Interstellar Encounters:

Supergiant Star-Binary Black Hole Collisions

and

Relationships between Science & Science Fiction

Des Rapports entre la science & la science-fiction

By
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Emma M. Chambers

This work is mine unless otherwise cited.

Professor Jamie Lombardi	*Professor Briana Lewis*	*Professor Adelé Poynor*
Co-First Reader	*Co-First Reader*	*Second Reader*
Date	*Date*	*Date*

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Interstellar Encounters: Supergiant Star-Binary Black Hole Collisions and Relationships between Science & Science Fiction

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Abstract

Supergiant stars are some of the largest known stars to exist in the universe. While they may be few and far between, they do, in fact, exist. Because these stars exist, it is important to learn about their behaviors and how they might interact differently with a black hole compared to a smaller, main sequence star. Within this project, I describe the process of relaxing a supergiant star with mass 37.9434 $M_\odot$ and six subsequent dynamical collisions with a binary black hole that contains two black holes that have masses of 32 $M_\odot$, which is on the same order of mass as the supergiant star. I employ smoothed hydrodynamics code for both the relaxation and the collision processes. Three main categories come out of the six collision runs: total tidal disruption events, partial tidal disruption events with black hole replacement, and partial tidal disruption events with stellar ejection. I analyze how the final masses of each black hole in the system affects its spin, and I make the assumption that half of the stellar mass will be accreted onto the black hole by the end of the collision in the cases where there is a stellar remnant.

In the second part, I analyze the influence that science communication in science fiction has on science in reality with *Dernier Départ (Final Departure)* by Christophe Martinolli. First, I take a look at the book itself and the relationship between the elite class and the role that framing science communication to inspire hope plays in taking scientific and political action. Then, I look at the ways that the elite class manipulates different forms of communication in order to

retain control and power over the lower class. They disguise different forms of communication such as public addresses and propaganda as science communication. However, their goal is not to inform the public of scientific development and advances, but to provoke a sense of hope and safety to gain and maintain loyalty and therefore control. In the second part, I take a look at science fiction as a genre and how it benefits science communication and encourages scientific discovery and creativity. Finally, I analyze the ways that Martinolli implements the facets of science-fiction as a genre and the potential effects it could have on the scientific community.

Part I

Supergiant Star-Binary Black Hole Collisions

1 Introduction and Background

1.1 Motivation

The obscure and mysterious relationship between binary black holes (BBHs) and stars when collided, here specifically supergiant stars, motivates this research. My goal is to explore a niche case in which a massive supergiant star is colliding with a BBH that contains black holes (BHs) of the same order of mass. Due to the fact that the star is of similar mass to the BH, it is projected to produce a more drastic interaction, and it is more likely that one of the BHs of the system will be ejected rather than the star. In simulations where the star is less massive than the BHs, more commonly the result is a stellar ejection.

Another side of this research is to analyze the changes in parameters of the three-body system as a whole, specifically the relationship between mass transfer onto the colliding BH and how the spin of each BH is affected over the course of the collision. Parameters that might be affected by the mass transfer and change in mass distribution are the total spin of the system, the eccentricity of the BBH orbit, and the semi-major axes of the BBH orbit, along with the eccentricity and semi-major axis between the star and each of the BHs.

The BBH in this particular system was formed in a dense globular cluster which increases the probability of a stellar interaction. The dimensionless spin parameter χ_{eff} can be computationally determined as well as observationally through observations of laser interferometers such as the Laser Interferometer Gravitational-Wave Observatory (LIGO). This parameter allows us to understand how different characteristics of a system impact BHs and their spins. The motivation behind choosing a supergiant star is these stars have not been commonly used in dynamical simulations. It is important to explore this area of collisions because they do exist, even if they are rare.

1.2 Prior Work

Many studies have been done based on various aspects of these collisions between stars and BHs. For example, Lopez et al. [1], focuses on disruptions of stars by BBHs. They discuss the dynamical formation of BBHs in dense stellar clusters, which is how the BBH in the system I work with was formed. The mass distribution between the two BHs is also discussed and analyzed in this paper, specifically that the BHs can gain a significant amount of mass from the star that it disrupts, which then alters the spin of the BHs, and subsequently $\chi_{\rm eff}$. It is concluded that how the spins are altered is determined by how much mass is accreted onto the BH and even though these BBHs are formed dynamically and the spins of the BHs are expected to be random – not correlated in any way – the spins can be altered in either or both direction and magnitude during these collisions. The spins of the BHs can be aligned or misaligned with respect to their orbit. It is mentioned that this phenomenon contradicts the previously accepted belief that BH spins are set at birth and are unchanging and non-evolving.

The ways that these BBHs are formed is also discussed, referred to as 'formation channels' that depend on the each BH mass, orbital eccentricity, and the spin parameter $\chi_{\rm eff}$. A final remark of the paper is that less massive objects in three-body systems get ejected, and this object is generally the star, but in my system, the BHs are less massive than the star, and BH1 is just barely smaller than BH2. Typically, when the star is less massive than the BHs, subsequent encounters after the initial encounter are less likely to happen. Due to the fact that my supergiant star is about 5 $M_\odot$ larger than each BH, so the behavior of the star and BHs during the collisions, the changes in the initial parameters, and which body of the system is ejected by the end will be an interesting aspect to analyze.

The simulations in Kıroğlu et al. 2023a-b [2], [3] are performed in the realm of main sequence stars, or middle-aged stars, in which they are collided with Intermediate Mass BHs (IMBHs). IMBHs are BHs that have masses between 100 times the mass of our Sun and 10^4 times the mass of the Sun. The units that are typically used to measure the mass of celestial bodies such as BHs and stars among other objects, are solar masses ($M_\odot$), which is equal to the mass of the sun, $M_\odot = 2 \times 10^{30}$ kg. Kıroğlu et al. focuses specifically on partial tidal disruptions of main sequence stars by IMBHs where the dependence of outcomes of the collisions on the BH mass is analyzed. The outcomes ranged from total tidal disruptions to partial tidal disruptions to small tidal interactions. It was concluded that stronger partial interactions between the star and the BBH lead to more stellar mass loss, resulting in the stellar remnant being ejected from the system. It was also claimed that the number of close passages of the star decreased with increased BH mass.

Next, Fishbach et al. [4] focuses on systems with the most negative dimensionless spin parameter of BHs in a BBH are formed through hierarchical BH mergers, that is to say the current BH was formed through various past mergers of smaller BHs. The spin parameter, χ_{eff}, is the spin of the total system based on the BH spin(s) is in the direction of the angular momentum of the binary orbit. This parameter will be covered more thoroughly in section 2.3.2. Although Fishbach et al. focuses on a different type of formation channel for BBHs than what I am doing, it is relevant to this work. The χ_{eff} values that have been observed through gravitational waves (GWs) and laser interferometers are more positive than negative. The lowest value for χ_{eff} that has been observed is no less than –0.2. Fishbach et al. runs systems that have a χ_{eff} value of less than –0.3 and concluded that less than 4.2% of their runs had a $\chi_{\text{eff}} < -0.3$. They mention that the χ_{eff} distribution is not centered around zero, as

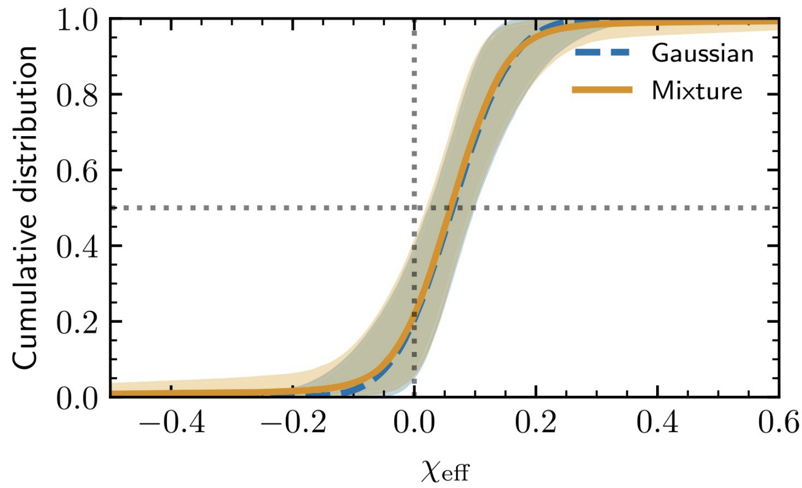

Figure 1.2.1: Inferred χ_{eff} cumulative distribution function (CDF) for the BBH population. This graph fits BBH events in the latest LVK catalog GWTC-3 to two models, Gaussian (blue) and a mixture model between a Gaussian and a uniform distribution, with limits $-1 \leq \chi_{eff} \leq 1$ [4].

had been previously assumed, and is shown in the distribution graph in Figure 1 below. This asymmetry suggests that the scenario involving isolated BHs that initially have zero spin is not well understood yet. The outcome may depend on factors related to angular momentum transport in more massive stars, but this is unclear.

The BHs I am working with will start with a spin of zero and will be isolated from other stars in the cluster during the simulations, other than the star it is colliding with. The LIGO-Virgo-KAGRA collaboration is a collaboration between the two LIGO (Laser Interferometer Gravitational-wave Observatory) locations, and two other GW interferometers (see section 2.3.1 for more detail): Virgo in Italy and KAGRA (Kamioka Gravitational Wave Detector) in

Japan. The GWTC-3 catalog is the latest observation run that the four interferometers have run together.

2 Theory

2.1 Gravity

One of the most vital phenomena in the known universe is gravity. Most of the time we take no notice of it, but gravity is the glue that holds galaxies together and the force behind stellar explosions.

2.1.1 Laws of Motion

The foundation of several concepts in introductory physics comes from Newton's laws of motion. One of the first equations that is taught to aspiring physicists and scientists alike is

$$\vec{F} = m\vec{a}, \tag{2.1.1}$$

where $\vec{F}$ is the force acting on the object, m is the mass of the object or the center of mass between two particles, and $\vec{a}$ is the acceleration of the object. Equation 2.1.1 is crucial to most physics calculations, especially when doing calculations with the center of mass of a system. Due to the fact that equation 2.1.1 uses the center of mass to calculate the force, it is not the equation we use for the large-scale collisions, rather, we use it to do small calculations between individual particles in the star. Another familiar equation that is used when doing physics calculations from the beginner level to the advanced level is Newton's third law of motion,

$$\vec{F}_{12} = -\vec{F}_{21}, \tag{2.1.2}$$

where $\vec{F}_{12}$ is the force of object 1 on object 2 and $\vec{F}_{21}$ is the force of object 2 on object 1. This law states that each force has another equal and opposite force to counteract it. We implement Equation 2.1.2 in the same manner as equation 2.1.1, on the individual particles themselves. Each particle will exert a force on the particle or particles next to it, and an equal and opposite force will be applied back onto the original particle from the neighboring particle(s).

2.1.2 Newton's Law of Universal Gravitation

An important aspect of astrophysical calculations is Newtonian mechanics, especially those dealing with interactions of celestial objects. *StarSmasher*, our smoothed particle hydrodynamics (SPH) code, relies on equation 2.1.3 to make the calculations for each collision that is run. Specifically, Newton's Law of Universal Gravitation is used in *StarSmasher*'s calculations. For example, if there are two objects, object 1 and object 2, where object 1 is exerting a force on object 2, it can be written as

$$\vec{F}_{21} = -G\frac{m_1 m_2}{{r_{21}}^2}\hat{r} \tag{2.1.3}$$

where $\vec{F}_{21}$ is the force of gravity that object 1 exerts on object 2, G is Newton's gravitational constant ($G = 6.67 \times 10^{-11}\,\frac{\mathrm{m}^3}{\mathrm{kg\,s}^2}$), m_1 is the mass of object 1, m_2 is the mass of object 2, r_{21} is the distance between objects 1 and 2, and $\hat{r}$ is the unit vector that points from object 2 to object 1 (because object 1 is exerting the force). The negative sign at the beginning of the equation indicates an attractive force between the two objects. The same is true for object 2 exerting a force on object 1, except $\hat{r}$ would be directed toward object 2.

2.2 Black Holes

In the known universe, there is a lot we as scientists do not understand. Part of this gray area are BHs, which are elusive objects that do not produce electromagnetic radiation and cannot be seen with the naked eye. BHs have three intrinsic properties: spin, mass, and charge, much like the intrinsic properties of a particle. There are different types of BHs as well: stellar mass black holes, intermediate mass black holes (IMBHs), and super-massive black holes (SMBHs). I will be working with stellar mass BHs, as they are the most observed, at this point, in the universe. These BHs have masses less than 100 $M_{\odot}$. There still is not a lot of evidence for the existence of IMBHs (masses between 100 $M_{\odot}$ and 10^4 $M_{\odot}$), but it is likely that they do exist. SMBHs have masses greater than 10^4 $M_{\odot}$ and are usually found at the centers of galaxies. There are also BBHs, which occur when two BHs are bound to each other in an elliptical orbit. The bulk of this work will be with a BBH formed in a dense cluster of stars called a globular cluster.

2.2.1 Schwarzschild Radius

The distance at which the escape velocity is equal to the speed of light is called the Schwarzschild radius. At this point, not even light can escape once it passes the event horizon or the edge of the BH. Not only is light unable to escape, but it has also been concluded that light is frozen in time at the point of the Schwarzschild radius. This radius can be calculated using Newton's gravitational constant, the mass of the BH M, and the speed of light $c = 2.998 \times 10^8$m/s

$$R_s = \frac{2GM}{c^2}. \tag{2.2.1}$$

The Schwarzschild radius is also defined as the distance between the center point or singularity of the BH to the event horizon, which is the mathematical surface that prevents observers from directly seeing what happens inside of the BH. However, the properties of the BH itself are still able to be calculated through alternate methods, which are described in section 2.2.

2.2.2 Tidal Radius and Tidal Forces

Tidal forces occur due to differences in gravitational forces at different positions within the same object. The most common example of tidal force interactions is the relationship between the Earth and the Moon. The Earth experiences ocean tides (high tide and low tide), which depend on the position of the Moon relative to the position of the Earth. The Moon causes a bulging of the Earth as well so that it is actually more of an elongated spherical shape. This is the same idea that the star in a collision with a BH experiences. When the star gets close enough to the BH, it experiences a tidal force that pulls on the star and causes bulging of the star as a result. The force between any two objects is Newton's Law of Gravitation given by equation 2.1.3. In the context of the collisions being ran for this project, the force of gravity between a small mass element on the surface of the star that has mass m, and a BH of mass M_{BH}, where r is the distance between the center of the star and the BH is

$$\vec{F}_{\mathrm{gc}} = \frac{GM_{\mathrm{BH}}m}{r^2}. \tag{2.2.2}$$

Next, consider the force of gravity between the BH and the star starting at the surface of the star, where R is the radius of the star and r is the distance between the surface of the BH and star

$$F_{\mathrm{gs}} = \frac{GM_{\mathrm{BH}}m}{(r-R)^2}. \tag{2.2.3}$$

From here, the tidal force is an approximation of the difference of equations 2.2.2 and 2.2.3

$$F_t = 2G\frac{RM_{BH}m}{r^3}. \tag{2.2.4}$$

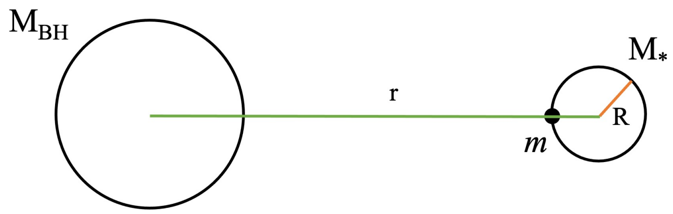

Figure 2.2.1: Diagram of the tidal force case presented above.

The tidal radius is the distance from a BH at which the incoming star begins to be deformed as a result of tidal forces. To calculate the tidal radius, we have to acknowledge that the tidal radius is the point at which both the force of gravity and the tidal force are equal. So, we set these two forces equal to each other

$$\vec{F}_t = \vec{F}_g = 2G\frac{R_* M_{BH} m}{r_t^3} = \frac{GM_*}{R_*^2}. \tag{2.2.5}$$

Solving for r_t^3, we get

$$r_t^3 = 2R_*^3\frac{M_{BH}}{M_*}, \tag{2.2.6}$$

then by taking the cube root of equation 2.2.6 and neglecting the factor of 2, the tidal radius is given by

$$r_t = R_*\left(\frac{M_{BH}}{M_*}\right)^{\frac{1}{3}}. \tag{2.2.7}$$

When the separation between the BH and star is less than the tidal radius, $r < r_t$, the star is expected to be destroyed. There are two main types of disruptions that stars experience as a result of tidal forces: tidal disruption events (TDEs) and partial tidal disruption events (PTDEs).

In the former, the star is completely destroyed and there is nothing left of the star except the leftover mass that is bound after the collision. Even though there is mass from the star left in the system, it is no longer considered a star because there is no longer a core, it is simply bound mass. In PTDEs, the core of the star does remain after the collision, so the result is a stellar remnant. There is a possibility that at later times that stellar remnant will collide with the BH again and be completely destroyed.

2.3 Gravitational Waves

Waves that travel through space and interact with virtually nothing are GWs. These waves are produced when any object in the universe accelerates, but they are not easily detectable unless they originate from a massive celestial object such as a BH, and even then, it is difficult to detect them on Earth because of the expansive distance between the origin of the GWs and the Earth. There are various types of these waves, but for BBHs specifically, the type of waves that are produced are called compact binary inspiral GWs due to the nature of the orbit of the BHs. Over millions of years, the BHs in the binary orbit each other, and as GWs are produced from each BH, energy is carried away from the system by the GWs. From GWs, the origin, nature, and properties of the detected BH(s) can be determined.

2.3.1 Laser Interferometers for Observing Gravitational Waves

One of the ways BHs are detected is through laser interferometers. Interferometers like LIGO take advantage of the properties of lasers and mirrors to detect the GWs that are produced by massive objects in the universe. There are two locations of LIGO: Hanford, Washington, and Livingston, Louisiana. These observatories work in the same way: there are two arms, each 4 kilometers long, called the Fabry Perot cavities, that house the lasers. The laser beam is emitted, and then reaches a beam-splitter that splits the laser into the two arms. In each arm, there are two mirrors, one that is partially reflective, and one that is fully reflective. The partially reflective mirror is placed at the end of the arm that is closest to the beam-splitter. The photons from the laser travel between the two mirrors in the arm around 300 times before recombining and arriving at the detector, shown by the black dot in Figure 2.3.1. The number of times the lasers bounce back and forth inside the arms increases the sensitivity of LIGO.

Additionally, a power recycling mirror was a necessary addition to allow for an increase in power in the LIGO system. This mirror ensures that as laser power is being continuously supplied into the interferometer, the power from the existing laser is being reflected or 'recycled' back into the interferometer. This increases the power inside of the 4 km cavities, which also increases the sensitivity of LIGO by sharpening the interference peaks when the lasers are superimposed, making it easier to tell if gravitational waves have passed through the interferometer.

Gravitational wave interferometers exist outside of LIGO, however. There are three other interferometers on Earth, and one that will be in space within the next decade or so. The other three interferometers are Virgo, located in Pisa, Italy; KAGRA (Kamioka Gravitational Wave Detector), located underground in Gifu prefecture, Japan; and GEO600, located in Hannover, Germany. There are other gravitational wave interferometers being built all over the world, but these are the ones in operation. Within the next decade, a gravitational wave interferometer is to be launched into space called LISA (Laser Interferometer Space Antenna). This will be a significant breakthrough in gravitational wave detections and astrophysics because LISA will be able to detect waves that would not have been able to be detected on Earth, even with the increasing sensitivity of the Earth-based interferometers.

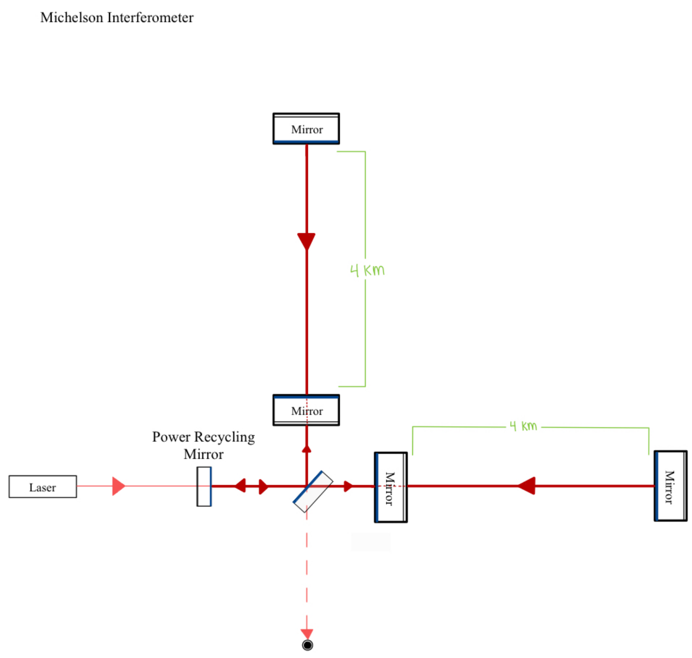

Figure 2.3.1: Diagram of the version of the Michelson Interferometer that LIGO uses. There are enhancements applied such as the 4 km arms with mirrors and a power recycling mirror to elevate the capabilities of the interferometer.

2.3.2 The Dimensionless Spin Parameter

The dimensionless spin parameter χ_{eff} measures the total spin of a system in the direction of the angular momentum of the BBH orbit. It can be both observationally determined by LIGO and calculated from simulation data. The range of χ_{eff} is between –1 and 1, but it is more typical for the values to fall closer to zero on either side, but mainly on the more positive side. This parameter is expressed computationally through a weighted average of the masses of each BH and their respective spins, dotted with the angular momentum unit vector

$$\chi_{\text{eff}} = \frac{M_{\text{BH}_1}\vec{S}_{\text{BH}_1} + M_{\text{BH}_2}\vec{S}_{\text{BH}_2}}{M_{\text{BH}_1} + M_{\text{BH}_2}} \cdot \hat{L}, \tag{2.3.1}$$

where M_{BH_1} and M_{BH_2} are the masses of each BH, $\vec{S}_{\text{BH}_1}$ and $\vec{S}_{\text{BH}_2}$ are the spins of their respective BH, and $\hat{L}$ is the unit vector of the angular momentum of the BBH orbit, which gives the direction of the angular momentum. The spins of BHs are determined at birth and are intrinsic to a BH. In my simulations, and in the simulations run by Lopez et al. [1], the BHs start with zero spin so that after the simulation is run, how much spin each BH picked up during the run can be analyzed. Due to the fact that the spin of the BBH depends on the mass ratio of the star and BH, the mass of the star that is to be disrupted plays an important part in the outcome of the spin of the BH. More massive stars will have more of an effect on the spin of the BH it is colliding with, whereas lower mass stars will not typically have a large effect on the spin of the BH. However, it is not yet clear what would occur when the BH and intruder star have similar masses, and this is what I aim to focus on.

To find the spins of the BHs, Lopez et al. gives

$$S\left(M_{\mathrm{BH,f}}\right) = \left(\frac{2}{3}\right)^{\frac{1}{2}} \frac{M_{\mathrm{BH}}}{M_{\mathrm{BH,f}}} \left\{4 - \left[18\left(\frac{M_{\mathrm{BH}}}{M_{\mathrm{BH,f}}}\right)^2 - 2\right]^{\frac{1}{2}}\right\}, \tag{2.3.2}$$

which assumes an initially low- or non-spinning BH. This allows us to calculate the spins of each BH to use in equation 2.3.2. The mass of the BH after it had accreted a fraction of the star mass is given by $M_{\mathrm{BH,f}}$.

To visualize χ_{eff}, see Figure 2.3.2 below. There are many different orientations that the angle between the angular momentum of the BBH ($\vec{L}_{\mathrm{BBH}}$) and the angular momentum of the accretion disk ($\vec{L}_{\mathrm{disk}}$) can take, but there are three special cases for the way the orientation of the angular momentum of the BH can align: parallel, anti-parallel, and perpendicular. These three cases are the cases in which the values of χ_{eff} are equal to positive, zero, and negative values, respectively. The limitations of χ_{eff} are between –1 and 1. The accretion disk is the disk of matter that forms around a BH that has disrupted a star and collected some or all of the mass of the star. These orientations are only special cases, so the angle between the two angular momentum values can take on any angle between the three. Additionally, the BH can get spin in the direction of the angular momentum of the accretion disk $\vec{L}_{\text{disk}}$ through effects that the spin of the disk on the BH, causing the BH to spin.

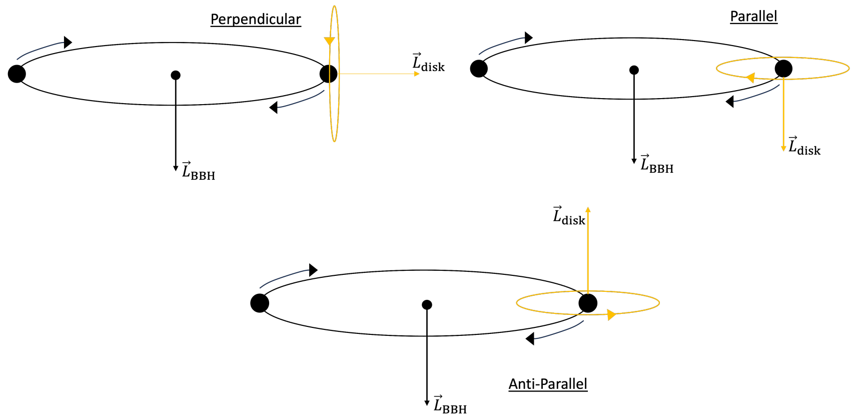

Figure 2.3.2: The top left image shows the special case where the angular momentum of the accretion disk (shown in yellow) is perpendicular to the angular momentum of the BBH. The top right image shows the parallel case, where the angular momentum of the accretion disk is parallel to the angular momentum of the BBH. The bottom image shows the case where the angular momentum of the accretion disk is anti-parallel to the angular momentum of the BBH.

2.4 Stellar Structure and Evolution

The accuracy of simulations relies on the evolution of the star used in the collisions. If the star does not have the correct age, radius, mass, type, temperature, etc., the resulting collisions will not be aligned with the results we should have from the desired star. By paying close attention to the details of the star, we can match scenarios and compare with previous ones.

2.4.1 Density, Pressure, and Hydrostatic Equilibrium

Three of the main phenomena allow us to perform these simulations: density, pressure, and hydrostatic equilibrium and are the reason that stars can exist. The first of these is density which is generally described as $\frac{\text{a mass}}{\text{a volume}}$. In the more specific terms of this research, the average density of a star is,

$$\rho = \frac{M_*}{\frac{4}{3}\pi R_*^3}, \tag{2.4.1}$$

where M_* is the mass of the star and R_* is the radius of the star.

The pressure of a star is given by

$$P_* = \frac{\rho k T}{\mu m_\mathrm{h}}, \tag{2.4.2}$$

where P is the pressure, ρ is the density of the gas given in equation 2.4.1, μ is the mean molecular mass, m_h is the mass of a hydrogen atom, k is Boltzmann's constant (1.381×10^{-23} J/K), and T is the temperature.

A star is characterized by its ability to maintain this hydrostatic equilibrium along with fusion. If a star is out of equilibrium, it means that either the force of gravity or the force of the internal pressure of the star won over the other. If these forces are not balanced, the star would either implode on itself or it would explode. The condition of hydrostatic equilibrium,

$$\frac{dP}{dr} = -G\frac{M_\mathrm{r}\rho}{r^2} = -\rho g \tag{2.4.3}$$

where $g = \frac{GM_r}{r^2}$, which is the acceleration of gravity at radius r, M_r is the mass inside the radius r, and ρ is the density of the gas inside the star. This equation is important for the structure of stars being simulated because it is also an important part of real stars, so we must include this for accurate simulations. In equation 2.4.2, the pressure gradient expressed, $\frac{dP}{dr}$, is necessary because it must be equal to the force of gravity onto the star, so that it counteracts the force of gravity, allowing the star to be static. This is pictured in Figure 2.4.1.

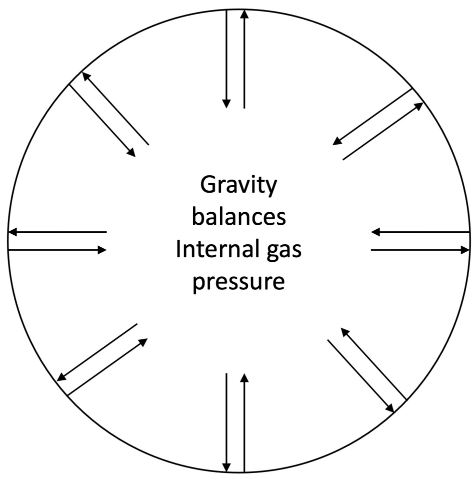

Figure 2.4.1: Depiction of the equilibrium of forces that work against each other to keep the star at hydrostatic equilibrium. This prevents the star from collapsing in on itself or exploding.

2.4.2 Stellar Evolutionary Stages

Every star that has existed has followed a stellar evolutionary track. This track starts when regions of gas and dust in space collapse under the weight of gravity and this low temperature, high density region is perfect for star forming. It is gravity that ends up causing a new star to form, as the beginning of a star starts out as a low temperature, low density ball of gas, but as gravity pulls all of the gas down in on itself, it heats up. This is called the protostar phase. Once the protostar becomes dense enough to start trapping heat from the gravitational collapse, it starts getting hotter and moving along the track. When the star gets hot enough to start fusing hydrogen, it is then considered a main sequence star. This is the phase that a star spends the most time in during its life because hydrogen is the most abundant element in stars, so there is a lot of it to fuse into helium.

Once the star is finished fusing the hydrogen into helium (a process that takes billions of years), it moves onto the giant phase of its life.

This means that the star begins to expand, and as the surface temperature decreases, the core temperature increases, all while the star gets more luminous. At this stage, the star begins

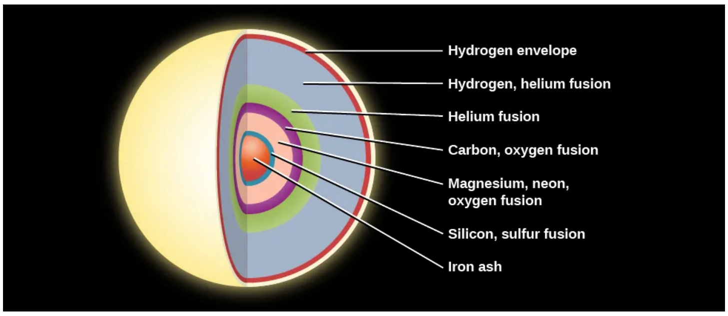

Figure 2.4.2: A look at the interior structure of a massive star before it dies [5].

igniting helium in its core. Once it runs out of elements to provide the star energy, massive stars collapse in on themselves and explode, causing a supernova. These massive stars fuse through a series of elements shown in Figure 2.4.2. A supernova is an explosive event that happens at the end of a massive star's life where neutrons, gas, and energy are expelled out of the area of the former star, sometimes colliding with and destroying other stars in the vicinity.

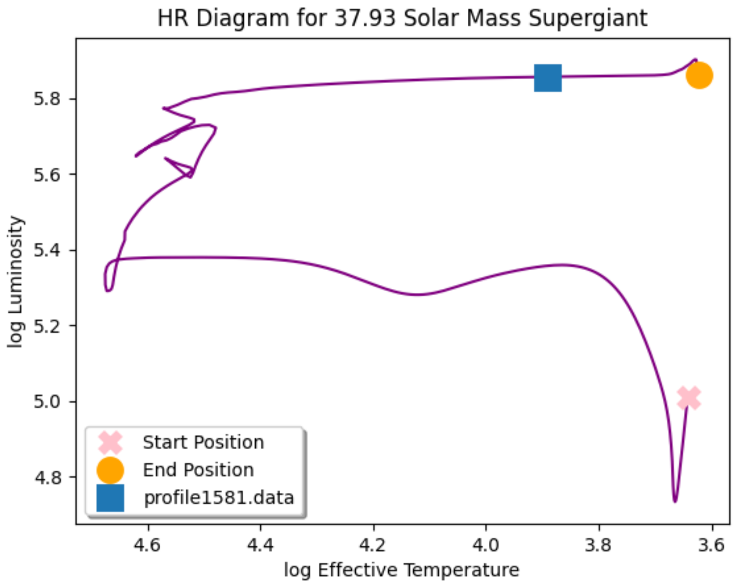

Figure 2.4.3: A Hertzsprung-Russell diagram showing the evolution of my 37.94 $M_{\odot}$ supergiant star. The loops in the top left of the graph show the temperature fluctuation of the star as it ages. The star is born in the bottom right of the graph and ends in the top right on the supergiant branch. The mostly horizontal part of the middle is where the star followed the main sequence path for most if its life. The supergiant branch can be found at the top part of the graph where the second horizontal line is.

In Figure 2.4.3, a plot of the path a star follows during its lifetime, and which shows the relationship between the star's temperature and luminosity is pictured. These graphs, called

Hertzsprung-Russell diagrams (HR diagrams), help us understand where the star is at in its life cycle when simulating them, and when to stop the simulation. This is the evolution of the star that I will be using for my collisions, and it surpassed the normal red giant branch and moves directly to the supergiant branch because of its size. HR diagrams also help us understand what sorts of changes it experiences in its lifetime. For example, in Figure 2.4.3, we can see a few loops in the left of the graph. These loops show the temperature fluctuations in the star as it evolves.

2.5 Elliptical Orbits

Elliptical orbits mean that the body orbiting another is bound unless an intruding body comes in and disrupts the orbit. Consider a star orbiting a BH on an elliptical orbit. A few important aspects of this type of orbit are periapsis distance, apoapsis distance, eccentricity and semi-major axis. Periapsis is the point of closest approach between the star and BH, apoapsis is the farthest point that star gets from the BH, the eccentricity determines how circular or elliptical the orbit itself is, and the semi-major axis of the orbit is the radius of the ellipse.

The periapsis distance r_p is characterized by

$$r_\mathrm{p} = a(1-e) \tag{2.5.1}$$

where a is the semi-major axis and e is the eccentricity of the orbit. The apoapsis is similar to periapsis

$$r_\mathrm{a} = a(1+e). \tag{2.5.2}$$

The eccentricity of the orbit tells us how circular or elliptical the orbit is. The eccentricity of an elliptical orbit can between 0 and 1, where 0 corresponds to a circular orbit and 1 corresponds to a parabolic orbit. So, in order for the orbit to be elliptical, the eccentricity cannot equal 1, because then the star would be on a parabolic orbit, or if it is greater than 1, it would be a hyperbolic orbit, meaning the object is unbound to the system. An eccentricity of 0.8 is considered very eccentric and is an elongated ellipse, much like the one shown in Figure 2.5.1.

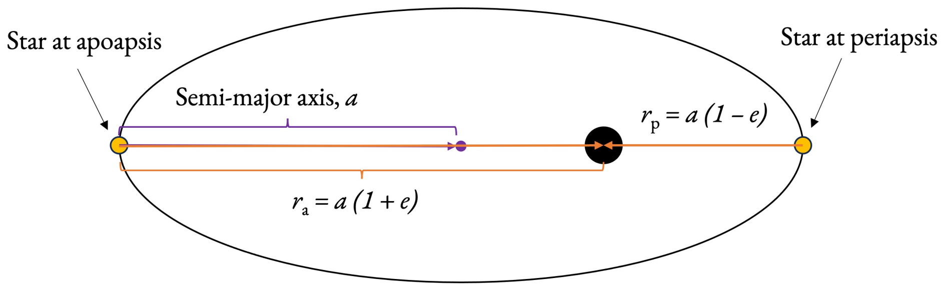

Figure 2.5.1: Breakdown of where periapsis and apoapsis are, with the semi-major axis labelled as well. The black dot is the BH, and the purple dot is the center.

This is the type of orbit the star in my collisions is on, as the big picture of the system is that it is in a large star cluster, so the star will not be bound to the BBH orbit.

3 Methodology

The motivation behind the types of collisions that are being done come from a code called Cluster Monte Carlo (CMC) code. This code simulates globular clusters using an N-body approach to model stellar dynamics and collects data on the individual collisions that are happening within a globular cluster simulation. The term N-body refers to the idea of a dynamical simulation of particles. This allows us to gather information on the types of collisions that are more typical in these dense star clusters and which ones are more common. CMC simulates clusters using statistical treatment of stellar dynamics [6], which models collisions as nearest-neighbor encounters. Our collaborators at Northwestern University provide us with the data from the CMC simulations, and we run our simulations based off of that data. The case that I chose from the CMC data file was the result of going through the data and figuring out which cases suit the goals of the research the best. In this research, I filtered through each case based on a few expectations for the parameters of the star and how it is related to the BHs of the system.

First, I was looking for a supergiant star, so I made a spreadsheet with all of the supergiant stars and their respective data. Then, I was looking for a star that was of similar mass to the individual BHs in the binary. Once I found a few cases where the star and BHs were similar masses, I started looking at a couple different parameters. The first parameter I looked at was the ratio of the periapsis distance to the semi-major axis of the orbit of the BBH. I was looking for numbers close to 1 but accepted a range between 0.5 to 1.5. The next criteria I looked at was the ratio between the mass of the first colliding object to the second colliding object. I was looking for values of this ratio that were less than 2.5 because I wanted the masses to be as similar as possible.

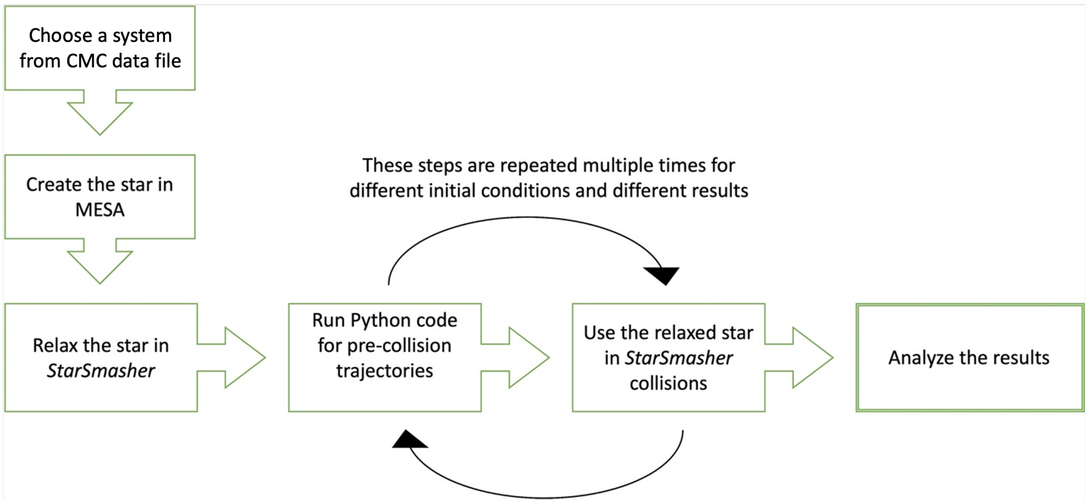

Figure 3.0.1: A flow chart showing the overview of the steps I take to run simulations based off the data file provided by Northwestern University and CMC.

The star and system that matched these criteria are as follows: a supergiant star of 37.94 $M_\odot$, with a radius of 462 $R_\odot$ (where the radius of the Sun is $R_\odot = 6.96 \times 10^8$ m), the first BH is 32.68 $M_\odot$, and the second BH is 32.69 $M_\odot$. The radius of the star was slightly different in the MESA model, as it was 465 $R_\odot$. This small difference can be ignored as it is already such a large radius and 3 $R_\odot$ is negligible. A few important parameters of this system are the eccentricity of the BBH is 0.15, which means it is on the more circular side of an ellipse, and the semi-major axis of the BBH orbit is 744 $R_\odot$. This research has many steps to it, which are shown in the flow chart in Figure 3.0.1.

3.1 Modules for Experiments in Stellar Astrophysics (MESA)

Once a star is chosen, it needs to be evolved in a stellar evolution code called MESA (Modules for Experiments in Stellar Astrophysics). This program evolves the star according to the input given, so we match it closely to the data being pulled from the CMC code output. For the input, I told the code that I wanted a 37.94 $M_\odot$ star. Once the run was done, I looked back through the output to find the file that had a radius of 462 $R_\odot$. This file ended up being profile1581.data, as shown earlier in the HR diagram of Figure 2.4.3. Once we have a file that matches the parameters of the star, we can start running a program with Python to find out at which initial angles between the star and the BH actually collide and how long it takes.

3.2 Pre-Collision Trajectories

Pre-collision trajectories are important as they help us know when or if a collision occurs in the chosen system. This helps us choose which angles are the most efficient; if one set of angles results in a collision at an earlier time than another set of angles that results in a collision at a later time, then we would choose the set of angles that results in a collision at an earlier time for efficiency. This is not to say that the second set would not be used, it would just be used at a later date in the research. The angles used to start the collision are pictured in Figure 3.2.2. This program calculates all of the needed information to start a simulation. The output includes initial velocities and positions, along with the set of initial angles of the star with respect to the

BBH. In Figure 3.2.1, you can see what one of the graphs of a pre-collision trajectory run looks like.

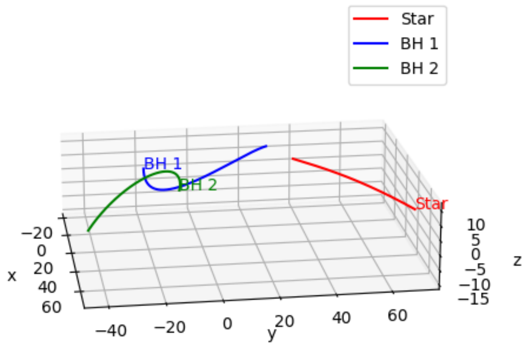

Figure 3.2.1: 3-D graph of the motion of the three bodies up until there is a separation of ten tidal radii between the star and the colliding BH. The starting point of the evolution is where the labels of each object are. The ending points are where there are no labels. This is the point at which the initial conditions of the simulation are set and where the simulation will start each object (It varies with each system and set of angles). This graph is produced from a run done during summer URSCA research, explained in section 4.1.

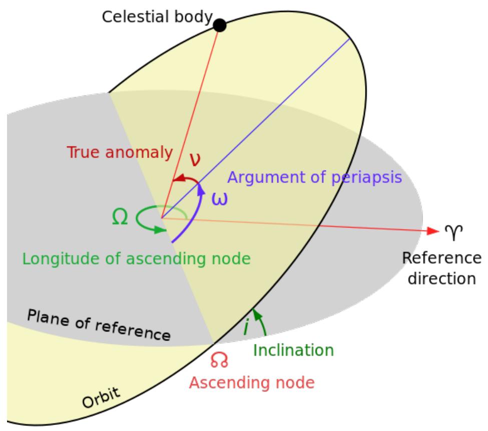

Figure 3.2.2: Pictured are visual definitions of what each angle that we use for the initial parameters of collisions. Each of these angles allows us to see how the objects in a system are placed in relation to each other. For more information, see this in-depth video on orbital dynamics `https://www.youtube.com/watch?v=N_njPJYaXaU` [7].

In Table 6.0.1, the initial angles as described in Figure 3.2.2 for eash collision are shown. These angles describe how each object is oriented in space as it is not always easy to visualize where each object is located in space.

3.3 *StarSmasher* and SPH code

The main program that will be used for simulations is *StarSmasher*, which is a smoothed particle hydrodynamics (SPH) code that allows us to accurately simulate dynamical collisions. *StarSmasher* uses a Lagrangian method to represent gas as a collection of particles [8]. It uses kernels, which are essentially pockets of fluid, as shown in Figure 3.3.1. In this figure, we can see that there are three different colors of particles. The black particles are outside of the kernel and have no effect on the kernel itself. The blue kernels are within one smoothing length and do have an effect on the red central particle and are referred to as neighbors of the central particle.

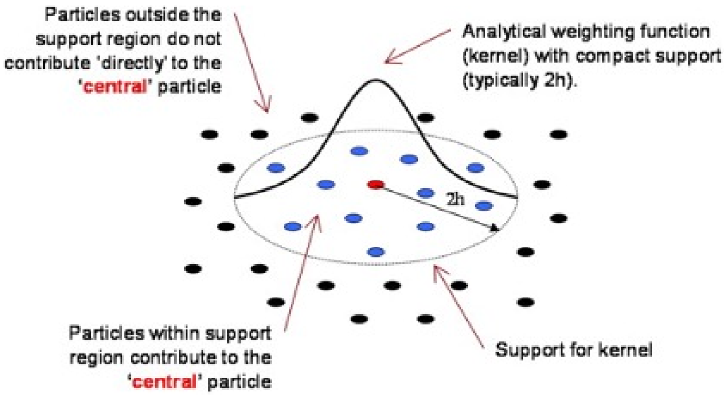

Figure 3.3.1: The breakdown of a kernel in SPH code, where h is the smoothing length of the particle, which is half the radius of the kernel. The smoothing length depends on the number of particles that are inputted by the user, decreasing as the number of particles increases [9].

3.4 Importance of Relaxations

When a star that is created in MESA is transferred to *StarSmasher*, the particles are left with an abundance of energy from the transition from MESA to *StarSmasher*. In order for the dynamical collisions to be as realistic as possible, we need to release this energy so that the particles can be brought to equilibrium and act more fluidly. The process of doing this is called relaxation. When transferred to *StarSmasher* from MESA, the particles of the star are laid in a rigid lattice. During the relaxation we look for various characteristics of the data to tell us if it is a good relaxation.

There are a couple different graphs that can help us do this. The first set of graphs are called profile plots, shown in Figure 3.4.1. There are a total of six plots in one window, and we are able to go through the different output files and see the difference of the six plots between one output file to the next. The graphs in the left column are of the density of the star plotted against its radius. The red lines seen on these graphs are what the black line is projected to line up with, and although they are not usually exactly lined up, they are close. However, if the relaxation is not good, these lines will not match up. On the right side of the graphs, there are plots that relate to different parameters of the star.

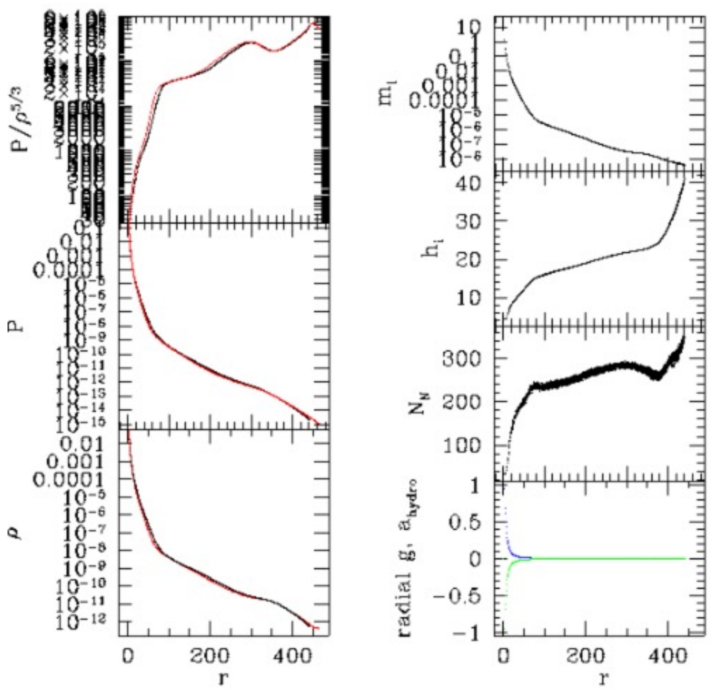

Figure 3.4.1: Early properties of an example relaxation run. In *StarSmasher*, the units of G, $M_\odot$, and $R_\odot$ are all equal to 1. The units of density are determined as $\frac{M_\odot}{R_\odot^3}$, which results in the density being on the order of 1000 $\frac{kg}{m^3}$.

The graphs in the left column of Figure 3.4.1 show profiles of pressure P and density ρ with the top one being the ratio of $\frac{P}{\rho^{5/3}}$. We can see that the alignment is fairly good between the red and black lines. On the right side of Figure 3.4.1, we can see four graphs that represent various properties of the star as a function of the radius of the star. At the top, there is m_i, which is the individual particle mass of each SPH particle. Below that, there is h_i, which is the smoothing length that was described in Figure 3.3.1.

Next is the number of neighbors for each particle N_{N}. The number of neighbors is how many particles are within $2h$ of any given particle. Having a smaller neighbor number can improve spatial resolution when running collisions. We can see that this number increases as the radius increases. Last on the figure is a graph of radial gravitational acceleration (green, lower) and hydrodynamic acceleration (blue, upper). In a good relaxation, these should mirror each other.

Another plot that is useful in helping us determine if a relaxation is good or not are energy plots like the ones pictured in Figure 3.4.2. These plots show us if the overall energy is decreasing and helps us confirm that the star is actually losing the extra energy it was holding after being transferred from MESA.

These graphs can also show us if the star starts expanding unexpectedly after the drag force is turned off at the halfway point in the relaxation run. If this happens, as seen in the example in Figure 3.4.2, it is signaled on the plot of kinetic energy T by a sudden jump in energy values. If the star starts expanding after the drag force is turned off, there is an issue which can be due to any number of parameters in the input file for the relaxation. However, if the star does not seem to be expanding after that point, and there is good alignment with the profile plots, then it is considered a good relaxation.

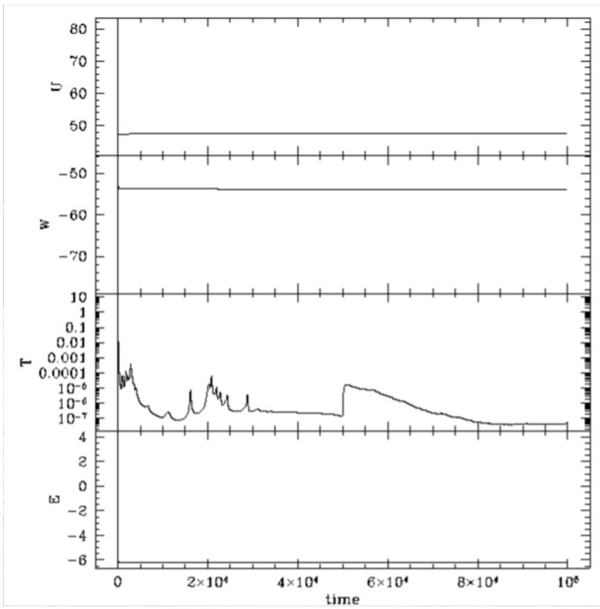

Figure 3.4.2: Various energy graphs during an example relaxation as functions of time. In this example, the expansion of the star after the drag force in turned off can be seen at about the halfway point with the jump in kinetic energy T in the third plot. The top plot is the internal energy U of the star, the second is the gravitational potential energy W, and the last plot is the total energy E. The units of energy are $E = \frac{GM_{\odot}^2}{R_{\odot}}$ and the units of time are $t = \sqrt{\frac{R_{\odot}^3}{GM_{\odot}}}$.

3.5 Dynamical Collisions in *StarSmasher*

The main part of this research is in the realm of collisions. To run these collisions, another feature of *StarSmasher* is used. This means that the particles are treated as fluid-like blobs to produce realistic collisions. To start a collision, we take the pre-collision trajectory data and choose a collision case somewhat arbitrarily. We want to have an even balance of co-planar inclination angles with respect to the x-axis) and some angles in between for a comprehensive spread of data points to analyze.

In addition to the initial angles, the starting x, y, and z positions are given for each of the three objects (2 BHs and one star), as well as their initial velocities. The initial data is used from the pre-collision trajectory data and entered into an input file in each respective collision folder. *StarSmasher* then reads the data from the input file with the initial values as well as the original *StarSmasher* input file to begin the run. These collision runs can take anywhere from a couple of weeks to a month or longer. The length of time required for the collision depends on the outcome of the collision itself and the amount of dense regions of particles and the density of those regions that *StarSmasher* is evolving near the BHs. For example, if the collision results in a TDE where the star collides with a BH head on, the rate at which output files are being generated will slow because of the density of particles in a small area. On the other hand, if the collision results in a PTDE, then the run will progress slightly faster because the density of the particles is not as concentrated in one area of space.

In these collisions, the BHs are treated as a single particle with zero spin for simplicity. When starting the BHs with an initial spin of zero, we are able to tell how much the mass transfer from the star had an effect on the spin of the BH and the angular momentum of the accretion disk as mentioned previously. Valuable insight can be gained here into the interactions of stars with BHs and how the spin of the BHs in the system evolve with respect to mass transfer.

4 Preliminary Results

4.1 URSCA Summer Research

For six weeks during the summer of 2023, I had the opportunity to do research similar to the research I am doing now. I collaborated with Hans Vanderzyden '25, Dr. Lombardi, and Fulya Kıroğlu of Northwestern University. We spent the summer running three different star-binary combinations of main sequence stars colliding with BBHs and analyzing the mass transfers of the systems and the effects that the collisions had on χ_{eff}. We ran a total of 42 simulations in these six weeks, with the help of computers from the Allegheny Lab for Innovation and Creativity (ALIC). The star that I focused on was a 10.11 $M_{\odot}$ main sequence star that was colliding with BHs of masses 37 $M_\odot$ and 40 $M_\odot$. I ran these simulations with many different initial conditions, and in total ran about 15 simulations for this star-binary combination. Figures 4.1.1, 4.1.2, and 4.1.3 show the HR diagram of the 10.11 $M_\odot$ star, its relaxation profile plots, and energy plots, respectively.

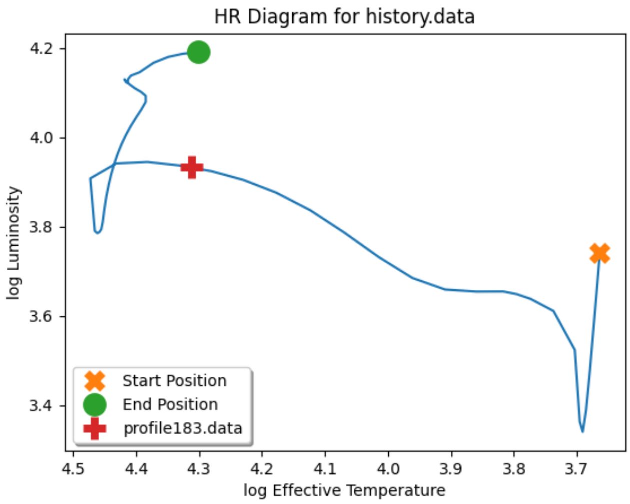

Figure 4.1.1: The HR diagram for the 10.11 $M_\odot$ main sequence star. We can see that the profile (marked by the red '+' that was chosen from the MESA run is on the horizontal area of the path, indicating that the star is in the main sequence phase of its life.

After running the MESA evolution for the star and running a successful relaxation, I could move on to the collisions part of the research. To start, I ran the three-body integration code to find initial conditions of the system that would result in a collision at relatively early times (so we were not waiting days for the star to collide, but instead getting a collision almost right off the start of the run). Figure 4.1.4 shows four screenshots of a movie of a collision I ran and made. It is in the 3-D perspective, giving a different perspective of the collision and details that were previously unable to be seen with a 2-D perspective. I experimented with this feature of our visualization software, SPLASH [10], because it had not been used recently to visualize these collisions in 3-D. The 3-D perspective allows the viewer to see how the collision might actually look in space. I also used the options of a white 3-D box for a frame of reference and used the zoom and rotation features of the program. In the figure, we can see a color bar as

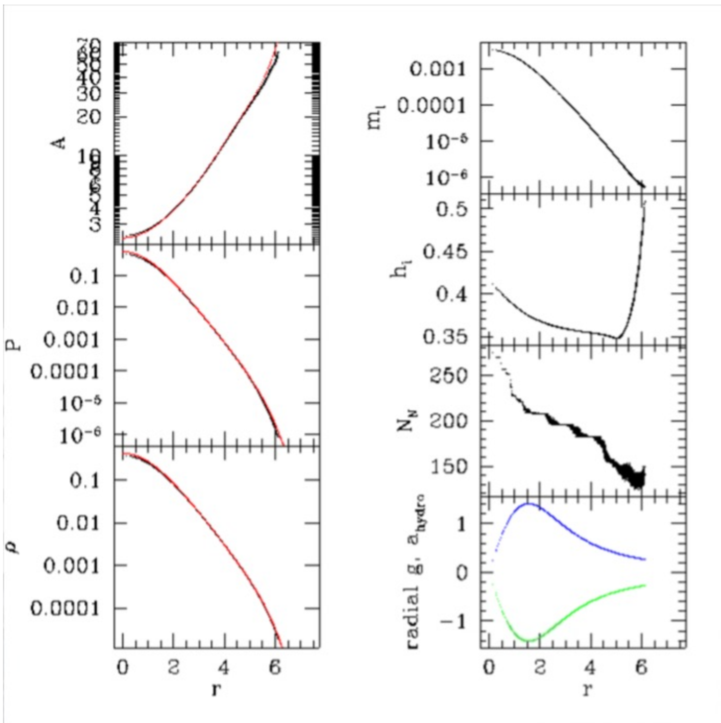

Figure 4.1.2: The properties of the 10.11 M$_\odot$ main sequence star that was relaxed over the summer. We can see that there is good alignment in the graphs, indicating a good relaxation of the star.

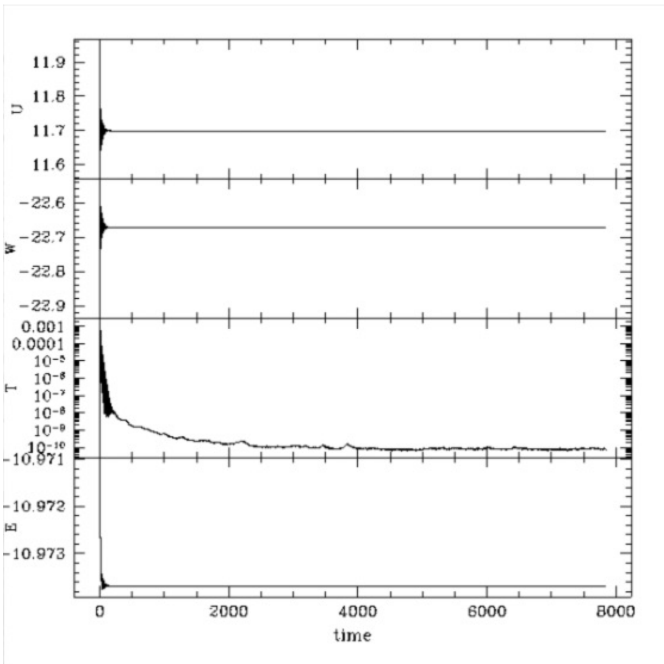

Figure 4.1.3: Here we see the energy graphs for the relaxation of the 10.11 M$_\odot$ star. We can see that the energies are all low, and the gravitational and internal energies are mirroring each other, which is what we are looking for. There is not a lot of noise at late times, indicating that the majority of the extra energy has been released from the particles.

well. This indicates the density of particles in a given region, so when the color is yellower, that means there are more particles in that region of the simulation and when the colors are bluer, that means the density of particles in that region is lower.

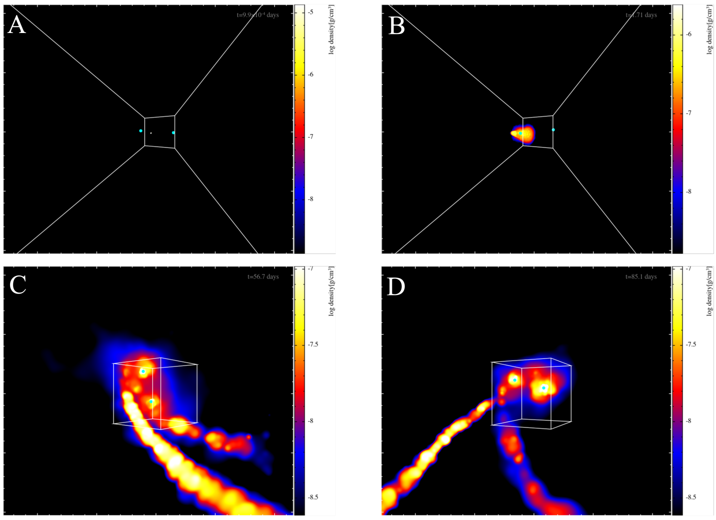

Figure 4.1.4: Multiple stages of a 3-D SPLASH visualization of a TDE scenario involving a 10.11 $M_\odot$ star and a 76 $M_\odot$ binary. Stage A shows the initial placements of the bodies at the start of the run. Stage B shows the system shortly after the collision. Stage C shows the tidal tails that are created as a result of the collision. Stage D shows the end of the run, the tidal tails are accreted back into the BHs in a winding motion. **Stages C and D are zoomed out, with rotations of the z-axis in the clockwise direction. Note: This run has initial angles i115, a90, p180, and l90. More about these angles can be found in Figure 3.2.2).

After running the simulations, we did an analysis of the data. We looked at the mass transfer and how it might have affected χ_{eff}. We found that the more mass that was accreted by the BH, the more χ_{eff} changed. This is to say that when the mass transfer onto the BH will result in a higher spin, and when there is less mass transfer onto the BH, the less the spin will be affected, and a lower value will result.

5 Relaxation of the 37.94 $M_\odot$ Supergiant

The relaxation of this star proved to be more difficult than anticipated, and it took longer than expected to produce a relaxation that could be used in dynamical collisions. Due to its steep density profile, it was nearly impossible to get a perfect relaxation of the star. I ran into a problem of the particles of the star expanding once the drag force is turned off. The particles kept expanding to larger radii after that point, which would not have produced a good model for collisions. The star would have been much bigger than originally described in the CMC data file, which is not what we want because the parameters and characteristics of the bodies in the system should be as close to the same as the ones described in the data file.

However, I was able to relax the star well enough to use in SPH collisions. This is a significant breakthrough for relaxations of giant stars because to my knowledge, a relaxation of this scale has not been completed before and used in hydrodynamics collisions. Pictured below in Figure 5.0.1 are the profile plots for this relaxation.

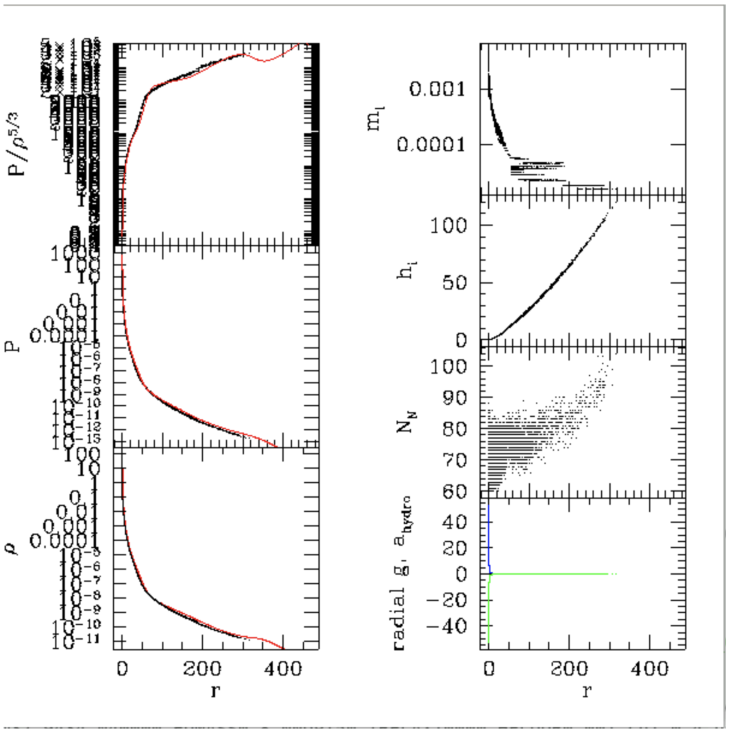

Figure 5.0.1: Properties of a good relaxation of the 37.94 $M_\odot$ star. We can see good alignment in most of the plots on the left and the right sides. Notably, the second plot from the top on the right is what I am looking for. The particles in this plot are in one line, and there is no doubling of the smoothing length values, indicating a good run that is usable in collisions.

The main change I made to produce a better relaxation of this supergiant star was changing the approach of relaxation. I spent a large amount of time varying the parameters of each relaxation with little results. So, this warranted a change in approach. There is another area of

StarSmasher code that takes a different approach to both relaxing and colliding the star, called parallel bleeding edge. This method ensures relatively constant neighbor numbers even when using particles that are not of equal masses, and provides more consistent smoothing length values for each particle. This process estimates the number of neighbors for any given particle i given by the equation below, provided in Gaburov et al. [11].

$$N_i = \sum_j G(|\vec{r}_i - \vec{r}_j|, h_i) \equiv \sum_j G_{ij}(h_i), \tag{5.0.1}$$

where N_i is the number of neighbors for each particle, i denotes a particle, j denotes the neighbor of that particle, $\vec{r}_i$ and $\vec{r}_j$ are the positions of particles i and j respectively, and h_i is the smoothing length discussed previously. G is a weighting function that depends on the distance a neighbor j is from a particle i.

6 Collision Results and Analysis

For this project, I ran six dynamical collisions with the supergiant star and BBH with different initial positions, velocities, and angles. Due to time and resource limitations, six was the maximum number of runs I was able to do, so the results are limited, but nonetheless significant. Four out of the six collisions result in PTDEs, and two are TDEs that collide head-on with one of the BHs. Both of the TDE cases present almost identical behavior and are therefore classified into the same category.

Within the PTDE category, there are sub-categories classifying the collision further. These sub-categories describe how each BH and the star are interacting. The first sub-category is BH replacement, which describes the event of the star disrupting the BBH and taking the place of one BH, which is then ejected from the system. The second category is stellar ejection, which describes the event of the star being ejected from the system after the interaction, while the BBH remains bound and is not disrupted. This category is an assumption based on the behaviors of the collision up to this point, and it is likely that letting the runs progress longer will result in a stellar ejection.

In order to know if one of the objects has become unbound from the system, I wrote a Python code that reads in the final masses of each object in the system and the velocity components of each. I start by calculating the distances between each object respectively. Depending on which distance is greater, I calculate the center of mass components of the binary that is closest in proximity, and then calculate the relative distance and relative velocity between the object that is expected to be ejected and the binary of the other two objects. Then, by calculating the escape velocity of the binary and comparing it with the relative velocity of the object expected to be ejected, I am able to tell if the object is in fact ejected or not. If the relative velocity is greater than the escape velocity of the binary, then the object is no longer bound to the system, and if the relative velocity is less than the escape velocity, the object is still bound. Knowing if an object in the system is bound or not is essential to the analysis of the two PTDE categories, and also allows me to know exactly which BH the star is colliding with.

The data file produced by CMC at Northwestern by Fulya Kıroğlu, gives the initial parameters of the BBH orbit as follows: the initial semi-major axis of the BBH orbit is 744.09 $R_{\odot}$, the intial eccentricity is 0.149, the velocity squared at infinity is 9.73 km/s. These values are the same initially for each run.

It is important to note that all of these runs need to be run for a longer period of time before any definitive statements can be made about their nature and tendencies. The assumptions that have been made here are probable, however, unexpected things always have some likelihood of occurring. The details of the initial parameters of each run are tabulated in Table 6.0.1.

Run	Inclination	True Anomaly	Argument of Periapsis	Longitude of the Ascending Node
1	85	180	90	90
2	95	-90	-90	0
3	106	-90	0	180
4	117	180	-90	180
5	145	0	90	-90
6	180	180	0	-90

Table 6.0.1: The initial conditions chosen in the output given by the pre-collision trajectories Python code referenced in section 3.2 which includes the initial orbital elements (see Figure 3.2.2 for more details).

6.1 TDEs - Head on Star - BH Collisions

The first category describes TDEs, where the star collides with one of the BHs head-on. I ended up with two runs, run 1 and run 6, that fall into this category. In both cases, at the point when the star initially collides with the BH, its outer layers rapidly expand, and it appears as though the star is exploding. However, taking a closer look at the core of the star reveals there is something completely different happening than what meets the eye: the core of the star embarks on an inspiral path to the BH that it collided with. Over the course of the runs, the stellar remnant spirals closer and closer to the BH.

For run 1, pictured in Figure 6.1.1, the star collides with BH1, and as a result, BH2 is shot out. Pictured in the frame on the top left is just before the collision between the star and BH1. There is then an 'explosion' of the star as it collides with the BH and the outer layers of the star expand rapidly outward. In the bottom left, the frame is zoomed in on the star and BH1 while the BH2 is ejected from the system, and there is evidence of a bound elliptical orbit because of the redder 'bridge' of mass between the remnant and the BH. In the bottom right, the star and BH binary are zoomed in even further, showing that the stellar remnant is on an inspiral orbit with the BH. In run 6, the star also collides with BH1. However, due to the long duration of the run, run 1 has not yet reached the point where the mass of the stellar remnant has been completely accreted by BH1.

On the other hand, run 6 looks almost identical to run 1 and the collision had reached the point where the star had been completely accreted by BH1. Unfortunately, the conservation of energy of the run at this point had varied more than 10% from the start of the run, so only the collision data up to that point will be used for analysis. Run 1 maintained good energy conservation (within 2%), so the results seen here are relatively reliable.

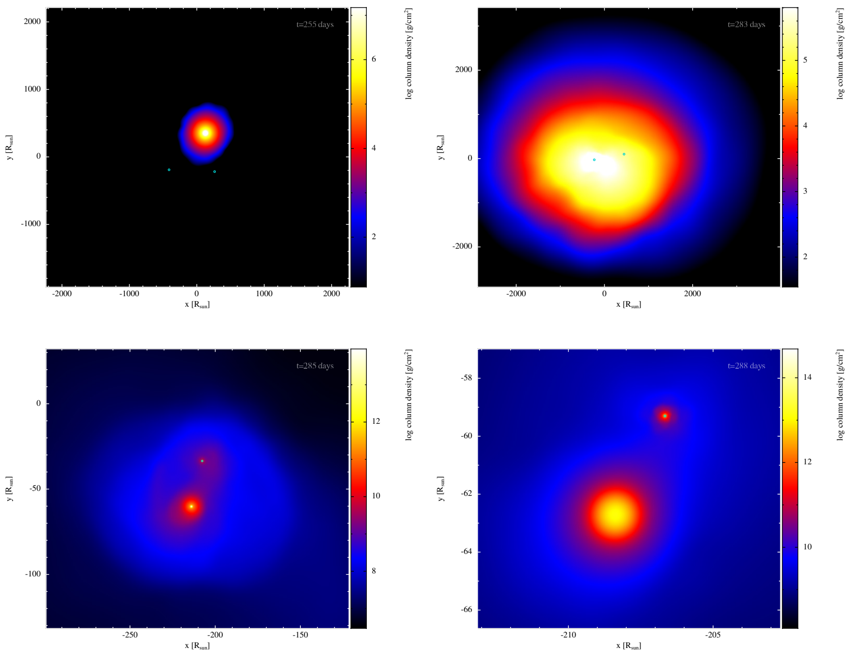

Figure 6.1.1: Sequence of four snapshots of the TDE in run 1.

6.2 PTDEs - BH Replacement

There are also two runs in which the star disrupts the BBH and replaces one of the BHs. In Run 4, the star replaces BH1, but in run 5, the star replaces BH2. The details of the colliding BHs and how the effects on the BHs differed between these runs can be found in section 6.4.

These differences could be related to the orientation of the BBH at the time of intrusion, the 3-D orientation of the star relative to the BBH, or the difference in the behavior of the star and its outer layers after the first interaction with the BH. With run 4 seen in Figure 6.2.1, the star comes in and is swung around the entire BBH and it seems to grab onto BH2 as it is moving away from the system. BH2 and the stellar remnant become bound on an elliptical orbit and BH1 is ejected from the system.

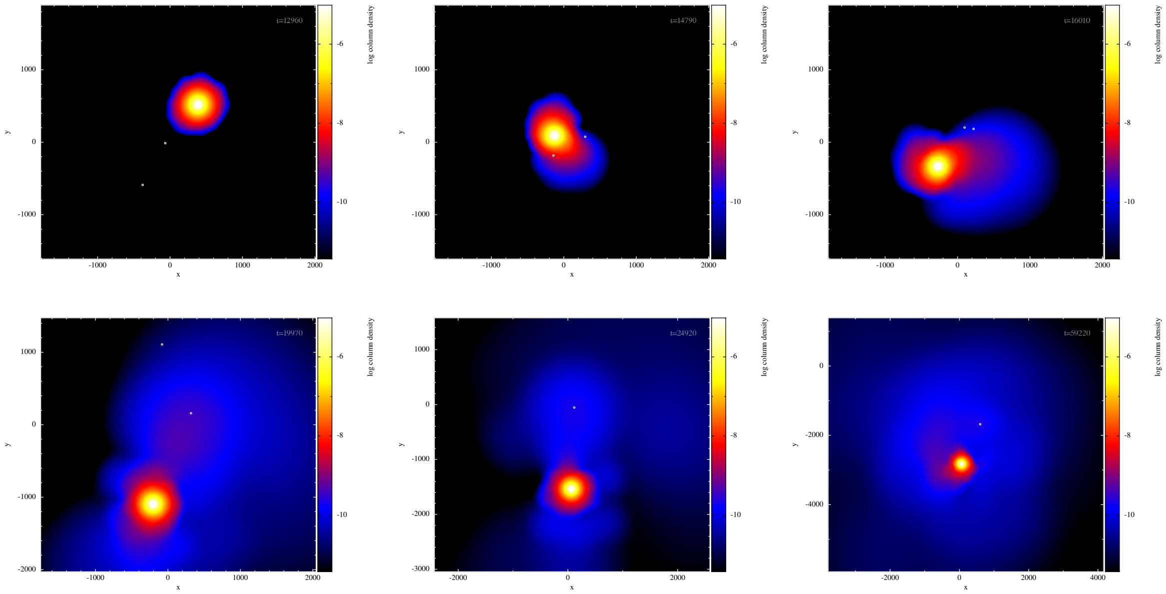

Figure 6.2.1: Sequence of six snapshots of the PTDE in run 4.

However, in run 5 shown in Figure 6.2.2, the BBH is in a different orientation when it encounters the star, and the star is not swung around the entire BBH, just BH2 and a little bit of BH1. The stellar remnant passes directly over BH1 as it is flung out of the system, which is telling that BH1 is at a lower point on the z-axis. The stellar remnant and BH2 continue to move away from each other and the remnant and BH1 become bound on an inspiral elliptical orbit. If these runs were continued from this point, the BH in each case would be expected to eventually accrete at least half of the mass from the stellar remnant.

Run 3 is a little different, which makes it difficult to categorize, because in this run, the star is barely disrupted at all. Much like run 4, the star encounters the BBH at a point in the orbit

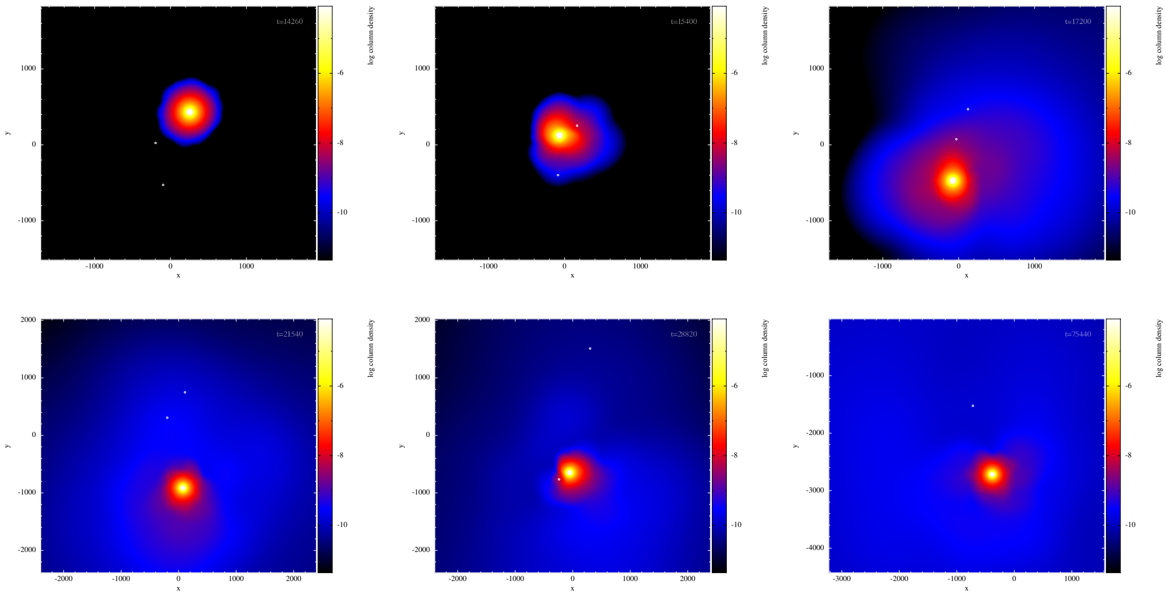

Figure 6.2.2: Sequence of six snapshots of the PTDE in run 5.

where the BHs are close together. The star swings around the outside edge of the BBH and is brought all the way around and flung back in the positive *y*-direction. However, this run would need to be run for longer to make a definitive decision on which category it should fall into. The Python code I wrote says that the BBH has been disrupted and BH1 is the farthest object from the BH2-star binary, but that the relative velocity of BH1 is less than the escape velocity of the BH2-star binary, so it is still bound. These velocities can be found in section 6.4, in 6.4.1. Visually though, the star looks as though it is being ejected. It is possible that continuing this run go for longer will reveal that the BBH orbit has been softened, but not disrupted, meaning its eccentricity gets larger but the two BHs are still bound. Or, running the run could show that BH1 is indeed kicked out of the system and the star and BH2 will become bound.

6.3 PTDEs - Stellar Ejection

The final run, run 2, is pictured in Figure 6.3.1. The BBH is not disrupted and both BHs remain bound to each other. The star encounters one of the BHs and is pulled around it so that it

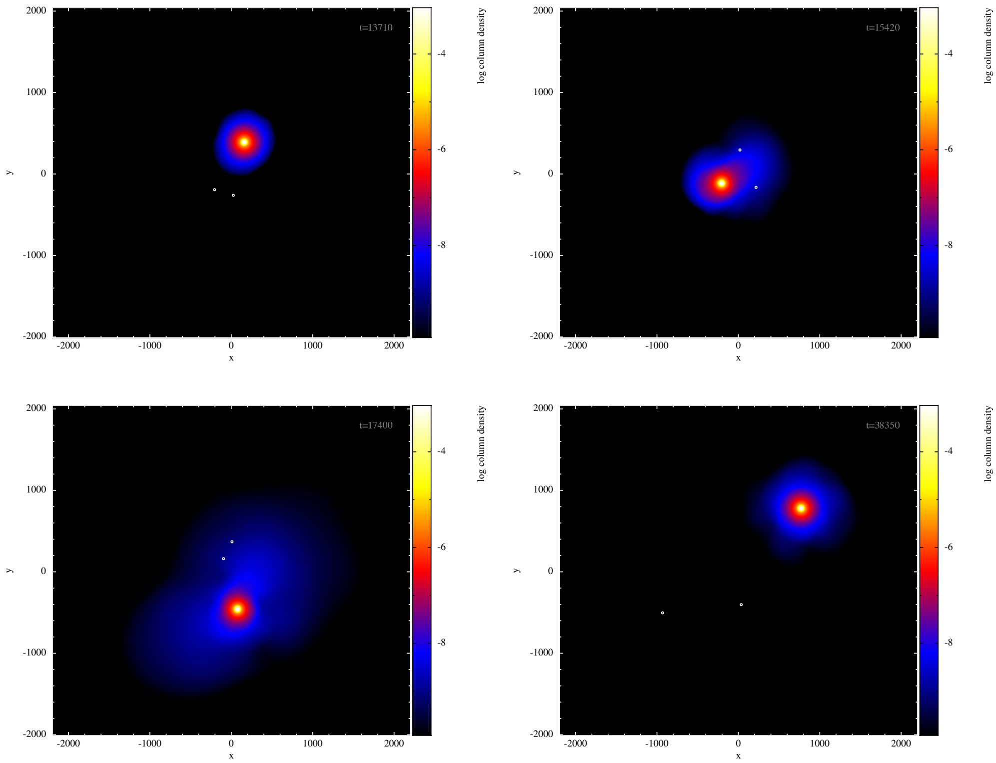

Figure 6.2.3: Sequence of four snapshots of the PTDE in run 3.

looks as though it might travel through the middle of the BBH. However, it does not go through the middle, but rather the second BH is at a point in its orbit that it comes back and pushes the star out of the middle of the BBH. The star then swings around both BHs and as seen in the lower right of Figure 6.3.1, the star is getting farther and farther away from the BBH and it is not likely that the star will return for another interaction with this BBH.

This run is slightly easier to estimate which category it should fall into because the Python code does determine that the star is the farthest object and the distance between the BHs is smaller than the distance between both BH1 and the star and BH2 and the star, which can be interpreted as the BBH is not disrupted.

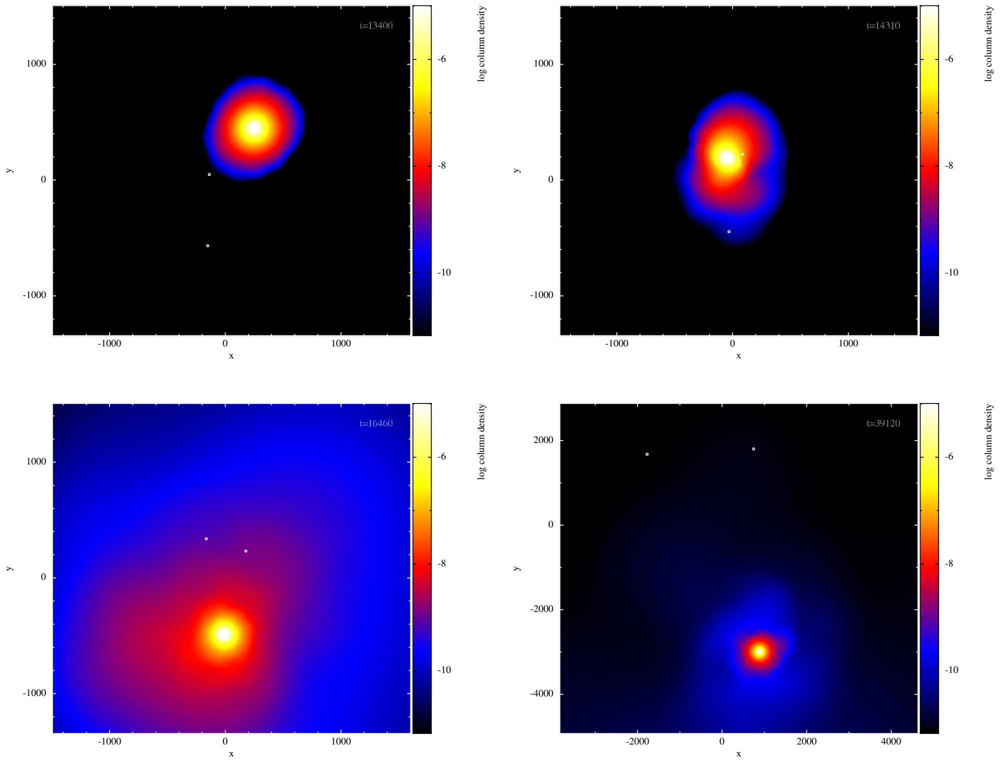

Figure 6.3.1: Sequence of four snapshots of the PTDE in run 2.

6.4 Collision Outcomes

The results of the collisions are tabulated in the two tables below. It is interesting to see in Table 6.4.1 the differences in objects that are kicked out of their respective systems. It can be seen in run 2 and 3 how the object that is being kicked out is not certain, but their relative velocities to the binary are not quite large enough to be considered ejected.

Additionally, the relative velocities of BH2 in runs 1 and 6 are significantly greater than the escape velocity of the binary, and it is clear that BH2 has been ejected in both cases. In runs 4 and 5, the same result between the two is seen, only the order of the BHs is switched.

In Table 6.4.2 the final spin values for each BH in each system is tabulated along with final masses for the BHs and the star. The rows for runs 1 and 6 both show the final star mass is zero because of the head-on collisions in those runs, but there is a significant effect on the spin of

Run	Colliding BH	Object Kicked Out	Final Separation of Object (km)	Velocity Relative to Binary (km/s)	Escape Velocity from Binary (km/s)	BBH disrupted?
1	BH1	BH2	4.90E8	265.3	140.3	yes
2	BH1	Star?	3.49E9	48.5	70.4	no
3	BH2	BH1?	3.53E9	55.5	73.0	?
4	BH2	BH1	6.72E9	62.5	52.9	yes
5	BH1	BH2	8.38E9	62.1	47.2	yes
6	BH1	BH2	4.78E8	231.6	142.9	yes

Table 6.4.1: The qualitative results of each collision at the final time, showing which BH was the colliding BH, which object was kicked from the system, its relative velocity to the center of mass of the other two objects referred to as the binary, the escape velocity of that binary, and information about if the BBH was disrupted or not.

Run	Final Star Mass	Final BH1 Mass	Final BH2 Mass	Spin of BH1	Spin of BH2	Estimated Final BH1 Mass	Estimated Final BH2 Mass
1	0	36.3487	32.6902	0.336	0	36.3487	—
2	37.9403	32.6826	36.6902	1.12E-05	0	51.6528	—
3	37.9428	32.6826	32.6902	1.12E-05	0	—	51.6620
4	37.9422	32.6825	32.6903	0	1.12E-05	—	51.6610
5	37.9275	32.6826	32.6904	1.12E-05	2.25E-05	51.6464	—
6	0	36.7100	32.6902	0.362	0	36.7100	—

Table 6.4.2: Quantitative spin results of the collisions that correspond to the data plotted in Figure 6.5.1. The last two columns contain the estimated final mass of the colliding BH (which is why there are not values in every box) assuming the BH accreted half of the final star mass. All of the masses are in $M_\odot$

the colliding BH, which in both cases is BH1. The spin values for these BHs is much higher than the other spins in the other runs, and this is due to the head-on collision of the star having a noticeable effect on the BH spins as the star is destroyed and its mass is accreted onto the BH.

Additionally, $\chi_{\rm eff}$ is useful to know when there is a BBH at the end of the system because it can give information about the behavior and orientation of the BH spins in the BBH orbit. If we make the assumption that run 2 does result in a BBH, there is only one run where this happens. The $\chi_{\rm eff}$ value for run 2 is -0.73894×10^{-6}, which is close to zero, but negative. If we also assume that run 3 does end up with a BBH, its $\chi_{\rm eff}$ value is -0.25917×10^{-6}, which is not much different from run 2.

The data for run 3 shows that even though the star collided with BH2, BH1 had a change in spin as opposed to BH2 having the change in spin as one might expect, and I am not entirely sure why this is. In run 5, both BHs pick up spin, even though BH1 is the colliding BH.

In runs 2 and 4, the colliding BH picks up the spin as expected. Overall, it is interesting that in the partial interactions, the spins of the BHs are almost exactly the same except for BH2 in run 5 and runs 1 and 6 where there were head-on collisions.

6.5 Changes in BH Spin Values

For this project, while $\chi_{\rm eff}$ is still useful, the individual spins of each BH and how they change with the mass of the system is more insightful. Due to the small mass transfer in the PTDE systems, many of the data points are indiscernible for both plots.

This is also the case with the set of diamond shaped points for the estimated final accreted mass for the BHs. We assume that the colliding BH will accrete half of the mass of the star. While this value is commonly accepted and used in research, there is the possibility that is is an overestimate of the actual amount of mass that will be accreted. The data points of the estimated accreted mass for the runs that were TDEs (runs 1 and 6) are on top of most of the circular data points for the final BH1 mass because the star is no longer recognized as a star, and so there is little mass to estimate will be accreted, so the estimate is therefore only slightly larger than the initial mass of the BH1.

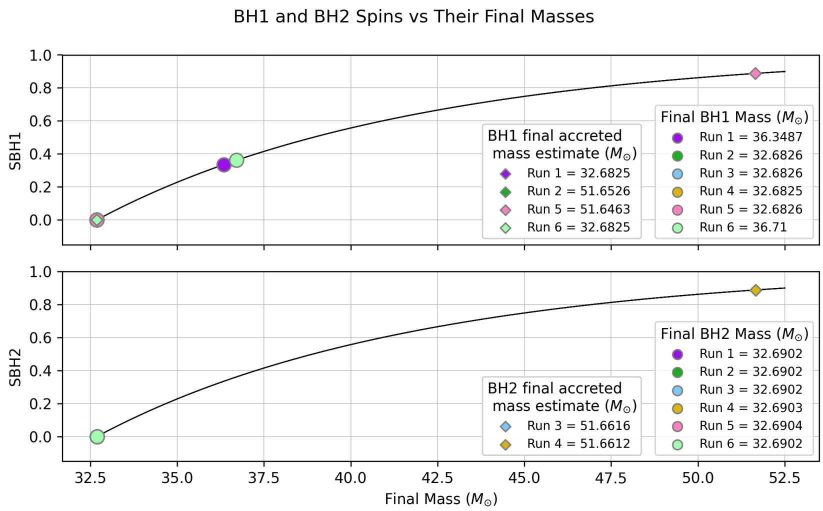

Figure 6.5.1: Two plots of the individual spins of each BH vs. their final masses in $M_\odot$. The data points marked by circles indicate the final masses of each BH at the end of the simulation and the diamonds indicate estimation of the final mass of the colliding BH, which changes depending on the run, which is reflected in the legends on each plot. The diamond data points are an estimate based on the assumption that the colliding BH will accrete half of the star mass by the end of the simulation. These values are tabulated in Table 6.4.2.

It is hard to tell how realistic this value for the mass is, specifically in these two runs due to the scale of the star and the system and because these are the first runs of their kind on our machines.

It can be seen in the figure that the spins start at zero and asymptotically approach 1. These plots agree well with the limits of spin which say that spin can never exceed a value of 1. The purple and mint green points on the SBH1 plot show the final masses of BH1 in each of the TDE runs. These two points show that each BH accreted at least some of the mass of the star, but due to the outer layers of the star containing significantly less mass than the core of the star, there is not significant mass transfer in PTDE runs.

On the bottom plot, which depicts the spin of BH2, there are not any points that are placed farther out on the curve because there were not any TDEs that occurred with BH2. All of the BH2 masses vary only slightly between each other and the initial BH2 mass, so these points are on top of each other and at low spin and mass values. It is also shown by the diamond points that there are only two cases where BH2 is the colliding BH, which occurs in runs 3 and 4, and this is also tabulated in Table 6.4.1.

7 Conclusion

Four out of the six collisions result in PTDEs, and two are TDEs that collide head-on with one of their respective BHs. Both of the TDE cases present almost identically and are therefore classified into the same category. Within the PTDE category, there are sub-categories classifying the collision further. These sub-categories describe how each BH and the star interact over the course of the run. The first sub-category is BH replacement, which describes the event of the star disrupting the BBH and taking the place of one BH, which is then ejected from the system. The second category is stellar ejection, which describes the event of the star being ejected from the system after the interaction, while the BBH remains bound and is not disrupted. This category is an assumption based on the behaviors of the collision up to this point, and it is likely that letting the runs run longer will result in a stellar ejection.

In terms of distribution of the outcomes and types of collisions for these six runs, it is relatively even. If we assume that run 3 will turn out be a stellar ejection, then there are two runs for each category. However, even though there are two runs for each, each run is unique within itself. For example, runs 4 and 5 are categorized the same, but their outcomes and behavior throughout the collisions are completely different. As given in Table 6.4.1, the colliding BH for run 4 is BH2, and the colliding BH for run 5 is BH1. Additionally, as shown in Table 6.4.2, it can be seen that in run 5, both BHs pick up spin by the end of the collision, and the non-colliding BH actually gains slightly more spin.

The most similar runs overall are runs 1 and 6, which have the same outcome, the same colliding BH, about the same effect on that BH's spin, and about the same estimated final BH mass as described in Tables 6.4.1 and 6.4.2. They also have similar relative velocities to the binary they are ejected from, which are large values compared to other relative velocities in the other runs. This is evidence that head-on collisions have a heightened effect on not only the star, but all bodies in a system.

Furthermore, there is only one (maybe 2, depending on the outcome of run 3) case where the BBH is not disrupted and survives the collision with the star, and this occurs in run 2. I think the initial mass of the star being larger than either masses of the BHs has a significant role in this outcome. It is not common that the BBH gets disrupted in dynamical collisions between main sequence stars and stellar mass BHs, the BHs usually have a much greater mass than the mass of the star, so the effect on the star from the BHs will be much greater than the effect of the star on the BHs.

However, in this system, with the star having a greater mass than the BHs, it is expected that the star would have a greater effect on the BHs compared to the effect that the BHs would have on the star, and this is exactly what is being seen where there is only one run that has an intact BBH at the end. It can also be seen that there is no significant bound mass on either of the BHs in run 2 (or any PTDE run), which is telling that the relationship between the BBH and the star is far from blanced, the star's effect on the BHs is much more significant than the effect that either of the BHs have on the star.

7.1 Future Work

I believe that my project has cleared a path for future research to pave the way into further investigation of these topics. There are quite a few different paths that future research could follow to take this project further. Starting with the fundamentals of the code, investigating the accuracy of the mass transfer onto the BHs in systems like these would be helpful in validating the results shown here. Additionally, possibly incorporating more accurate physics into the calculations done for these large scale systems and collisions could be helpful in the more accurate visualization of the collisions, and also in maintaining good energy conservation when there are dense regions of particles to map.

The main part of this project that would enhance its significance is allowing these runs to run until all three objects are settled and there is no longer any mass transfer occurring and then doing an analysis with the final masses at the very end of the run. I think doing an analysis with the actual final mass values could bring a more insightful perspective regarding the behavior of such massive systems, specifically ones like mine that deal with red giant or super giant stars.

The range of effects that each collision could have is difficult to predict, so this is why we need as many dynamical collision runs as possible and for them to run as long as possible. Having more runs allows a larger spread of data and leads the way into a clearer analysis.

Arguably the most important improvement is already having the initial conditions of the system in the CMC data file. Having the actual initial positions, velocities, and orbital angles could change the way that these collisions are approached. For example, having these initial parameters would allow us to run more than one individual system because we would not need to guess which angles or positions would result in an interaction. It would be possible to learn more about these kinds of systems in general if we could analyze more than one at a time because we could look for trends or correlations between the different systems and not need to run 42 simulations of the same three systems to see these trends like we did over the summer.

Part II

Des Rapports entre la science & la science-fiction

8 Résumé du livre

Ce livre de science-fiction, *Dernier Départ* de Christophe Martinolli, a été publié en 2019. Martinolli est scénariste, réalisateur, auteur de bandes dessinées et romancier. Il vient de Nice et il habite à Paris actuellement. Il n'est pas très connu, il a publié deux séries de livres et il est auto-publié. L'intrigue se déroule en l'année 2101 dans la Cité-État de France, commençant seulement quelques jours avant l'impact. L'idée centrale est le retour d'une comète qui va annihiler la Terre ainsi que l'humanité. La crise climatique à l'époque a forcé l'humanité à regarder en face l'effondrement imminent. En 2026, la découverte du Graviton, a donné l'espoir à tout le monde parce que l'humanité peut survivre. Le livre communique plusieurs messages à propos de la société, la crise climatique, l'action gouvernementale, ainsi que les messages de l'importance de la communication scientifique et la manière dont l'est faite. Surtout la dépendance d'un sens d'espoir de vivre à travers la communication scientifique en comparaison du manque de ce sens en conséquence de la manipulation des informations scientifiques.

9 La Communication scientifique à l'intérieur du livre

Premièrement, je vais discuter de l'importance de la manière dont Martinolli raconte cette histoire. Tout au long du livre, les actions des personnages sont influencées par le cadre de la communication scientifique et le sens d'espoir qu'ils se sentent. L'espoir du monde est la motivation principale de l'action et il est très dépendant du cadre des communications scientifiques. Quand il n'y a pas un sens collectif d'espoir, il n'y a pas d'action. S'il y a un sens d'espoir, il y a des actions pour changer la situation. Une connexion forte est cultivée tout au long du livre entre l'information scientifique et la manière dont la communication scientifique est communiquée. Cette connexion est importante parce qu'elle est la motivation de la division entre les deux classes. La manière dont la communication scientifique est communiquée influence le sens d'espoir que les citoyens se sentent pour l'avenir et pour leur vie. La différence entre les deux classes est souvent leur sens d'espoir qui explique pourquoi les élites peuvent construire des Arches et quitter la Terre lorsque les pauvres doivent se débrouiller et la plupart meurent. Mais, sans l'espoir, les élites – les citoyens et les scientifiques indifféremment – sont vides de sens et il n'y pas plus d'action comme peut être voir avant la découverte du Graviton quand la crise climatique se détériore.

La communication scientifique explicite et non explicite de la classe élite ont un impact égal. Explicitement, des informations qu'Angelo a partagées avec ses petites filles quand elles étaient petites sont informatives et claires, et les discours de Melissa Dalbera visent à dévoyer les citoyens et leur donner un sens d'espoir pour la vie même s'il est faux. La communication scientifique implicite est aussi importante parce que les gouvernements devront être le modèle pour les citoyens. Cependant, leur irresponsabilité et négligence à l'environnement et à l'être bien de leurs citoyens communiquent que les seuls qui sont importants sont eux-mêmes. De plus, je vais discuter des formes de la désinformation que les élites répandent aux citoyens pour retenir le contrôle et le pouvoir. Par conséquent, une division même plus profonde entre les classes est formée. Souvent, les interactions entre les deux classes sont composées de mensonges, de désinformations, et de nombreuses promesses non-tenues.

9.1 La Dépendance d'un sens d'espoir sur la communication scientifique

La seule découverte dont tous les suivants viennent est la découverte du Graviton, une particule théorisée jusqu'à maintenant. Il a été trouvé dans une météorite dans les Alpes, et avait quatres effets principaux : il y avait un espoir immense; le plus profondément épuisement des ressources naturelles; les gouvernements mondiaux prennent enfin action immédiate pour sauver l'humanité; et comment l'espoir des citoyens dépendait de leurs réactions à la communication scientifique des élites. Il est important de noter qu'Aelys apprend toutes les informations suivantes de cette section de la bouche de son grand-père parce qu'il aime bien la science, la communication scientifique, et il communique la science avec compassion. Malgré cela, il n'est pas une source objective, il a ses opinions et surtout avec sa petite fille, il en est attendu.

D'abord, la découverte du Graviton a été faite juste avant qu'ils sachent qu'une comète était sur une trajectoire collision avec la Terre. Le Graviton est arrivé quand l'humanité était face à l'urgence extrême climatique et la découverte a provoqué un espoir profond de l'avenir pour l'humanité et la colonisation de l'espace. L'annonce du Graviton décrit au public comme une grâce salvatrice pour l'humanité, parce qu'ils pourraient quitter la Terre où la température devenait de plus en plus élevée : « Face à l'urgence climatique, cette découverte incroyable pouvait permettre à l'humanité de construire sur Terre des vaisseaux de taille gigantesque en vue de coloniser l'espace. Un espoir immense est né » (Martinolli 24) [12]. L'espoir qui se répand à travers le monde est un résultat direct du cadre de la communication du Graviton. Les scientifiques présentent la découverte comme la chose qui pourrait sauver l'humanité et les conditions de l'environnement étaient si mauvaises que le monde s'attache à une particule qui ne se voit pas à l'œil nu. Ils étaient au désespoir à cause de l'état du climat du monde et devaient faire face à l'effondrement climatique doucement. Le monde cherche même le plus petit bout d'espoir de survie et ils le tiennent avec toute leur force. Le Graviton inspire non seulement l'espoir pour l'avenir de l'humanité, mais il inspire quelque chose de plus matériel : les Arches.

Avec le Graviton, les scientifiques peuvent construire ces Arches sur Terre. La raison de l'importance et de l'excitation du Graviton est plus profonde que juste la survie de l'humanité, il a des propriétés plus intéressantes : « il fût nommé par les scientifiques français le "Graviton" pour sa capacité à compenser localement les effets de la gravité terrestre » (Martinolli 24) [12]. À cause de cette propriété, les vaisseaux spatiaux peuvent enfin être construits après quelques tentatives avortés. En plus de cela, le Graviton et la capacité de construire des Arches inspirent plus d'espoir dans la population. Ils resserrent leur emprise sur l'espoir qui déjà commence à disparaître de portée.

Ensuite, les pays internationaux s'unissent pour construire chaque Arche et l'espoir de survivre est la motivation. Depuis le début de 2026, le plan international est exposé : « Construire des Arches fonctionnelles en moins de soixante-quinze ans : voilà l'exploit que peu de pays, même parmi les plus développés ont réussi à faire. Seules les nations spatiales y sont parvenues. Les USA, la Russie, la Chine, le Japon, l'Inde, et l'Europe ont érigé des Cités stellaires entièrement dédiées à leur construction » (Martinolli 25-26) [12]. Alors, les Arches construisent dans les pays qui ont déjà un programme spatial, et la construction des Arches dépend de la coopération entre tous s'ils voudraient sauver l'humanité. Le niveau de coopération internationale est plus remarquable à cause du manque d'action climatique depuis des décennies. Cet espoir touchait tout le monde à l'époque, surtout les scientifiques, comme le grand-père d'Aelys, Angelo.

Angelo exprime à Aelys ses sentiments sur la découverte à l'époque et sa vue du Graviton comme un immense espoir et un signe du destin : « Je me suis enthousiasmé comme beaucoup de mes confrères de pouvoir, à long terme, quitter ce berceau qui nous a vu naître grâce au Graviton. Mais mes ardeurs ont vite été calmées. Nous ne pouvions pas sauver tout le monde » (Martinolli 25) [12]. Angelo lui raconte ses expériences au moment de la découverte et la réalisation que tout le monde ne pouvait pas être sauvé de l'effondrement climatique. Son enthousiasme et l'espoir pour la préservation de l'humanité souligne l'importance qu'il donne à la science et la communication de la science. Angelo est un très bon scientifique et en 2026, il a beaucoup d'influence du monde, mais il a choisi d'utiliser son influence pour la bonne communication scientifique au lieu de manipulation et de contrôle comme la majorité des autres élites à l'époque et au présent. Aelys a appris son propre espoir intrinsèque qui la conduit à combattre les injustices du monde.

Malheureusement, l'espoir du Graviton et du destin de l'humanité était de courte durée. Peu de temps après la découverte de Graviton, les scientifiques trouvent la comète et sa trajectoire, laquelle explique toutes les météorites : « . . . car les astronomes découvrirent que cet essaim de météorites bienfaitrices n'était que le précurseur d'une menace bien plus importante » (Martinolli 25) [12]. L'espoir du monde chute. Ils n'ont pas plus de temps. Mais, la découverte du changement de la trajectoire de la comète causait l'espoir de faire son retour, juste avant la découverte de la collision 75 ans à l'avenir. Alors, le cadre à lequel les informations scientifiques communiquent à travers définit le sens d'espoir du monde.

En 2026, les élites composaient seulement cinq pour cent de la population, mais ils utilisaient toutes les dernières ressources de la Terre. Depuis des décennies sans action climatique et sans changement de la vie quotidienne pour aider l'environnement, la classe élite continue à monopoliser les ressources naturelles pour elle-même. La découverte de la collision imminente entre la comète et la Terre pousse finalement les gouvernements internationaux à adresser la menace. Au lieu de reconnaître que les gens du monde en dehors des élites luttent pour la survie, ils décident de continuer de prendre les ressources naturelles, mais cette fois pour les Arches. Les élites ont l'intention de ne laisser aucune ressource aux gens qu'ils laisseront sur Terre quel que soit le nombre de jours ou d'heures qu'il leur reste à vivre : « Les toutes dernières ressources de la Terre furent pillées sans vergogne… Des glaciers et des lacs vont être asséchés pour assurer notre survie dans l'espace et le seront jusqu'à la dernière goutte. À quoi bon économiser ce qu'il reste puisque nous ne reviendrons jamais ? » (Martinolli 27) [12]. Il semble logique de prendre toutes les ressources possibles pour le voyage vers la nouvelle planète, surtout s'il ne reste rien sur Terre après la collision. Cependant, bien avant les Arches et le besoin de toutes les ressources pour la survie du voyage vers la nouvelle planète, les ressources étaient déjà utilisées de manière irresponsable par les élites. Même s'ils n'ont pas communiqué directement sur le problème des ressources naturelles, les actions des élites, année après année, donnent un message très clair : les élites tiennent le pouvoir. Ils ont l'espoir de survivre. Les pauvres n'ont plus d'espoir de vivre.

9.2 La Manipulation des informations pour retenir le contrôle

Une dynamique qui est déjà tendue depuis des décennies entre les classes sociales s'empire après la découverte de la collision imminente à cause de l'augmentation de quelques actions, surtout la manipulation des informations scientifiques et sociales et l'avidité de pouvoir et de retenir ce pouvoir des élites. La forme principale de la manipulation des informations scientifiques au public sont des discours. La plus significative manipulation des informations sociales sont les discours de Melissa Dalbera, qui est membre permanent du Conseil du Consortium Magonia. Avant le discours, il y a un indice de ce qui se passe en coulisse : « Tout est impeccable, calibré, pensé, millimétré. La communication doit être à la hauteur de l'événement : solennel, précis, rassurante, grave, et plein d'espoir » (Martinolli 31) [12]. Ce détail souligne les gros efforts pour maintenir une apparence de confiance et de calme. Le discours a été fait quatre jours avant l'impact parce qu'elle veut inspirer tout l'espoir et toute la confiance possible dans les élites avant le départ vers la nouvelle planète. Cette stratégie encourage la soumission pendant le voyage pour éviter des soulèvements ou d'autres problèmes. Elle utilise leur peur, leur désespérance, et leur vouloir à tout prix pour gagner leur loyauté et confiance. Pour assurer cela, Melissa dépeint les pauvres comme l'ennemi de la survie de l'humanité bien que les élites sont l'ennemi.

Elle souligne l'aliénation des personnes qui sont au dehors des murs de la Cité : « Sans [Graviton], nous serions tous morts à petit feu, nous battant comme des animaux pour les dernières ressources. Sans lui, nous serions retournés à l'âge de pierre. Le chaos, au-delà de ces murs, prouve que nous avions raison ! Entre la civilisation et la sauvagerie, il n'y a qu'un pas ! Nous avons choisi la civilisation ! Et cette civilisation décollera dans quatre jours ! » (Martinolli 32-33) [12]. En surface, ce discours apparaît comme un discours pour motiver les citoyens et pour affirmer leurs sentiments d'espoir de la continuation de l'humanité. Cependant, même si elle n'accuse pas explicitement les personnes en dehors de la Cité d'être des sauvages, elle implique l'idée avec ses exclamations que les citoyens de la Cité ont choisi la civilisation. Cette déclaration qu'un choix peut faire implique que les personnes en dehors de la Cité *choisissent* de mourir sur Terre, alors qu'ils n'ont pas le luxe de choisir.

Aelys reconnaît un fait à propos d'elle-même pendant le discours quand Melissa insinue que les personnes au dehors de la Cité sont sauvages : « Au fond d'elle-même, elle ne supporte plus le discours de sa mère, des élites autoproclamées *utiles*, et refuse de croire que les gens qui vont rester, au-delà des murs sont tous des sauvages... il n'y a que très peu de gens qui méritent vraiment de partir...les plus fortunés ont fait la loi et se sont arrangés pour n'inviter que ceux qui les servaient » (Martinolli 33-34) [12]. Le Consortium ne communique pas au public les méthodes de sélection des passagers et les personnes considérées comme inutiles étaient en colère. Le choix a été fait dans une manière calculatrice et sans pitié, sauf pour les élites, qui empirent la division qui existe déjà entre les classes sociales. Le manque de communication souligne le mépris des pauvres et des personnes « inutiles ». Alors, une situation déjà mauvaise est encore aggravée par le manque de communication parce que les gens de la classe inférieure se sont sentis qu'ils sont sans valeur et ils n'ont pas encore d'espoir. Sans espoir, ces personnes commencent à détester plus profondément les élites.

De plus, Aelys reconnaît que les élites exploitent ces gens et leurs intentions : « La plupart des ouvriers qui ont construit ce vaisseau, et qui ont cru qu'ils pouvaient partir avec leur famille ont été dupés » (Martinolli 34) [12]. Clairement, on a promis aux ouvriers une place sur le vaisseau, l'Arche, mais ils ne savent pas que les élites ne tiendront pas la promesse. Le Consortium ne s'attendait pas à ce que des ouvriers découvrent la vérité de leurs fausses places, et les élites prévoient d'exploiter des ouvriers pour leur travail sur l'Arche parce qu'ils ne voulaient pas le faire eux-mêmes. La tromperie des élites pour convaincre des pauvres de construire des Arches est un acte de la communication implicite et par conséquent, quelques ouvriers quittent la Cité pour risquer leurs vies au dehors avec la Terre inhospitalière au lieu de mourir dans l'espace avec des élites. Donc, le manque de communication aux ouvriers cause plus de problèmes pour les élites parce qu'une nouvelle animosité entre les classes naît.

Nolan est l'ouvrier qui apprend le secret des sarcophages et il apprend cela par écouter aux portes. Trois ans avant le départ de l'Arche, il découvre que des sarcophages donnés aux ouvriers par les élites sont anciens. Les ouvriers n'étaient pas censés survivre au voyage vers Magonia : « Pire, qu'ils ont hérité des sarcophages de première génération, fonctionnels, mais potentiellement instables. Au lieu de leur prolonger la vie, ces machines risquent bien de la raccourcir plus tôt que prévu ! ... Sa colère est à la hauteur de sa déception. Il ne sera jamais comme eux, les élites. Quel idiot d'y avoir cru ! » (Martinolli 36) [12]. À ce moment, le ressentiment vers les élites de Nolan commence. Après des années de bons et loyaux services à la Cité, juste au moment qu'il a pensé qu'il sera accepté par les élites, il est toujours snobé.

Il convainc quatre de ses collègues de le rejoindre en dehors de la Cité pour obtenir la liberté même s'ils ont seulement trois ans, c'est mieux de mourir sur Terre avec leur liberté que dans l'espace avec les élites qui voulaient seulement préserver leurs organes. Pour convaincre ses collègues de le suivre, il utilise la peur de mort, et donc il n'est pas très différent des élites : « Rien ne garantit qu'on arrivera tous vivants à la fin du voyage, rien. J'y ai cru comme vous, mais quand je vois qu'ils nous traitent comme des chiens après les avoir servis toute notre vie, je donne pas cher de notre peau. Nous ne sommes plus indispensables. J'ai entendu des trucs sur le fait que les ouvriers les plus vaillants serviraient de banque d'organe une fois à bord. Ces sarcophages assurent une parfaite conservation de la viande, mais pas pour faire revivre la personne ! » (Martinolli 37) [12]. Même si Nolan a raison d'être en colère, ses techniques de persuasion sont assez similaires à celles des élites. Il fait supposer que les élites veulent utiliser des organes des ouvriers pour leur propre survie pendant le voyage bien qu'il ne connaisse pas leurs plans. Il canalise la douleur de sa trahison et son mépris des élites dans des désinformations pour gagner la confiance de ses collègues.

En général, des gens en dehors de la Cité expriment leur colère aux élites avec le vandalisme de la propagande de la Cité. Quand Aelys quitte la sécurité de la Cité : « De grands panneaux rouillés prônent la propagande officielle : *Construisons l'Arche tous ensemble, of-*

frons une chance à nos enfants. Mais partout des messages de colère et de désespoir dénoncent le mensonge et le pillage des élites qui ont abandonné le peuple qu'ils jugeaient inutiles à leur sort. Partout, le logo du programme spatial du Magonia Consortium, qu'il soit apposé sur les bâtiments ou les panneaux, est brûlé, détourné, tagué » (Martinolli 72) [12]. Les pauvres en dehors de la Cité expriment leurs sentiments aux élites de la seule manière qu'ils peuvent. Les élites ne les entendent pas et il n'y a plus d'espoir pour l'avenir, donc, ils ne risquent rien en faisant du vandalisme. Tout l'espoir a disparu à cause des élites et des formes fausses de la communication sociale et scientifique. Ce message, « *Construisons l'Arche tous ensemble, offrons une chance à nos enfants* » communique qu'en principe, tout le monde travaille ensemble vers le même objectif. Mais, en réalité, les élites profitent des ouvriers pour leur propre survie.

10 Le Rôle général du genre de science-fiction dans notre société

À travers l'histoire du genre de science-fiction, il a été commun pour des idées scientifiques que des auteurs imaginent dans leurs livres de devenir la réalité au proche avenir. Mais il est important de noter qu'il y a une différence entre la science-fiction et le *fantastique* : la science-fiction n'inclut pas de magie ou d'autres idées non possibles. La science-fiction est basée sur des faits de la science et des auteurs dans un sens appliquent la méthode scientifique : leurs idées peuvent être des hypothèses de comment le monde répond si un certain événement se passe. Il est aussi évident que des livres de science-fiction préparent les jeunes pour l'avenir et les choses qui peuvent être possibles.

Par conséquence de leur accès à des nouvelles idées scientifiques, même s'ils semblent impossibles à l'époque, les jeunes doivent plus ouvert à l'idée d'un monde avec l'invention ou la découverte qui décrit dans des livres. Les idées scientifiques qui semblent impossibles à leur conception sont souvent les idées qui deviennent réalité dans quelques décennies ou siècles. Or, quand nous parlons des possibilités scientifiques, nous percevons habituellement des possibilités positives, mais il y a aussi des aspects plus terrifiants qui sont hypothèses dans des livres de science-fiction qui, sans doute, sont en réalité.

10.1 L'imaginaire est possible

D'habitude, des livres de science-fiction semblent irréalistes et improbables. Cependant, si nous regardons en arrière aux thèmes des livres de science-fiction au début et au milieu du XXème siècle, il y a des idées qui semblent vraiment improbables qui seront devenues réalité. En 1957, il y avait une conférence à l'Université de Chicago où un auteur, Robert A. Heinlein a fait un discours sur l'importance de la science-fiction. Son discours reste toujours pertinent à la science-fiction d'aujourd'hui. Il parlait de tous ces aspects et il donnait une nouvelle perspective sur la science-fiction et son l'importance.

Il a vécu directement la main influente de la science-fiction avec sa propre histoire : « I had a completely imaginary electronics device in a story published in 1939. A classmate of mine, then directing such research, took it to his civilian chief engineer and asked if it could possibly be done... The bread-boarded first model was being tried out aboard ship before the next installment of my story hit the newsstands. The final development of this gadget was in use all through World War II » (Heinlein 23) [13]. Il est remarquable que Heinlein avait sa propre expérience avec l'influence de sa propre histoire sur la science. D'habitude, cette influence est abstraite, comme les voyages dans l'espace ou des idées de voyages dans le temps. Par conséquent, dans les mots de Jules Verne, « Tout ce qu'un homme est capable d'imaginer, d'autres hommes seront capables de la réaliser » (Heinlein 23) [13], l'effet de la science-fiction sur le développement de la science est incarné. Cette idée peut se voir tout au long du siècle passé et même avant le début de la science-fiction, comme l'a dit Oscar Wilde, « Nature mirrors art » (Heinlein 23) [13]. Dans ce cas, l'art est la science-fiction et la nature est le développement de la science et au moins au cours du siècle dernier, cette déclaration reste valable.

10.2 L'Application de la méthode scientifique

Dans un autre sens, la science-fiction est une application de la méthode scientifique. Selon Heinlein, la science-fiction permet faire des expériences « in imagination too critically dangerous to try in fact. Through such speculative experiments science fiction can warn against dangerous solutions, [and] urge toward better solutions » (Heinlein 36) [13]. Les auteurs ont la capacité d'expérimenter avec des possibilités de l'avenir qu'on ne peut pas essayer en réalité et en faisant de cela, les auteurs et leurs lecteurs peuvent gagner une compréhension de l'effet que cet événement ou cette invention pourrait avoir dans le monde s'il existait. Les auteurs sont des scientifiques du monde de la science-fiction.

Unique à la science-fiction est la force et la joie, sans hésiter, avec lesquels les auteurs s'adressent aux questions de leur époque et des conséquences de certains événements ou des prédictions de l'effet d'une certaine invention. Heinlein soutient qu'aucun genre ne pourrait s'attaquer à cette tâche de la même manière que la science-fiction. Il souligne son assertion : « science fiction is the most realistic, the most serious, the most significant, the most sane and healthy and human fiction being published today » (Heinlein 36) [13]. De plus, dans un entretien intitulé *Les futurs possibles du présent, La science-fiction à l'épreuve de l'astrophysique*, Roland Lehoucq discute de son expérience comme astrophysicien avec la science-fiction et le lien de la science. Il dit qu'il y a surement un lien fort entre les deux : « cela vient-il d'un goût commun pour la spéculation : en science comme en science-fiction, l'imagination et les idées nouvelles, même les plus extravagantes, jouent un rôle essentiel » [14]. Il est d'accord avec

Heinlein que la science-fiction partage les caractéristiques de la spéculation avec la science, même si elles suivent des règles différentes.

Il continue : « une proposition scientifique doit aussi être prédictive, capable de suggérer des phénomènes nouveaux qui, faute d'être observés, invalideront la proposition. La science-fiction n'a évidemment pas les mêmes contraintes et c'est le privilège des artistes de pouvoir jouer avec des idées folles ou dont la maturation technique n'est pas atteinte parce que les enjeux sont ailleurs » [14]. Les différences dans les expectations des deux sont liées dans leur rôle dans la réalité et leur niveau d'impact. La science-fiction ne risque rien dans les conséquences scientifiques, juste des critiques de leurs lecteurs. De l'autre main, les scientifiques risquent un peu plus quand ils théorisent parce que leurs hypothèses ont besoin d'être observables. Ils ne peuvent pas créer des théories juste basées sur l'imagination comme des auteurs de science-fiction. Lehoucq formule cette différence comme liberté pour des auteurs parce qu'ils peuvent exprimer leur créativité plus librement. Cependant, il dit que cette différence est la raison qu'il aime les deux. La science-fiction complémente la science, surtout l'astrophysique vraiment bien, et vice versa.

10.3 Le Rôle de la science-fiction dans la préparation de la génération prochaine

À l'époque, Heinlein a fait son discours bien avant qu'un homme soit allé à la lune en 1969, mais il a toujours mentionné la possibilité d'exploration spatiale : « It has prepared the youth of our time for the coming age of space. Interplanetary travel is no shock to youngsters, no matter how unsettling it may be to calcified adults… Our children have been playing at being space cadets and at controlling rocket ships for quite some time now. Where did they get this healthy orientation? From science fiction and nowhere else » (Heinlein 38) [13]. Comme Heinlein a dit, la science-fiction est une raison de l'avancement de la science parce que des idées qu'il propose et des germes plantés par ces livres ont un grand effet sur le cours des découvertes scientifiques de l'avenir. Comme noté, ce discours a été fait avant la course aux étoiles et à l'époque la science-fiction d'espace gagnait en popularité. La possibilité de l'exploration spatiale était à peine hors de portée, mais la notion de la possibilité a été plantée par des livres de science-fiction à l'époque. Il mentionne que l'idée des voyages dans l'espace est troublante pour des adultes, mais il y a des enfants qui jouent le rôle d'astronaute depuis quelques années. Ces enfants vont devenir les scientifiques, les ingénieurs, et les astronautes qui aideront le monde à toucher l'espace.

Sans la germe de l'idée des voyages dans l'espace dans des livres de science-fiction à découvrir par les enfants, il aurait été plus difficile pour l'humanité de toucher les étoiles douze ans après. Cette idée appliquée généralement aussi, comme Heinlein soutient : « In a broader sense, all science fiction prepares young people to live and survive in a world of ever-continuing change by teaching them early that the world does change » (Heinlein 38) [13]. Il soutient que la science-fiction non seulement prépare les jeunes pour des voyages spatiaux, mais aussi pour le changement qui vient avec le passage du temps. Introduire les jeunes au changement tôt en vie leur peut aider plus tard et il les encourage à s'adapter aux changements au cours de leurs vies. Malgré cela, lorsque la science-fiction a la capacité de préparer les jeunes pour les bonnes découvertes de l'avenir, elle a aussi une capacité de préparer les jeunes pour les événements plus malheureux.

Dans des années plus récentes, le terme « cli-fi », qui veut dire la fiction climatique, a gagné de plus en plus de popularité. La fiction climatique est similaire à la science-fiction parce que l'intrigue se déroule dans l'avenir, mais l'idée centrale est le changement climatique, souvent plus exagéré pour communiquer et théoriser les possibilités de l'effondrement climatique. Souvent, la science-fiction partage plusieurs des mêmes aspects qui sont trouvés dans la fiction climatique. C'est cette raison qui vise à préparer les jeunes pour la probable crise climatique dans le proche avenir. À travers l'exposition de ces hypothèses, ils seront plus prêts à combattre les effets et de trouver une solution possible. Ils auront aussi la capacité de survivre plus ou moins grâce à l'exposition des personnages dans les deux genres et la manière dont les personnages font face à la crise.

11 Martinolli dans le contexte de la réalité

Dernier Départ expose et fait bon usage de ces trois aspects à travers l'intrigue et par des actions des personnages. Le livre est un mélange de science-fiction ainsi que de fiction climatique. Il rend clair la présence de la crise climatique et l'inclusion de l'année 2026 a rendu les événements climatiques plus réels pour les lecteurs à cause des événements climatiques que Martinolli décrit en fait dans la vie réelle. Quand il a écrit ce livre, c'était 2019. L'année 2026 était toujours sept ans à l'avenir et donc la réalité du livre n'était pas tellement menaçante, mais aujourd'hui, 2026 est seulement deux ans à l'avenir. Sauf la comète, la réalité du livre n'est pas très différente de la nôtre. Il souligne plusieurs exemples de l'inégalité entre les classes sociales, la crise climatique, la désinformation scientifique et l'égoïsme ainsi que d'autres choses à travers les pages. Martinolli a imaginé un monde où il n'y a pas de choix, l'action est urgente. Dans le cadre du livre, Martinolli utilise son imagination pour proposer les événements qui se passent si l'existence du genre humain est menacée d'une chose physique comme une comète. Le choix de faire une comparaison entre une menace invisible, telle qu'une crise climatique, et une menace visible, telle qu'une comète, souligne les intérêts des élites dans le livre et notre réalité.

De l'autre main, Martinolli imagine quelques inventions et découvertes qui sont vraiment possibles à l'avenir. Le Graviton est une particule réelle dont l'existence est théorisée par les scientifiques autour du monde. La spéculation des effets qu'une telle découverte ouvre les yeux des personnes aux possibilités de l'avenir avec le Graviton. Les effets et les caractéristiques de la particule ne sont peut-être pas la réalité ou la vérité, mais il a commencé la conversation des possibilités qu'il apporterait. De plus, le plus grand aspect qu'il a inclut, était la construction des Arches qui peuvent supporter cent mille personnes pour faire un très long voyage vers une nouvelle planète. La possibilité de faire cela à l'avenir est impressionnante, surtout pour les jeunes qui peuvent lire ce livre.

Aujourd'hui, les jeunes sont exposés à toutes les tribulations de ce monde dès leur plus jeune âge et ce livre prend deux côtés de cela. Aelys est la plus petite sœur et elle a seulement vingt ans, et puis, elle quitte la seule endroit qu'elle connaît, elle quitte son propre confort pour être fidèle à elle-même et à la classe en dehors de la Cité. Le courage de bien faire pour le bien du monde est vraiment inspiré pour les jeunes d'aujourd'hui. Martinolli a aussi inclus un message à propos de la classe élite et le pouvoir que les gouvernements tiennent en réalité à travers l'action très rapide qu'ils ont prise au moment de la nouvelle de la trajectoire de la comète. Ce message aux jeunes les encourage à ne pas avoir peur de défendre leur avenir.

12 Relationship between Science Fiction & Science

This book, titled *Dernier Départ (Final Departure)* by Christophe Martinolli, was published in 2019. Martinolli is a screenwriter, film director, comic book author, and novelist. He is not widely known, but he has published two book series and is self-published.

The book is set in 2101 in the French City-State, and starts a few days before the anticipated collision with a comet set on a path to collide with Earth, likely wiping out any trace of life on it in the process. The same comet made a close passage with Earth 75 years before in

2026, but thankfully, while passing through the asteroid belt, its initial trajectory was altered, causing it to miss Earth at the time, but then setting it on a new path to return in 75 years with a direct collision. As a result of the first passage, many meteors pelted Earth, and in the process, scientists made a life-altering discovery. They discovered a widely theorised particle named the Graviton, which would allow humans to construct huge Arks so that the human race can survive the collision of the comet. This discovery inspired hope throughout the world that humanity would survive this event. However, around the same time period, the climate crisis had reached a point beyond control or repair. The elite class was taking all of the natural resources that were left for themselves while the rest of the world suffered.

This book follows two stories: the elite Dalbera family and a band of former City workers who chose to brave the Earth outside of the City walls. The Dalbera family is a highly respected family and the mother, Melissa Dalbera is a member of the Council for the Magonia Consortium, the organization that was created to oversee humanity's voyage to the new planet. Aelys, the youngest daughter, is the main character, and she has an older sister named Laura. Her grandfather, Angelo, left the City when she was little to give up his spot on the Ark for a younger person. Angelo provides most of the background information about the past to Aelys before he left when she was still young. The choice of her grandfather has a significant influence on the choice she makes herself to leave the City.

Nolan, one of the workers who chose to leave the city when he found out that the elites intended to give the workers second-rate cryogenics machines for the voyage to the new planet and the likelihood of survival with those machines is low. He resents the elites for what they have done and continue to do to the lower class and for their selfishness, deceit, and hunger for power and control over their citizen, no matter the cost.

12.1 Scientific Communication within the Book

There is an importance in the approach in which Martinolli takes in writing this book. Throughout the book, scientific communication plays a significant role in the collective sense of hope felt in the population. There is both implicit and explicit scientific communication found in the book, and both have a mostly equal effect. Explicitly, Angelo's communication of events of the past, such as discovering the Graviton and the comet, along with the state of the climate crisis at the time has a significant impact on the way Aelys views the world. Angelo had hope for the world, and he wanted to see scientific success and liked communicating new discoveries to the people of the City. So, when he retold the history of the Graviton, comet, and the state of the climate crisis, he passes a profound sense of compassion and hope to Aelys.

Mainly, the discovery of the Graviton links all of the events of the book together, because without it, humanity would not be able to be saved. The Graviton leads to the ability to build the Arks and a sense of hope. It is discovered at a time of collective despair and dark outlook for the survival of humanity. It also indirectly leads to the discovery of the comet because without the meteors, scientists would have never discovered the imminent collision, and it would have been too late by the time they did. The Graviton is also one of the reasons that the nations of the world came together and and worked toward a common goal, which had not happened in years. After decades of no progress politically or scientifically, the Graviton is able to jump start new action.

Between the different time periods of the successive discoveries, the sense of hope in the population fluctuates drastically, from the Graviton to the comet to the altered trajectory that results in a near miss and then to the discovery of a collision on the comet's return to Earth. All of these fluctuations have a dependence on the way the information in framed.

On the other hand, Melissa Dalbera's speech a few days before they are set to depart from Earth is aimed to mislead and creates biases toward the people outside of the City, but also creates a strong sense of unity and hope within the elite class. The speech adds more stress on an already tenuous relationship between the two classes because it reinforces and even encourages the biases in the minds of the elites toward the people outside the city. She calls them savages, uncivilized, and chaotic, reinforcing the already strong biases of the elites. During this speech, Aelys has strong feelings of disagreement with what her mother is saying because they did not choose to be exiled and left to fend for themselves, and the because the elites make the laws, they chose themselves and then only the people deemed useful enough to go on the journey. She knows that the situation is not morally right, and decides that she wants to follow in Angelo's footsteps and leave the City to help the people left behind.

Another aspect of communication is implicit communication, which is done by the elites when they choose to monopolize the natural resources for decades and refuse to leave any for the people they are abandoning on the Earth after they leave. Both explicit and implicit communication create a deep division between social classes based on resentment and hostility. When Nolan discovers that the elites plan to give the workers outdated cryogenics machines and that they are far from reliable to keep a person alive for the duration of the journey, he convinces three of his colleagues to leave the City with him because he would rather die on the Earth free than in space as essentially a prisoner among the elites. He is angry because he has sacrificed so much to his work and helping build the vessels that would save the human race just for his work and loyalty to be disregarded and completely ignored. In general, the lower class presents a collective hatred for the elite class and this is clearly seen in descriptions of vandalism of official propaganda when Aelys travels outside the City. All hope for their survival has been lost at this point, and they have nothing left to lose because their hope of survival has been stripped from them.

12.2 The General Role of Science Fiction in Our Society

In 1957, Robert Heinlein, a science fiction author, gave a lecture at a conference at the University of Chicago about the significance of science fiction in society. Three of the main things that he claims science fiction does for society is help make the imaginary possible, it is an application of the scientific method, and it helps prepare the younger generation for future possibilities and fosters an open attitude toward change and scientific innovation and discoveries.

One of the main details he includes in his talk is about a first hand experience he has had with science fiction influencing the path of science, and it was a result of his own book that he wrote. He created a gadget within the story, and one of his colleagues actually went on to make it a reality and it ended up being used in World War II. This shows that science fiction truly does have an influence on the direction of scientific discovery.

According to Heinlein, science fiction literature is an explicit application of the scientific method because writers of science fiction have to follow these steps to produce a good, quality book. They have to do their own research so that the scientific facts the include in the story are sound, otherwise it would lead to a fantasy story. The thing that makes science fiction science fiction and not fantasy is that it is closely based on scientific facts, and the authors make educated guesses based on the scientific facts and that what they write in the story is their hypothesis.

In an interview, Roland Lehoucq discusses his experience with science-fiction growing up and even in the present. He says that science and science fiction are closely related to each other in the sense of speculation. The author and the scientist both have to speculate what could happen when creating a theory or a story line. He says the only difference is in the expectations of the two. In science, a theory is expected to be a sound claim that can be reproducible and observable. In science fiction, the author has more freedom in the claims that are made because they are not bound by scientific expectations or put through rigorous tests. This also allows the author to exercise their creativity more freely, he says.

Heinlein gave his speech well in advance of the moon landing in 1969, and yet it was still a subject of his talk. He discusses the importance of science fiction in the sense that it prepares the younger generation for scientific discoveries, and at the time this was the potential for space travel. It prepares them to live in a constantly changing world and exposing children to such change and possibility can not only help them adapt to change easier later in life, it can also encourage their creativity. However, with the positive side, there also comes a more negative side of this.

In recent years, the popularity of climate fiction has increased dramatically. Climate fiction and science fiction share many common details, but the main idea is based solely on a climate crisis that is typically beyond repair. Climate fiction has essentially the same effect on the younger generation as science fiction, but it is preparing them to live in a world where they have to fight to simply survive something they had little part in creating. It also is the reason why there are so many young climate activists today. They have been exposed to ideas surrounding it since they can remember and feel a responsibility to fight for their futures.

12.3 Martinolli's Context in Reality

This book is somewhat of a mixture of climate fiction and science fiction because it is heavily based around the climate crisis, but is primarily science fiction. The book was written in 2019, which was seven years before 2026, but now, in 2024, eerily enough, we are inching closer and closer to the climate reality that Martinolli describes. In the sense of the book, he uses the imagination to theorize what would happen if, in the face of a climate crisis gone too far, a physical object that can be seen directly would force humanity to take action to save themselves. He compares the invisible, slow change of the climate to a relatively immediate threat to the very existence of human kind.

In terms of scientific discoveries and inventions, the Graviton is a currently theorised particle that scientists are actively trying to discover. The properties that it hold may not be the same as the ones that Martinolli describes, but that is part of his hypothesis. The Arks that are described are also a prediction of what humanity might have to do one day if the climate crisis goes too far, even if there is no comet threatening the extinction of humanity.

Moreover, children and young adults today are being exposed to topics of climate change and apocalyptic scenarios. In the case of Aelys, she is only 20 years old and the youngest in her family, but she is fighting for her beliefs with admirable courage. The message that this sends to potential younger readers is inspiring them to take charge and fight for their values and for their future.

13 Conclusion

Scientific discovery and advancement and science fiction are not mutually exclusive. Science fiction influences the path of scientific discoveries as much as scientific discoveries influence science fiction. Both sides never cease to inspire awe in the minds of people young and old all over the world. Heinlein's lecture is a perfect example of this because even though it has been over sixty years since he gave the lecture, the statements and claims he made at the time still apply today.

Another example of this is the black hole. The BH has been a topic of conversation and speculation for well over a century. The idea of black holes has existed in the minds of scientists and science fiction authors alike for far longer than we have been able to observe them. The first observation of gravitational waves that indicated a black hole did not occur until 2015, only 9 years ago. However, interestingly enough, the earliest mention of a black hole dates back to 1763, to a man named John Michell who was an author and philosopher.

In the twentieth century, Einstein published his theories of general and special relativity, the science fiction world gained popularity exponentially in the subsequent decades. This is evident of an innate desire to want to discover the universe around us. It is in our nature as human beings to imagine the possibilities of discoveries, make the guesses about what might be out there, to read and to create the speculative science fiction to take part in a larger experiment of possibility, and to do the research, so that even though everyone contributes a different piece, it can all come together as a whole to unlock the secrets that the Universe holds so dear.

Even for the ability to do this research, colliding stars and BHs, somewhere, at some point, authors and scientists alike had to dare to use their imagination, to theorize the improbable, and along the way plant the seeds of curiosity in the minds of young people, encouraging them to actively search for the keys to the Universe so that the reach of science can expand to topics beyond the imagination of our predecessors both in science and in fiction.

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