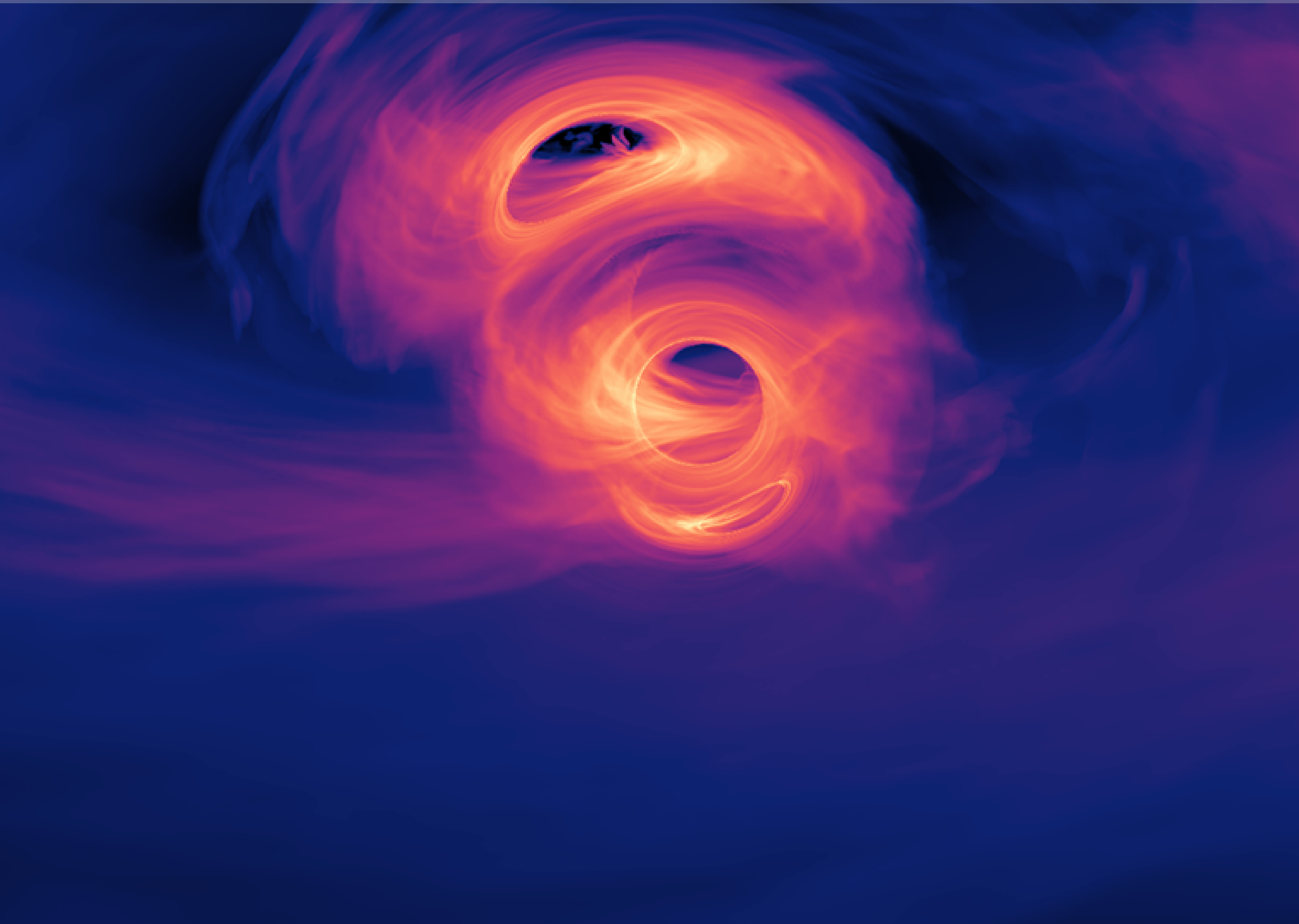
Binary Black holes from Scratch

Using COMPAS

Arash Dev Ahlawat



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Krittika Summer Project
5.0

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1. Stellar Evolution

Stellar evolution takes place over a vast expanse of time compared to the time the human civilisation has been in existence. So how did we come to know how it takes place?Well there exists stars that show changes on timescales that we can observe. Such stars that show change periodically are known as `Variable stars`.

These stars serve as 'Experimental Laboratories' for Stellar Physics. Studying the physical properties such as Mass,Temperature and Radius are best studied using Variable Stars. To study the complex systems that govern the stellar systems, we must fist know study about stellar evolution:

1.1 The Hertzsprung-Russell Diagram

In the 1910s, 2 astronomers named Ejnar Hertzsprung and Henry Norris Russell observed that when you plot the brightness of individual stars versus their spectral type(colour), the stars lie within a well-defined area of the diagram.This diagram shows stars in various ages of their life cycle.

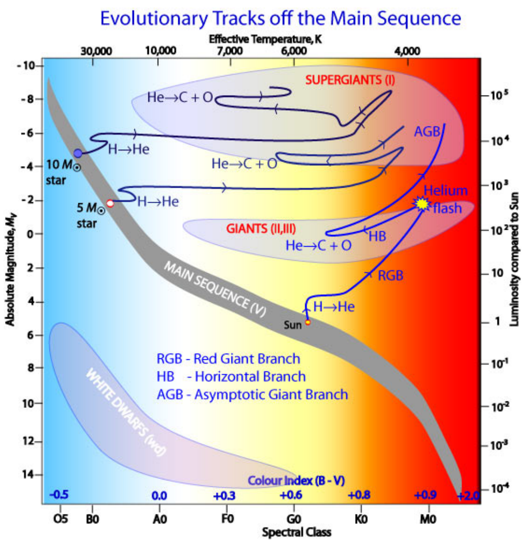

Figure 1.1: Hertzsprung-Russell diagram showing evolution of main sequence

Stars of certain Brightness can only lie in a particular spectral region while stars of certain colours can only lie in a particular range of brightness.`Variable stars` of a region in the diagram can tell us the general properties of the stars in that region.

When we talk about stars in general, we refer to them based on their position on this diagram. Hydrogen Burning stars are referred to as *main sequence stars*. Stars that have evolved well beyond the main sequence are often on the *red giant branch* or might be *asymptotic giant branch*. In the following section we will study some of the stages of stellar evolution and see what studying variable stars can tell us about them.

1.2 Star Birth

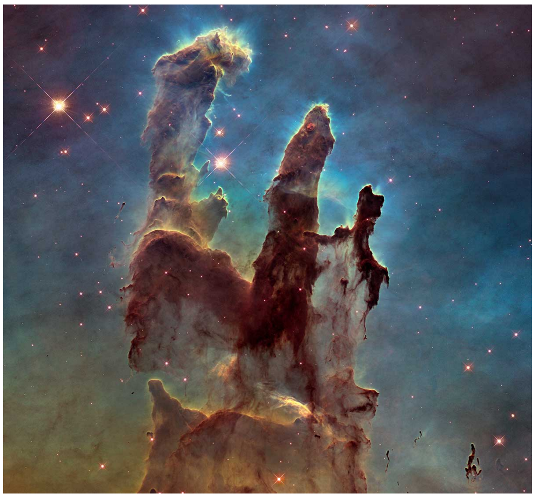

Figure 1.2: Hubble's legendary Pillars of Creation, seen bathed in the blistering ultraviolet light from a group of young, massive stars located off the top of the image

Hubble has observed many bizarre looking landscape sculpted by young, incredibly bright stars. One of them, dubbed the Pillars of Creation, show trunks of interstellar gas in the Eagle Nebula which is part of the Serpens constellation.This is a nursery to a cluster of young massive stars that are radiating ultraviolet light.

Young stars like these are formed in interstellar molecular clouds when the mass of it reaches a critical point called Jean's mass. Gravitational Collapse in initiated and is continued until a point when the gas is hot enough for the internal pressure to withstand it.**Hydrostatic Equilibrium** is achieved.The star is now referred to as a `protostar`.

Accretion of material on the protostar continues. Deuterium fusion is initiated which slows down the collapse of the star a little.During this stage bipolar-jets are produced termed as **Herbin-Haro Objects** which helps the protostar to expell the excess angular momentum of the accreting material.

Finally when the core pressure becomes large enough, nuclear fusion begans and the star is officially born.

These young stars can be extreme in there variability and as they are mostly formed in nebulae they are often referred to as *nebulae variables*. The most famous class of these nebular variables are the **T Tauri** stars, named for the prototype, *T Tauri*.

They're less bright than we would expect a star of their size and color to be and they show emission lines of highly excited atoms of a thin gas.

But why are these stars variable?

Their variability can be caused by a number of things but much of it is related to accretion. The infalling dust and gas has some viscosity (or friction) and as it falls toward the protostar, viscosity within the gas causes it to heat up. As it gets hotter, it gives off more and more light until it impacts the surface, where it gives off even more light.

1.3 The Main Sequence

Once a young protostar has accreted all of the gas and dust that it can from the cloud from which it was born, it may be massive enough to burn hydrogen in its core and shine as a star. If and when this happens, it becomes a **zero-age main sequence star *(ZAMS)***.A star enters the main sequence when it starts burning hydrogen and stays on it as long as it is burning it.The Sun will spend 9 to 10 million years in the main sequence which is a lot shorter than the 100 million years a star with lower mass than the Sun may spend. The time interval a star stays on the main sequence is **entirely dependent on its mass.**

1.3.1 Studying the variability of Main Sequence Stars

We have been talking about how nuclear fusion happens in the core,hydrostatic equilibrium etc. But how can we confirm it? This is where **Asteroseismology** comes in.

As is done on Earth to study its interior,The vibrations on the surface of these stars are studied by seeing how the brightness of different parts of the star's surface change over time. These vibrations are called pulsations, and we can measure the properties of these pulsations to say something about the conditions inside the star. In many stars – including our own Sun – there are many different vibrations happening at the same time; each vibration frequency is called a pulsation mode.

1.4 Post Hydrogen Phase

As all the hydrogen in the core has been converted to helium, the nuclear reactions temporarily cease. As it was the heat and pressure created by these nuclear reactions that prevented the outer layers from gravitational collapse.The stars therefore goes through a readjustment phase where both the inside and outside goes through complex physical changes.

As the stars starts collapsing, the outer layer starts shrinking, As it shrinks it increasing the temperature of the layer just outside the core. After a limit, the hydrogen in the layer outside the core starts to undergo fusion.This results in expanding the outer layers of the star to much higher extent than before as the fusion is happening much closer to the outer layer. The star expands exponentially and cools down resulting in a star that is much cooler but larger than before.

As the core is still not hot enough to start helium fusion, the core keeps contracting while the outer layer remain as they are. Once the core is small enough, it starts undergoing fusion and starts producing carbon through the **Triple α process** where 2 α particles combine to produce an unstable isotope of Beryllium which quickly captures another α particle to form stable carbon isotope.

$$^{4}He +^{4} He \longrightarrow^{8} Be \tag{1.1}$$

$$^{8}Be +^{4} He \longrightarrow^{12} C + \gamma \tag{1.2}$$

If the temperature and pressure conditions are met this carbon captures another α particle to form Oxygen isotope.

$$^{12}C +^{4} He \longrightarrow^{16} O + \gamma \tag{1.3}$$

1.4.1 Variation in these Stars

As stars undergo these changes they may become true variable stars, or if they are currently variable, that variability may change or even cease altogether. So what are some types of variable star of the post main-sequence?

- Instability Strip :

  Located from the upper right*(luminous and cold)* to the lower left*(faint and hot)* on the H-R diagram.

  In all stars, certain layers within them can become more opaque to radiation as they become hotter or cooler. When this happens, energy from inside the star can become trapped in that layer, increasing its temperature and pressure. In the stars of the Instability strip, this layer is located at just the right depth,So the layer acts like a piston that drives the outer layers of the star up and down in a periodic fashion, making the star pulsate. Stars having a few times more mass than the sun cross the instability strip after the main sequence. These are Cepheid variables and they follow the unique property that the time period of their fluctuation is proportional to the luminosity of the star.This is known as the ***Period-Luminosity Relation or the P-R relation*** which was given by *Henrietta Swan Leavitt*

  Cepheids are used in determining the distance to various astronomical objects and also finding the length of the Universe by finding the Hubble's Constant to an acceptable error limit. Other types of Variables found are **delta Scuti** and **RR Lyrae**.Delta Scuti stars are used to find distances within the Milky Way, RR Lyrae are used for globular clusters and Cepheids are used to find distances millions of light years away.

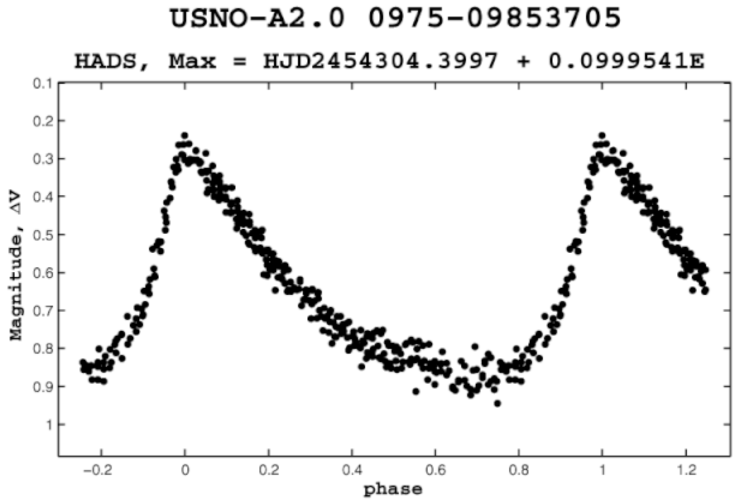

Figure 1.3: Absolute Magnitude vs time for Delta-Scuti stars showing the Regular Pulsation that its Luminocity goes through.

- Hertzsprung Gap ***(HG)***

  There is a small gap between the main sequence and the red giant branch which represents the stars that are undergoes transition from core hydrogen burning stars to core Helium burning stars.

- Horizontal Branch ***(HB)*** The HB is the region on the H-R diagram where stars are found when they have completed the Red giant phase of their life and have begin burning helium in there core.

  1. Helium Main Sequence Stars ***(HeMS stars)***:

     When a cloud of Helium gas collapses under its own gravity and starts nuclear fusion. They lie on or near the Hydrogen Main Sequence

  2. Core Helium Burning Stars ***(CHeB stars)***:

     CHeB stars have a Helium-carbon-oxygen core which are still burning Hydrogen in their outer layers. These stars were Red Giants before Helium ignition occured.

  3. Helium Horizontal Branch Giant ***(HeBG stars)***:

     These are typical low mass stars that have evolved beyond the Horizontal Branch but have not reached the Asymptotic Giant Branch ***(AGB*** yet.

- Asymptotic Giant Branch ***(AGB)***:

  the asymptotic giant branch (or AGB) stars is considered the last stage of stellar evolution , when it still shines due to energy created by thermonuclear reactions. After a star has passed through the red giant branch and landed on the `red clump`(younger and more metallic helium burning stars) or the horizontal branch , it has a core made mostly of carbon or oxygen surrounded by layers of helium and hydrogen.Burning helium slowly settles onto the carbon core, while burning hydrogen slowly settles onto the helium shell.These burning shells are the main reason why AGB stars are so luminous; because the shell is closer to the surface, the outer layers become much hotter and so the star puffs up to enormous size. Due to the large surface area, the energy produced is distributed more widely, therefore, resulting in a much cooler surface. That's why AGB stars are red – most have temperatures no more than 3000 to 3500 K.

The AGB is the locus of the most famous and earliest known variable known as `Mira Varables`. These are giant, variable pulsating stars with time period of approximately 100 days and have light madnitudes of at least 2.5 magnitudes going as high as 10 magnitude,a brightness level 10,000 higher than that of the Sun. Most of the matter(if not all) came from inside an AGB star.

- RV Tauri stage:

  These are characterized by pulsations of period ranging from 30 - 150 days.These pulsations aren't regular, but instead seem to be weakly chaotic, that is while they may have cycles of maxima and minima that are fairly regular, their lightcurves often don't repeat from one cycle to the next, and often get out of sync over many cycle.These are headed to become planetary nebulae or white dwarfs.

1.5 The Glorious Death

What happens to the star post AGB is completely dependent on one thing. Its mass. If the mass of the star in less than 1.4 $M_\odot$ ($M_\odot$ depicts the mass of the Sun),the star will end up as a `White Dwarf`. This mass limit is known as ***Chandrasekhar Limit***. As the core of the star becomes more metallic, the gas inside the star becomes so dense and the atoms become so compressible that it stops acting like normal matter.

Figure 1.4: *An Image showing the Helix Nebula,captured through infrared filters, a Planetary Nebula in the constellation of Aquarius. It is often referred to as 'The Eye of God'*

The matter becomes degenerate i.e. the electronic fields of the individual atom can no longer keep them separated. The fundamental nature of the gas changes and it begins following a degenerate equation of state.

1. **WHITE DWARF**

   A star whose core is in such a state will soon head towards its paradise so to say.Mind you the "soon" is in cosmic terms i.e. The core of these stars is referred to as `White Dwarf`. These stars begin to shed off their layers with the help of until only the core is remaining. This happens in the most spectacular way popular. As the material flows away from the star into the space, it forms a nebular structure while having a hot remnant in the centre. What we now observe is called a ***Planetary Nebula.***

   Stars that die as a White dwarf go through one last phase of substantial mass called the *post-Asymptotic Giant Branch* ***(pAGB)***in which they undergo mass-loss through processes like Stellar Wind and Thermal Pulses*(these are periodic short-lived bursts of Thermonuclear Energy which are causes when Helium clumps together at some places*

   When all the mass has been shed, All that remains is a whitish core which releases energy only through thermal means and it continues this for billions of years until eventually it freezes into a solid state from inside out. The greater the temperature of the white dwarf, the faster they will cool. Hence the cold White dwarfs provide a lower limit to the age of the universe.

   A carbon–oxygen white dwarf that approaches this mass limit, typically by mass transfer from a companion star, may explode as a `type Ia supernova` via a process known as ***carbon detonation***. More on this in the next section.

2. **NEUTRON STARS**

   What happens if a star in AGB happens to be more than 1.4 $M_\odot$?

   A low mass stars stops its nuclear reactions once it has a Carbon-Oxygen ***(CO)*** core. Great deals of pressure and temperature is required to begin thermonuclear reaction of these elements. For masses greater than the Chandrasekhar limit, these conditions are met and a thermonuclear reaction chain is initiated which goes on until we have Iron***(Fe)***.As Iron is the most stable element, the reactions till the formation of Iron are exothermic. These provide energy to the star and helps to further increase the temperature and pressure in the core.If all the core is converted to Iron, it will start to draw energy from the surrounding as further reactions will be endothermic. This proves to be catastrophic for the star as the very energy that was being

   used to withhold the star form gravitational collapse is being absorbed by the core. What follows is one of the most spectacular events in the life of a star, a **supernova**. In a flash, the pent up gravitational potential is released creating one of the brightest explosions in the universe. The explosion causes the runway nuclear reactions to take place creating every heavy element in the periodic table.

   For a few months the light releases by the supernova can be equivalent to the combined light of every other star in its galaxy - the light of 100 billion stars or more.

If the mass of of collapsed core of the Supernova > 3 M⊙, then if may form a ***Neutron star*** which is a super-dense object spanning nearly 10 km in diameter but having 3 or more solar masses in them. The matter is very densely packed, so much so that the electrons and protons combine to form neutrons and thus the star is essentially just composed of neutrons.
These stars spin very rapidly, many times a second, and also possess a strong magnetic field (magnetic flux is conserved, as the surface area of the star has decreased exponentially, the magnetic field increases exponentially as well).

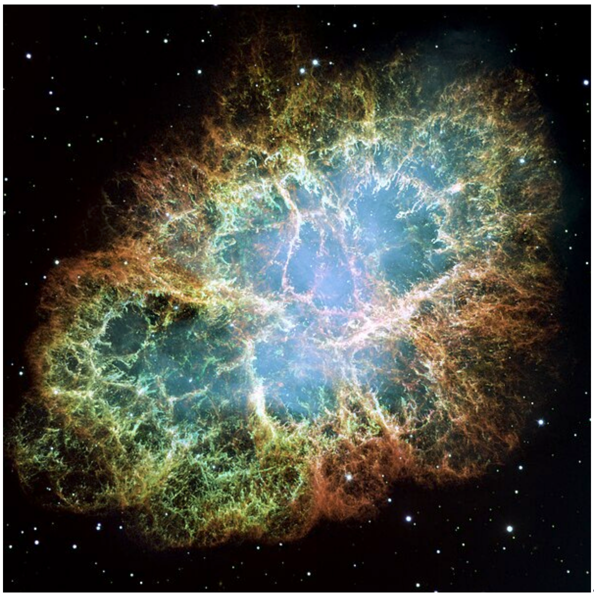

Figure 1.5: *An Image of the Crab Nebula, a supernova Remnant in the constellation of Taurus having a neutron star at the centre*

So some bursts of radiation are released from their magnetic poles and these magnetic poles are not always aligned with their equatorial Poles. So these bursts can be observed periodically from the Earth as the neutron star rotates. Such types of neutron stars are referred to as `Pulsars`.

An ever more extreme form of neutron stars are `Magnetars`. They possess an even higher magnetic field and they undergo enormous outbursts at high energy. Sometimes there energy may even reach the Earth's atmosphere and cause disturbance in our communication.

3. **BLACK HOLES**

   Black holes don't require any introduction. When the mass of the remaining core after the supernova is > 3 M⊙, then even the atomic forces aren't strong enough to withhold the star from collapsing further. Their gravitational field becomes so strong that even light can't escape once it enters the **Event Horizon**, a point in space a few kilometers away from the black hole.

   Black holes are one of the most interesting objects in the Universe but we won't we discussing it any more as we would go on a long tangent and the matter of the topic won't be discussed

2. In case they go BINARY

We just looked how an isolated star evolves throughout its time, but as we know most stars in the universe are formed in bulk and they ain't alone. In fact, a large percentage of the stars(about half) exist in either a binary or a multi star system.The presence of other stars greatly affect the evolution of these stars. Here we will study how the star evolves if it exists in a binary system.

2.1 Binary Interactions

Stars in binary systems, interact in many special ways and produce many different types of systems as they evolve.We will be studying some of them and how likely they to form in this project.

How they evolve essentially depends on three factors:

1. Their **Masses**
2. Their **Metallicity**(how much heavier elements they possess)
3. The **Semi-Major** axis of their orbit.

Based on these One of the following things may happen

2.1.1 Roche Lobe Overflow

- There exists a surface around the stars, where the gravitational forces of the 2 stars cancel each other out. This surface is referred to ad the `Roche Lobe`. As a star grows bigger than the Roche lobe (during its Red Giant phase), the companion star starts accreting some matter onto itself from it through the inner Langragian point (L1).
- If the companion star in a **Compact Object**(i.e. a Black Hole, a Neutron Star or a White dwarf), then a `Accretion disk` may form around it to conserve the angular momentum of the infalling material. /item As the material falls into the companion star, The intense gravitational field heats the material to the point that it may start radiating X-rays.More on this later.

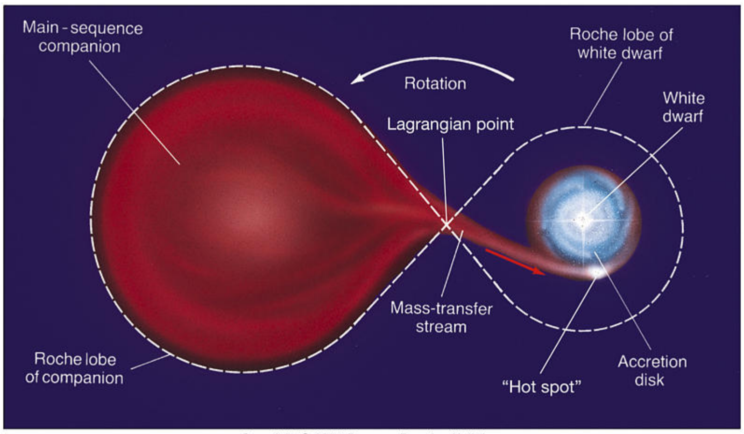

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Figure 2.1: An image depicting mass transfer from one star to its companion depicting Roche-lobe Overflow

- This type of Mass transfer is stable as the hydrostatic Equilibrium of the donor star remains stable.This mass transfer may make the mass on the companion star more which results in weird cases where stars which had mass less than 1.4 $M_\odot$initially to form black holes and neutron stars at the end of their lives.

2.1.2 Common Envelope

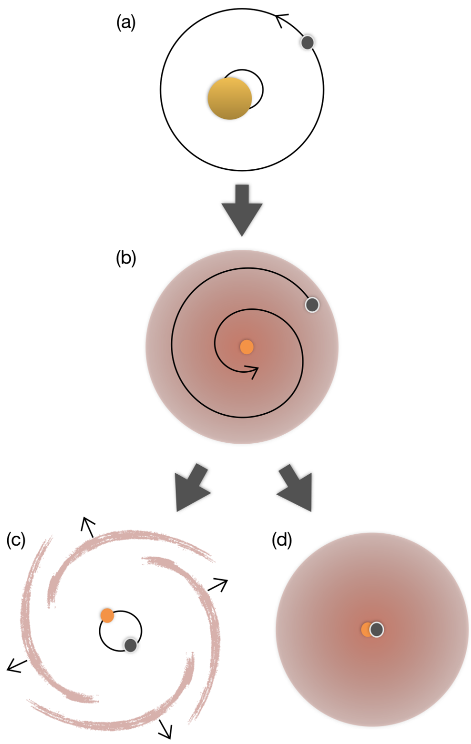

Figure 2.2: Common Envelope Evolution

- If the 2 stars are born in a relatively wide binary,allowing them to expand. The star with more mass, while undergoing expansion as a Red Giant may engulf its entire companion and form a common Envelop surrounding both of them.
- This Envelops cause friction which results in loss of Angular momentum of the system causing them to come closes by a factor of 2 or more. This also results in unstable mass transfer.
- At the end of this process, The 2 binary may be close enough that they merge together to form a single star. If they aren't that close the envelope is erected out and we get a binary w orbiting each other at a much closer distance.

2.1.3 Separate Evolution

If the distance in the system is too large for them to interact in any way, The star undergo Evolution separately without the influence of their companion star.

2.2 After the Mass Transfer

Once the mass transfer process is over, one of the following events may take place depending on the components of the system:

2.2.1 X-ray Binaries

If one of the stars is a Compact object, while the other is a main sequence star, as the matter is being accreted onto the compact object, the intense gravitational potential causes the matter to release X-ray radiations(upto 30 percent of its rest mass).

It is further divided into *Low Mass X-ray Binary* and *High Mass X-ray Binary* based on the mass of the donor star. `As high mass stars may be more closer`

`to the Compact Object when they expand, the major mass transfer in that case might be stellar winds and not through an accretion disk while the case is opposite for low mass stars`

2.2.2 Dwarf Novae

When the binary is composed of a white dwarf and a main sequence star, the material is pulled of off the main-sequence star, and spirals towards the white dwarf.In some cases if the mass transfer rate is very high, the accretion disk may undergo outbursts,brightening by a factor of 100 or so.

- At the highest mass accretion rates, the accretion disk doesn't go out of its outburst state and the matter keeps piling onto the disk very quickly. Such stars are called `novalike`.
- Sometimes, if enough mass builds up on the white dwarf's surface, the temperature and pressure of the accreted material can rise high enough that it undergoes thermonuclear fusion, just as it would in the star's core. When this happens, the system becomes a `classical nova`, brightening by a factor of 10000 or more for a short time.
- Most novae recur on very long timescales, as it takes a long to build up enough mass to trigger a thermonuclear explosion. But in very few cases, the rate of mass transfer and the mass of the white dwarf are high enough that they recur on observable timescales of years or decades.These are known as `recurrent novae`
- If the mass of the White dwarf is close to the Chandrasekhar Limit, then the collapse of the white dwarf results in a supernova. Such supernova

that happen due to the binary nature of the system are known as `Type 1a Supernova`.These supernovas hold the special property that the peak brightness reached by them is almost identical at of -19.3 ± 0.03. Therefore they are considered as **Standard Candles** which help us to find the distance to the galaxy of their residence.

2.2.3 When a `Black Hole` met another `Black Hole`

These are systems in which both the stars have evolved to their latter stages. The most interesting of them being binary black holes and neutron star - black hole pairs.

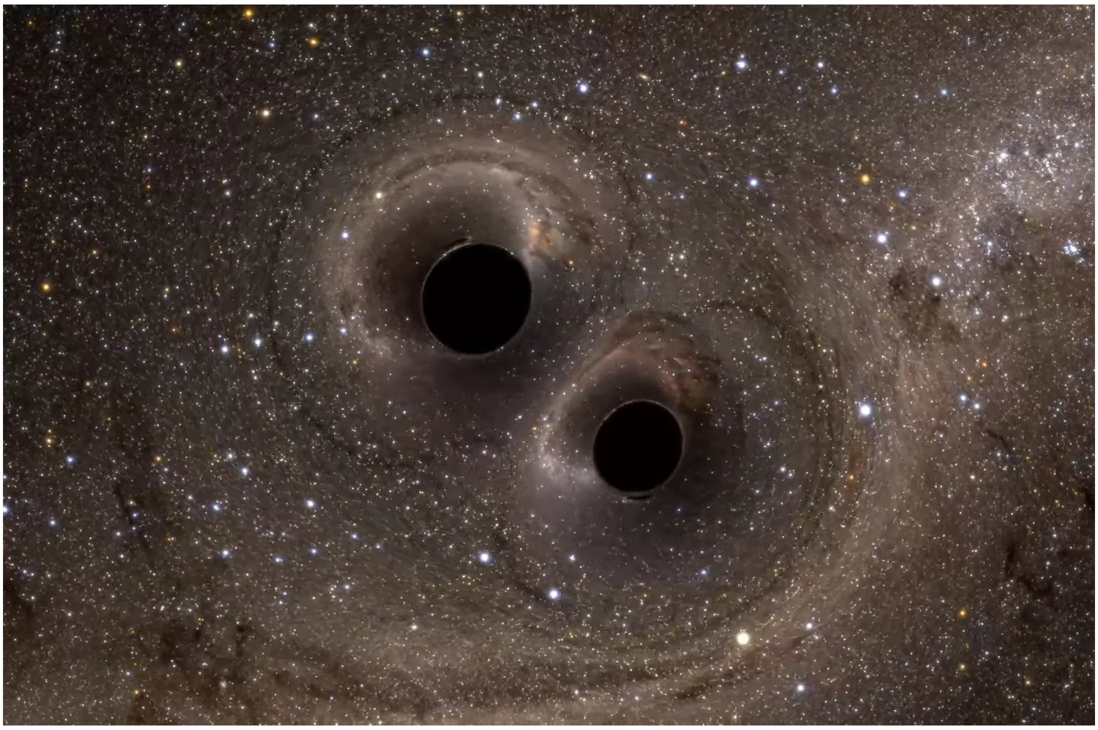

Figure 2.3: *A still from an animation depicting what a binary system of Black holes would look like*

Einstein's General Theory of Relativity states that accelerating mass release gravitational waves(Ripples through space time). Pertaining to the high mass of the black holes and their high acceleration, they lose a lot of their orbital energy in the form of Gravitational Waves.

- These Gravitational Waves are observed here on Earth through Laser Interferometry by **LIGO**(*The Laser Interferometer Gravitational-Wave Observatory*. LIGO detected the first gravitational Waves when they detected GW150914 (detected September 2015, announced February 2016).

- The life cycle of such binaries have 3 different phases:

  1. **Inspiral Phase:**
     Initially the orbit is gradually shrinking releasing very Weak Gravitational Waves are released. This goes on for a very long time. But as the orbit comes shrinks, the speed increases and the frequency of gravitational waves increases until in reaches the innermost stable Complete Orbit **ISCO**.
  2. **Merger:**
     A plunging orbit follows and it results in the merging of the Compact Objects. Gravitation Wave emission peaks here.
  3. **Ringdown:**
     The now single black hole will "ring". This ringing is damped in the next stage, called the *ringdown*, by the emission of gravitational waves. The *ringdown* phase starts when the black holes approach each other within the photon sphere*(a sphere outside the black hole where light bends so much that it boomerangs)*.

- These mergers happen in a very ... very long time. They may take longer than **Hubble Time** which is the current age of the Universe. Such **Double Compact Objects *(DCO)*** that merge in less time than Hubble time are said to merge in *Coalescence Time*. We will study them further in detail.

`Note:`
`The Helium core star that is left after the envelope is transferred or lost is called a Wolf-Rayet star.`

2.2.4 Merger Methods:

1. the **'Vanilla' method**(pun intended)

   `Here we are studying a particular case where accretion disk is initially formed on the companion star while a common envelope is formed when the it undergoes expansion.[75M ⊙and 100 M⊙with a seperation of 10 AU in low metallic environment.]`

   - This is what we discussed earlier where the stars undergo an inspiral phase and merge.
   - Initially as the star with the greater mass goes through its red giant phase and expands past the Roche-lobe, it starts mass transfer to the other star which is still in the main sequence.
   - Mass is lost as the companion star can't accept the mass at the rate it is being donated. This along with stellar winds results in mass loss which widens the system.
   - The primary star in converted into a Wolf-Rayet star before it collapses into a black hole/neutron star.

- Some time later the companion star reaches the end of the main sequence and the process is repeated in reverse. Then the companion star undergoes expansion and forms a common envelope. Expulsion of the envelope is followed by it becoming a black hole resulting in a binary black hole that will eventually merge.
  (Eventually $\longrightarrow$ 10 billion years)

2. **Chemical Homogeneous Evolution**

   if the stars, at the onset of hydrogen burning are in near contact to each other, tides are raised in the component stars which triggers instabilities in the stellar interior which may result in meridional circulation throughout the stellar structure causing gradual enrichment of Helium in the envelope.

   The stars soon become tidally locked to each other as the rotation period of the star is synchronized to the orbital period of the Binary.

   As the stars undergo nuclear fusion more efficiently, they form Wolf-Rayet stars and continue to contract and eventually produce binary black holes with comparable mass that will merge before Hubble Time.

3. **Dynamical formation**

   For 2 black holes to merge, It isn't necessary that they lie in a Binary system from the start, but they can me made into a Binary system by a matchmaker or rather a bunch of matchmakers.

   Such a system can be formed by a initial 3 body system,where one of the object gets sufficient kinetic energy to be ejected from the system. Else, there can be a substitution case, where a black hole interrupts a stellar binary and ejects the lightest star, forming a binary with the more massive star.

   There can be many permutations and combination to this. Basically other stars/objects may result in them forming a binary by ejecting it towords the other through a natal kick, Gravitational Sling etc. Other stars may also come into their binary orbit and end u closing their distance as it takes away angular momentum from the system as ot goes away.

3. Tasks

Here are the tasks that we were given to present:

3.1 Task 0

We have to run a simulation of 10 stars with fully conservative mass transfer as the condition. Here is the code fore that:

```
./COMPAS -number-of-systems 10 -mass-transfer-accretion-efficiency-prescription
FIXED -mass-transfer-fa 1 -detailed-output
```

When we compare the total mass of the system initially and finally we see the total mass does not add up. This happens as even though the mass transfer is fully conservative, If and when the system undergoes through a common Envelope phase, and the supernova explosion, novae explosions in case of white dwarfs, expel the mass of the common envelope.Supernovae in general also expel a lot of stellar mass. Stellar winds may also cause mass loss. We can see some cases in the following graphs.

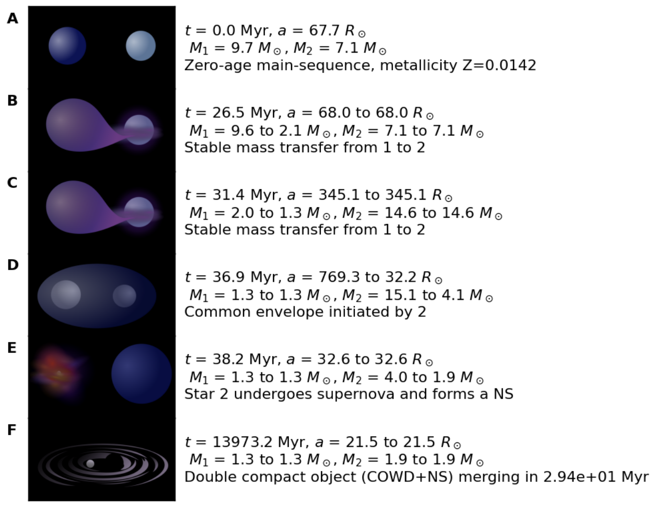

Figure 3.1: *COMPAS processed timeline showing reduction of mass through expulsion of common envelope*

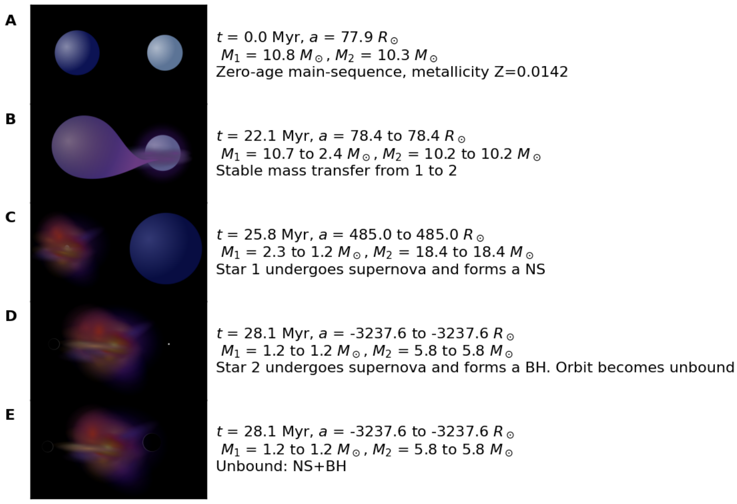

Figure 3.2: *COMPAS processed timeline showing expulsion of mass through a supernova explosion*

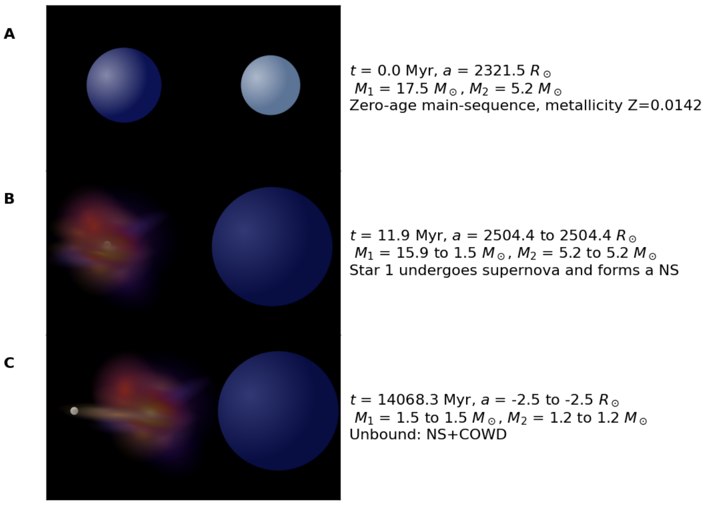

Figure 3.3: *COMPAS processed timeline showing expulsion of mass by formation of Wolf-Rayet Star*

3.2 Task 1

We will be studying Seed 1719454779 in detail.

- Initially, we have 2 ZAMS stars having 7.7M⊙and 3.7M⊙respectively.The metallicity of the stars Z = 0.0142. The semi Major axis = 2689.5 R⊙.
- After 45.9 Myrs(million years),The bigger star goes Supernova and experiences a mass loss of 6.1M⊙.There was no interaction between the stars as the distance between them was quite vast.The semi-major axis has decreased slightly though as the 2 stars spiral towards each other slowly releasing negligible gravitational waves.

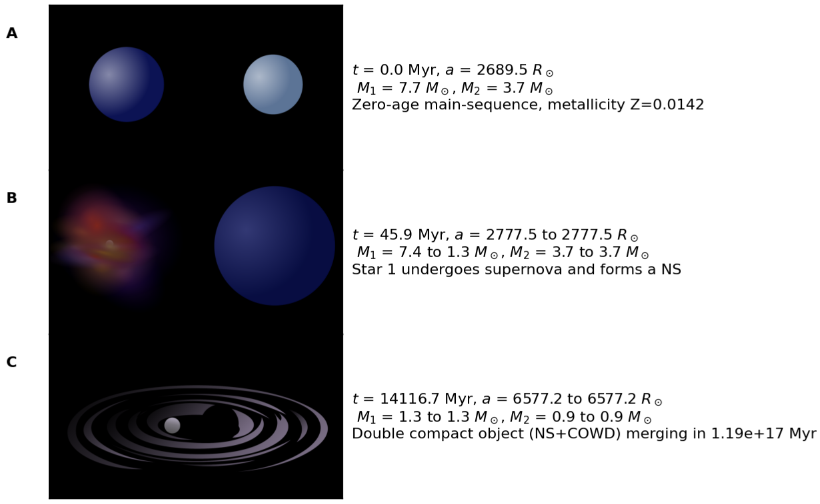

Figure 3.4: *COMPAS processed timeline showing evolution of Seed 1719454779*

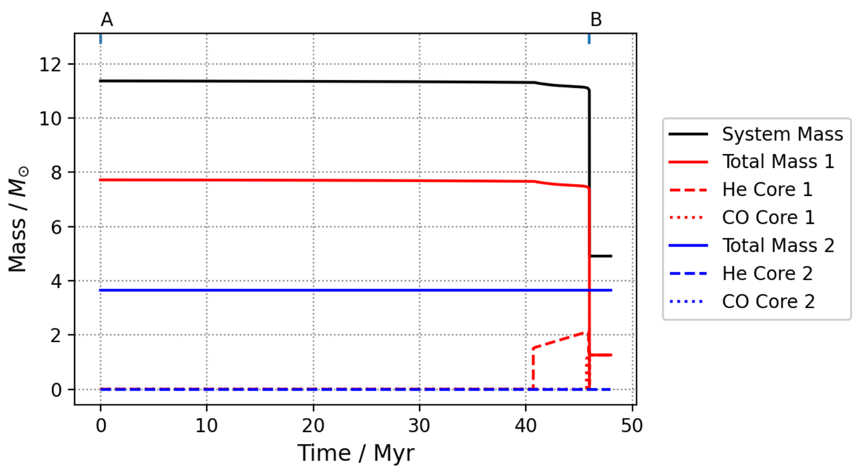

Figure 3.5: *M⊙vs time(Myr) for Seed 1719454779*

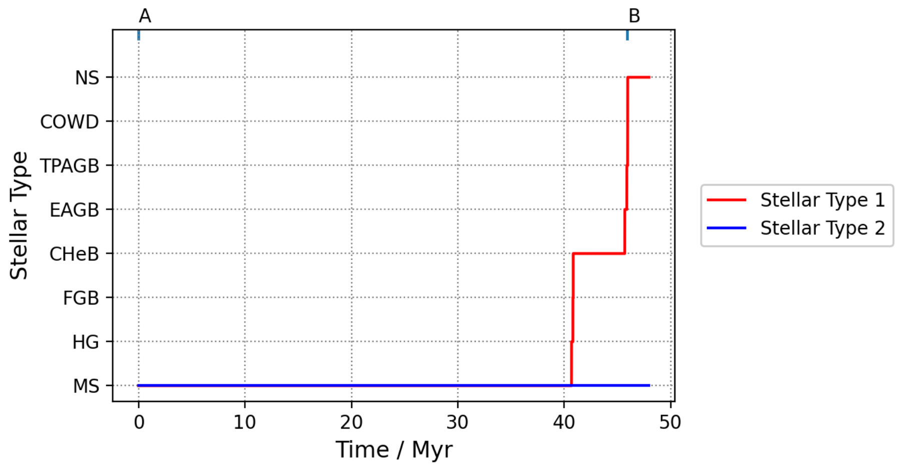

Figure 3.6: *Stellar-Type vs time(Myr) for Seed 1719454779*

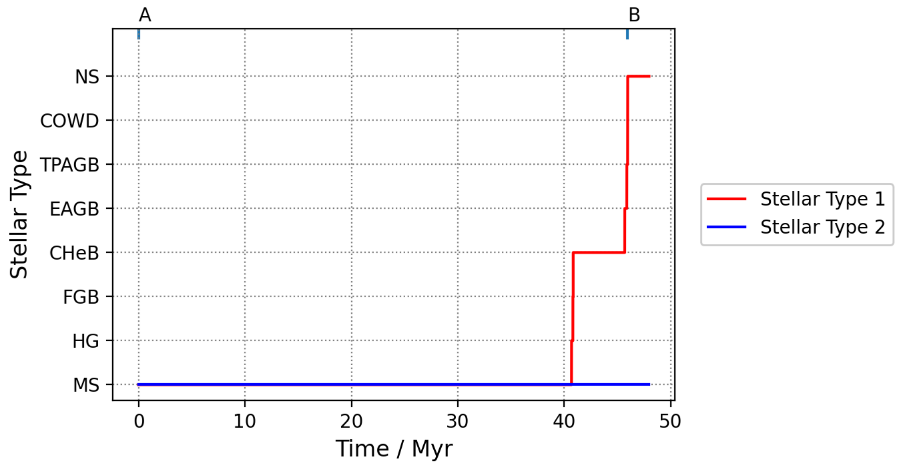

Figure 3.7: *R⊙vs time for Seed 1719454779*

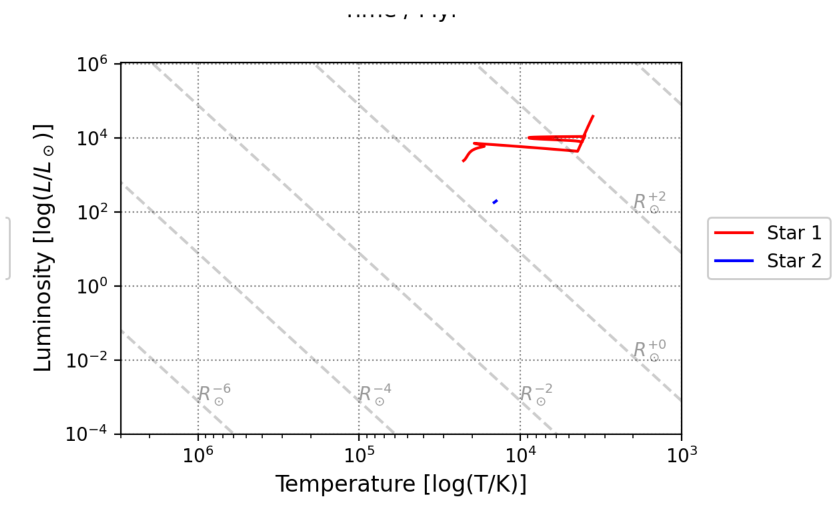

Figure 3.8: *Log(L/L⊙) vs Log(T/K) for Seed 1719454779*

- The second star eventually forms a Carbon-Oxygen White-Dwarf **COWD** 267 myrs down the line.
- The 2 objects eventually form a double Compact Object (**DCO**), at 14116.67 Myrs after slowly spiraling towards each other.
- These stars don't merge within The Hubble Time and remain like this.

3.3 Task 2

- In this task, I ran 10,000 simulations and distribute the number of binaries according to how they interacted through different mass transfer channels.
- Also, we had to demonstrate the distribution of occurrences of supernovae among these binaries. These binaries were simulated on default settings.
- the table below summarizes my results:

Statistics	**Value**
Time taken to simulate	94.567336
Number of binaries that never interact	4087
the binary pair that undergo only stable mass transfer are	1366
the binary pair that undergo stable mass transfer along with 1 common envelope are	1694
the binary pair that undergo stable mass transfer along with 2 common envelope are:	238
the binary pair that undergo common envelope without stable mass tranfer are	2614

Table 3.1: *Dataset for the simulation of 10,000 binaries without mass conservation on*

3.3.1 Plots

As the life cycle depends of a binary system of stars `isolated` depends on 3 factors: Semi Major Axis(a), and the Mass of both the primary and secondary star It is difficult the show the trends of such evolution using a graph. A unique method which one of the members of the project group `Advait Mehla` presented was to create a 2-D plot of Semi-Major Axis vs Mass Ratio with the size of the dot representing the combined mass of the system.

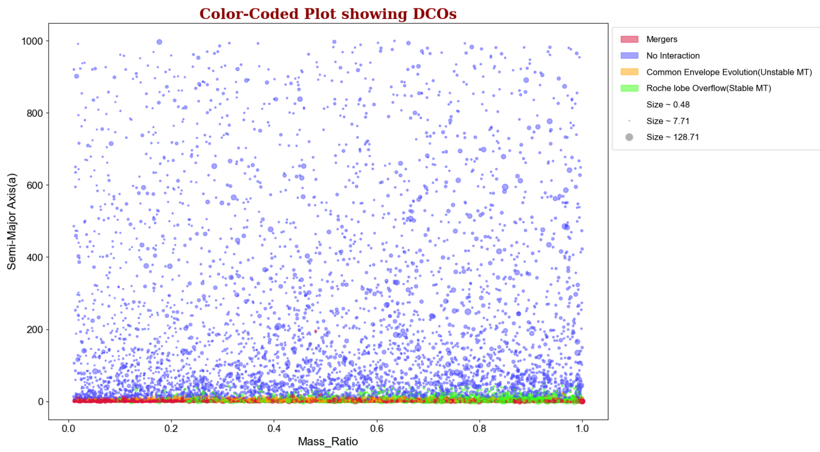

Figure 3.9: *Scatter Plot showing the mass transfer mechanisms they go through depending on their initial mass ratio and Semi-Major Axis(AU))*

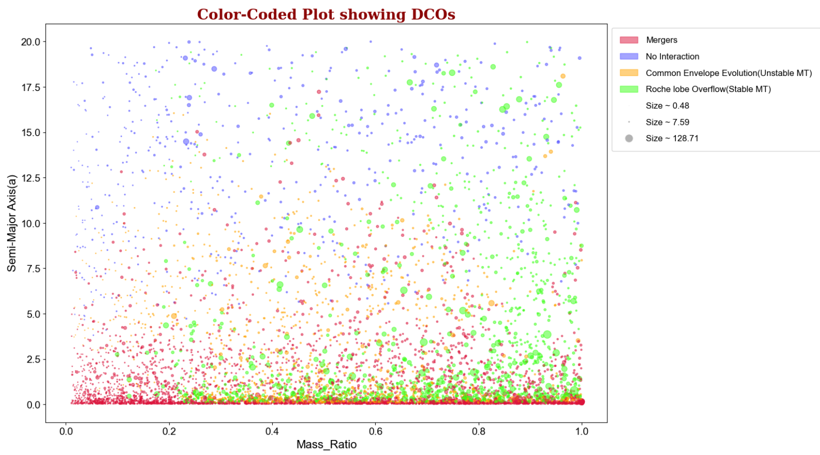

Figure 3.10: *Scatter Plot showing the mass transfer mechanisms they go through depending on their initial mass ratio and Semi-Major Axis(AU)* `unto 20 AU`

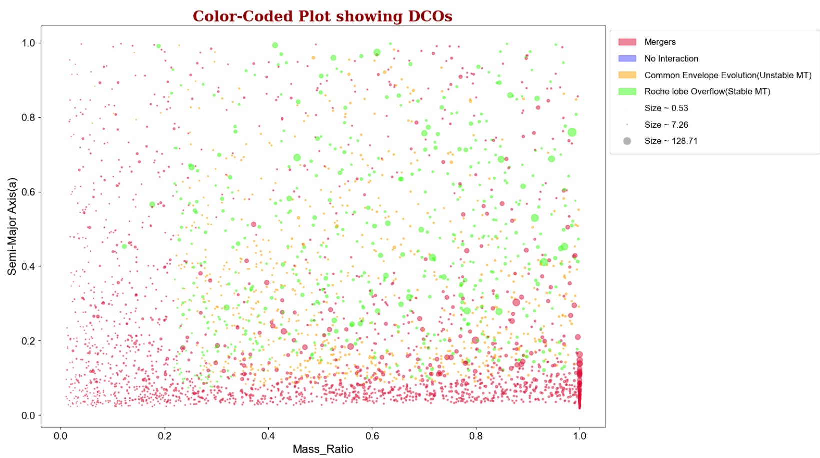

Figure 3.11: *Scatter Plot showing the mass transfer mechanisms they go through depending on their initial mass ratio and Semi-Major Axis(AU)* `unto 1 AU`

- Straightaway we can notice some trends that for a > 20 AU, No interaction takes place and both the stars evolve separately.
- For Mass Ratio < 0.2 Roche Lobe Overflow(RLOs), don't take place . This can be accounted to as the Primary star can envelope the small star to undergo Common Envelope evolution.
- CEEs are mostly restricted to a < 15.0 AU as farther than that it would take a quite massive star for it to somehow have a common envelope with its companion star.
- Most of the massive stars undergo RLO as we can see a lot of big green dots. This can be attributed to that in their Red Giant phase, they become supergiants and their outer mass is now so far away and much closer to the secondary star that Roche lobe overflow is possible.
- there is a patch for Mass Ratio < 0.2 and a < 2.5 AU where mostly every system results in a merger. This must be because the more massive star engulfs the smaller star And CEE brings it so close that merger becomes inevitable.
- Almost every system for a < 5.0 AU undergoes some type of interaction.
- There is one outlier here which we can see visible as a red dot at a ≈ 200 AU and mass ratio ≈ 0.5 which seems to be undergoing merger.

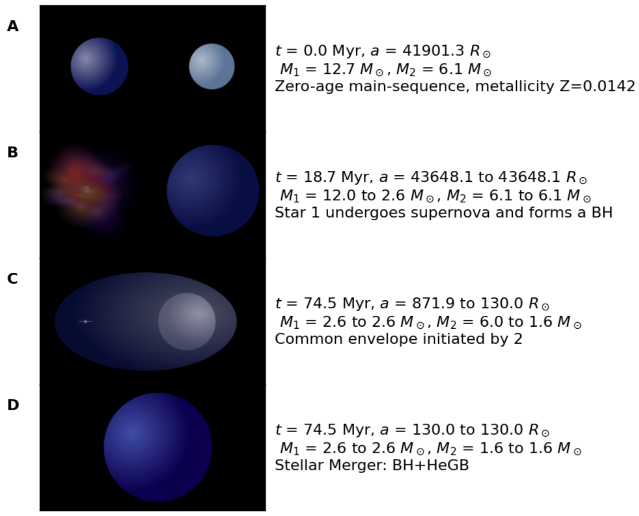

Figure 3.12: *Outlier Timeline generated though COMPAS*

- This is not possible and we see the error happening from B to C as s is decreased from 43648 R ⊙ to just 871.9 R ⊙. This is theoretically impossible without external factors being involved.

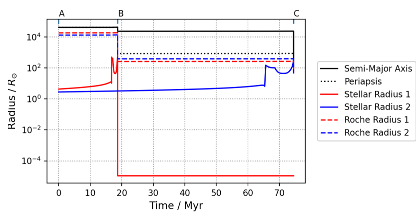

Figure 3.13: *Outlier Mass Timeline generated though COMPAS showing that the Semi Major Axis change at step 3 is not followed here thus it is an outlier*

Mergers

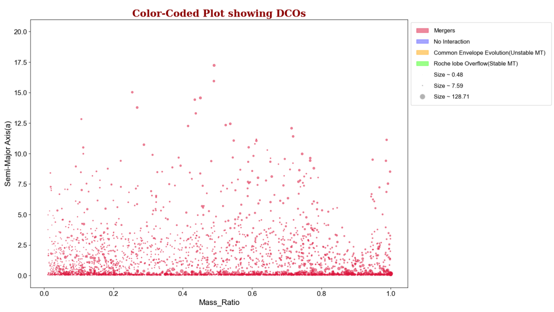

Figure 3.14: Binary Systems undergoing Mergers

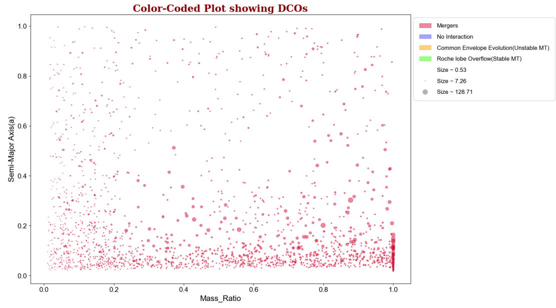

Figure 3.15: Binary Systems undergoing Mergers with a < 1 AU

- A total of 3150 systems undergo stellar mergers.Almost all mergers took place when the semi major axis was less than 10 AU.
- The masses vary from 0.1 M ⊙ to 100 M ⊙, with only a handful systems having masses of the stars beyond 100.
- We can notice a spike at mass ratio = 1 which is expected as this comes from how COMPAS initializes close binaries. Since it randomly samples mass, mass ratio, and a, sometimes we get binaries that are overflowing their Roche Lobe's right at birth. This is non-physical and come from the fact that we are not considering the birth environment of these systems,therefore, COMPAS simply assumes that these stars would have interacted pre ZAMS, and would have equilibrated their masses (`i.e we get M1 = M2 = 0.5(initial total mass)`. That's the spike we see.

Roche Lobe Overflow (RLO)

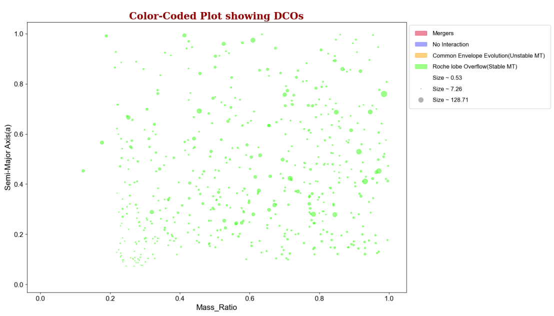

Figure 3.16: Binary Systems undergoing Mergers

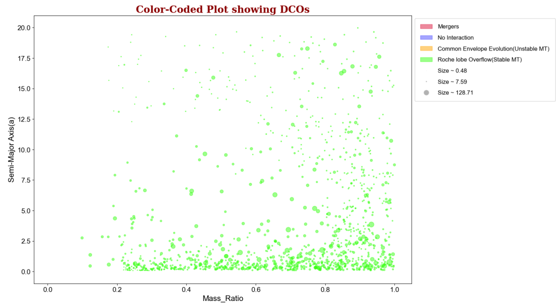

Figure 3.17: Binary Systems undergoing Mergers with a < 1 AU

- a total of 1362 binaries that experience Roche Lobe overflow (RLO) without undergoing merger.
- RLOs occur mostly when a < 20 AU. However, the systems having primary mass (@ZAMS) around 5-8 M⊙ are able to experience stable mass transfer even when the semi-major axis (@ZAMS) is as high as 40 AU.

- The primary masses of these systems vary from 5 $M_\odot$ to 150 $M_\odot$, while the secondary masses vary from 0.1 (minimum limit) all the way to 140 $M_\odot$.

Common Envelope Evolution

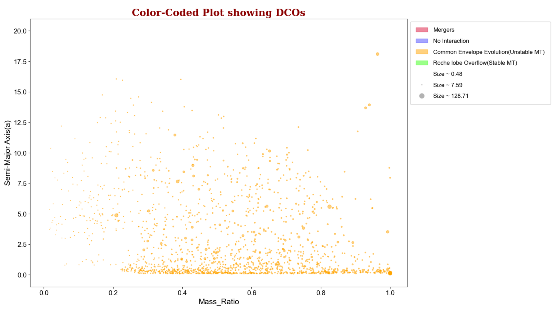

Figure 3.18: *Binary Systems undergoing CEE*

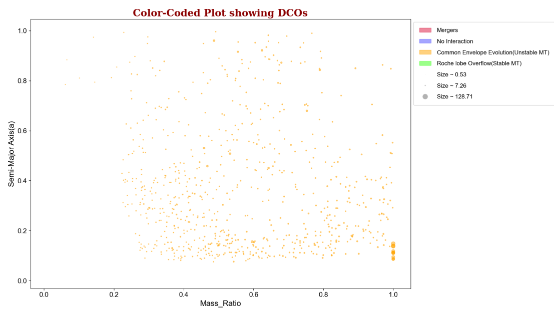

Figure 3.19: *Binary Systems undergoing CEE with a < 1 AU*

- A total of 1606 binarie experience CEE. Most of these systems have a < 10 AU, with only a few experiencing Common Envelope Evolution near 15 AU.
- Majority of the systems have masses less than 10 $M_\odot$, with only a few heavier systems experiencing CEE upto the limit of 50 $M_\odot$.

No Interaction

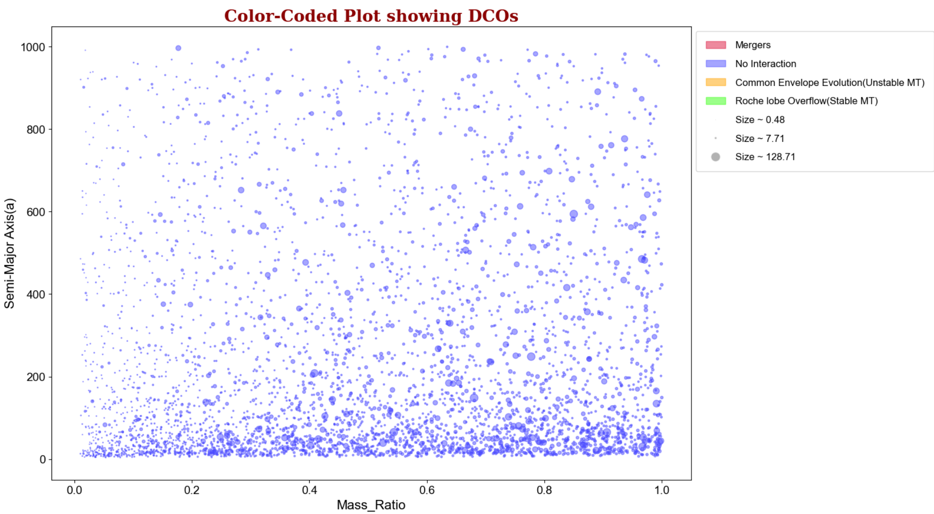

Figure 3.20: *Binary Systems undergoing no interaction*

- The total number of systems that do not interact are 4087. Almost all of these systems have semi-major axis to be greater than ≈ 10AU, all the way upto 1000 AU.

3.4 Task 3

Now we had to run 10,000 binaries with conservative mass transfer. To do this, the Mass Transfer Accretion Efficiency was set to 1. All the other parameters were default.

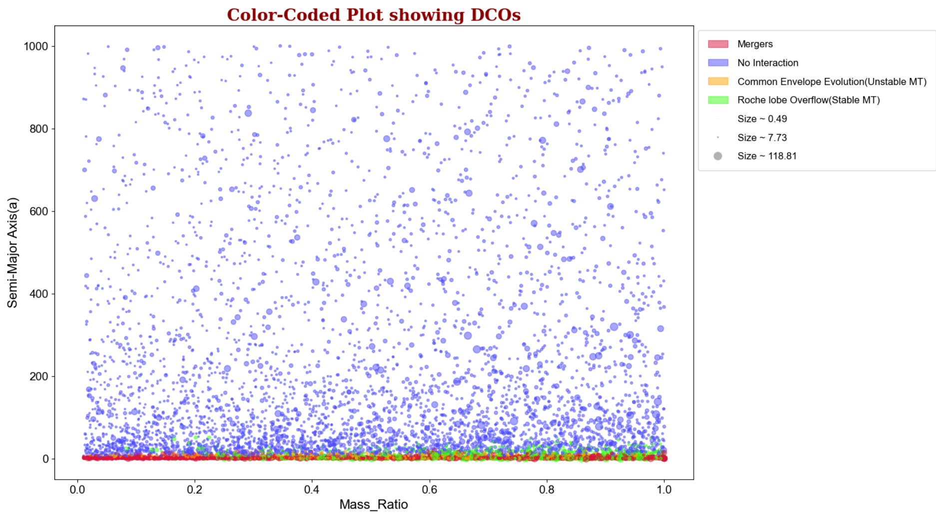

Figure 3.21: *Scatter Plot showing the mass transfer mechanisms they go through depending on their initial mass ratio and Semi-Major Axis(AU))*

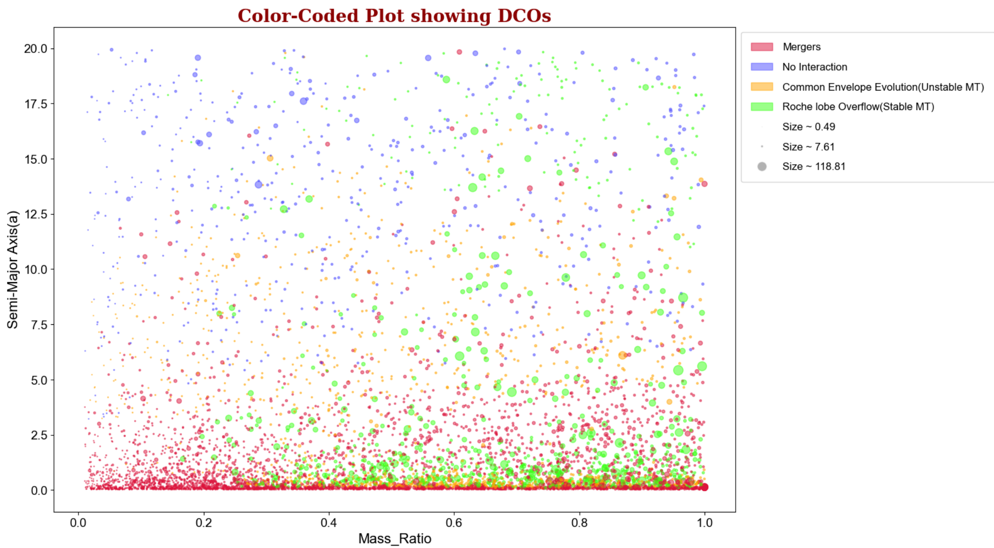

Figure 3.22: *Scatter Plot showing the mass transfer mechanisms they go through depending on their initial mass ratio and Semi-Major Axis(AU)* `unto 20 AU`

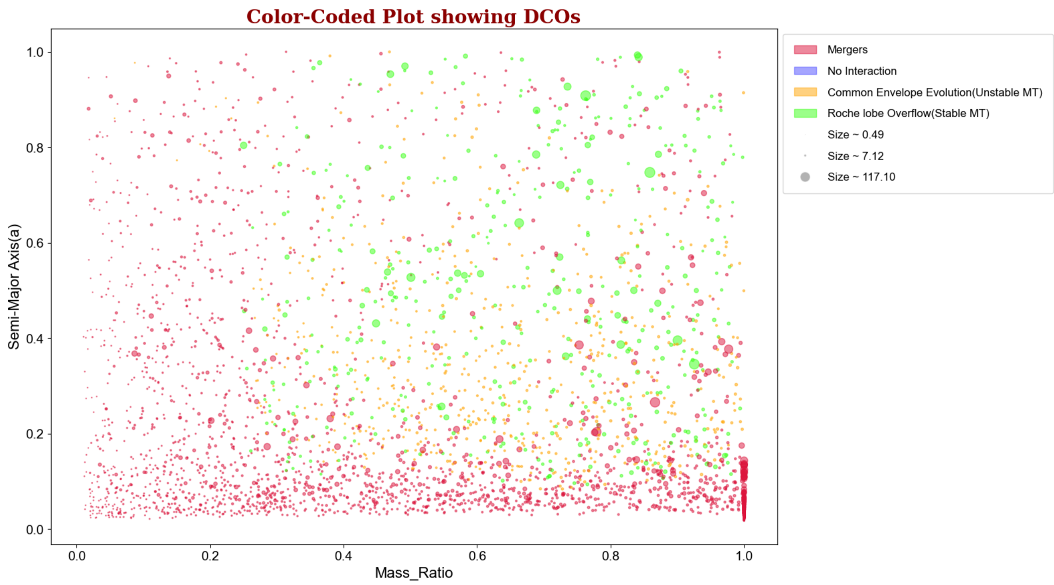

Figure 3.23: *Scatter Plot showing the mass transfer mechanisms they go through depending on their initial mass ratio and Semi-Major Axis(AU)* `unto 1 AU`

- One major difference that comes with mass conservation is that during RLOF, the mass loss due to stellar winds and other factors does not happen. This means that during the red giant phase of the Primary star, the mass lost to space all goes to the secondary star.
- This means that on average the secondary star will have more mass than the default case before there red giant phase. This means the formation of neutron stars and black holes should increase if only a little as more mass is conserved

Statistics	Value
Time taken to simulate	176.144812
Number of binaries that never interact	4140
the binary pair that undergo only stable mass transfer are	1012
the binary pair that undergo stable mass transfer along with 1 common envelope are	1594
the binary pair that undergo stable mass transfer along with 2 common envelope are:	312
the binary pair that undergo common envelope without stable mass transfer are	2942

Table 3.2: *Dataset for the simulation of 10,000 binaries without mass conservation on*

- We can notice the time taken to stimulate the events has almost doubled. This can be assumed to have come from the extra computation required to disregard for mass loss and other factors such as computer heat etc.
- we can straight away notice that the number of stable mass transfers have decreased and CEEs have increased. This can be attributed to the fact that as we saw in task 0, as all mass goes towards the secondary star, when it undergoes expansion, the stars have reached close enough at this point that CEE takes place. Therefore the case for only stable mass transfer drops.
- the number of individual CEE events also increased which was a little strange as individual mass transfer events shouldn't have been affected for the given change.

Mergers

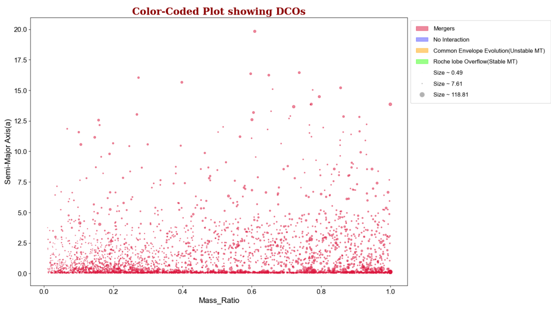

Figure 3.24: *Binary Systems undergoing Mergers*

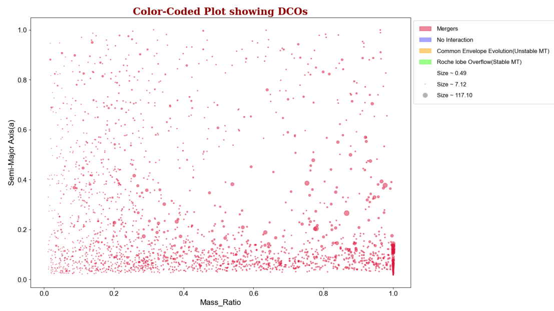

Figure 3.25: *Binary Systems undergoing Mergers with a < 1 AU*

- A total of 3621 systems undergo stellar mergers

Roche Lobe Overflow (RLO)

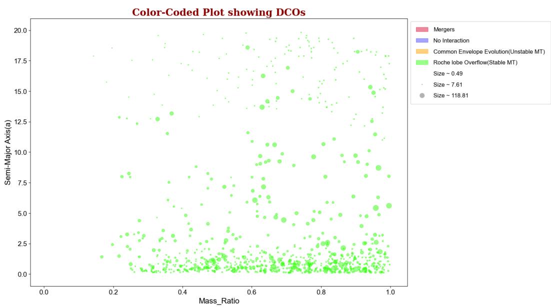

Figure 3.26: *Binary Systems undergoing Mergers*

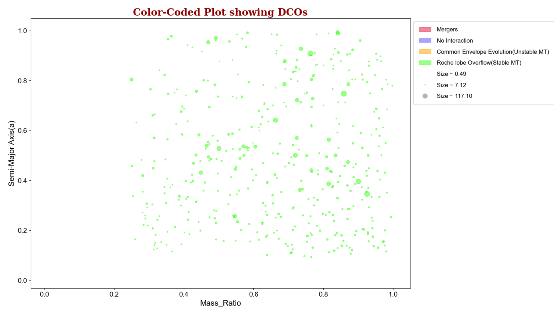

Figure 3.27: *Binary Systems undergoing Mergers with a < 1 AU*

- a total of 1011 binaries that experience Roche Lobe overflow (RLO) without undergoing merger.