On The Run: How Fast Runaway Stars Can Escape From Their Home Cluster?

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Abstract

Galaxies contain a wide variety of star clusters with different properties. Each cluster is a possible source of runaway stars, which can be progenitors of supernovae in other parts of the galaxy than their home cluster. Considering runaway stars in galaxy simulations has shown to increase the galactic feedback. This project investigates how the initial condition of a star cluster affects the velocity distribution of runaway stars. To do this, I performed simulations of star clusters solving the N-body problem with the NBODY6tt code. First, different initial conditions for each cluster are simulated, with varying half mass radius and primordial binary fraction. This is followed by an analysis of the velocity distribution for each simulated cluster after 40 Myr.

Dark matter is not taken into consideration in these simulation. Including dark matter components would imply an added gravitational force acting on each star in the cluster, and thus a higher escape velocity needed to be ejected. Thus, one can argue that including dark matter would result in less runaway stars being produced by the cluster, but should however be investigated further.

With initial radii of 1 and 10 pc, the bigger clusters produce fewer runaway stars after 40 Myr compared to the cluster with a radius of 0.1 pc. This result is because the interaction rate between stars is longer for clusters with greater radii.

The number of ejected stars from a system increases when primordial binaries are introduced. However, the velocity distribution of a bigger cluster does not change when increasing the binary fraction with a factor of 2. The results imply that initial conditions of the star cluster affect the velocities of runaway stars. Consequently, it means that if runaway stars are included in galaxy simulations, the variations of initial conditions in star clusters should be considered. Instead of generalising the velocity distribution of runaway stars, the differences shown in this project should be taken into account. It can change how far runaway stars travel away from their home cluster, but also how many of these stars end up in a new environment, far from their home cluster.

Further investigation on which initial conditions affect the velocity distribution of runaway stars is needed. Especially a deeper understanding of how primordial binaries can be implemented in N-body simulations is of high interest. However, I leave it to future projects to continue an exploration of this parameter space in detail.

Populärvetenskaplig beskrivning

Metoderna för att testa olika hypoteser har genom åren utvecklats drastiskt. Fortfarande finns många experiment som utförs på det klassiska viset i en laborationssal, med fysiska hjälpmedel och mätverktyg för att få fram en slutsats. Dock har den omfattande tekniska utvecklingar breddat möjligheten för vilka hypoteser som är testbara. Genom simuleringar kan tidigare omöjliga teser kontrolleras och mängder av olika scenarion kan undersökas, med endast några få justeringar i parametrar.

Men även i denna teknik-dominerade värld stöter forskare på problem med att skapa realistiska simuleringar med hög noggrannhet. Detta gäller även för astrofysiker när de i sitt arbete strävar efter högupplösta och fysiskt korrekta resultat. I simuleringar av galaxer har det fram tills nyligen varit vanligt att bortse från de stjärnor som på engelska kallas runaway stars. Dessa flyende skenande stjärnor har genom interaktioner med andra stjärnor flytt sitt hem-kluster.

Tidigare argument för att ignorera dessa flyende stjärnor har dels varit för den låga optiska upplösningen. Dels har uppfattningen att individuella stjärnor inte skulle påverka den stora strukturen som en galax utgör. Detta tillsammans med det svåra beräkningsarbete som skulle krävas, har gjort att astrofysiker inte brytt sig om inkludera dessa stjärnor i sina galax simuleringar.

Nyligen publicerat arbete från Institutionen för astronomi och teoretisk fysik vid Lunds Universitet visar dock hur inräkningen av runaway stars har en tydlig effekt på galaxens energi och evolution. Men det finns fortfarande oklarheter i vilka parametrar och förutsättningar som påverkar dessa stjärnors hastigheter.

Föreställ dig att du är en massiv stjärna liggandes på din dödsbädd, vilken sekund som helst redo att explodera som en supernova. Detta kommer du symbolisera genom att trycka ut dina armar från din kropp, i ett försök att pressa ifrån dig så mycket gas som möjligt i din omgivning. Om du är omgiven av flera människor som står nära dig fysiskt, kommer det vara svårare för dig att ta ut dina armar. I motsats kommer det vara väldigt lätt för dig om du gör denna manöver i ett rum där du är ensam. Samma analogi kan göras med dessa runaway stars. När de dör och exploderar långt utanför sitt hem-kluster, kan detta ske i en region av galaxen som har lägre densitet. När denna typ av explosion sker i en lägre densitet, kommer energin att fördelas i galaxen på ett annorlunda sätt, än om den flyende stjärnor dog i sitt hem-kluster.

Vad som avgör hur långt en runaway star kan färdas beror på dess hastighet. Eftersom den nya positionen hos kommande supernovor är viktig för galaxens utveckling, är det av största vikt att förstå hastighetsfördelning på de rymmande stjärnorna. Målet med detta projekt är att undersöka vilka olika initiala parametrar hos stjärnkluster det är som påverkar hastighetsfördelningen. En större förståelse för detta kommer leda till en ökad kunskap gällande den roll som runaway stars spelar i galax-simuleringar. Detta i sin tur kommer att öka skapandet av mer realistiska simuleringar och därmed även förståelsen för alla de galaxer Universum innehåller.

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Chapter 1

Introduction

The Universe contains a wide variety of galaxies, many similar to that in shape and components. There are, however, differences which can be attributed to how a galaxy forms and subsequently evolves. It is important to know how these behave since they contain a majority of the celestial objects scientists are interested in. Different scenarios are often simulated and tested on computers to expand our understanding of this. Simulations of realistic galaxy formation have improved over the last decades through numerical and computational advances. Different models suggest numerous methods to investigate various parameters in the evolution of the galaxy and connect these with real observations. As technology and instruments improve, our ability to study and obtain data on the structure of galaxies also increases. Current obstacles include spatial resolution and accounting for details. Both on the cosmological scale with the cosmic web and the impact of stellar feedback (Somerville & Davé 2015).

This stellar feedback shows to be very important in galaxy formation since it affects the interstellar medium, ISM. One contribution to the added energy in the feedback is the energy explosion originating from supernovae (Grisdale 2017). Energy explosions in low-dense regions can repel gas more efficiently than in denser regions, hence impacting the galactic outflow more. The location of the supernovae is therefore of interest when stellar feedback is taken into account in galaxy simulations.

Progenitors of supernovae in a region with lower density can originate from nearby star clusters, from which they have been ejected. Massive stars that leave their home clusters with a high velocity are called runaway stars. There exist no strict limit for what is the exact value for which values higher are classified to be a high velocity, but v>30 km/s is often used (Oh & Kroupa (2016), Andersson et al. (2020), Eldridge et al. (2011)) but other suggested values at v>40 km/s exist (Perets & Šubr 2012). Even if ejected massive stars with lower velocities exist, they do not have time to travel sufficiently far away from the cluster before dying. They can still be assumed to deposit their energy in the cluster. The high velocity and massive stars are of interest as they may end up in a new environment when ending their life as supernovae.

1.1 Runaway stars

What produces these runaways are star-star interactions within a cluster. Stars ejected from the cluster's gravitational well have a certain velocity. One way of obtaining these velocity kicks was first suggested by Blaauw (1961), where the more massive star in a binary system explodes as a supernova. When this happens, the second component of the system will no longer experience the gravitational force from its previous companion and as a result be ejected from the cluster (Eldridge et al. 2011; Oh & Kroupa 2016). This process happens after a few million years as it depends on the lifetime of the more massive star in the binary system. Motivated by the work done by Keller & Kruijssen (2022), a lower mass limit of 8 $M_{\odot}$ is chosen. The lower mass limit for the progenitors of supernovae is more important than the upper limit since it sets the maximum lifetime for which these stars evolve (Keller & Kruijssen 2022). A maximum timescale of 40 Myr is also chosen. Even if it may be an upper limit for the lifetime, it ensures all velocity kicks from the star cluster are included.

Another way of gaining energy sufficient enough to escape is through converting binding energy to kinetic energy through dynamical interactions for a star with a binary system. This process has no dependence on the lifetime of massive stars and can therefore occur earlier in the evolution of the cluster (Oh & Kroupa 2016). The two interactions are the main origins of producing runaway stars in clusters. However, it is still somewhat unclear what affects the kinetic energy of these ejected stars and the velocity distribution they give rise to.

1.1.1 Previous work

An earlier study by Oh & Kroupa (2016) focused on how the initial conditions of star clusters can influence the properties of dynamically ejected runaway stars. However, they focused more on the properties of the dynamically ejected stars and not the velocity distribution of these systems (Oh & Kroupa 2016).

A recent study has revealed the importance of including runaway stars in galaxy simulations. Andersson et al. (2020) was the first to show how the ejected energy from these supernovae has an effect on the galactic outflow and how wrong the neglecting of runaway stars is for the galaxy formation.

The results produced by Andersson et al. (2020), however, assume one velocity distribution for all runaway stars and do not take into consideration that properties like radius and binary fraction of the cluster might affect this. They discuss that the variation of initial conditions for star clusters should be taken into consideration even for larger-scale simulations since it might change how long runaway stars travel from their home cluster (Andersson et al. 2020).

A full exploration of the parameter space of star clusters and how, if, they affect the velocity distribution of runaway stars must be performed. Inspired by the work done by Oh & Kroupa (2016), a couple of initial parameters are chosen to be investigated in detail. By varying one initial condition at a time, each concept is evaluated and its importance in the producing of runaway stars. If multiple parameters are changed simultaneously, one might be able to deduce whether the effects cancel or amplify when combined.

This thesis describes the exploration of parameter space of initial conditions for star clusters and how it affects the velocity distribution of massive runaway stars. Starting with a description of the N-body problem and code used for simulations in chapter 2, I then explain why variations of each initial parameter are important to consider in chapter 3 together with the results. Next, chapter 4 contains a discussion of the results, assumptions made and future projects. Finally, a conclusion about the project is done in chapter 5.

Chapter 2

Method

2.1 N-body problem

The trajectory of each star in a star cluster with N stars follows Newtonian dynamics, where all stars experience the gravitational force from the N-1 other stars in the system. Since every star travels with a given velocity and is affected by the other, it is located differently after each time step, and the total gravitational influence from the N-1 stars must be calculated again. The integration of the star's motions can be done numerically with different codes solving the N-Body problem. (Khalisi & Spurzem 2014). One of the most well-known and used code is the NBODY code by Aarseth (1963), which since the early 1960s have been under development, presenting new, improved versions numbered NBODY0-7. The version called NBODY6 has been used for the simulations in this project and is written in FORTRAN. It generates a star cluster based on a number of initial parameters set by the user in an input file. The integration time step is given in the same input file, and each star's properties (e.g. velocity, position, mass) are written in an output file for every snapshot. Several other files are created during the simulation, e.g. a file with any occurring errors or warnings, to locate any problems if a simulation for some reason was interrupted or crashed (Khalisi & Spurzem 2014). Information about the individual stars must be read from the binary format it is created in. Not only to provide data that can be analysed but to obtain and convert the correct units from the simulation.

2.1.1 Plummer's density profile

Plummer model is applied to the clusters gravitational potential and is

$$\Phi = -\frac{GM}{\sqrt{r^2 + b^2}}, \tag{2.1}$$

where G is the gravitational constant, M the total mass of the cluster, r the distance, and b the Plummer scale length which is a constant. It generates a density on the form

$$\rho(r) = \frac{3M}{4\pi b^2}\left(1 + \frac{r^2}{b^2}\right)^{-5/2}. \tag{2.2}$$

The Plummer model describes a system where the density is approximated to be constant in the core of the system but decreases and goes to zero as we go outwards. Equation (2.2) has been used by Plummer (1911) to describe the distributions of stars from observations (Binney & Tremaine 2008).

2.1.2 Galaxy - external force on star cluster

Simulating a star cluster without any external force can be a convenient simplification when the internal dynamics of the cluster are considered. Then the assumption that any star with energy $E < 0$ is bound to the cluster can be made. However, the presence of an external gravitational force F_{galaxy} has consequences on the energy boundary of what belongs in the cluster or not. This force arises from the potential energy all the mass in the galaxy contributes.

This is an important concept to keep in mind for simulations since it changes the critical energy needed for a star to escape and be considered outside the cluster. If one assumes a point mass cluster with mass m to give rise to a spherical potential limit, the potential of the galaxy it is located in produces a total asymmetric potential boundary due to tidal forces.

The tidal effect on the cluster's potential is a compression in the axes perpendicular to the line between the galactic centre and the cluster. There is also an elongation of this energy limit in the direction towards the centre of the galaxy, creating an almost lemon shape described by Renaud et al. (2011).

Lagrange points are defined as the location between the cluster and galactic centre, where there is a balance between the two gravitational forces, $F_{cluster} = F_{galaxy}$. The tidal radius is the distance between the cluster's point centre out to the Lagrangian point, describing a sphere (Renaud 2018). As already mentioned that the assumption of a symmetric sphere is somewhat misleading; the more realistic lemon shape approach should be considered. Nonetheless, a mathematical correct potential limit is computationally heavy and the spherical assumption is often applied. The error between the real critical energy and the sphere with a radius equal to the tidal radius is small relative to other approximations in star clusters simulations and hence negligible.

Including a galaxy and external potential in a N-Body problem requires a method refined by Renaud & Gieles (2015) called Nbody6tt. Assuming the external potential can be described as a numerical routine and the initial position and velocity of the cluster's centre is given, Nbody6tt produces accurate simulations including tidal forces (Renaud & Gieles 2015).

2.1.3 The NBODY6tt code

NBODY6tt is an extended version of the NBODY6 code. One of it's extended characters is the possibility of adding a galaxy to the cluster's environment. This is done by introducing the tidal tensor arising from the external force in the form of a galaxy potential to the star cluster simulation (Renaud 2018). There are similarities between NBODY6tt and the

NBODY6 code, so a guide dedicated for the later is used in this project, taken from Khalisi & Spurzem (2014).

Several input parameters are given in a specific order, and one example is illustrated in table 2.1. Depending on desired initial conditions of the star cluster and galaxy, the input file varies.

```
1 10000.0
4000 1 50 92 200 1
0.01 0.01 0.35 0.1 3.0 400 1000.0 0.1 1.0
1 2 1 0 1 0 5 0 0 0
0 1 0 0 2 1 1 1 3 0
1 0 0 0 0 2 0 1 0 1
1 0 0 0 1 0 0 1 0 3
0 0 0 0 0 0 0 0 0 0
1.0E-04 0.001 0.2 1.0 1.0E-06 0.001
2.3 120 0.1 0 0 0.02 0.0 0.1
0.5 0.0 0.0 2.0 0.125
```

Table 2.1: Example of different values for the the input file used by Nbody6tt code to run in simulations.

Only the input parameters are varied, and the final output is analysed. More information about the specific details on how the code operates is found in previous work; see Khalisi & Spurzem (2014); Renaud (2018).

Due to time limitations, the addition of an external force must be investigated in future projects. Possible effects of the presence of a galaxy are, however, discussed under section 4.1.2.

2.2 Escape velocity

Every star has an individual escape velocity. This is the velocity needed for a star to have enough kinetic energy to overcome the potential energy, i.e. $E_{kin} = E_{pot}$. For a star with mass $m_\star$ and located a radial distance $R_\star$ from the centre, the escape velocity v_{esc} is calculated as

$$\frac{m_\star v_{esc}^2}{2} = \frac{GM_{encl} * m_\star}{R_\star} \tag{2.3}$$

$$v_{esc} = \sqrt{\frac{2GM_{encl}}{R_\star}}. \tag{2.4}$$

Where G is the gravitational constant and M_{encl} is the enclosed mass experienced by the given star. This results in different escape velocities for all stars since it depends on the enclosed mass and not the star's mass itself.

Chapter 3

Results

When exploration of parameters space is performed, it is convenient to have a reference cluster that all simulations start from. The cluster chosen to be the initial starting point is designed to show strong dependency on any effects of varied parameters. This is achieved with a small cluster with a half mass radius of 0.1 pc and 4000 stars. Even if such a small size and number cluster is not realistic, it can be more effective in demonstrating what behaviour the runaway stars have when initial conditions are varied. The initial mass function of our reference cluster follows a defined power law function with a negative slope of 2.3. The choice is based on the well known Salpeter (1955) IMF.

The maximum mass an individual star can have is chosen to be 120 $M_\odot$, and a minimum limit of 0.1 $M_\odot$ is set as well. When the cluster evolves, it forms binary systems, but the primordial binary fraction is chosen to 0% for the reference system. It is still debated what the typical value for the initial fraction of binaries star cluster is. This project assumes a spherical symmetry with the star's starting position following a Plummer (1911) distribution. The shape of the cluster's potential as a function of radius gives its density profile. This can be the explanation for why the centre of the reference cluster is not located at exactly origin in figure 3.2. Small fluctuations and the inner structure of the cluster can also shift the centre in this way.

Stellar evolution is activated for every simulation to obtain more realistic results. The evolution of a binary system is described as for a single star, arguing that no other methods for binaries are currently available. Accounting for stellar evolution leads to a decreasing total mass of the cluster over time (Khalisi & Spurzem 2014).

O star and massive B stars with mass $m > 8M_\odot$ have a lifetime shorter than 40 Myr. Based on this, I analyse the results of the cluster simulation after 40 Myr. This ensures all velocity kicks have happened and since the number of ejected stars and their velocities are of interest, the specific time is not of great importance.

Radial velocity and enclosed mass

Figure 3.3 shows the radial velocity as a function of radius for a 0.1 pc cluster with 4000 stars, together with the escape velocity for each star at a given radius. Some of the stars

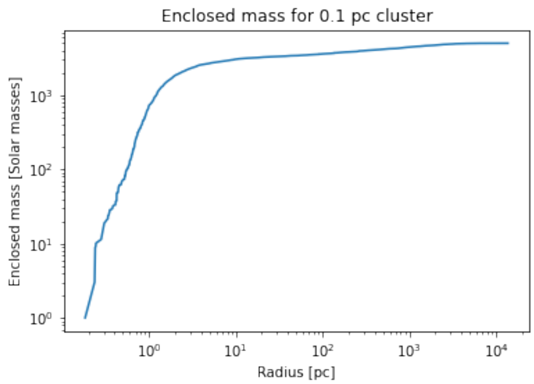

Figure 3.1: Enclosed mass for the reference system.

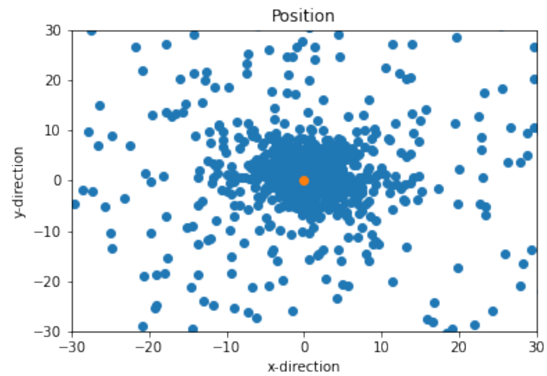

Figure 3.2: Figure of the projected positions on the xy-plane.

with a small radial distance to the centre do not have a radial component of their velocity greater than the escape velocity. This suggests that the definition of ejected stars, i.e. $v/v_{esc} > 1$ might not be the most realistic limit. Even if a star has a high velocity, it might be directed inwards toward the cluster's centre. This star still satisfies $v/v_{esc} > 1$ but is not directly leaving the cluster at the observed snapshot of simulation. There are several

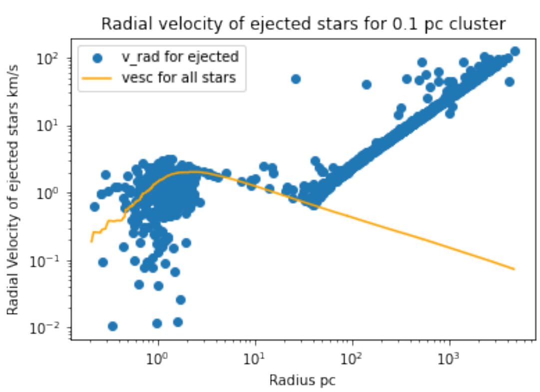

Figure 3.3: Radial velocity as a function of radius for ejected stars

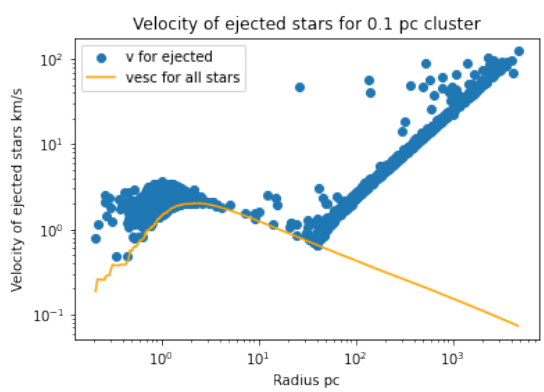

Figure 3.4: Radial velocity as a function of radius for ejected stars

interesting features in figure 3.3 and 3.4. First is the maximum peak of escape velocity around 2 pc. This behaviour is explained by the definition of v_{esc} and the enclosed mass seen in figure 3.1. From the cluster's centre of mass out to approximately two pc, I see a steady increase of enclosed mass with minor changes in the radius, and most of the stars seem to be concentrated in this inner region. The enclosed mass as a function of radius shows no significant increment after two parsecs. A plateau of this kind is expected as there are fewer stars in the outer region of the cluster. The almost linear relationship between enclosed mass and radius after a certain distance explains both the maximum in figure 3.3

and 3.4, as well as the linear decrease of escape velocities for each star up to $\sim$ 50 pc.

Secondly is an increasing linear relationship between radial velocity as a function of radius at $\sim$50 pc. These stars are located very far from the cluster and increase their radial velocity when they are further away. Comparing these ejected high radial velocity stars with their total velocity in figure 3.4, I can confirm that it seems like these star's velocity only have a component in the radial direction away from the cluster. This is because these stars started leaving the cluster early with a relatively slow velocity. Alternatively, they were ejected in a later snapshot but with a higher velocity and therefore have the velocity needed to travel the significant distance for a shorter period of time. Why we see this increase after $\sim$50 pc can be explained by the fact that the graph represents the velocities and positions of stars after 40 Myr. If a later time had been considered, the stars around 50 pc would have had time to travel further out from the centre of the cluster, shifting the linear branch of the velocity to the right. There are very few or no stars below the linear increase, and the given snapshot also explains that. A star needs a certain velocity to travel a given distance. So, therefore, there are no stars located at, for example, 200 pc with a velocity less than 3 km/s.

Stars closer to the cluster can have enough speed to leave but are directed towards the centre. These stars might leave at a later time when they have moved to the other side of the cluster, but there is always a possibility for other interactions to take place, where this energy might be transferred to other stars. One might argue that it would be better to only investigate stars with a radial velocity greater than the escape velocity. However, since they might leave the cluster in a later snapshot, I choose to stick to the definition that possible ejected stars have $v > v_{esc}$.

3.1 Initial radius

The size of a star cluster affects how close each star is initially positioned to each other. This affects the interactions between stars since the gravitational force is proportional to the inverse of the distance squared. As the force between them increases, so does the probability for them to interact closely and exchange energy. A higher probability for interactions between stars leads to a higher chance of runaway stars, and the initial radius is therefore important to study.

Initial radius of 0.1, 1 and 10 pc

With our original star cluster, the initial radius is changed to investigate the influence the cluster's size has on the velocity distribution of runaway stars. According to the catalogue by Harris 1996 (2010 edition), a typical star cluster in the Milky Way has a half-light radius of a couple of parsecs. Three different cases are explored and compared with each other. Starting from the reference cluster, the radius is increased to a more realistic 1 pc and a 10 pc radius. Figure 3.5 shows the different velocity distributions for all cases after 40 Myr.

The differences between the three sizes can be explained with the relaxation time t_{relax}

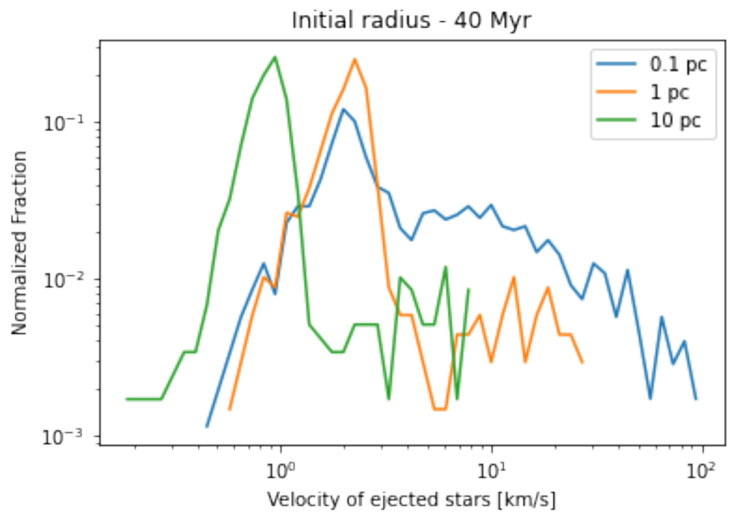

Figure 3.5: Comparison of 0.1, 1 and 10 pc initial radius for star cluster

at the half mass radius of the cluster. t_{relax} is the time it takes for a star to encounter other stars in the cluster. The density becomes lower with a larger cluster but the same initial number of stars. When the density is low, stars can travel a long time before meeting other stars. The relaxation time at the half mass radius relates to the time it takes for a star to cross the cluster t_{cross} according to Binney & Tremaine (2008), by

$$t_{relax} = \frac{0.17N}{\ln(\lambda N)}\sqrt{\frac{r^3}{GM}} \approx \frac{0.1N}{\ln N} t_{cross}. \tag{3.1}$$

Here, N is the number of particles in the cluster, and r is the half mass radius. G is the gravitational constant, and M is the cluster's total mass. $\ln(\lambda N)$ comes from the Coulomb logarithm. Typical values of λ is ≈ 0.1. Further details about this are referred to Binney & Tremaine (2008). Equation (3.1) shows the dependence between the number of stars in the cluster together with the timescale for crossing the cluster. A larger initial sized cluster indicates a greater distance to cross and hence a bigger t_{cross}. Observing the velocity distribution after 40 Myr does not consider that the simulated cluster in this project has a longer relaxation timescale depending on its size. The longer relaxation time for the larger cluster explains why we do not see as many ejected stars after only 40 Myr (Binney & Tremaine 2008).

3.2 Primordial binary fraction

Primordial binaries are produced in the formation and birth of the star cluster itself, compared to other binary systems which form under the cluster's evolution. The energy a star can obtain from a binary system is large compared to the kinetic energy obtained from individual stars elsewhere (Binney & Tremaine 2008). So even if there might be a low fraction of initial binaries compared to the binaries produced as the cluster evolves, the introduction of primordial binaries enables stars to gain high energy early on in the cluster's evolution.

There are two possible ways to introduce primordial binaries in the cluster simulation in NBODY6tt. One of them requires a separate file containing information about all particles but is not the method chosen here since it adds a level of complexity. Different parameters are instead varied in the input file (table 2.1), to activate primordial binaries through random pairing. This requires an addition of an extra line in the input file describing the properties of the binaries, like the initial semi-major axis, eccentricity, mass ratio and range of distribution. The IMF is also changed in the input file, to include stars in the Brown Dwarf regime, from Kropua(2001). This is a necessary change since the code initializes the mass of the primordial binaries based on this (Khalisi & Spurzem 2014).

Each binary system is treated as a single particle in the code and N is the total number of particles in the system, set by the user in the input file. $NBIN0$ defines the number of primordial binaries and is given together with other initial condition. The fraction of stars in binaries is calculated as

$$f = \frac{2N_B}{2N_B + N_S}, \tag{3.2}$$

where $N_B = NBIN0$ at initialization and N_S are the number of binary system and individual stars respectively. This is in agreement with other definitions (Trenti et al. 2007), where the total number of stars, $N_\star$, and the number of particles N treated by the code are defined as

$$N_\star = 2N_B + N_S, \tag{3.3}$$

$$\text{and } N = N_B + N_S. \tag{3.4}$$

Expressions for N_S and N_B are then given by

$$N_S = N_\star(1 - f), \tag{3.5}$$

$$\text{and } N_B = N_\star\frac{f}{2}. \tag{3.6}$$

For a given initial binary fraction, f, and $N_\star$; N_S and N_B are calculated from equation (3.5)-(3.6) respectively. N is obtained with equation (3.4). For all simulations, $N_\star$ is set to 4000 to have a consistent total number of stars. To control the initial binary fraction in the beginning of the simulation, at $T = 0$, the first lines of the output files is read and it gives the value of N_S. This control is done to obtain the binary fraction the code actually used in the simulation. Table 3.1 shows the results for three clusters with different initial radius. The actual binary fraction is calculated from

$$f = 1 - \frac{N_S}{N_\star}. \tag{3.7}$$

Given input and desired f	Output 0.1 pc	Output 1 pc	Output 10 pc
N_S=4000 0 %	N_S=4000 0 %	N_S=4000 0 %	N_S=4000 0 %
N_S=2000 50 %	N_S=3202 20 %	N_S=2738 32 %	N_S=2000 50 %
N_S=0 100 %	N_S=2402 40 %	N_S=1428 64 %	N_S=0 100 %

Table 3.1: Table of given number of individual stars N_S with corresponding initial binary fractions. Outputted values for three different sized clusters are also given. The total number of stars is always $N_\star = 4000$ in this project.

3.2.1 Control of binary fraction in code

As seen in table 3.1, there is a difference between the given initial parameters in the input file and the values used for the beginning of the simulation ($T = 0$). This difference results in a lower initial binary fraction than anticipated for the 0.1 and 1 pc clusters. One reason might be that some primordial binaries are not considered binaries at initialisation. However, since the code's values of N and N_S are checked at $T = 0$, there is no time for the binaries to dissolve if they are soft. Another explanation of the differences is that the input parameters are not fully understood. Consequently, the properties of the generated binary system are not controlled.

One possible reason for this can be the inconsistent use of N-body units compared to physical ones. Everything in the code is scaled and runs with N-body units, e.g. the radius, except the initial description of primordial binaries. These are given in actual physical units with, for example, the semi-major axis value in AU. Since the values for the primordial binary fraction are not directly comparable with the other properties of the cluster, changing one forces the other to scale if the same relation wants to be obtained. The code generates binaries based on comparing the gravitational force between the possible binary component and the other stars in the cluster. If the gravitational force from the individual star dominates over the collective one, it is considered a binary.

Different variations of input parameters were tested by increasing the value of the semi-major axis of the primordial binary system in the input file. A decrease in what range the binaries are created was also tested, but the technical issue could not be solved.

It is unclear what in the code is causing our confusion, and due to the limited time of this project, further investigation is postponed. The consequence is that parameter space exploration is not as controlled and structured as anticipated. However, differences in the velocity distribution between varying primordial binary fractions can still be compared and analysed. They can still show dependency between the initial condition of star clusters with the velocity distribution of runaway stars.

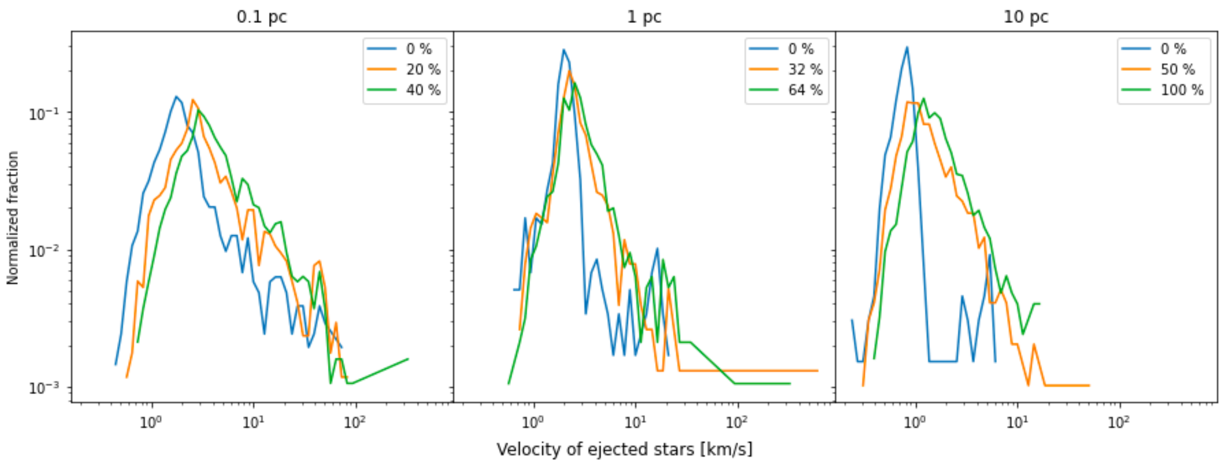

Figure 3.6: Normalized velocity distribution for three different clusters with varying initial radius and binary fractions.

3.2.2 Differences in initial binary fractions

The combination of changing both the radius and binary fraction is of interest to investigate if the two parameters cancel out or maximise the effect of each other on the velocity distribution. Three different initial binary fractions are tested for the reference cluster (radius 0.1 pc), but also clusters with initial radius 1 and 10 pc. Results from the previous section show that bigger clusters have a longer relaxation time. Introducing primordial binaries results in an increased number of 3-body encounters and interactions between stars in the cluster during the early evolution of the star cluster.

The normalised velocity distribution for ejected stars after 40 Myr is shown in figure 3.6 for each initial binary fraction for the three different sized clusters. The curves in the cluster with 0.1 pc radius all share a similar shape, with small fluctuations. However, there is a difference in the shape of the curves representing the initial radius 1 pc and 10 pc. The 0% initial binary fraction does not follow the same form as the other initialised fractions.

For the radius of 0.1 pc case, the maximum velocity of ejected stars is not increased with various binary fractions. There are some differences in the maximum velocity in the cluster with a radius 1 pc, but these could be small fluctuations. It is hard to conclude anything about this from the curves. For both the 1 pc and 10 pc clusters, there are very few stars with velocities greater than the maximum for 0% initial binary fraction. The two distinct peaks around $\sim$4 km/s in the 10 pc cluster can be considered to be noise, and it is evident in figure 3.7 that it is only $\sim$6 stars producing these peaks and can therefore be neglected. So the maximum velocity of runaway stars does change when a big cluster introduces primordial binaries.

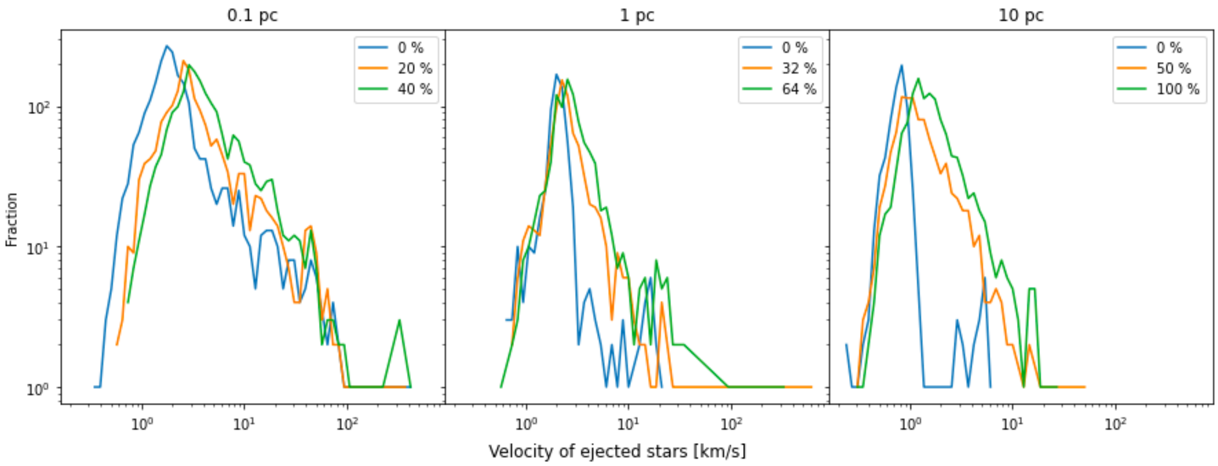

Figure 3.7: Non-normalized velocity distribution for three different clusters with varying initial radius and binary fractions.

Increasing the initial binary fraction seems to shift the velocity distribution towards higher values, implying that with more primordial binaries, runaway stars gain higher velocity. From figure 3.7, more stars with high velocity are produced. This is an anticipated result since an increase in binary system fraction increases the number of systems where encounters can gain kinetic energy from binding energy.

The cluster with no initial binary fraction produces fewer stars with high velocity. Even if there are some fluctuations in the 1 pc cluster, at ∼11 km/s, the slope of the velocity distribution is very different compared to the higher binary fractions. The same behaviour is visible in the 10 pc cluster as well.

The differences between the intermediate and high initial binary fraction for the 1 pc and 10 pc case are not as great as in the cluster with 0.1 pc. Therefore, it seems that for a bigger cluster, changing the binary fraction does not lead to a change in velocity distribution.

It seems that varying the initial binary fraction for large values does not change the velocity distribution as much as variations in the smaller values.

Chapter 4

Discussion

I remark on the absence of dark matter in all simulations done in this project. Several previous works discuss the little or very weak observational evidence for the presence of dark matter in star clusters (Heggie & Hut 1996; Bradford et al. 2011), even if some models are suggesting that dark matter halos might be significant (Ibata et al. 2012). Including dark matter components in this project's simulations would possibly add to the system's total mass, resulting in a stronger gravitational force acting on each star. This leads to a higher enclosed mass for each component and, thus, higher escape velocities needed to escape. This would suggest that including dark matter results in fewer runaway stars, but is something that should be investigated in more details. There exist recent work by Vitral & Boldrini (2021), illustrating a difference when clusters are formed in their own dark matter halo or not. Their work shows, however, that up to 10 pc from the centre of the cluster, the mass ratio between stars and dark matter components are only $\sim 1\%$, independent on dark matter halos.

Variation in the radius of the star cluster leads to a change in both the cluster's compactness and density. These are parameters of their own that could be analysed to investigate what ratio of the mass and radius of the clusters affect the velocity distribution of runaway stars the most.

A higher density would lead to similar results as decreased radius, where the average distance between stars decreases and increases the probability of interactions. Another exciting aspect is the distance between components in a binary system (if included), i.e. the semi-major axis of the binary systems. These properties of the binary system are distributed based on a set of given initial conditions. The conditions used were not changed or varied during this project. Since the number of binaries plays an important role in the interactions and production of runaway stars, the other properties (such as the range or eccentricity of these systems) should be examined. Whether different eccentricities and semi-major axes of binary systems play a role in the velocity distribution of runaway stars or not is still not clear. However, one can assume that since these parameters affect the structure of the binary system and its energy, it may change how fast ejected stars can leave the cluster. Oh & Kroupa (2016) showed, for example, how the properties of the binary systems affected the number of ejected stars. They showed that when the mass fraction between stars in a binary system where close to 1, the cluster ejected the most number of stars.

4.1 Future projects

4.1.1 Including gas

Massive runaway stars can be progenitors of supernovae, and their role in galaxy simulations is described in the work done by Andersson et al. (2020). Runaway stars' influence on the feedback at the galactic scale would not be as significant if one did not assume there are different regions of density in the galaxy. This assumption is essential to make since the previously mentioned work sees a difference between if supernovae explosion occurs in low- or high dense regions (Andersson et al. 2020). However, in the N-Body simulations performed here to model star clusters, gas is not considered. This is motivated by the complexity and computational cost it would add. Nevertheless is the presence of gas an essential part of cluster evolution, contributing to both star formation and pressure (Krause et al. 2020).

4.1.2 Galaxy

When a cluster orbits along with the galactic disc, it experiences the tidal force. As a result, stars in the given cluster are affected. However, as the cluster moves along its orbit, it does not experience any drastic variations in the external gravitational forces. Therefore, it is considered an adiabatic process, and the effect of the tidal forces is not immense. The impact on the cluster is more significant if the orbit instead, at some point, crosses the galactic disc. See Renaud (2018) and see references therein.

Tidal shocks

Tidal shocks describe how the stars in a cluster experience a rapid change in tidal forces. This can happen when the cluster's orbit crosses the galaxy's disc. When the gravitational forces acting on the cluster change rapidly, the shape of the cluster's potential boundary changes and expands and shrinks drastically. After the cluster has crossed the galactic disc, it goes back to its initial shape. Nevertheless, some stars get accelerated outwards at the moment of expansion of the cluster's potential due to the stronger external gravitational forces in the disc. As the cluster leaves the disc, these stars have potentially escaped. If the cluster had not crossed the galactic disc, these stars might not have been ejected from the interactions within the cluster. Tidal shocks could, therefore, contribute to the number of runaway stars. If more stars leave the cluster with a certain velocity, it contributes to the velocity distribution of runaway stars.

As a result of earlier technical difficulties and the limited time of the project, different initial positions and velocities for the cluster in a galaxy with a given mass were not simulated and analysed.

4.1.3 Different density profiles

The density profile of the cluster is described using Plummer's model. Nevertheless, other models exist describing the gravitational potential of a stellar system in different ways corresponding to a slightly different density profile. One group of famous models are the King models (Binney & Tremaine 2008), where the assumption of an isothermal sphere is only applied to the inner parts of the cluster. For the system's outskirts, the density profile varies depending on different parameters in Kings models. Suppose stars follow a different density profile, and their location and distribution in space change. The concentration of stars in the cluster is different, and this can change the interactions between stars since the interacting gravitational force depends on the distance. When the interaction rate changes, so does the runaway stars' velocity distribution. Varying the density profile, therefore, changes and effect the velocity of ejected stars from a cluster.

4.1.4 Rotating clusters

Another aspect to consider is the assumption of spherical symmetry of the star cluster. Even if the assumption of spherical symmetry is an established practice, there is observational evidence that star clusters that rotates exist (Varri et al. 2020). With a non-rotating cluster, the kinetic energy of the star is the only energy competing with the gravitational potential of the cluster. However, the system's rotation results in an addition of a centripetal force. As a result, the stars experience a lower effective potential energy due to the additional non-inertial centrifugal force. Thus the effective energy boundary to escape the cluster is lowered (Renaud 2018).

If this leads to more or faster runaway stars is still unknown. The results can also combine increased velocity and the number of the ejected stars. Therefore, further investigation of the effects of the centripetal force on the velocity distribution is necessary.

Chapter 5

Conclusions

With NBODY6tt, different initial conditions of star clusters have been investigated to conclude if any dependence between these and the velocity distribution of runaway stars exists. Our results indicate the importance of the cluster's initial conditions in the production of runaway stars. With varying initial radii, the production of runaway stars with high velocities is dependent on how long the cluster has evolved. A larger cluster with an initial radius 10 pc has, compared to a smaller cluster with an initial radius 0.1 pc, produced fewer runaway stars after 40 Myr. A smaller radius implies a faster production of runaway stars where all velocity kicks have taken place after 40 Myr. Therefore, a large cluster may need a longer time before the interactions that produces high-velocity runaway stars occurs. This could be tested with a longer simulation time. However, the motivation for this project was to investigate if different clusters produced other velocity distributions that can be used in galaxy simulations when accounting for runaway stars. Since the supernovae progenitors are the ones of interest in galaxy simulations, their lifetime can be seen as a time limit. Even if a longer run for the larger cluster could have been tested, all possible supernovae progenitors would have already exploded in the higher density region of the cluster. So even if more interactions in the larger cluster can happen with a longer run, the massive runaway stars have already exploded.

Due to limited time, I have not reached a complete conclusion about the effects of binary stars. This calls for follow-up studies. Nevertheless does our results indicate the importance of primordial binaries. An increase of the initial binary fraction leads to more ejected stars reaching a high velocity, but the maximum velocity of these ejected stars is not increased. This implies that if runaway stars are to be included in galaxy simulations, the distance at which ejected stars travel should not be altered, but rather the number of stars in these regions. One exception is the runaway stars from large initial sized cluster, where the maximum velocity does increase when introducing primordial binaries. Further investigations why this is only occurring in the big cluster are needed. With a higher number of progenitors of supernovae in low dense regions in the galaxy, the effect on the feedback on galactic scale might change. As discussed by Andersson et al. (2020), future work on galaxy simulations should investigate how a different velocity distribution on runaway stars, affects the feedback.

I finally remark that further exploration of which parameter of star clusters affects the velocity distribution of runaway stars is needed. Future projects should continue the investigation of the properties of the primordial binary systems. Not only the initial binary fraction, but also the structure of the system itself, as the semi-major axis between the two binary components.

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