Binary black hole merger models: Common envelope theory vs chemically homogenous theory

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Black holes and the evolution of stars

Black holes are regions of space so packed with matter to the extent that their gravity prevents anything from escaping. They are formed through two main channels: the death of stars and the direct collapse of gasses. As massive stars age, their unstable centers eventually collapse and compress into themselves. At the end of this process, the stars explode and create a black hole. Black holes that are formed through the collapsing of gasses are more massive. This pathway is believed to have operated more commonly in the early universe (Tillman and Dobrijevic). Inside black holes, the immense intense gravitational pressure creates an escape velocity greater than the speed of light, preventing light and matter from escaping. There are two main parts of a black hole: the event horizon and the singularity. The event horizon of a black hole is the boundary at which light cannot escape and is dependent on the amount of matter the black hole accretes. Black holes can accrete gas, cosmic dust, other stars, and more, and exist at the center of all galaxies. The singularity of a black hole is "the point in space-time where the mass of the black hole is concentrated" (Tillman and Dobrijevic). Black holes can be classified by their spin, charge, and mass. The four main categories of black holes are: Kerr (spinning and uncharged), Schwarzchild (non-spinning and uncharged), Kerr-Newman (spinning and charged), and Reissner-Nordstrom (non-spinning and charged). (Baird) The most common Kerr black hole is known to have two event horizons and a ring-shaped singularity at the center of the black hole (Németi).

The radiation and winds from a black hole impacts nearby planets and their general environments. Black hole winds can drive atmospheric escape, lead to ozone depletion, and heat up the atmosphere of nearby planets (Lingam and Perlman). The radiation emitted from black holes can erode atmospheres and supply dangerous amounts of UV radiation (Randall). Black holes can also affect the formation of galaxies, as an association was found between mass of the black hole at the center of a galaxy and the size of the galaxy, and they can release energy to surrounding gas (Lewton).

GW150914

LIGO (Laser Interferometer Gravitational-Wave Observatory) is an observatory founded in 1984 to directly detect the gravitational waves that were described by Einstein's General Theory of Relativity. LIGO relies on laser interferometry to measure the ripples in spacetime caused by cosmic events like the merging of black holes.

In 2015, LIGO detected the first ever observed gravitational waves with their ultrasensitive detectors (Abbott et al.). This gravitational wave event, GW150914, originated from the most prominent binary black hole merger to be observed, around 1.3 billion lightyears away. GW150914 was observed to have a signal increase in both frequency and amplitude from

35 to 150 Hz in about 8 cycles and a little over 0.2 seconds. The most likely explanation for this observation is that GW150914 originates from the inspiral of two orbiting masses—a binary black hole merger. Utilizing generic transient search and binary coalescence search, it was determined GW150914 was a statistically significant and verifiable event, with a false alarm probability of < 2×10^{-7}, or 5.1σ.

GW150914 originates from a binary star system of two very massive stars that eventually collapsed and formed a pair of stellar mass black holes. The two initial stars had metallicities less than half of the Sun's and the spin of the GW150914 was very low (LIGO). The merging of these two black holes released energy equivalent to 8 solar masses and created an even larger black hole of around 142 solar masses (Chu). The pathway of how this merger event and following observed black hole mergers is heavily debated and studied. The mass, metallicity, and spin of this GW150914 merger event provided researchers with essential information when coming up with merger models.

This GW150914 observation established that binary black holes can naturally form and merge in a Hubble time, the estimated age of the universe, and opened the field up to questions about how such an event could have happened. It is significant that these events can happen within a Hubble time because most black holes formed in that time. Showing that a binary black hole system can form in a Hubble time shows that it is possible for it to exist and be observed. GW150914 challenged our understanding of the life and death of stars, how mass, composition, and rotation rates affect the evolution of stars, and provides insight on the beginning of the universe. In the years following the first observation of black hole mergers, LIGO targeted a sample of binary black hole mergers and inferred their intrinsic properties like their meriger rates, their masses, and their inspiral spins. This data is used to further support and explain the different proposed merger models.

Common Envelope Evolution model and Chemically Homogenous Evolution model

The chemically homogenous evolution model was proposed because researchers had argued that the black holes produced through the common envelope model did not have a large enough mass and very little metal, which was what was observed with GW150914. Because of this, researchers looked into different models to see which could better fit the features of the observed binary black holes (Wolchover et al.). The chemically homogeneous process includes rapidly rotating binary stars spinning at specific speeds and conditions that allow the stars to evolve chemically homogeneously as an explanation for the binary black hole merging. Internal mixing from fast stellar rotation influences the

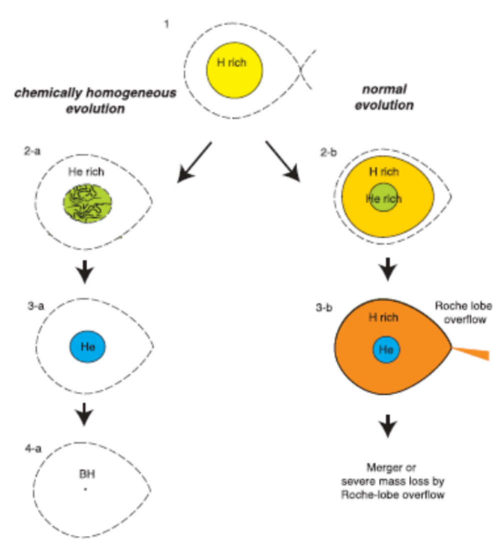

Figure 1

evolution of binary black holes by transporting material from the hydrogen-rich envelope to the central burning regions of the star and vice versa. If this rotation is efficient enough to prevent a build-up of a chemical gradient which separates the core of the star from the envelope, the stars can evolve homogeneously. As this process continues, hydrogen is exhausted in both the center and throughout the envelope of each star, resulting in the two stars contracting towards their helium centers, staying within their Roche lobes, the region around a star in a binary system within which any material is gravitationally bound to that particular star ("Roche Lobe"). The two close stars then evolve into two separate black holes, neither overfilling their Roche lobes nor initiating mass transfer like with common envelope evolution. These two black holes spin together and eventually merge 4-11 Gyr after they are formed. This model finds that more massive stars with lower metallicity are more prone to evolving chemically homogeneously. At higher metallicity, angular momentum loss slows down the stars and shuts off rotational mixing. More massive stars are more prone to chemical homogenous evolution as they have a weakened entropy barrier due to radiation pressure (Mandel and de Mink).

Common envelope evolution model proposes a process that emphasizes unstable mass transfer as an explanation for the binary black hole merging. With this model, the two stars initially spin with a very wide orbit. As one star evolves, its hydrogen envelope enlarges and forms a red supergiant. The envelope of this red supergiant then interacts with and enters the gravitational field of the smaller star, sucking the smaller star away. This process draws the two stars together until the smaller star overgrows the red supergiant and the supergiant collapses into a black hole. Now, when the second star forms a red supergiant, it engulfs the black hole in a common envelope. The second star then collapses into a black hole as its hydrogen envelope is lost to space. The two black holes are then close enough to eventually merge. It is assumed that a binary enters a common envelope phase if both binary components fill their Roche lobes, if the mass transfer rate exceeds 0.1M y^{-1}, or if the photon trapping radius of a compact object accretion extends beyond the Roche lobe radius (Mandel and de Mink).

This paper aims to answer the question: What evidence is there to support the 2 different types of merger models? Researching the different types of models is important because it can give us potential answers to many different things relating to the beginning of the universe. It also provides us with more information and context for other events that occur in space.

Evidence for the two models

Chemically homogeneous model

Chemically homogeneous evolution is difficult to investigate because massive, rapidly rotating stars with low metallicity are very rarely observed. This in itself is a major flaw of this model. Majority of the merger events include stars that do not spin very rapidly, so there is little hard evidence for chemically homogenous evolution. However, there are some observational clues and simulations that can be interpreted as evidence for this model.

In 2016, Mandel and de Mink performed Monte Carlo simulations of expected merger rates for a model that underwent chemically homogenous evolution. The process went as follows: estimating the rate of local mergers to serve as a sanity check for the Monte Carlo simulation results, creating a model of massive binary populations over cosmic time that accounts for various factors, performing the Monte Carlo simulation, and analyzing the results. While simulating massive binary populations, a few assumptions were made:

1) The primary mass m_1 follows a Kroupa initial mass function
2) The distributions are separable and measured with fair approximation for the distribution of binary properties at higher redshift and low metallicity.
3) The minimum equatorial velocity is as follows:
    a) $$\omega_c = \begin{cases} 0.2 + 2.7 \times 10^{-4} \left(\frac{m}{\mathrm{M}_\odot} - 50 \right)^2 & \text{for } m < 50\,\mathrm{M}_\odot, \\ 0.2 & \text{for } m \geq 50\,\mathrm{M}_\odot. \end{cases}$$
4) Mass loss driven by stellar winds and envelope ejection during the final explosion is accounted for by adopting "f_{MS} = 0.1 for the fraction of mass that is lost during the main-sequence evolution, and f_{WR} = 0.25 for the fraction of mass lost during post-main-sequence evolution as a Wolf–Rayet star"
5) Changes in orbit due to wind-driven/supernova mass loss are accounted for by assuming the mass loss is both fast and spherical compared to the orbital motion and the angular momentum of mass lost is equal to the orbital angular momentum of the star.
6) The binary remains circular throughout its evolution.

A graph presented by Mandel and de Mink of the star formation rate (SFR) versus redshift shows the SFR for different metallicities (fig 2). The solar metallicity predicted for the chemically homogenous model is Z = 0.0134 (Asplund et al. 2009) with a mean metallicity of ~ $1.06 \times 10^{-0.15}$ Z with a standard deviation of ~0.38Z, with significant uncertainty. This metallicity corresponds to the red dotted line in the graph and shows that the star formation rate of the chemically homogenous model increases the further back in time we look and that there is a very small formation rate in recent years. This is significant because it shows that as we progress, we are more likely to observe gravitational wave events that are the result of chemically homogenous mergers, as it takes a sizable amount of time before we can observe events in the past.

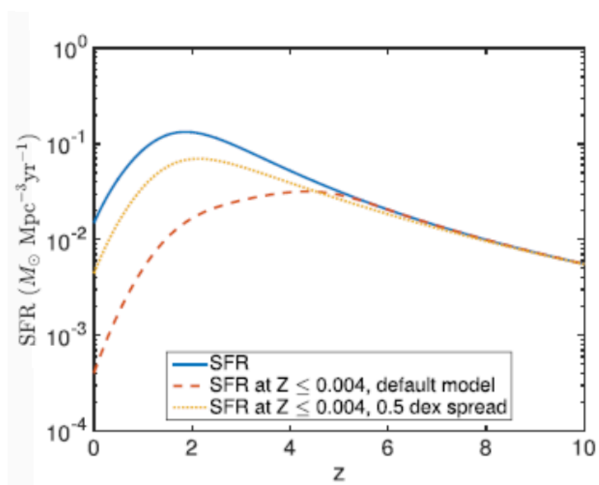

Figure 2

The results of the Monte Carlo simulation find that out of 10^8 simulated binaries, 500 binaries satisfy the conditions for chemically homogenous mixing. The merger rate is found to increase the further we go back in cosmic time, before dropping again as we approach present day, with a peak merger rate of 20 Gpc^{-3} yr^{-1} at z<0.5 as shown in figure 3. Within figure 3, the solid black line represents the total binary black hole merger rate, while the colored, smaller lines represent the 500 sample binary systems.This simulation shows that within sufficiently massive tight binaries, mixing processes can indeed give rise to stars evolving chemically homogeneously.

The results of this simulation serve as evidence for the significance of the chemically homogenous model. Systems of close massive binary black stars can give rise to significant merger rates with peaks of 20 Gpc^{-3} yr^{-1}. This merger rate is also consistent with the lack of LIGO detections that placed upper limits (70-170 Gpc^{-3} yr^{-1}) above the predicted merger rate of 10 Gpc^{-3} yr^{-1}. By avoiding the common-envelope phase, the chemically homogenous model is able to avoid the uncertainties that are associated with that formation channel and does not produce short time-delay mergers.

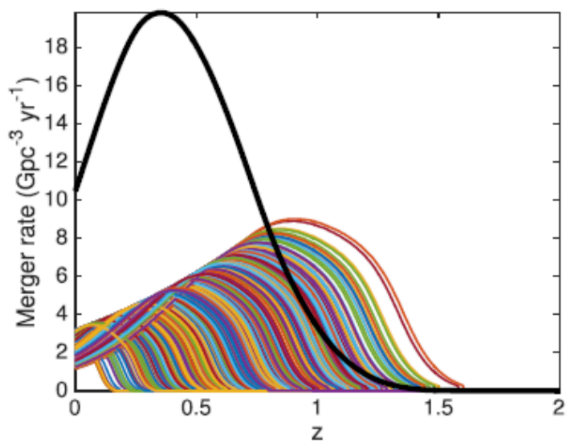

Figure 3

Common Envelope Model

Olejak & Belczynski showed that fast-spinning black holes in merging binary systems can be formed by tidal spin up and a common envelope phase, forming two equal mass black hole components. In low metallicity environments, a large number of massive stars are predicted to survive common envelope evolution (Zevin et al.).

F. Lyu et al analyzed data from GW190814 and showed that GW190814 and similar events have all the initial conditions for common envelope evolution. They identify that GW190814 was more likely formed through common envelope evolution than chemically homogenous evolution.

The graph of the result of the simulations (Figure 4) shows that with a short enough orbital period (<0.5d), events that go through common envelope evolution can end up with spins that match with the observed black hole spin (x>0.3). As shown in Figure 4, as the orbital period decreases, the black hole spin starts to increase. This provides evidence for common envelope evolution by being able to match up observational data about the spin of the black hole with simulated spins of resultant common envelope merger black holes.

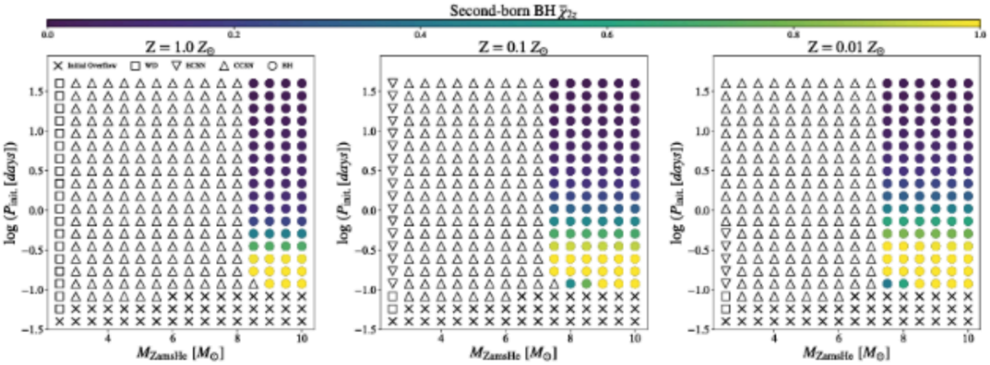

Figure 4

In 2021, Zevin et al. modeled five different channels: late-phase common envelope, stable mass transfer, chemically homogenous evolution, metal-poor globular clusters (GCs), and formation in neutral star clusters (NSC). Looking at a network of LIGO Hanford, Livingston, and Virgo operating at signal to noise threshold of p=10, they found the detection probabilities of the different models. Unlike many other investigations, they accounted for spin, which is said to have greatly affected their results. Looking at their results, they determined that the common envelope channel dominates the underlying binary black hole population in their models. When considering only the common envelope and metal poor GC models, they found that around 90% of the underlying population comes from the common envelope channel. They also found that there was a preference for highly inefficient common envelopes (a = 0.2) by a Bayes factor of >10, with a marginal preference for larger values (a = 5.0) by a Bayes factor of 5 (Figure 5).

Table 1

Bayes Factors $\log_{10}(\mathcal{B})$ across χ_b Models (Columns) and α_{CE} Models (Rows)

		χ_b				
		0.0	0.1	0.2	0.5	
α_{CE}	0.2	−0.63	−0.56	−1.24	−1.71	−0.35
	0.5	−0.06	−0.58	−0.96	−1.11	0.00
	1.0	≡0	−0.77	−1.02	−1.29	≡0
	2.0	0.34	0.05	−1.19	−1.15	0.42
	5.0	0.56	0.39	−0.54	−0.87	0.70
		≡0	−0.27	−1.11	−1.35	

Figure 5

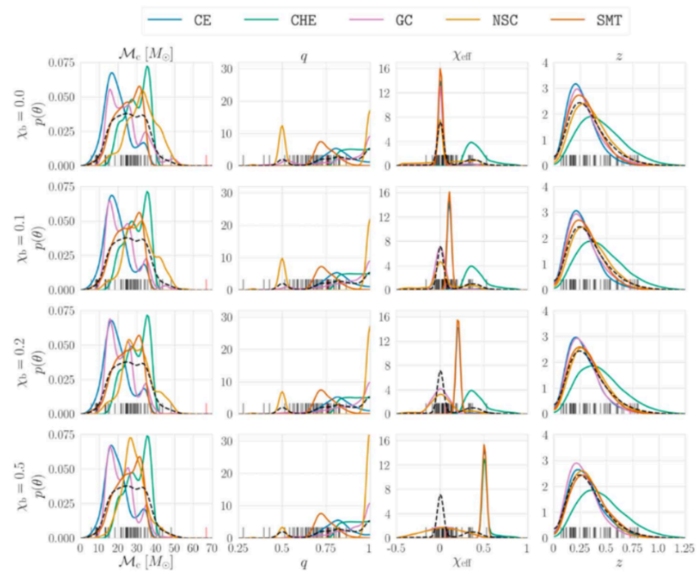

Figure 6

The results of considering all five formation channels with varying natal spin prescriptions is shown in Figure 6. When testing for chirp mass, at lower natal spins, common envelope evolution and chemically homogenous evolution are competitive, with the largest probability peaks. As natal spin increases however, chemically homogenous evolution and NSC dominate common envelope evolution. When testing for redshift, common envelope evolution proves to be dominant for all lower natal spins, only being overtaken by GC at X=0.5.

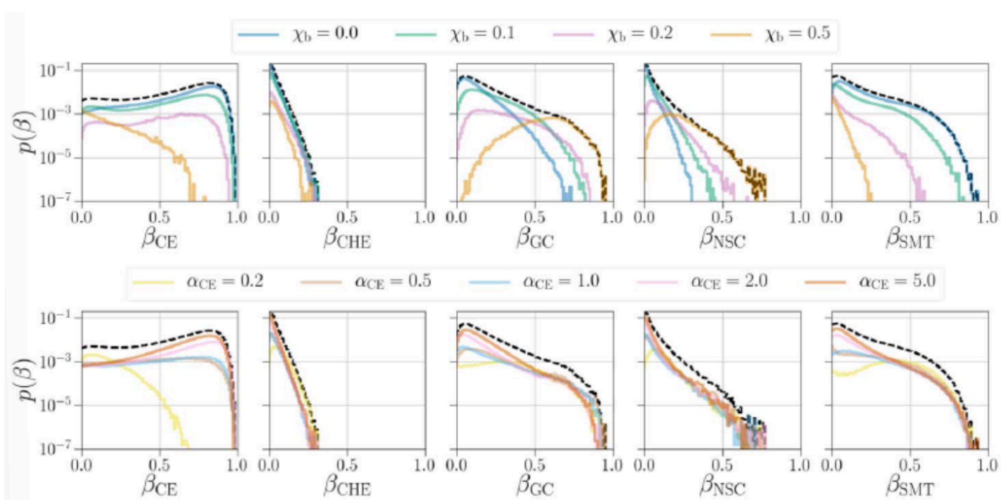

Figure 7

When looking at the inferred branching fractions for all five channels shown in Figure 7, common envelope evolution dominates the field channels which make up the majority of the underlying population.

Differences between the two models

The chemically homogeneous model, unlike the common envelope, requires rapid spin and rotation for instabilities in the chemical makeup of stars to prevent the build up of a chemical gradient. It also requires low metallicity and larger initial star mass. The common envelope model, on the other hand, requires overfilling of the roche lobe, and initiation of unstable mass transfer with rates above 0.1M y^{-1}. When approaching the question of the more dominant model, we need to consider the features of the typical binary black hole and how they align with the characteristics required from either model.

Other potential channels

The Marchant et al. investigation showed that the stable mass transfer channel could produce more mergers within a Hubble time than common envelope evolution could.This opens up the field to more possibilities than just the two channels of common envelope and chemically homogenous evolution. Zevin et al. provided us with channels like NSC and GC that were competitive with both common envelope and chemically homogenous evolution. When looking at inferred branching fractions for all five channels, the peaks of the NSC and SMT channel are even larger than the peaks of common envelope evolution, showing that they are competitive and worth further examining.

Additionally, Zevin et al.'s simulations were unique in that they considered different numbers of channels. They considered all five, just three channels, and just two channels, and saw that the results were different. This shows the importance of considering other possibilities and that going forward, for more accurate conclusions, it is necessary to take into consideration other formation channels.

Flaws

The chemically homogeneous model requires rotational rates of 20-30% of the Keplerian velocity. Because this can only be achieved when two nearly equal mass stars are close to filling their Roche lobes, there is a very small parameter space window for chemically homogenous evolution. "The spin periods of wide-period systems are too low for chemically homogenous evolution while short-period systems would have already overflowed their Roche lobes at zero age" (Mandel and de Mink). The window for chemically homogenous evolution, shown in figure 8 is significantly smaller than the window for normal evolution, and the chances of a system adhering to the dotted line, the binaries that satisfy a more stringent threshold on chemically homogeneous evolution, are even smaller. The likelihood of having the right mass (>40 M) and orbital period (1.5-2.5d) is very low and

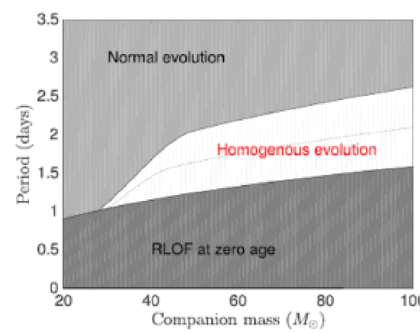

Figure 8

therefore puts the chemically homogenous model at a disadvantage when considering the more dominant model (Mandel and de Mink).

There are significant uncertainties with the chemically homogenous channel, including the efficiency of the mixing processes in tidally locked binaries which could potentially close off this channel entirely. Additionally, there have been observational electromagnetic constraints. In principle, it may be possible to observe chemically homogenous evolution, but the phase is short lived and observations can only be done in environments where low metallicity is rare. This constrains the possible galaxies that we can examine to look for traces of observational evidence of chemically homogenous evolution. Predictions regarding the merger rates of chemically homogenous evolution are not sensitive to Roche lobe overflow, because of how poorly understood it is, and common envelope phases, while being very sensitive to uncertain internal mixing processes (Mandel and de Mink).

Common envelope evolution has large uncertainties surrounding its efficiency, the mass boundary at which it terminates, and the conditions required for it to initiate. Marchant et al. investigated the role of common envelope evolution in the formation of merging binary black holes by computing binary simulations using MESA code of a 30 M donor star in low metallicity environments with a black hole companion. They computed mass transfer rates, modeled mass transfer and the common envelope phase, and applied their model to 2 other models where there is an increased overshooting and increased mass loss rates. The results of their simulation of the overshooting model show that there were no cases of successful envelope ejection from the common envelope phase below initial orbital periods $\log_{10}(\pi/d) < 3.2$. Below this range, the systems undergoing stable mass transfer and merging through common envelope evolution varies. They find that common envelope evolution only happens for black hole masses that are less than 5 M, but that stripping the hydrogen envelope of a 30M star already results in a 14M helium core. Additionally, the models with efficiency a = 1 that do manage to eject their envelopes during common envelope evolution result in wide black hole binaries which cannot merge within a Hubble time.

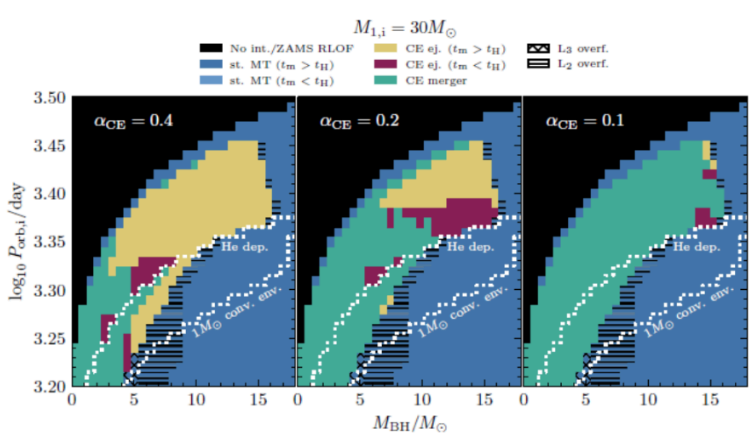

Figure 9

The outcome of the simulations with CE efficiencies of 0.4, 0.2, and 0.1 are represented in figure 9. This graph shows that most systems that produce wide binary black holes would merge during common envelope evolution, with the chances of merging increasing as efficiency decreases. With all three cases of different efficiencies, envelope ejection cannot be found below an initial orbital period $\log_{10}(\pi/d) < 3.2$. The majority of common envelope ejections observed resulted in mergers that took greater than a Hubble time merge. Even with the extreme cases that a system that undergoes common envelope evolution can produce a black hole that merges in less than a Hubble time, the ratio between the systems formed through common envelope evolution to the systems formed via stable mass transfer is 0.35. When examining the model with an efficiency of a=1, we see that the ratio is even smaller, at 0.017.

The results of this investigation show that cases of successful envelope ejection in common envelope evolution is very rare, and the cases that were successfully simulated were unable to merge within a Hubble time. The results also show that the channel of stable mass transfer seems far more dominant.

Moving forward

As the detected population of binary black holes increases, the diversity of potential formation channels also increases. Moving forward, people plan to include additional formation channels and make more comprehensive analysis including the new data provided. There are significant uncertainties with the two common envelope and chemically homogenous evolution models that can only be clarified with research and understanding of other factors like the Roche lobe. More observational evidence and information like the spin of black holes in the binaries, their metallicities, and masses is also necessary to make arguments for either model. Because most mergers happened very long ago, in the future, we will observe more gravitational wave events of binary black hole mergers, and the data from LIGO detectors can be used to support different models. There are uncertainties regarding the efficiency of common envelope evolution and mixing processes in chemically homogenous evolution that people plan to investigate to clear up the picture on what the true dominant channel, or channels, of formation is.

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