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N-body simulations of open clusters and their destruction

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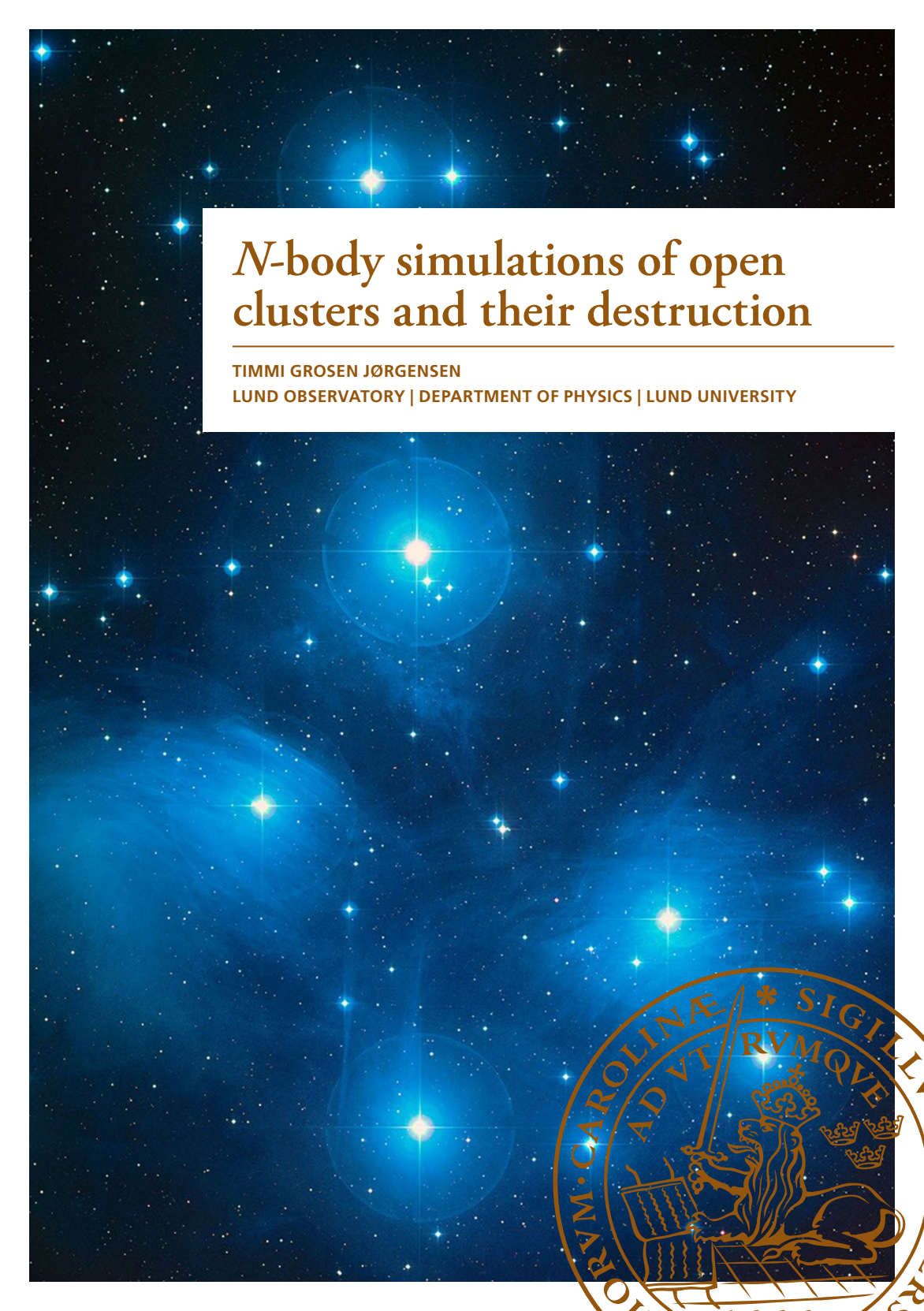
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N -body simulations of open clusters and their destruction

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N -body simulations of open clusters and their destruction

Timmi Grosen Jørgensen



LUND
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Thesis for the degree of Doctor of Philosophy

Thesis advisor: Dr. Ross Church

Co-advisor: Prof. Lennart Lindegren

Faculty opponent: Prof. Simon Goodwin

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Abstract Stellar clusters are structures of stars that are bound together by their mutual gravitational forces. As a cluster evolves, it will lose stars as a consequence of internal and external effects. The external effect is the most important and affects the cluster via gravitational tidal forces that can strip stars away from the cluster. Stellar clusters are subject to gravitational scattering and tidal disruption by giant molecular clouds (GMCs) which can significantly affect their orbit and evolution. This thesis investigates the impact that GMCs have on clusters, and how this affects their observed populations. We do this by using a combination of galactic models and N-body simulations. In paper I, we investigate if the Sun could have originated from the open cluster M67 which is currently located high above the disc of the Milky Way. The Sun is located in the Galactic disc so there is a clear dynamical discrepancy between the two objects. We show that it is possible, but unlikely, for the Sun to have been born in M67 if the Sun escapes the cluster at a young age, before M67 is scattered to its current orbit by GMCs. In paper II, we investigate how tidal disruption by GMCs affects the cluster population of the galaxy M51 over a period of the last 200 Myr. We do this by simulating 5000 unique clusters twice: with and without being affected by tidal forces from the GMCs. We are able to reproduce the majority of the observed population and find that low-mass clusters, that are located close to the galactic centre, are most likely to be disrupted. Clusters that are subject to GMC encounters are more rapidly destroyed and contain stars with higher kinetic energies. In paper III, we perform a similar investigation as in paper II, but this time for a population of open clusters in the Solar Neighbourhood over the last 1 Gyr. We simulated 20692 clusters and find a good agreement with the observed population if we assume an initial cluster mass function that is truncated. High-mass clusters survive to 1 Gyr and are much less affected by GMCs. Lower-mass clusters are strongly affected by GMCs, but also by their distance to the Galactic centre since the tidal field becomes stronger closer to the centre. Observations show an early disruption of clusters which indicate that they form less bound compared to the initial state of our simulated cluster population. We find that clusters that have had a GMC encounter within the last 20 Myr have tidal tails that are randomly orientated with respect to the direction of the Galactic centre.			
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N -body simulations of open clusters and their destruction

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Cover: The hot blue stars of the Pleiades. The brightest stars of the open cluster are visible to the naked eye and located about 430 light years away. Credit: NASA, ESA, and AURA/Caltech.

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List of publications

This thesis is based on the following peer-reviewed publications:

- I **Stellar escapers from M67 can reach solar-like Galactic orbits**
Jørgen, Timmi G.; Church, Ross P.
Monthly Notices of the Royal Astronomical Society, Volume 492, Issue 4, pp. 4959–4974 (2020)
- II **The young stellar clusters in M51 and the impact of GMC encounters**
Jørgen, Timmi G.; Church, Ross P.
Monthly Notices of the Royal Astronomical Society, Volume 543, Issue 2, pp. 1410–1428 (2025)
- III ***N*-body simulations of the open cluster population in the Milky Way and the impact of GMC encounters**
Jørgen, Timmi G.; Church, Ross P.
To be submitted to MNRAS (2026)

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Popular summary

The planets in our Solar System are bound on their orbits around the Sun by gravity. In a similar fashion, many stars are bound together in stellar clusters. These structures can consist of tens of stars up to clusters where millions of stars are bound together. As a cluster evolves dynamically, it will lose a portion of its stars that will be able to escape the gravitational force of the cluster. This process continues until the cluster has lost so many stars that the remaining stars inside the cluster can no longer be held together by gravity, and the cluster dissolves. The evolution of a stellar cluster is dictated by its internal evolution where the stars inside gravitationally affect each other, but most importantly by external tidal forces produced by the galactic environment in which the cluster resides. For example, tidal forces produced by the Moon cause sea levels to rise and fall here on Earth.

In my research, we investigate how the galactic environment affects the dissolution and destruction of stellar clusters by using computer simulations. In terms of the galactic environment, I have mostly been interested in how large an effect giant molecular clouds (GMCs) have on the evolution of clusters. GMCs are large structures of gas where new stars and clusters are formed. Besides being stellar nurseries, GMCs can also have a destructive effect on already formed clusters if these come into close proximity with the GMCs.

In the first article, we investigate whether the Sun could have originated from the stellar cluster M67. The connection between the Sun and M67 has been suggested because the stars in M67 have a similar age and chemical composition as the Sun. However, M67 is located high above the disc of the Milky Way, whereas the Sun currently resides in the disc similar to where most of the stars in the Galaxy are located. There is therefore a dynamical discrepancy between the orbit of the Sun and M67. In the first article, we show and explain the possibility of a dynamical connection between the Sun and M67. We propose that M67 was born in the Galactic plane, and the Sun escaped M67 early in the cluster's evolution while M67 was still in the Galactic plane. After the Sun had escaped the cluster, M67 was scattered to its current orbit by interactions with GMCs.

In the second and third articles, we turn our focus towards the cluster populations of the galaxy M51 and the Milky Way. In addition, we investigate how the GMCs affect these populations. This is achieved by simulating each cluster twice: once where the gravitational tides of the GMCs are included (C_R), and once where this effect is ignored (C_N).

The simulated cluster populations in M51 and the Milky Way show similar trends, and we are able to reproduce most of the observed populations. Low-mass clusters are most sensitive to the tidal forces from GMCs, and this is also where we see the biggest difference between the C_R and C_N clusters. Low-mass clusters have much shorter lifetimes before they are destroyed compared to high-mass clusters. This is reflected by the fact that the relative number of high- to low-mass clusters changes as the cluster population evolves. The galactic environment of a cluster also plays a crucial role. Clusters that spend most of their lifetime closer to the centre of their host galaxy will be disrupted much faster, compared to clusters far from the galactic centre.

C_R clusters that have been affected by GMC encounters contain a larger fraction of stars with higher velocities compared to their C_N counterparts. In addition, C_R clusters which have had recent GMC encounters have different morphologies and orientations. For the cluster population in the Milky Way, we find a larger amount of young low-mass clusters that survive compared to observations. This could indicate that these clusters are less gravitationally bound when they are born compared to what is assumed in our simulations.

Populærvidenskabelig sammenfatning

Planeterne i vores Solsystem er bundet til deres kredsløb omkring Solen som følge af tyngdekraften. På samme måde er mange stjerner bundet sammen i stjernehobe, der kan bestå af mellem ti og op til flere million stjerner. Når en stjernebob udvikler sig dynamisk, kan den miste en del af sine stjerner, som vil være i stand til at undslippe stjernebobens tyngdekraft. Denne proces fortsætter, indtil stjerneboben har mistet så mange stjerner, at de tilbageværende stjerner ikke længere er bundet sammen af tyngdekraften, og stjerneboben bliver derved opløst. Udviklingen af en stjernebob er dikteret af den interne evolution, hvor stjerner gravitationelt påvirker hinanden. Den eksterne udvikling af stjerneboben er dog den mest vigtige. Denne proces skyldes tidevandskræfter, der er produceret af det galaktiske miljø, hvori stjerneboben befinder sig. For eksempel får tidevandskræfter, produceret af Månen, vandstanden i havene til at stige og falde her på Jorden.

I min forskning har jeg undersøgt, hvordan det galaktiske miljø påvirker opløsningen og ødelæggelsen af stjernehobe ved at bruge computersimuleringer. I forhold til det galaktiske miljø har jeg været mest interesseret i at undersøge, hvordan kæmpe molekyleskyer, giant molecular clouds (GMCs), påvirker evolutionen af stjernehobe. GMCs er store strukturer af gas, hvor stjerner og stjernehobe bliver dannet. Udover at være fødested for stjerner, så kan GMCs også have en destruktiv effekt på allerede færdigdannede stjernehobe, hvis disse kommer i tæt kontakt med GMCs.

I min første artikel undersøger vi, hvorvidt Solen kunne være dannet i stjerneboben M67. Forbindelsen mellem Solen og M67 har været foreslået, fordi stjernerne i M67 har lignende aldre og kemisk sammensætning som Solen. M67 er derimod lokaliseret højt over Mælkevejens skive, hvorimod Solen befinder sig i skiven, hvori størstedelen af stjernerne i Mælkevejen også er lokaliseret. Der er derfor en dynamisk uoverensstemmelse imellem kredsløbene af Solen og M67. I artiklen viser og forklarer vi en mulig løsning på denne uoverensstemmelse. Vi foreslår, at M67 er født i Mælkevejens skive, hvor Solen undslipper tidligt i stjernebobens udvikling, imens M67 stadigvæk befinder sig i skiven. Efter Solen undslipper stjerneboben, bliver M67 gravitationsmæssigt spredt til sit nuværende kredsløb af GMCs.

I den anden og tredje artikel retter vi vores fokus mod populationen af stjernehobe i galaksen M51 og i Mælkevejen. Derudover undersøger vi, hvordan GMCs påvirker disse populationer. Det gør vi ved at simulere hver stjernebob to gange: en gang hvor vi inkluderer tidevandskræfterne fra GMCs (C_R), og en gang hvor vi ignorerer denne effekt (C_N).

De simulerede populationer af stjernebøer i M51 og Mælkevejen viser den samme tendens, og vi er i stand til at reproducere de fleste af de observerede populationer. Stjernebøer med lav masse er mest sensitive overfor tidevandskræfter fra GMCs, og det er også her, hvor vi ser den største forskel imellem stjernebøene C_R og C_N . Stjernebøer med lav masse har meget kortere levetid, før de bliver ødelagt i forhold til stjernebøer, der er mere massive. Dette faktum afspejler, hvordan det relative antal af stjernebøer med høj og lav masse ændrer sig i takt med, at populationen udvikler sig. Det galaktiske miljø spiller også en vigtig rolle for en stjernebø. Stjernebøer, der tilbringer mest af deres levetid tættere på centrum af deres værts galakse, bliver hurtigere opløst i forhold til stjernebøer, der befinder sig langt fra det galaktiske centrum.

C_R stjernebøer, der er blevet påvirket af nærkontakt med GMCs, indeholder en større andel af stjerner med høje hastigheder i forhold til deres C_N modsætning. Derudover har C_R stjernebøer, der har haft nylig nærkontakt med en GMC, en anden morfologi og orientering. For stjernebøerne i Mælkevejen finder vi en stor del af unge stjernebøer med lav masse, der overlever, i forhold til hvad observationer viser. Det indikerer, at disse stjernebøer er mindre gravitationelt bundet, når de er født, sammenlignet med hvad vi antager i vores simuleringer.

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¹It might actually happen this year, COYG!

Chapter 1

Introduction

1.1 Stellar clusters

The existence of stellar clusters has been known since antiquity: one of the first mentions of the Pleiades was made by Homer in the *Iliad* (Homer 1909). In 1609, Galileo Galilei was the first to point a telescope to the night sky, revealing the vast number of stars that reside in stellar clusters like the Pleiades, but which were previously hidden from the naked eye (Galilei 1610).

Now we know that stellar clusters come in a variety of different sizes, shapes, and ages. Stellar clusters can be divided into three main classes, namely open clusters, globular clusters, and associations¹. Open clusters consist of tens to several thousands of stars that have formed from the same giant molecular cloud (GMC). Open clusters typically have ages below 1 Gyr and are located mostly in the disc of the Milky Way and other spiral galaxies (Krumholz et al. 2019). GMCs are mostly located in the arms of spiral galaxies, where massive stars are also found in young, massive clusters. Not all GMCs are found in the spiral arms of galaxies, though: for example Colombo et al. (2014a) observed a high fraction of GMCs in the inter-arm regions of the galaxy M51.

Globular clusters are typical old with ages of ~ 10 Gyr (Krumholz et al. 2019) and can contain hundreds of thousands to millions of stars and are mostly found in the haloes or centres of galaxies. Unlike open clusters, globular clusters show anti-correlations between the abundances of several chemical elements such as Na-O and C-N (Pancino et al. 2017) and can have multiple stellar populations. An association is a group of stars that were once born together, but are no longer

¹Also known as moving groups.

gravitationally bound. Stars in associations are therefore in the process of being dispersed, which will occur over a period of a few Myr.

1.2 What is a stellar cluster?

What is a stellar cluster? The answer seems like it should be straightforward: it is a collection of stars that are held together by their mutual gravitational forces. Unlike galaxies, stellar clusters are not dominated by dark matter (Wan et al. 2023; Taylor et al. 2025), however, some globular clusters such as Omega Centauri (Evans et al. 2022) may possibly contain a significant amount of dark matter, indicating that these globular clusters might be remnant cores of dwarf galaxies (Krumholz et al. 2019).

When working with simulated clusters, where all information is known about the stars, it is relatively straightforward to define a cluster. However, observationally it is a lot harder to define what a stellar cluster actually is since we are limited by the precision of the observations. Throughout the years, this has resulted in numerous definitions. Lada & Lada (2003) defined a cluster as a group of stars where the mass density is large enough to avoid disruption by tides while also having enough stars to not be dissolved by internal dynamical effects within a period of 100 Myr. For stellar clusters in the Solar Neighbourhood, this corresponds to a group with 35 or more stars. Gieles & Portegies Zwart (2011) proposed that a group of stars younger than the time it would take for them to disperse are likely unbound and should not be considered clusters. Adopting the definition of Lada & Lada (2003) would mean that stellar overdensities older than ~ 10 Myr must be gravitationally bound and can be classified as clusters. This boundness issue for young clusters is a particular problem for cluster observations in other galaxies, since individual member stars cannot be resolved and the analysis is based on the collective light from all the stars in the cluster.

The *Gaia* satellite was launched in December 2013, and has helped revolutionise our understanding of open clusters in the Milky Way (Cantat-Gaudin 2022). *Gaia* repeatedly measured the positions of stars with extreme precision, and these measurements are used to obtain the stars distances and motions on the sky. Furthermore, *Gaia* also measured the apparent magnitudes and colours of stars. From *Gaia*'s astrometric catalogue, new open clusters have been discovered, and the membership of known clusters has been updated and made more complete (Castro-Ginard et al. 2018; Cantat-Gaudin et al. 2019; Liu & Pang 2019; Castro-Ginard et al. 2020; Cantat-Gaudin & Anders 2020; Hunt &

Reffert 2021; Castro-Ginard et al. 2022; Hunt & Reffert 2023, 2024). The recent open cluster catalogue of Hunt & Reffert (2024) classifies clusters as groups of at least 10 observed stars that are gravitationally bound and more massive than $40 M_{\odot}$. We compare this catalogue against our theoretical models in Paper III.

1.3 The importance of clusters

The importance and usefulness of stellar clusters cannot be understated. Here we go through some of the most important aspects and recent discoveries that have been made by the observations of stellar clusters.

Measuring the distance or age of a single star is difficult, and age estimates for individual stars generally have large uncertainties. However, since the stars in clusters are all born at approximately the same time, a colour-magnitude-diagram (CMD) of the cluster can be fitted to isochrones which gives a much better age determination of the cluster compared to single star estimates. Since high-mass stars evolve faster than low-mass stars, the CMD changes as the cluster gets older. Stellar clusters are therefore ideal laboratories for testing stellar evolutionary models (Cantat-Gaudin 2022). Furthermore, the uncertainty of the distance measurement for a cluster goes down as $1/\sqrt{N}$, since the stars are located at almost exactly the same distance².

The star formation history is important to understand since it reveals how stars, clusters, and galaxies form and evolve. As stars evolve and die, they will enrich the surroundings gas with heavier elements that have been produced by nuclear burning. As a consequence of this, the next generation of stars will have a different chemical composition due to this gas enrichment. Combining spectrophotometric codes with spectroscopic observations of stars can therefore reveal the star formation history of a galaxy. Because stellar clusters have much better age estimates, they can help constrain the chemical evolution (Boucher et al. 2026), which can supplement and improve the analysis of the star formation history. Because the distance to clusters can be much better determined, they can also be used to map the chemical composition of the Milky Way as a function of Galactocentric radius (Magrini et al. 2023). The observed ratio of different elements in stars can be used to estimate stellar ages, which can be further calibrated using clusters (Casali et al. 2019).

Since most star formation occurs in the spiral arms of galaxies, young stellar clusters can be used to track star formation as well as the shape of the spiral

² N is the number of observed stars in the cluster.

arms. This has been done by [Castro-Ginard et al. \(2021\)](#) who determined that the spiral arms of the Milky Way have different pattern speeds, indicating that the spiral arms are transient features. Furthermore, by tracking the orbits of young clusters back in time, [Swiggum et al. \(2024\)](#) showed that 155 young clusters in the Solar Neighbourhood originate from three specific birth regions. Using the ages of young stellar clusters in a nearby star-forming region, [Ratzenböck et al. \(2023\)](#) have been able to investigate how the star formation history in this region has changed over a period of ~ 25 Myr. Stellar clusters observed in other spiral galaxies can similarly be used to track the spiral arms. Estimating the age of a cluster population can reveal how clusters depart from their initial birth regions and consequently become disassociated with the location of the spiral arms.

The observations of cluster masses and ages can tell us about their evolution and can be used to test numerical models and help our understanding of the different dynamical processes which shape the cluster populations. This has been a main focus in this thesis.

1.4 The virial theorem

A widely used relation in astrophysics is the virial theorem, which relates the kinetic and potential energy of a self-gravitating system ([Binney & Tremaine 2008](#)). It states: for a system in virial equilibrium, the potential energy, $|U|$, should be twice as much as the kinetic energy, T . The virial parameter is defined as

$$Q_{\text{vir}} = \frac{T}{|U|}, \quad (1.1)$$

and is equal to 0.5 if the system is in virial equilibrium. The virial theorem is a powerful tool which allows astrophysics to calculate the mass of objects based on their kinematics.

1.5 Time-scales

When studying an astrophysical system, it is important to consider the different roles of each physical process that occurs within that system. The time-scales on which these processes occur relative to the age of the system itself are particularly important. A process which occurs over a short time-scale compared to the system age will be relevant to consider. Instead, if a process has a longer time-scale than the age of the system, it will be less relevant to the evolution of the system. It

is therefore important to quantify these different processes and time-scales when talking about stellar clusters and other self-gravitating systems.

The dynamical time-scale, also sometimes called the crossing time, is the time required for a typical star to cross the system, and is an estimate of the time it takes the system to react to gravitational perturbations or to establish dynamical equilibrium. The dynamical time-scale is linked to the size of the system, S_R , and the velocity of a typical star which can be expressed in the form of the velocity dispersion, σ , of the stars in the cluster by (Binney & Tremaine 2008):

$$t_{\text{dyn}} = \frac{S_R}{\sigma} \simeq \sqrt{\frac{3\pi}{16G\bar{\rho}}} \simeq (G\bar{\rho})^{-1/2}. \quad (1.2)$$

Here G is the gravitational constant and $\bar{\rho}$ is the average density. The dynamical time can be estimated for any system, even one with inhomogeneous densities, so long as the average density is known. For clusters, it is common to express the radius of the cluster in terms of the half-mass radius, r_h , within which half of the mass of the cluster is contained. For a stellar cluster in virial equilibrium, the velocity dispersion is given by (Portegies Zwart et al. 2010)

$$\sigma = \sqrt{\frac{GM}{\eta r_h}}, \quad (1.3)$$

where M is the mass of the cluster, and η is a constant that depends on the spatial distribution of stars within the cluster. For a typical cluster, η is ~ 10 , but its value can range from ~ 5 and up to ~ 30 .

Another important time-scale for stellar clusters is the relaxation time-scale, t_{relax} . As a star orbits inside a stellar cluster, its orbit is gravitationally perturbed by other stars in its vicinity. After many of these two-body interactions, the star will eventually end up on an orbit which is completely different from its original orbit. The time it takes for this to occur inside a cluster is called the relaxation time-scale, and is of the order of (Binney & Tremaine 2008):

$$t_{\text{relax}} \approx \frac{0.1N}{\ln(N)} t_{\text{dyn}}, \quad (1.4)$$

where N is the number of stars in the cluster. The relaxation time-scale is not constant over the radius of a cluster, and it is useful to also consider the relaxation of the cluster in terms of the half-mass relaxation time (Binney & Tremaine 2008), which is given by

$$t_{\text{rh}} = \frac{0.17N}{\ln(\lambda N)} \sqrt{\frac{r_h^3}{GM}}, \quad (1.5)$$

where $\lambda \simeq 0.1$ (Giersz & Heggie 1994). For gravitational systems, where the relaxation time-scale is short, the stellar orbits cannot be described by a smoothed gravitational field, and one needs to consider the gravitational contribution of each star in the system. For stars in galaxies, the relaxation time-scale is much longer than the age of the galaxies which means that the individual interactions between stars can be ignored. They can, in other words, be considered collisionless systems. For stellar clusters, especially open clusters, the story is very different. A typical open cluster in the Milky Way with a mass of $10^3 M_\odot$ and $r_h = 2$ pc, will have $t_{\text{dyn}} \approx 4$ Myr and $t_{\text{rh}} \approx 74$ Myr, which means that clusters with ages older than a few hundred Myr will have their structure strongly influenced by two-body relaxation. As a consequence of this, to accurately investigate the evolution of stellar clusters, the individual gravitational force of each star needs to be considered. Simulations that do this are called direct N -body simulations, and we discuss them more in Section 2.2.1.

The evolution of the stars themselves can also play a role in the dynamics of stellar clusters. High-mass stars evolve on a short time-scale of ~ 10 Myr where they inject energy and momentum back into their surroundings. This is known as stellar feedback which can play a role in ejecting surrounding gas, while also decreasing the mass of the stars themselves.

1.6 The birth of a stellar cluster

A star is born when a gas cloud becomes dense and cold enough (~ 10 K) that the internal gas pressure cannot resist the force of gravity. As the gas continues to collapse, potential energy is converted into heat which increases the temperature of the protostar, which starts to burn deuterium in its core at a temperature of $\sim 10^6$ K (Krumholz 2014). Contraction continues until the core of the protostar becomes dense and hot enough ($\sim 10^7$ K) to burn hydrogen (Stahler & Palla 2004). The release of energy from hydrogen burning prevents further contraction and creates a state where the star is in hydrostatic equilibrium on the main sequence.

Most stars are believed to form in clusters (Lada & Lada 2003; Krumholz et al. 2019), which are born in GMCs that provide the gas reservoir needed to form the stars. These GMCs are large structures and have typical masses and radii of $\sim 10^6 M_\odot$ and $\sim 10 - 30$ pc (Dame et al. 2001; Colombo et al. 2014a; Rice et al. 2016; Miville-Deschênes et al. 2017). As stars and clusters form, they are hidden by the molecular gas and dust that surround them and are referred to as embedded



Figure 1.1: An image taken by ESO’s VLT of the star forming region RCW 36. The region contains a newborn embedded cluster that is hidden behind gas and dust. Credit: ESO.

clusters. Infrared observations are needed to reveal them: for example, an image of the star forming region RCW 36, obtained from ESO’s Very Large Telescope (VLT), can be seen in Fig. 1.1, where an embedded stellar cluster is hidden behind the dark filaments of gas and dust. The star cluster consists of at least ~ 350 stars (Baba et al. 2004) with an estimated age of 1.1 ± 0.6 Myr (Ellerbroek et al. 2013).

As star formation requires dense gas, not all of the gas in a GMC will be converted to stars (McKee & Ostriker 2007). This is quantified as the star formation efficiency (SFE) which is the mass ratio between the stars that form and the initial gas. The SFE depends on the scale on which it is measured, but it is typically in the range of 1 to 30 per cent (Renaud 2018). The global SFE of a GMC is relatively low: only a few per cent of the total gas mass is converted into stars (Kruijssen 2026). It is only the densest parts of the GMC that are able to form stars: this happens in filaments or cores that are distributed nonuniformly inside the GMC. These high density regions are physically associated with the birth of stellar sub-clusters, which can grow hierarchically into clusters. Observations in the Solar Neighbourhood show that these highly dense regions have typical sizes of the order $\sim 0.5 - 1$ pc, with observed SFEs between 10 and 30 per cent

(Lada & Lada 2003). The estimated SFE is also consistent with the SFE observed in star forming regions in other galaxies (Pathak et al. 2025), with estimated SFE values between 6 and 17 per cent. Furthermore, simulations by Polak et al. (2024) suggest that the SFE in these highly dense regions can be as high as 85 per cent, where young massive clusters are born via short, efficient bursts of star formation.

Not all clusters are born as bound structures, and the stars within these associations will disperse on a dynamical time-scale (Lada & Lada 2003). The fraction of stars born in bound clusters is known as the cluster formation efficiency (CFE). If most stars are born in clusters, these clusters quickly become unbound since the typical CFE found in galaxies is $\sim 0.01 - 0.1$ for cluster ages of ~ 10 Myr (Krumholz et al. 2019). The CFE needs to be calculated for clusters older than their dynamical time-scale, since these cannot otherwise be considered bound structures (Gieles & Portegies Zwart 2011). However, this assumes that no significant disruption of the clusters has occurred over the age period investigated. The low observed CFE is sometimes referred to as infant mortality.

It has been suggested that the SFE needs to be $\gtrsim 30$ per cent in order for a cluster to stay bound (Lada & Lada 2003). Otherwise, stellar feedback would be able to disrupt star formation by expulsion of the remaining primordial gas that has not yet been converted into stars. This would not only prohibit further star formation, but also lower the gravitational potential of the cluster environment, which is assumed to be in virial equilibrium. If the SFE is not high enough, the dispersal of gas driven by stellar feedback could therefore put the cluster in a supervirial state. This can lead to the cluster becoming unbound on a dynamical time-scale (Goodwin & Bastian 2006). Several young clusters in the Milky Way have been observed to be superviral (Bravi et al. 2018; Kuhn et al. 2019; Pang et al. 2021) and are likely to be disrupted in a few Myr. Cluster dissolution as a result of gas expulsion is very dependent on the virial state of the system at the onset of feedback. If the cluster is in a subvirial state, i.e. $Q_{\text{vir}} < 0.5$, the SFE is not required to be as high as ~ 30 per cent for the cluster to remain bound, and vice versa (Goodwin 2009).

Simulations of massive cluster formation in the dense regions of a GMC suggest that gas expulsion from stellar feedback plays a minor role when it comes to whether or not a cluster is bound (Ćalović et al. 2025; Kruijssen 2026). This is because the majority of the gas has already been turned into stars before the onset of stellar feedback. This is also supported by observations of high-mass protoclusters in which the majority of the mass is traced by the stars (Ginsburg et al. 2016).

The CFE has been linked to the surface density of the star formation rate, Σ_{SFR} (Kruijssen 2012), where a high Σ_{SFR} will produce a higher CFE. Galaxies with high star formation rates and high density gas should therefore have a greater CFE: this idea is based on observations (Portegies Zwart et al. 2010). However, additional observations of CFE (Chandar et al. 2017; Fensch et al. 2019) together with simulations (Lahén et al. 2020) show that there might not be a clear correlation between Σ_{SFR} and CFE.

Whether all stars form in clusters that then quickly dissolve, or whether a larger fraction of stars are born in smaller groups is still up for debate (Wright 2020). The work done in this thesis focuses on the dynamical evolution of clusters after they have emerged from their embedded phase and are now gas free. In our N -body simulations, the clusters are always born in virial equilibrium, and we follow their evolution from this stage. This may be an oversimplification of the initial state for a cluster population with a wide range of masses, which we discuss further in Chapter 5.

1.7 Initial cluster mass function

Like stars, clusters are not all born with the same mass. In fact, most clusters are low-mass, i.e. a few $100 M_{\odot}$, whereas high-mass clusters are rare. The mass distribution of clusters that are born from a population, is given by the initial cluster mass function (ICMF) which can be described by a power-law as

$$\frac{dN}{dM} \propto M^{\beta}. \quad (1.6)$$

Here, $\beta = -2$ and is based on empirical observations of young cluster populations (Zhang & Fall 1999; Hunter et al. 2003; Larsen 2009; Messa et al. 2018a; Hunt & Reffert 2024). The slope of -2 is also what is expected when structures form from a scale-free hierarchical gravitational collapse (Elmegreen & Falgarone 1996; Guszejnov et al. 2018).

There seems to be an upper limit for how massive a cluster can be, which is probably related to the truncation of the mass distribution of GMCs (Colombo et al. 2014a; Rice et al. 2016; Miville-Deschênes et al. 2017). Therefore, the ICMF can also be represented by a truncated mass function in the form of a Schechter (1976) function

$$\frac{dN}{dM} \propto M^{\beta} \exp\left(-\frac{M}{M_t}\right), \quad (1.7)$$

where M_t is the truncation mass of the distribution. As high-mass clusters slowly lose their stars, they will transverse to lower and lower masses. The resulting mass function will therefore be very dependent on the shape of the ICMF.

The GMC truncation mass could be linked to the truncation mass seen for stellar clusters (Kruijssen 2014), where the maximum possible mass that a GMC can have is believed to be set by two mechanisms, namely shearing motions and stellar feedback. The gas in a galactic disc will experience centrifugal forces produced by shearing motions due to differential rotation. This can prevent the gravitational collapse of the gas and thereby set a maximum limit for how massive a GMC can become (Kruijssen 2014). Furthermore, stellar feedback of massive stars might become effective before the gas has entirely collapsed and thereby interrupt the mass growth of the GMC (Reina-Campos & Kruijssen 2017). Model estimates of this scenario matches observations and suggest that shear sets the upper limit for GMC masses in the inner parts of several galaxies, whereas stellar feedback sets the limit at larger galactocentric radii (Reina-Campos & Kruijssen 2017; Messa et al. 2018b). The dominant mechanism for the GMC upper mass limit is set by the gas surface density of galaxies.

1.8 Cluster evolution

As the cluster emerges from its parent cloud with all its gas removed, its internal cluster evolution is now entirely governed by the gravitational forces between the stars and stellar evolution. Stellar evolution will cause the cluster to lose mass (Lamers et al. 2010), which will be most significant in the first few Myr as the most massive stars in the cluster evolve. Two-body relaxation (White 1977; Bonnell & Davies 1998) drives the interaction between the stars in the cluster, which contains stars with a wide range of masses (Kroupa 2001). As the stars interact gravitationally, they exchange kinetic energy. On average, stars with large kinetic energies will lose energy to stars with less kinetic energy. This will cause the high-mass stars to decrease their speed and sink deeper into the centre of the cluster where their kinetic energy increases via the cluster’s negative dynamical heat capacity (Lynden-Bell & Wood 1968; Lynden-Bell 1999). Likewise, the low-mass stars gain energy, causing them to occupy the outer part of the cluster which in turn expands.

Clusters are not isolated structures, but are subject to external perturbations in the form of gravitational tidal forces. If tides are sufficiently strong they can strip the stars from the outer layers of the cluster, which over time will cause the

cluster to dissolve. If the external effects of the galactic environment are ignored, a cluster can evolve in isolation for 1000 times the initial relaxation time (Giersz & Heggie 1994; Baumgardt et al. 2002). It is therefore the galactic environment and the associated tidal perturbations which has the largest effect on the lifetime of a cluster (Gieles & Baumgardt 2008).

1.9 Tidal perturbations

Tides are well known in the Earth-Moon system where the tidal forces of the Moon cause the sea levels to rise and fall here on Earth. Tides can both be extensive and compressive, i.e. they can either stretch or squeeze an object.

Tidal perturbations which occur on a time-scale longer than the internal evolution of the cluster, i.e. a dynamical time, are referred to as adiabatic (Renaud 2018). If the perturbations happen over a shorter time-scale they are referred to as shocks. Clusters that are located far from the centre of their host galaxy, like halo globular clusters, are mostly affected by adiabatic tides, whereas clusters located close to the centres of galaxies can experience tidal shocks produced by spiral arms, galactic discs, and encounters with GMCs.

1.9.1 Spiral arms

As a cluster travels through a spiral arm it can experience shocks which can potentially cause the loss of a significant fraction of its stars. However, this is mostly important for clusters which are extended: Gieles et al. (2007) showed that most of the energy gained by the cluster is converted to high velocities for stars in its outer layers. As such, clusters that are not sufficiently extended will not experience a large mass loss, and spiral arms do not contribute to the majority of cluster disruptions (Renaud 2018).

1.9.2 Disc shocks

A cluster located high above the galactic plane is subject to disc shocking when its orbit takes it through the galactic disc. Such shocks come in the form of compressive tides, where energy is injected into the stars of the cluster (Ostriker et al. 1972). The amount of energy injected depends on the surface density of the disc. Clusters that go through the disc close to the galactic centre or through the spiral arms, where the surface density is higher, will gain more energy. Furthermore, clusters that go through the disc at low speed will suffer weaker

tidal shocks. [Martinez-Medina et al. \(2017\)](#) found that clusters which are located several 100 pc above the Galactic plane will experience the most disruptive disc shocks.

1.9.3 GMC encounters

GMCs are not only the birth places for cluster formation, but can also act as the villain when it comes to cluster disruption. [Spitzer \(1958\)](#) was the first to consider the tidal heating induced by shocks as a consequence of close GMC encounters, and analytically found that the disruption of a cluster occurs on a time-scale that scales with the cluster’s density. This was later confirmed by simulations ([Gieles et al. 2006](#)), where the dissolution time-scale by GMC encounters was found to be several times shorter than that from adiabatic tides. The tidal effects of GMC encounters must therefore be considered when it comes to understanding the disruption and destruction of stellar clusters: this is a main focus of this thesis.

Even though the shocks from spiral arms have shown to contribute little to the disruption of clusters, they are still relevant since most of the GMCs are located in spiral arms. As such, clusters that go through spiral arms are more likely to encounter GMCs. These GMC encounters can also scatter clusters to higher galactic altitudes, which can potentially remove the cluster from the disruptive environment which is found in galactic discs ([Gustafsson et al. 2016](#)).

1.10 Tidal radius

The tidal radius of a cluster is a useful parameter which can describe the strength of the tidal field around a cluster. It can be used to estimate which stars are bound to a cluster and which have escaped. However, the tidal radius can sometimes be defined differently and does not always refer to the same quantity. For example, the tidal radius appears as a parameter in the [King \(1966\)](#) density profile, and represents the radius where the surface density of the cluster begins to drop. This is not necessarily dependent on the tidal forces that a cluster experiences. We therefore want to make a clear definition of how we define the tidal radius in the work that follows.

The Lagrange point, L_1 , defines the point where the gravitational forces of a cluster balance that of its galactic environment. This sphere of influence, which is centred on the cluster, is called the Jacobi surface and its radius is what we define as the tidal radius ([Renaud 2018](#)). The Jacobi surface is displayed in 2D as the solid line in [Fig. 1.2](#) where the remaining surfaces are the equipotential

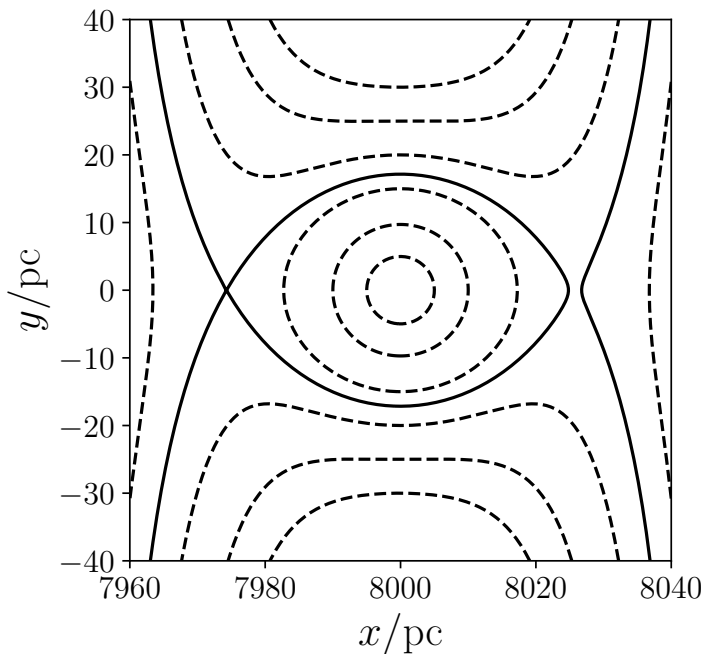


Figure 1.2: The 2D equipotential surface of a rotating two-body system representing a galaxy and a cluster which are both approximated as point-masses located at $(0, 0)$ and $(8000, 0)$, respectively. The Jacobi surface is represented as a solid line.

lines in a rotating two-body system of a galaxy and a cluster. Both objects are represented as point-masses with the galaxy located at $(x, y) = (0, 0)$ and the cluster at $(8000, 0)$. The shape of the Jacobi surface is more like a prolate spheroid than a sphere, but it is often convenient to describe it by a single value. Depending on the tidal strength of the galaxy, i.e. which kind of environment the cluster is in, this radius can decrease or increase. The orbits of stars that are within the tidal radius will be dominated by the gravitational force of the cluster and can be considered bound. We explain how we calculate the effective tidal radius from the instantaneous gravitational field that a cluster experiences in our models in Section 2.2.6.

Chapter 2

Simulations

The work presented in this thesis is based on comparing numerical simulations to observations. It is therefore important to explain and clarify what methods have been used and how they work. In this chapter, we describe how the galactic models and N -body simulations were used to generate the work within this thesis.

2.1 Galactic model

In order to understand the evolution of clusters in any galaxy, we have to investigate their environments. The orbit of an object is dictated by the gravitational potential in which it resides, and it is therefore important to create realistic models to describe these environments. Once this has been done, the orbital evolution of each object can be followed via numerical integration of the equations of motion.

The program we used to integrate the orbits of particles is called `FALPOT` (Dehnen & Binney 1998), originally written by Walter Dehnen in 1996 and later modified by Paul McMillan in 2008. The program includes axisymmetric structures which can be used to describe a disc galaxy, such as the Milky Way. In this thesis, we have updated the program such that it now allows inclusion of structures like spiral arms, a galactic bar, and GMCs. Furthermore, it also includes the option to have particles created as a function of time, with either specific birth locations, or birth locations based on a distribution function. Here we will explain the basic structures that are used to create the galactic models which have been used to investigate the clusters in the Milky Way and M51.

2.1.1 Axisymmetric potential

The axisymmetric potentials of both the Milky Way and M51 were inspired by previous work and the density profiles chosen to represent the two galaxies therefore varies. For the Milky Way, we based the dark matter halo's density profile on the models used by [Binney \(2012\)](#), where the density is given by

$$\rho_{\text{DMH}}(r') = \frac{\rho_0}{\left(\frac{r'}{r_0}\right)^{\gamma_0} \left(1 + \frac{r'}{r_0}\right)^{\beta_0 - \gamma_0}} \exp \left[- \left(\frac{r'}{r_{\text{cut}}} \right)^2 \right]. \quad (2.1)$$

Here $r' \equiv \sqrt{R^2 + (z/q_0)^2}$, r_{cut} is a cutoff radius, and R and z are the cylindrical radius and height, respectively. The parameters chosen were identical to Potential I of [Binney \(2012\)](#).

Unlike the Milky Way, which has a Galactic bar, the centre of M51 is better described as a bulge. Our model of M51 was inspired by [Tress et al. \(2020\)](#) and we therefore adopted a spheroidal [Hernquist \(1990\)](#) profile for both the bulge and dark matter halo, given by

$$\rho_{\text{spheroid}}(r) = \frac{M_{\text{spheroid}}}{2\pi} \frac{a_r}{r(r + a_r)^3}. \quad (2.2)$$

Here r is the spherical radius, a_r is the radial scale length, and M_{spheroid} is the mass.

The stellar and gas discs for both galactic models are represented by double exponential density profiles of the form

$$\rho_{\text{disc}}(R, z) = \frac{\Sigma_0}{2h_z} \exp \left(\frac{-|z|}{h_z} \right) \exp \left(- \frac{R}{h_R} \right), \quad (2.3)$$

where Σ_0 is the disc's central surface density, h_R is the radial scale length, and h_z is the vertical scale height.

2.1.2 Galactic bar

The Milky Way has a bar in its centre ([Bland-Hawthorn & Gerhard 2016](#)) which we represent as a prolate inhomogeneous spheroid ([Pichardo et al. 2003, 2012](#)). The density of this bar decreases linearly as

$$\rho(\alpha) = \rho_0(1 - \alpha), \quad (2.4)$$

where ρ_0 is the central density and $\alpha = (x^2/a_0^2 + y^2/c_0^2 + z^2/c_0^2)^{1/2}$. The semimajor and semiminor axes are a_0 and c_0 and have the values 3.13 kpc and 1.0 kpc, respectively. The force exerted by the Galactic bar was pre-calculated by constructing a force grid which was a function of distance and orientation angle. The Galactic bar was given a mass of $1.6 \times 10^{10} M_\odot$ (Pichardo et al. 2012) with a constant pattern speed which determines the rotation rate. The Milky Way model used in Paper III was updated from the model used in Paper I, in order to match the latest observational estimates. These updates include several parameters in the two different Milky Way models and we therefore only describe the latest version. The current estimate for the pattern speed of the Galactic bar is $33.29 \pm 1.81 \text{ km s}^{-1} \text{ kpc}^{-1}$ (Clarke & Gerhard 2022). We adopt an angle between the major axis of the Galactic bar and the Sun-Galactic centre line of $-19.2^\circ \pm 1.5^\circ$ (Gaia Collaboration et al. 2023b).

2.1.3 Spiral arms

The spiral arms in the galactic models are represented by oblate spheroids with a linear density identical to Eq. 2.4 with $\alpha = (x^2/a_0^2 + y^2/a_0^2 + z^2/c_0^2)^{1/2}$. The semimajor and minor axes of each spheroid are $a_0 = 1.0 \text{ kpc}$ and $c_0 = 0.5 \text{ kpc}$, respectively. Each spiral arm consists of 100 spheroids that are evenly spread out like pearls on a string. The central density of each spheroid follows that of the gas disc and declines exponentially by

$$\rho_0(R) = \rho_{02} e^{-(R-R_s)/h_R}. \quad (2.5)$$

Here, R_s is the galactocentric radius where the spiral pattern starts and ρ_{02} is given by Pichardo et al. (2003) as

$$\rho_{02} = \frac{3M_s}{2\pi a_0^2 c_0 \sum_{j=1}^{N_s} e^{-(R_j-R_s)/h_R}}, \quad (2.6)$$

where M_s is the total mass of the spiral arms, N_s is the number of spheroids in each spiral arm, R_j is the galactocentric radius of each of the spheroid's centres which is summed over one spiral arm.

The problem with living in the Milky Way is that we cannot view it from the outside, like we can for other galaxies. M51 clearly has two distinct spiral arm features which can be seen in Fig 2.1. The current evidence suggests that the Milky Way has four spiral arms (Reid et al. 2019; Castro-Ginard et al. 2021), with two main arms and two less pronounced arms. We therefore chose to represent



Figure 2.1: M51, also known as the Whirlpool Galaxy, together with its companion NGC 5195. The pink regions signify star forming regions while the blue light reveals stellar clusters. Credit: NASA, ESA, S. Beckwith (STScI) and the Hubble Heritage Team (STScI/AURA).

the Milky Way by its two main arms. [Castro-Ginard et al. \(2021\)](#) found that the spiral arms have a differential rotation, where their pattern speed decreases with Galactocentric radius that varies from ~ 50 to $\sim 20 \text{ km s}^{-1} \text{ kpc}^{-1}$. For simplicity's sake, we chose a constant pattern speed of $24 \text{ km s}^{-1} \text{ kpc}^{-1}$ which is in good agreement with the average pattern speed of the three nearest spiral arms as estimated by [Castro-Ginard et al. \(2021\)](#).

The shape of the spiral pattern is described by the pitch angle, i_p , where the angle of the loci of each spheroid is obtained with the function g_i ([Roberts et al. 1979](#))

$$g_i(R) = - \left(\frac{2}{N_s \tan(i_p)} \right) \log \left[1 + \left(\frac{R}{R_s} \right)^{N_s} \right]. \quad (2.7)$$

As the pattern speed of the spiral arms vary, so do their pitch angles. For our Milky Way model we chose a fixed pitch angle of 14° based on the findings of [Reid et al. \(2019\)](#).

The spiral pattern of M51 was based on hydrodynamical simulations by [Dobbs et al. \(2010\)](#), who were able to reproduce a spiral pattern similar to the one observed. [Dobbs et al. \(2010\)](#) estimated the average pattern speed as a function of

galactocentric radius of M51. From this, we fit a function to describe the pattern speed as a function of galactocentric radius. Similar to the Milky Way, the spiral pattern speed of M51 decreases with radius. As a consequence, the spiral pattern in our M51 model winds up over the 200 Myr period in which we simulate the galaxy.

2.1.4 GMCs

The implementation of GMCs in the galactic models is done by having them being continuously born and destroyed within a fixed lifetime. A GMC's lifetime depends on the environment in which it exists, the SFE, stellar feedback, and the mass of the GMC (Ni et al. 2025). Looking at the age differences in stellar clusters, Elmegreen (2000) estimated that the lifetimes of GMCs should be of the order of their dynamical time-scales. By investigating the lack of $\sim 5 - 10$ Myr old stars in star-forming regions in the Solar Neighbourhood, Hartmann et al. (2001) found that GMCs should form stars in a short period of time before dispersing. Assuming that GMCs are destroyed by stellar feedback, Murray (2011) estimated a lifetime of 27 ± 12 Myr which is in agreement with the studies of Williams & McKee (1997) and Matzner (2002), who predict GMC lifetimes in the range of $10 - 30$ Myr. This is also in agreement with the estimates of GMC lifetimes by Meidt et al. (2015) in M51 which lie in the range of $20 - 30$ Myr.

The estimate of the typical lifetime of a GMC can vary substantially and is probably unique for each GMC. For simplicity, we used similar lifetimes for all GMCs in our galactic models, of 20 and 30 Myr for the Milky Way and M51, respectively. The mass of each individual GMC follows a parabolic evolution, such that the mass grows in the first half of its lifetime, which can be thought of as the formation of the GMC. After reaching the halfway point, the GMC will lose mass which can be thought of as disruption which is a consequence of star formation and stellar feedback.

The mass functions of the GMCs are based on the catalogues of Colombo et al. (2014a) and Miville-Deschênes et al. (2017) for M51 and the Milky Way, respectively. In this thesis, we are only interested in the most massive GMCs, i.e. $\sim 10^5 - 10^7 M_{\odot}$, since these will have the biggest impact on the orbits of clusters and their disruption. Both GMC mass functions show a truncation at the higher GMC masses.

We describe the GMCs as Plummer (1911) potentials

$$\Phi_{\text{GMC}} = -\frac{GM_{\text{GMC}}(t)}{\sqrt{r^2 + r_0^2}}, \quad (2.8)$$

where M_{GMC} is the mass of the GMC and r_0 is the scale parameter. The scale parameter is related to the virial radius of the GMC which is further related to its mass. It is therefore important to know the size-mass relation of the GMCs that best describe the galactic environment which we want to replicate. Using the Milky Way GMC catalogue of [Miville-Deschênes et al. \(2017\)](#), we found that the size-mass relation for GMCs with masses $\geq 10^5 M_\odot$ is

$$R_v(t) = 23.9 \left(\frac{M_{\text{GMC}}(t)}{10^5 M_\odot} \right)^{1/2} \text{ pc}. \quad (2.9)$$

Here R_v is the virial radius and is related to the scale parameter as $r_0 = 3/16 \pi R_v$.

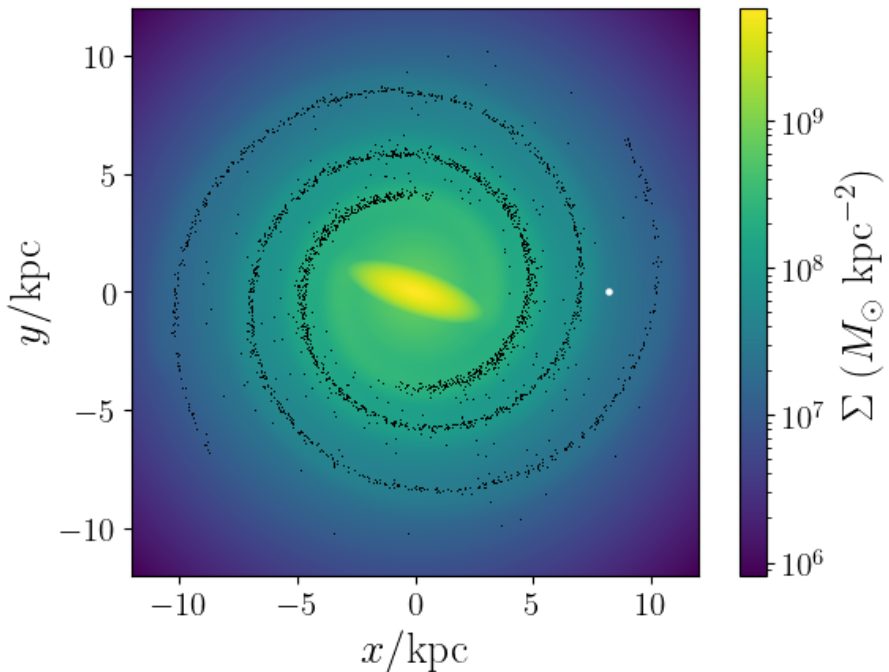


Figure 2.2: The surface density of the baryonic matter in the Milky Way model seen at the present time. The majority of GMCs are born in the spiral arms, at Galactocentric radii between 4 and 11 kpc, and are shown as black points. The position of the Sun is indicated by the white dot.

The radial distribution of GMCs follows the exponential decline of the gas disc observed in each galaxy, where the majority of GMCs are distributed along

the spiral arms. From [Colombo et al. \(2014a\)](#) we know that a large fraction of GMCs are located in the inter-arm regions of M51, and so we allow for 10 per cent of GMCs to be born in the inter-arm regions for both galactic models. The rest of the GMCs are born within 50 pc of the spiral locus. The clusters are simulated as test particles in our models and follow the same spatial distribution as the GMCs. The surface density of the baryonic matter in our Milky Way model can be seen in [Fig. 2.2](#), together with the current distribution of GMCs and the location of the Sun.

The initial velocity distribution of the GMCs is an important factor in terms of the chance of an encounter between a cluster and a GMC. A high initial velocity distribution means that the GMCs can travel further from their birth locations which decreases their number density in the galactic disc. Since clusters are born from GMCs, they will have a similar velocity dispersion which will increase the relative velocity between a possible encounter. The energy injected into a cluster as a consequence of a GMC encounter decreases as V^{-2} , where V is the relative velocity (see [Eq. 2.13](#)). Having a large velocity distribution does not only lower the chance of a GMC encounter, but it also decreases the impact that the GMCs have on the clusters. For our galactic models, we found good agreement between observations when choosing an initial Gaussian velocity distribution of 7 km s^{-1} and 35 km s^{-1} for the Milky Way and M51, respectively. The initial velocity distribution in M51 is quite high compared to the Milky Way and was based on the radial velocities of GMCs in the catalogue of [Colombo et al. \(2014a\)](#). M51 is currently interacting with its companion galaxy, NGC 5195, and [Dobbs et al. \(2010\)](#) and [Tress et al. \(2020\)](#) have shown that this interaction is the cause of the formation of the grand spiral arms in M51. It is therefore not unlikely that this interaction is also responsible for the high velocity distribution of the GMCs in M51.

2.2 N -body simulations

All cluster simulations have been performed using the direct N -body code NBODY6TT by [Renaud et al. \(2011\)](#) which is a modified version of NBODY6 ([Aarseth 2003](#)). The modifications in NBODY6TT allow for the use of a tidal tensor to describe the local galactic environment of a cluster. Instead of having a static potential, the tidal tensor makes it possible to describe the local environment of a cluster as it orbits in a galactic model which can have evolving structures in

the form of a galactic bar, spiral arms, and GMCs. We will first describe the basic principle of the N -body code and then explain how the tidal tensor is constructed.

2.2.1 Direct N -body simulation

NBODY6TT is what is known as a direct N -body code. This means that each star is treated as a single particle, and the equations that describe the motion of each particle are integrated without artificially softening the potential. The dynamical evolution of a cluster with N particles is solved by numerically integrating the equation of motion of a particle with index i and vector coordinates $\mathbf{r}_i$ in the form

$$\mathbf{a}_i = -G \sum_{j=1; j \neq i}^N \frac{m_j(\mathbf{r}_i - \mathbf{r}_j)}{|\mathbf{r}_i - \mathbf{r}_j|^3}, \quad (2.10)$$

where $\mathbf{a}_i$ is the acceleration vector. The summation is done over all other particles with mass m_j and coordinates $\mathbf{r}_j$.

2.2.2 Regular and irregular integration

The numerical integration of the equations of motion quickly becomes slow when the number of particles becomes large, since the number of particle pairs which must be evaluated to compute the force increases as N^2 . The integration also depends on the time-step which is used. A larger time-step means that the code will be faster, but it will also introduce bigger errors. Furthermore, the integration of stars that are far from each other does not require as small a time-step as stars that are close together, since their relative position does not change much. However, stars in the centre of a cluster will be moving much faster relatively to each other and their positions and relative forces therefore need to be updated more frequently.

To optimize the integration, the code uses the Ahmad-Cohen (AC) neighbour scheme (Ahmad & Cohen 1973). The AC scheme employs a neighbour list for each particle, which is defined by a neighbour radius. The integration in the code is then separated into two parts: a regular integration for large time-steps and an irregular integration for small time-steps. The regular integration is done by summation over all particles outside the neighbour radius and the irregular integration is done for all the particles in the neighbour list. The integration of each particle can then be done with varying time steps, depending on how far away each particle is, and employs a fourth-order Hermite integrator (Makino & Aarseth 1992).

2.2.3 Binaries and compact subsystems

Close encounters, binaries, and multiple systems play a significant role in the dynamical evolution of a stellar cluster. However, these strong interactions also require very small time-steps and can easily produce large errors when using the Hermite integration scheme (Wang et al. 2015). In order to correctly integrate the orbit of these systems, other methods are therefore needed.

NBODY6TT solves this issue by replacing binary and other hierarchical systems with centre of mass particles. These particles then interact like normal particles when interacting with the rest of the stars in the stellar cluster. The internal binary orbit is solved separately, using KS regularization (Kustaanheimo & Stiefel 1965) which involves a change of variables in order to avoid singularities in the binary orbit. Interactions of the higher order subsystems, that can occur in the dense regions of a cluster, are described by chain regularization (Mikkola & Aarseth 1989, 1993, 1996) which involves applying successive KS regularisations to pairs of particles along a chain.

2.2.4 Stellar evolution

In order to make realistic simulations of stellar clusters, one has to consider the effect of the evolution of the stars themselves. As stars evolve, they lose mass which changes the gravitational potential of the stellar cluster and hence affects the motions of the stars. Stars that are born with the highest masses evolve on time-scales of a few Myr, whereas the least massive stars evolve over time-scales longer than the age of the Universe. Similarly to the ICMF, low-mass stars are also more common in stellar populations. For all our N -body simulations, we assume an initial mass function (IMF) according to Kroupa (2001) for stellar masses in the range of 0.1 to 50 $M_{\odot}$.

Star clusters are dense environments, and stars can come into physical contact with each other. Binary stars also evolve, which can cause mass transfer between the two stars. NBODY6TT uses the synthetic stellar evolution (SSE; Hurley et al. 2000) and binary evolution (BSE; Hurley et al. 2002) codes to track the evolution of single and binary star systems.

2.2.5 Tidal tensor

The tidal tensor is defined (Renaud et al. 2011) as

$$T_{ij} = -\frac{\partial^2 \Phi}{\partial x_i \partial x_j}, \quad (2.11)$$

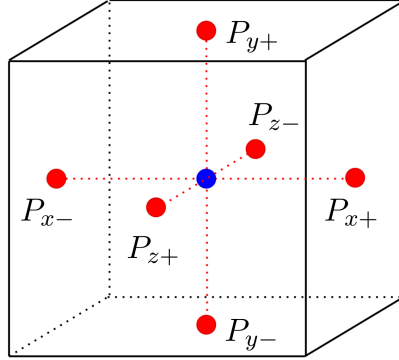


Figure 2.3: The six pseudo-particles (red) that are used to create the tidal tensor. The pseudo-particles are placed around the cluster (blue) in a box of size 2δ .

where i and j are the indices of the 3×3 matrix and Φ is the local galactic gravitational potential. To compute the tidal tensor, a box of size 2δ is defined around the cluster. Then six pseudo-particles are created on the surface of the box where it intersects with the base vectors $\hat{x}$, $\hat{y}$, and $\hat{z}$ as seen in Fig. 2.3. The acceleration vector, $\mathbf{a}_i$, is calculated for each pseudo-particle, which is then used to construct the nine components of the tidal tensor. This is done by taking the pair of pseudo-particles on opposite sides of the box and performing the first order symmetric differencing. As an example, the calculation for the x -axis would be

$$\mathbf{T}_{xj} = \frac{\mathbf{a}_j(P_{x+}) - \mathbf{a}_j(P_{x-})}{2\delta}, \quad (2.12)$$

where $\mathbf{a}_j(P_{x+})$ and $\mathbf{a}_j(P_{x-})$ are the acceleration vectors for the pseudo-particles at position P_{x+} and P_{x-} , respectively.

The construction of the tidal tensor depends on the value of δ , which must therefore be chosen carefully. The value of δ should be of the order of the size of the cluster. If δ is too big, the tidal tensor will fail to resolve the fine structure of the galactic potential. For all our work, we chose a δ value of 15 pc which is of an order of a few half-mass radii for the majority of our simulated clusters.

The tidal tensor assumes that the potential is smooth enough, such that the tidal force can be represented as a linear force. In the case of strong GMC encounters, where the GMCs come very close to the cluster, the tidal tensor becomes a bad approximation for the tidal field. The strength of a GMC encounter

can be estimated by the fractional change in kinetic energy, δ_E , of a cluster, as a result of a GMC encounter. The approximation (Gustafsson et al. 2016) is described by

$$\delta_E = \frac{8GM_{\text{GMC}}^2 r_h^3}{3Mb^4V^2}, \quad (2.13)$$

where M is the mass of the cluster, M_{GMC} is the mass of the GMC, b is the impact parameter, and V is the relative velocity between the cluster and GMC at infinity. Gustafsson et al. (2016) found that GMC encounters with $\delta_E < 0.01$ have little to no effect on the evolution of a cluster. In our work, we define a strong GMC encounter as $\delta_E \geq 0.01$. For our chosen δ , the tidal tensor approximation cannot be used when the closest distance between the GMC and the cluster is less than 60 pc. In such cases, we recreated the GMC encounter directly in NBODY6TT. This was done by integrating the orbit of the GMC back in time to its birth location in order to find the initial position and velocity. The GMC was then implemented as an additional time-varying gravitational potential in NBODY6TT.

2.2.6 Tidal radius

The eigenvalues of the tidal tensor reveal what kind of tides are affecting the cluster, and also the strength of the tides. The corresponding eigenvectors describe in what direction the cluster is either being compressed or stretched. A positive eigenvalue means that the tide is extensive, and a negative value means that it is compressive. The tidal radius of a cluster is defined by the maximum eigenvalue, λ_{max} , of the tidal tensor (Renaud et al. 2011) by

$$r_t = \left(\frac{GM}{\lambda_{\text{max}}} \right)^{1/3}. \quad (2.14)$$

The three eigenvalues of the tidal tensor can take on a combination of different values. One might be positive while the two other eigenvalues are negative, like the tides in the Earth-Moon system. However, the tidal tensor can sometimes have eigenvalues which are all negative, i.e. only compressive tides, which means that the tidal radius is not defined. In such a scenario, the stars will be compressed which will increase their kinetic energy, but without the stars being able to escape the cluster even though the stars have positive energies. This leads to an increase of Q_{vir} and can cause the cluster to become supervirialized, i.e. $Q_{\text{vir}} > 1.0$, which has been shown by Webb et al. (2017) to be a consequence of compressive tides. This supervirialized state of the cluster is temporary and as the cluster moves back

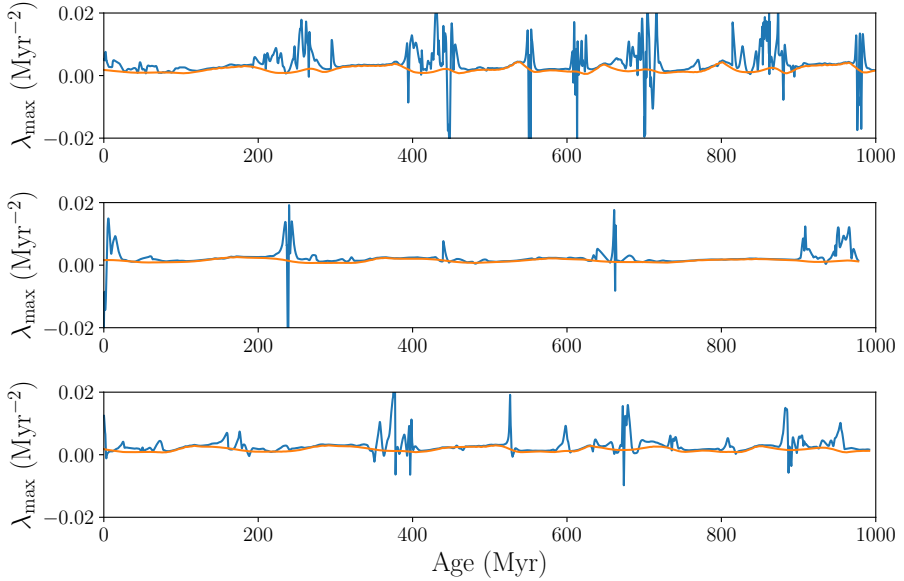


Figure 2.4: The evolution of $\lambda_{\max}$ for the tidal tensors of three different clusters in our Milky Way model. The blue and orange lines represent the tidal tensors with and without the tidal forces of the GMCs, respectively.

into a region with extensive tides, the stars will be able to escape the cluster. This process can cause the cluster to lose a significant fraction of its stars as it transitions back towards virial equilibrium.

The evolution of $\lambda_{\max}$ for the tidal tensors of three different clusters orbiting in our Milky Way model can be seen in Fig. 2.4. The blue and orange lines represent $\lambda_{\max}$ for the tidal tensors with and without the tidal forces produced by GMCs, respectively. When the tidal forces of the GMCs are not included in the tidal tensor, the tidal evolutions of the clusters are very similar and $\lambda_{\max}$ varies smoothly. On the other hand, the clusters experience very different evolutions of $\lambda_{\max}$ when the tidal influence of GMCs is considered. Here $\lambda_{\max}$ can vary rapidly as a consequence of close GMC encounters that can result in fully compressive tides, i.e. $\lambda_{\max}$ becoming negative. The presence of GMCs means that stellar clusters can experience very different tidal evolutions, which will impact their masses and sizes and will eventually determine whether the clusters are destroyed or survive.

Chapter 3

Paper I

3.1 Scientific motivation

The open cluster M67 is shown in Fig. 3.1 and has been suggested as a possible birth place for the Sun. M67 is an unusual open cluster in the sense that it is old, with an age in the range of 3.5 – 4.8 Gyr (VandenBerg & Stetson 2004; Yadav et al. 2008; Sarajedini et al. 2009; Castro et al. 2011; Barnes et al. 2016; Reyes et al. 2024), and is located high above the Galactic plane, at an altitude of ~ 465 pc (Hunt & Reffert 2024). As well as having a similar age to the Sun, M67 also shows the same chemical composition with $[\text{Fe}/\text{H}] = 0.00 \pm 0.06$ (Heiter et al. 2014) and a large number of stars known as solar twins. A solar twin is a star that has a similar mass, age and chemical composition to the Sun. M67 does not only contain many solar twins, but stars analysed in M67 show abundance patterns that are in better agreement with the Sun than solar twins located in the Solar Neighbourhood (Önehag et al. 2014)¹.

But can a cluster located high above the Galactic plane be dynamically linked to the Sun, which is located in the disc of the Milky Way? This is essentially the question that we aim to answer in paper I. Pichardo et al. (2012) made a similar investigation into this question and their answer was “The Sun was not born in M67”. Their result was based on integrating the current position of M67 backwards in time in a Galactic model very similar to our Milky Way model. They search for instances where the Sun and M67 are within the tidal radius of M67 and find that their relative velocity is always greater than 20 km s^{-1} . If the Sun

¹Except for the star HD183658 (Nissen 2015).



Figure 3.1: An image of the open cluster M67. Credit: Jim Mazur, CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>, via Wikimedia Commons.

had been ejected with such a high relative velocity, via three-body encounters in M67, the Solar System would have been destroyed or at least strongly perturbed.

The analysis of [Pichardo et al. \(2012\)](#) assumed that M67 was born on its current orbit. However, [Gustafsson et al. \(2016\)](#) showed that if M67 was born on a disc-like orbit, it is possible that the cluster was later gravitationally scattered to high altitudes by GMC encounters. If the Sun was able to escape the cluster before this scattering took place, it could remain on an orbit very close to the one we see today. In my work, we investigate this scenario by implementing GMCs into the Galactic model and combine it with N -body simulations done in NBODY6TT to estimate the stellar escapers and to verify that the cluster survives to a similar age as M67.

Our investigation can be thought of as a three step process. *First step:* we simulate the orbits of clusters as test particles in our Milky Way model for 4.6 Gyr. At the end of the simulation, we identify the clusters with orbits similar to the present orbit of M67. *Second step:* we run N -body simulations of the M67 candidates that we believe will survive to an age of 4.6 Gyr and keep track of stellar escapers from the clusters. *Third step:* we repeat the first step, but now stars escape

the M67 candidates, according to their N -body simulations. The orbits of the stellar escapers are then followed, and at the end of the Milky Way simulations we compare their orbits to the current orbit of the Sun.

3.2 Finding M67-like orbits

To find cluster orbits that are scattered to similar locations in the Milky Way as M67, we simulated 25 000 test particles divided into 5 independent runs. We were only interested in finding orbits similar to M67, and as such, the test particles did not follow the same spatial distribution as the GMCs, but were instead randomly placed in the Galactic disc at Galactocentric radii of $4 \leq R \leq 10$ kpc.

We selected test particles with similar orbits of M67 based on three orbital parameters: the guiding radius R_g , eccentricity e , and the maximum height above the Galactic plane $|z|_{\max}$. The guiding radius relates the angular momentum in the plane, L_z , to the local circular velocity, i.e. $R_g = L_z/v_c$. As a test particle orbits the Galactic centre, its Galactocentric radius will oscillate around its guiding radius over an orbital period. The guiding radius therefore gives a better description of the orbit than the instantaneous Galactocentric radius. The eccentricity is calculated over a full orbital rotation of 360° in the Milky Way as $e = (r_a - r_p)/(r_a + r_p)$, where r_a and r_p are the apoapsis and periapsis, respectively.

These parameters were calculated for the Sun and M67 by integrating their orbits back in time for 300 Myr in our Milky Way model to ensure a full orbital rotation. We adopted initial positions and velocities based on observations by Bellini et al. (2010) for M67 and Reed (2006); Schönrich et al. (2010); Brunthaler et al. (2011) for the Sun. Based on the uncertainties of their observed parameters, we repeated this backwards integration 5000 times for both M67 and the Sun in order to evaluate the uncertainties of their orbital parameters. In our model, we assume that the Sun is located at a Galactocentric radius of 8.0 kpc.

3.3 Evaluating M67 candidates

We found 37 test particles that had an orbit similar to that of M67. Based on Eq. 2.13, we calculated the cumulative energy gain as a consequence of GMC encounters for each cluster. Clusters with a cumulative δ_E less than unity are therefore more likely to remain bound after the GMC encounters. Here we adopted initial cluster properties from previous investigations of M67 by Hurley et al. (2005), namely a half-mass radius of 4 pc and 36 000 stars which corresponds

to a mass of $\sim 2.2 \times 10^4 M_{\odot}$. Only 16 out of the 37 clusters are estimated to be able to survive their journey to the orbit of M67, whereas the rest of the clusters will be disrupted before the present day. For the 16 clusters that are estimated to survive, we performed N -body simulations of the clusters' evolution with NBODY6TT.

The evolution of these 16 M67 candidates can be very different. We found that they could be divided into three different categories based on their initial z -velocity and final number of stars. We refer to these categories as hot, depleted, and scattered. Hot clusters are born with a high initial z -velocity; depleted clusters are born on dynamically cold orbits but are destroyed by GMC encounters in the Galactic disc; and scattered clusters are born on dynamically cold orbits and survive to have more than 1000 stars at an age of 4.6 Gyr.

Out of the 16 clusters, 4 were depleted, 8 were hot, and 4 were scattered. In our investigation, the most interesting were the scattered clusters since their M67-like orbits are obtained mainly through GMC scatterings and not because they are born hot, while they are still able to maintain an amount of stars similar to M67.

3.4 Stellar escapers

As a cluster evolves in NBODY6TT, stars continuously escape the cluster and are removed from the simulation. In NBODY6TT, this happens when the stars have positive energies and are further than 10 times the half-mass radius away from the cluster centre. To investigate the orbit of these stars as they escape their cluster, we repeated the orbital integration of the 16 M67 candidates in our Milky Way model. In these integrations, both the cluster and stars were treated as test particles. However, as the stars are escaping the cluster they will still be affected by the gravitational potential of the cluster. As such, we described the cluster as a [Plummer \(1911\)](#) potential with parameters based on the dynamical evolution of the cluster in NBODY6TT.

In our work, we define the fraction of stellar escapers that end up on a Solar-like orbit as $f_{\odot}$. We find that $f_{\odot}$ is on the order of a few per cent for the depleted and scattered clusters. Hot clusters generally have a lower value of $f_{\odot}$ since these clusters are already born on orbits that differ from the Sun's orbit.

3.5 Cluster evolution histories

The evolution of each cluster is somewhat stochastic, both in terms of the stellar escape rate and the cluster orbital evolution. Hot clusters only interact with GMCs when they cross the Galactic disc, which means that the number of strong GMC encounters that these clusters experience is very low. Depleted clusters have the most GMC encounters, which also means that they experience the most disruption. Scattered clusters are somewhere in between hot and depleted clusters: they encounter GMCs in the disc but are scattered towards higher Galactic orbits before the disruption becomes extreme. The estimated mass of M67, $2779 \pm 399 M_{\odot}$ (Hunt & Reffert 2024), corresponds well with the final mass for several of the scattered and hot clusters.

In order for a star to stay in the Galactic disc and end up on a Solar-like orbit, it needs to leave its cluster before the cluster's orbit is heated too much. The fraction of stars that end up on Solar-like orbits is therefore very dependent on time. Adams (2010) showed that the Sun would have to leave M67 before the cluster reached an age of 250 Myr in order not to perturb the orbits of Uranus and Neptune caused by stellar flybys in the cluster. Adams (2010) assumed that the birth cluster of the Sun had a stellar number density of $\sim 1000 \text{ pc}^{-3}$ which is far greater than for our models. However, suppose that the stars need to leave our M67 candidates before an age of 250 Myr, then we see a decrease of $f_{\odot}$ between 43 to 95 percent for the four scattered clusters. The chance for a Solar-like star to end up at the Solar location varies greatly between the scattered clusters, and can be very dependent on the stochastic evolution of the cluster. The rates of stellar escapers from the clusters vary, and for some clusters there is a clear periodic signature linked to crossing a spiral arm in our Milky Way model. Depending on the strength of the GMC encounter, there is also a clear increase in stellar escapers as a consequence of GMC encounters. The earlier a star can escape the cluster, the higher the chance that it can remain on a Solar-like orbit, which is further increased if the cluster has an early GMC encounter.

As the stars escape their cluster they start to disperse, which makes it hard to trace them back to their birth cluster. As an object moves along its orbit in the Galactic plane, it is subject to perturbations from the structures in the Milky Way, namely: the bar, spiral arms, and GMCs. As well as affecting the object tidally and heating its vertical orbit, the perturbations may also change the object's orbit in the plane of the Galaxy. This is known as radial migration, which changes the guiding radius of the object. There are two types of radial migration: churning and blurring. Churning is caused by the repeated interactions between structures such

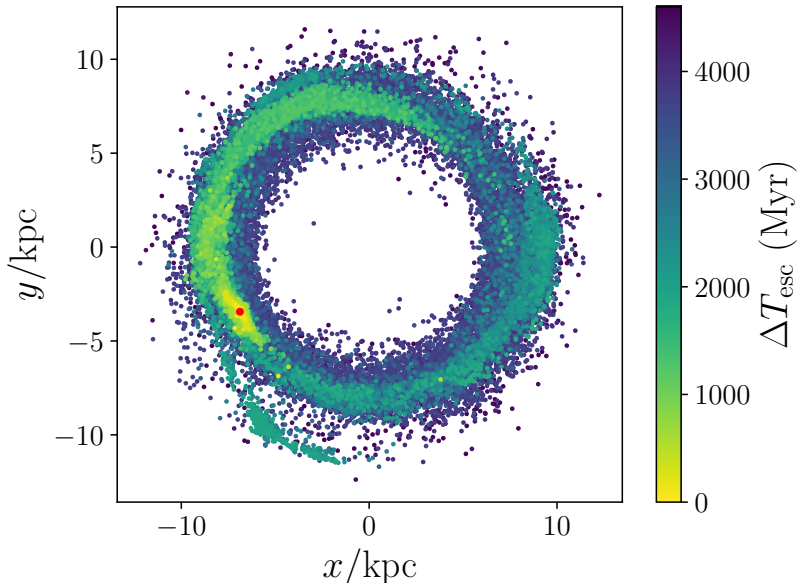


Figure 3.2: The stellar escapers from cluster A in paper I which have been colour coded according to how long ago they left the cluster. The cluster itself is represented as a red circle.

as the spiral arms or Galactic bar, where an object has a similar orbital frequency as a structure, also called co-rotation. Blurring is a consequence of scattering by the Galactic bar, spiral arms, or GMCs. Churning can radially migrate an object's orbit without changing its eccentricity (Sellwood & Binney 2002), while this is not the case for blurring.

Due to radial migration, the current guiding radius of an object does not necessarily reflect where it was born. As high-mass stars evolve they will chemically enrich their surroundings via feedback, which will increase the metallicity of the next generation of stars that are born. This process continues while the stars also radially migrate, which will cause chemical mixing of the stars. Based on models of chemical enrichment and radial migration, the Sun is believed to have been born far from its current position, at a Galactocentric radius between 4.4 and 7.7 kpc (Minchev et al. 2013, 2018; Frankel et al. 2018). The 16 M67 candidates investigated in our work have initial birth guiding radii between 7.2 and 10.0 kpc with a median value of 8.0 kpc. Radial migration is highly dependent on the

dynamical evolution of the Milky Way and the transient nature of the spiral arms. This makes it hard to trace stellar escapers from clusters over a longer period of time. In paper I, we see that the escapers disperse in the phase space of R_g , e , and $|z|_{\max}$. The distribution of stellar escapers in the $x - y$ plane from cluster A in paper I can be seen in Fig. 3.2. The final position of the cluster is shown as the red circle and the stars are coloured according to how long ago they left the cluster, ΔT_{esc} . Stars that have recently escaped can be seen as tidal tails, whereas stars that have escaped several Gyrs ago are distributed throughout the Milky Way. The tail of stars in the lower left corner of the figure are stars that have escaped the cluster over a period of 230 Myr which started when the cluster had an age of 2.5 Gyr.

3.6 Backtracing stellar escapers

Fig. 3.2 demonstrates the difficulty in linking stars to their birth cluster. Based on *Gaia* DR2 data, [Farias et al. \(2020\)](#) tried to find potential stellar escapers from the Orion Nebula Cluster (ONC) by backtracing stars that have overlapped in angular position with the cluster in the last ~ 10 Myr. Of the ~ 17000 stellar escaper candidates, they find 25 stars that are strong candidates, whereas the rest are contaminants and do not originate from the ONC. [Schoettler et al. \(2020\)](#) have conducted a similar investigation of the ONC but considered a smaller search region with a radius of 100 pc around the cluster, compared to the radius of 285 pc investigated by [Farias et al. \(2020\)](#). [Schoettler et al. \(2020\)](#) report a total of 85 potential candidates. There is some overlap between the evaluation of stellar escapers between the two investigations, and their difference is a result of using different criteria for a star being classified as an escaped member of the ONC. The backtracing is only done over a short period of time, since the ONC is very young with an age of a few Myr ([Da Rio et al. 2010](#); [Reggiani et al. 2011](#)).

Using *Gaia* DR3, [Vaher et al. \(2023\)](#) did a similar backtracing for ten clusters, but now with radial velocities, which were previously missing for the majority of stars in the investigations done by [Farias et al. \(2020\)](#) and [Schoettler et al. \(2020\)](#). The combination of the five astrometric parameters, together with the radial velocities of the stars, makes the backtracing more robust, and [Vaher et al. \(2023\)](#) are able to backtrace stars that have escaped the clusters several tens of Myrs ago.

The backtrace of stellar escapers is limited by how well the stars' positions and velocities can be determined and the gravitational perturbation of their orbits in the Milky Way. The effect of the perturbations will become stronger as time passes

and the stars depart from the orbit of their birth cluster, which is evident in Fig. 3.2 where escaped stars can end up on the opposite side of the Milky Way.

The relation between M67 and the Sun is mostly made via their similar age and chemical abundance. Linking groups of stars with the same age and chemical abundance profiles is known as chemical tagging ([Freeman & Bland-Hawthorn 2002](#)). This method has been used to identify large structures such as the thick and thin disc of the Milky Way ([Ivezić et al. 2012](#)). Chemical tagging has also been proposed to be able to connect groups of stars to their birth cluster. However, [Casamiquela et al. \(2021\)](#) conclude that linking groups of stars to their birth cluster via chemical tagging is near impossible. This is because clusters have overlapping chemical signatures, and a chemical grouping of stars does not necessarily come from the same cluster. Only if the cluster has a specially significant chemical signature is it possible to recover stellar escapers from their birth cluster via chemical tagging. However, combining chemical tagging with backtracing can help constrain the stellar escapers and it might be able to push the backtrace time further back.

Chapter 4

Paper II

4.1 Scientific motivation

The scientific motivation behind paper II was the work of [Messa et al. \(2018a\)](#) and [Messa et al. \(2018b\)](#), who investigated the cluster population of the nearby spiral galaxy M51. [Messa et al. \(2018a,b\)](#) analysed data from the Legacy ExtraGalactic UV Survey (LEGUS) which is a Cycle 21 Treasure program on the *Hubble Space Telescope* (*HST*). LEGUS aimed to investigate star formation across galactic environments in 50 nearby galaxies (within 12 Mpc), on scales ranging from those of individual stars to $\sim$ kpc-sized structures ([Calzetti et al. 2015](#)). LEGUS uses five-band imaging from the ultraviolet to the near-infrared, obtained using the Wide-Field Camera 3 and the Advanced Camera for Surveys on the *HST*.

M51 is an excellent laboratory for investigating the populations of GMCs and clusters since it is oriented nearly face-on to us ([Tully 1974](#); [Shetty et al. 2007](#); [Colombo et al. 2014b](#)) and because it is relatively nearby, at a distance of 8.58 ± 0.10 Mpc ([McQuinn et al. 2016](#)). At this distance, the individual stars in the clusters cannot be resolved, so the clusters are analysed using the combined light of their stars. This is done via Spectral Energy Distribution (SED) fitting, where ([Messa et al. 2018a,b](#)) used different colour filters to derive the physical properties of the clusters.

The aim of paper II is to recreate the young cluster population of M51 and compare it with the observational analysis of [Messa et al. \(2018a,b\)](#). Our work also explores the impact that GMCs have on the cluster population over this time period.

4.2 Simulated cluster population

To investigate the cluster population, we ran our model of M51 over a period of the last 200 Myr. We represented clusters by 10 000 test particles, which were born at a constant rate. Out of these, we selected 5000 test particles which had final galactocentric radii between 1.3 and 6.0 kpc. The lower limit is based on the detection limit in the observations, whereas the upper limit ensures that the perturbation from NGC 5195, the companion galaxy to M51, would not have an impact on our results, since we omit its presence in our model of M51.

The mass range investigated by [Messa et al. \(2018a,b\)](#) has a minimum cut at $5000 M_{\odot}$, which is the completeness limit of their population for clusters younger than 200 Myr. Our simulations have cluster masses between 600 and $24000 M_{\odot}$, represented by 5000 clusters which are born following an ICMF with a slope of $\beta = -2$. Because low-mass clusters will be more affected by GMC encounters, we investigated a lower mass interval compared to the observations. Our higher cluster mass limit was much lower than the observed upper cluster mass, because of the computational time requirement to simulate very massive clusters. The nature of the ICMF means that far more low-mass clusters are born than high-mass ones. As such, to be able to robustly investigate the higher mass end of the cluster population, we split the population into two intervals. For low-mass clusters we simulated 4000 clusters in the mass range between 600 and $6000 M_{\odot}$, while the remaining 1000 clusters had initial masses between 6000 and $24000 M_{\odot}$. Based on the 1000 high-mass clusters in our simulations, following the ICMF would require us to simulate 12000 low-mass clusters. To reduce the total computational effort, we instead simulated 4000 low-mass clusters and normalised the distribution when analysing the cluster population.

Clusters are not all born with the same physical size, which affects how sensitive they are to disruption by tidal perturbations. Hence, it is important to recreate a realistic distribution of cluster sizes. We based our initial cluster radius function (ICRF) on observations by [Chandar et al. \(2016\)](#) for clusters younger than 10 Myr in M51, which had radii between 1 and 6 pc. There is no obvious relation between cluster mass and radius for the young clusters, and our ICRF is therefore not dependent on initial cluster mass.

In our work, we were especially interested in investigating how big an impact the GMC encounters have on the cluster evolution. We therefore performed two N -body simulations for each of the 5000 unique clusters: one where the tidal effects of the GMCs are present, and one where they are ignored. We refer to the realistic clusters, which experience the tidal effects of the GMCs, as C_R clusters.

Clusters that do not experience tidal effects from the GMCs are referred to as C_N clusters.

At the end of the N -body simulations, we used Eq. 2.14 to evaluate the tidal radius for each cluster. To make a more direct comparison between the C_R and C_N clusters, $\lambda_{\max}$ was based on the tidal tensor used for the C_N clusters. If a star was located beyond the tidal radius and had a positive energy, it was classified as an escaper and not considered to be part of the cluster.

4.3 Mass function

For our analysis, we fit the present-day mass function of the C_R and C_N clusters to a single power-law, Eq. 1.6. We find no significant difference between the two populations. The effect of the GMCs is not strong enough to change the overall distribution of the population. The observed mass function shows no change from the IMCF with $\beta = -2$, compared to our clusters which have a higher disruption of low-mass clusters, i.e. a steeper slope of β of -1.79 ± 0.02 . Our cluster mass range is lower than the completeness cut of $5000 M_\odot$ of Messa et al. (2018a,b) and if we apply the same mass cut, we are able to reproduce the observed mass function.

It is useful to divide the mass function into different age intervals, since low-mass clusters are disrupted on shorter time-scales than the high-mass. This leads to a mass function slope that becomes flatter as the cluster population becomes older. Therefore, a young stellar population should have a mass function slope that is identical to the slope of the ICME, which is also observed by Messa et al. (2018a,b). As the cluster population of M51 gets older, Messa et al. (2018a,b) observe a drop in the number of clusters. However, the slope of the mass function remains constant until the clusters have ages between 100 and 200 Myr. The young population of our simulated clusters agrees with the ICME, but beyond 10 Myr there is a clear change in the slope of the mass function. The discrepancy between our results and the observations can be contributed to the lower mass range of our clusters.

4.4 Age function

The evolution of the cluster population can be investigated by its age function. The age function is parameterised similarly to the mass function as $dN/dt \propto M^\gamma$, where γ is the age function slope. If clusters are born at a constant rate and

are not disrupted, we would expect the slope of the age function to be equal to 0. The interpretation of the age function therefore depends on knowing the star and cluster formation history of a galaxy. If there has been a change in the cluster formation rate of the galaxy over the period which is investigated, it can be misinterpreted as disruption. M51 is interacting with its companion galaxy which can lead to a change in star formation rate. However, since the cluster population is limited to ages below 200 Myr, [Messa et al. \(2018a,b\)](#) assume a constant cluster formation rate and expect that their analysis is only partially affected.

The age function of our simulations shows a clear dependence on cluster mass. Low-mass clusters have a significantly lower γ than high-mass clusters. This effect is slightly greater for the C_R clusters compared to the C_N cluster. However, this effect is not significant enough to conclude that the GMCs have an effect on the age function. Since there is an overlap in cluster masses between our simulations and the observation, we are able to directly compare two mass intervals, namely: $[0.5 - 1.0] \times 10^4$ and $[1.0 - 2.4] \times 10^4 M_\odot$. For the higher mass interval, we find good agreement between our results and the observations. However, we observe significantly less disruption in the lower mass interval compared to the observations. We investigated this discrepancy and tried to only analyse clusters that were born with higher initial radii, since these will be less bound. Furthermore, we estimated how a higher GMC destruction rate produced by a lower relative velocity between the clusters and the GMCs would affect the cluster population. None of these effects could resolve the discrepancy between our models and the observations. The cluster masses analysed are at the lower end of the completeness limit of the observations, and the discrepancy could be caused by incompleteness in the observations.

4.5 Environmental dependence

The environment in which a cluster is located affects its evolution. The tidal field is stronger closer to the centre of the galaxy and in the spiral arms. Most of the GMCs reside in the arms, which also increases the possibility for disruption there through GMC encounters. These effects are observed when calculating mass and age functions for clusters which have been divided into radial bins and separated, according to whether they are located in a spiral arm (SA) or inter-arm (IA) region. Clusters closer to the galactic centre show more disruption with a flatter mass function slope. Similarly, clusters in the SA region show higher disruption compared to those in the IA region. These environmental trends are also observed

by [Messa et al. \(2018b\)](#), and agree well with similar observations in M101 by [Linden et al. \(2022\)](#).

4.6 GMC protection

We expect C_R clusters to lose more stars compared to their C_N counterparts, since encounters with GMCs strip stars from the clusters. However, in rare cases the presence of the tidal perturbation caused by the GMCs can actually counteract the rest of the galactic tides affecting the cluster. In our work, we found 32 clusters where the C_R clusters had more stars than the C_N clusters. However, one has to consider whether this is a true reflection of the dynamics of each of the 32 clusters, or if the clusters will drastically change over the subsequent dynamical time-scale. For seventeen of the clusters, we find that they are in fact in a supervirial state where compressive tides have increased the kinetic energy of the stars inside of the clusters. These C_R clusters will therefore be very similar to the C_N clusters after a few Myr, and we are just ‘lucky’ to catch them in a supervirial state. The remaining fifteen clusters do, in fact, show a true difference between the C_R and C_N clusters which is caused by the C_R clusters having been protected by the tidal effects of GMCs at some point in their evolution.

4.7 Supervirialized clusters

Looking further into the virial state of the C_R and C_N clusters, we find that 16.2 per cent of the C_R and 12.8 per cent of the C_N clusters are in a supervirialized state. If we compare Q_{vir} of the C_R clusters which have had at least one strong GMC encounter to their C_N counterparts, we find a median Q_{vir} of 0.96 and 0.72 for the C_R and C_N clusters, respectively. From our work, it is therefore clear that interactions with GMCs can greatly increase a cluster’s virial ratio. The velocity distribution of six C_R clusters with different virial states can be seen in [Fig 4.1](#). The blue histogram represents the stars which have negative energies, whereas the orange histogram represents potential escapers, i.e. stars with positive energies that are located inside the tidal radius. Clusters that are supervirialized will likely lose a significant amount of their potential escapers over a dynamical time-scale. It should therefore be possible to identify clusters that have had recent tidal perturbations, since they should have an extended velocity distribution inside their tidal radius. This is not realistic to do for clusters in M51 since the individual

stars cannot be resolved. However, it should be possible to detect for clusters in the Milky Way.

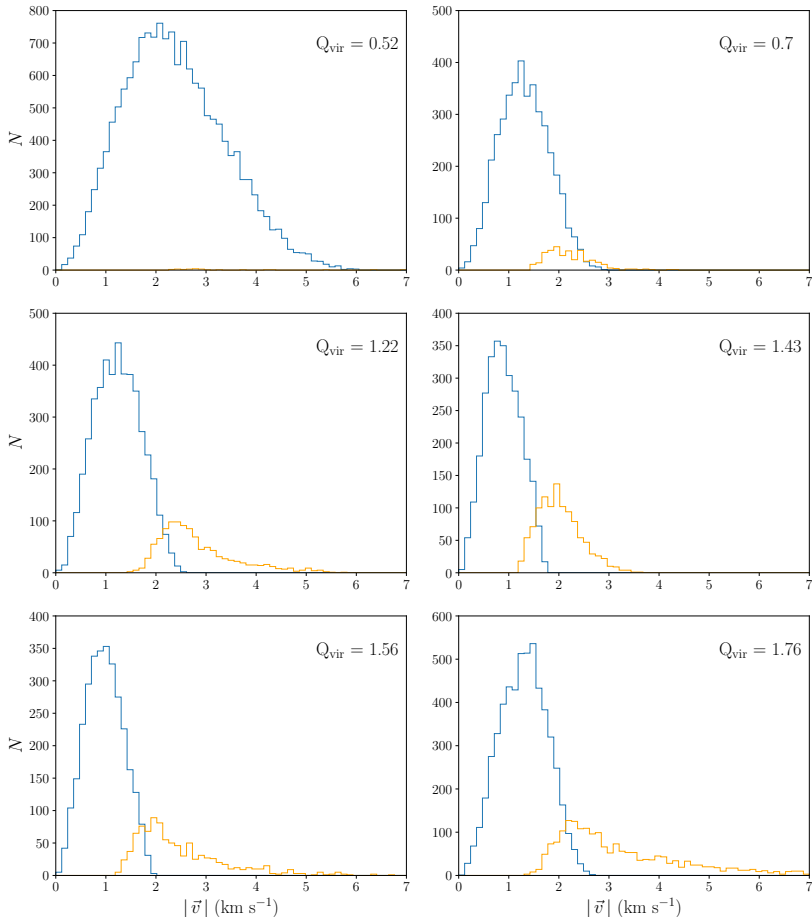


Figure 4.1: The velocity distribution for bound stars (blue) and potential escapers (orange) for six C_R clusters in different virial states.

The increase of Q_{vir} implies an increase in the velocity dispersion of the cluster. As such, assuming that a cluster is in virial equilibrium, Eq. 1.3 can be used to calculate the expected velocity dispersion based on the observed mass and size of a cluster. Several dynamical studies of clusters in the Milky Way (Bravi et al. 2018; Kuhn et al. 2019; Pang et al. 2021) have used this approach and find that, in many cases, the clusters are in a supervirial state.

Chapter 5

Paper III

5.1 Scientific motivation

Cluster masses are distributed accordingly to the ICMF which means that the majority of clusters are born low-mass. Our investigations in paper II revealed that the effect of GMC encounters is very strongly related to the mass of a cluster. However, since the mass completeness of the observations in M51 only enabled us to compare cluster masses above $5000 M_{\odot}$ with ages below 200 Myr, the effect of the GMCs is not strongly reflected in the observed population. Using *Gaia* DR3 (Gaia Collaboration et al. 2023a), Hunt & Reffert (2024) (hereafter, HR24) have created a new open cluster catalogue of the Milky Way which includes a total of 5647 clusters. The catalogue contains clusters with masses down to $40 M_{\odot}$ where the majority of clusters are located within a distance of ~ 3 kpc with ages less than 1 Gyr. The catalogue of HR24 therefore allows us to do a much better test of the impact of GMC encounters. In this work, we extend the ICMF down to $50 M_{\odot}$ and investigate the impact of GMCs on the cluster population in the Solar Neighbourhood over the last 1 Gyr which we compare to the HR24 catalogue.

5.2 Simulated cluster population

We investigate the cluster population of the Milky Way by running 36 independent runs of our Milky Way model in which 10 000 test particles are born continuously over a period of the recent 1 Gyr. The test particles follow the spatial distribution of the GMCs and are born at Galactocentric radii between 4 and 11 kpc. We are only interested in clusters that end up within a distance of 3 kpc of

the Sun at the present time, since this will give us a similar spatial distribution to the observations. This criterion results in ~ 6 per cent of test particles for each independent Milky Way model run and amounts to a total of 20692 clusters.

To investigate the cluster population, we used an ICMF with a slope of -2 in a mass range of $[50 - 24000] M_{\odot}$. To reduce the total computational effort while also being able to investigate a high number of high-mass clusters, we divided the clusters into different mass ranges, similarly to paper II. However, this time the clusters were divided into three different mass ranges: $[50 - 600]$, $[600 - 6000]$, and $[6000 - 24000] M_{\odot}$, with 13227, 6350, and 1115 clusters in each, respectively. To investigate the impact of the GMCs on the cluster population, we follow the same procedure as in paper II, where each unique cluster is simulated twice: once with the tidal effects of GMCs (C_R), and once without (C_N).

5.3 Defining a cluster

Defining a cluster based on its tidal radius and the energies ($U + T$) of the stars, is straightforward for simulated clusters. However, it is much more difficult to determine which stars are gravitationally bound to a cluster from observations. This is because the velocities observed can have uncertainties that are comparable in magnitude to the velocity dispersion of the cluster. Furthermore, the observed velocity can be boosted by binaries, if not corrected: the internal velocities of a binary system will have much higher velocities between the two stars which can lead to erroneous estimates of the velocity. This is especially important if the cluster has a high fraction of binary systems.

To determine stellar masses, [HR24](#) fitted each star to isochrones. Not all observed cluster stars are necessarily classified as member stars in the algorithm that is used to detect clusters, and these selection effects are therefore corrected for by [HR24](#). Selection effects depend strongly on the astrometric precision and whether the cluster is located in a crowded stellar field. Furthermore, the stellar mass estimates in [HR24](#) do not account for binary stars and as such, the stellar mass estimates are therefore only of the primary star in a potential binary system. The majority of stars with masses similar to the Sun and more massive are members of binary systems ([Boffin & Jones 2025](#)), and the presence of unresolved binary stars therefore also needs to be accounted for. [HR24](#) correct their masses by assuming a binary distribution that is similar to the distribution of observed field stars ([Moe & Di Stefano 2017](#)).

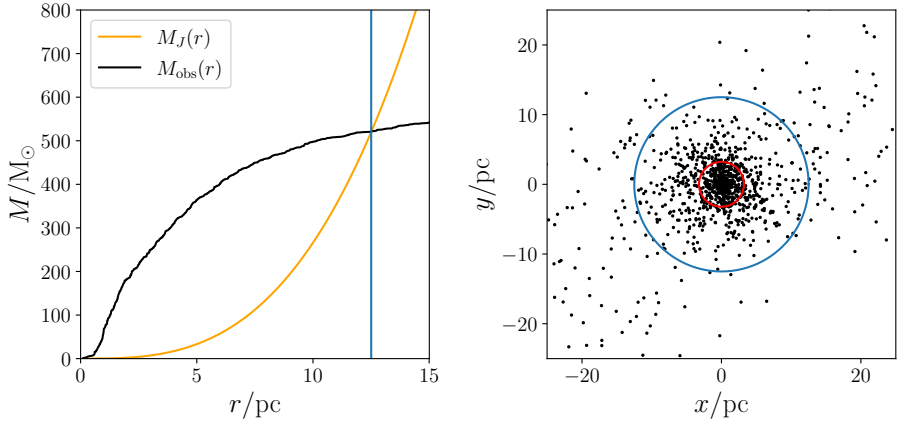


Figure 5.1: The stars of a C_R cluster where member stars are defined by using the method of HR24 to calculate the cluster mass. The comparison between $M_J(r)$ and $M_{\text{obs}}(r)$ is shown to the *left* and the stars of the cluster can be seen in the $x - y$ plane of the Galaxy to the *right*. The tidal radius and half-mass radius are shown in blue and red, respectively.

There is also a completeness limit in terms of which stars can be observed by *Gaia*. Since stars with low masses have lower luminosities compared to high-mass stars, they are harder to detect, and this naturally creates a lower stellar mass limit which is dependent on the distance to the cluster. In the HR24 catalogue, the minimum stellar mass limit varies between 0.09 and 0.7 $M_\odot$. To correct for the mass of stars that are not visible by *Gaia*, HR24 adopted a Kroupa (2001) IMF to estimate the total stellar mass of the clusters. This also means that the half-mass radius of the cluster can be difficult to determine and HR24 instead uses the parameter r_{50} to define the radius of the clusters. For a bound cluster, r_{50} is defined as the radius at which half of the stars are contained.

To determine which of the member stars are bound to a cluster, HR24 uses a method which calculates the tidal radius based on the strength of the local Galactic tidal field, similar to Eq. 2.14. This method does not depend on the kinematics of the stars, but is instead based on an estimate of the enclosed mass of the cluster as a function of radius, $M_{\text{obs}}(r)$, that is compared against a theoretical predicted mass, $M_J(r)$, which is based on its predicted tidal radius. By inverting Eq. 2.14, $M_J(r)$ can easily be estimated as long as the local tidal field is known. If $M_{\text{obs}}(r) = M_J(r)$, r is adopted as the tidal radius and the stars within the

tidal radius are considered bound to the cluster. If $M_{\text{obs}}(r) > M_J(r)$ for all r , all member stars are considered bound. If $M_{\text{obs}}(r) < M_J(r)$ for all radii, the cluster is considered unbound and classified as an association.

In our previous work, we classified a cluster by its tidal radius and the energies of its stars. If stars were beyond the tidal radius and had positive energies, they were not considered bound to the cluster. However, for our analysis in paper III, we adopt the method of [HR24](#) for cluster classification since we are directly comparing our results to their catalogue. An example of a cluster defined by the method of [HR24](#) can be seen in [5.1](#). In paper III we compare the mass of our simulated clusters using both methods and find that the difference in mass is smallest for the most massive clusters and varies by less than 10 per cent for most clusters. This difference is comparable to the mass uncertainties estimated for the clusters in the [HR24](#) catalogue. The cluster masses calculated by using the method of [HR24](#) are always less massive than when using our previous method. This is because stars that are beyond the tidal radius are always classified as escapers, whereas our method also requires the stars to have positive energies.

5.4 Truncated ICMF

When comparing the cluster mass functions, we find that our simulated clusters are a bad representation of the observations which show a clear truncation of higher mass clusters, whereas our simulated clusters can be well described by a power-law. We are able to reproduce a cluster population that matches well with the observations if we assume that the ICMF follows a Schechter distribution with a truncation mass of $9000 M_{\odot}$. We refer to this population as C_{RT} clusters.

The C_{RT} population is able to reproduce most of the population of the [HR24](#) clusters with a similar Schechter mass slope of $\beta_s = -1.54 \pm 0.03$ and truncation mass of $M_t = (4.04 \pm 0.49) \times 10^3 M_{\odot}$, compared to the observations with $\beta_s = -1.50 \pm 0.04$ and $M_t = (3.52 \pm 0.47) \times 10^3 M_{\odot}$. The evolution of the mass functions between the two populations also follows similar trends, where the mass function flattens as the cluster populations become older.

Cluster populations in other spiral galaxies have shown similar mass function truncation ([Jordán et al. 2007](#); [Adamo et al. 2015](#); [Hollyhead et al. 2016](#); [Adamo et al. 2017](#); [Johnson et al. 2017](#); [Messa et al. 2018a](#)). However, the truncation masses found in these galaxies are significantly higher compared to the one observed in the Milky Way, where most of the truncation masses are $\sim 10^5 M_{\odot}$. Environmental dependencies observed by [Adamo et al. \(2015, 2017\)](#) and [Messa](#)

et al. (2018b) show that M_t decreases significantly from the inner to the outer regions of galaxies. M_t could be related to the star formation rate surface density which has been suggested by Johnson et al. (2017). We therefore suggest that the environmental dependence of M_t might explain the low observed M_t , since the HR24 clusters are located at relatively large Galactocentric radii. HR24 estimate that their catalogue contains ~ 4 per cent of the total cluster population of the Milky Way and a low sample size might then explain why the observed M_t in the Galaxy is so low.

The observations suggest that cluster disruption occurs at an early age of ~ 1 Myr, whereas our simulated clusters do not show significant disruption before an age of ~ 50 Myr. The observations indicate that the clusters are born in a higher virial state, i.e. less bound, compared to the clusters in our simulations which are all born in virial equilibrium.

5.5 Survival fraction

In paper III, we define all clusters that have less than 10 stars as destroyed. We investigate the survival fractions of clusters with different initial masses as a function of their ages and median Galactocentric radii, R_m . By comparing the C_R and C_N populations, we can reveal the impact of GMCs. The clusters are classified according to their initial mass as low-mass, intermediate-mass, and high-mass corresponding to $[50 - 600]$, $[600 - 6000]$, $[6000 - 24000]$ $M_\odot$, respectively.

The impact of GMCs is very dependent on the initial cluster mass. High-mass clusters show no significant variation in their survival fraction with R_m . Only high-mass clusters older than 800 Myr show signs of destruction by GMCs, where the survival fraction drops to ~ 92 per cent for the oldest clusters. The C_N clusters show no significant destruction.

The population of intermediate-mass clusters is, in one sense, more affected by GMCs compared to low-mass clusters. This is because the majority of low-mass clusters only live for ~ 450 Myr before they are destroyed, regardless of whether they are affected by GMCs or not. Intermediate-mass clusters can, on the other hand, survive for much longer in the Galactic tidal field, which means they have a greater chance of being affected by GMCs. The biggest difference between C_R and C_N for low-mass clusters occurs when they have ages between 100 and 300 Myr. Compared to intermediate-mass clusters which show a linear relation between their survival fraction and R_m , low-mass clusters show a more

or less constant survival fraction, regardless of R_m . Only low-mass clusters with $R_m > 10$ kpc show an increase in their survival fraction.

To conclude, intermediate-mass clusters with ages of 1 Gyr are most affected by GMCs, where the C_R population has a survival fraction of ~ 25 per cent compared to the C_N population with ~ 55 per cent. Clusters that are located closer to the Galactic centre experience more destruction where intermediate-mass clusters with $R_m = 4.5$ kpc show a survival fraction of ~ 39 and ~ 67 per cent for the C_R and C_N populations, respectively.

5.6 Morphology

As stars escape a stellar cluster in a tidal field which is not dominated by tidal shocks, but instead by adiabatic tides, the stars will escape at a steady rate through the Lagrangian points, L_1 and L_2 ¹. This means that the shape of the cluster, including the stars of its tidal tails, can be approximated as a triaxial ellipsoid where the major axis will be somewhat in the direction of the Galactic centre. However, if the cluster has recently had an encounter with a GMC, the shape of the clusters will be elongated in a direction dictated by the geometry of the encounter. It should therefore be possible to identify clusters that have recently had GMCs encounters by analysing their shape and the direction of their tidal tails. [Ratzenböck et al. \(2025\)](#) have found evidence that the stellar disc stream Theia 368 is in the process of being destroyed by the primordial gas of the star forming region Scorpius-Centaurus.

To estimate the shape of a cluster, we used Principal Component Analysis (PCA) to calculate the principal axes of our simulated clusters. The PCA can identify the principal axis where the distribution of stars varies the most. This is done by calculating the covariance matrix of the spatial positions x , y , and z of the stars in a cluster. The eigenvalues and principal components, i.e. eigenvectors, of the matrix reveal the magnitude and direction of the principal components. The eigenvalues are defined as λ_1 , λ_2 , and λ_3 , where the maximum eigenvalue is λ_1 .

The morphology of the cluster can be estimated by calculating PC_1 which is given by

$$PC_1 = \frac{\lambda_1}{\sum_{i=1}^{N_D} \lambda_i}, \quad (5.1)$$

where N_D is the number of spatial dimensions which in our analysis is 3. For a cluster that has a spherical shape, PC_1 is $\sim 1/3$. Whereas, if instead the shape of

¹ L_2 is located on the opposite side of the cluster compared to L_1 .

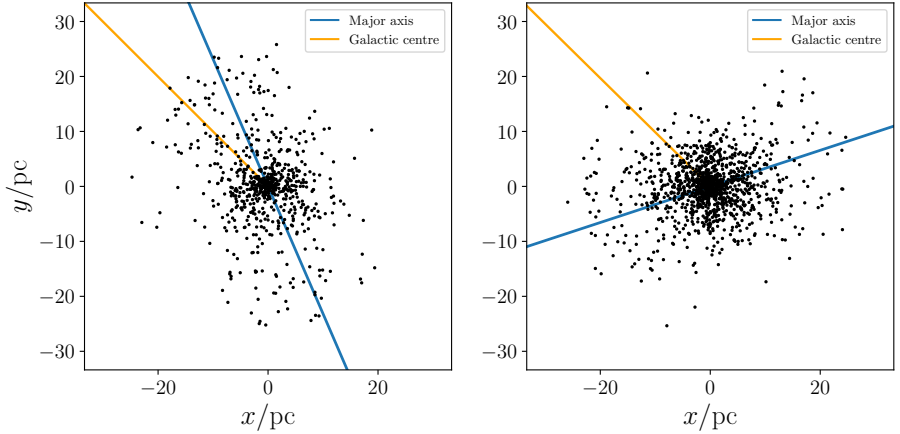


Figure 5.2: *Left:* The stars of a C_R cluster that have had a GMC encounter within the last 20 Myr. *Right:* The stars of the corresponding C_N cluster counterpart. The directions of the major axis is indicated by the blue line while the orange line points towards the Galactic centre. The stars are projected into the $x - y$ plane of the Galaxy and the orbital rotation of the cluster is clockwise.

the cluster is highly elongated, PC_1 will be close to 1. For our analysis in paper III, we included stars that are within $2r_t$ when calculating PC_1 in order to ensure that the tidal tails are considered. In our work, we find that high-mass clusters are more spherically shaped. As the cluster mass decreases, PC_1 increases and converges to a median value of ~ 0.6 . Furthermore, the spread in PC_1 increase as the cluster mass decreases, which reflects that low-mass clusters are more sensitive to tidal perturbations.

In paper III, we find 43 C_R clusters that have had a recent GMC encounter within the last 20 Myr and compare their PC_1 and the direction of their tidal tails to their C_N counterparts. There is a clear sign that the clusters which have had recent GMC encounters have tidal tails that have random orientations, whereas the C_N clusters show a much more structured relation. The *left* of Fig. 5.2 shows the stars of one of these 43 clusters, whereas the stars of the corresponding C_N cluster are shown to the *right*. The stars are projected into the $x - y$ plane of the Galaxy where the major axis and the direction of the Galactic centre are shown. The C_R and C_N clusters have similar PC_1 of ~ 0.57 , however, the directions of the tidal tails of the C_R cluster have clearly been affected by the recent GMC encounter.

C_N clusters with higher PC_1 have tidal tails that point in directions that are less parallel to the direction of the Galactic centre. As stars escape the cluster, the differential rotation of the Milky Way causes stars escaping at L_1 to overtake the clusters, whereas stars escaping at L_2 will lag behind the cluster. This can also be seen to the *right* of Fig. 5.2. Our work shows that a recent GMC encounter will have a significant impact on the morphology of a stellar cluster. It could therefore, in theory, be possible to identify such clusters based on their morphology.

Chapter 6

Reflection and outlook

The investigations carried out in this thesis have been based on combining galactic models with N -body simulations to study the orbital and dynamical evolution of stellar clusters. Comparing our results to observations, we find good agreement with most of our simulations. However, the work done in the thesis is not without limitations. In this chapter, we reflect on some of these limitations, possible improvements, and outlook.

6.1 Binary stars

M67 is known for its high population of blue stragglers with an estimated number of ~ 30 (Deng et al. 1999; Xin & Deng 2005). Blue stragglers are stars that are bluer and more luminous than expected, compared to the rest of the main sequence stellar population in a cluster. A blue straggler is believed to be the result of either the merger or mass transfer between stars in a binary system, which results in the creation of a star that appears younger than its true age.

Hurley et al. (2005) investigated the blue straggler population in M67 using N -body simulations, and were able to reproduce a total of 20 blue stragglers in their model of M67 which was initialised with 36 000 stars with a binary fraction of 50 per cent, i.e. 12 000 single stars and 12 000 binary stars. Binary systems can play a significant role in the evolution of a stellar cluster. Besides creating blue stragglers, binary systems can exchange binary members with other stars or eject them from the cluster at high speeds. In paper I, the N -body simulations of M67 assumed the same number of initial stars as in Hurley et al. (2005), however, all stars were born as single stars. Our choice of only using single stars for M67

was a result of computational difficulties in NBODY6TT. In order to ensure that the energy of the cluster is conserved, NBODY6TT will adjust the time-step size of the numerical integration, which, in the case of a simulation with a high binary fraction, can lead to time-steps that are so small that the code stops. The inclusion of a tidal tensor and GMC encounters significantly increases the occurrence of this issue, making a simulation period of 4.6 Gyr for M67 unrealistic. The same is true when investigating large cluster populations in papers II and III, which is why we only ever considered clusters born with single stars.

Most stars are formed in binaries and as such, our simulations lack this dynamical effect. This is not necessarily a big issue when simulating low-mass clusters, since their evolution will be dominated by the tidal field. However, for our analysis in paper I, where our models of M67 evolve over a period of 4.6 Gyr, it restricts us from comparing a potential blue straggler population with observations. A high binary fraction also decreases the relaxation time-scale of the cluster which affects the internal dynamics.

6.2 Static galactic models

Galactic hydrodynamic simulations, like the one of M51 by [Dobbs et al. \(2010\)](#) which we used in paper II to construct an evolving spiral pattern, are essential when constructing realistic galactic models. The mass distribution of a galaxy determines the orbits and tidal environments of stellar clusters, and thus impacts their evolution, which we also show in our work. The galactic potentials of M51 and the Milky Way are not static: their discs show clear signs of warping ([Oikawa & Sofue 2014](#); [Mertsch & Phan 2023](#)); their spiral arms are transient and each arm has its own evolution ([Dobbs et al. 2010](#); [Tress et al. 2020](#); [Castro-Ginard et al. 2021](#)); GMCs have different evolutions that can depend on their galactic environment ([Lee et al. 2025](#)) which impact the initial parameters of the stellar clusters born from them.

To improve our work, we could therefore base the cluster formation and galactic environment on hydrodynamical simulations that evolve into galaxies similar to the Milky Way and M51. From these simulations, we would be able to construct corresponding tidal tensors which could be used in NBODY6TT. One caveat to this is of course that the tidal tensor is a poor approximation of the tidal field when a cluster undergoes strong GMC encounters, as explained in [Sec. 2.2.5](#). The hydrodynamical code therefore needs to be able to have a sufficient

resolution of the GMCs, so an analytical expression can be used to describe them in NBODY6TT.

Codes that combine direct N -body and hydrodynamical simulations are also of interest since they remove the need for a tidal tensor. The proposed code RAMBODY does this. Similarly, the N -body code PETAR (Wang et al. 2020) has been implemented into the hydrodynamical code TORCH (Wall et al. 2019, 2020) to study how a stellar cluster is born from the collapse of a GMC (Polak et al. 2024). Codes such as TORCH are very computationally expensive and it is therefore not realistic to follow the entire evolution of a cluster. However, these codes can potentially provide insight into the initial structure and virial state of a cluster.

6.3 Virial states

The observed age functions of clusters in both the Milky Way and M51 indicate that some clusters might be born in high virial states, compared to our simulations where we assume that the clusters are born in virial equilibrium. N -body simulations show that early cluster evolution can be very dependent on the initial sub-structure and Q_{vir} of a cluster (Allison et al. 2010). The discrepancy in the age function could therefore be explained by the fact that stellar clusters are born in a less bound state (Bravi et al. 2018; Kuhn et al. 2019; Pang et al. 2021) and can therefore be destroyed by tidal forces shortly after they form. Follow-up simulations that test how the age function differs for cluster populations with different initial virial states would help reveal if this is in fact true.

6.4 Selection function

The catalogue of HR24 is not complete. An incomplete sample means that some of the clusters in the volume explored by *Gaia* are not necessarily identified as clusters, and this needs to be corrected when constructing the mass and age function of the observed population. HR24 provide a completeness limit described as the two-dimensional distance from the Sun in the Galactic plane, $R_{100\%}$, where the sample of clusters with a specific mass can be considered complete. This means that only clusters within $R_{100\%}$ can be used in the analysis of the population which thereby limits the sample size of the observations.

Hunt et al. (2025) have created a selection function for the HR24 catalogue which depends on four parameters: ρ_{data} , n_* , $\text{median}_{\text{px}}$, and S_{thres} . ρ_{data} is the

parameter density of the *Gaia* data at the cluster location and n_* is the number of observed member stars of the cluster. Clusters which are located in high density fields with a low number of observed stars will be harder to detect, compared to clusters in low density regions of the *Gaia* data. The median parallax error of the stars in the cluster is given by $\text{median}_{\text{px}}$, and S_{thres} is the statistically significant threshold set for the cluster. The selection function estimates the probability of a given cluster being detected as a cluster in the [HR24](#) catalogue and can be used to sample the simulated cluster population, which can be compared to the observed population. Creating a sample of our simulated clusters in paper III based on the selection function by [Hunt et al. \(2025\)](#) would therefore be of interest.

6.5 Cluster observations

Using simulations to understand how clusters evolve are only useful if we can compare our results to observations. We therefore briefly mention some of the upcoming surveys which will help improve the knowledge of stellar clusters.

The future *Gaia* data releases DR4 and DR5, which are based on 5 and 10 years of data gathered, will improve the astrometric knowledge of stars in the Milky Way. The parameter estimations and member stars of known clusters are therefore expected to be improved and the discovery of new clusters is inevitable.

The upcoming spectroscopic surveys *WEAVE* ([Jin et al. 2024](#)) and *4MOST* ([de Jong et al. 2019](#)) will supplement the *Gaia* data with more radial velocity measurements and will simultaneously provide stellar parameters and chemical abundances, which can further help determine the cluster membership of stars.

Another upcoming survey is *LSST* ([Ivezić et al. 2019](#)) which will observe half the sky with optical imaging in six different colours. Over a period of ten years, *LSST* will repeatedly observe the sky and thereby record the time evolution of billions of objects and will be able to detect new clusters in the Milky Way and other galaxies ([Usher et al. 2023](#)).

The proposed mission of *GaiaNIR* ([Hobbs et al. 2016](#)) will be a similar type of mission as *Gaia*. However, instead of observing in the optical, *GaiaNIR* will be looking at the stars in the near-infrared and will therefore be able to observe stars in the Milky Way that are hidden by dust. This is especially the case for stars in the plane of Milky Way disc, which is where most open clusters are found and where cluster formation occurs. *GaiaNIR* will therefore be able to observe the stars in clusters as they are forming.

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Part I

Scientific Publications

Author contributions

A summary of my contribution to the papers included in this thesis.

Paper I

Stellar escapers from M67 can reach solar-like Galactic orbits

Jørgensen, Timmi G.; Church, Ross P.

Monthly Notices of the Royal Astronomical Society, Volume 492, Issue 4, pp. 4959–4974 (2020)

In this study, I led the modifications of the codes `FALPOT` and `NBODY6TT`, and the numerical simulations and their analysis, together with assistance from Ross Church. Assistance with modification of the output files of `NBODY6TT` was provided by Guido Moyano. Discussion and suggestions for this project were provided by Bengt Gustafsson, Melvyn Davies, Florent Renaud, Guido Moyano, and Lennart Lindegren. I analysed the data and led the writing of the paper with comments and corrections provided by Ross Church and Lennart Lindegren.

Paper II

The young stellar clusters in M51 and the impact of GMC encounters

Jørgensen, Timmi G.; Church, Ross P.

Monthly Notices of the Royal Astronomical Society, Volume 543, Issue 2, pp. 1410–1428 (2025)

In this study, I led the modifications of the codes `FALPOT` and `NBODY6TT` and carried out the numerical simulations. I analysed the data and led the writing of the paper with comments and suggestions from Ross Church, Angela Adamo, Matteo Messa, and Sean Linden. Corrections to the paper were provided by Ross Church.

Paper III

***N*-body simulations of the open cluster population in the Milky Way and the impact of GMC encounters**

Jørgensen, Timmi G.; Church, Ross P.

To be submitted to MNRAS (2026)

In this study, I carried out and analysed the numerical simulations. Discussion and suggestions for this project were provided by Ross Church, Carlos Vázquez,

Laura Magrini, and Emily Hunt. I analysed the data and led the writing of the paper with comments and corrections provided by Ross Church.