How Does the Primordial Binary Fraction Affect the Survival Time of an Open Cluster in the Galactic Disk?

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Abstract

This study investigates how primordial binary star populations influence the long-term stability of globular clusters. Using a custom-built 2D N-body simulation, clusters with varying initial binary fractions (0%, 8%, 16%, 24%) were modeled over extended periods. Results show that clusters with binaries consistently retained more mass and exhibited slower core contraction compared to those without, supporting the theory that binary interactions act as an internal energy (or heating) source that delays core collapse. Notably, the stabilizing effect increased steadily with binary fraction across all tested values, with no observed threshold where binaries became detrimental. These findings suggest that the size of the primordial binary fraction has a significant positive effect on star cluster longevity.

1 Introduction

One of the most important stellar formations that play significant roles in the structure of our galaxy are globular star clusters, which are dense, gravitationally bound systems made up of hundreds of thousands to millions of stars. They are inherently chaotic, as are all systems with more than two bodies so their internal structure of a globular cluster changes over time, progressively losing mass and structure as a result of internal processes like two-body relaxation, in which a large number of weak gravitational interactions cause some stars to drift towards the cluster's centre while others gain energy and escape.

Gravitational interactions between stars become more frequent and intense as more stars concentrate at the centre, increasing the mass density. As a result, more low-mass stars are expelled, speeding up the process. The system eventually has a dense core made up of enormous stars. Core collapse is the term for this. Given the length of time needed to reach this phase, the majority of the remaining stars have already evolved into neutron stars or black holes, hence the term "dark remnant core" in actual astrophysical contexts.

The existence of primordial binaries, or binary stars that formed early in the cluster's development, is a crucial component of this dynamical evolution. By releasing energy gradually through weak gravitational interactions with nearby stars, these binary systems serve as energy reservoirs. By preventing the central region of the cluster from becoming excessively dense, they can theoretically prevent core collapse. Alternatively, they might hurl smaller stars out of the system, hastening collapse.

The precise effect of various primordial binary fractions on cluster longevity is difficult to measure, despite the fact that binary stars are known to be important in cluster dynamics. Higher binary fractions should theoretically extend a cluster's life by adding more energy, but they also cause smaller stars to be expelled more frequently. Nevertheless, little is known about the type and magnitude of this effect. The computational intensity of N-body simulations, which scale at $O(N^2)$, is partially to blame for this. However, trends that are applicable to larger systems can still be found in simulations conducted at a smaller scale.

In this work, I examine the effects of changing the proportion of primordial binary stars on a globular cluster's decay rate and structural evolution. I model clusters with various initial binary fractions and track their dynamical behaviour over time using a series of N-body simulations. My goal is to find a direct correlation between the number of binary stars and the cluster's longevity by comparing internal structural changes and mass loss rates.

2 Theoretical Background

Gravitational interactions between the stars in a globular star cluster drive its dynamical evolution. These systems are intrinsically chaotic and unstable over long timescales, resulting in collisions and ejections. Two-body relaxation, mass segregation, and binary star interactions are important physical processes.

2.1 Two-Body Relaxation

However, weak gravitational interactions with nearby stars gradually change trajectories, causing a process known as two-body relaxation, whereby stars exchange energy and angular momentum through countless random encounters, changing their velocities and orbits over time, even though stellar motion can be roughly described as straight-line movement over short periods of time.

The characteristic timescale for significant evolution from two-body relaxation depends on the number of stars and usually ranges from hundreds of millions to several billion years in globular clusters. This results in energy equipartition: slower-moving stars gain energy and migrate outward, while faster-than-average stars lose energy and migrate inward.

2.2 Mass Segregation and Core Collapse

More massive stars have a tendency to lose kinetic energy and move towards the cluster's centre as energy is redistributed. Lighter stars acquire energy as a result of this process, known as mass segregation, and migrate out of the cluster or towards its periphery.

Massive stars are migrating inward, increasing central density and increasing the frequency and intensity of gravitational encounters. Core collapse is a runaway process in which the core contracts. White dwarfs, neutron stars, and black holes—collectively referred to as the remnant core—usually dominate the central region, which at this point becomes extremely compact.

2.3 Primordial Binary Stars and Binary Heating

Cluster evolution is significantly impacted by primordial binary stars, or those that formed in the early phases of the cluster. Binary heating occurs when binary systems come into close contact with other stars, which can impart kinetic energy to the system. By halting the development of a dense, low-energy core, this energy release can counteract core contraction.

Through such interactions, hard binaries (tightly bound systems) transfer energy outward while becoming even more tightly bound. They function as the system's internal "heaters" as a result. Clusters with a high proportion of primordial binaries might lose mass more slowly and withstand core collapse longer. On the other hand, unbound binary stars can release a lot of kinetic energy during interactions, which can sometimes cause the cluster to become unstable more quickly than hard binaries.

2.4 Theoretical Evolution

Due to two-body relaxation and mass segregation, globular cluster evolution typically follows these stages:

1. Initially, stars are widely spaced with low average velocity.
2. Two-body relaxation causes high-energy stars to be pushed outward or ejected.
3. Mass segregation leads massive stars to sink inward, transferring energy to lighter stars, ejecting them.
4. The cycle repeats until core collapse, leaving behind a dense core of low-energy, high-mass stars—often collapsed remnants.

3 Methodology

3.1 Simulation Overview

To study the impact of primordial binary stars, I conducted a series of custom N-body simulations measuring the longevity of globular clusters under different binary fractions.

3.2 Program Overview

I decided to create my own simulation code because of the particulars of this investigation. I utilised the NumPy library to speed up mathematical operations and the Python programming language because of its ease of use. Scalability was a major drawback: the simulation complexity scales as $O(N^2)$, making it computationally costly because every star interacts with every other star.

The time step presented another difficulty. The smallest effective time step in simulations is closer to (10-9) seconds (in practice, often much longer), in contrast to real time, where the Planck time ((10-44) s) is the smallest measurable interval. Errors are introduced because trajectories must be modelled as a sequence of straight segments. This was lessened by running the simulations at extremely small time steps, which kept energy conservation errors below $10^{-6}\%$.

The simulations resolved tight binary interactions and global evolution using individual time-step schemes and a high-accuracy direct N-body integrator. Since there was no softening length applied, close encounters were accurately modelled. Direct calculations of gravitational forces were made, and for numerical stability, energy conservation was carefully observed. Particle positions were randomised, but initial kinetic energy and total system mass were controlled. Each scenario was run ten times to lessen the effect of chance.

The simulation modeled Newtonian physics in a 2D space. Each particle experienced a force of attraction from every other particle, calculated as:

$$F_g = \frac{Gm_a m_b}{r^2}$$

The gravitational constant G was scaled to speed up simulation results.

3.3 Initial Conditions

The following parameters define the simulation setup. Units are abstract, and time is measured in simulation frames.

Table 1: Simulation Parameters

Parameter	Value / Meaning
G	500 — gravitational constant
Mass scale	500 — size-to-mass ratio
Collision radius	0.01 — merging threshold
Init. speed	5 — max initial particle velocity
Cluster radius	400 — defines system boundary
Total mass	7000 — total system mass

3.4 Analysis Metrics

Each simulation was analyzed based on:

1. **Cluster Mass:** Total bound mass over time, to assess decay rate.
2. **Half-Mass Radius:** Radius enclosing half of the cluster's mass, to measure structural evolution.

A cluster was considered decayed when less than 50% of its original mass remained bound. Snapshots were taken at regular intervals. The results for different binary fractions were then compared.

4 Results

To examine the effect of binary fraction, I simulated clusters with binary fractions of 0%, 8%, 16%, and 24%. Each scenario was repeated ten times, and averages were computed.

4.1 Mass Retention Over Time

Figure 1 displays the retained cluster mass over time. As expected, the cluster with 0% binaries showed the fastest mass loss. Higher binary fractions resulted in greater mass retention.

Clusters with 8–24% binary fractions consistently outperformed the binary-free model. The 24% binary model retained the most mass, suggesting continuous energy input from binary interactions helped delay collapse and limit ejections.

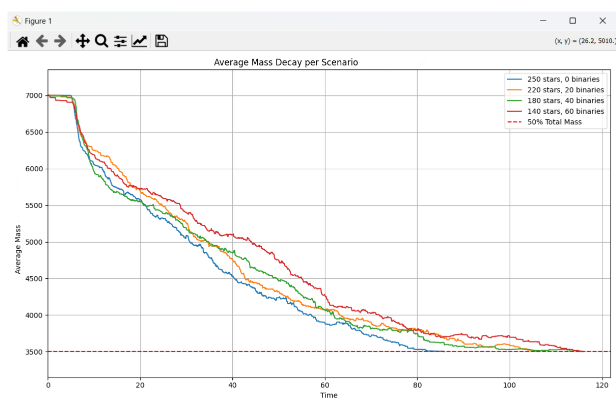

Figure 1: Mass retention vs. time for varying binary fractions.

As shown on this graph, clusters with around 24% binary stars had a half life of around 30,000 time units longer than when this fraction is 0%. The simulation terminated each reading once the mass of the cluster hit 50% of it original weight.

4.2 Core Radius Evolution

Core radius (radius containing the innermost 10% of mass) was also tracked. Figures 2 and 3 show that higher binary fractions correlate with slower core contraction, consistent with the theory that binaries stabilize the core and delay collapse.

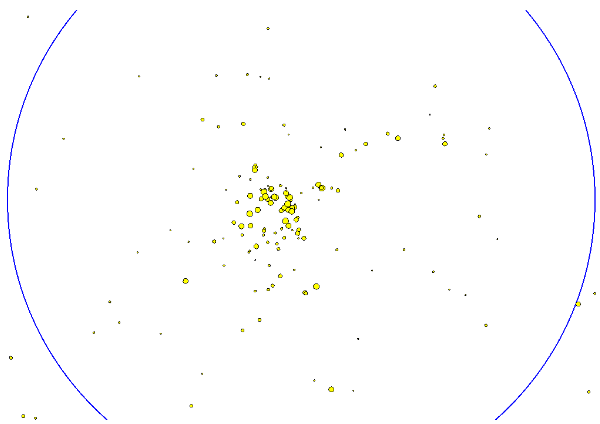

Figure 2: Core structure for 250 non-binary stars.

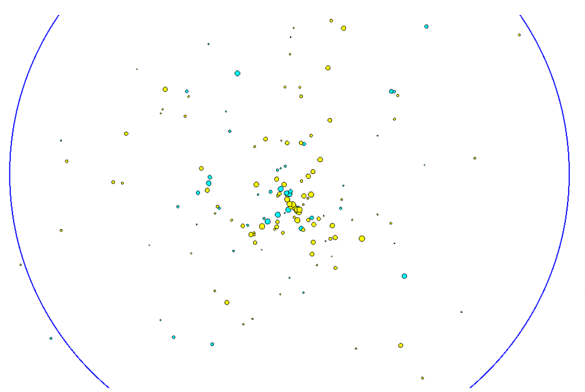

Figure 3: Core structure for 180 non-binary stars and 35 binary pairs.

These diagrams are snapshots taken 20,000 time units after simulation start. Yellow dots are non-binary stars; blue dots are primordial binaries. In Figure 2, the core is more compact. In Figure 3, more stars remain off-center yet bound to the system. This supports the idea that binary heating allows off-center stars to stay in the system without being ejected. Both clusters show core collapse tendencies, but the one with more binaries will likely last longer due to the presence of energetic stars orbiting and heating the core.

5 Discussion

The findings demonstrate a strong relationship between cluster longevity and primordial binary fraction. Greater binary fractions slow core collapse and enhance mass retention.

Energy from binary interactions keeps mass ejection and rapid contraction at bay. Without this energy, the system rapidly decayed in the 0% case. Up to 24%, the benefit of binaries did not plateau or reverse, indicating that, at least under simulation conditions, the stabilising influence of binaries was not outweighed by the ejection events they caused.

Despite being 2D with abstract units and artificial constants, the results align with theoretical predictions and can be applied to real clusters with proper scaling.

6 Conclusion

The function of primordial binary stars in the development of globular star clusters was investigated in this study. Using specially constructed N-body simulations with different binary fractions, I discovered that cluster longevity was consistently enhanced by higher binary content.

Clusters with more binaries were able to maintain structural stability and retain mass over time. Binary stars acted as an internal heat source, distributing kinetic energy and delaying collapse.

Despite their simplification, the simulations validate theoretical predictions. To more accurately simulate real-world conditions, future research should incorporate external gravitational effects, 3D modelling, and higher particle counts.

A Code Repository

The full Python source code and LaTeX document are available at: https://leonid-elkin.github.io/