X-RAY BINARY FORMATION IN LOW AND HIGH METALLICITY SIMULATED STELLAR ENVIRONMENTS

by

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HONORS THESIS

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LIST OF ABBREVIATIONS

Abbreviation

1. HR Diagram .... Hertzsprung-Russell Diagram
2. XRB .... X-ray Binary
3. Myr .... Million Years
4. XLF .... X-ray Luminosity Function

ABSTRACT

This project addresses the temporal evolution of binary star systems and investigates the initial conditions that produce X-ray Binaries (XRBs). Because stellar evolution occurs over millions or billions of years, we can only track the entire evolution of these systems in computer simulations. XRBs are systems where a star is losing material to a compact object (black hole or neutron star). As the material is being accreted by the compact object, the infalling gas is heated to such high temperatures that it emits in X-rays. X-rays are relatively short and have high-energy wavelengths of light, ranging from 10^{-8} to 10^{-12} meters on the electromagnetic spectrum. Using the binary_c rapid stellar evolution code, we seek to understand the implications of high and low-metallicity stellar environments on XRB formation and evolution. Exploring the effects of metallicities from 0.0001 to 0.01 (near Solar metallicity of 0.018) on the formation of XRB systems, we have found the formation of black hole XRBs has a bimodal distribution in low-metallicity environments, with local maximums near 12.5 and 85 million years (Myr). We conclude that further exploration of these environments is called for to understand how the low-metallicity environment affects black hole formation after the initial maximum.

I. INTRODUCTION

A. Stellar Evolution: What It Is and the Origins of Study

Stellar evolution is a process that occurs over millions and billions of years. Beginning with the birth of a star, stellar evolution describes how the star is influenced by its surrounding environment, other objects it encounters, and time. However, studying stellar evolution is not necessarily easy since it occurs on a timescale much beyond a human lifespan. The solution for overcoming the scale of stellar evolution begins with the work to see that stellar evolution occurs at all.

Historically, the positions of stars and constellations in the night's sky have shown religious and agricultural significance and were used to guide the navigation of the Earth. Studying the positions of stars in the sky, or the changes in positions of stars, became more accessible after the invention of the telescope in the 1600s and allowed early astronomers to explore a new goal, beginning to posit about our place in the solar system and universe (Ostlie & Carroll 31). Before the use of telescopes to observe changes in stellar positions and the first uses of spectroscopy, which came another two hundred years later, the primary subject of stellar interest was the Sun. As technological advances were made in the early 1600s that would eventually allow astronomers to study distant stars, astronomers such as Johannes Kepler and Galileo Galilei were making revolutionary discoveries about the orbiting of planets around the Sun and of sunspots and other solar activity (Ostlie & Carroll 32).

Beginning in the middle of the 1800s, spectroscopy was used to explore the chemical compositions of the Sun and other stars. Spectroscopy analyzes the wavelengths of light emitted by an object and works by splitting the light from an object. This process reveals the full-color rainbow of light with dark bands or absorption lines, pieces missing from the color scale. These lines correspond to specific wavelengths of light and are significant of specific chemicals in the composition of the light source, as each chemical has a particular spectral absorption.

When an astronomer, Gustav Kirchhoff, studied the spectra of the Sun and found various absorption lines, he was then able to connect the patterns of dark bars to indicate which chemicals were present in the Sun and their abundances (Ostlie & Carroll 125). This process of analyzing the wavelengths of light emitted by different objects was applied to more distant stars, revealing similarities and differences in their compositions to that of our Sun. While the revelation of stellar compositions has wide implications and gives information on the evolution of the star and the processes that occur within it, the light given off from a star also informs us about its luminosity or brightness, temperature, and distance. Together, these characteristics, now determined about a large sample of observable stars, could be used to begin classifying stars and placing them in different categories based on their attributes.

One method of classification came from the composition of the star, using letters (O, B, A, F, G, K, M) to denote spectral class. A star's composition of helium, hydrogen, and metals gives its spectral class or stellar type (Ostlie & Carroll 223). Perhaps even more revolutionary is the apparent relationship of composition to luminosity, temperature, and color. The result of this data and the relationships between stellar characteristics is the

Hertzsprung-Russell (HR) Diagram (Figure 1), a plot that relates spectral class, temperature, absolute magnitude, and luminosity.

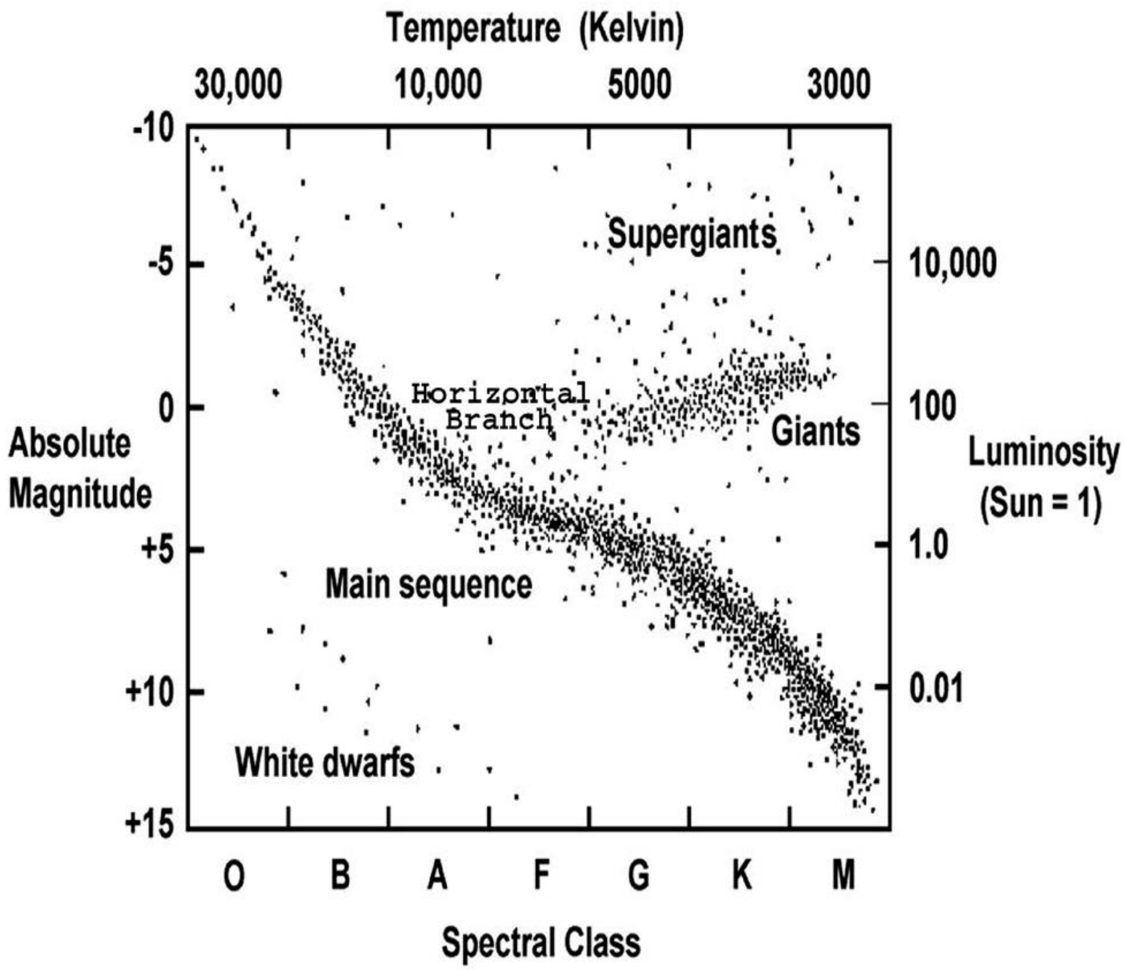

Figure 1. "The H-R Diagram" (2013) NASA and the Harvard Smithsonian Center for Astrophysics. Plot displaying relationships between spectral class, absolute magnitude, luminosity, and temperature for observed stars.

On the HR Diagram, a correlation between the characteristics of the stars that Kirchhoff had worked to categorize was found. The main sequence shows stars in the most common stages of stellar evolution and where a star will spend most of its life. This stage signifies that a star is undergoing nuclear fusion of hydrogen to helium at its core. As a star continues to burn its fuel, the star will move to a different stage of life depending on its type and mass.

Other areas of the HR Diagram include the giants and supergiants, located at lower temperatures and early stellar types. The giants typically evolve from main sequence stars close to the mass of our Sun, supergiants being stars initially at least 5 solar masses, that have run out of hydrogen to fuse into helium. When the star exhausts its hydrogen, it begins to fuse helium into heavier elements. As more energy is created in the core, the star expands until the star does not have enough fuel to continue fusing successive elements.

Also of significance is the collection of stars in the lower left corner of the diagram, white dwarfs. These are stars that have evolved past the giant stage of stellar evolution, having a lower initial mass and unable to continue fusion as a giant. The white dwarf is the result of the star's inability to continue fusing elements, collapsing to leave the stellar core behind. These stars, as individual objects, no longer fuse elements and will slowly cool in this final stage of their evolution.

While this explanation of the formation of a white dwarf addresses a star with a low mass, near that of our Sun, there are other evolutionary paths for higher mass stars. A higher mass star in the main sequence will become a supergiant when it can no longer fuse hydrogen to helium. As before with a lower mass star, this will cause a collapse into the core of the star that energizes the fusion of heavier elements. Expanding to the size of a supergiant, this star will fuse heavier and heavier elements until it runs out of energy and collapses. Seemingly the same story as before, the key difference is that the higher initial mass of this object gives it more energy when it finally collapses into its core after fusion ends. This energy is enough to create the heavier elements unavailable to it before in an event called a supernova. While there are different types of supernovae, in its simplest form it is a high-energy explosion of which stellar material is left behind. If the remnants of the star have a high enough mass, this can lead to the creation of a black hole or neutron star. Since the mass of the star was much greater than that of our Sun in this case, it results in a different type of compact object: neutron star or black hole. Each of these evolutionary paths is explored in Figure 2, an illustrated representation of how the mass of a star initially can influence the potential evolutionary paths. This evolution addresses an individual star, little influenced by other objects or its environment after formation.

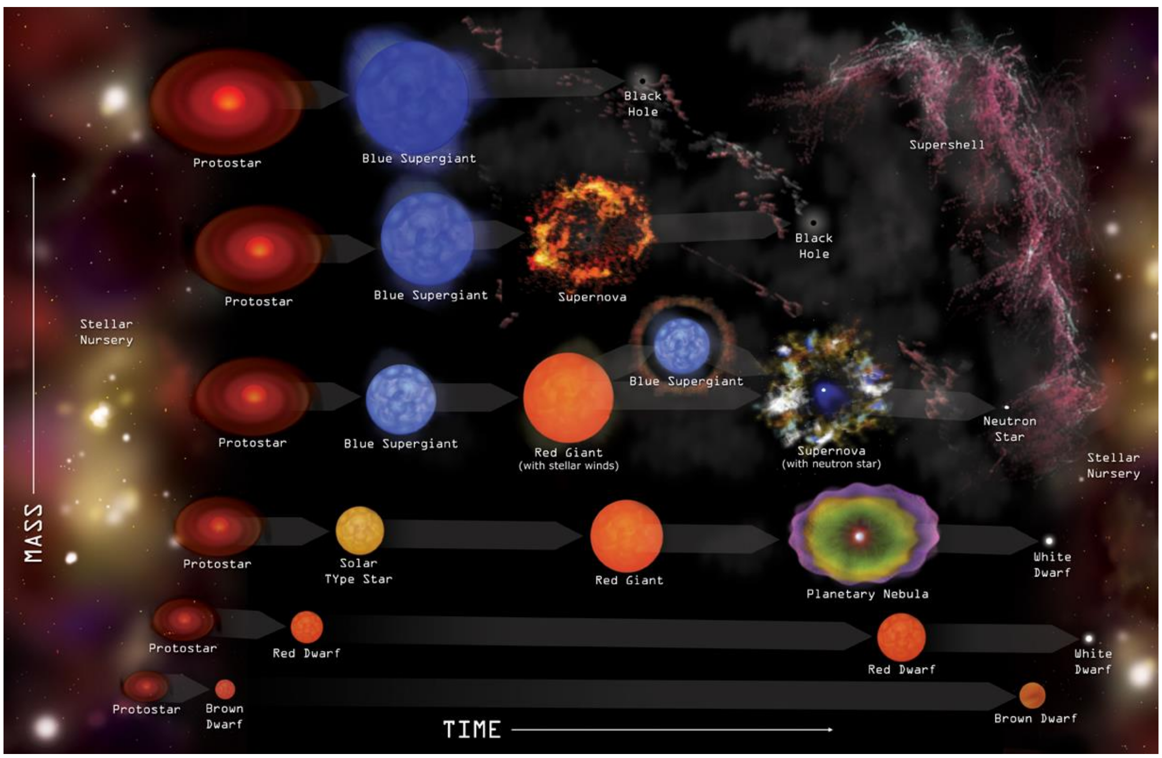

Figure 2. “Stellar Evolution” (2012) NASA and the Harvard Smithsonian Center for Astrophysics. Graphical representation of the stellar evolution of varied mass stars over time.

Astronomers quickly and widely accepted spectral classification and the HR Diagram, a combined discovery that allowed researchers to examine the different stages of stellar life, the ages of stars and star clusters, and the relationships of stellar characteristics given from spectroscopy to stellar evolution (Ostlie & Carroll 241). By the end of the 1800s, spectral classification and the use of spectroscopy were tools used by many astronomers, opening a promising door to the study of stellar evolution despite the ever-present barrier of time.

Spectral classification allowed astronomers to determine important stages in stellar evolution and the influence of indications for mass, composition, luminosity, and more to determine the evolutionary stage a particular star is in, how it got there, and how it could evolve in the future.

B. Exploring Compact Objects

A neutron star is a compact object created when a high mass main sequence star dies in a supernova explosion. If the star's mass is great enough at the time of its death, the core can collapse and create an incredibly dense object. For a neutron star to be formed, the compact object must be less than about 2 solar masses, or 2 times the mass of our Sun. This is known as the Tolman–Oppenheimer–Volkoff limit where within this mass there will still be some internal pressure keeping the mass from collapsing on itself further. Composed entirely on neutrons, giving it its name, the neutron star has a radius ranging from ten to fifteen kilometers and a mass 1.4 times the mass of our Sun. The creation of and evolution of this object is linked to some of the highest energy events in the universe, gamma ray bursts. These are releases of the highest energy of light, occurring during neutron star interactions and supernovae.

A black hole is formed in a similar manner to that of a neutron star. In this case, a star has evolved past the stage of a supergiant. When it finally runs out of fuel and collapses, causing a supernova explosion. The mass left behind after the explosion is large enough, exceeding the limit for neutron star formation, that an even denser object is formed. The gravitational attraction of the black hole is so great that there is no internal pressure that can prevent gravitational collapse. This causes the object to occupy only a single point of space, infinitesimally small but with great mass. While the black hole itself is very small, it will consume nearby material that surrounds it. When the surrounding material gets closer to the black hole, having such a strong gravitational force that even light cannot escape, the matter is accreted by the compact object. This accretion and the presence of surrounding material makes the black hole identifiable and visible, as light cannot escape the black hole itself. Little can be determined about a black hole observationally, making them rich with opportunities for study. Three characteristics can be determined about this object once it is formed, is mass, spin, and charge.

C. The Significance of Stellar Environment on Stellar Evolution

The first interest to study stellar evolution came from discoveries made by spectroscopy in the 1800s. Interest in astronomy exists for some people in determining the characteristics, life span, and more of our Sun, as these characteristics are so important to life on Earth. Exploring stellar evolution to reason about the fate of our Sun and how this creates the circumstances for life on Earth is a primary reason. Other reasons for exploring stellar evolution are to determine our place in the Milky Way Galaxy, and the galaxy's place in the greater universe. Exploring how we came to be and investigating the origins of life on Earth as well as the events of the early universe.

While stars are born, aging for billions of years, and dying, it is important to explore how the broader environment of an individual star affects its evolution. Many stars are formed in clusters, giving the group of stars in that cluster similar ages and characteristics. Since star clusters consist of stars near the same age, this is helpful in studying their evolution. Of star clusters, there are open clusters and globular clusters, each containing stars around the same age but varying greatly in size (Ostlie & Carroll 530).

Star clusters can consist of hundreds to thousands of stars. While open clusters expand over about 5 parsecs of space and globular clusters can be ten times this size, it is very possible that two stars in the cluster are close enough to begin revolving around each other, transferring mass, colliding, and several other things as they interact with each other. This system of two stars is called a binary.

Binary star systems consist of two stars closely bound by a gravitational attraction and revolving around some center of mass between them. Depending on the characteristics of each star, such as their masses, the eccentricity of the binary (the measure of how circular their paths are), individual luminosities, and more, the stellar evolution of each object is greatly affected. So far, we have explored only the evolution of individual stars and thereby the evolutionary paths they take when they are relatively uninfluenced by their environment.

Visually, star clusters can be observed and the stars that make up that cluster can be compared to determine the age of the cluster itself. We can generalize and say that large stars will burn through their fuel faster and this helps to determine cluster age. Using isochrones, we can categorize the stars in a cluster and plot them on the HR Diagram (Ostlie & Carroll 531). Isochrones can be used similarly to a line of best fit, each one corresponding to a cluster of a different age, to determine what age the observed cluster most closely fits.

Observationally, binaries can also be studied and information about the components of the binary and how each star interacts with the other can be determined. In the study of binaries, we are greatly limited by distance. The further away an object is in space, the greater resolution we need to observe it. This requires incredibly large and powerful optical telescopes. If the binary can be distinguished visibly, it is considered a visual binary. However, without being able to resolve the small distance between the stars of a binary compared to the distance of this system from Earth, the binary may appear as a single light source.

Confronting this obstacle to study binaries with a smaller separation, dimmer stars, or systems further from the earth is possible by analyzing the light from the apparent single source and how this light changes over time. The light from a binary star system as the objects pass in front of each other is unique and can tell us the brightness of each object, their distances from each other, and more. The result of this observation is called a light curve and can be found when dealing with a visual binary. Depending on the resolution of the observation instruments, more information about the distance between the stars, their orbit, and individual masses and luminosities of the binary can be determined. Among these systems are eclipsing and spectroscopic binaries. Both can be studied through the changes in light from the object over time. This is because as the objects pass in front of and behind each other, shifts in the spectroscopy of the light source may be observed, revealing information about the separate sources. Alternatively, a change in the amount of light the object is emitting, which can be significant of light from a companion being blocked, will cause the luminosity observed to decrease.

Observing binary stars and determining their characteristics only gives a small window of information into the impact of the interactions between the stars. As was discussed of stellar evolution, the interactions between a star and the environment it is in can alter its evolution. When a star forms far enough from other objects it is isolated and much of its stellar material is contained in the gravitational field it creates. In this space, the individual star will evolve as we discussed before. However, a binary is unique because it brings this star close enough to another that mass can be transferred between the two. Since stellar evolution occurs as a star burns through its fuel, the loss of stellar material to another object can influence the speed of the star's exhaustion of fuel and the mass left over after collapse. Alternatively, if a large amount of mass is gained by a star during its time on the main sequence it could cause it to exhaust its fuel much faster and lead to the creation of a black hole or neutron star compact object, where there wouldn't have otherwise been. Regardless, this mass transfer greatly impacts the course of stellar evolution for both objects, offering binary star systems as an interesting alternative to the known path of stellar evolution. While the characteristics of the stars influence their interaction, as mass transfer takes place changes will occur for both stars.

D. Computer-Simulated Stellar Evolution

By observing individual stars as well as binaries, the evolution path each takes can be predicted. For example, if most stars in a cluster are formed around the same time, different clusters and their characteristics can be compared to inform us about stellar evolution. Various observable binaries can be compared in this manner as well. Wanting to study many binaries and how they evolve over time, finding distant binary star systems in the sky is not always the most fruitful exploration. Still limited by the timescale at which stars evolve and now as well by the relatively small number of binary star systems that can be observed, computer simulations offer a solution. Addressing stellar evolution as a whole, only so much information about the course of observed stars can be gathered by categorizing them. The observations that are made of stars, star clusters, and binaries can be used to inform the writing of computer simulations.

The information gained from studying observable stars, clusters, and binaries, informs simulations of the evolution of similar objects or systems. Computer simulations of stellar evolution work by creating stars with certain parameters, randomly generated or inputted. As a great variety of programs have been developed and are continually refined as a greater picture of stellar evolution is created from observations, stellar evolution can be studied through stellar structure, individual stellar evolution, the evolution of clusters and galaxies, and even the evolution of a simulated protostar. Stellar structure programs may model how changes in the internal structure of a star will affect its evolution, or how fluctuations and stellar activity are indicated on the surface. Alternatively, simulations of clusters and galaxies may show how many stars evolve over time and interact with each other.

Simulations of the evolution of a star work to reveal how the components of the environment influence a star and can affect the stellar type. As the conditions of a star influence its evolution, the program will consider how the mass, luminosity, stellar type, and more could influence its place on the HR Diagram as well as the likelihood for it to evolve through the stages of the main sequence and into its death.

Simulated binary systems can show the influence of a star's environment in a similar way. Allowing the two stars to interact based on their separation, the computer can follow pathways to recalculate the forces felt between stars, how mass changes over time, and how changes to a star should alter its evolution.

E. X-ray Binary System Evolution

Most simply, an X-ray Binary (XRB) is a binary system where one of the objects is a compact object. This system, consisting of a star and a black hole, neutron star, or white dwarf, is considered an XRB because the interaction between the objects causes X-ray light to be emitted. This process occurs as the star's mass is accreted by the compact object, superheating the matter, and emitting photons energized into the X-ray range of light. This aspect of XRB systems is part of what makes them easy to observe against the variety of other events in the sky. Releasing high-energy light makes the system unique against the light emitted from a cluster, for example. X-ray light is the second wavelength range of light that is considered high-energy, having a shorter wavelength than visible light by 10^{-2} nanometers.

Of XRBs there are high and low mass systems, which can vary greatly in their observed characteristics and certainly vary in their evolution as a system. The mass classification of the system can also influence which compact object forms. For lower mass systems, a donor star will not have enough mass during its collapse to cause a supernova, leading to the formation of a white dwarf. Low mass XRBs are classified by a regular star and compact object system, where the star is in a later stage and can be much dimmer in the optical range than the system is luminous in the X-ray range of light.

A high mass XRB is distinguished by having a donor star which is a much larger, hotter star type. As we explored while discussing stellar evolution, such a star would have to have enough mass to cause a supernova during its collapse, leaving behind a neutron star or black hole compact object (Ostlie & Carroll 724).

When binaries interact by transferring mass to each other, it occurs by a process called Roche lobe overflow. Generally, the star's mass is contained in its own gravitational field but being so close to another object can cause stellar material to be pulled further and further from the core. As this occurs, stellar material will fill a region of space outside of the star, called the Roche lobe.

II. METHODOLOGY

This project will address the stellar evolution of XRBs using computer simulations. Using the binary_c rapid stellar evolution code (Izzard 2021) in the computer programming language, C, we can study large populations of binary star systems. We wrote a smaller program in python, Code 1, which can communicate with the binary_c program, edit the initial parameters of the binaries created, and the information recorded about them. For our simulations, we used a set mass distribution derived from observed mass distributions of clusters, the masses of the binaries we set to be randomly determined between 5 and 100 solar masses, since we are interested in evaluating the high-mass systems that may lead to the creation of black holes and neutron stars. The eccentricity of simulated binaries is randomly distributed. As stars are simulated in clusters, many will form in binaries. Of these simulated systems, those that meet our requirements for mass and luminosity will begin to be recorded. Characteristics of these binaries include individual masses, mass change, stellar type, the eccentricity of the system, separation of the system, and Roche lobe overflow terms. As the system evolves through the binary_c code, these characteristics are recorded in data files, citing each time step as data changes.

Once the stars meet the necessary conditions to transfer mass to each other, we can record the luminosity of each object. Later in the evolution, the luminosity range of each object can tell us if the system contains a compact object and indicates how much mass is being transferred. This luminosity is also recorded by time and creates single files that describe the evolution of each binary. Code 1 sorts through the resulting data files, containing time-based data on each binary's mass, stellar type, mass change, luminosity. A useful result of this simulation in determining changes in the evolution of different binary types is a plot of the number of XRBs, black hole XRBs, and neutron star XRBs.

Depending on the results of the distribution of binaries, we can look further into the relevant changes of the systems at specific times, using the global picture to instruct closer investigation. For this purpose, we wrote a python code, which sorts the data produced originally and for time periods of interest, selects the individual stellar types, eccentricity, and separation of the systems. Results from this code illuminate more specific characteristics of binaries present in the original distribution.

High mass XRBs are of interest because of the compact objects they contain, black holes and neutron stars. These objects offer an area of research rich with possibility and, being responsible for high-energy emission, are relevant sources for study in high-energy astrophysics. Determining the conditions that may create such systems and how the changes in the composition of the environment will affect their evolution or appearance can help future researchers explore them observationally.

For this project, we also constrain the metallicity component of the simulated star clusters. Metallicity, or the composition of elements other than hydrogen and helium, can greatly influence the stellar type of the stars in the binary, their temperature, luminosity, and of course, their evolution. We will simulate binary formation and evolution at a range of metallicities to better evaluate how the changing environment may affect the binary system. We picked three metallicities: 0.01, 0.001, and 0.0001. These give us a range from high metallicity to low metallicity, respectively. Using Code 1 to input the relevant parameters, we conduct simulations of 100,000 binaries. Among these, only a portion will evolve into XRB systems, so we begin with many binaries to better analyze how the XRBs form over time.

Our goal is to explore the effects of metallicity or environment on the evolution of XRB systems. We can explore when an XRB is formed and how many occur over the simulated period, distinguishing between neutron stars and black hole compact objects. The comparison of this result to simulations of other metallicities will determine the research path, as we then work to explore the resulting distributions of XRBs and compare them to observed distributions.

III. RESULTS

Using a range of high to low metallicities, 0.01 (near that of the Sun with a metallicity of 0.018), 0.001, and 0.0001, we evaluated the appearance of binaries, black hole XRBs, and neutron star XRBs in their temporal evolution. Beginning with a high metallicity of 0.01 and a simulated population of 100,000 binaries, we saw a single maximum for black hole XRBs and a single maximum for neutron star XRBs. As shown in Figure 3, the maxima were near 90 and 35 million years (Myr), respectively. Important to note, too, is the number of XRBs produced. In the simulation of 100,000 binaries around 5,000 resulted in XRB systems. Further, we find that the simulation of 100,000 binaries is a large enough population to create a reasonable resolution of XRBs. The resulting distribution of this simulation is most useful in comparison to simulations of other environments, with varied metallicities.

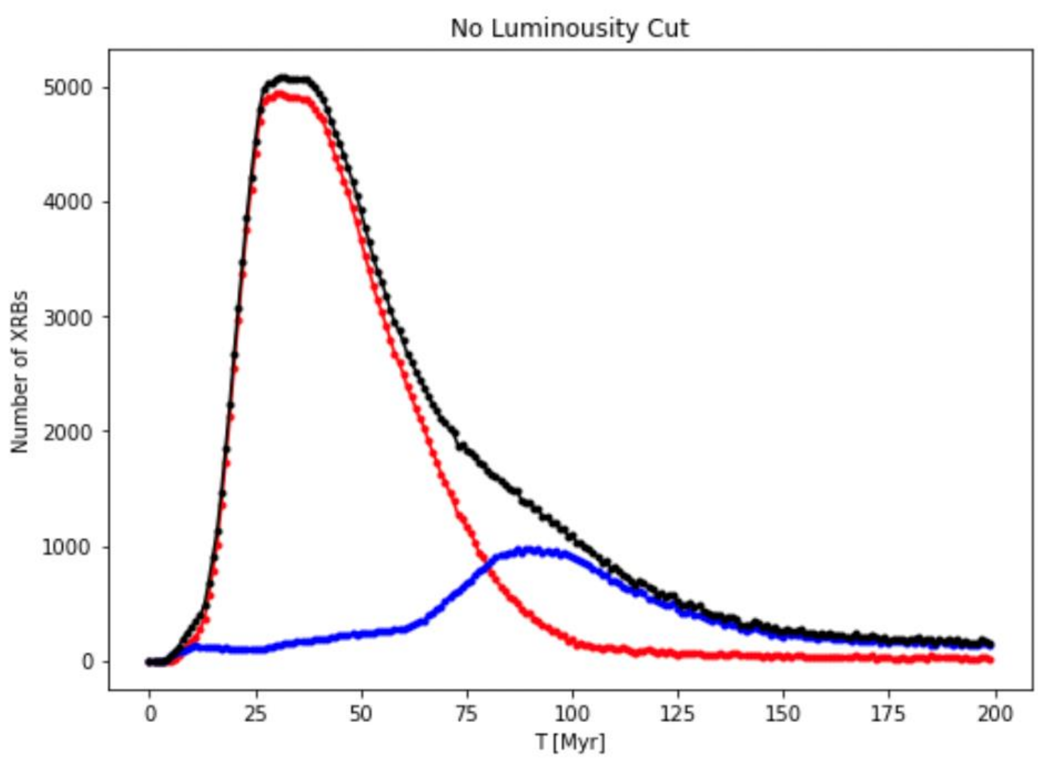

Figure 3. Simulation results for 100,000 binaries at high metallicity (0.01). Shows total XRBs (black), neutron star XRBs (red), and black hole XRBs (blue) over 0 to 200 Myr and at all luminosities.

Our initial results for simulations of 100,000 binary star systems in differing metallicities showed a surprising, bimodal distribution of black hole XRBs as metallicity decreased. Figures 4 and 5 show the number of XRBs over time for simulations of metallicities 0.001 and 0.0001, respectively. For each of the lower metallicity simulations, we noted neutron star XRBs had a similar maximum at each metallicity and the total number of X-ray sources was also comparable, leaving us with the change in black hole XRB creation as the primary result of varying metallicity (Figure 4, Figure 5).

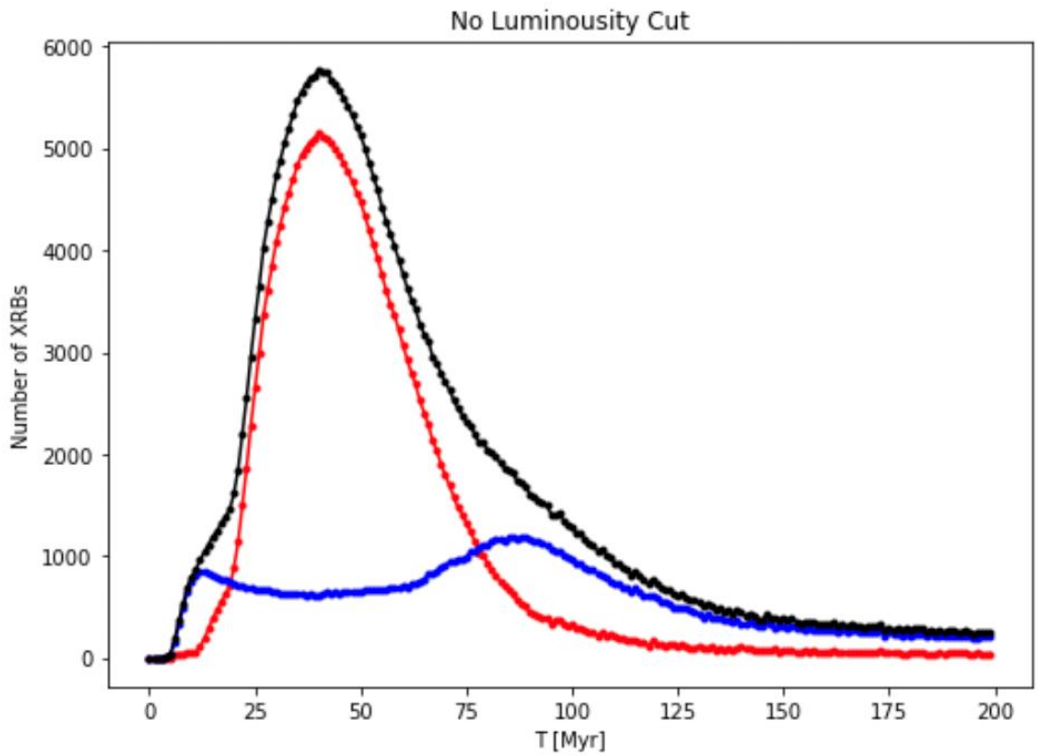

Figure 4. Simulation results for 100,000 binaries at a metallicity of 0.001. Shows total XRBs (black), neutron star XRBs (red), and black hole XRBs (blue) over time and at all luminosities.

For each of these simulations, the black hole XRBs have maxima near 12.5 and 85 Myr. Since the evolution of neutron star XRBs is nearly the same at each metallicity, we will further evaluate the characteristics of black hole formation by introducing luminosity bins. Since Figures 4 and 5 are created by summing XRBs at each point in time no matter how luminous they are, we may find a clear path for analysis by creating a similar plot with a specified luminosity range.

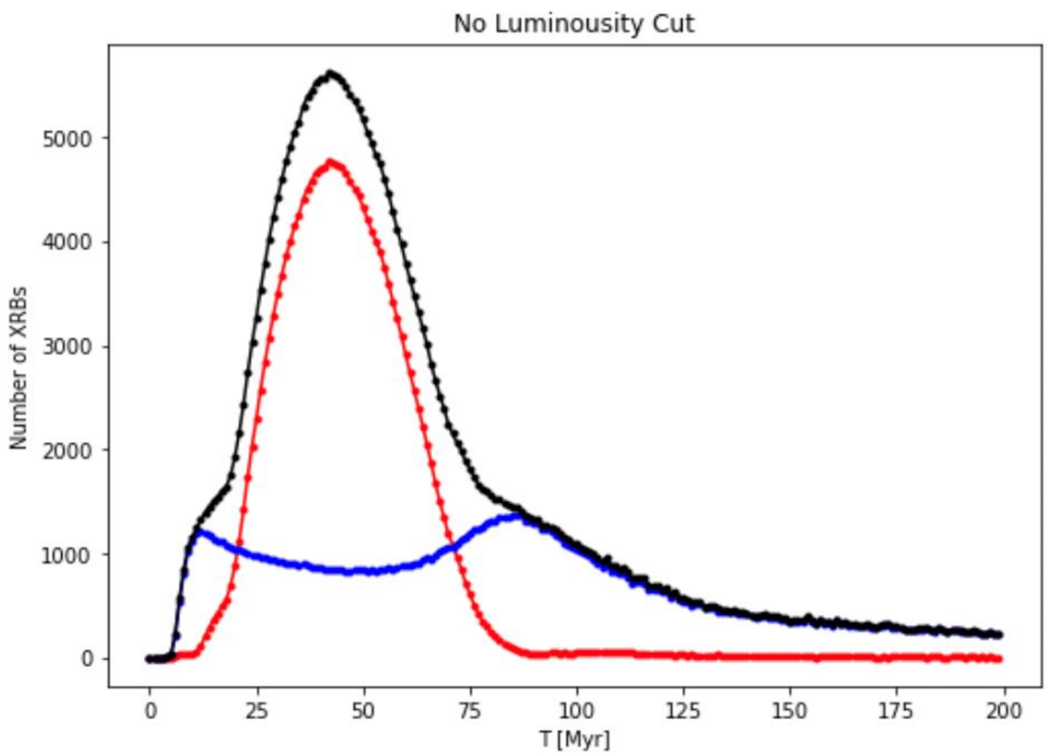

Figure 5. Simulation results for 100,000 binaries at a metallicity of 0.0001. Shows total XRBs (black), neutron star XRBs (red), and black hole XRBs (blue) over time and at all luminosities.

Creating luminosity cuts in our data, we can sort through the binary data and see the evolution of binaries in a specified luminosity range (Figure 6). Based on observation and the relative brightness of XRB star systems, we created luminosity bins ranging from 1E30 to 1E40 ergs/s. Effectively, this allows us to see the temporal evolution of XRBs that are luminous in the specified range. Selecting the lowest metallicity, 0.0001, revealed that the bimodal distribution of black hole XRBs is most prevalent between 1E33 and 1E36 ergs/s. The evolution of these binaries is shown in Figure 6, where the same maxima are noted for black hole XRBs near 12.5 Myr and 85 Myr.

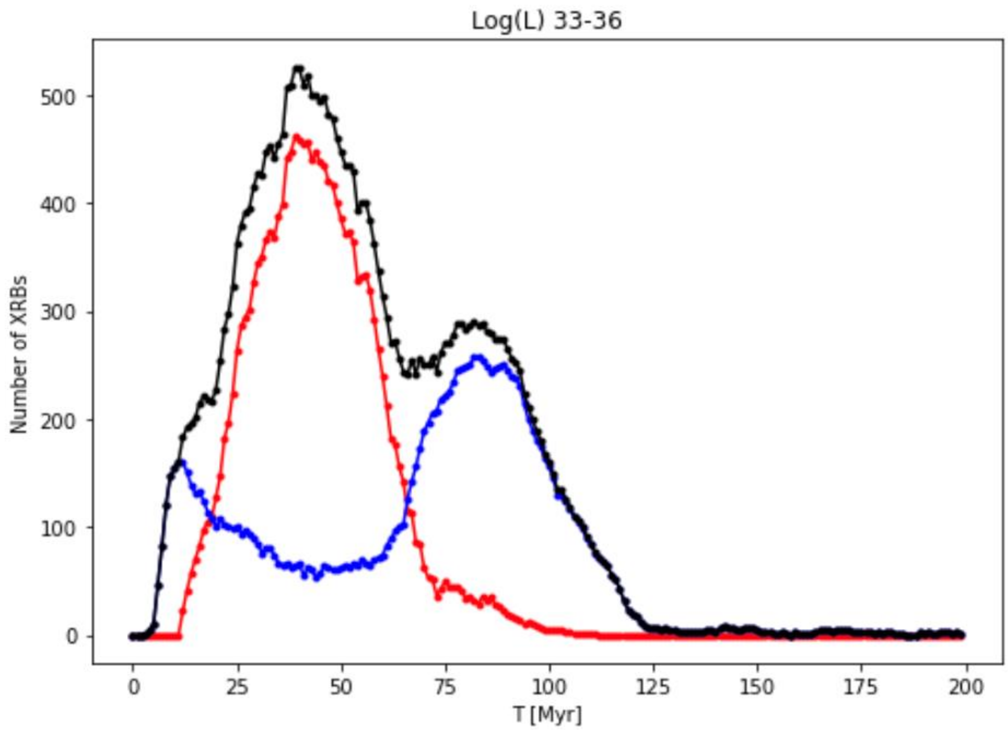

Figure 6. Simulation results for 100,000 binaries at a metallicity of 0.0001. Shows total XRBs (black), neutron star XRBs (red), and black hole XRBs (blue) over time between luminosities of 1E33 and 1E36 ergs/s.

To analyze this distribution, we must further evaluate the stars contributing to this distribution. We developed a second program, Code 2, that collects data on the characteristics of systems at points of interest. In our analysis, we will further explore the origins of the binaries contributing to the two black hole XRB maxima with this program.

IV. ANALYSIS

The bimodal distribution of black hole XRBs was surprising to us. This distribution may indicate that changes in the environment alter the evolution of binary systems enough to slow the formation of black hole compact objects, causing a portion of them to form in the first maxima and the rest to form near the second maxima. Alternatively, this distribution may have been a result of conditions creating a space for black hole formation with two evolutionary points. To answer these questions on the creation of black hole compact objects during each of the maxima, we created a second program that evaluates the characteristics of these binaries, hoping to better understand their evolution. This program, Code 2, is written in python as well.

Code 2 works by taking inputs on points of interest and collecting characteristics of the binaries at those points of interest. In this case, we look near 12.5 and 85 Myr, the maxima noted from the results of Code 1. By inputting the time ranges we are interested in, Code 2 will sort through the original data from Code 1 and binary_c. While this data contains information about the binaries at every time point, Code 2 will only save information when each condition is met. We input the conditions so Code 2 can record the characteristics of black hole XRBs that were active near 12.5 and 85 Myr and had a luminosity between 1E33 and 1E36 ergs/s. When these criteria are met and data is recorded, Code 2 creates a table of the individual masses, mass change, stellar type, the eccentricity of the system, separation of the system, and Roche lobe overflow terms, and individual luminosities. Altogether, this allows us to evaluate how the binaries that contributed to the maxima looked when they were formed and evolved to create this distribution.

We found that black hole XRBs that were active in the first maxima had larger initial separations. Separation, or the distance between the two objects in the system, is determined randomly from an observed distribution with Code 1. With Figure 7 we can compare the distribution of separations in binaries active at each maximum.

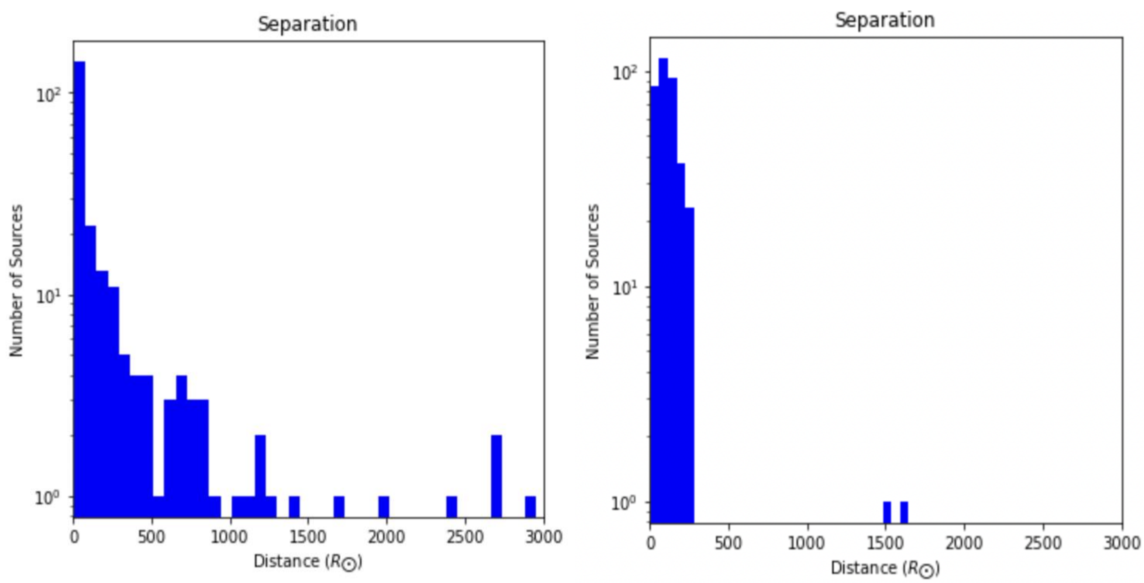

Figure 7. Histogram of separation for black hole XRBs active near 12.5 Myr (left) and near 85 Myr (right). Distance is in terms of solar radii.

We note that the distribution of initial separations for binaries that contributed to the first point of interest was much more varied. Conversely, the initial separation for binaries that contributed to the second point of interest ranged almost entirely between 0 and 500 solar radii. This is a relatively small distribution and a small separation for the binaries.

Following separation, we turn to the mass distribution for each point of interest. To evaluate how the masses of the companion and black hole may contribute to each maximum, we found the initial mass of the companion, the mass of the companion during the maxima, and the mass of the compact object during the maxima. Figure 8 explores the result of this analysis for the first maxima, near 12.5 Myr.

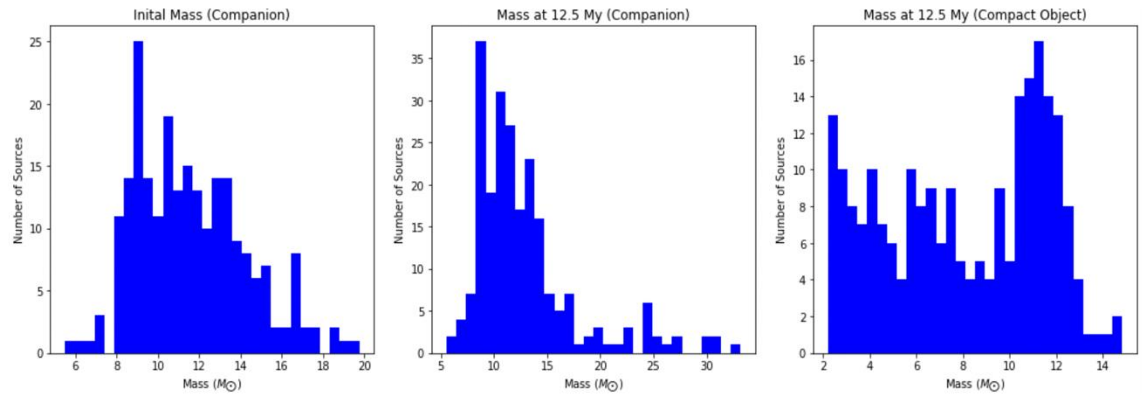

Figure 8. Histogram of mass (in solar masses) for black hole XRBs active at 12.5 Myr. Showing initial mass of the companion stars before evolution (left), mass of the companions during the point of interest (middle), and mass of the black holes during the maxima (right).

The distributions found in Figure 8 show that the companion is initially a high mass star and is still very massive when the black hole compact object has been created near 12.5 Myr. For the compact object, we see a wide range of masses, nearly evenly distributed with a point of concentration around 12 solar masses. We can explore how these mass distributions compare to the XRBs that contribute to the second maxima by exploring Figure 9, which shows the mass distributions for XRBs in the second maxima, near 85 Myr.

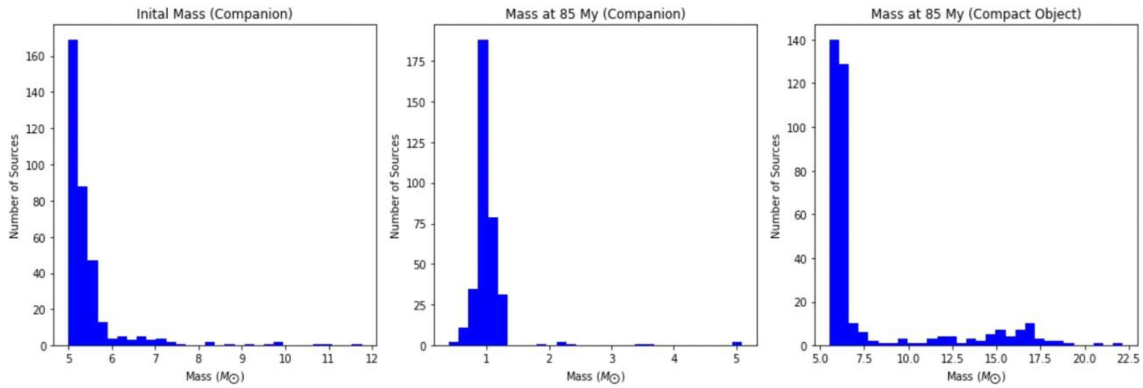

Figure 9. Histogram of mass (in solar masses) for black hole XRBs active at 85 Myr. Showing initial mass of the companion stars before evolution (left), mass of the companions during the point of interest (middle), and mass of the black holes during the maxima (right).

After evaluating the mass distributions for the second maximum, we found that initially the mass of the companion was low, near 5 solar masses. While these are still considered high mass stars, the limited distribution is notable. Further, this companion is much less massive during the maximum at 85 Myr, as shown by the center plot. We notice the black hole compact object here has some range in its mass but also has a peak for mass between 5 and 7 solar masses.

Reflecting on our findings on the separation of the XRBs and the distribution of their masses, we find that we can characterize each maximum. The first maximum is primarily identified by its high mass companion and varied separation, while black hole XRBs contributing to the second maximum are identified by a small separation and lower-mass companion stars.

Our findings from Code 2 allowed us to explore the stars contributing to XRBs, allowing us to compare our results to observed data. Observations tell us that XRB systems form with a particular distribution of luminosities. This distribution is given by the X-ray

Luminosity Function (XLF). To support this analysis, we created an XLF for the high (0.01) and low (0.0001) metallicity data sets (Figure 10). While the benefit of our project is the ability to study many binaries and the full evolution of these binaries in a short period of time, it is important to compare the binaries produced by the simulation to characteristics of observed XRB populations.

Observations of XRBs show a distribution of these sources from 1E35 to 1E40 ergs/s, due to observational capabilities and limitations. Figure 10 shows a comparison of the XLF of each data set and was created by recording luminosities for XRBs at a sampling of time points. These points were 10, 20, 50, and 100 Myr.

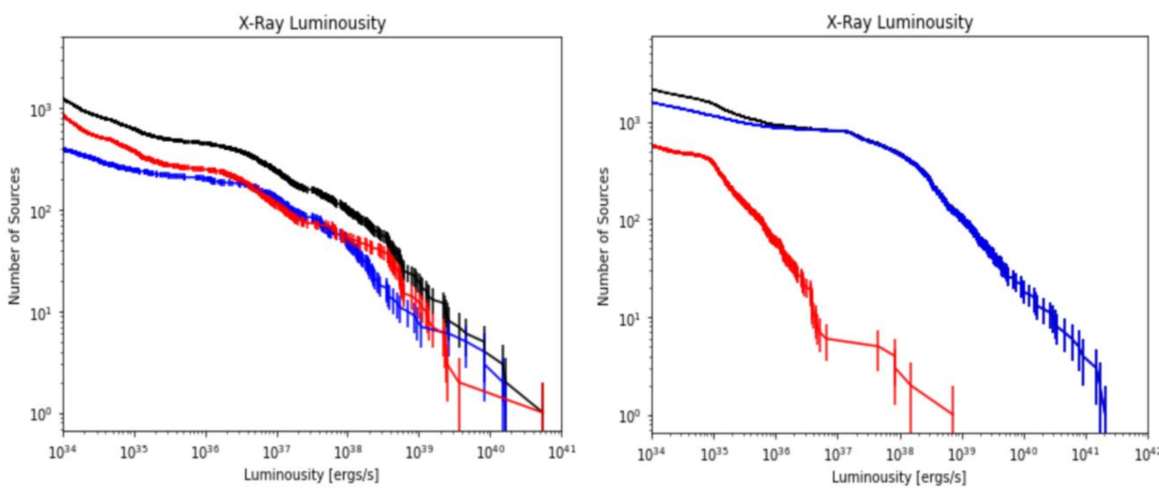

Figure 10. X-ray Luminosity Function of simulated XRB systems with error. Showing all XRBs (black), black hole XRBs (blue), and neutron star XRBs (red), and the distribution of their luminosities with error. Including high (left) and low (right) metallicity XLFs. Luminosities are recorded from times 10, 20, 50, and 100 Myr.

V. CONCLUSION

To evaluate the stellar evolution of binary systems to XRBs we utilize a complex computer program simulation, addressing the limitations of time and complexity in evaluating these systems. When evaluating the effects of metallicity on XRB formation and evolution in a simulated environment. We found that metallicity does affect binary evolution and the formation of XRBs. Particularly, when decreasing the metallicity of the environment from a high (0.01) to a low (0.001) we noticed a bimodal distribution of black hole XRBs. Lowering the metallicity again yielded the same bimodal distribution, showing black hole XRBs with local maxima near 12.5 and 85 Myr. We found that by constraining the luminosity of the XRB sources, this distribution was even more exaggerated. For black hole XRBs with luminosities between 1E33 and 1E36 ergs/s, the bimodal distribution was clear, with maxima near or greater than the neutron star XRBs in that luminosity range.

To continue exploring the causes of this distribution at low metallicities, we developed a new program, Code 2, which recorded relevant information at points of interest. With our criteria of black hole XRBs active near 12.5 Myr or 85 Myr and with luminosities between 1E33 and 1E36 ergs/s, we were able to compare the initial separations and mass distributions of binaries that contributed to the two maxima. In doing so we found that black hole XRBs that contributed to the first maximum had relatively high mass companions that remained very massive after the creation of the compact object. We find that these characteristics are most likely significant of wind-driven accretion. Here, the massive companion loses its matter to the forming compact object when active stellar winds between the binary keep the companion from maintaining its stellar material.

Alternatively, we were able to categorize the systems contributing to the second maximum of black hole XRBs as having a small initial separation between the components of the binary. Combining this small separation with the lower mass of the companion stars, we determined that black hole formation likely occurred after the Roche lobe of the companion overflowed. This process will occur at a smaller separation as the gravitational attraction from the forming compact object pulls at the companion star. This process will contribute to accretion and is likely the source of these later-forming black hole XRBs.

These criteria allowed us to categorize the binaries contributing to the bimodal black hole XRB distribution in particular but we find that this method could be applied to any distribution. The development of Code 2 will allow us to further explore this distribution and others we may come across, as we can adjust the points of interest that Code 2 evaluates. This gives opportunities for future work with Code 2 and the investigation of changing metallicity on the evolution of XRB systems.

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