Stellar-Mass Binary Black Holes formed through Chemically Homogeneous Evolution

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Abstract

The subject of this research is a recently proposed channel of binary black hole evolution: chemically homogeneous evolution. This theory has the potential to explain how binary black holes could possibly merge within the age of the universe and emit detectable gravitational waves. A sufficient amount of rotation achieved through tidal forces can cause internal mixing within each star in a binary system. This mixing keeps the stars from expanding past their Roche Lobes and eventually converts most of the hydrogen in the star to helium, creating a pair of Wolf Rayet stars and eventually a black hole binary. This research adds the channel of chemically homogeneous evolution into population synthesis code COMPAS, creating a single environment for self-consistently testing multiple channels of binary evolution, including isolated evolution via mass transfer and common envelope phases. Furthermore, the merger rate for chemically homogeneously evolving binaries is calculated as a function of redshift, and the results are shown for runs at two different metallicities.

I. Introduction

Scientists have struggled to learn about black holes for a long time because of the lack of observational data. The recent gravitational-wave detections have given humanity the opportunity to explore both how binary black holes and neutron stars can be formed and how they can evolve. Eventually, there will be enough gravitational-wave observations to compare against theoretical results, and one of the best ways to do this could be through population synthesis. The idea of population synthesis in the context of this research is to generate large populations of interesting astrophysical objects based off of theory. By comparing the distributions of simulated outputs to distributions of observations, one can test the accuracies of different astrophysical theories.

One of the most fundamental questions in binary black hole evolution is the following: through what channels of binary evolution are binary black holes capable of merging within the age of the universe? In other words, what channels of binary evolution can produce the black holes capable of being observed with gravitational-wave detectors?

II. COMPAS

Compact Object Mergers: Population Astrophysics and Statistics, or COMPAS, is written in C++ and combines statistical analysis and model selection with rapid population synthesis*. Essentially, COMPAS creates an environment that quickly evolves a large population of isolated binaries with the goal of understanding the many uncertainties involved with binary evolution. Rather than simulating every detail of binary and stellar evolu-

*Link for COMPAS: http://www.sr.bham.ac.uk/compas/science.html tion, COMPAS uses simple fits from the results of more detailed prescriptions and observations. This allows COMPAS to evolve each binary in less than a second, making the evolution of an entire population computationally inexpensive.

COMPAS follows the stellar evolutionary models of Hurley (2000) and uses Monte Carlo sampling methods to draw its initial parameters. The initial mass function (IMF) is a 4-component power-law, taken from Weidner & Kroupa (2003) to be

$$\xi(m) = k \begin{cases} (\frac{m}{m_H})^{-\alpha_0}, & m_{low} \leq m < m_H, \\ (\frac{m}{m_H})^{-\alpha_1}, & m_H \leq m < m_0, \\ (\frac{m_0}{m_H})^{-\alpha_1}(\frac{m}{m_0})^{-\alpha_2}, & m_0 \leq m < m_1, \\ (\frac{m_0}{m_H})^{-\alpha_1}(\frac{m_1}{m_0})^{-\alpha_2}(\frac{m}{m_1})^{-\alpha_3}, & m_1 \leq m < m_{max}, \end{cases} \tag{1}$$

where k is the normalization constant and the exponents are given as

$$\alpha_0 = +0.30, \text{ for } 0.01 \leq m/M_\odot < 0.08, \tag{2}$$

$$\alpha_1 = +1.30, \text{ for } 0.08 \leq m/M_\odot < 0.50, \tag{3}$$

$$\alpha_2 = +2.30, \text{ for } 0.50 \leq m/M_\odot < 1.00, \tag{4}$$

$$\alpha_3 = +2.35, \text{ for } 1.00 \leq m/M_\odot. \tag{5}$$

The number of stars in the mass interval m to $m + dm$ is given as

$$dN = \xi(m)dm, \tag{6}$$

and thus total number of stars with mass greater than m_1 is

$$N = \int_{m_1}^{m_{max}} \xi(m)dm. \tag{7}$$

Kroupa & Weidner (2003) takes this a step further by calculating the stellar mass of an imbedded cluster to be

$$M_{ecl} = \int_{m_{min}}^{m_{max}} m\xi(m)dm, \tag{8}$$

where m_{min} and m_{max} are the respective lower and upper mass limits of the cluster. For each binary, the mass ratio $q = \frac{M_2}{M_1}$ is drawn randomly from a flat distribution in the range of $[0.01, 1.00]$. In this research, COMPAS restricts the initial lower mass limit of the generated binaries in order to be computationally efficient. Ideally, one would want to run COMPAS with an initial mass range of $[0.01, 150.0]M_\odot$. Thus if M_{gen} is the total mass of all generated binaries in COMPAS and dM_{SFR} is the total mass that would have been generated without the lower mass restrictions, we see that

$$\frac{dM_{SFR}}{M_{gen}} = \frac{\int_{0.01M_\odot}^{150M_\odot}(1+q)m\xi(m)dm}{\int_{m_{res}}^{150M_\odot}(1+q)m\xi(m)dm}, \tag{9}$$

where m_{res} is the restricted lower mass limit of the generated population and q is randomly picked for each step dm from $[0.01, 1.00]$.

III. Chemically Homogeneous Evolution

i. Channels of Binary Black Hole Evolution

COMPAS has thus far only explored isolated binary evolution via mass transfer and common envelope phases. In this theory, stars who begin in a binary with a wide orbit expand past their Roche Lobes as they evolve through the main sequence. The gravitational attraction between the two stars cause episodes of mass transfer, producing a thick envelope of gas that surrounds the pair (Mandel & Farmer (2017)). As the stars move through this envelope a sort of friction is created, causing the orbit to shrink enough such that when double compact objects are formed they are able to merge within the age of the universe. However, the parameters constraining the common envelope phases, as well as the parameters involved with natal supernovae kicks, are very uncertain. One of the long term goals of COMPAS is to analyze how different assumptions of these parameters and their effects on the simulated outputs compare statistically to information obtained from populations of both electromagnetic and gravitational wave signals.

Recently, a new theory of binary black hole evolution has been proposed. The concept of chemically homogeneous evolution within single stars was first described by Maeder (1987). The theory predicts that if a zero-age main sequence star is rotating fast enough it can experience a large amount of internal mixing. This mixing would allow material from the hydrogen-rich envelope to be transported to the central burning regions, and vice-versa. Because of this mixing, the chemical gradients that normally build up during evolution through the main sequence can be avoided. Rather than expanding, stars would slowly contract and become more and more helium rich. The evolutionary models of these hotter, more luminous, more compact stars have been shown to be more likely to occur at lower metallicities by Yoon & Langer (2005) and Yoon, Langer, & Norman (2006).

This theory has recently become attractive for those who study binary black hole formation and evolution. If stars in binaries can achieve high enough angular frequencies from tidal forces, chemically homogenous evolution could be a channel of binary black hole evolution with little to no mass transfer, and thus no common envelope phases.

ii. Threshold for Chemically Homogeneous Evolution

A study by Yoon, Langer & Norman (2006) used detailed models to produce a grid of the stars who did and did not evolve chemically homogeneously. This grid was used in Mandel & de Mink (2016) to determine a threshold rotation for when a star will evolve chemically homogeneously. In Yoon, Langer, & Norman (2006), the threshold is expressed as a function of the ratio of the equatorial velocity to the Keplerian velocity, $\omega_c = v/v_k$. Mandel & de Mink use the $Z = 0.004$ grid to approximate the minimum ω_c for single stars to achieve rotationally-induced quasi-homogeneous evolution with the following fit:

$$\omega_c = \begin{cases} 0.2 + 2.7 \times (\frac{m}{M_\odot} - 50)^2 & \text{for } m < 50 M_\odot, \\ 0.2 & \text{for } m \geq 50 M_\odot. \end{cases} \tag{10}$$

Recently, a new grid has been created by Kaila Nathaniel, a previous summer student at the University of Birmingham. This new grid was created by using stellar evolution code MESA. Modules for Experiments in Stellar Astrophysics, or MESA, is a software primarily developed by Bill Paxton of University of California, Santa Barbara, with rotational chemically homogeneous evolution models written mainly by Pablo Marchant of Argelander-Institut fur Astronomie, Universitat Bonn. Using MESA, Kaila was able to identify the minimum angular frequency that a star would need to evolve chemically homogeneously as a function of mass and metallicity. By taking a numerical fit to these grids, the threshold used in this research is represented in the following equations:

$$\Omega(M, Z = 0.001) = \begin{cases} \frac{a(\frac{M}{M_\odot})^3 + b(\frac{M}{M_\odot})^2 + c(\frac{M}{M_\odot}) + d}{(\frac{M}{M_\odot})^{0.4}} & , \frac{M}{M_\odot} < 70, \\ \frac{a(70^3) + b(70^2) + c(70) + d}{(M/M_\odot)^{0.4}} & , \frac{M}{M_\odot} \geq 70 \end{cases} \tag{11}$$

and

$$\Omega(M, Z) = \frac{1}{0.1 \ln(\frac{Z}{0.001}) + 1} \Omega(M, Z = 0.001), \tag{12}$$

where $a = -4.2975 \times 10^{-10}$, $b = 1.8478 \times 10^{-7}$, $c = -1.8551 \times 10^{-5}$, and $d = 7.8773 \times 10^{-4}$. The above fits lay the foundation for most of the research presented in this report.

IV. Implementation into COMPAS

i. Flagging Initially Chemically Homogeneous stars

In order for a binary to evolve chemically homogeneously, both stars must rotate faster than the threshold given in the previous section. One of the ways this can be achieved is through tidal locking. In COMPAS, no assumptions are made about the stars' rotation. Thus, for the purposes of this research, stars are identified as chemically homogenous if the synchronous rotation achieved through tidal locking is greater than the threshold found in MESA. In addition, if a star is initially overflowing its Roche Lobe, it is not flagged as one that will evolve chemically homogeneously. COMPAS uses a fit from Eggleton (1983) to determine if a star overflows its Roche Lobe, given by the equation

$$r_{RL} = a \frac{0.49 q^{2/3}}{0.6 q^{2/3} + \ln(1 + q^{1/3})}, \tag{13}$$

where $q = \frac{M_1}{M_2}$ (unlike in COMPAS) and a is the separation. Using Kepler's Law one can determine the upper limit for a star's synchronous rotation to cause it to evolve chemically homogeneously without overflowing it's Roche Lobe. In Figure 1, the upper limits of angular frequency for the minimum and maximum mass ratios are plotted from the following equation:

$$\omega = 2\pi \sqrt{\frac{M}{r^3} \Big(\frac{0.49 q^{2/3}}{0.6 q^{2/3} + \ln(1 + q^{1/3})} \Big)^3}, \tag{14}$$

where M is the total initial mass of the binary and r is the radius of the primary mass, found by taking a numerical fit of the COMPAS radii as a function of mass. It is shown in this figure that for stars with a metallicity of 0.004, it is impossible to be initially chemically homogeneous if their mass is below roughly $40 M_\odot$. Any stars with initial masses lower than this would need to have orbits so close that they would have already expanded past their Roche Lobes and initiated mass transfer before achieving a synchronized rotation fast enough to evolve chemically homogeneously. The window for a star to evolve chemically homogeneously is the area in between the black and reds lines, with the exception of mass ratios that are very close to 0.01.

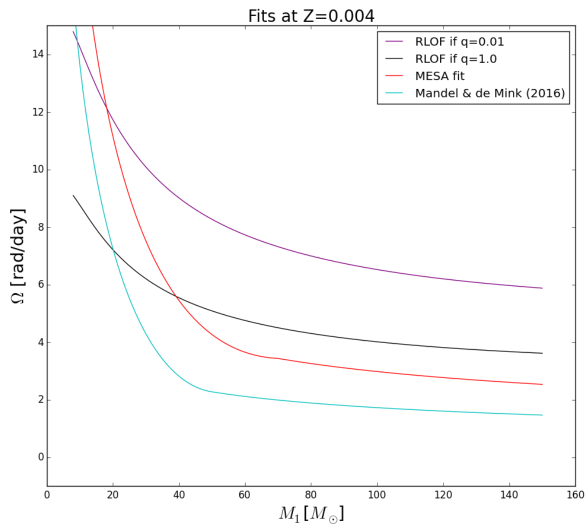

Figure 1: *Plot comparing the threshold angular frequencies found in MESA for $Z = 0.004$ and the fit used in Mandel & de Mink (2016) as functions of mass. M_1 is the mass of the primary star in the binary, which by the construction of COMPAS is more massive than its companion. The purple and pink lines represent the angular frequencies of tidally locked stars who's radii are equal to their respective Roche Lobe radii. Thus is if a star has an Ω value above the Roche Lobe line corresponding to its mass ratio, it is initially overflowing its Roche Lobe and is therefore not going to evolve chemically homogeneously. If the Ω value is below the threshold line for chemically homogeneous evolution, then it is also not going to evolve chemically homogeneously, thus creating a small window of angular frequencies.*

If both of the stars in a binary are flagged as initially chemically homogeneous, they each follow the stellar evolution channel of a "Type 16" star, created in this research to fit with the convention in Hurley (2000). With the crucial exception that the radii of these stars remains constant, Type 16 stars in COMPAS follow the same evolutionary steps as main sequence stars. Throughout their evolution, the Type 16 stars are monitored to determine whether mass loss due to stellar winds may cause enough widening in the binary to decrease the angular frequency beneath the threshold for chemically homogeneous evolution. At the end of the main sequence, COMPAS turns these Type 16 stars directly into Wolf-Rayet stars and evolves them as such.

ii. Initial Results

Since the lower mass limit for initially chemically homogeneous stars is known from Figure 1, it is more computationally efficient to restrict the initial mass range for all primary stars in COMPAS between 39-150 solar masses. The initial separation ranges from 0.01-1000 AU, the mass ratio $q = \frac{M_2}{M_1}$ ranges from 0.01-1, and the beginning runs set the initial set metallicity for all stars to be $Z = 0.004$.

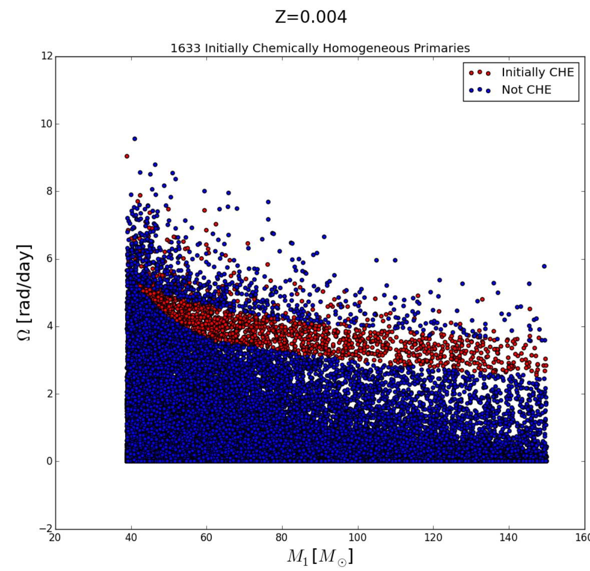

Figure 2: *This plot shows the amount of initially chemically homogeneous primary stars out of the ten thousand generated. Most of the binaries have orbits that are too wide, and some of the primary masses are in binaries that are to close and cause initial Roche Lobe overflow. The area of the space with red dots illustrates the window for being initially chemically homogeneously evolving, similar to the he fits in Figure 1.*

Out of the 10^5 binaries generated, there are 283 pairs whose primary and companion stars both satisfy the conditions for chemically homogeneous evolution. Figure 2 shows the amount of primary masses that qualify as initially chemically homogeneous, while Figure 1 illustrates how much smaller the window for being initially chemically homogeneous is when using the MESA fit compared to that of Mandel & deMink et al (2016). One can see the relatively short period required for a star to be initially chemically homogeneous from Figure 3, as well as the amount of pairs that are not initially chemically homogeneous because of the stars in the binary does not make the cut.

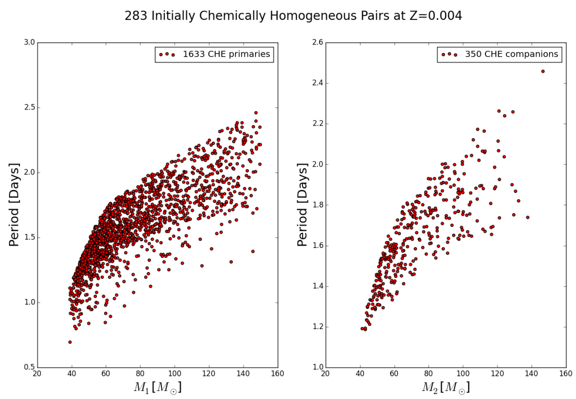

Figure 3: *Plot of periods vs the masses for initially chemically homogeneous stars. For a binary to be considered chemically homogeneously evolving, both stars must be flagged here as CHE.*

These results assume initially synchronized orbits due to tidal locking. If the condition of being tidally locked is dependent upon the the ratio between a star's radius and its Roche Lobe (the fill factor), one can see in Figure 4 how the number of initially chemically homogeneously stars is affected by different restrictions on tidally locking. There is only a significant decrease in the amount of initially chemically homogeneous binaries if one assumes that the radii of each star must be greater than 80 percent of its Roche Lobe to be tidally locked and to have synchronized orbits.

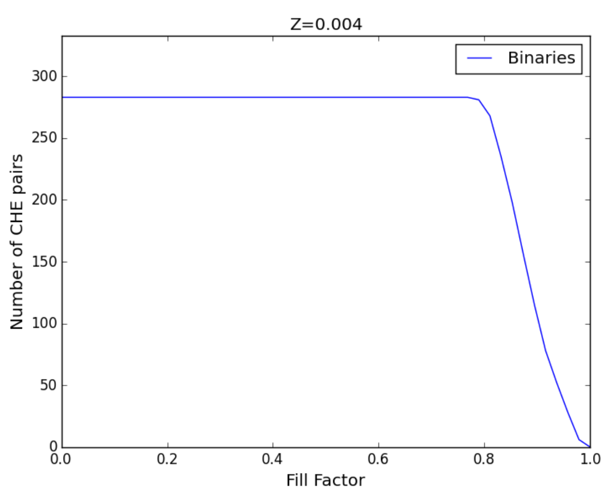

Figure 4: *The fill factor is defined here as the ratio between the stellar radii and their respective Roche Lobe radii. Here is a plot showing how many initially chemically homogeneous pairs are eliminated when the condition for being tidally locked with the synchronized orbits depends on the fill factor.*

V. Results

i. Binary Black Hole Mergers

None of the 283 initial binaries at $Z = 0.004$ have orbits that widen to the point where they can no longer be considered chemically homogeneously evolving. Thus, all of the initially chemically homogeneous binaries evolve into binary black holes and merge within the age of the universe, as shown in Figure 5. Here it can be seen that the most massive stellar-mass binary black holes have progenitors that evolved chemically homogeneously.

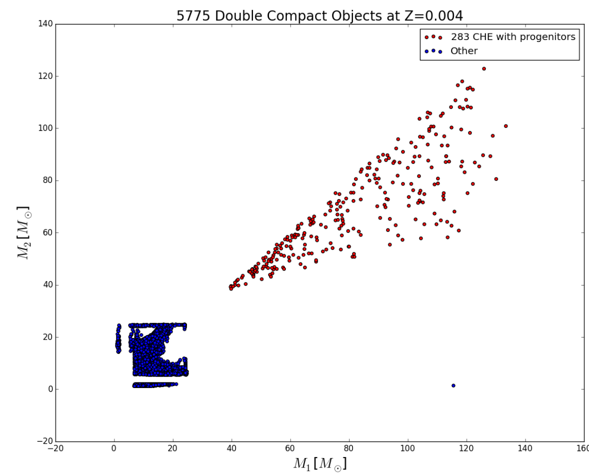

Figure 5: *All 283 pairs from the initially chemically homogeneous group evolved into binary black holes. This plot displays the final double compact objects that merged within the age of the Universe. The companion final masses are plotted on the y-axis while the primary final masses are plotted on the x-axis.*

The amount of time it takes from the formation of double compact objects to merger is given by Peters (1964) as

$$\tau_{GW} = \frac{5}{256}\frac{c^5}{G^3}\frac{a^4}{m_1 m_2 (m_1 + m_2)}, \tag{15}$$

where the m_1 and m_2 are the component masses and a is their separation. Because the binaries need to be initially very tight in order to be evolve chemically homogeneously, along with the facts that the component stars have high masses and the stellar evolutionary timeframe is relatively short, one would expect very short time delays between the zero age main sequence stage and the double compact object merger. This is confirmed in Figure 6.

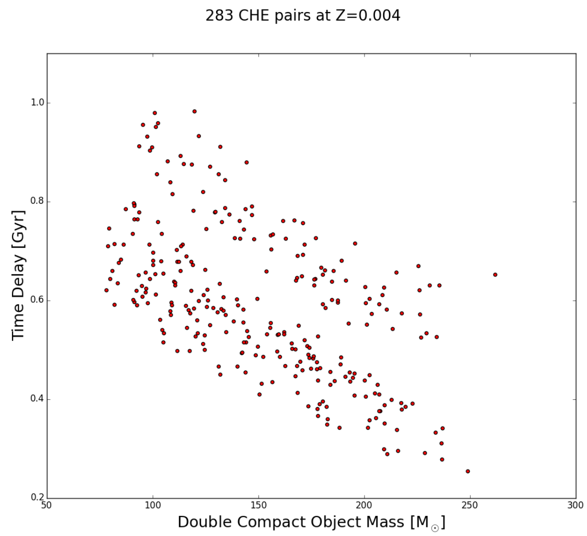

Figure 6: *Here the time delays between the formation of the chemically homogeneous binaries at zero-age main sequence and the time at which they merge as black holes are taken from COMPAS and displayed. The time delays here are much shorter than those found in Mandel & de Mink (2016).*

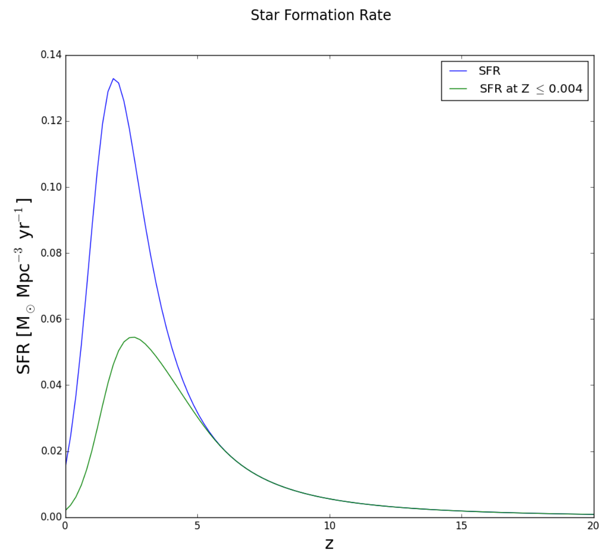

Figure 7: *This plot serves as a sanity check for modeling the star formation rate as a function of redshift, as given by Madau & Dickinson (2014). Similarly, the star formation rate for stars under metallicity $Z = 0.004$ is plotted using the fit from Langer & Norman (2006)*

ii. Cosmic Merger Rate

In order to analyze whether enough detectable binary black hole mergers have chemically homogeneous origins, it is necessary to calculate the cosmic merger rate. To do this, one needs to first know how star formation rate changes with redshift. This research, like Mandel & deMink (2016), uses the following equation from Madau & Dickinson (2014) to model star formation rate per unit source time per unit comoving volume as a function of redshift z:

$$\frac{d^2 M_{SFR}}{dt dV_c}(z) = 0.015 \frac{(1+z)^{2.7}}{1+(\frac{1+z}{2.9})^{5.6}} \frac{M_\odot}{Mpc^3 yr}. \quad (16)$$

Additionally, a fit from Langer & Norman (2006) is used to determine the fraction of star formation that occurs at a metallicity $\leq Z$ and redshift z:

$$CDF(Z, z) = \hat{\Gamma}\left(\alpha + 2, (Z/Z_\odot)^\beta 10^{0.15\beta z}\right). \quad (17)$$

Here $\hat{\Gamma}$ is the incomplete gamma function, $\alpha = -1.16$, $\beta = 2$, and $Z_\odot = 0.0134$. As a sanity check, both the star formation rate and the the star formation rate of stars with $Z \leq 0.004$ are plotted in Figure 7.

Similarly to Mandel & deMink (2016), this research divides the universe into bins of redshift. The look-back time to an object, defined in Hogg (1999) to be the difference between the present age of the Universe (at observation) and the age of the Universe at the time the signal was emitted (according to the object), is given as a function of redshift by the equation

$$t_L(z) = t_H \int_0^z \frac{dz'}{(1+z')E(z')}, \quad (18)$$

where

$$E(z) = \sqrt{\Omega_M (1+z)^3 + \Omega_k (1+z)^2 + \Omega_\Lambda} \quad (19)$$

and

$$t_H = 9.78 \times 10^9 h^{-1} yr. \quad (20)$$

A standard flat cosmology is used with $\Omega_\Lambda = 0.718$, $\Omega_M = 1 - \Omega_\Lambda$, and $h = 0.697$ (Hinshaw (2013)).

Each one of the 283 binary black holes with chemically homogeneous progenitors is denoted with an index k. The birth rate for a specific binary k, again from Mandel & de Mink (2016), is given by

$$\frac{dN_k^{birth}}{dt dV_c}(z) = CDF(Z, z) \frac{d^2 M_{SFR}}{dt dV_c}(z) \frac{1}{dM_{SFR}}, \quad (21)$$

where

$$dM_{SFR} = M_{gen} \frac{\int_{0.01 M_\odot}^{150 M_\odot} m(1+q)\xi(m) dm}{\int_{39 M_\odot}^{150 M_\odot} m(1+q)\xi(m) dm} \quad (22)$$

is the total mass that would be generated for this COMPAS run based off of the Kroupa IMF discussed in Section II. M_{gen} is the total mass of all binaries generated in the COMPAS run, and q is the ratio between the primary and companion masses.

For a binary k that merges at a given redshift z_j,

$$t_L(z_j) = t_0 - t_j, \tag{23}$$

and

$$t_i + \tau_k = t_j, \tag{24}$$

where t_0 is the present age of the universe, t_j is the age of the universe at the time of the merger, t_i is the age of the universe when the binary was born, and τ_k is the time delay specific to the binary k. In this research, for a given z_j, equation (18) was used to find $t_L(z_j)$ and equation (23) was used to find t_j. For a specific binary k with time delay τ_k, t_i was found with equation (24). Then, using a computer, the z_i at which the difference between t_i and $t_L(z_i)$ is closest to zero was found. This z_i is the redshift at which the binary k was born. This was done for a range of z_j's. The merger rate for all binaries with chemically homogeneous progenitors as a function of redshift is given by

$$\frac{dN^{merge}}{dtdV_c}(z_j) = \sum_k \frac{dN_k^{birth}}{dtdV_c}(z_i)\frac{dt_i}{dt_j}, \tag{25}$$

where dt_i and dt_j are the widths of the time bins, both of which decrease as redshift increases. The greater τ_k is, the greater the difference is between dt_i and dt_j.

The cosmic merger rate for binary black holes formed through chemically homogeneous evolution is plotted in Figure 8.

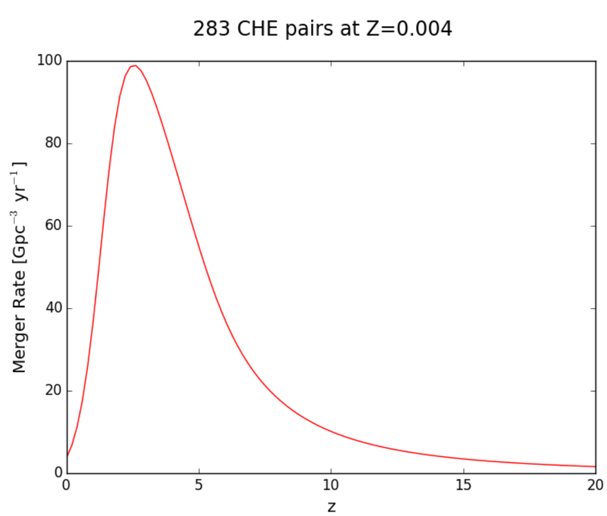

Figure 8: *Here the merger rate for binaries that evolved chemically homogeneously at $Z = 0.004$ is plotted against redshift.*

iii. Quick Analysis

The cosmic merger rates found in this work have a significantly larger peak than that of Mandel & de Mink (2016). Another major difference is that the time delays in this research are all under $1Gyr$, while those from Mandel & de Mink (2016) range from roughly $3 - 11Gyr$. Long time delays imply that for every merger redshift bin z_j, the corresponding birth redshift z_i is greater than if the time delays were short. As one can see in Figure 7, a higher redshift generally means smaller star formation rate, and a smaller star formation rate at z_i leads to a smaller merger rate at z_j. Long time delays also imply that $\frac{dt_i}{dt_j}$ is always less than 1 and seems to decrease in a linear fashion as redshift increases. This research found $\frac{dt_i}{dt_j}$ to be always nearly equal to 1 and the birth redshift to be very close to the merger redshift for $z < 20$. This is likely to cause the shape and peak of the merger rate plot in Figure 8 to coincide with those of the star formation rate plot in Figure 7.

iv. Z=0.001

Another COMPAS run was made with the metallicity for all stars set to $Z = 0.001$. Out of the 10^5 binaries generated, 464 initially qualified to evolve chemically homogeneously. Figure 9 shows that the window for stars with a metallicity of $Z = 0.001$ to be initially chemically homogeneously evolving is larger than that of $Z = 0.004$.

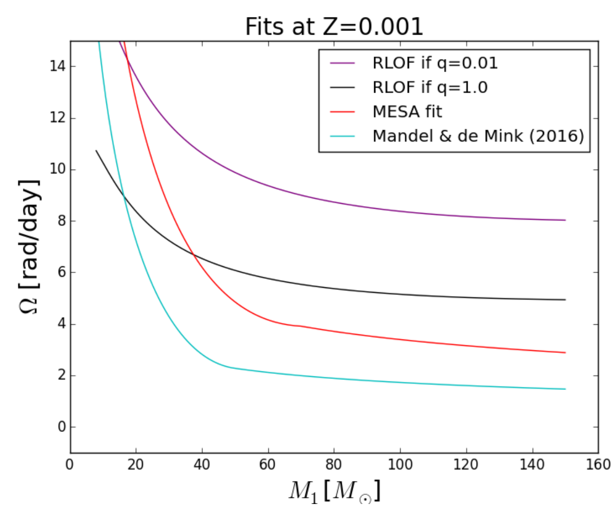

Figure 9: *Plot comparing the threshold angular frequencies found in MESA for $Z = 0.001$ and the fit used in Mandel & de Mink (2016) as functions of mass. Note that the window for stars to be initially chemically homogeneous is larger than that of $Z = 0.004$, hence the reason there are almost 200 more pairs.*

One might want to think that more initially chemically homogeneous pairs results in higher peaks when plotting the final merger rate, but this is not necessarily the case.

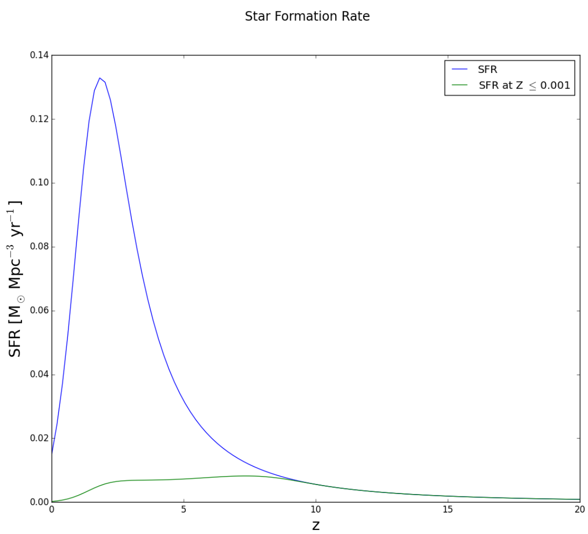

Figure 10: *Star formation rate for stars with $Z \leq 0.001$.*

The merger rate for binary black holes with chemically homogeneous progenitors of metallicity $Z = 0.001$ is plotted in Figure 11. Note that the peak of this curve is about a fourth of the peak of the plot in Figure 8. While it may be more likely for stars to evolve chemically homogeneously at lower metallicity, the star formation rate at $Z \leq 0.001$ in Figure 10 is also lower, causing the final compact object merger rate to be lower as well.

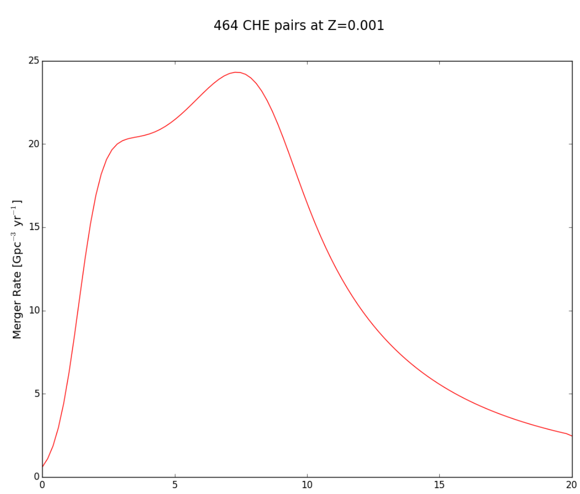

Figure 11: *Plot of the merger rate for binary black holes with chemically homogeneous progenitors run in COMPAS.*

VI. Future Work

There are more MESA grids being currently created at the University of Birmingham, so an obvious next step would be to update the threshold function once again. Another possible next step would be to run COMPAS at a wider range of metallicities.

There are some results from this research that might be suspicious and should be investigated or analyzed in greater depth. Firstly, the widening due to stellar winds should be documented in more detail to assure that no binaries cease to evolve chemically homogeneously. Something that should possibly be investigated is the shrinking of the orbits between the birth of the binaries to their formation of double compact objects, as shown in Figure 12 for the COMPAS run at $Z = 0.004$.

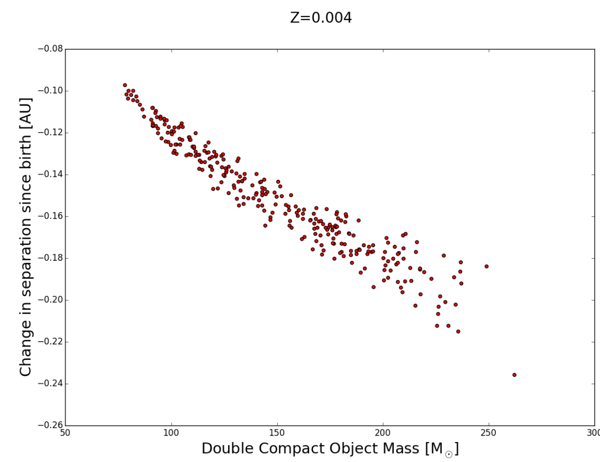

Figure 12: *Here, the x-axis shows the total final mass of the double compact object, which in this case is a pair of stellar-mass black holes. The y-axis shows the change in separation between the two stars of each binary from zero-age main sequence to their formation as binary black holes.*

Further investigation should reveal where and when this shrinking occurs. If there is any radial expansion of the stars following their becoming of Wolf Rayet stars, it could be possible that a common envelope is bringing them closer together. It should then be decided how to treat Wolf Rayet stars with chemically homogenous progenitors in regard to their radial expansions.

A similar investigation should take place with regard to Figure 13, which shows the mass lost between the time of the binary birth to the formation of double compact objects for the run at $Z = 0.004$. Understanding when the mass is lost in these binaries will help determine how the separation should behave.

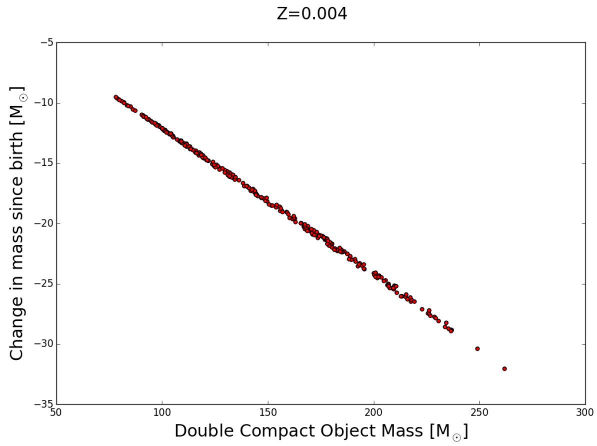

Figure 13: *Here, the x-axis shows the total final mass of the double compact object, which in this case is a pair of stellar-mass black holes. The y-axis shows the change in mass between the two stars of each binary from zero-age main sequence to their formation as binary black holes.*

VII. Thanks

I would like to thank the University of Florida for organizing this IREU program and the National Science Foundation for funding it. I would also like to thank the University of Birmingham for being such a wonderful host.

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