NUMERICAL SIMULATIONS OF THE EVOLUTION OF HIGH MASS X-RAY BINARIES

by

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ABSTRACT

High-mass X-ray binaries (HMXBs) consist of a massive star and a compact object such as a neutron star (NS) or black hole (BH). They are important for astrophysics as they provide insights into the life cycles of massive stars and the formation of compact objects. This thesis investigates the evolution of HMXBs, focusing on the influence of initial parameters such as mass, separation, eccentricity, and metallicity. The simulations reveal that the mass distribution and metallicity significantly impact the formation and evolution of HMXBs. We also explore other observable outcomes such as the luminosity of HMXBs and the overall shape of the distribution of the number of binaries at different epochs. These findings provide a deeper understanding of HMXBs and have significant implications for future astrophysical research.

I. STAR FORMATION AND LIFE CYCLE

Star formation begins with the slow collapse of a gas and dust cloud, or nebula, under its own gravity. As the cloud collapses, pressure and heat increase and the new protostar begins to spin rapidly and accumulate more material. Protostars that accumulate enough material can become sufficiently massive enough to begin nuclear fusion, first fusing hydrogen into helium to release energy. As the star runs out of hydrogen and evolves, it must fuse heavier and heavier elements to continue to generate energy. This fusion causes the star to get hotter, brighter, and larger. There is a delicate balance to be maintained between the inward force of gravity from the stars own mass and the outward pressure from fusion and electrostatic forces. The outward electrostatic pressure arises from the high density of the core and the interactions between subatomic particles. These particles, such as neutrons and electrons, are forced near each other and particles with the same charge strongly repel each other and limit how small and dense a star can be. Unlike all the lighter elements before it, iron has the highest binding energy and therefore releases less energy than it takes to fuse it. A star cannot fuse iron, and this marks the beginning of the end stages of stellar evolution.

A low mass star will inevitably collapse and most of the material will rebound off itself and form a planetary nebula surrounding a small, dense core known as a white dwarf. However, if the star is sufficiently massive, its collapse is known as a supernova which is a very energetic and luminous explosion. Sufficient gravitational force may be present to crush the protons and electrons present in the core together to form neutrons in a process called neutronization. The result is a neutron star (NS). If the star is incredibly massive, then the supernova can also lead to the formation of a black hole (BH). Figure 1 provides a visual depiction of the evolution process and possible end results. The ultimate fate of a star can be closely tied to its mass, which is sensitive to the conditions under which it is formed and evolved.

There are many characteristics astronomers use to classify stars such as: mass, radius, luminosity, surface temperature, and chemical composition (i.e., metallicity). Several of these characteristics can be combined to outline spectral types. Spectral types describe stars with several similar characteristics that tend to evolve in similar and predictable manners. Most stars will evolve along the main sequence which is a distinct population of stars with a certain relationship between temperature and luminosity as shown in a Hertzsprung-Russell (HR) diagram such as Figure 2. Once a star has depleted most of its hydrogen, it begins fusing helium and then subsequently heavier and heavier elements. At this point, very massive stars can expand to more than twice their original size to become giants or even supergiants. Massive stars tend to burn fast and bright and evolve more quickly than their low mass counterparts. For example, a 1 solar mass star will spend around 10 Gyr on the main sequence (MS), a 0.1 solar mass star will spend around 1 Pyr or more on the MS (greater than the age of the universe), and a 10 solar mass star will spend around 32 Myr on the MS.

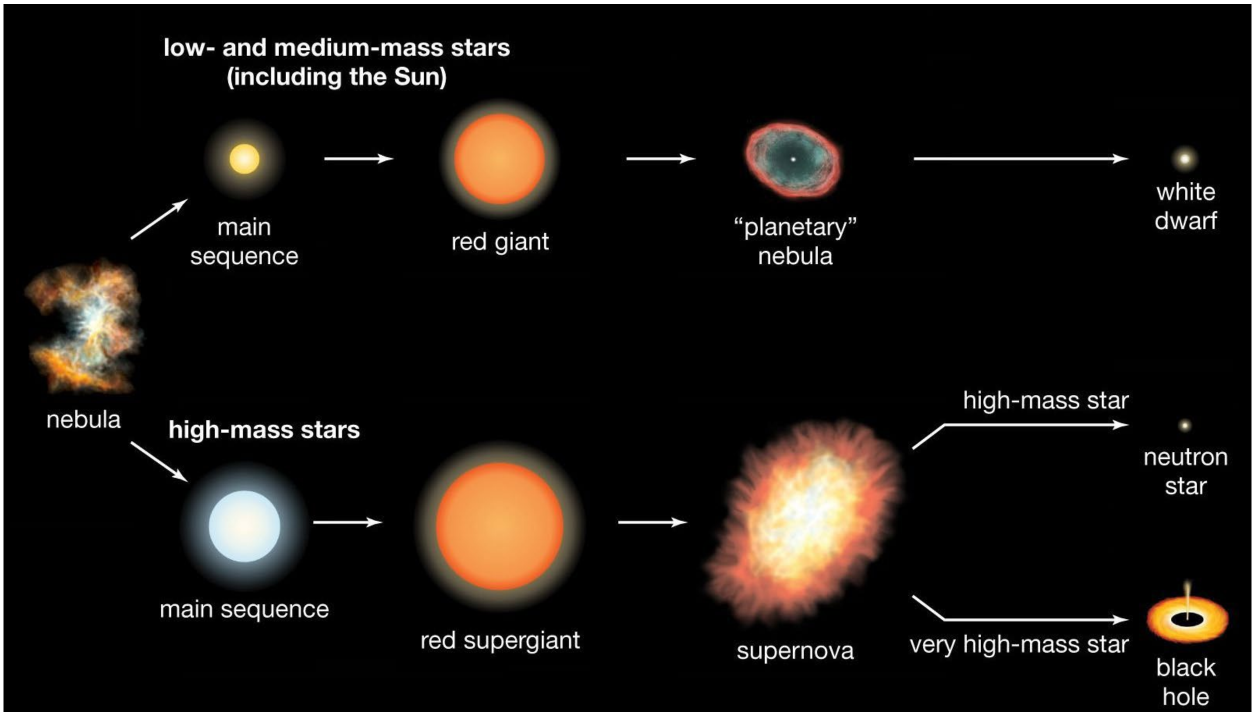

Figure 1: The life cycle of a star (Britannica, 2019)

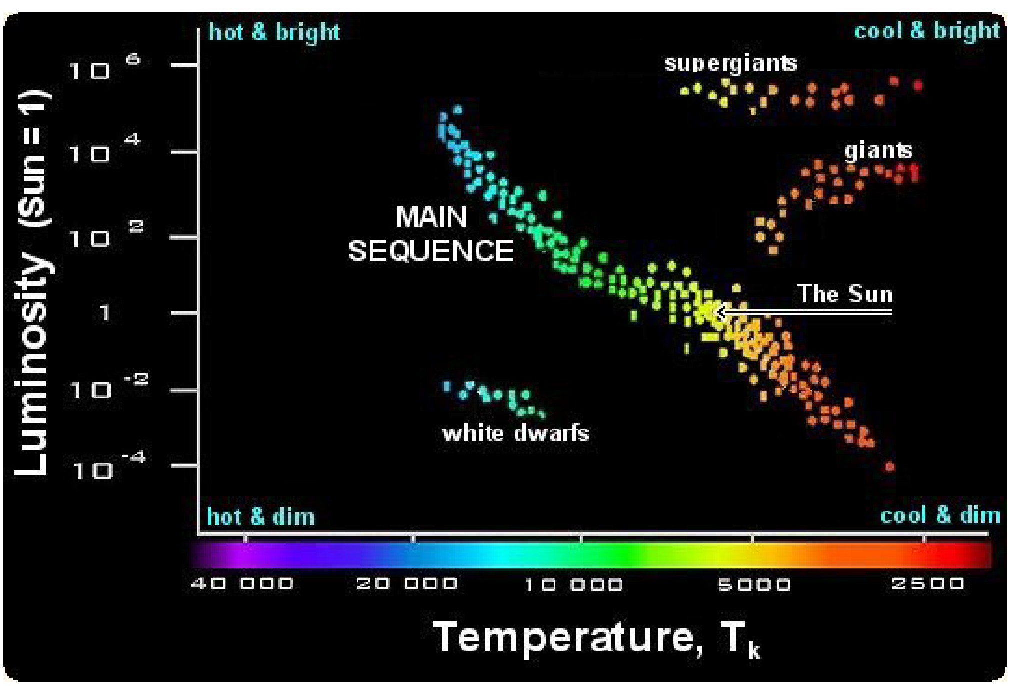

Figure 2: Standard populations on an HR diagram (Western Washington University, 2020)

II. BINARY SYSTEMS AND EVOLUTION

Binary star systems are a curious type of astronomical object whereby two stars are gravitationally bound to each other. The evolution of each star can be closely tied to the other and initial conditions of the system play a large role in the fate of each star. As these systems are incredibly common, one study suggests that up to 85% of stars are part of a binary, they provide a unique opportunity to study stellar evolution (Australia Telescope National Facility). Binary systems can form when stars are born sufficiently close to one another to become gravitationally bound or the stars can come into sufficient contact with one another later in life. In the latter scenario, the more massive star ‘captures’ the less massive one. A binary system whose stars have radii much smaller than their separation is considered a detached binary. In this case, when there is no mass transfer, the stars will evolve almost independently, as if they weren’t in a binary at all. If one of the stars in a binary expands to fill its Roche lobe, then the system is considered semidetached. A Roche Lobe is a teardrop shaped region of material that is gravitationally bound to a star. Each component of a binary system has a Roche Lobe and material that passes beyond this region is no longer bound to the star. As depicted in Figure 3, the Roche Lobes of a binary system interact and when one component grows larger than its Roche Lobe, it will begin transferring matter to the other. The stream of matter from the donor star will form an accretion disk around the compact object and material from the disk will continue to in-spiral feeding the larger component. Generally, the star that has filled its Roche lobe and is losing material is called the primary component. In simplest terms, the mass transfer rate can be calculated as the product of the density of the material being lost, the speed that the material is leaving the primary star, and the area of the opening that the material is leaking through. If both stars fill their Roche lobes, then the system is called a contact binary. Figure 4 demonstrates the different kinds of binaries.

In this work, we are mainly interested in binary systems with at least one massive star whose remnant is a NS or BH. Either of these compact objects can be formed by a massive star that goes supernova. Stars on the MS that are not considered massive or supermassive can become sufficiently massive enough to form a compact object through the process of accretion. In systems with a compact object and a massive star, the mass transfer is very likely driven by wind accretion. Generally, stars emit streams of material and the outflows are described as a "wind". In a binary system, the winds produced by a high mass donor star can feed material to the compact object. This will result in an accretion disk (similar to Roche-Lobe overflow) that forms around the compact object as material spirals in. Accretion disks are typically very dense so there is a tremendous amount of friction generated as the material rotates around the compact object. This friction heats up the disk, allowing for more energetic emissions, all the way to X-rays. That is why this type of binary system is historically known as an X-ray binary (XRB). XRBs can further be classified by the mass of the donor star. One type is called a low mass X-ray binary (LMXB) whereby the donor star is a low mass star (typically less than 2 solar masses), and these systems tend to be longer lived. On the other hand, a high mass X-ray binary (HMXB) exists when a massive donor star is paired with a high mass star (typically more than 8 solar masses) and these systems are shorter lived as they burn through their fuel faste

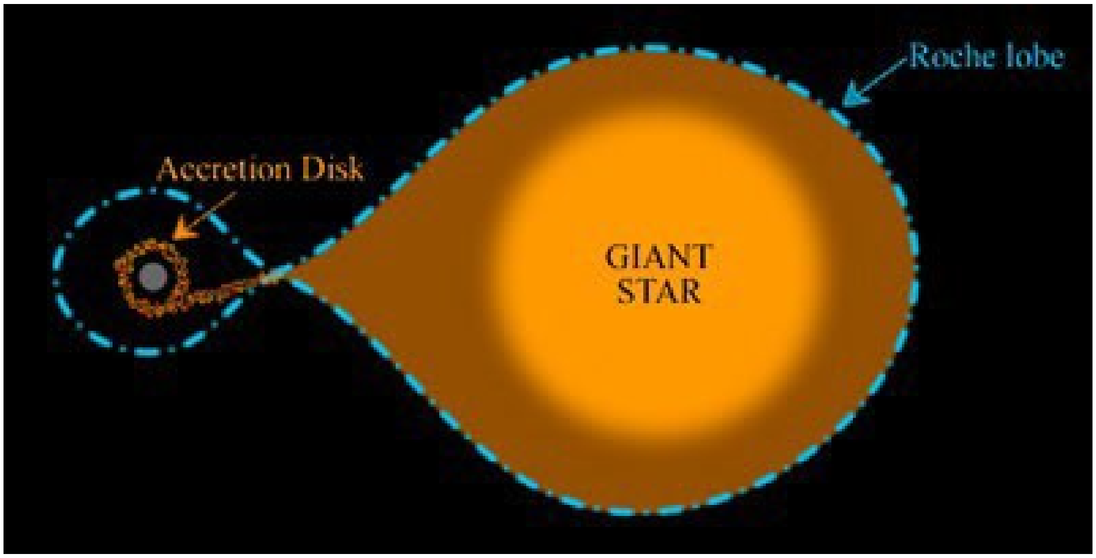

Figure 3: A giant star exceeds its Roche lobe and accretes onto its binary counterpart forming an accretion disk (Swinburne University)

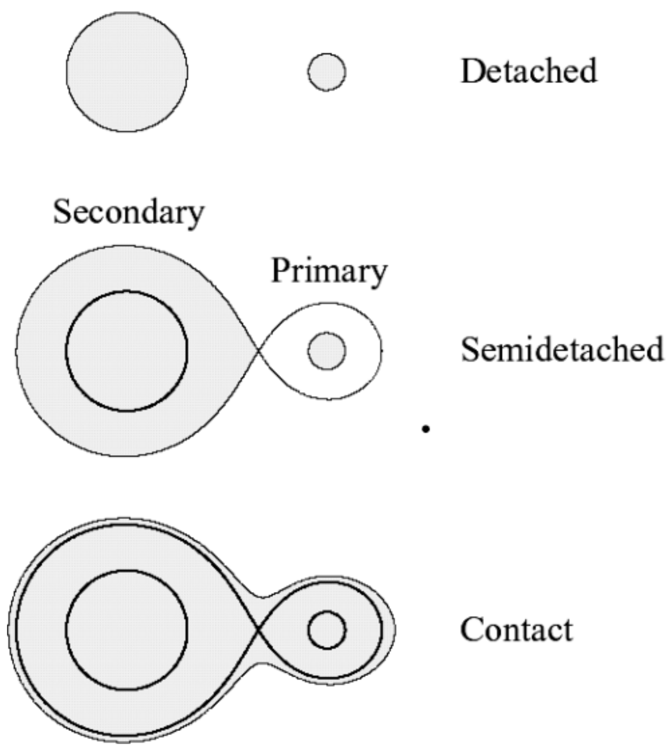

Figure 4: The three general types of binary systems (Carroll and Ostlie, 2017)

III. BINARY_C

The goal of this study is to use computer simulations to model HMXBs and their evolution. We can modify these simulations for different initial conditions to understand how they affect evolution. Binary_c is a software framework for modelling nucleosynthesis in single and binary star systems. For our purposes, the software was used to model the evolution of thousands of independent binary systems under various initial conditions. The program is fed by an input card which is a file containing parameter values that are used to drive the simulations. These parameters can control a specific value for a variable, or they can allow the user to change settings or the overall configuration as to how the simulation is run. For example, Binary_c has different mathematical models available to choose from for different stages of evolution. The program has a predefined list of phases that it uses to classify stars, track their evolution, and decide which models to use. Table 1 shows the full list of evolutionary phases used by Binary_c and their description. Stars on the MS are grouped based on similar characteristics and evolution. Stars that start on the MS and then evolve off the MS follow a specific path known as an evolutionary track. These tracks are typically depicted beginning from the time the star exits the MS, a time known as the zero age main sequence (ZAMS). Figure 5 shows an example of evolutionary tracks for stars of different masses for a fixed metallicity. There is a notable "hook" feature early in the track where sufficiently massive stars transition from fusing hydrogen in their inner core to the shell. The star gets hotter and brighter until the core becomes degenerate or the shell contracts and heats up. For low mass stars, they do not get much hotter or brighter during this phase, so they do not need to shrink much at the end of the phase hence the less prominent hook or absence altogether. Another notable feature is a loop towards the end of the evolutionary track for the lower mass stars. The loop begins after lower mass stars go through the first giant branch (GB) phase. The point where the track begins to turn around to form the beginning of the loop is from the explosive fusion of helium. Lower mass stars lack the temperatures required to immediately begin fusing helium once they've depleted the hydrogen in their core and shell. As previously discussed, after hydrogen has been depleted the core eventually becomes degenerate or shrinks whereby the temperature increases until it is hot enough to fuse helium. Helium ignites around 10^8 K and does so explosively, hence it's called "helium flash". Helium is fused through the triple-alpha process and after helium flash this process is briefly a runaway chemical reaction. The star again becomes hotter and brighter until the reaction stabilizes, and the star resumes its previous evolutionary trajectory.

Hurley et al. (2000) describes the underlying mathematical models used in Binary_c. The authors define three critical masses: M_{HOOK} (the initial mass above which a 'hook' appears on the MS), M_{HeF} (the maximum initial mass for which helium flash is ignited via degeneracy), and M_{FGB} (the maximum initial mass for which helium flash is ignited on the first giant branch). These critical masses are given by the analytical formulae:

$$M_{HOOK} = 1.0185 + 0.16015\zeta + 0.0892\zeta^2$$

$$M_{HeF} = 1.995 + 0.25\zeta + 0.087\zeta^2$$

$$M_{FGB} = \frac{13.048(Z/0.02)^{0.06}}{1 + 0.0012(0.02/Z)^{1.27}}$$

where Z is the metallicity and $\zeta = \log(Z/0.02)$. Metallicity can be calculated as $Z = 1 - X - Y$ where X is the mass fraction of hydrogen and Y is the mass fraction of helium. A low mass star has a mass less than M_{HeF} and ignites helium flash through degeneracy at the top of the GB. An intermediate mass star has a mass between M_{HeF} and M_{FGB} and ignites helium flash at the top of the GB without becoming degenerate. A high mass star has a mass greater than M_{FGB} and ignites helium flash before the GB. Binary_c chooses how to evolve the star based on these definitions. Figure 6 is an excellent depiction of the possible evolutionary path for a particular star based on the current stage and presence/absence of mass transfer.

Table 1: Descriptions of evolutionary phases used by Binary_c (Hurley et al. 2000)

Evolution Phase (number)	Description
0	MS star $M \lesssim 0.7\ M_{\odot}$ deeply or fully convective
1	MS star $M \gtrsim 0.7\ M_{\odot}$
2	Hertzsprung Gap (HG)
3	First Giant Branch (GB)
4	Core Helium Burning (CHeB)
5	Early Asymptotic Giant Branch (EAGB)
6	Thermally Pulsing Asymptotic Giant Branch (TPAGB)
7	Naked Helium Star MS (HeMS)
8	Naked Helium Star Hertzsprung Gap (HeHG)
9	Naked Helium Star Giant Branch (HeGB)
10	Helium White Dwarf (He WD)
11	Carbon/Oxygen White Dwarf (CO WD)
12	Oxygen/Neon White Dwarf (ONe WD)
13	Neutron Star (NS)
14	Black Hole (BH)
15	Massless remnant

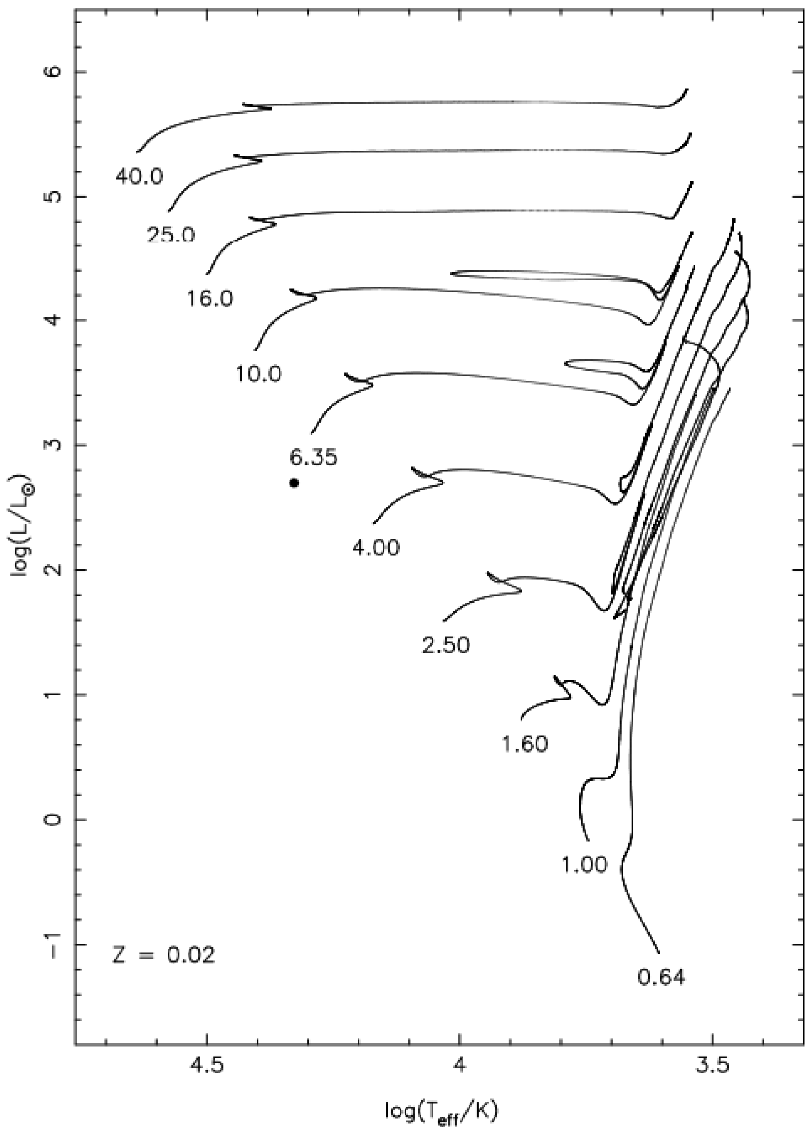

Figure 5: Selected evolution tracks for various mass single stars at fixed metallicity Z = 0.02 (Hurley et al. 2000)

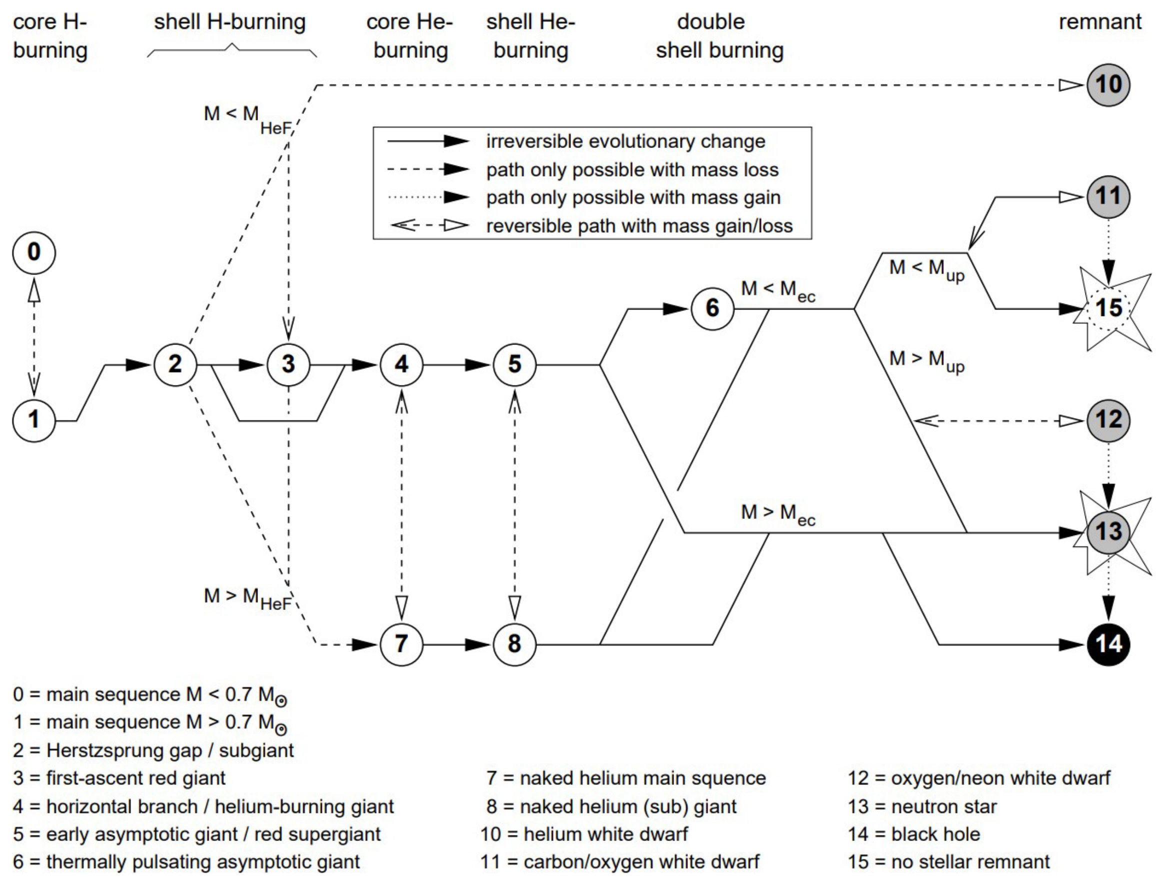

Figure 6: Possible evolutionary paths for a single star (Hurley et al. 2000)

IV. METHODS

The simulations were carried out through a combination of Binary_c and Python scripts. We chose to run on the preset models and only change the values of the initial variables for mass (of each star), separation, eccentricity, and metallicity. The initial masses were determined for each binary system from a power law distribution. A power law describes a relationship between two quantities where a change in one quantity results in a relative change in the other. Here, we used the mass function $f_m(m) \sim m^{-\alpha}$ (de Mink et al. 2014) with a power law of $\alpha = 2.35$ (Salpeter 1955) and a minimum and maximum mass range of 0.2 and 100 solar masses. Not all simulations were run with this mass range, but this is the extent of the mass ranges that were used. The negative power law slope is important because there is a negative correlation between the mass of each counterpart: HMXBs consist of large and small counterparts. Semimajor axis (in solar radii) and eccentricity of the binary system were chosen from a uniform distribution. For these, we used the *random.uniform* function from the numpy package. Assuming that the population is in statistical equilibrium (the probability distribution of possible states in the system is constant over time), the eccentricity distribution is given by $e(X) = \sqrt{X}$ where $X \in [0,1]$ is a uniform random variate (Kroupa 1995). Kroupa (1995) assumes that the initial distribution of semimajor axes $a(X)$ is flat and centered on $a \approx 30$ au from the distribution of semimajor axes in the MS. The distribution is well modeled by a Gaussian distribution in log10(a) and is given by $a(X) = a_{min} 10^{X log_{10}(a_{max}/a_{min})}$. The maximum semimajor axis a_{max} was chosen to be 1690 au and the minimum semimajor axis a_{min} was chosen to be 1.69 AU (Kroupa 1995). We converted the units of the semimajor axis from AU to solar radii using a factor of 215.04. Metallicity was fixed for each simulation run. The default metallicity was 0.02 (approx. solar metallicity), but we also tested metallicities of 0.0001, 0.001, 0.01, and 0.03. Each simulation was run for 100,000 independent binary systems. These values were appropriately entered into the input card which was then fed to the main Binary_c program. Once the simulations began, the program output large amounts of data about the system such as the evolutionary phase and orbital parameters of each stage at certain predefined time intervals. We chose time intervals or "epochs" of 1 Myr and were only interested in systems with only one component whose evolutionary phase was 13 (NS) or 14 (BH).

A python script was used to generate the distributions and select individual values for each binary system. The script used these values to generate the input card and initiate Binary_c. Once the program was running, the script parsed the output data stream to generate a data file that was useful to us. To minimize the size of the date file, we were only interested in saving data from epochs where something relevant to this research occurred such as when the binary contained a neutron star or black hole. Binary_c tracks the stellar type of each component, so it was relatively easy to track the binaries at time intervals of 1 Myr for the first 200 Myr. A csv output file was generated with the number of HMXBs at each epoch. In addition to the total number of HMXBs, the output csv also contained the number of HMXBs for different luminosity cuts. Namely: under 30, 30-32, 32-34, 34-36, 36-38, 38-40, over 30, and over 40 in log(erg/s). The results were then plotted using another python script and the matplotlib package.

V. RESULTS

Our simulations, as depicted in Figures 7 through 14, have yielded several key insights into the evolution of HMXBs and the factors that influence their formation and development:

1. The mass distribution of the binary system plays a pivotal role in the evolution of HMXBs. The lower mass limit of the mass distribution is particularly significant, as it influences the formation and evolution of NS and BH binaries (Figures 7 to 12).
2. The metallicity of the system, which refers to the proportion of its matter made up of chemical elements other than hydrogen and helium, also significantly impacts the evolution of HMXBs. We see large numbers of NS and BH HMXBs at low metallicity (Figures 7-12). However, as the mass distribution increases, the evolution of the system becomes more dependent on the initial mass of each component than the initial metallicity (Figures 10 to 12).
3. The evolution of HMXBs shows a strong peak relatively early in their evolution.

For NS binaries, this peak occurs around 50 million years (Myr), while for BH binaries, it occurs between 0 and 25 Myr (Figures 7 and 8). After the initial peak, there is a gradual decline in the number of NS binaries and a secondary peak in the number of BH binaries (Figures 9 to 12).

4. The number of HMXBs that exist after the initial peak can decline due to various factors, such as the non-compact object evolving into a compact object, the non-compact object being depleted of material, the two objects merging into one, or the two objects

separating from each other (Figures 7 to 12).

5. The two separate peaks observed in the number of BH binaries formed are due to the different processes that can form those BHs. The primary peak is likely due to wind-fed accretion, while the secondary peak is likely due to Roche-Lobe overflow (Figures 9 and 10).

6. There is an apparent preference for a moderate initial mass distribution. Systems with low mass donor stars are unlikely to have enough mass transferred to create a compact object, while systems with a very massive donor star are more likely to collapse entirely or form two compact objects (Figures 11 and 12).

7. The X-ray brightness of NS and BH binaries varies with age. NS binaries are most X-ray bright when they're young (less than 75 Myr), while BH binaries take longer to become X-ray bright, typically after 75 Myr (Figure 13).

8. Figure 13 shows the evolution of BH and NS binaries under different luminosity cuts for a moderate initial mass distribution. NS binaries are most X-ray bright when they're young (less than 75 Myr) while BH binaries take longer to become X-ray bright, typically after 75 Myr. The fourth panel for the luminosity cut 32-34 shows a clear distinction between the two types of systems and most of the binaries modelled had an X-ray luminosity in this range.

9. At higher luminosity, it appears that some NS binaries are able to become X-ray bright at later epochs more similar to the BH binaries. Figure 14 shows a comparison of the different mass distributions for the luminosity cut 32-34. Again, there is a strong distinction between the age when NS and BH systems become X-ray bright. The peak in the number of binary systems becomes sharper as the mass distribution increases. The majority of the NS systems in this luminosity cut are from the mass distribution 8-100

while the majority of the BH systems are from 10-100. This is likely because a mass distribution, such as 10-100, has a greater chance of creating a BH binary so these systems dominate the higher mass distributions.

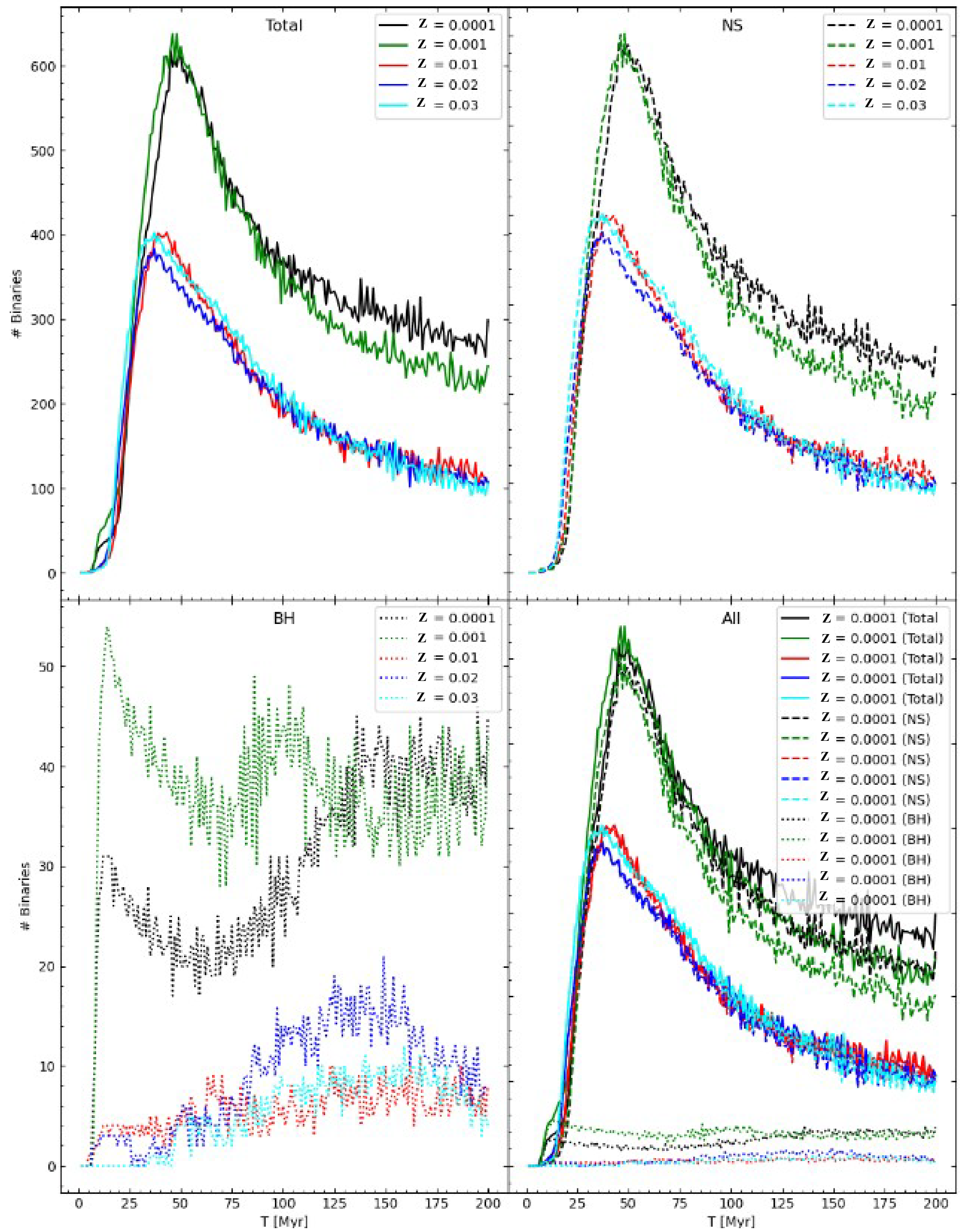

Figure 7: A four panel plot depicting the evolution of the total number of binaries (upper left), the number of NS binaries (upper right), the number of BH binaries (lower left), and the number of each binary (lower right) for different metallicities and a mass distribution of 0.7-100 solar masses over 200 Myr

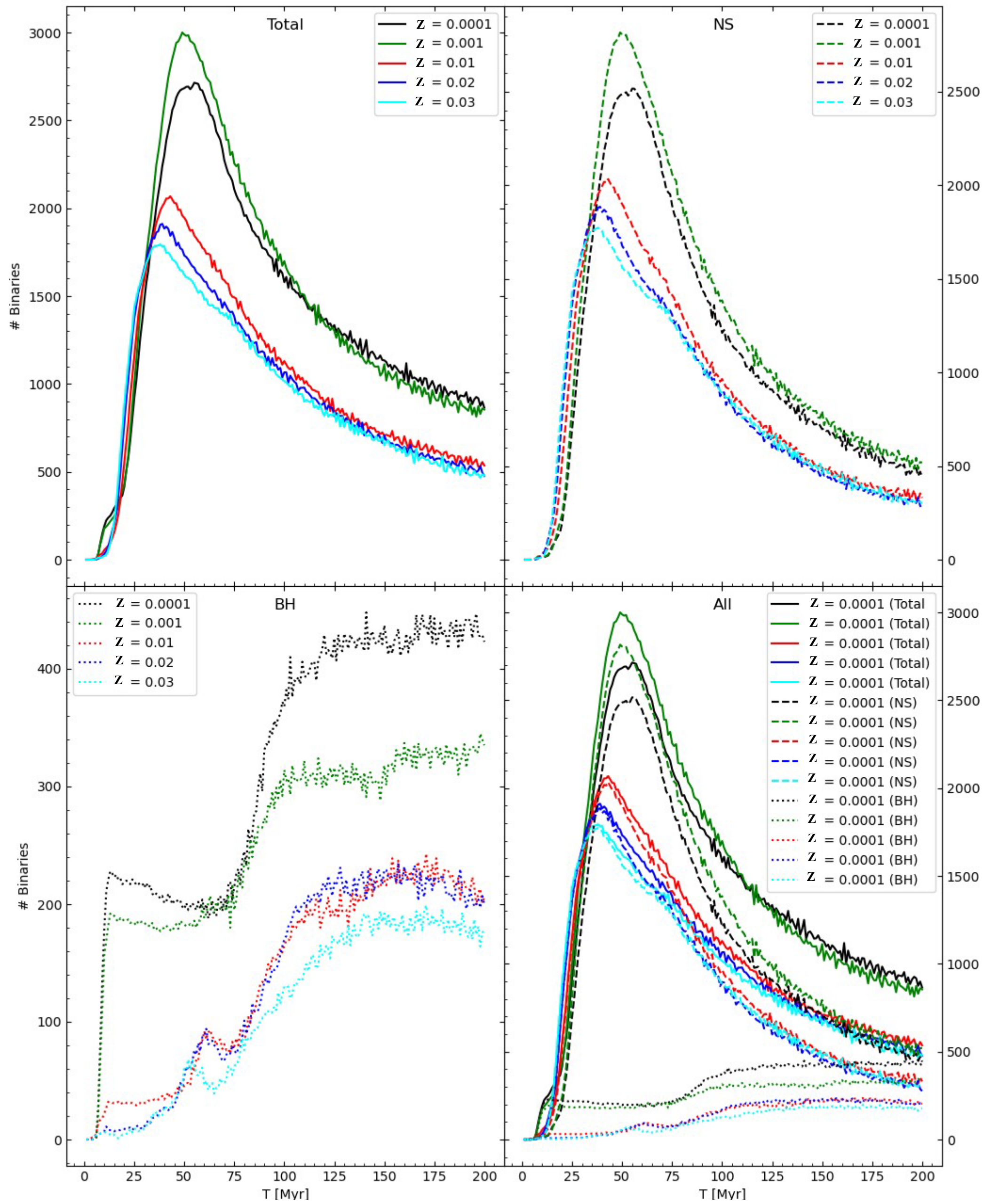

Figure 8: A four panel plot depicting the evolution of the total number of binaries (upper left), the number of NS binaries (upper right), the number of BH binaries (lower left), and the number of each binary (lower right) for different metallicities and a mass distribution of 2-100 solar masses over 200 Myr

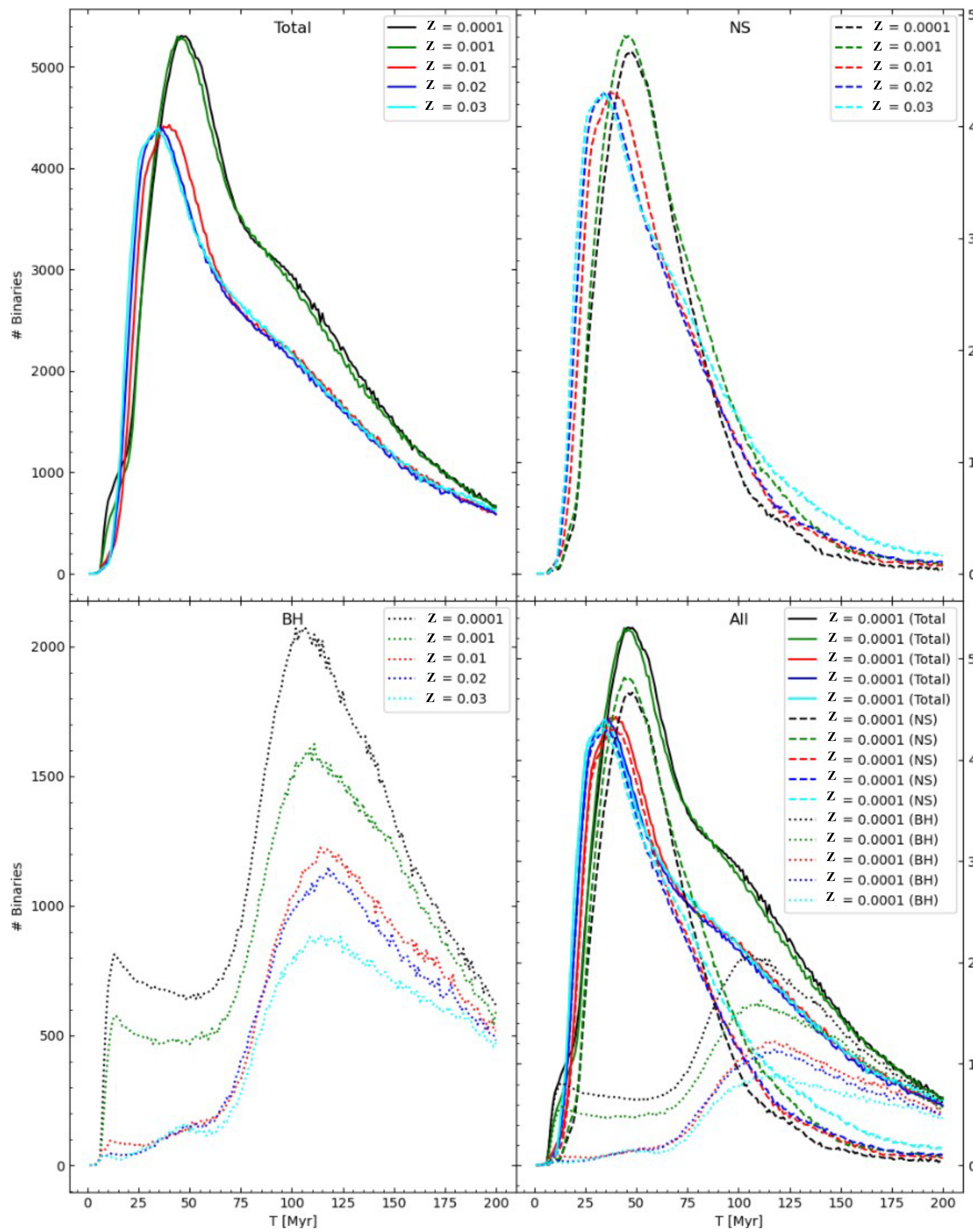

Figure 9: A four panel plot depicting the evolution of the total number of binaries (upper left), the number of NS binaries (upper right), the number of BH binaries (lower left), and the number of each binary (lower right) for different metallicities and a mass distribution of 4-100 solar masses over 200 Myr

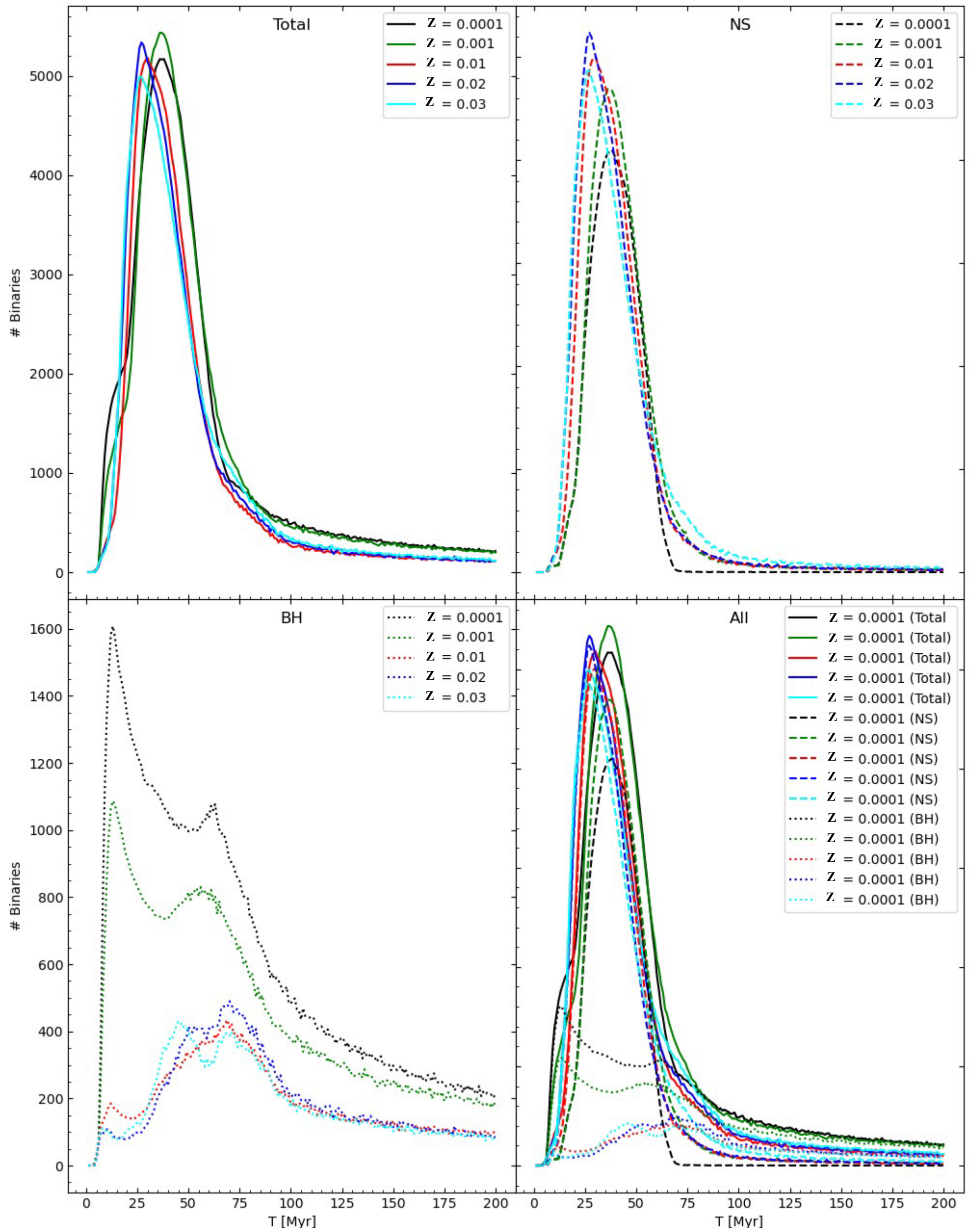

Figure 10: A four panel plot depicting the evolution of the total number of binaries (upper left), the number of NS binaries (upper right), the number of BH binaries (lower left), and the number of each binary (lower right) for different metallicities and a mass distribution of 6-100 solar masses over 200 Myr

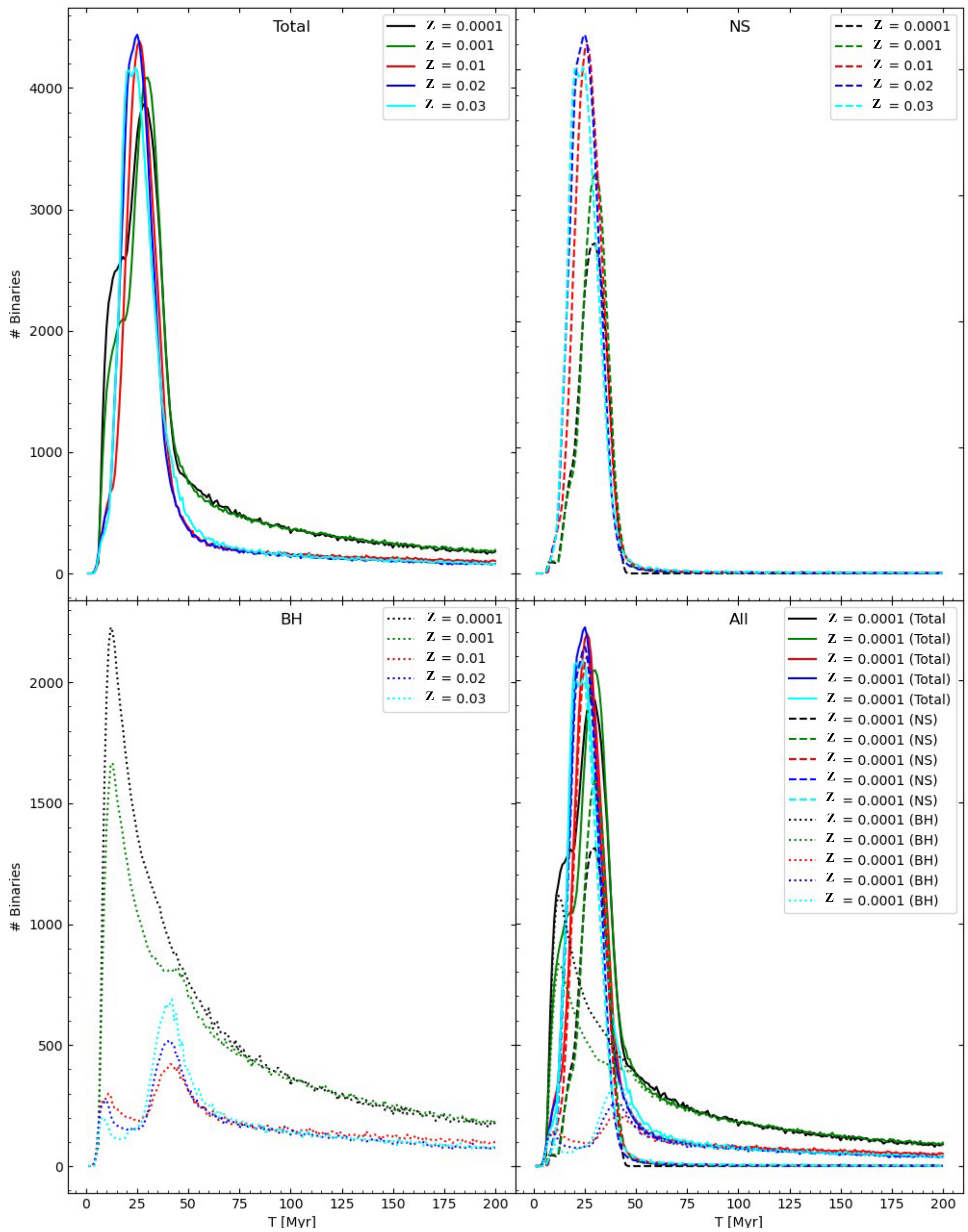

Figure 11: A four panel plot depicting the evolution of the total number of binaries (upper left), the number of NS binaries (upper right), the number of BH binaries (lower left), and the number of each binary (lower right) for different metallicities and a mass distribution of 8-100 solar masses over 200 Myr

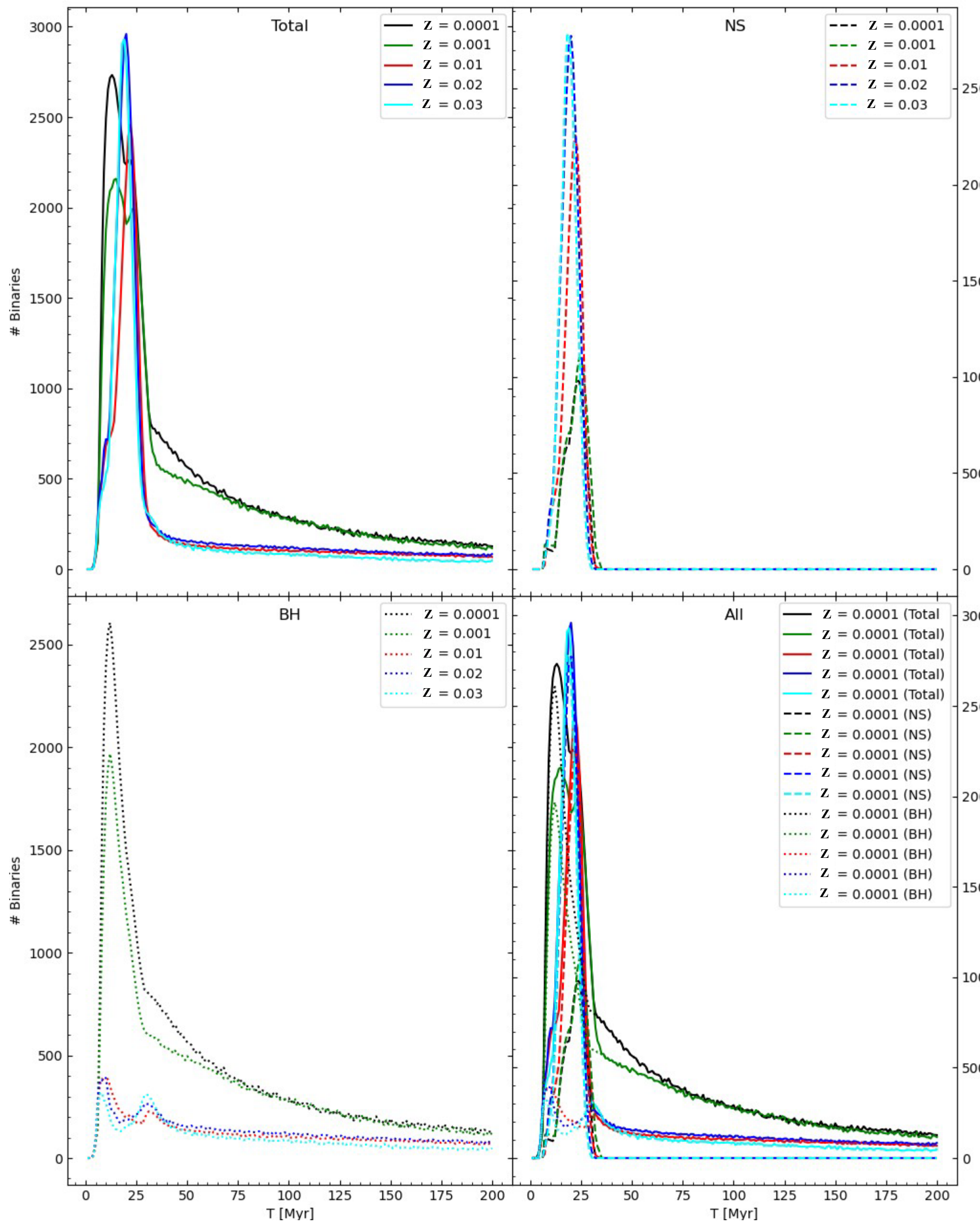

Figure 12: A four panel plot depicting the evolution of the total number of binaries (upper left), the number of NS binaries (upper right), the number of BH binaries (lower left), and the number of each binary (lower right) for different metallicities and a mass distribution of 10-100 solar masses over 200 Myr

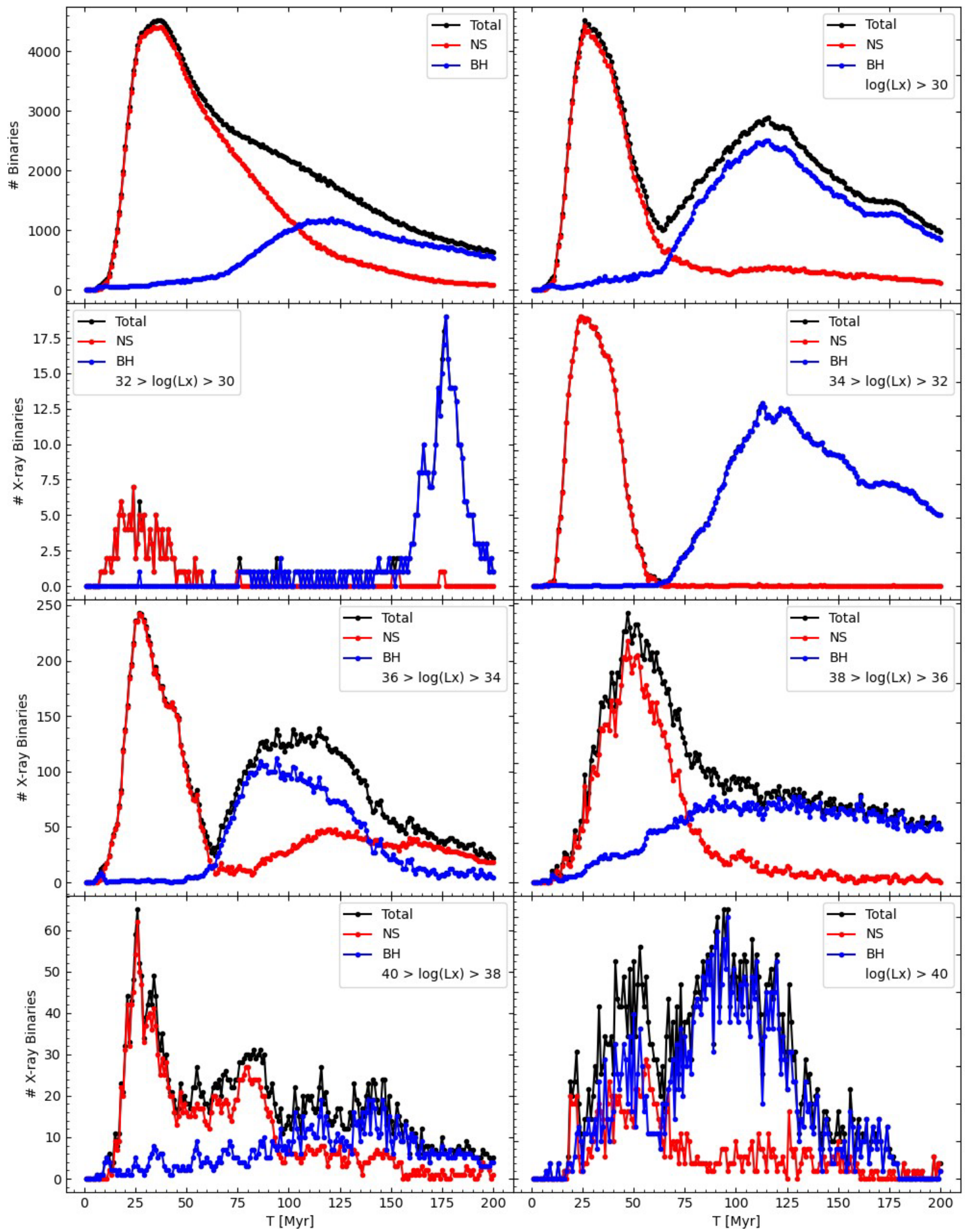

Figure 13: An eight-panel plot depicting the evolution of the binaries at different luminosity cuts from left to right and top to bottom: no cut, over 30, 30-32, 32-34, 34-36, 36-38, 38-40, and over 40 log(erg/s) for Z=0.02 and a mass distribution of 4-100 solar masses over 200 Myr

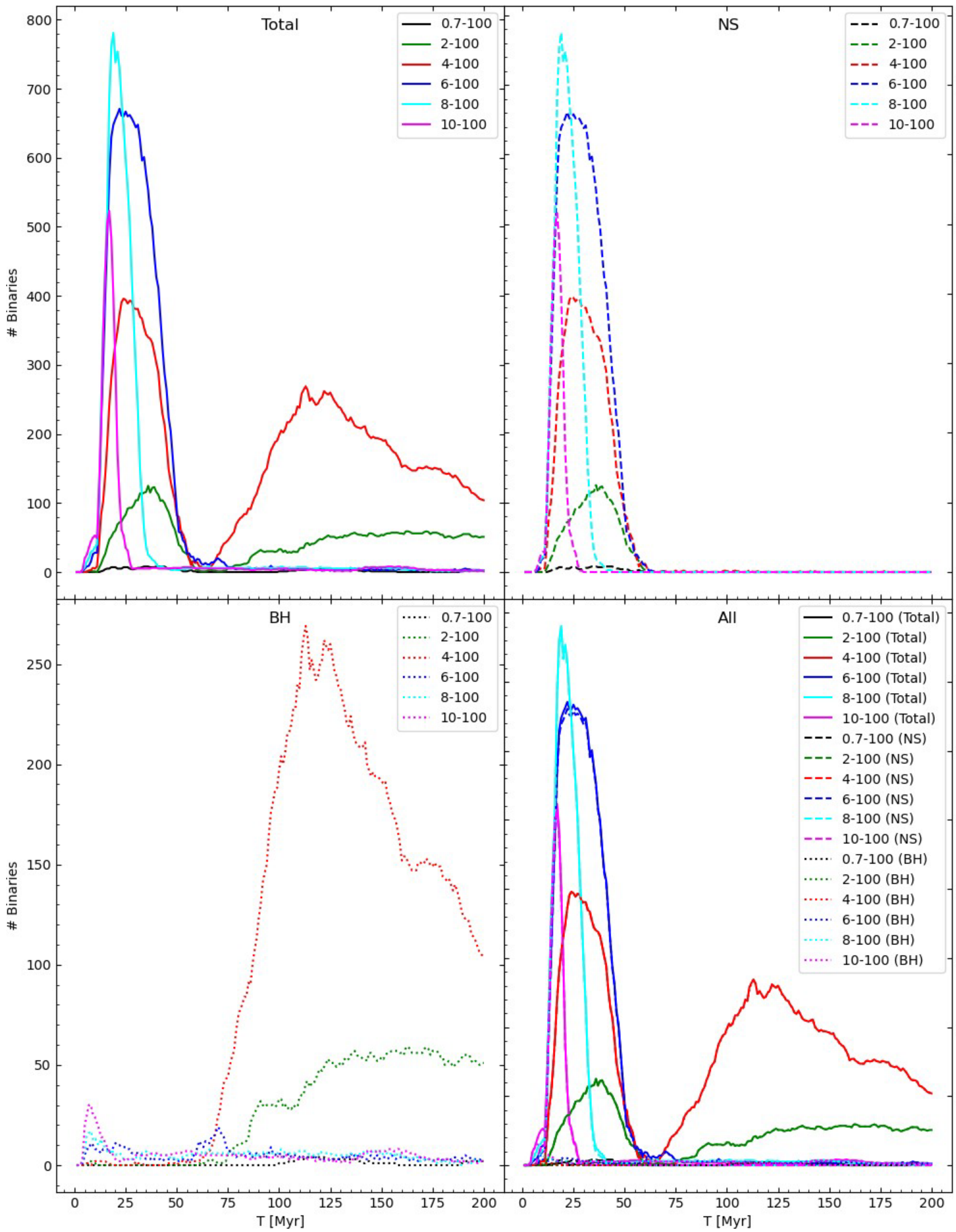

Figure 14: A four-panel plot depicting the evolution of the binaries of each mass distribution for a luminosity cut of 32-34 log(erg/s) and Z=0.02 over 200 Myr

VI. CONCLUSIONS AND FUTURE WORK

Our simulations have underscored the importance of initial parameters in the evolution of HMXBs. Specifically, the mass distribution of the binary system and the metallicity of the system play pivotal roles. We have observed that both NS and BH binaries favor low metal conditions, suggesting that the initial metal content significantly influences the formation and evolution of these binaries. Additionally, the lower mass limit of the mass distribution is particularly significant, as it influences the formation and evolution of NS and BH binaries.

Interestingly, as the mass distribution increases, the evolution of the system becomes more dependent on the initial mass of each component than the initial metallicity. This suggests that the mass of the stars in a binary system is a crucial factor in determining the system's evolution.

Our study has also revealed that the evolution of HMXBs exhibits a strong peak relatively early in their evolution. This peak is followed by a gradual decline in the number of NS binaries and a secondary peak in the number of BH binaries. We theorize that these peaks are due to different processes that can lead to the formation of black holes, namely wind-fed accretion and Roche-Lobe overflow.

Furthermore, our simulations have shown a preference for a moderate initial mass distribution. Systems with low mass donor stars are unlikely to transfer enough mass to create a compact object, while systems with a very massive donor star are more likely to collapse entirely or form two compact objects.

The complex nature of these systems suggests numerous avenues for further exploration and research.

1. **Further Investigation into Accretion Processes**: Our research has highlighted the importance of two key processes in the formation of black holes within binary systems: wind-fed accretion and Roche-Lobe overflow. In simple terms, these processes involve the transfer of material from one star to another, either through stellar winds or when the star expands beyond a certain limit, respectively. Future research could delve deeper into these processes, exploring the specific conditions under which each.
2. **Extending the Timescale of Simulations**: Our simulations covered the first 200 million years of evolution. However, some binary systems may take longer than this to fully evolve, such as LMXBs. Future simulations could extend beyond this time frame to capture the full evolution of these systems.
3. **Comparison with Observational Data**: Finally, it would be beneficial to compare the results of our simulations with actual observational data. This could involve comparing the predicted number and types of HMXBs with those observed in our galaxy and others. Such a comparison could help validate our results and identify any areas where our model may need refinement.

In conclusion, our study has provided valuable insights into the evolution of HMXBs and the role of initial parameters such as mass distribution and metallicity. These findings contribute to our understanding of the complex dynamics of binary star systems and the factors that influence their evolution. Future research in this area may further elucidate the intricate processes that govern the formation and development of these fascinating celestial objects.

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