
HR 5171, Simulating a Massive Contact Binary

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Submitted in fulfillment of the senior thesis requirement of the
Department of Physics at Allegheny College
and approved by the senior thesis committee.

Dr Lombardi

Date

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Date

I hereby recognize and pledge to fulfill my responsibilities, as defined by the Honor Code,
and to maintain the integrity of both myself and the College community as a whole.

Signed: _____

Zachary J. Bauer

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- Dr. Lombardi: You have forgotten more about Astrophysics than I will ever learn. Your expertise has been invaluable over this process, and for that I am eternally grateful.
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Abstract

HR 5171 is a binary star made up of a Yellow Hyper Giant primary and a main sequence secondary star characterized by a large circumstellar medium. Observations indicate the system is eclipsing and causing fluctuations in the luminosity of the system. Simulations are performed to put constraints on the system to more accurately determine the masses of the system.

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Chapter 1

Introduction and Background

In early 2014, scientists began to study the archival data of HR 5171, a yellow hypergiant (YHG) that resides towards the center of the Milky Way Galaxy. Chesneau et al. (2014) aimed to observe both the long-term evolution of the radius of HR 5171 and any short term mass loss events. The rarity of YHGs drew Chesneau et al. to study HR 5171, and he was able to rely heavily on archival data to draw conclusions about HR 5171, and its evolution. In his review of over 60 years of photometric data, a level of asymmetry was observed, and attributed to a newly discovered secondary star. Observations indicated that the secondary orbits with a period of 1304 ± 6 days. The two stars are also thought to be in either a contact or over contact binary, meaning the outer layers of the stars are touching, in an orientation that allows us to observe the stars eclipsing. The binary nature of the stars means HR 5171 is a prime candidate for study with a Smoothed Particle Hydrodynamics (SPH) code (Section 2.1). This code allows us to study binaries in detail, and observe how changing parameters affect the orientation and interactions within the binary system.

1.1 HR 5171 and its Roche-lobe

HR 5171A, the primary star of the binary, is characterized by high luminosity, or rate of energy release, and rapid mass loss. The evolution of a YHG involves movements across the Hertzsprung-Russel (HR) diagram, which shows how stars relate based upon temperature and luminosity. HR 5171A begins its life on the main sequence, which can be seen in Figure 1.1, where it quickly burns through much of the hydrogen fuel in its core. At this point of stellar evolution, HR 5171A begins to expand and fuse hydrogen in the core rapidly, creating a helium rich center. As the star runs out of hydrogen, the stars intense gravity causes

helium to fuse in the core, a process referred to as the helium flash. After the helium flash, it begins climbing the HR diagram, increasing in luminosity. The abundance of material in the star allows it to continue fusion, pushing it further up the HR diagram. HR 5171 currently sits at the top of the HR diagram because of its high luminosity and large radius. The rate of fusion quickly uses up available fuel, shortening the remaining life time of the star.

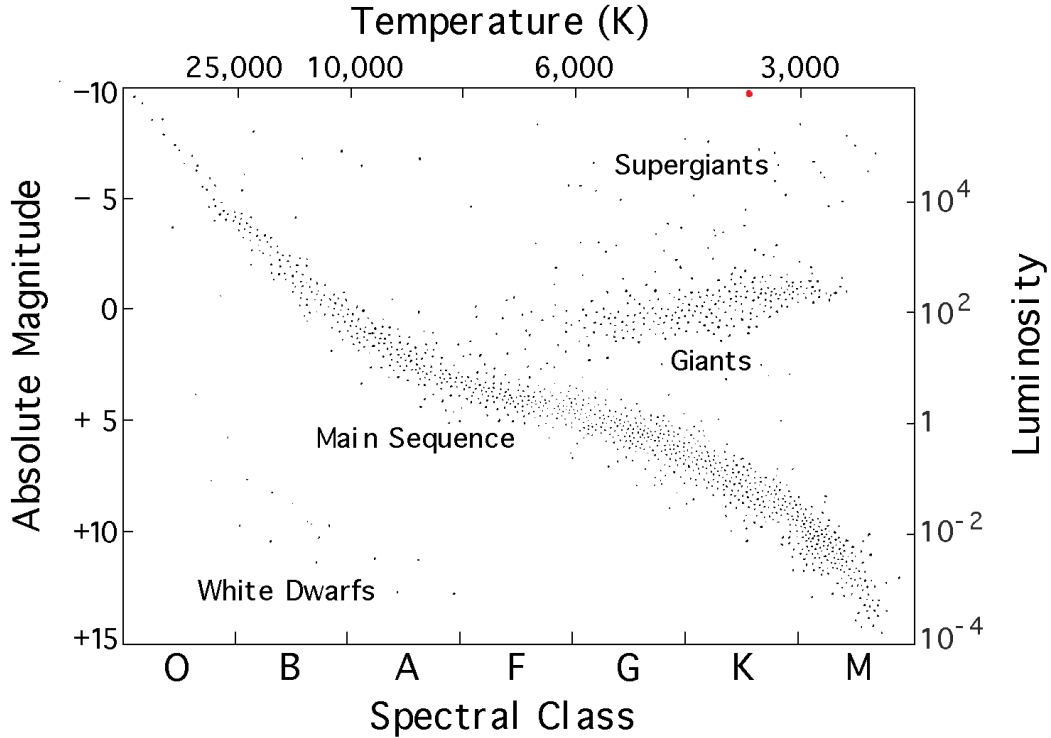


Figure 1.1: HR Diagram showing how temperature and luminosity relate during the evolution of stars. HR 5171A has a luminosity of $\log L/L_{\odot} = 5.7 - 6$ (Chesneau et al.) and spectral type K. Its likely location of the diagram is represented by the red dot. (From USCD.edu)

The system is thought to be undergoing Roche-lobe overflow. This overflow is characterized by mass from the primary moving to the secondary as a result of the primary becoming too large and having some amount of mass escape the gravitational influence, or Roche-lobe, of the primary. In binary systems, some of the mass lost by the primary can flow through the inner Lagrangian point, or point of equal gravitational influence between the stars, and move into the gravitational influence of the secondary. The particular Roche-lobe overflow is thought to be Wind Roche-Lobe Overflow (Abate et al. 2013, WRLOF), which is caused by stellar winds and will be talked about more in-depth in Section 2.3. These winds are the result of radiation pressure from within the star. According to Chesneau et al., the

primary fails to fill its Roche-lobe without the WRLOF mechanism, but the strong solar wind associated with post-main-sequence stars fills the lobe, and encourages mass flow to the secondary. While some of this mass is gravitationally transferred to the secondary, much of it escapes the system and exists as circumstellar material in the area of HR 5171.

1.2 Observations of HR 5171

Observations of this system were taken over several nights in 2012, by the Paranal Observatory in Chile. These observations of the flux of the system, with wavelength in the near infrared, give us information about the binary configuration of the star system. By measuring the angular size of the system, Chesneau et al. were able to establish limits on the radius of the primary, and resolve the secondary star against the backdrop of the primary. These observations allowed Chesneau to confirm a large circumstellar environment around the star. The contribution of flux from the secondary can also be determined from these observations. It is expected that $7 \pm 2\%$ of the observed flux comes from the secondary while the stars are eclipsing. The overall change in flux due to the eclipse is $17 \pm 5\%$ (Chesneau et al.).

Observations indicate the primary has a mass of $39^{+40}_{-22} M_{\odot}$, and a radius of $1315 \pm 260 R_{\odot}$. The secondary, HR5171B, is thought to be a main sequence star, characterized by a mass ratio $q \leq 10$, meaning the mass of the secondary is 0.1 times the mass the primary, as an upper limit. Observations indicate the secondary has a radius of $400 R_{\odot}$ which is useful in determining the interference that can be expected when the secondary eclipses the primary.

These observations can also be taken to be indicative of a fairly recent outburst, which contributed to the circumbinary environment. It can also be expected that these large mass loss events contribute to a less than smooth light curve, showing the turbulence the stars go through as they evolve. This turbulence can lead to rare stars, and future observations may very well lead to a clear view of the evolution of these stars.

Chapter 2

Theory

2.1 Smoothed Particle Hydrodynamics

In order to study HR 5171, I am using a Smoothed Particle Hydrodynamics code (SPH code). In an SPH code, stars are modeled as a collection of fluid blobs, often referred to as particles. These blobs are a contrast to grid based codes in that they allow for a more free flow of material and the particles are not limited by grid size, meaning material can easily escape to infinity without wasting computing resources. These blobs of fluid are first laid out in a hexagonal close-packed lattice structure to match the density profile of a star. The close-packed lattice structure is chosen because it has a high particle density, simple configuration, and is close to the end state of a star allowing the star to settle to equilibrium faster. The next step is to relax the star. Relaxation entails allowing the code to balance pressure and gravity forces within the star. These pressure and gravity forces are calculated within the code and then allowed to act upon the particles for a small time step. These forces are diminished by a drag force during relaxation to ensure small movements of particles. The forces are then calculated again, accounting for the new positions of the particles. This process is allowed to continue until the star has reached a stable configuration. In order to model the star accurately, a smoothing length is used to calculate the pressure forces within a star. A smoothing length, h , is used to establish a sphere of influence around a particle. Within that sphere, a particle has a number of neighbors. Depending on the distance from the particle, the neighbor has a different influence on the pressure forces being calculated. A function determined using a smoothed quantity can be given by the integral interpolant,

$$A_s(\vec{r}) = \int A(\vec{r}') W(\vec{r} - \vec{r}', h) d\vec{r}', \quad (2.1)$$

where the integration is over all space and W is an interpolating kernel. When particle separation is small, the kernel is near its maximum. As particles approach a separation of $2h$, their influence falls off and particles past a separation of $2h$ have no effect on hydrodynamic forces.

The computer treats this formula as a summation of all particles within the star, indexed over b . The summation is given by

$$A(\vec{r}) = \sum_b \frac{m_b}{\rho_b} A_b W(\vec{r} - \vec{r}_b, h), \quad (2.2)$$

Though done over all particles, the summation falls off quickly as $\vec{r} - \vec{r}_b$ grows large since W goes to zero quickly. In this case, m_b is the mass of the neighbor particle, ρ_b is its density, A_b is the function, and W is the kernel. In this way we can calculate pressure forces without wasting computing time on particles far from $\vec{r}$.

If the star is laid out correctly, it will settle into the lowest energy configuration and will be entirely stable. At this point, another star can be introduced to complete the binary. How this star is introduced will be discussed in the methods section.

Once the second star is introduced, the stars will be placed into orbit. The SPH code can then model the orbits of the stars, as well as any interactions that take place within the Roche-Lobe (Section 2.3). As the stars orbit, information about their configuration is dumped into files which are then used to plot the paths of the stars. Information from these files can also be used to create light curves, graphs showing visual magnitude of stars versus time, using a computation routine, which can then be compared to observations. These data can be manipulated to adjust the orbital inclination of the stars or the angle at which the system is viewed. This adjustment means the light curve can be viewed from any direction, and observe how the inclination affects the light curve. SPLASH, a program developed by D. Price (2007) allows me to create detailed visualizations of the stars, which are useful for understanding density profiles and orbital relationships.

2.2 Equations of Motion

Two equations govern the movements of SPH particles. To calculate particle movements due to pressure forces we use

$$\vec{a} = -\frac{\nabla P}{\rho} \quad (2.3)$$

where a is the acceleration, P is the pressure gradient, and ρ is the density. Using equation 2.2 and applying the gradient the acceleration of particle a due to particles b is given by

$$\vec{a}_{a,p} = - \sum_b m_b \left(\frac{P_b}{\rho_b^2} - \frac{P_a}{\rho_a^2} \right) \vec{\nabla} W. \quad (2.4)$$

This is one of the fundamental SPH equations that governs particle movements due to the particles near it.

Gravity forces are calculated with a summation as well, though this time, it considers all particles rather than just particles within a smoothing length. Thus, the equation for the acceleration due to gravity on a particle is given by,

$$\vec{a}_{a,g} = \sum_b \frac{Gm_b}{r_{ab}^3} \vec{r}_{ab} \quad (2.5)$$

for particles where r_{ab} is the magnitude of $\vec{r}_{ab} = \vec{r}_b - \vec{r}_a$. Here m_b is m_b if $|\vec{r}_{ab}| < 2h$, but if $|\vec{r}_{ab}| > 2h$ it's the portion of the mass inside of the radius. These equations are balanced by

$$\frac{dP}{d\rho} = -\rho g. \quad (2.6)$$

When equation 2.6 is true, the particles in a star are in hydrostatic equilibrium. Pressure forces within the star, as calculated in equation 2.4 are balance by the forces in equation 2.5, and particles do not move. In the event that these forces are not balanced, particle acceleration is calculated for each particle with equations 2.4 and 2.5. We apply the acceleration to all particles to update the velocity. Then a small time step is taken to move the particles, and the equations are applied again.

Without a model for the interactions within a star, I would not be able to determine the luminosity of these stars since they would appear to eclipse one another, which is what will enable me to match observations of these stars and set limits on mass and radius of the secondary. The fluid movement also allows me to observe how the Roche-Lobe of the system evolves in time. The movement of stellar material is important to the long term evolution of the system and a key part of this project. If the star is rapidly losing mass, it is extremely likely the orbit will decay, and the stars will spiral together.

2.3 Wind Roche-Lobe Overflow

HR 5171 is most likely undergoing Wind Roche-Lobe Overflow (Chesneau et al. 2014, Abate et al. 2013). This Roche-Lobe overflow is a combination of Roche-Lobe overflow associated with gravitational force, as well as stellar winds coming from the primary. Stellar winds are a flow of gas particles away from the surface of a star. These winds have many causes, depending on the conditions of the star. In stars nearing the end of their lives, like HR 5171A, this is generally understood to be the result of radiation pressure pushing on the dust that has condensed on the outer layers of the star. For binary stars, this wind is generally in the direction associated with the orbital plane of the system, or the geometric plane in which the orbit lies.

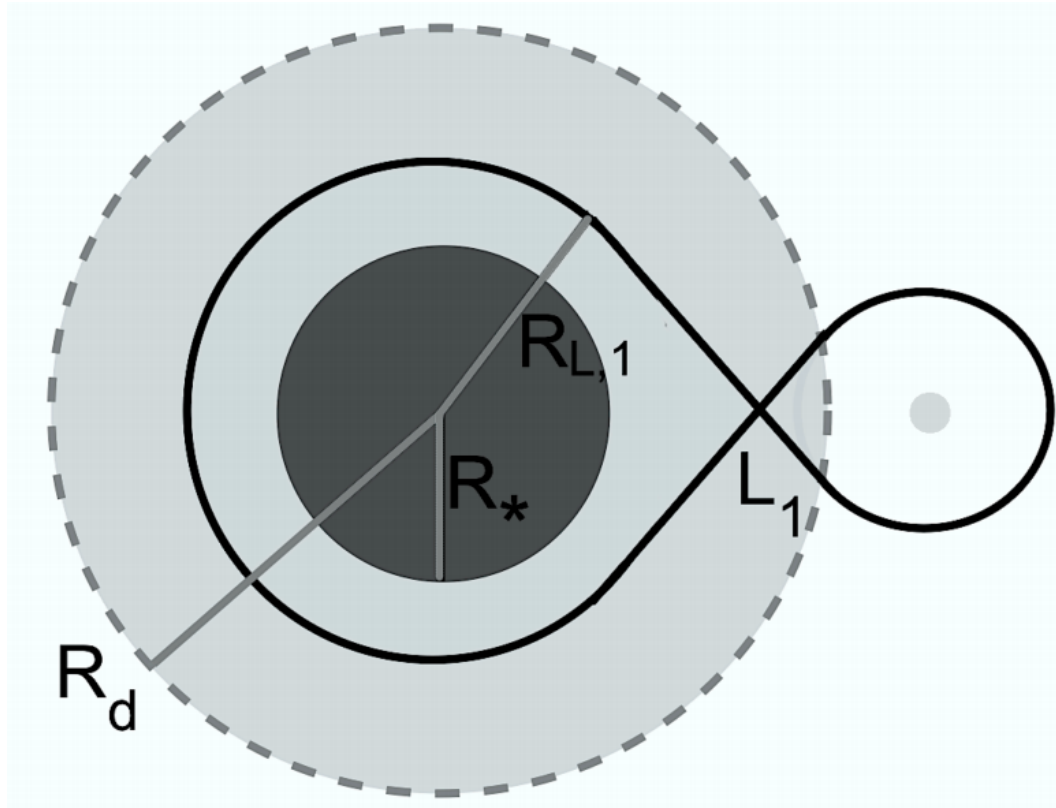


Figure 2.1: Schematic picture of the WRLOF of a star, where R_* is the radius of the star, $R_{L,1}$ is the Roche-Lobe radius, R_d is the dust radius, and L_1 is the inner Lagrangian Point. Sizes not to scale. Source: Abate et al. 2013

The effect of this wind causes much higher than expected mass transfers to the secondary, and an extended region of mass that has not been accreted onto the secondary. Figure 2.1 shows how HR 5171 fits inside its Roche-Lobe, and how the wind moves mass from the star.

Figure 2.2 shows potential energy, as it relates to the Roche-Lobe.

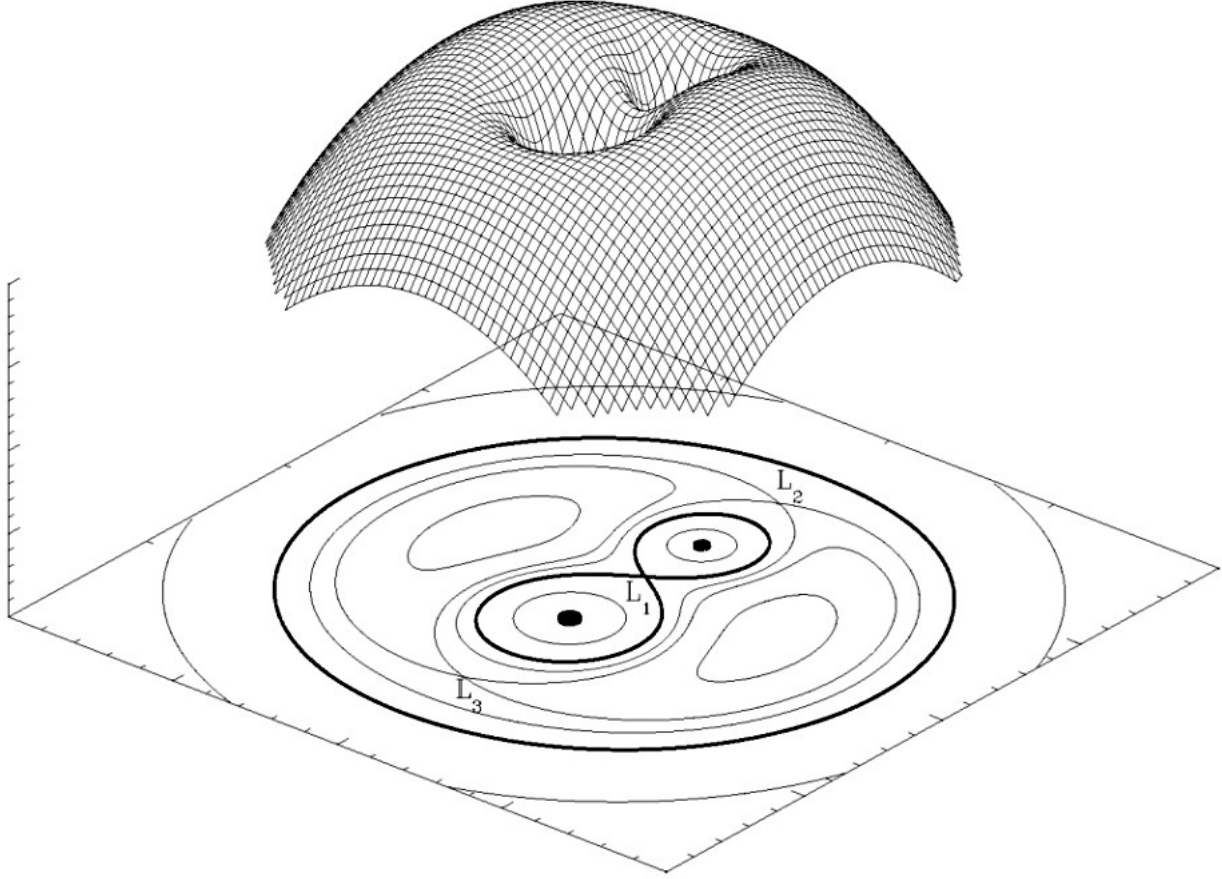


Figure 2.2: The grid pattern shows the effective potential wells that exist as points corresponding to the Lagrangian points on the lower plane. The black line shows the Roche Lobe of a binary. (Taken from Wikipedia: Roche lobe)

The likely cause of the mass transfer from HR 5171A to HR 5171B is WRLOF, and the low density region observed by Chesneau et al. can also be explained by this overflow. WRLOF can greatly alter the orbit of the system. High mass loss can remove orbital momentum from the system, which could lead to a binary collapse. Mass moving to the secondary would cause the orbit to shrink, and cause the system to rotate more rapidly, due to conservation of angular momentum.

2.4 Polytropes

A polytropic star is a star that satisfies a solution to the Lane-Emden equation,

$$P = K \rho^{\frac{n+1}{n}} \quad (2.7)$$

where P is pressure, K is a constant of proportionality, ρ is density, and n is the polytropic index. This equation is used to determine density profiles of stars, and lead to an equation of state. Low indices, generally in the range of $n = 0.5$ and $n = 1$ are used to model extremely dense objects, like neutron stars. An index of 5 is a star with an infinite radius. Equation 2.6 is also satisfied for a polytrope, ensuring the star is stable. In order to create an accurate star model, a polytope will be used to approximate the conditions of the secondary, as will be explained in Chapter 3.

Chapter 3

Methods

3.1 Star Creation and Relaxation

Creating an accurate model of a star is key in performing good simulations. In the case of HR 5171, two separate stars are required, the primary, with a radius of $1300R_{\odot}$, and a mass of $40M_{\odot}$. The secondary, with a radius of $400R_{\odot}$ and a mass of $4M_{\odot}$ is also created. The number of particles required of the primary is much larger than that of the secondary in order for the stars to have similar particle number per volume. Due to the mass overflow of the primary, a much more detailed density profile is required, and so the process of creating an accurate model is more involved than that of the secondary. For the secondary, a polytrope was good enough for the simulation, since the exact density profile of secondary stars are poorly understood.

3.1.1 HR 5171A

In order to begin my simulation, I create an initial model of the primary star, HR 5171A, using *Stargarden*, a website developed by Dr. Lombardi's former student Rebecca Kosnik to create star models. I begin by assigning initial parameters for the desired age and mass of the star. In this case, the star was evolved to 3.72 Myr, the expected age of the star, and assigned an initial mass of $43M_{\odot}$. The star is allowed to evolve, as described in Section 1.1. Eventually the star loses mass, to $39M_{\odot}$ and radius $1300R_{\odot}$. Once the star has evolved to the desired age, the star data file is moved to a different computer, where we are able to perform a relaxation run.

To begin a relaxation of a star, several parameters of the code needed to be changed.

First, I requested 800,000 particles. In early runs of the code, pressure and gravity forces were not balanced near the core of the star. This imbalance led to a strong inward force at early times. This inward force pushed the particles together, which created large pressure forces, that made the star explode, leaving a relaxed star with a radius over $5000R_{\odot}$. The large particle number creates a better resolution at the center of the star, which enables the code to accurately compute the forces at the center of the star. I also changed the number of neighbors the code initially uses in calculating the forces. Rather than the typical $\text{NNOPT}=22$, which leads to 40 about neighbors, I opted for $\text{NNOPT}=11$, which evolves the star with about 13 neighbors for each particle at early time steps. This contributed to fixing the pressure problem described earlier, because it allowed particles near the core to consider fewer particles, and be treated with a higher resolution. I also applied an artificial drag force. The drag force slows the moving of particles, again stopping the early pressure forces. Figure 3.1 shows the star at early and late time steps.

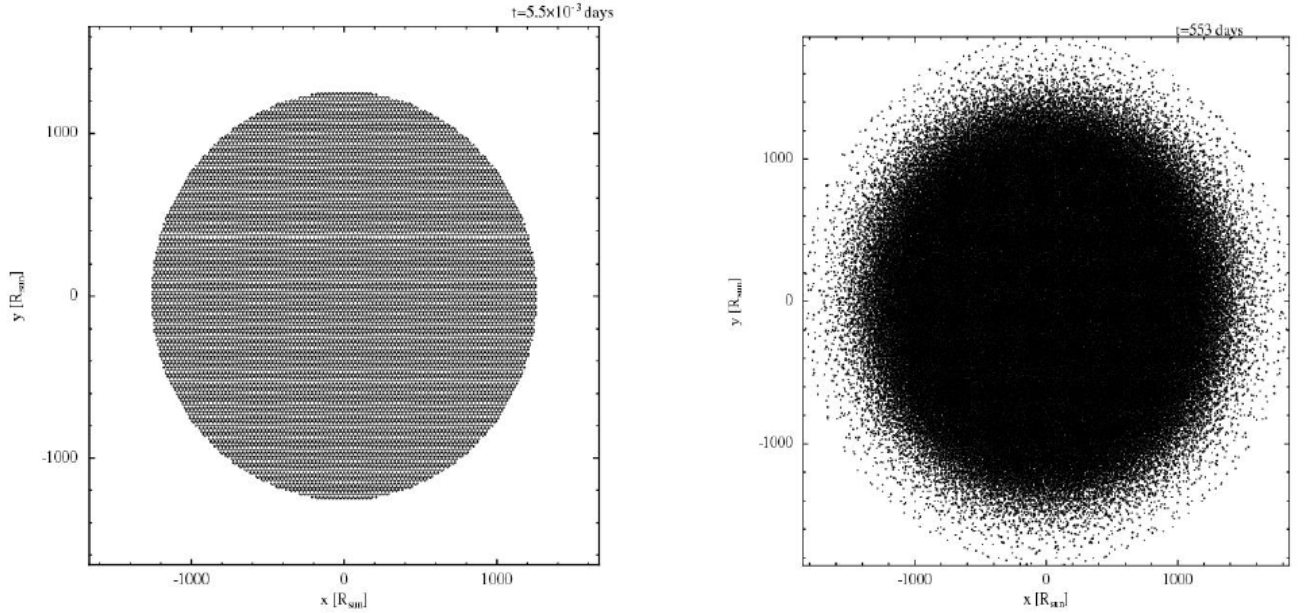


Figure 3.1: Visualizations of HR 5171A before (left) and after (right) relaxation. Notice the regularity of the close packed hexagonal lattice in the unrelaxed image, and the diffuse outer layers in the fully relaxed model.

3.1.2 HR 5171B

Initially, the secondary was a point mass. Since the resolution of the secondary is not very important, a point mass modeled it well enough. However, the point mass causes the

code to take very small time steps, so a simple polytropic star is used instead. The polytropic model used to create the secondary is using a polytropic index of $n = 2$. To arrive at this index, we simply attempt relaxations while varying the index. Two was chosen because it created the most stable relaxation at small particle numbers and large radius. The density profile may not be consistent with the actual secondary, but companion stars are poorly understood, and the massive radius of this star is most like caused by the overflow from the primary. The star mass is $4M_{\odot}$, and the radius is $400R_{\odot}$, which is consistent with what was suggested in Chesneau et al. The neighbor number is also 11, which was chosen to be consistent with the primary. The particle number, 1000, was chosen so that the outer layers of the secondary had smoothing lengths similar to that of the primary, allowing the particles to mesh together without having to resolve large differences in smoothing length.

3.2 Scanning

Once the stars are relaxed, I initiate a scanning run. In a scanning run, the two stars are placed at a large distance, in this case $3900R_{\odot}$, and marched to $1200R_{\odot}$. Small code modifications are needed to ensure that Starsmasher knows which star is which. As the stars move closer, the code will give us information about the separation of the two stars. Using

$$\Omega = \frac{2\pi}{P} \quad (3.1)$$

where P is the orbital period and Ω is angular velocity, we can determine the proper separation of the stars. Part of the data output by the code is a value for Ω . This value corresponds to an output file with the separation needed to get the desired orbital period.

3.3 Dynamical Run

Using equation 3.1, an output file corresponding to the proper separation is chosen, and the star is put into a dynamical run. The stars then orbit according to equations 2.5 and 2.4. As the stars orbit, the primary loses mass to the secondary, leading to the stars existing in a common envelope. As the stars orbit, the code recognizes the mass transfers that are occurring, and implements the changed masses immediately. This allows the orbits to change. The stars could merge, slow their orbit, or increase their orbital speed. This allows us to observe the development of the system.

Chapter 4

Results

I have successfully modeled HR5171, and allowed the system to orbit for an extended period of time. I have also been able to observe orbital period, luminosity, and orbital separation of the primary and the secondary over 10 orbits at a separation which would give an orbital period close to that observed by Chesneau et al. The ten orbits I will be examining are late in the evolution of the system. These late time steps of the system will more closely match the real system, since mass has escaped the Roche Lobe of the system.

4.1 Orbital Period

The orbital period observed by Chesneau et al. is 1304 ± 6 days. Using equation 3.1, we chose a value of Ω that corresponded to the observed period. After allowing the system to evolve, the period of the average orbit in my simulation was 1203.69 days, but it was decreasing as time went on. This give me a percent error of $5.6 \pm .4\%$. This error can be attributed to mass leaving the Roche Lobe of the system and the orbit not being entirely stable.

In order to arrive at a period of 1230.69 days I looked at separation data as well as light curve data. The actual period was calculated with separation data, which is shown in Figure 4.1. These data assume that orbital frequency and separation oscillation frequency are the same. Though the light curve data would give a more accurate prediction, since it relies solely on eclipsing and not osculations in the separation, it was not used because only data for one complete orbit was recorded. The data for this eclipsing period were consistent with that of the oscillation period, as shown in figure 4.2.

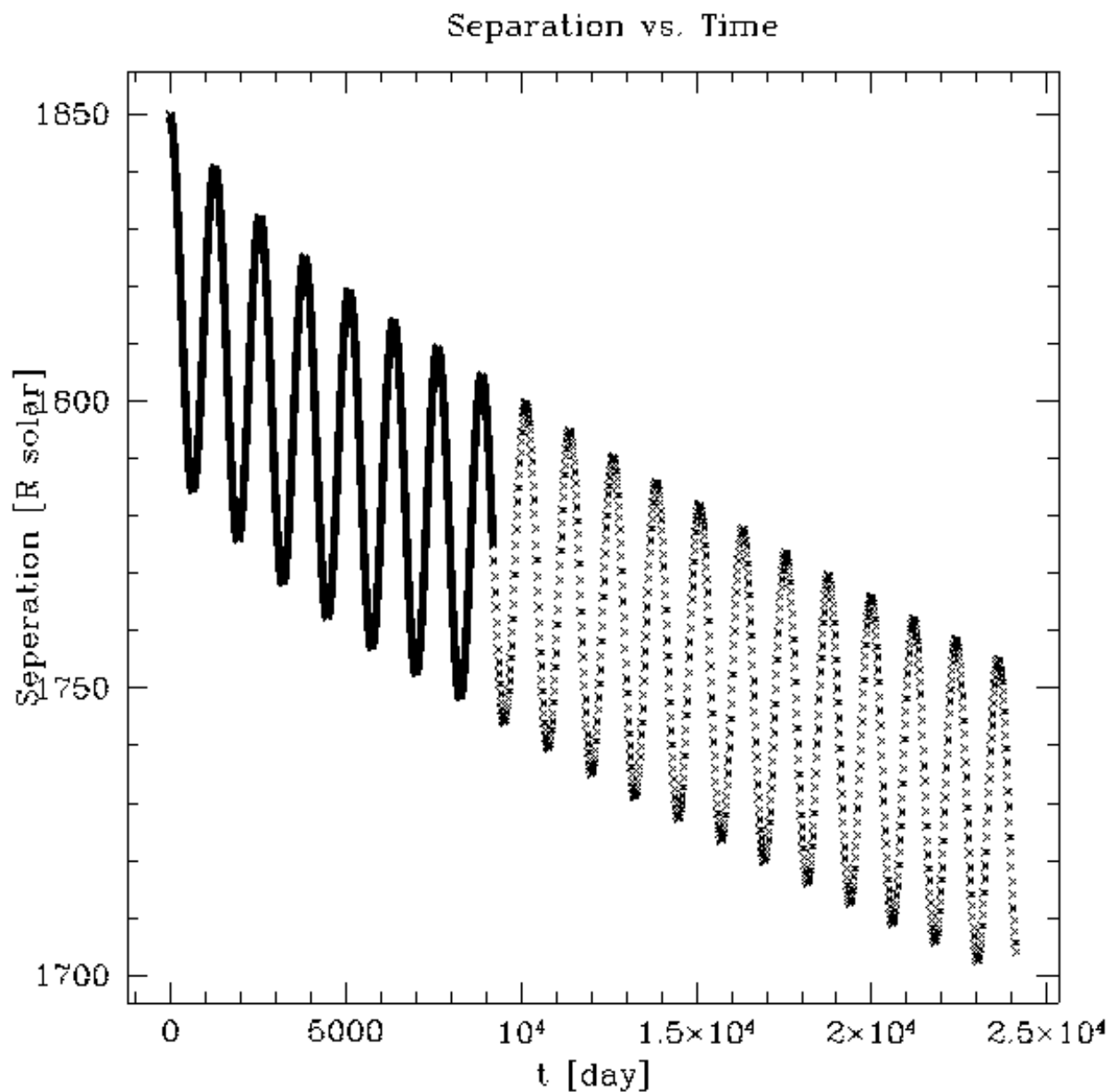


Figure 4.1: A graph showing the orbital decay of HR 5171. This data was used to calculate the orbital period of the data because of insufficient light curve data.

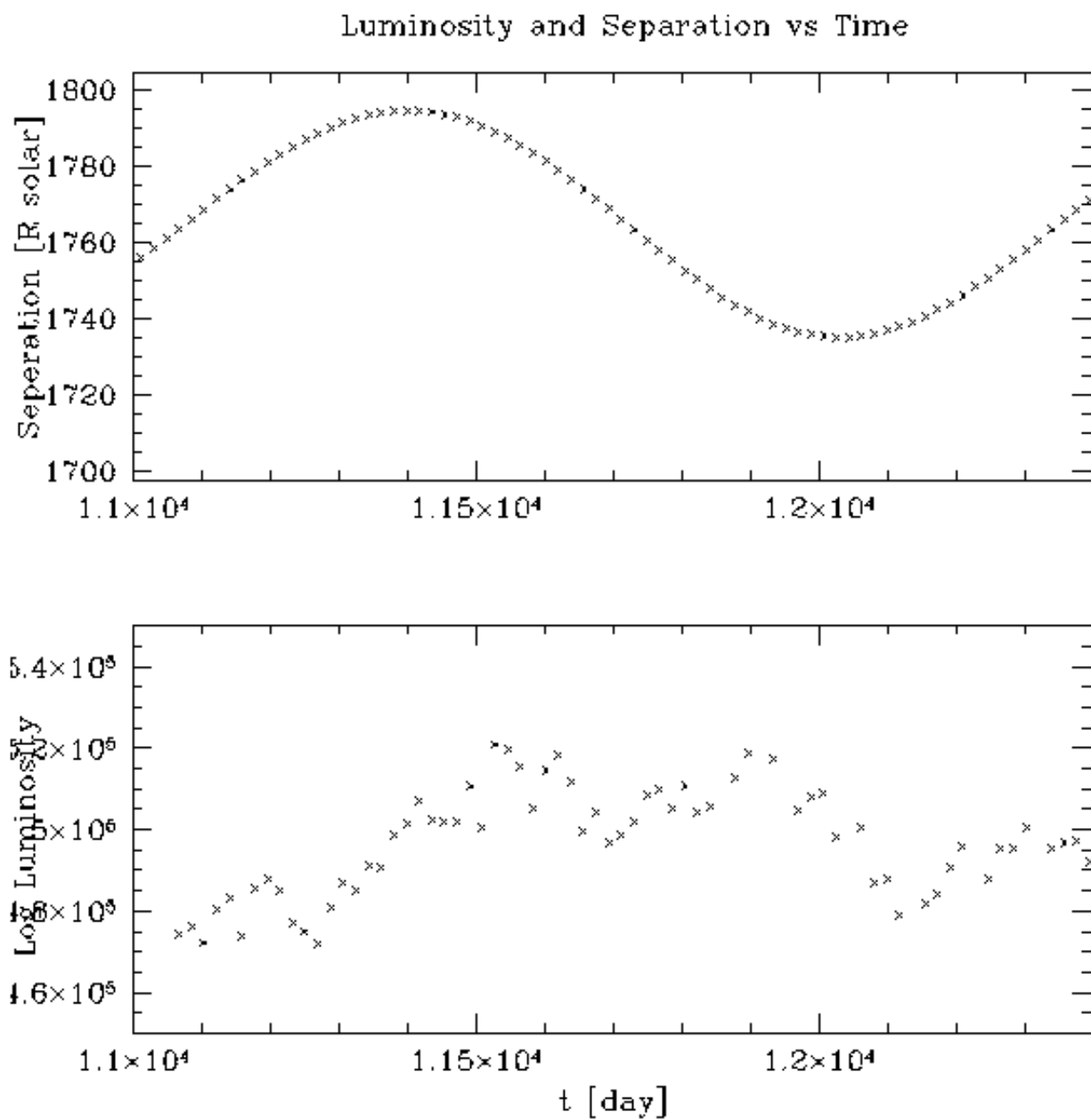


Figure 4.2: A comparison between separation oscillation (top) and light curve data (bottom) for one period of HR 5171. The low points in the light curve data correspond to a similar separation in the oscillation graph.

4.2 Orbital Separation

Chesneau et al. also put constraints on the orbital separation of the star system. Their estimates, which they used in their simulations using NIGHTFALL, put the radius between 1800 and $2600R_{\odot}$. My initial scanning run, placed my stars at $1850R_{\odot}$, which is within the parameters studied by Chesneau et al. Though my orbit decayed to $1752.94R_{\odot}$ over 15 orbits, that is still an orbit within 2% of the low end of their estimate. Figure 4.3 shows the change in orbital separation over a number of orbit late in the simulation of HR 5171. I would expect them to continue to approach no change in separation over a large number of orbits. At this point, the orbit is shrinking by 0.2% or less each orbit, which is rather insignificant.

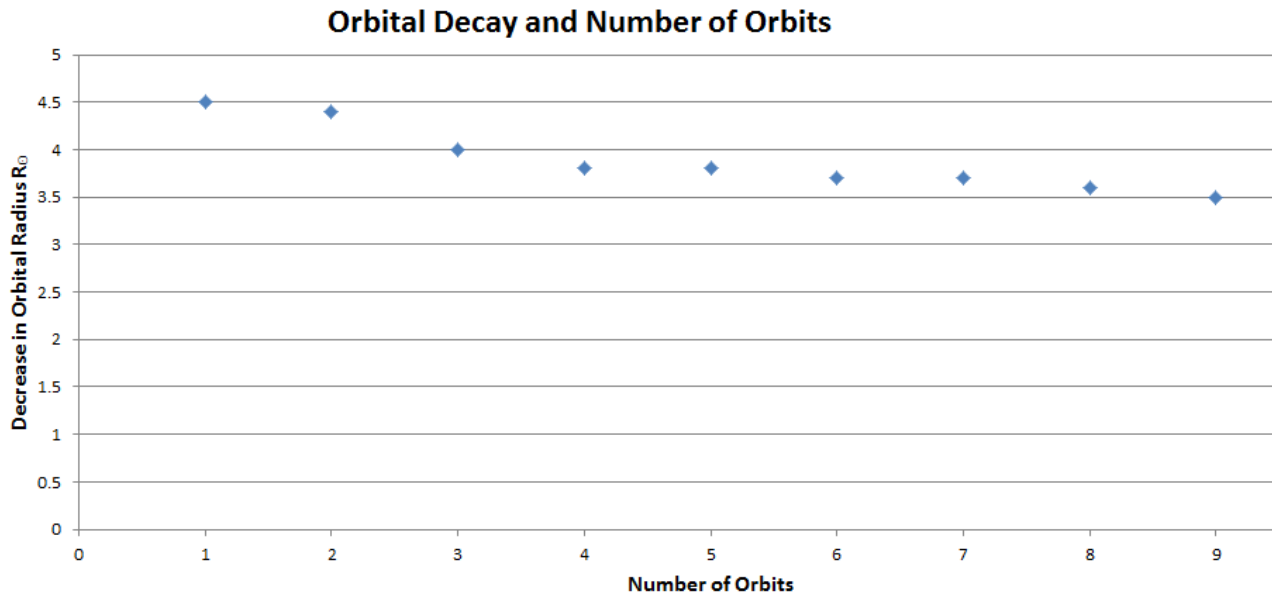


Figure 4.3: A graphic showing the change in orbital separation of the binary star system against the number of orbits completed. Notice how after each orbit the change decreases, suggesting the stars are approaching an equilibrium. The darker points indicate the initial run, while the lighter space indicate the continued run.

4.3 Light Observations

4.3.1 Luminosity

Calculating the luminosity of the system is a very computationally expensive process. As a result, luminosity data are not known for the entire simulation length. Figure 4.4 shows a luminosity curve over approximately two orbits of the star.

As can be seen in figure 4.4, there are both primary and secondary minima which are associated with eclipses of the stars. The red line indicates where the primary is hidden partially behind the secondary. The blue line primary is between the observer and the secondary. The luminosities observed, from $4.5 * 10^6$ to $5.5 * 10^6 L_{\odot}$, when we used 60° as the angle from the negative z-axis. Similar luminosities were calculated using 30° from the negative z axis, though those results were limited to much less than one orbit. This comparison of luminosity can be seen in figure 4.5 This change in luminosity corresponds to a 9.7% change in flux from the minimum to the maximum. Chesneau et al. observed a change in flux of $17 \pm 5\%$ over the course of an orbit. In order to observe this change in flux with our simulation we would need to increase the angle of observation, leading us to observe the system closer to the orbital plane.

4.3.2 Visual Magnitude

Historic observational data of HR 5171 is taken in the V band of light. This corresponds to a peak wavelength of 555.6 nm (Tokunaga, 2000). The routine used to determine the magnitude of light in a given wavelength is makes use of the equation which converts a flux density, S_V , to a magnitude, m_V

$$m_V = m_{ext} - 2.5 \log_{10} \frac{S_V}{3540 mJy}. \quad (4.1)$$

The code uses this equation to determine what the magnitude of light is focused on a band let through by a filter. In this case, the filter lets through light in the visual wavelengths, from about 380nm-700nm. Figure 4.6 shows the data generated by this routine while Figure 4.7 shows the data collected from observations.

Unfortunately, the routine to calculate the magnitude of light from HR 5171 did not provide good data. I don't think that this shows that the simulation is not accurate to the system, but rather something is wrong with the routine that computes the magnitude. Magnitude is proportional to the log of the luminosity. Since the luminosity values are so

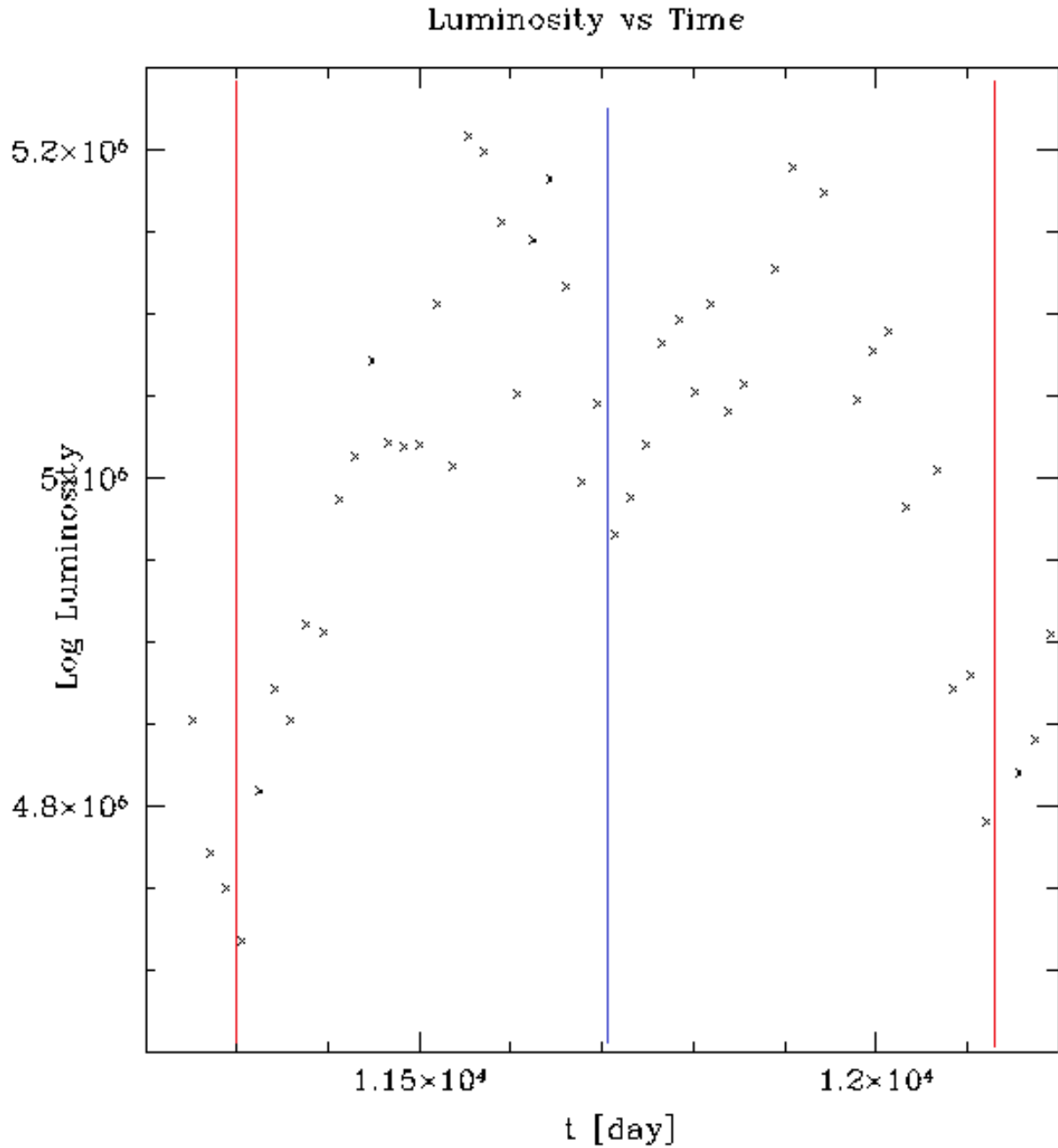


Figure 4.4: Luminosity data for HR 5171 over one orbit. The minimum shown by the blue line shows when the primary is between the secondary and the observer. The red lines are where the secondary is between the primary and the observer. This luminosity data was taken with an angle of 60° from the negative z-axis.

close to expected, I'm forced to conclude something is wrong with the way in which the magnitude was calculated.

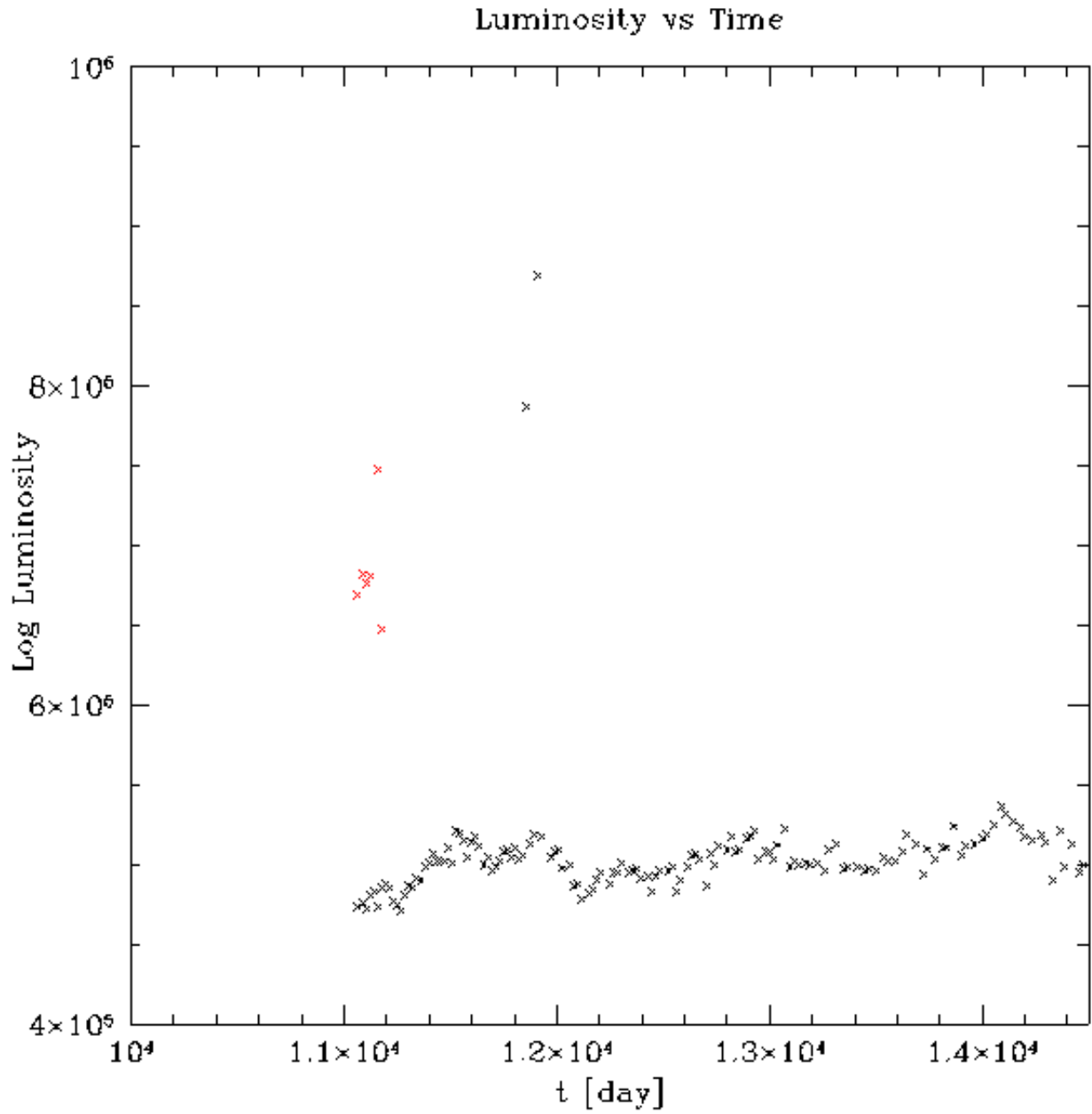


Figure 4.5: Luminosity for one simulation. Data points shown in red correspond to an observation angle of 30° from the negative z axis and black data points correspond to an observation angle of 60° from the negative z axis.

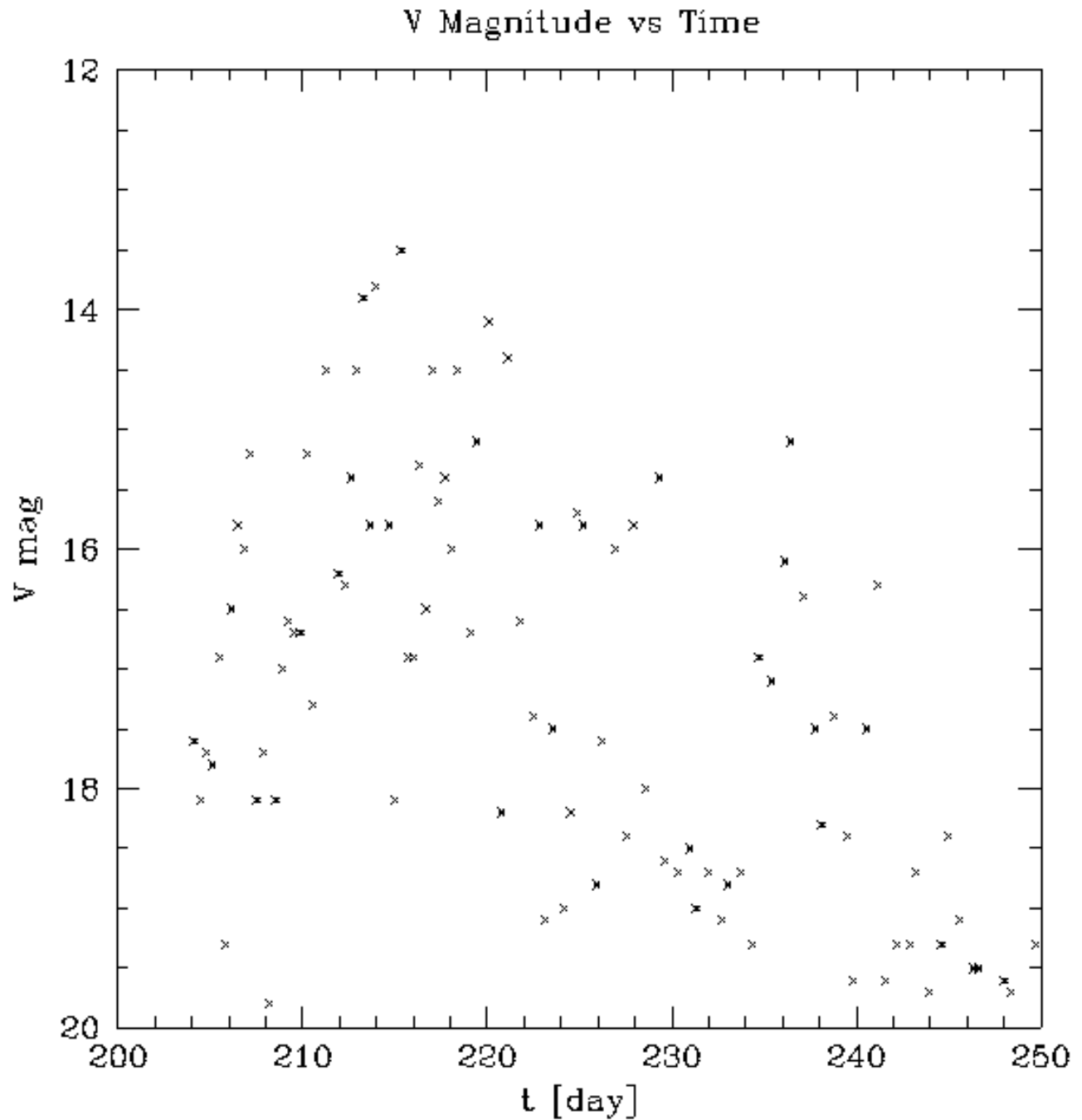


Figure 4.6: Simulation data of the magnitude of light emitted from HR 5171 in the visual wavelength vs time. Shows 2 orbits, or about 6 years of observation. Lower magnitudes means brighter light.

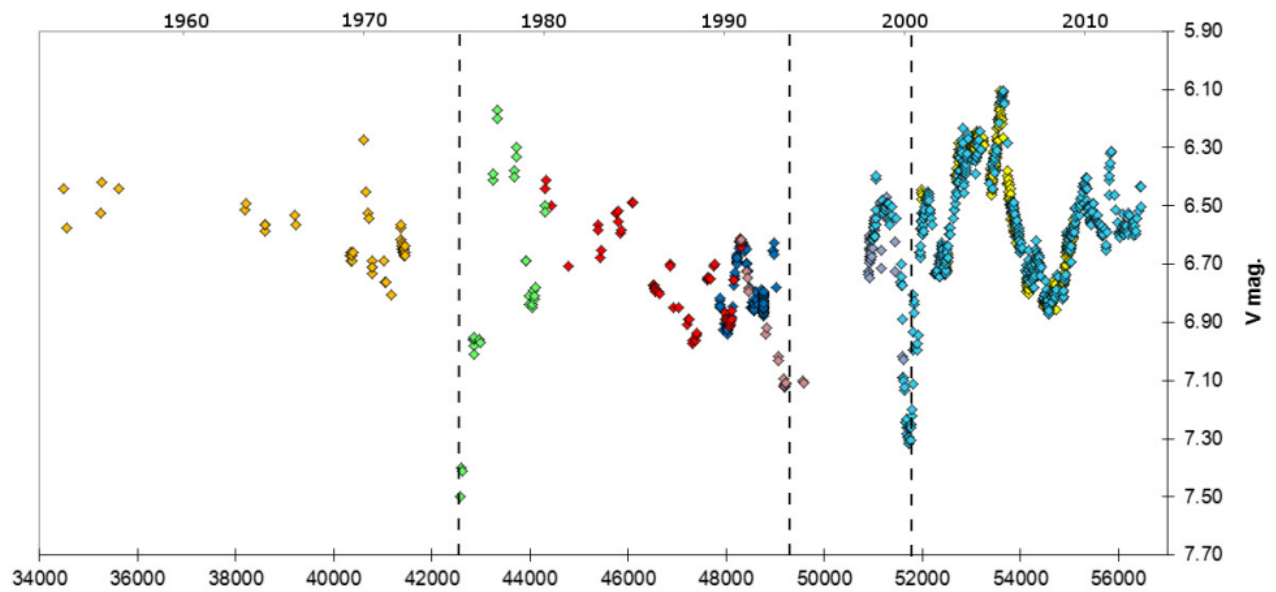


Figure 4.7: Magnitude of light emitted from HR 5171 in the visual wavelength vs time. Data spans 60 years of observation. Lower magnitudes means brighter light.

Chapter 5

Discussion and Future Work

I consider this project to be a success. While I was unable to duplicate the V mag curves provided in Chesneau et al. I was able to create a system with orbital parameters the closely matched those expected of the system. This is after relaxing a star that was several times larger than anything *Starsmasher* had relaxed before. I was able to create a luminosity graph that clearly shows the interference pattern expected from a binary star system. The change in flux as a result of this eclipsing is reasonable close to the change in flux expected by Chesneau et al.

While I didn't get to explore parameter space as much as I would've liked, I think simulations like this can lead to more being learned about the system. By scanning the secondary to $1900R_{\odot}$ and allowing it to move closer to the primary as it loses mass we can attempt to match the orbital period and orbital radius to a higher degree of precision. Unfortunately, fine tuning a system that take 3 weeks for usable data to be generated is very time consuming.

Future work on this system would include varying the mass of the secondary and changing the starting separation. It would be interesting to observe how a series of stars with starting separation varied by $50R_{\odot}$ would behave relative to each other. I would also like to see the mass of the secondary increase until the system becomes unstable and collapses into a single star, or have a low mass secondary that is allowed to escape, to put an upper and lower bound on the mass of the secondary. Of course, varying the mass of the primary would be interesting parameter space as well.

Determining the problem with the routine that failed to determine the magnitude of the system would be interesting. I would guess it is not just a scaling factor, because the magnitudes were spread over a range of 6, rather than the expected 1.1. Should that problem

be corrected, it would be interesting to see how varying the angle of observation changed the visual magnitude curve. With time, I feel we can determine a significant amount of data about HR 5171 from *Starsmasher*.

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