

A Piece of the Universe: Simulating and Rendering NGC 4349-127(b)

Using MESA and StarSmasher to simulate a system within the
newfound cluster NGC 4349 with visual rendering in Splash



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Abstract

In a newfound open cluster, a suspected red giant (NGC 4349-127) and its orbiting brown dwarf (NGC 4349-127b) are modeled in a simulation. First, MESA (Modules for Experiments in Stellar Astrophysics) is used to simulate the red giant. Then, Starsmasher is used to collide the brown dwarf and the presumed red giant. The simulation is used to confirm the existence of both interstellar objects, as well as determine if the red giant changes in terms of surface rotational velocity and mass when in a collision with the brown dwarf, or if the brown dwarf become a star or be destroyed. Finally, using the rendering program Splash, the results of each simulation are rendered into animated density and particle mass plots.

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1 Introduction

In the constellation Crux exists a cluster known as NGC 4349, and in 2007 there was a brown dwarf (NGC 4349-127b) identified to be orbiting (NGC 4349-127) which is suspected of being a red giant. [1] NGC 4349 is an open cluster found by the High Accuracy Radial Precision Spectroscopy telescope (HARPS) which found that there are higher traces of heavy elements, common in clusters that are newly formed. [2] For this study, we will be studying a system within this cluster that contains the brown dwarf and supposed red giant. It is significant to study open clusters to be cognizant of astronomical model limits. Within NGC 4349, the discovery of both NGC 4349-127 and its orbiting brown dwarf is notable since brown dwarfs are elusive to typical methods of detection. Brown dwarfs are objects found in space by using the infrared part of spectra. Whilst there is minimal data on this brown dwarf, a simulation is developed to uncover how NGC 4349-127b will behave concerning its effects on NGC 4349-127 and provide data on this unique system. Questions regarding; if NGC 4349-127 is a red giant, how it changes in terms of surface rotational velocity and mass when in a collision with the brown dwarf, or if the brown dwarf become a star or be destroyed, will be answered. To conduct this research, a program named StarSmasher utilizes data about the mass and radius of an object to simulate collisions and orbits to see a realistic result within our lifetime. [3]

2 Theory

Extrasolar planets are being identified every year, leaving astronomers with copious amounts of data to study. In turn, the study of distant interstellar objects requires the use of Newton and Kepler's Laws in correspondence with the radial velocity technique and spectra. Telescopes with methods like HARPS (which will be discussed in sections 2.4 and 2.5) allow astronomers to derive information from objects in space that is hundreds or thousands of light years away. Since NGC 4349-127b is over 7,000 light years away, these methods were critical to obtaining the information necessary to run a simulation and gather realistic data.

2.1 Brown Dwarfs

A common name for this common astronomical object is a “Failed Star” also known as a brown dwarf. These interstellar objects are known as failed stars because they cannot reach the temperature necessary for hydrogen fusion to take place, which is a requirement for an interstellar object to be categorized as a star. [2] This is due to the brown dwarf's mass, or lack of. Their mass is often measured in Jupiter masses known as M_{jup} . Since brown dwarfs lack a core that can perform hydrogen fusion, their appearance also differs from stars. Without the complete fusion of hydrogen atoms into helium, the dwarf is much duller in color as well as colder than other astronomical objects.

Only after 1990 when the Keck Telescopes were constructed was there a sensitive enough

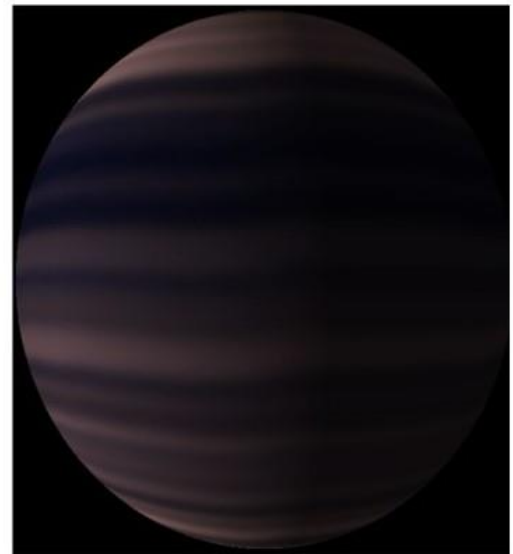


FIGURE 1: A SIMULATED IMAGE OF THE BROWN DWARF NGC 4349-127B, BY KYOTO UNIVERSITY. [7]

infrared detector built to find and record brown dwarfs. [2] This difference is the reason it is difficult to study and identify brown dwarfs, as they are not found on the same spectra as stars.

It is also important to distinguish why a brown dwarf cannot be treated as a planet. As seen in its units, M_{jup} . Jupiter is referenced due to brown dwarfs having masses that are ten times larger than Jupiter. [4] In a study by Lovis and Mayor, they found that the NGC 4349-127 cluster is profound since it is only 200 million years old. [1] Therefore, this cluster exists as an upper limit for the formation of brown dwarfs, concerning their timescale when it comes to intermediate size stars. [1] Although unable to fuse hydrogen, brown dwarfs act as the missing link between stars and planets. This study will show aspects of some of the effects brown dwarfs have on a system especially when the brown dwarfs have considerable mass and youth.

Due to this large mass that brown dwarfs possess, questions regarding the effects of its gravitational pull and its remaining hydrogen arise. Three types of simulations are run. Within these types, there will be variable changes in particle numbers and physical features. The first simulation requires MESA to evolve and create NGC 4349-127. The next simulation involves relaxing the MESA model and the brown dwarf. Then, the final simulation involves an in spiral case where the brown dwarf collides with the red giant. Since the brown dwarf still contains hydrogen, the simulation will demonstrate how the suspected red giant handles this influx of mass.

2.2 Red Giants

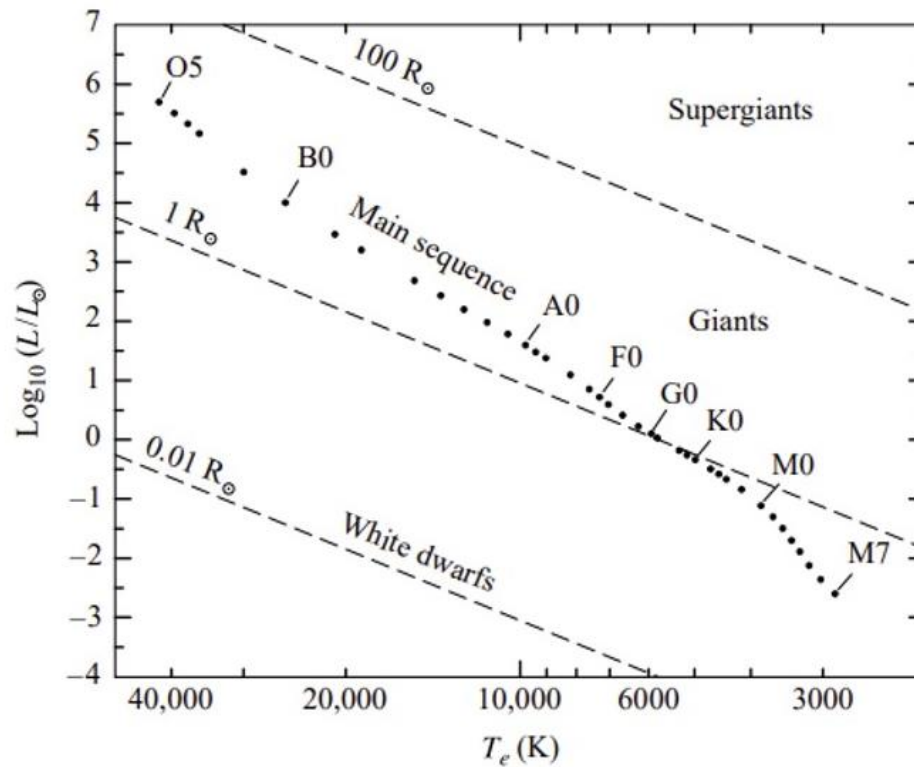


FIGURE 2 FROM CAROLL AND OSTILLE, THIS FIGURE IS A HERTZSPRUNG-RUSSEL DIAGRAM WITH DASHED LINES TO DISPLAY CONSTANT RADIUS. ON A LOGARITHMIC SCALE, THE LUMINOSITY OF THE STAR IS PLOTTED AGAINST ITS SURFACE TEMPERATURE IN KELVIN. [4]

Red giants are large stars that lack mass but make up for it in luminosity. Red giants have a surface temperature of around 5,000 K which results in a deep red or maroon appearance as seen in figure 3. After reaching temperatures high enough to fuse helium in their cores, red giants evolve from the main sequence. In turn, these massive stars are a step closer to the end of their lives as the amount of hydrogen in its core runs out, slowing the fusion necessary to stay at equilibrium. However, they are still brighter than our sun, only due to the vast size of their radius. These stars are seen in the upper right of a Hertzsprung-Russell (H-R) diagram along the red giant branch. [4] The star in question, NGC 4349-127 that this study is focused is estimated to be found in the “Giants” section of figure 2, as opposed to the supergiant section.

These high luminosity-low density stars continue vertically up the graph; however, it is important to note that they do not stray much farther to the left since they do not increase in temperature much over their lifespan. Red giants do not stray far from the main sequence “with the nearly adiabatic temperature gradient associated with convection throughout much of the stellar interior”, which presents as a non-uniform red sphere, as seen in figure 3. [4] This temperature gradient can be attributed to the small shell of hydrogen burning and the helium core that these massive stars possess.

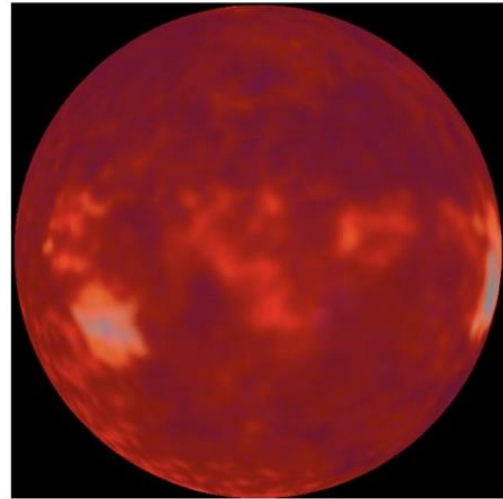


FIGURE 3: A SIMULATED IMAGE OF THE RED GIANT NGC 4349-127, BY KYOTO UNIVERSITY.

Due to their sheer size and varying density, it is important to use a simulation program that can account for such variations, which leads us to use MESA for this red giant. Since NGC 4349-127 has an initial solar mass of 3.9, this red giant will inevitably end as a “consumer of nuclear fuel while on the red giant branch” as it slowly burns through or expels its hydrogen envelope. [5] As a result, the smaller mass red giants also contribute to the development of planetary nebulae. When studying and simulating a red giant's life, accurate measurements of mass and radius are critical. This factor is what makes studying these stars so difficult, as their primary masses can be difficult to determine “due to the degeneracy of evolutionary tracks in the H-R diagram” as seen in a study by the University of Geneva. [5] These researchers obtained the mass through the radial velocity technique, which is implemented through the HARPS (High Accuracy Radial Precision Spectroscopy) telescope. This technique is elaborated upon in section 2.4. Such high precision is necessary for tracking the changes in light from a host star, Despite the Doppler Effect's spectral line measurements, this method of studying red giants only functions if their spectral types are earlier than spectral type F stars. [1] Due to the stars' rotational velocity, the Doppler Effect lacks overall precision for red giant measurements due to “intrinsic jitter” especially when the red giants are on the smaller end of the scale. [1] Utilizing spectroscopy efficiently is imperative to accurately simulate and collect data on stars.

2.3 Spectroscopy in Astronomy

The use of spectroscopy allows astronomers to see what elements interstellar objects are composed of and it relies heavily on the properties of light. Isaac Newton first experimented with the dispersion or bending of light. [2] Today, astronomers can use spectrometers and the lines they show to measure and categorize the implications of different colors of light. It was Gustav Kirchhoff, a theoretical physicist who found that each element produces its individual spectral lines; one of his laws known as “Emission lines” allows astronomers to use spectra to measure the bright spectral lines of hot diffuse gases commonly seen in stars. [4] There are three types of spectra, continuous, absorption, and emission spectrums, with their differences lying in their electron's behavior. Emission spectrums occur when electron shifts from a higher to lower orbital, and in turn, a photon is emitted to release the energy lost from said electron. [4] This spectrum provides evidence for the elemental composition of the object, as each element has unique emission and absorption lines. In contrast, the absorption spectrum shows when electron shifts from a lower to a higher orbital, after absorbing a photon with the exact amount of energy that was required to make an upward transition on the orbital. [4] Absorption spectra differ visually from emission spectra, as it presents black bands in the spectra and can determine how many elements are in a sample.

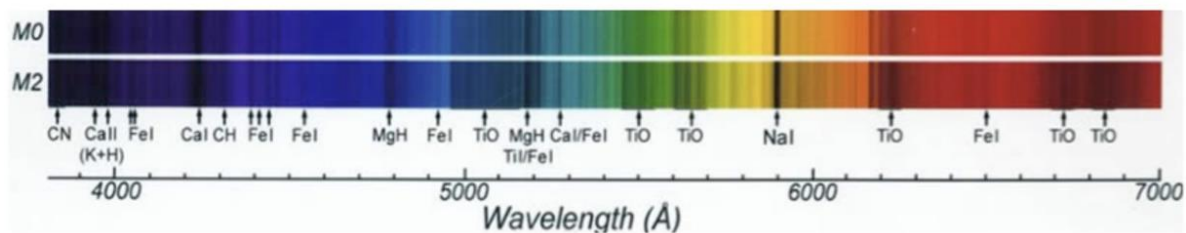


FIGURE 4 A CONTINUOUS SPECTRA OF TWO SPECTRAL TYPE M RED GIANTS BY CASE WESTERN UNIVERSITY. [18]

There are 7 spectral classes that astronomers use to categorize stars which are based on their surface temperature and spectra. Spectral classes are organized from hot to cool surface temperatures of interstellar objects. The classes are in a temperature sequence, labeled as O B A F G K M, from hot to cool respectively. In this study, we will be focusing on spectral class M which covers surface temperatures from 2,000 to 3,000 kelvin and are red. [6] Both NGC 4349-

127 and its orbiting brown dwarf NGC 4349-127b are categorized as spectral type M9 stars. [7] The subcategory “9” reiterates that these interstellar objects are in the coolest spectral class, and reside in the lowest subcategory.

2.4 The Radial Velocity Technique with the Doppler Effect (HARPS)

The use of spectra is imperative to the Radial Velocity Technique, which also works with the Doppler effect to become an optimal resource for finding and collecting data on interstellar objects like brown dwarfs and red giants. In spectra, if the spectral lines are spread apart by the Doppler effect, the result is the object’s rotational velocity. [2] This technique utilizes the velocity of the star that is within the line of sight of the observer and can be used to study its gravitational effects on what it is orbiting. [4] Since the Doppler effect is the increase or decrease (redshift or blueshift) in frequency as it appears to the observer, it aids in determining directions of objects and their orbits. Equation 1 is the Doppler effect, and it derives radial velocity from a person’s observed wavelength of a moving source from the difference of the wavelength at rest as seen below in equation 1.

$$\frac{\lambda_0 - \lambda_{res}}{\lambda_{res}} = \frac{\Delta\lambda}{\lambda_{res}} = \frac{v}{c} \quad \text{(Equation 1)}$$

The variable lambda naught (λ_0) represents the observed wavelength, whereas the variable lambda rest (λ_{res}) represents the accepted value or the wavelength at rest. By taking the difference of the wavelengths and dividing it by the accepted, the result will be the velocity (v) of the source over the speed of light (c). The measuring of radial velocity and its variations that are induced by the gravitational pull of two objects is an indirect way to overcome luminosity disparities and the need to directly observe a star or planet. [4] In the case of NGC 4349-127, the presumed red giant and brown dwarf are both located in an open cluster, which is known for having small but detectable dispersions in radial velocity. [8]

When using the radial velocity technique, it is important to account for jitter from the surface of stars. The surface of a star can produce “jitter” that can overwhelm planetary signals or mimic them. [9] More specifically, stellar jitter entails anomalies like star-spots and flares that

can affect how their spectra appear. This randomly distributed signal is most notably detected in this method. Researchers from Penn State University found that after studying 600 stars of both young and old age that the young stars experienced jitter due to magnetic activity and the older stars' jitter was driven primarily through convection but also by granulation and oscillations. [9] With their range of data, it can be concluded that radial velocity jitter occurs through the entire stellar evolution track but is most prominent in the giant and subgiant phases. Young stars are still blazing from their formation, and if these new stars are in the galaxy far away, astronomers must use direct imaging to collect their data. The telescope known as HARPS (High Accuracy Radial Velocity Planet Searcher) uses the Doppler effect to detect a low mass, M-type star like NGC 4349-127!

2.5 Newton's Laws

Isaac Newton's three laws of motion not only apply to objects on the Earth but to all objects in the galaxy. From Newton's second law we know that objects in motion will stay in a straight line of motion unless acted upon by another force. If that was not the case for outer space, the planets in our solar system would not elliptically orbit our sun! To bridge this gap, Isaac Newton derived the reason for these orbits to be attributed to gravity. [2] More specifically, he derived Newton's law of gravitation stating that there is a force of gravity or attraction between any two objects- even in space!

$$F = G \frac{Mm}{r^2} \quad \text{(EQUATION 2)}$$

Equation 2 is Isaac Newton's law of gravity; represented in this equation is the mass of two objects (M, m) that are multiplied by the gravitational constant ($G = 6.67 \times 10^{-11} \text{ Nm}^2/\text{kg}^2$) divided by distance (r). With distance (r) being in the denominator, astronomers deduced that the force of gravity (F) is inversely proportional to the square of the distance between two objects. This equation, therefore, calculates the magnitude of the gravitational force that is exerted on two objects. Hence, there is a force of attraction between all material bodies, whether on earth or in space. [2]

From Equation 2, the distance (r) must be between the two objects' centers of mass. However, when calculating the radius of celestial objects, astronomers use Kepler's third law which finds the orbital radius of the planet, which we will elaborate on further in the next section, 2.6.

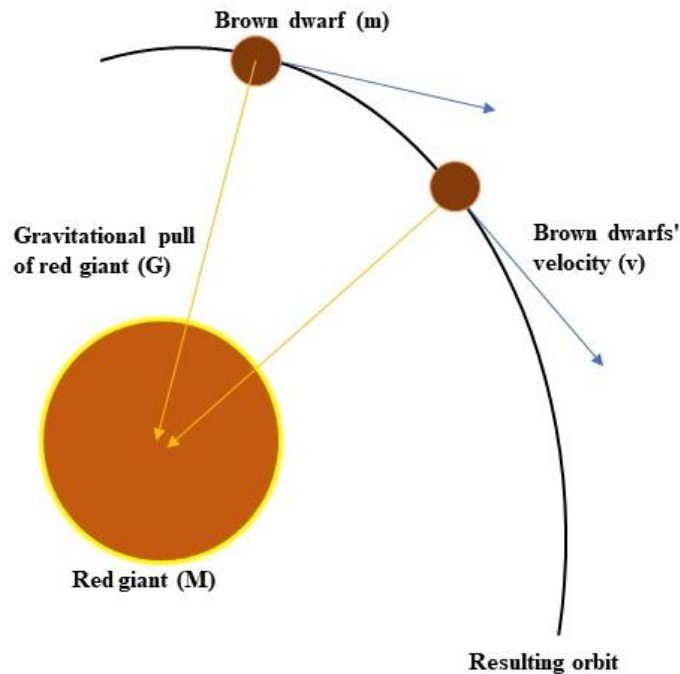


FIGURE 5 IS A DIAGRAM (NOT DRAWN TO SCALE) OF THE COMPONENTS OF NEWTON'S LAW OF GRAVITATION ON A RED GIANT AND A BROWN DWARF.

In figure 5 we depict the brown dwarf NGC 4349-127b orbiting around its host star, the red giant in question. Noted in the yellow arrows is the gravitational pull of the red giant on the brown dwarf's orbit. The yellow ring surrounding the red giant in figure 5 represents the shell of hydrogen fusion around its core, also known as its photosphere radius. Despite the otherwise straightforward velocity of the brown dwarf (as noted in blue), the gravity of the star alters the brown dwarf's orbit to form an elliptical shape. The HARPS spectrograph that found the NGC 4349 cluster utilizes these properties of gravity, and it accounts for the slight pull of a parent star. This slight movement of the radial velocity of a star is what HARPS detects, and from the

Doppler effect, (see section 2.4) astronomers can measure the redshift or blueshift of the spectra to identify planet/exoplanets.

It is important to note that each arrow points to or comes from the center of mass of each object where density is concentrated. For many stars their overall density is not uniform. However, Newton's laws can still apply if the center of mass is used much like Kepler's laws of planetary motion.

2.6 Kepler's Laws of Planetary Motion

Johannes Kepler was a German astronomer who founded the laws of planetary motion that astronomers use today. Kepler's laws were created based on Isaac Newton's 'discovery' of gravity also known as the law of gravitation, and he used this principle to find a relationship between the orbital period of a planet and its distance from the Sun; this is Kepler's third law. [2]

$$P_{yr}^2 = a_{AU}^3 \quad (\text{EQUATION 3})$$

Equation 3 states that the squared orbital period (P) in years is proportional to the cubed semimajor axis (a) in astronomical units. Equation 4 shows Newtons' reformulated equation which accounts for the masses of the two objects. The objects move with respect to their center of mass, or where all parts of a system sum to equal zero. [2] By using the center of mass, objects can be simplified to point masses providing easier calculations. Astronomers can use this equation to derive the masses of planets or stars by observing the objects that orbit them. [2] Equation 3 can be generalized into equation 4 which is easier to use in these simulations, where the period is in years, the masses are in solar masses and the semimajor axis a is in astronomical units.

$$a_{AU}^3 = (M_{1sol} + M_{2sol})P_{yr}^2 \quad (\text{EQUATION 4})$$

With these equations, the HARPS telescope's data identifies hundreds of exoplanets and stars each year. [6]

2.7 Visual Rendering in Splash

Upon looking into the night sky with the naked eye we can see hundreds of different stars and constellations. What about the stars out of reach from our naked eye? Astronomers use telescopes and spectra to find and identify stars. Regarding the everyday connoisseur of astronomy, I would like to visually render my simulation results so that anyone can appreciate this type of celestial interaction that occurs within our galaxy.

To go from the Starsmasher simulation to an interpretive image, I will use Fortran software named ‘Splash.’ Splash is a visualization tool specifically for Smooth Particle Hydrodynamics (SPH) code, just like Starsmasher (which will be defined in section 3.3). [10] This program takes the SPH data in the form of output files directly from Starsmasher and renders it into plots of physical quantities to provide an aesthetically pleasing representation of the data instead of regular particle plots. [10] Each particle within the SPH code has a region around it called a ‘kernel’: when particles overlap this kernel region, they contribute to density calculations, and conversely when outside of this region these particles contribute to gravitational acceleration calculations. [11]

While Splash has many visualization features, I will be using a select few. The automatic stepping through of timesteps feature will be used to make an animation or projection of StarSmashers’ 2D data (with the data being column density plots of the red giant) to visualize this distant star. Upon the creation of the red giant through MESA, I will relax this star in Starsmasher and use the animation of 3D data to display how the density of this red giant is not uniform. For my collision simulation, where the brown dwarf spirals into a collision with the star, I will use the automatic stepping feature to capture this impact into a graphics interchange format, known as a gif. I also intend on using this feature for the orbiting case of the brown dwarf and red giant, to display the overall magnitude of these two massive interstellar objects in one image.

3 Methods

To run the simulations of the brown dwarf orbiting a red giant, there must be data to input into Starsmasher. First MESA (Modules for Stellar Experiments) utilizes a star's mass and radius to create a star with varying density, as seen in red giants. Once the star has been created, an output file that meets 2 observed and 2 empirically determined conditions (mass, radius, luminosity, and surface temperature, respectively) will be inputted into Starsmasher to simulate the orbit and the collision. See section 3.2 for elaboration on how the constraints were calculated. This SPH code utilizes the observed data of the mass and radius of each object from the HARPS method to recreate the stars' conditions. Once the simulations have been completed, Splash will be used to turn those output files into animated plots. Finally, we will look to see if energy is conserved after each simulation using the `smx` command.

3.1 Calculating the Luminosity of a Red Giant

When using MESA for the evolution of the red giant star (NGC 4349-127) in question, we had to implement simulation values that are consistent with the expected values of red giants. These values were specific to the mass, age, and luminosity of the red giant. The energy emitted by the star was obtained using the HARPS method. [1] First, the red giant was set to have its actual values of $3.9 M_{sun}$ star with a stellar radius of $2.3 (R_{sun})$. [1], [7]. Once the run reached a stopping point, a comparison of the final luminosity as compared to the empirically calculated value of the luminosity. Therefore, equation 5 was implemented. We chose this equation since it provides a relationship between the known value of the star's absolute magnitude, M (equal to its apparent magnitude if it were 10 parsecs away) to its luminosity (which is being confirmed). [4]

$$M = M_{sun} - 2.5 \log_{10} \left(\frac{L}{L_{sun}} \right) \quad \text{(EQUATION 5)}$$

Equation 5 is the distance modulus equation, where M represents the absolute magnitude of the red giant and M_{sun} represents the absolute magnitude of the sun. The variable L represents the luminosity of the red giant.

Upon entering the known values $M = -4.29$ and $M_{sun} = 4.83$, the resulting luminosity of the red giant is $4446 L_{sun}$. However, MESA will produce values on a logarithmic scale to trend toward the significant values.

This value as calculated in equation 5 is a value we will look to see on the MESA run for the red giant. For further disclosure of MESA see section 4.1 for the implementation of this code and its implications.

3.2 The Temperature, Radius, and Luminosity Relation

There are few accepted values on NGC 4349-127(b), specifically they were the variables of radius, mass, magnitude and distance, with a few incredulous sources approximating surface temperature and luminosity. When producing simulations, it was imperative to have the most accurate input for these values in order to produce an accurate simulation. Previously, in section 3.1 we calculated the expected luminosity of NGC 4349-127 to be ~ 4446 solar luminosities. In effort to input 4 concise constraints on what the model of the supposed red giant should amount to, I utilized the temperature, radius and luminosity relation, also known as equation 6. [4]

$$L = 4\pi R^2 \sigma T^4 \quad \text{(EQUATION 6)}$$

The luminosity equation, equation 6 was rearranged to solve for the radius, R or temperature, T , where 4 , π and σ are constants with sigma representing the Stefan Boltzmann constant. Within the code of StarSmasher (see section 6 for the code itself) the radius constraint was given in the MESA profile that was used in StarSmasher, and it measured the photosphere radius of the star. Measuring the radius with the photosphere of the star is an appropriate approximation as the photosphere is not a sizeable layer of a star, however it is uniform enough to accurately predict the stars radius. [4] This variable, R is in solar radii within the code, however in calculations it is converted into meters. The temperature variable, T measures the surface temperature of the star, in kelvin.

Out of the three variables, L , T , and R , the radius of NGC 4349-127 was the most credible, being 2.3×10^{23} solar radii or 1.6×10^9 meters [7]. We had previously calculated the expected luminosity from the accepted magnitude value in section 3.1 to be 4446 solar luminosities, or 1.7×10^{30} watts. Using these two known values, equation 7 was used to calculate the expected surface temperature value for this star.

$$T = \sqrt[4]{\frac{L}{4\pi R^2 \sigma}} \quad \text{(EQUATION 7)}$$

The calculated value for temperature was approximately 3200 K, which appeared relatively low for a red giant. From the MESA model, the profile that was chosen as the best representative of the star met all constraints earnestly aside from this one, as it held a value of ~ 4400 K, over 1,000 kelvin higher than calculated. This could be attributed to any oversights in the luminosity

calculation. The simulations proceed with this MESA profile despite the increased surface temperature value.

3.3 StarSmasher

The focal point of this paper revolves around Starsmasher, a three-dimensional smooth particle hydrodynamic code (SPH) used to model interstellar objects from brown dwarfs to black holes! [3] This is possible through fluid dynamics or the study of liquids/gases, which is suitable for working with stars that are essentially burning balls of gas. The equations used in Starsmasher are “nothing more than a suitable Lagrangian equation, a density prescription that depends on the first law of thermodynamics” which conserves the physical variables we will study. [12]

To run a simulation on StarSmasher, a subsidiary text editor program is used to input data (stellar mass and radius) relative to an object into the SPH code. Once these conditions are set (see section 3.4 for the specific simulation values) the program calculates energy, velocity, and position for every particle. [11] Using timesteps, StarSmasher proceeds in time calculating these particles and their successors repeatedly. Timesteps provide an intermittent point for the code to create out files, which are individual snippets of time in the simulation where the energy, position, and velocity are recorded. These timesteps will be crucial to visually rendering StarSmashers’ final simulation.

Once data regarding the mass and radius of the red giant are inputted into Starsmasher the first step in this research is to relax the star. A relaxation run models each star in a system individually. Next, will utilize the equation of state for a protostar which will have a polytropic index of $n = 1.5$. A polytropic index of 1.5 is less than ideal for a model of a red giant which has a dense core. [13] Finally, the star mass and radius are inputted to finally relax a star.

Then, to collide the star, the following conditions are changed; *dtout*, *bimpact*, and *sep0*. The *dtout* variable when set to 1 tells Starsmasher that there will be one output file created every 1-time unit in Starsmasher. When changing the *bimpact* variable we are considering the nearest point to the red giant would get to the brown dwarf if they were point masses in the SPH simulation. Finally, the *sep0* variable inputs the semi-major axis of the initial orbit, which is depicted in section 4.2.

3.4 NGC 4349-127's Simulation Conditions

Sections 3.1 and 3.2 were used to identify and obtain the necessary inputs for simulating a relatively newfound open cluster containing a brown dwarf and an alleged red giant. The last calculation for these conditions is depicted in figure 6. Initially, we gathered the stellar mass and radius of the brown dwarf and red giant using the radial velocity technique (HARPS). The mass of NGC 4349-127 is 3.9 solar masses and a stellar radius of 2.3×10^{23} . [1], [7] The mass of the brown dwarf NGC 4349-127b was found to be 19.8 Jupiter masses and its radius to be 0.91 Jupiter radii with an eccentricity e of 0.19 on a semimajor axis, a of 2.38 AU. [1], [7]

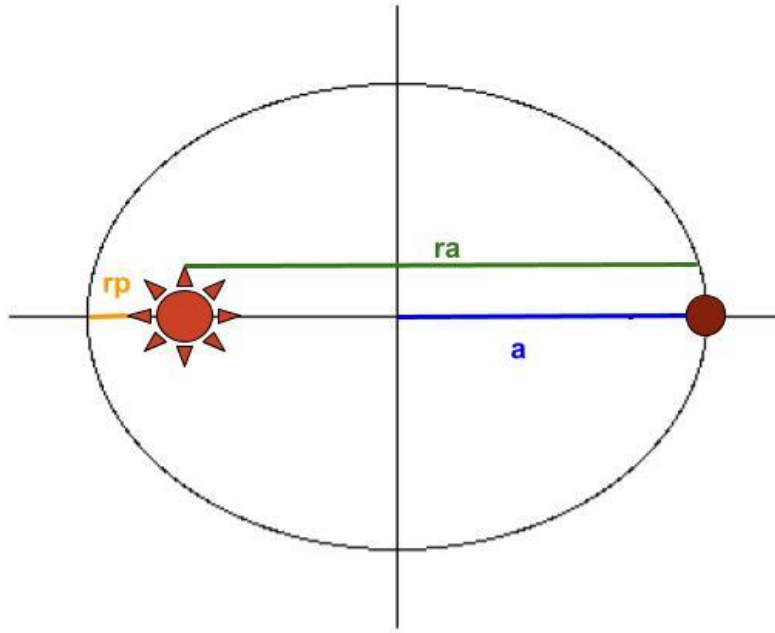


FIGURE 6 DISPLAYS THE APASTRON, PERIASTRON AND SEMIMAJOR AXIS OF NGC 4349-127B ORBITING NGC 4349-127, WHERE THE RED STAR IS THE SUSPECTED RED GIANT AND THE BROWN CIRCLE REPRESENTS THE BROWN DWARF. IN ADDITION, THIS FIGURE DEPICTS THE INITIAL POSITIONS OF THE ORBIT BEFORE IN SPIRALING INTO THE COLLISION.

From this data I used the apastron, r_a and periastron r_p equations 8 and 9 to create figure 6 which was used to set up the collision simulation.

$$r_a = a(1 + e) \quad \text{(EQUATION 8)}$$

$$r_p = a(1 - e) \quad \text{(EQUATION 9)}$$

For the collision, the *bimpact* variable, or r_p the periastron separation was calculated to be 1.93AU, which was converted into ~ 415 solar radii for StarSmasher. The *sep0* variable will represent the initial separation, which is set to the brown dwarfs' semimajor axis a which in solar radii is 511.78. [7]

Within the creation of the red giant in MESA, output files were produced as the star evolved through the main sequence. The file that was selected to best represent the giant in the collisions was chosen based on four pre-measured values. These included the star's mass, radius, luminosity and surface temperature. Section 3.2 elaborates on how we empirically evaluated for the expected values of luminosity and surface temperature. The output file profile32 (see section 6 for the code) depicted a luminosity value of 600 solar luminosities, a solar radius of $2.3 * 10^{23}$ and a surface temperature of $\sim 4000\text{K}$. This step was imperative to creating the most realistic rendition of the orbit and collision.

4 Results and Analysis

MESA effectively produced the out file “*profile32*” representing NGC 4349-127 which met the constraints of mass, radius, luminosity and approximately surface temperature. StarSmasher then relaxed this profile to create the out file “*out0480.sph*” which was used in both rendering and colliding. In addition, StarSmasher then relaxed the model of the brown dwarf NGC 4349-127b, producing the out file “*out0200.sph*” which was also rendered and used in the collision simulation (see sections 4.3 and 4.4). Figure 7 depicts the energy conservation of the relaxation of the brown dwarf.

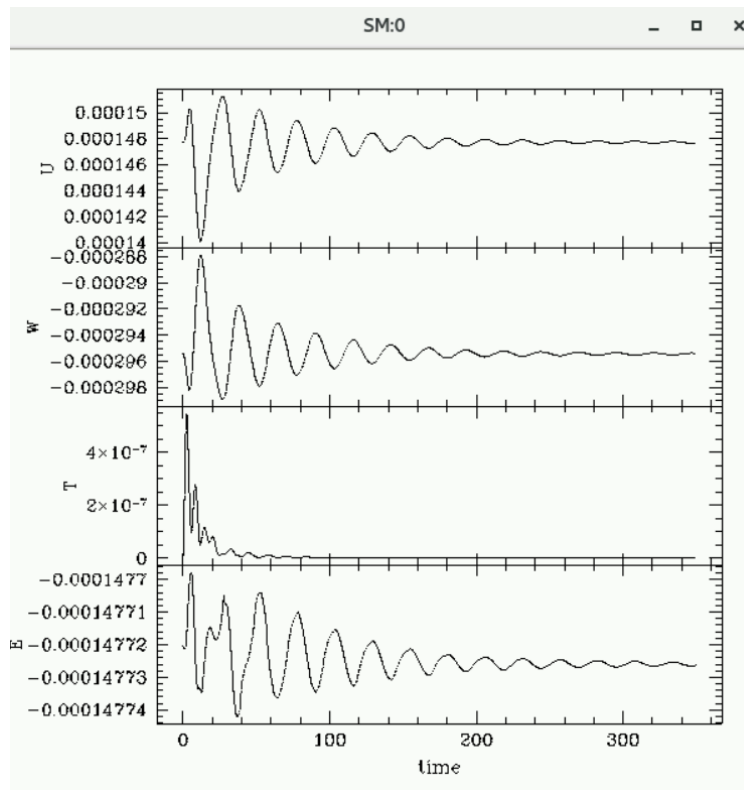


FIGURE 7 IS A PLOT MADE BY SMX DEPICTING THE ENERGIES OF THE BROWN DWARF WHILST BEING RELAXED IN STARSMASSHER. WHERE U REPRESENTS POTENTIAL ENERGY, W REPRESENTS GRAVITATIONAL ENERGY AND T IS THERMAL ENERGY. THE LAST GRAPH E REPRESENTS THE TOTAL ENERGY OF THE SIMULATION.

Although there remain slight oscillations in the total energy E graph, it can be assumed that the energy would taper off to the same value presented here. This supports the model’s

integrity, since this brown dwarf conserves energy. In turn, we continued to use this model in the collision simulation. Upon rendering NGC 4349-127b, it further fits the definition of a brown dwarf. In contrast, the model of NGC 4349-127 which was alleged and vaguely confirmed as a red giant is not supported by this simulation. Using the energy out file for NGC 4349-127, figure 8 was created.

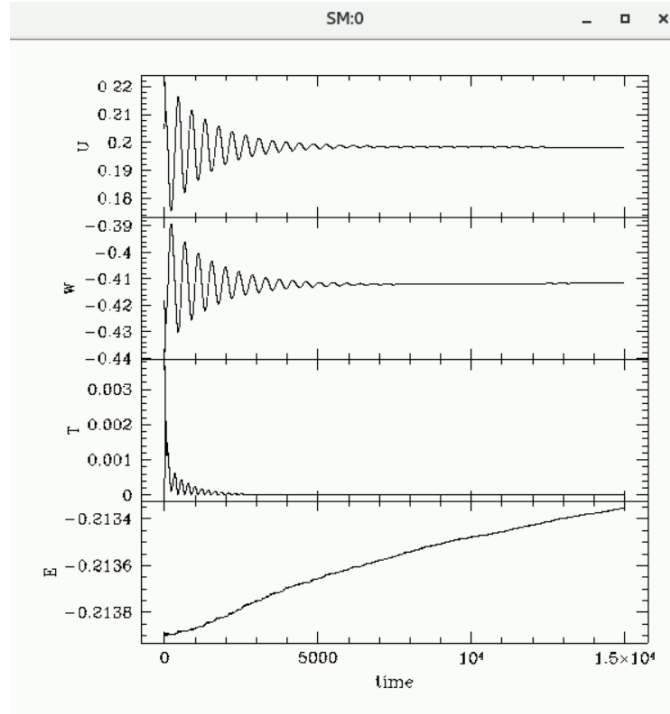


FIGURE 8 USING THE PROGRAM SMX AND THE ENERGY OUT FILE CREATED BY STARSMAHER, ENERGY PLOTS FOR NGC 4349-127 WERE PRODUCED.

From figure 8 we can conclude that our model effectively did make a star, as both the potential U and gravitational energy W , oscillations stabilized and tapered off. We also see that the thermal energy T peaked early in time and quickly tapered to close to 1. If figure 8 had shown that energy was not conserved, the error would be attributed to an inaccurate variable that was implemented in the relaxation file, most likely the luminosity or surface temperature value. However, I believe the error when trying to simulate the red giant NGC 4349-127 comes from an incorrect initial parameter when the star was first created in MESA. This may stem from the luminosity approximation in section 3.1.

By rendering the star we created aided this determination (see section 4.4 for the rendered images), as the particle plot proved to be relatively uniform, unlike the true characteristics of a red giant which does not have uniform density and surface temperatures. [4] Despite this finding, we proceeded with the simulation of the brown dwarf orbiting into collision with this star that had qualities like those of a red giant.

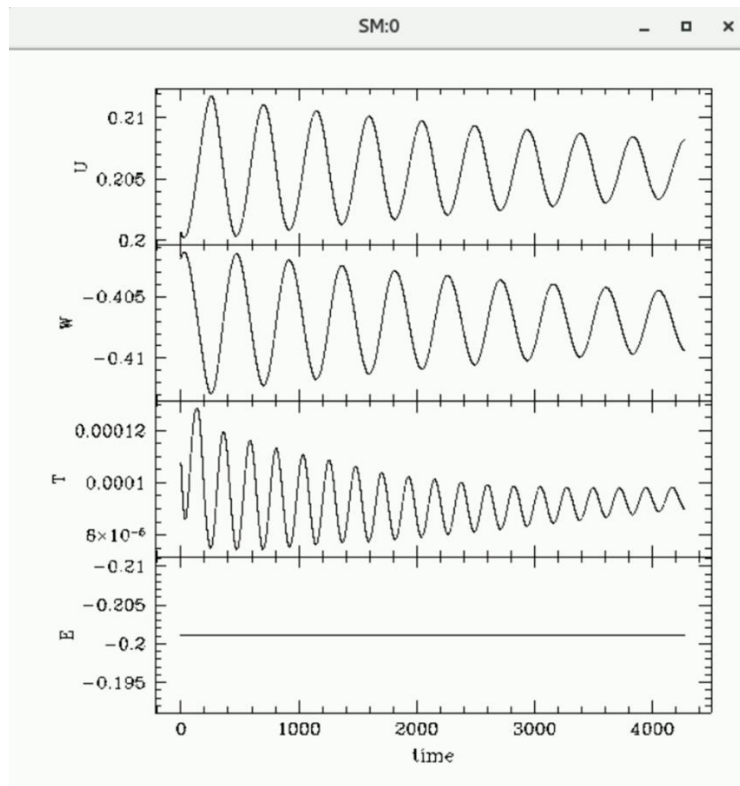


FIGURE 9 REPRESENTS THE ENERGIES OF THE COLLISION BETWEEN THE BROWN DWARF AND ITS ORBITING STAR THAT WAS CREATED IN MESA/STARSMASHER. THIS FIGURE PLOTS ENERGY AGAINST TIME.

Finally, figure 9 represents the energy conservation (or lack of) during the collision simulation. As depicted in the gravitational and potential energy graphs, the oscillations in energy over time did not converge. Although these plots did begin to trend in the direction of smaller oscillations, this program most likely needed a longer run time than 3.5 days as the total energy of the simulation did not waiver, showing that the simulation was not completed.

4.1 The Red Giant as Simulated by MESA

The simulation of the red giant in MESA (Modules for Experiments in Stellar Astrophysics) has been completed in its pre-sequence phase. This pre-sequence phase showed the red giant mainly forming from its parent molecular cloud to a size where it could properly fuse hydrogen and become a star. It is imperative to succeed in creating an accurate simulation of this red giant with the correct mass as well as distribution of density.

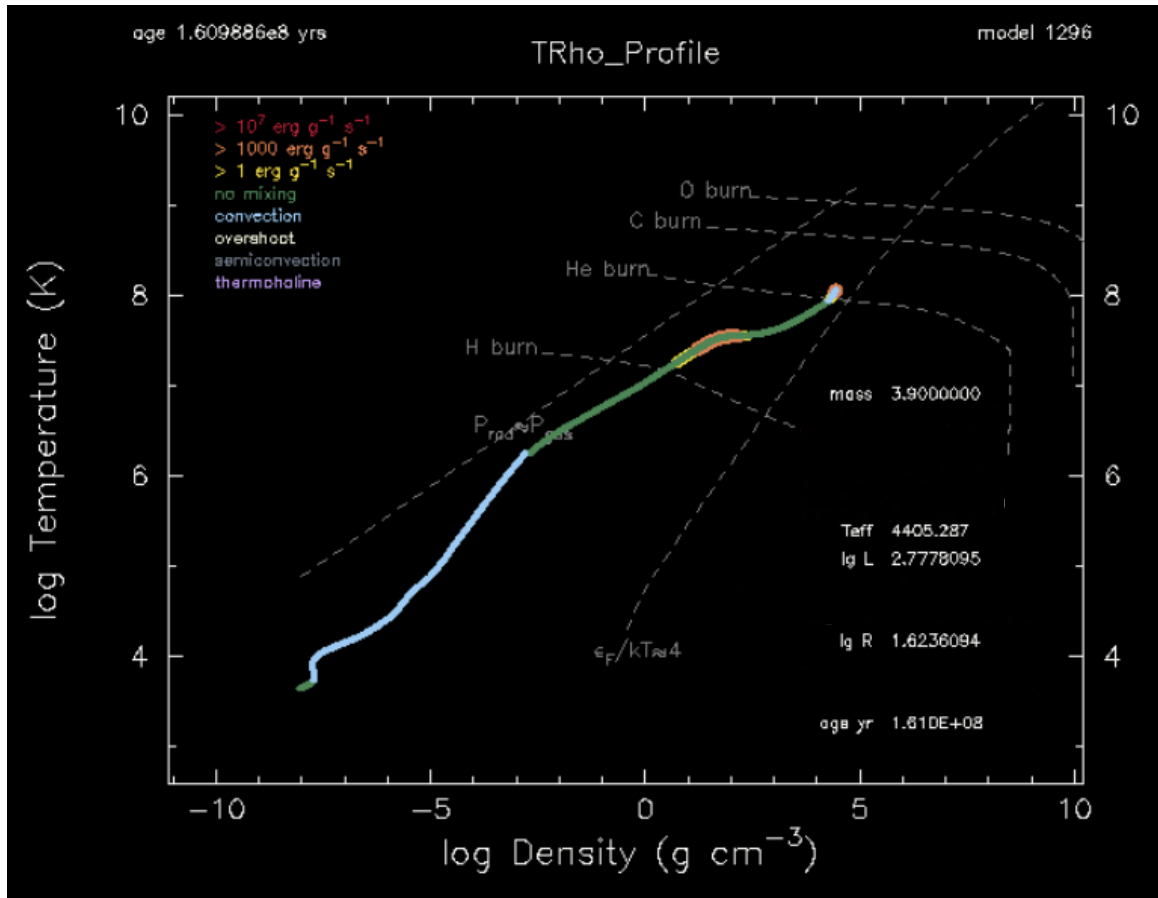


FIGURE 10 DISPLAYS THE CONCLUSION OF THE MESA PRE-SEQUENCE PHASE OF THE 3.9 SOLAR MASS SUSPECTED RED GIANT. THIS MODEL PLOTS THE DENSITY OF THE STAR AGAINST ITS SURFACE TEMPERATURE AND RADIUS ON A LOGARITHMIC SCALE TO BEST TREND TOWARD LARGER VALUES.

As seen in figure 10, this version of the red giant has not reached the point where the “ $lg L$ ” variable is equal to 3.648. This was not the first indicator that the simulation was not complete. The age of the protostar (as shown in the upper left-hand corner of figure 10) when the

program stopped running was 1.6×10^8 Myr or 160,000,000 million years old. After consulting the exoplanet database, it revealed that NGC 4349-127 was currently 200 Myrs old, therefore leaving time for our protostar to evolve further into a red giant.

4.2 The Brown Dwarf's Accelerated Orbit

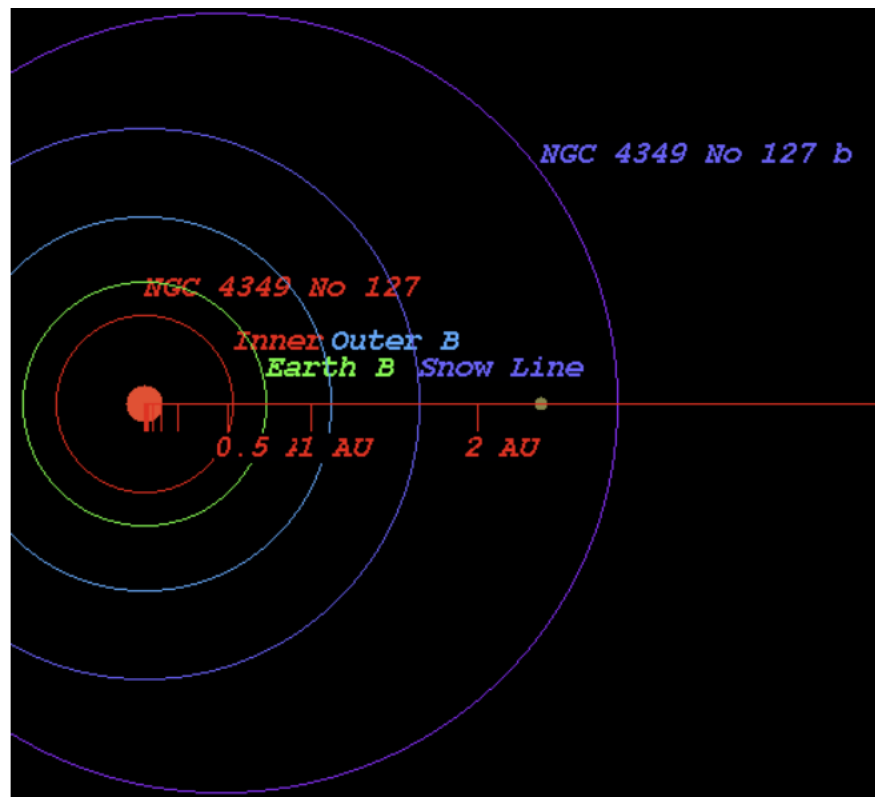


FIGURE 11 IS A DIAGRAM OF THE BROWN DWARF IN ITS ORBIT (DEPICTED BY THE FURTHEST PURPLE CIRCLE) AROUND NGC 4349-127, DEPICTED IN RED. [7]

As displayed in figure 11, the orbit of the brown dwarf resides at approximately 2.38 AU from the red giant, a great start to simulating its orbit! The orange point displayed in this figure is the furthest the brown dwarf will be from its parent star, with an eccentricity of 0.19. [1], [7]

When observing the accelerated orbit case, factors like the giant's luminosity as well as the rotation speed will be evaluated. In a study by Macquarie University, researchers noticed an increase in the red giants' luminosity "over a relatively short time scale" referring to the beginning of the in spiral toward a collision. [15] In our simulation however, both our star and its orbiting brown dwarf are larger in mass and radius and as a result, we may be able to observe a

trend in this data. Upon completion of the red giant in MESA, the simulation of this orbit will require the input of this information into Starsmasher.

4.3 The Collision

In a study by Macquarie University, a hydrodynamic simulation of the interactions between giant stars and planets was performed. This study, much like this one will use the ZAMS red giant which had a solar mass of 3.5 (which is close to our mass of 3.9)! [15] Although our brown dwarf is not considered a ‘planet’ (but a failed star), it fits their criteria of being a 10 Jupiter mass object interfering with an alleged red giant (which has a mass of over 19 Jupiter masses! From this, they found that the orbiting object was destroyed and “polluted the envelopes of giant stars” upon collision. [15] An interesting point to look for in this simulation comes regarding the rotational velocity of each interstellar object. The Macquarie study found that once collided, the red giant experienced faster rotation in the outer layers. [15]

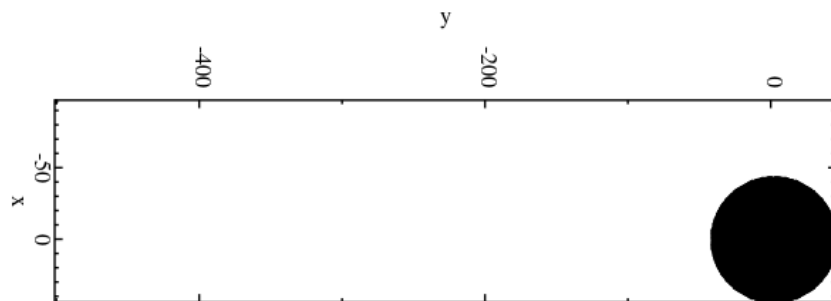


FIGURE 12 IS THE VISUAL RENDERING FROM SPLASH OF THE INCOMPLETE COLLISION BETWEEN NGC 4349-127 AND ITS ORBITING BROWN DWARF.

Despite the brown dwarf moving out of frame, it is apparent that the star was unaffected by any of the brown dwarf’s mass in its orbit, and did not collide with NGC 4349-127. The orbit matched that of figure 11, and in spiraling the 0.018 solar mass brown dwarf into the 3.9 solar mass star left it relatively unaffected, supporting the Macquarie study’s findings as well. [15] Figure 9 additionally proved that the simulation was unfinished, and by increasing its run time we may be able to specifically see the effects of the collision on the star’s rotational velocity as

well as mass composition. The periastron separation in line 6 of the collision code could also be reduced, however this simulation used the calculated r_p to provide a realistic orbit.

4.4 Splash's Visual Rendering Results

Initially using StarSmasher's relaxation code, the brown dwarf had over 200 outfiles which were converted into png files in Splash. Once these png files were created Splash was able to render them into the gif which is figure 13

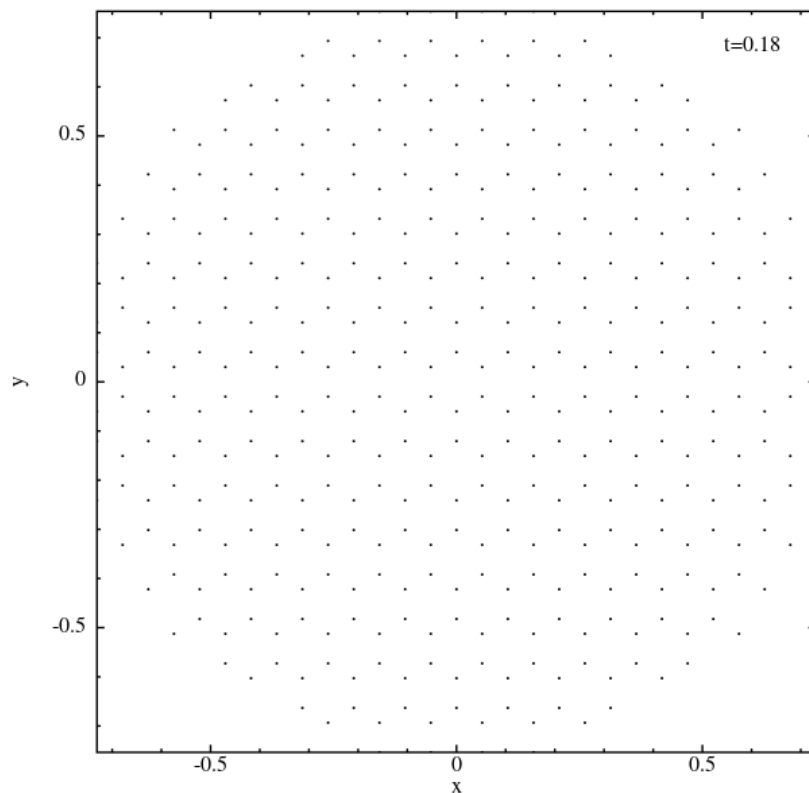


FIGURE 13 IS THE VISUAL RENDERING OF THE BROWN DWARF BEFORE IT WAS IMPLEMENTED INTO THE COLLISION SIMULATION, CREATED IN SPLASH.

Figure 13 shows the lack of density in the brown dwarf, which was anticipated as it is relatively small in mass and unable to fuse hydrogen. Throughout the relaxation, this model shows the brown dwarf condensing into itself, and it remains small as expected. This is supported by the values of the x and y axis, which only range between -0.5 and 0.5 respectively.

The mass of the brown dwarf played a large role in this simulation, as its mass of $19 M_{jup}$ has been proven by similar computer simulations that this low mass object can burn heavy hydrogen. [4] Given that these cool, failed stars are only able to be detected in the infrared scale, this visualization of NGC 4349-127b is one of few!

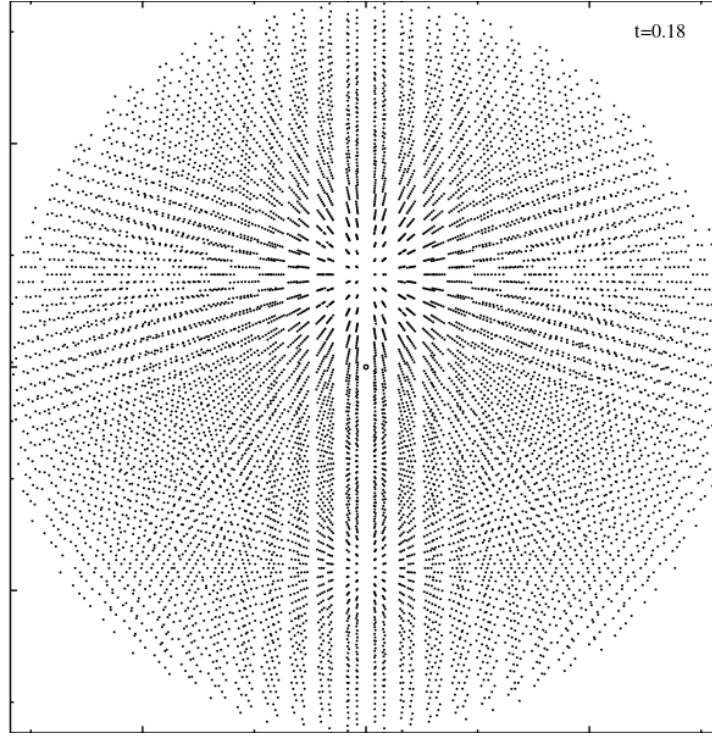


FIGURE 14 IS THE VISUAL RENDERING OF NGC 4349-127 PRODUCED BY SPLASH (SEE SECTION 6 FOR CODE).

Figure 14 is the summation of over 500 out files created by StarSmasher. This visually rendered gif lasts much longer than its orbiting brown dwarf and does not stabilize until approximately $t = 13300$. This gif shows the density of particles of this red giant and shows where the particles are condensing as the star fuses hydrogen. The multitude of loose particles around the edge of the begins to support this simulation being a red giant, as red giants have an adiabatic temperature gradient which promotes convection out of the red giant's photosphere. [4] Although this simulation may represent the red giant that was presumed to be NGC 4349-127, it very well may represent a different red giant.

5 Conclusion and Future Work

Although the existence of NGC 4349-127 is confirmed by Lovis & Mayor while also being defined as a red giant, this specific red giant was not rendered here, as its luminosity value did not match the empirically calculated values. The simulation of the brown dwarf was successful, and the collision was run with this brown dwarf and the star created in MESA that was relatively like NGC 4349-127. Although the simulation was ran, it did not run long enough for the collision to be observed.

To further these preliminary findings of the system in the cluster NGC 4349, I would create a stellar model of the red giant to confirm that the out file used in the simulations had the most accurate luminosity and radius values. Although we calculated the luminosity based off apparent magnitude in section 3.1, the stellar model would either support or contradict the luminosity used in this study. The profile created by MESA that was used in these simulations could have been a version of the star when the core was expanding, furthering the hydrogen burning layer away from the center of the star. This would result in a brief decrease in its luminosity, which would explain why our expected and calculated values differed. In other future work, the MESA simulation that was run was a pre-main sequence model, and a main sequence model could supply these missing values as well. Most importantly, the simulation of the collision must exceed 3.5 days in run time in order to see the collision. Within the collision, the periastron separation should be reduced to accommodate for the stars radius, however in this simulation we began with the most realistic conditions. In addition, plots could be made of the collision regarding rotational velocity vs time to observe any changes in the stars surface rotational velocity. Finally in terms of future work, the brown dwarf simulation should run longer than 300 steps, to remove the oscillations in its energy diagram.

6 Code

In the subsections below are the inputs utilized in the functions of creating, relaxing and colliding the interstellar objects NGC 4349-127 and NGC 4349-127b, sequentially. Segments that are highlighted indicate that I changed these inputs to the case specific values in MESA and StarSmasher's. [16], [17] Lines that are not highlighted were originally written by Gaburov & Lombardi, et al. in StarSmasher and Paxton, et al. in MESA. [16], [17]

Input for creating NGC 4349-127 in MESA [17]

- 1) &controls
- 2) initial_mass = 3.9 ! in Msun units
- 3) initial_z = 0.02
- 4) &star_job
- 5) load_saved_model = .true.
- 6) saved_model_name = '3.9M_at_TAMS.mod'
- 7) pgstar_flag = .true.
- 8) read_extra_star_job_inlist1 = .true.
- 9) extra_star_job_inlist1_name = 'inlist_project'
- 10)/ ! end of star_job namelist
- 11)&eos
- 12)read_extra_eos_inlist1 = .true.
- 13)extra_eos_inlist1_name = 'inlist_project'
- 14)&kap
- 15)use_Type2_opacities = .true.
- 16) Zbase = 0.02
- 17)! ^ is metalicity
- 18)! read_extra_kap_inlist1 = .true.
- 19)! extra_kap_inlist1_name = 'inlist_project'
- 20)/ ! end of kap namelist
- 21)&controls

```

22) cool_wind_RGB_scheme = 'Dutch'
23) cool_wind_AGB_scheme = 'Dutch'
24) RGB_to_AGB_wind_switch = 1d-4
25) Dutch_scaling_factor = 0.8
26) read_extra_controls_inlist1 = .true.
27) extra_controls_inlist1_name = 'inlist_project'
28) / ! end of controls namelist
29) &pgstar
30) read_extra_pgstar_inlist1 = .true.
31) extra_pgstar_inlist1_name = 'inlist_pgstar'
32) / ! end of pgstar namelist

```

Input for relaxing NGC 4349-127 in StarSmasher [16]

```

1) &input
2) tf=15000, ! desired final time to stop simulation
3) dtout=10, ! how often an out*.sph files should be dumped
4) n=10000, ! desired number of particles.
5) starmass=3.9, !
6) starradius=42.05, !
7) nrelax=1, ! 1=relaxation of single star
8) treloff=0, ! time to end a relaxation and switch to a dynamical calculation
9) ngravprocs=1, ! the number of gravity processors
10) computeexclusivemode=1
11) profilefile = "profile32.data"
12) &end

```

Input for relaxing NGC 4349-127b in StarSmasher [16]

- 1) &input
- 2) **tf=350, !** desired final time to stop simulation
- 3) **dtout=1, !** how often an out*.sph files should be dumped
- 4) **n=2500, !** desired number of particles.
- 5) **starmass=0.018, !** The desired mass of your preMS star!
- 6) **starradius=0.94, !** The desired radius of your preMS star!
- 7) **nrelax=1, !** 1=relaxation of single star
- 8) **treloff=0, !** time to end a relaxation and switch to a dynamical calculation
- 9) **ngravprocs=1, !**
- 10) **computeexclusivemode=1, !**
- 11) &end

Input for Colliding NGC 4349-127 and 4349-127b [16]

- 1) &input
- 2) **tf=-9999, !**
- 3) **dtout=10, !** how often an out*.sph files should be dumped
- 4) **nrelax=0, !** 0=dynamical calculation
- 5) **sep0=511.78, !** initial separation of two stars in a binary or collision calculation
- 6) **bimpact=415d0, !** periastron separation
- 7) **semimajoraxis=511.78d0, !** the semimajor axis for the collision
- 8) **ngravprocs=1, !** the number of gravity processors
- 9) **computeexclusivemode=0, !**
- 10) **ppn=16, !**
- 11) &end

Rendering in Splash [10]

Using all the outfiles created by StarSmasher:

- 1) Jsplash out*.sph y 2 x 1 -r 0 -dev /png
- 2) convert -delay 10 -loop 0 splash_*.png animatedgif.gif [11]

Creating Energy plots in StarSmasher

- 1) cd into outfile directory
- 2) smx
- 3) v 0

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