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Master Minor Project

Population synthesis study of He-He merger progenitors for
Long Gamma-Ray Bursts

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Abstract

Progenitors of long gamma-ray bursts (LGRB) have always been under question from the time of their discovery. Between different progenitor scenarios, collapsar model is the most acceptable one however, it is still a subject of research what kind of stars can form a collapsar and consequently a LGRB. While hydrogen removal and large core angular momentum can not occur easily at the same time for most progenitors specially single stars, massive binary mergers with two helium companions seem to be one of the best possible progenitors since they are able to get rid of their hydrogen envelope without loosing angular momentum during double common envelope phase. In this research, population synthesis of He-He mergers with different metallicities have been studied to investigate if they are the dominant progenitors. We found out He-He mergers with masses larger than $2M_\odot$ for each companion have different evolutionary behavior comparing to low mass systems and are more abundant at lower metallicities. We also compared the abundance of He-He mergers with core collapse supernovas at each metallicity and realized even at most optimistic situation they are still much less than observed ratio of LGRBs and core collapse supernovas. Although, He-He mergers can fulfill all the conditions for collapsar model, it seems they are not abundant enough to be the dominant progenitors for LGRBs.
Chapter 1

Introduction

1.1 Gamma Ray Bursts

GRBs are flashes of gamma ray in the sky. These rare phenomena occur at distant galaxies. They are the most energetic bursts in the universe and can be divided into two different groups - Long and Short duration (LGRB and SGRB). Emission of gamma ray in SGRBs may last less than two seconds while in LGRBs it can continue to several minutes. The emitted gamma from the GRB can heat up the surrounding environment. Consequently, hot materials radiate in longer wavelength continuously for hours or even days after the main gamma burst. This second emission which can be detected at optical wavelength is called the GRB afterglow.

Short and Long GRBs have different progenitors. It seems that SGRBs are the product of merging of two compact objects in a binary system. Merging of two neutron stars in a binary is a good candidate for SGRBs. LGRBs seem to be related to massive stars and type Ic supernovae however, there are many different scenarios for their progenitors. Most of these scenarios are based on fireball and core collapse models.

1.1.1 Standard GRB Fireball model

LGRBs happen at cosmological distances and emit such a great energy in a few seconds. Their flux imply releasing huge amount of energy which could reach up to $10^{54}\text{ erg}$ if the emission was isotropic however, since their emission are highly collimated this energy reduces to $10^{50} - 10^{51}\text{ erg}$ which is still enormously great number (This is even greater than the energy that the sun produce during it’s lifetime). One can estimate a limit for the size of emitting region. The radius of the emitting region is $R = c\Delta t$ where $\Delta t$ is the LGRB duration time which is around a few seconds. Therefore, $R$ must be around several thousands kilometers which is quite small! All of these lead us to the formation of $e^-, e^+, \gamma$ fireball. When a large amount of energy is suddenly converted to high energy photons, then pair production process
is inevitable if photon density is large enough. Therefore, it must be opaque to pair creation process. This pair production was the main question for fireball model since it provide an extremely efficient way to suppress photons with energies above 1 MeV. Observation of a significant flux above 1 MeV in several LGRBs (see, for example, Matz et al. 1985 [29]) showed that pair creation was not predominant in these sources which implies low photon density. The energy flux of the nearby LGRBs can be produced by this low photon density, but cosmological LGRBs must have high photon density and therefore, a fireball which is initially opaque to pair production. Due to this large opacity the fireballs are expected to expand relativistically [32] [16]. Then, fireball radiation can be modified by its expansion. Photons will be blue-shifted. In the moving source frame photons have longer wavelength by a factor of \( \Gamma \) (the Lorentz factor of relativistic flow). As a result, X-ray can be seen as gamma ray from the stationary observer. Relativistic expansion therefore, provides a very efficient way to reduce the rate of pair production. Also the density of photons within the emitting region decreases enormously since the typical size for this region is \( \Gamma^2 c \Delta t \) instead of \( c \Delta t \). As an example, for a typical LGRB lasting 10 s, the size of the radiating region is about \( 3 \times 10^{15} \text{cm} \) if the Lorentz factor is 100.

At current time, fireball is the best model that can explain the physical properties of LGRBs. For more information about this model refer to [43] and [34].

### 1.2 The collapsar model

Usually LGRBs have energies at the order of \( 10^{50} \) to \( 10^{51} \) erg and this energy must be released in a few seconds. If one compares this energy to the binding energy of compact stars which can be easily approximated, he would realize that LGRBs released energy is even smaller than that. Binding energy of the star, \( \epsilon \), is sum of the gravitational potential energy, \( U \) and internal kinetic energy of the star, \( K \).

\[
\epsilon = U + K
\]

From Virial theorem we know the magnitude of this binding energy in Newtonian approximation is

\[
\epsilon = \frac{Gm^2}{r}
\]

For example for a neutron star with radius of 15 km and the mass of 1.4\( M_\odot \); the binding energy is about \( 3 \times 10^{53} \text{erg} \). This demonstrates the total energy which is released in LGRBs is smaller than the binding energy of compact objects. In addition, short releasing time implies a small region in the space which this energy must be produced in. Altogether, it appears natural to invoke compact objects or blackholes. Moreover, no repetition has been ever reported for LGRBs. This means that the progenitor must be completely
destroyed through the LGRB production process. Also, LGRBs are quietly rare phenomena. LGRBs rate is 1% to 0.01% of the supernovae rate which implies they should occur once per $10^4 - 10^6$ years per galaxy. Despite the fact that LGRBs are not instantaneous events; it is crucial to realize they can not be produced by any explosion. It has been suggested that they are products of newly born blackholes with massive accretion disk around them. These systems can be created by explosion of massive stars. When, these massive stars reach to their end, they will get rid of the hydrogen envelope around their heavy core. The core may collapse and form a blackhole with accretion disk around it. These systems can provide the conditions for the fireball model. Collapsars are rapidly rotating massive stars in isolated or binary systems. Accretion of the materials around the blackhole can form a collimated relativistic jet which can be seen as a LGRB if it is toward the earth. Collapsar model have three essential ingredients. The first one is massive core and the second is hydrogen removal mechanism. The star must have got rid of its hydrogen envelope to allow the relativistic jet penetrates into the thin envelope and escapes to the space. The third condition is core high angular momentum ($10^{15} \text{cm}^2\text{s}^{-1}$). The stellar core must have high angular momentum to support transient torus around blackhole. The blackhole itself must have enough angular momentum to make its rotational axis independent of matter and allows the relativistic jet to escape through this axis direction.

1.2.1 Astrophysical scenarios for collapsar model

There are different scenarios which can make a collapsar and at the end a probable LGRB. Some of these correspond to single massive Wolf-Rayet stars and the others are mostly associated with massive stars in binary systems. Many observations of LGRBs, such as association with star forming galaxies and star formation regions, have added support to the collapsar model. Accurate observations of LGRB positions in their host galaxies with Hubble Space telescope carried out by Fruchter et al. in 2006 showed LGRBs, unlike core collapse supernovas, do not follow the light in the galaxy but they are more concentrated at the brightest parts of the galaxy. Later studies also agreed with Fruchter’s results however, it was found that type Ic core-collapse supernovae like LGRBs do not follow the blue light in their host galaxies like other types of supernovas but they are more concentrated again at the brightest parts of galaxies. It seems that type Ic supernovas are associated with LGRBs however, some other observations indicate that not all broad-lined SNe Ic are associated with LGRBs. All of these, motivate us to search for scenarios which support the collapsar model.

In single star models, the star must be massive enough to form a blackhole after core collapse and also must somehow has been removed the hydrogen envelope before the collapsing phase. There are two methods for
hydrogen removal. The first one is valid for stars with strong winds which can remove the whole hydrogen envelope by losing mass due to their strong winds \[12\] and the second one corresponds to stars with extensive mixing which can burn all of their hydrogen to helium \[16\] \[15\]. Mass of single collapsar depends on the metallicity. Stars that lose their hydrogen mantle and still have enough mass to form blackhole lie in a narrow range. They should have $32 M_\odot - 40 M_\odot$ at twice solar metallicity, $34 M_\odot - 60 M_\odot$ at solar metallicity and greater than $60 M_\odot$ at 0.001 solar metallicity. The fraction of stars forming LGRB peaks at around 0.1 solar metallicity for this particular case \[14\]. It is important for single stellar models not to have any magnetic fields included \[33\] \[20\] since magnetic fields can cause strong core-envelope coupling. This coupling reduces the core angular momentum considerably \[33\] \[19\].

Single stars which lose their hydrogen mantle with stellar winds must face with one problem. This mass loss also reduce angular momentum of the star. One way to solve this is to assume a binary system. In binary systems it is possible for one of the stars or even both to remove their hydrogen envelope during common envelope phase without reducing their spin angular momentum. In most binary models; stars may merge at some point and form a single massive star without hydrogen and with large core angular momentum. One of the famous models is He-He merger. In this particular case two massive stars with almost the same mass and age should exist in a close binary system. The first star fills its Roche lobe, expands and consequently the first common envelope phase occurs. Subsequently, the second star may also expand and cause the second common envelope phase to occur. In this stage there are two He cores which circling around each other inside the hydrogen common envelope. These two He cores can merge while at the same time they remove their common envelope. The result is a single He Wolf-Rayet star which can make type Ib/Ic SN or LGRB \[13\].

Large angular momentum problem is one of the obstacles that many have tried to overcome applying a realistic model. According to Petrovic et al. \[33\] magnetic field has the same effect in binary systems as it does in single stars. At first magnetic field can increase the spin angular momentum of the companion core but with the start of core He burning, it can decrease the angular momentum by a factor of 100 faster.

The study carried out by Fryer et al. \[12\] in 1999 has a complete discussion about different scenarios that can form a blackhole with accretion disk around it however, only a few cases are able to make a LGRB using collapsar model. They categorized three different scenarios for LGRB progenitors which one of them is associated with massive single stars and the other two with binary systems. Their figures 11,12 and 13 (figures 1.1, 1.2 and 1.3) show a schematic sketch of these collapsar scenarios. In the first case the iron core of single massive star must collapse and form a blackhole directly. This iron core should have a mass larger than $10 M_\odot$ to avoid supernovae explosion.
and form a blackhole directly. According to MacFadyen and Woosley [28], this core must have an angular momentum between $3 \times 10^{16} - 2 \times 10^{17} \text{ cm s}^{-2}$. This star must also have lost its hydrogen envelope before core collapse and should still have enough angular momentum to form an accretion disk. It can not be achieved easily since mass loss should also cause loss of angular momentum. MacFadyen and Woosley suggested that at low metallicities, conditions for this scenario can be fulfilled easier. Due to weak stellar winds and low mass loss rate, stars are more massive. Low mass loss rate results in smaller loss of angular momentum however, hydrogen removal is a problem in this case since they do not have strong winds.

One way to get rid of hydrogen mantle and not losing the core angular momentum is to form a collapsar in binary system. Binary stars are able to remove their hydrogen envelope during common envelope phase and uncover their He core. If the primary star is massive enough and has sufficient angular momentum, after the common envelope phase it will collapse and

![Scenario X: Collapsar](image)

Figure 1.1: Collapsar formation scenario X proposed by Fryer, Woosley and Hartmann (1999), involving a single star. Wolf-Rayet winds blow off the hydrogen envelope of a rotating massive star, leaving behind a massive helium core, which then collapses to a blackhole.
form a blackhole and collapsar. This is demonstrated in figure 1.2. Unfortunately, both of these scenarios suffer by magnetic braking of the core rotation. Spruit & Phinney [41] in 1998 argued magnetic field can cause the core-envelope coupling - resulting the whole star to rotate as a rigid body which slows down the core rotation however, Zhang & Fryer [47] and Di Matteo et al. [6] argued this last He merger model can also suffer by too much of angular momentum.

Figure 1.2: Collapsar formation scenario XI proposed by Fryer, Woosley and Hartmann (1999), involving a binary system. Primary star loses its hydrogen mantle during common envelope phase and form a collapsar and a LGRB if it is massive enough and has sufficient angular momentum. The remnant could be a BH/WD or BH/NS binary.

There are also some other mechanisms in binary systems that can spin up stars. In 2010 Detmers et al. [5] performed a simulation to investigate tidal interactions in a binary system with Wolf-Rayet star and a compact companion. It has been suggested tidal interactions in close binary systems can spin up the Wolf-Rayet star and increase its angular momentum however, it became clear that this model is not valid in solar metallicity. In fact, it is only valid with low probability at low metallicities. In most cases some
other mechanisms like widening the binary orbit or merging do not let the WR star to produce a collapsar and LGRB.

It seems the third collapsar scenario which Fryer et al. [12] in 1999 have proposed does not have problem with magnetic coupling. In this case binary companions should have comparable masses to evolve simultaneously and leave the main sequence almost together. The primary star expands and first common envelope phase happens. At this time the secondary must also evolve off the main sequence and expands to form the second common envelope. At this stage they can remove their hydrogen envelope. If two He stars merge at this time; they can form a single massive He star with large angular momentum even if their individual cores rotate slowly.

Figure 1.3: Collapsar formation scenario XII proposed by Fryer, Woosley and Hartmann (1999), involving a binary system with comparable masses. Two stars evolve off the main sequence and make double He binary system. They merge and form one massive He star with large angular momentum.

In 2005 Fryer & Heger [13] for the first time simulated merging of two He stars during the common envelope phase. They found out in some cases with low mass loss rate the merger can produce cores that rotate 3-10 times faster than single star models. In their simulation each binary companion has first been evolved as a single star from birth up to a point that common
envelope phase and hence merger starts. This simulation has been done for three different cases with masses of $(8, 16)M_\odot$, $(8, 8)M_\odot$ and $(16, 16)M_\odot$ at the onset of central helium burning. They also used three different mass loss functions for each binary and finally were able to find some cases which can satisfy all three important conditions for making a LGRB. Models which do not have any mass loss or at least small mass loss rate, can evolve more massive binaries and are able to form blackhole much easier.
Chapter 2

Location and Redshift

2.1 Location of LGRBs in their host galaxies

Studying the position of LGRBs in their host galaxies and their redshift distribution can give us valuable information about their possible progenitors. If collapsar model is correct then one can expect that most LGRBs should be located in young star forming galaxies as they are associated with massive stars. In fact, Most of LGRBs are found in extremely blue host galaxies with strong emission lines which show the significant abundance of young massive stars. Fruchter et al. [11] in 2006 used high resolution images available from Hubble Space Telescope and made a sample of 40 LGRBs that have been observed with HST at various times after outburst. They developed a method for comparing LGRBs position in their own host galaxy. This method is independent of the morphology of the host galaxy. They sorted all the galaxy pixels from faintest to brightest and then measured the fraction of total light in the host galaxy which is contained in pixels fainter than or equal to the pixel that is the position of LGRB. Unlike core collapse supernovas which tracks the light of their hosts, LGRBs are not a good tracers. In fact, they are mainly located at the brightest parts of their host galaxies where the most massive O and WR stars are exist.

2.1.1 Is there any relation between LGRBs and young massive stellar clusters?

Young massive stellar clusters are interesting for formation of LGRBs for two main reasons. First, massive WR stars are often located at young massive clusters [4] and second, due to high stellar density in stellar clusters, the rate of stellar collisions and mass transfer is higher which can facilitate the process for forming blackhole that power LGRBs [17]. Portegies Zwart & MacMillan [37] also have argued that BH/BH binaries can be formed in massive clusters. These binaries are close enough to merge and make a LGRB however, they do not form a collapsar. According to collapsar model
progenitors must be massive fast rotating stars. Coalescence of massive stars in young massive clusters is one of the best ways to form such a massive fast rotating star [9]. Portegies Zwart & Van den Heuvel [36] also argued star clusters that experience core collapse before the most massive stars have left the main sequence are able to grow super massive stars via collision runaway. These clusters should be massive and dense enough to guarantee the dynamical core collapse within a few million years. Their calculation showed that there must be between 60 to 600 stars with masses greater than $8M_\odot$ as a product of collisions.

There is also some direct and indirect evidences for occurrence of LGRBs in clusters. For example Fynbo et al. [10] found an object at the location of GRB980425 associated with SN1998bw using high resolution imaging of Hubble space telescope. They argued that the object is a star cluster. Besides that, as it was mentioned earlier Fruchter et al. [11] and Kelly et al. [23] showed that LGRBs are located at the brightest parts of their irregular
and young host galaxies. Young massive clusters are often located in the same regions as LGRBs. Moreover, Chen et al. [3] in 2007 studied the ISM at the birth site of LGRBs and super massive star cluster NGC1705-1. They found many similarities.

All in all, it seems that there should be some correlations between young massive star clusters and long LGRBs however, further studies are necessary in this topic in future before making any conclusion.

2.2 redshift distribution

Redshift distribution of LGRBs can be used as a good diagnostic to distinguish between different progenitors. According to Fryer & Heger [13] at high redshifts or low metallicities single star collapsar model can not survive since this model is highly dependent on the existence of strong stellar winds. At low metallicities stars do not have strong winds and therefore are not able to remove their hydrogen envelope. If massive single stars are the progenitors of LGRBs then one can expect to observe an obvious decrease in LGRB rate at higher redshifts. However, it is vice versa for binary collapsar models. Binary models do not need strong winds to remove their hydrogen envelope. Moreover, at lower metallicities initial mass function will be skewed toward massive stars which increases the probability of making massive binary systems. Therefore, one can expect the number of LGRBs increases at higher redshifts if binary models are their possible progenitors. Besides that, stars are more massive at higher redshifts. Hence there should be a steady evolution of LGRB energy with increasing redshift.

In 2008 Kistler et al. [24] discovered a significant rise in LGRBs rate with increasing redshift at Swift data. They made a sample of 36 luminous LGRBs with redshifts in range of 0 - 4 and found out LGRBs are not following star formation history. Number of LGRBs which has been observed up to redshift 4 was almost 4 times of what one would expect from star formation history. Their figure 4 (figure 2.2) clearly shows the difference between star formation history and Swift data.

In 2010 Campisi et al. [2] also studied the luminosity function and redshift distribution of LGRBs from Swift data. Although, their results for redshift distribution are in agreement with Kistler et al. [24] they argued the best model to produce Swift data is the one which does not have any evolution in luminosity function which implies that high redshift LGRBs are not brighter than low redshift LGRBs. Finding more LGRBs at high redshift is in consistent with binary models according Fryer & Heger [13] however, since stars would become more massive they expected an evolution in luminosity function at higher redshifts which is not observed according to Campisi et al. [2].
2.3 Motivation for binary population synthesis study

Fryer & Heger [13] studied evolution of He-He binaries with certain masses. They found out these mergers are able to fulfill all three required conditions of collapsar model and producing LGRBs at some cases. One can always ask how many of these systems exist in the universe? Are they comparable to LGRBs occurrence rate? How does changing the redshift and metallicity affect these systems? etc.

Only a few percent of binaries are close and massive systems and even between this tiny group figure 2.3 clearly shows He-He merging is a quite rare phenomena which does not take place so frequently. Moreover, only some of these He-He mergers are able to to produce a blackhole. Fryer & Heger table 1 (figure 2.4) represents their simulation with different initial masses and mass loss functions. Only half of their mergers formed blackhole. This implies that the fate of He-He mergers is strongly depend on their properties like mass loss function.

In order to find out if He-He mergers are the dominant progenitors, population synthesis study can be very useful. These kind of studies can be used to estimate their birth rate in different metallicities and compare it to the observed LGRB rate. Even more, one can expect He-He mergers to be more abundant and massive at higher redshifts or lower metallicities if they are the dominant progenitors.
Figure 2.3: Fate of close massive binary stars as proposed in 2005 by Fryer & Heger. Systems with almost the same mass may merge and remove their hydrogen during double common envelope phase. Between these mergers only a few of them will produce a single WR star and Collapsar.

Summary of Simulations

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Binary Masses ($M_\odot$)</th>
<th>Angular Momentum ($10^{57}$ ergs s)</th>
<th>KEPLER Mapping</th>
<th>Remnant Fate</th>
</tr>
</thead>
<tbody>
<tr>
<td>M88a</td>
<td>8 + 8</td>
<td>2.4</td>
<td>1</td>
<td>NS</td>
</tr>
<tr>
<td>M88b</td>
<td>8 + 8</td>
<td>2.4</td>
<td>2</td>
<td>NS</td>
</tr>
<tr>
<td>M88c</td>
<td>8 + 8</td>
<td>2.4</td>
<td>3—no wind</td>
<td>BH</td>
</tr>
<tr>
<td>M1616a</td>
<td>16 + 16</td>
<td>7.3</td>
<td>1</td>
<td>BH</td>
</tr>
<tr>
<td>M1616b</td>
<td>16 + 16</td>
<td>7.3</td>
<td>2</td>
<td>NS</td>
</tr>
<tr>
<td>M1616c</td>
<td>16 + 16</td>
<td>7.3</td>
<td>3—no wind</td>
<td>BH</td>
</tr>
<tr>
<td>M816a</td>
<td>8 + 16</td>
<td>2.3</td>
<td>1</td>
<td>BH</td>
</tr>
<tr>
<td>M816b</td>
<td>8 + 16</td>
<td>2.3</td>
<td>2</td>
<td>NS</td>
</tr>
<tr>
<td>M816c</td>
<td>8 + 16</td>
<td>2.3</td>
<td>3—no wind</td>
<td>BH</td>
</tr>
</tbody>
</table>

Figure 2.4: Summary of Fryer & Heger (2005) simulations of He-He mergers. They used KEPLER code (Heger et al. 2000 [13]) for the evolution until the onset of core collapse. Three different mass loss function are used. Briefly, 1 corresponds to removing the super Keplerian mass, 2 corresponds to the enhanced rotational mass loss and 3 corresponds to the case which they have turned off mass loss for the entire stellar life. For more details refer to [13] and [18].
Chapter 3

He-He mergers population synthesis study

3.1 SeBa

SeBa is a model developed by Portegies Zwart & Verbunt [38] for the evolution of single stars and binary populations. SeBa has three different steps. The first step is evolution of single stars. There are two important parameters that affect the interaction of single star with its companion in a binary system, its mass and radius. They have used equations given by Eggleton et al. [8] for describing the evolutionary stages of single star and estimating these parameters. In SeBa, it is assumed that stars more massive than $25M_\odot$ should lose their envelope due to radiation pressure and leave only the He core. These stars will become Wolf-Rayet. At the end, stars with masses between 8 to 40 $M_\odot$ must form a neutron star and stars with masses larger than 40$M_\odot$ should end up as a blackhole. Stars with initial masses less than 8$M_\odot$ are assumed to form a white dwarf.

Second step is the evolution of binaries. They have defined three different kinds of binary systems which follow different evolutionary paths - detached, semi detached and contact binaries. In detached binaries both stars are smaller than their Roche lobe radius. These binaries can evolve via tidal interactions, radiation of gravitational waves and evolution of each star. If one of the stars expands or the orbit shrinks then it is possible that one of the them fills its Roche lobe radius. In this case binary can evolve one step further and become a semi detached system. Then mass transfer from the star which has filled its Roche lobe to its companion may occur. This process can also cause mass and angular momentum loss from the whole binary. If mass transfer is unstable then spiral in is inescapable. The result would be ejection of the envelope or merging.

Binary evolution can continue to form a contact binary which both stars have filled their Roche lobe radius. This can take place either by shrinking
the orbit or stars expansion due to their interior evolution. These systems are mostly stable and any change in system parameters is due to gravitational waves, stellar winds and magnetic braking however, whenever one of the stars evolves to the giant branch then the system will become unstable, spiral in may happen and the result would be a merger.

There are many mechanisms that contribute to binary evolution- stellar winds, gravitational wave radiation, tidal interactions and circularization, magnetic field, supernovae kick, etc. In general, these processes can cause mass and angular momentum loss in a binary system which plus the interior evolution of each star are responsible for changing the orbital parameters.

Third evolutionary step in Portegies Zwart & Verbunt [38] is initializing the binary population parameters. SeBa accept four main initial parameters to simulate a population of binaries. A binary system can be characterized by its primary mass $M$, mass ratio $q$, semi major axis $a$ and eccentricity $e$. They have assumed these four initial parameters have distribution functions.

In recent version of SeBa which has been used in this research, description of single stars are based on Hurley et al. [22] instead of Eggleton et al. [8]. This recent formula is metallicity dependent. Therefore, it is also possible to choose the initial metallicity of the stars which affects the evolution of stars and consequently binary system.

There are five different initial mass function available with SeBa- equal mass, power law, Miller & Scalo [30], Scalo [40] and Kroupa et al. [26]. Mass ratio has also different distributions which are Constant, flat, power law and Hogeveen [21]. Semi major axis has three different statistics- equal, power law and Duquennoy & Mayor [7]. The last one eccentricity follows also three distribution functions- equal, power law and thermal.

### 3.2 Simulation

SeBa has been used to simulate six populations of one million binary systems with different metallicities and then to search for binaries which have merged during their double common envelope phase when both primary and secondary were He star or He giant. There are only a few of these systems available while most binaries merged before the secondary could expand and form a double common envelope. Studying the evolution of binary populations at different metallicities are quite critical to check the validity of LGRB progenitor binary models. As it is explained in section 2.2, redshift distribution of LGRBs can be used as a good diagnostic for distinguishing between different LGRB progenitor scenarios. According to Swift data there is a rise in LGRB rate at higher redshifts up to the four. If He-He mergers are the dominant scenario, one can expect to make more of these mergers by decreasing the metallicity or increasing redshift since metallicity is a function of redshift in our universe. This is what that has been checked in this
research. SeBa has been used to simulate different binary populations with
variety of initial parameters and metallicities and to track each binary from
the birth time to the end however, SeBa is not able to track the fate of
mergers. According to Fryer and Heger [13] not all He-He mergers can make
a blackhole and LGRB at the end. More studies is necessary to investigate
the merger remnants.

3.2.1 Initial conditions

In this research six different simulations with one million binaries per each
has been done. All the initial parameters are exactly the same in all of
these simulations except the metallicity. Table 3.1 shows initial parameters
with their distribution functions. Since we are interested only in massive
stars, the minimum initial mass has been chosen to $8M_\odot$. There is also
a limit for maximum mass since extremely massive stars are not stable.
Initial mass function is a power law with exponent equal to -2.35 according
to Salpeter [39]. Semi major axis distribution has been chosen from Abt [1]
and Kraicheva et al. [25].

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Distribution function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min mass $m/M_\odot$</td>
<td>8</td>
<td>Salpeter IMF</td>
</tr>
<tr>
<td>Max mass $M/M_\odot$</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Min mass ratio $q$</td>
<td>0.08</td>
<td>Flat</td>
</tr>
<tr>
<td>Max mass ratio $Q$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Min semi major axis $a/R_\odot$</td>
<td>1</td>
<td>$P(a) \propto a^{-1}$ (Abt)</td>
</tr>
<tr>
<td>Max semi major axis $A/R_\odot$</td>
<td>10000</td>
<td></td>
</tr>
<tr>
<td>Eccentricity $e$</td>
<td>0</td>
<td>Equal</td>
</tr>
<tr>
<td>Evolution time $t \times 10^6 yr$</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Number of binaries $n$</td>
<td>$10^6$</td>
<td></td>
</tr>
</tbody>
</table>

Simulations have been done from very low (0.0001 [Fe/H]) to very high
(0.03 [Fe/H]) metallicity environments. This enabled us to study the varia-
tion of different characteristics of He-He mergers as a function of metallicity.
3.2.2 Results

As mentioned earlier, simulations have been done for six different metallicities (0.0001, 0.002, 0.003, 0.01, 0.02 and 0.03 [Fe/H]). First interesting result to look at is the number of He-He mergers formed in different metallicities. Figure 3.1 shows number of He-He mergers with final masses $M_{pf,sf} \geq 1M_\odot$. It is obvious that by increasing the metallicity number of these mergers rises. Although, not all of these mergers are able to make a collapsar. Only the most massive ones are the possible LGRB progenitors. Figure 3.2 represents exactly the same thing as figure 3.1 but this time He-He mergers with final masses $M_{pf,sf} \geq 2M_\odot$ has been chosen. In this case there are only a few mergers out of one million binaries that have final masses larger than two solar masses per each companion. One should notice that at lower metallicities they are more probable. It is in consistent with stellar evolution models. At lower metallicities stars does not have strong winds and so mass loss rate is small. Stars are more massive and the probability to make massive binaries is higher.

Figures 3.3 to 3.9 show some diagnostics of He-He mergers. In all of these diagrams at $z = 0.0001[Fe/H]$, He-He mergers with final masses larger than $2M_\odot$ per each star are plotted with filled squares and different color. From now on they will be called as population B binaries. The rest are plotted with filled circles. Primary initial mass vs orbital initial separation has been plotted in figure 3.3. At low metallicity ($z = 0.0001[Fe/H]$) there are three groups of binaries which end up as a He-He mergers. One with almost constant orbital separation (20$R_\odot$) and a wide range of masses from 12$M_\odot$ to 17$M_\odot$. The other two groups have different orbital separation and are not shown in the figure.
Figure 3.2: Number of He-He mergers with $M_{p,s} \geq 2M_\odot$ out of one million binaries in different metallicities. Unlike figure 3.1 at lower metallicities there are more massive He-He mergers.

to $18M_\odot$. The second group have almost a constant mass $10M_\odot$ but with wide range of orbital separation. This recent group is mostly dominated by population B binaries. The third group are less massive with almost constant mass of $8M_\odot$. By increasing the metallicity these three populations reduce to only two groups. Population B binaries are not distinguished in diagrams for higher metallicities since they are quite a few.

Figure 3.4 shows Primary and secondary initial masses at different metallicities. Stars are following two lines with different slopes in this diagram. The first group has almost mass ratio $q \approx 1 \pm 0.1$. There is a gap in this group specially at $z = 0.0001$ which separate population B stars from the rest. One should notice that population B stars always have initial masses larger than almost $9.5M_\odot$ with mass ratio around $q \approx 1$. The second line are full of stars with different companion masses. By increasing the metallicity binaries are mostly tend to be at the second line. There are only a small fraction of He-He mergers which still have mass ratio $q \approx 1 \pm 0.1$ at higher metallicities. The fact that He-He mergers are tightly lined up is an interesting point for future studies.

Final secondary and primary masses at different metallicities is represented at figure 3.5. At very low metallicities there are still three groups of stars with mass ratio $q < 1 \ , \ q \approx 1 \ and \ q > 1$. An interesting point about this diagram is that population B stars are not the ones with $q \approx 1$ as they were before but they mostly have $q < 1$. At $z = 0.002$ and $z = 0.003$ there are a few very massive stars which can not be seen at any other metallicity. In fact, they belong to population B stars however, they are not shown with filled squares in these sketches. In these systems the secondary star is al-
most 3 to 5 times more massive than the primary which implies a lot of mass transfer during the evolution. This huge mass transfer causes a big mass difference for the primary and secondary. One should notice that despite of big mass difference at final stages they both are He stars and perhaps have experienced double common envelope phase. At higher metallicities stars are less massive and almost there are no population B binaries however, number of He-He mergers rises.

Most of He-He mergers have periods around \( p = 0.001 \text{day} \). Changing the metallicity does not change their period distribution that much. Therefore, it seems that He-He mergers final period is independent of the metallicity. They are mostly distributed symmetrically around \( p = 0.001 \text{day} \). Figure 3.6 shows that mergers periods with good approximation do not depend on their mass ratios too.

Binary total mass distribution which is represented at figure 3.7 expresses that most of He-He mergers have total masses around \( 3M_\odot \) to \( 4M_\odot \) which seems to be independent of metallicity however at \( z = 0.0001 \) binaries with masses around \( 6M_\odot \) are also abundant. It is quite interesting that at \( z = 0.002 \) and \( z = 0.003 \) there are more massive binaries that even can not be seen at \( z = 0.0001 \). There must be a limiting threshold metallicity that these massive He-He mergers would not be able to form at metallicities lower than that. More studies is necessary to understand the reason.

Figures 3.8 and 3.9 are showing the orbital angular momentum of binaries vs total binary mass and final mass ratio. Orbital angular momentum rises in all metallicities with increasing binary mass. Since stars are more massive at lower metallicities, binaries have larger orbital angular momentum while population B binaries mostly have the largest amount of it between the rest of He-He mergers. According to figure 3.9 it seems there is a rise for orbital angular momentum of population B binaries while mass ratio increases however, it is almost independent of \( q \) and is constant for the rest mergers. It is very interesting for future studies to figure out why population B He-He mergers which suppose to differ only in their masses with the rest, have different behavior. Why orbital angular momentum in population B depends on final mass ratio of the binary but it is independent of \( q \) for the rest?

### 3.3 Conclusion

Between different scenarios for long gamma ray burst progenitors, collapsar model is the most accepted one in recent years. It is clear that LGRBs are associated with star formation regions and massive stars or even more precisely with type Ic core collapse supernovae however, despite all observations that have been done and all different scenarios that have been made, still it is not obvious what kind of objects are exactly responsible for all detected
LGRBs. According to Fryer & Heger [13] He-He mergers are able to satisfy all three necessary conditions to make a collapsar and then a gamma ray burst. These mergers can remove their hydrogen envelope without angular momentum loss during double common envelope stage which is a great advantage for this model. One way to figure out if they are dominant LGRB progenitors is to do population synthesis study and compare the number of He-He mergers with core collapse supernovas.

Fryer et al. [14] argued only a small fraction (≈ 0.01) of all core collapse supernovas can be a LGRB. Their estimation are corroborated by radio survey of supernovae remnants [42] [15]. Other people are even more pessimistic. For example Langer & Norman [27] and Porciani & Madau [35] believe there is only 1 LGRB for every 1000 core collapse supernovae in the universe.

Table 3.2: Ratio of He-He mergers over core collapse supernovas at different metallicities

<table>
<thead>
<tr>
<th>$[Fe/H]$</th>
<th>$Z_{Fe/H}$</th>
<th>$N_{SNe}$</th>
<th>$N_{HeHe}/N_{SNe}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001</td>
<td>1156792</td>
<td>0.00035</td>
<td></td>
</tr>
<tr>
<td>0.002</td>
<td>982177</td>
<td>0.00066</td>
<td></td>
</tr>
<tr>
<td>0.003</td>
<td>989432</td>
<td>0.00067</td>
<td></td>
</tr>
<tr>
<td>0.01</td>
<td>86541</td>
<td>0.00013</td>
<td></td>
</tr>
<tr>
<td>0.02</td>
<td>825392</td>
<td>0.00023</td>
<td></td>
</tr>
<tr>
<td>0.03</td>
<td>811315</td>
<td>0.00032</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.2 shows number ratios of He-He mergers over core collapse supernovas at different metallicities which have been studied in this research. At low metallicities this ratio is around $3 \times 10^{-5}$ to $6 \times 10^{-5}$ which is smaller than the observed number by a factor of two magnitudes. This implies at the most optimistic case only 1% of the observed LGRBs are associated with He-He mergers. At higher metallicities the situation is better although it is still smaller than the observed ratio by a factor of 0.1. Besides that, He-He mergers at higher metallicities have small masses however, they are more abundant. If one considers only population B mergers as the possible progenitors then at $z = 0.0001$ the ratio is $N_{HeHe}/N_{SNe} \approx 1.3 \times 10^{-5}$ which is very small and for higher metallicities it is almost negligible.

All in all, it seems He-He merger scenario is not the dominant LGRB scenario since it is not able to produce the observed number of LGRBs. Albeit He-He mergers can provide all ingredients for collapsar model much easier comparing to the other scenarios like single star models, it seems the abundance of these merging systems is smaller than the number of long gamma ray bursts in our universe.

Acknowledgements

I am indebted to Prof. Simon Portegies Zwart who supervised me with this research and made his binary population synthesis code SeBa available for my purpose. I also would like to thank Silvia Toonen for her help and useful comments specially about SeBa.
Figure 3.3: Primary initial mass vs orbital initial separation for different metallicities. At really low metallicity there are three different populations. One with almost constant orbital separation (20\,R\odot) and a wide range of different masses. The second population have almost a constant mass 10\,M\odot but with wide range of orbital separation. The third population are less massive with almost constant mass of 8\,M\odot. By increasing the metallicity these three populations reduce to only two groups. Filled squares are representing He-He mergers which have at least masses of 2\,M\odot per each star at the final evolutionary stages.
Figure 3.4: Secondary initial mass vs primary initial mass for different metallicities. Stars are following two different lines, one with almost equal masses and one with mass ratio between $q = 0.5$ to $q = 0.6$. At low metallicities there is a gap between the first population ($q \approx 1$). At higher metallicities stars are tending to be in the second population. Filled squares are representing He-He mergers which have at least masses of $2M_\odot$ per each star at the final evolutionary stages.
Figure 3.5: Secondary final mass vs primary final mass for different metallicities. At $z=0.0001$ clearly there are three different populations with $q \approx 1$, $q > 1$ and $q < 1$. At $z = 0.002$ and $z = 0.003$ there are some really massive He stars which do not exist at other metallicities. By increasing the metallicity He-He mergers have formed more often at regions with $q > 1$. Filled squares are representing He-He mergers which have at least masses of $2M_\odot$ per each star at the final evolutionary stages.
Figure 3.6: Final mass ratio vs final period at different metallicities. It is obvious that most of He-He mergers have period with the order of minutes which is independent of metallicity and mass ratio. Another point is that there are always a few He-He mergers with $q \approx 1$. Filled squares are representing He-He mergers which have at least masses of $2M_\odot$ per each star at the final evolutionary stages.
Figure 3.7: Number of He-He mergers vs total binary final mass at different metallicities. The peak is located between $3M_\odot$ to $4M_\odot$ however at $z = 0.0001$ there is another peak at $6M_\odot$. The maximum binary mass is around $6M_\odot$ or $7M_\odot$ though, at $z = 0.002$ and $z = 0.003$ there are few massive binary systems with masses larger than $10M_\odot$. 
Figure 3.8: Final orbital angular momentum vs total binary mass at different metallicities. Unlike other diagnostics, He-He mergers are almost lined up along one curve and can be categorized in only one group instead of two or three however, at \( z = 0.0001 \) there is a gap between population B stars (shown by squares) and the rest. These population B binaries have the highest angular momentum. Binaries at lower metallicities have higher angular momentum since they are more massive.
Figure 3.9: Final orbital angular momentum vs final mass ratio at different metallicities. At higher metallicities orbital angular momentum is independent of mass ratio but at lower metallicities population B binaries angular momentum depends on their mass ratio and by increasing $q_f$ it also will rise. Filled squares are representing population B binaries at $z = 0.0001$. 
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