by taking images of zero seconds, with the shutter closed. These bias frames, or zeros, are averaged and subtracted from the image of the starfield, sometimes called the science frame, as well as the other calibration images.

The second source of noise comes from the thermal energy of the electronics. The heat in the system causes some electrons to break free of the silicon layer on the CCD, despite the fact that the camera system is usually cooled to tens of degrees Celsius below freezing. This so-called dark current is continuous and accumulates during the exposure. To correct for this, astronomers take dark frames, which are exposures taken with the shutter closed for at least as long as the science frame integration time. Like the zeros, dark frames are averaged and subtracted from the image and the remaining calibration frame.

Finally, the pixels on a CCD have varying degrees of sensitivity to incoming photons. Accordingly, the detector is exposed to a source of uniform brightness, such as a part of the sky at twilight, to create flat field frames. Flats are normalized and averaged, and the science frame is divided by the averaged master flat. The science frame, cleaned up with the calibration images, is then ready for analysis as it now will give a much more accurate measurement of the photons from the stars and the background sky.

Our images of star fields were processed and calibration frames were applied using the computer package IRAF. IRAF contains many scripts and programs that are extremely useful in preparing images for analysis and extracting data from them. In the *ccdred* package, the commands *zerocombine, darkcombine*, and *flatcombine* were used to create master bias frames, darks, and flats, respectively. *Ccdproc* is used to apply the master calibration frames – subtract the biases and darks and divide by the normalized flat. The images are then reduced and ready for scientific analysis.

2.3 Photometry

Photometry is the process by which light from a star is measured to find its apparent magnitude. Although the light from a distant star is essentially a point, it will be spread out over many pixels on the CCD due to refraction of the light as it passes through Earth's atmosphere and diffraction as it passes through the optics of the telescope. In aperture photometry, a circle is drawn around a star such that it contains about 85% of the star's light – enough to measure the brightness of the star without containing too much of the noise from the background sky. The light contained within the circle is added up to find the star's magnitude.

A star's magnitude found via aperture photometry, however, isn't always an accurate measure of how bright the star actually appears at Earth. This is because measured starlight is affected by several things, such as moonlight, sky glow, or high cirrus clouds that still can be observed through but which block some of the light. In addition, as the field of view moves across the sky, it is subject to changes in the amount of atmosphere through which it is seen, i.e. less atmosphere overhead and more atmosphere closer to the horizon. The amount of atmosphere between an object and the telescope is called its airmass, and a greater airmass means that more light is absorbed and scattered. To compensate for these effects, astronomers use the process of differential photometry. Instead of just looking at the magnitude of the star of interest, astronomers compare it to the average magnitude of one or more nearby stars in the field. This is because the whole field of view will be affected by these distortions by approximately the same amount. It is necessary, though, that the comparison stars be relatively stable so that they don't introduce variabilities into the light curve of the target that are not intrinsic to it. Accordingly, if one comparison star is chosen, another check star is selected to verify the stability of the comparison star.

A program called *brightER* (Ranquist 2013), which was developed at BYU, performs the task of aperture photometry in quite an efficient manner. It has the ability to select many ensemble stars in the field and save their positions in a coordinate file. Comparing multiple stars is advantageous because it helps reduce errors in the differential magnitude. For each frame, the program chooses an aperture radius that will include as much of a star's light as possible with minimum sky background, and then measures the contained light to get the star's magnitude. It does this automatically for each frame, pausing only when there is an error from a star being too dim or from the stars shifting across the frame enough that the coordinate file can no longer match up.

Once the magnitudes for the target and ensemble stars have been obtained, the data is run through a program called *Varstar*. This program computes errors in magnitude for each of the stars so that the user can find those of high variability and remove them from the ensemble. Thus what remains is a group of stable comparison stars that can be used to find an accurate differential magnitude for the target star.

3. Light Curve Analysis and Modeling

3.1 Standard Stars and Color Indexes

A star's apparent magnitude indicates how bright it appears to observers on Earth. It is a function of the star's intrinsic brightness, or absolute magnitude, and its distance from Earth. But the magnitude of a star detected by a certain telescope varies according to particular observing conditions, such as sky brightness, and the specifics of the telescope system. To account for the inevitable discrepancies among different observations, astronomers have found precise apparent magnitudes relative to the star Vega for groups of stars called standard stars. These standard stars have known actual apparent magnitudes in multiple colors, or filters. Standards are observed and used to find a zero point, a value that indicates the offset of the instrumental magnitude relative to the true apparent magnitude according to the Vega system. This gives an accurate stellar magnitude in several filters, and this information gives a star's color and thus temperature.

From a compilation of observations of the standard star field SA110-503 (Landolt 1992), we derived a linear relation between the zero point and the airmass for the 0.9-m telescope. Using this, we determined that 1152EB has an average V magnitude of about 16.44 and ranges from about 16.17 to 16.83. Additionally, we found the color indexes to be approximately B-V = 0.51, V-I = 0.63, V-R = 0.34, and R-I = 0.27. Based on the table for main sequence stars in Flower (1996), from the B-V color index we estimated the temperature of the eclipsing binary to be 6240 Kelvin (K). In most cases during modeling, we fixed this as the temperature of the primary component and allowed the secondary temperature to vary.

3.2 Vartools

The *Vartools* program (Hartman et al. 2008) is a collection of algorithms with a variety of capabilities. Using the Analysis of Variance period search algorithm, we found that 1152EB has a period of 0.3462 days, which is about 8 hours 18 minutes (Schwarzenberg-Czerny 1989, Devor 2005). In addition, we used the Phase command to combine several nights of data by plotting it according to its position in the orbital cycle. Phase plots are shown in Figures 4 through 8.

3.3 Phoebe

Most of the modeling was done with a program called *Phoebe* (Prša and Zwitter 2005), which is designed specifically for eclipsing binaries and uses the Wilson-Devinney code, a primary method for modeling these objects (Kallrath and Milone 1999). Phoebe can take several light curves as input and then allows the user to adjust parameters until the synthetic curves produced by the models match well the observed data. The main parameters we hoped to find were the temperatures of the two stars, the mass ratio, the degree to which they are in contact with each other, and the inclination of the system's orbital plane relative to the plane of the sky. Phoebe is also capable of producing images of binary systems based on calculated parameters, and these are also included in this paper.

We worked to fit five different types of models to the eclipsing binary system:

overcontact binary of the W Uma type, overcontact binary not in thermal contact, double contact binary (where each component exactly fills its Roche lobe), semidetached with the primary component filling its lobe, and semidetached with the secondary component filling its lobe (Kallrath and Milone 1999). In accordance with the color indexes we found, we fixed the temperature of the primary component at 6240 K in each model. We allowed the secondary temperature to vary in each case except for the W Uma type model, where we also set the secondary temperature at 6240 K to keep the parameter values from blowing up.

4. Results

4.1 Parameters of 1152EB

In Table 1, we present the resulting parameters from modeling with Phoebe. For reference, Semidetached 1 refers to the semidetached model in which the primary component fills its Roche lobe, and Semidetached 2 refers to the semidetached model in which the secondary component fills its lobe. Additionally, the hotter stellar component is generally referred to as the primary, though terminology may vary (Kallrath and Milone 1999). In Phoebe, the primary star is the one eclipsed at phase 0. It can be seen in the table that some models converged to results in which the secondary component has a higher temperature, showing that the deeper eclipse actually occurs at phase 0.5, though the depths are so similar that it is difficult to tell a difference. Finally, an inclination of 90° means that the binary is edge-on.

	Secondary Temperature	Mass Ratio (secondary/ primary)	Degree of Contact	Orbital Inclination
Double Contact	6380 K	4.00	0.0%	90.79°
Semidetached 1	6239 K	0.23	17.9%	87.18°
Semidetached 2	6351 K	4.76	46.7%	92.08°
No Thermal Contact	6370 K	4.43	27.9%	89.41°
W Uma Type	6240 K	4.48	38.5%	86.81°

Table 1. Parameter results for the eclipsing binary from five different models. The primary temperature was fixed at 6240 K, while the secondary temperature was allowed to vary in all but the W Uma type model. Mass ratio and orbital inclination were also allowed to vary. The degree of contact was calculated from values of potentials found from Phoebe.

We also present, in Figures 4 through 8, visual interpretations of the modeling results. The left panel in each figure shows the phased observed data for each filter, shown as points, overlaid with the synthetic light curve as black lines. The right panel shows the binary stars at phase 0.25 of their revolution; these images were produced by Phoebe.

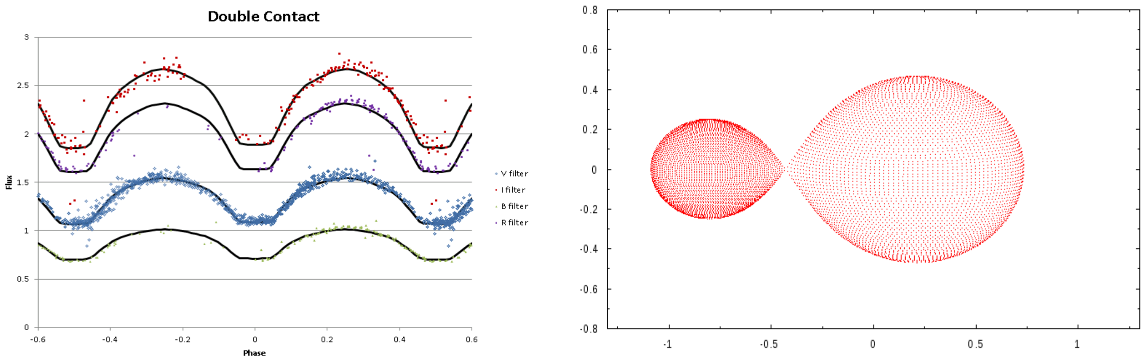

Figure 4. Double contact binary model. The left panel shows the observed data compared with the calculated solution. The points represent observed data, with each curve showing a different filter. In order from top to bottom, the I filter is shown in red, R filter in purple, V filter in blue, and B filter in green. The spacing of the data from different filters reflects the color indexes of the system. The black lines represent the best fit solutions in each filter. The right panel shows a visual interpretation of the system at phase 0.25, as generated by Phoebe.

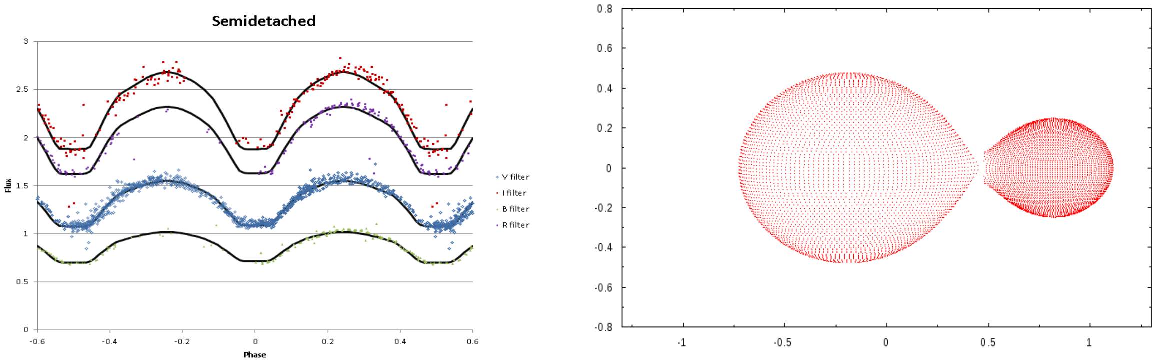

Figure 5. Semidetached binary model where primary component fills its Roche lobe. See Figure 4 for description.

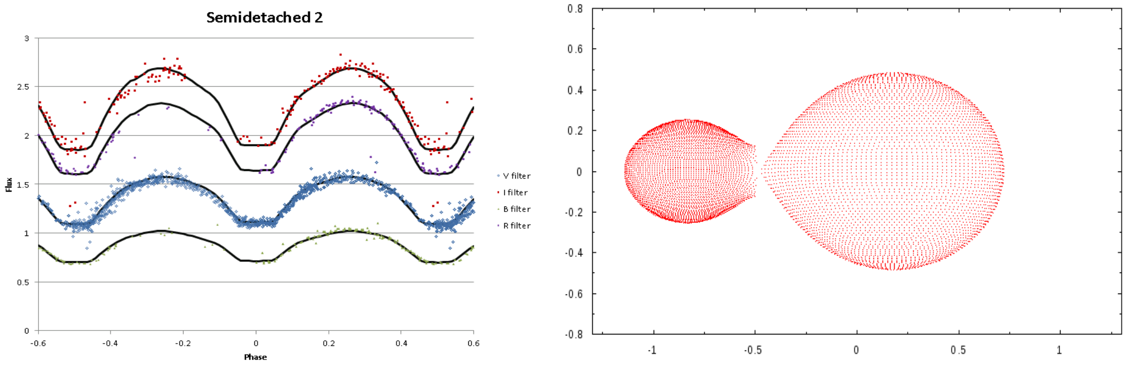

Figure 6. Semidetached binary model where secondary component fills its Roche lobe. See Figure 4 for description.

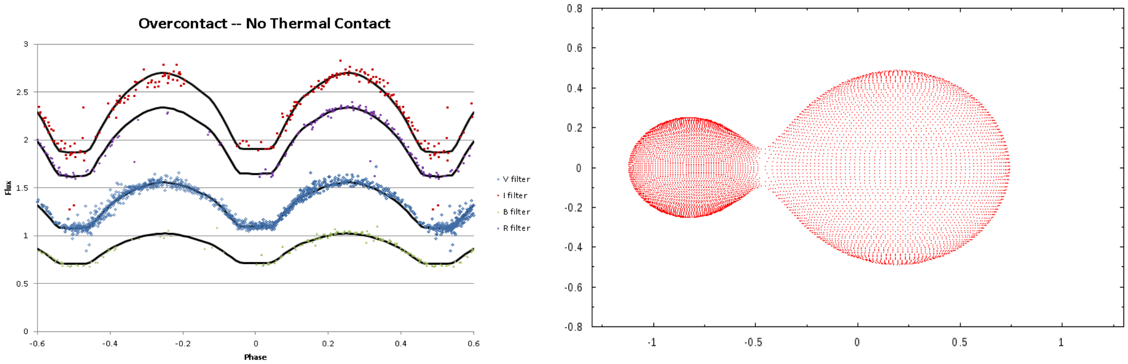

Figure 7. Overcontact binary model, not in thermal contact. See Figure 4 for description.

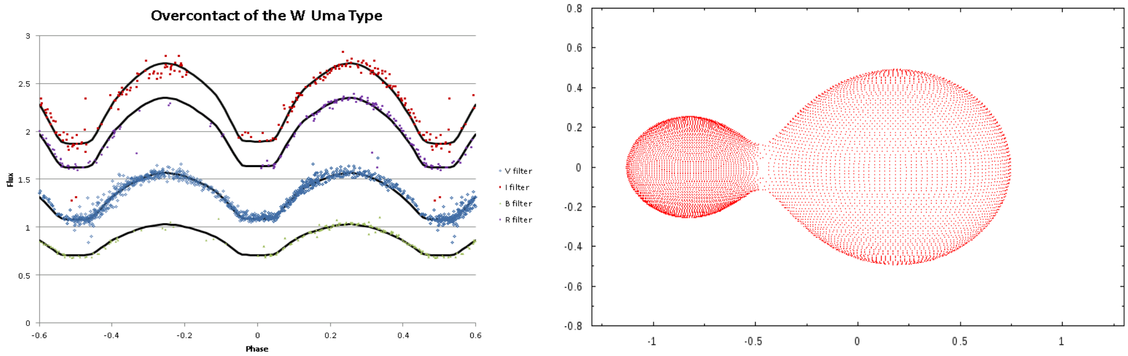

Figure 8. Overcontact binary model of the W Uma type. See Figure 4 for description.

4.2 Discussion of Results

The models all converged to solutions that are in fairly good agreement with each other. The results suggest that the 1152EB orbits nearly edge-on to the plane of the sky and that one component is 4-5 times more massive than the other. Both stars also have very similar temperatures, in accordance with our initial inspection of the light curve.

Although similar in general, close examination of the solution curves compared with the observed data shows that some solutions fit better than others. When the results in all filters are considered, it appears that the best solution is provided by either the Semidetached 2 model or the Overcontact model not in thermal contact. We therefore suggest that, according to these models, one star has a surface temperature of 6240 K while its companion is about 4.5 times more massive and 110-130 K warmer. The main discrepancy between these two solutions is the degree of contact, but the range is less than 20%, so even though we don't pinpoint one definite value, we know that the stars are indeed significantly in contact. These results also suggest that the components are not in thermal contact yet and still have slightly different temperatures, though perhaps over time the system will evolve to a thermal contact state.

The primary and secondary eclipses appear from the light curves to be evenly spaced, with minima occurring at phases of 0 and 0.5, respectively. This indicates that the stars' orbit has a very low eccentricity, i.e. is nearly circular, as might be expected for a contact system. Indeed, attempts with Phoebe to find the eccentricity resulted in minuscule values.

Consecutive maxima of different heights may result from starspots or other magnetic activity; this is often called the O'Connell effect (Kallrath and Milone 1999). Each maximum appears to be the same height, so there likely isn't much of anything of that sort in this system. Nevertheless, it may be valuable to try model 1152EB with spots to see if that has any noticeable positive effects.

4.3 Conclusion and Future Work

We have presented several possible models for the eclipsing binary system 1152EB, which has a period of 0.3462 days. We have determined that either the semidetached model or the overcontact model not in thermal contact provides the best fit to our observed data, but we hope to further refine our solution by continuing to work with Phoebe and introducing new parameters such as dark spots on one or both of the stars. More images of the system would also be valuable. The light curves in all filters except for V are incomplete. Filling in this missing data would help to refine the solutions. More images in all filters will help to reduce errors. Data taken on good nights could also help refine the color indexes. We emphasize that the other models may still be valid; more work is needed to confirm the nature of the system. What we have presented are simply the best results we have so far.

It should also be noted that we cannot yet completely rule out the possibility that this is an intrinsically variable star without radial velocity measurements, which involve the analysis of the object's spectral lines. Radial velocity observations can also reveal absolute values for parameters like mass that can only be found in a relative sense with light curves alone. Analysis of observations over longer timescales may show that the period changes over time. An analysis of this sort is usually presented in papers on contact eclipsing binaries, but we have not done it with 1152EB because our data only spans two years. Thus, more data, both spectral and photometric, would be useful in confirming the nature of the system and studying how it changes over time.

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