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

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Abstract

Star clusters are gravitationally bound groups of stars whose long-term survival is influenced by internal dynamics and external tidal fields. A key internal factor affecting their evolution is the presence of binary stars. This study investigates how the primordial binary fraction—the proportion of binary systems present at a cluster's formation—affects the dynamical stability and lifetime of open star clusters within a galactic disk environment.

Using a custom-built 2D N-body simulation written in Python, we modeled clusters with identical initial conditions but varying primordial binary fractions (0%, 8%, 16%, and 24%). We analyzed their mass loss rates, core contraction behavior, and kinetic energy distribution over time. Results demonstrate that higher binary fractions significantly delay core collapse and increase mass retention by injecting kinetic energy into the system through dynamical interactions—a process known as binary heating.

Clusters with more binaries maintained structural coherence for longer time spans, with the 24% binary model surviving nearly 30,000 simulation time units longer than the binary-free counterpart. These findings confirm that even modest increases in binary population can markedly enhance cluster longevity. The simplified 2D model provides strong support for theoretical predictions, while future work could extend this approach to full 3D simulations and include galactic tidal forces for more realism.

Introduction

Star clusters are dense, gravitationally bound systems composed of hundreds to thousands of stars. Due to their many-body interactions, they evolve dynamically over time, gradually losing mass and structure. A key process driving this evolution is **two-body relaxation**, in which repeated weak gravitational encounters cause some stars to sink toward the center while others gain energy and escape.

As more massive stars concentrate in the core, gravitational interactions become more frequent and intense, increasing the central density. This leads to the preferential ejection of lower-mass stars, further accelerating the contraction. Eventually, a dense core composed of stellar remnants forms—a process known as **core collapse**. In many cases, the remaining massive stars have evolved into neutron stars or black holes, creating a "**dark remnant core**."

Primordial binaries (binary systems that formed early in the cluster's history) play an important role in this evolution. These binaries serve as internal energy (or **heating**) sources, gradually releasing energy through gravitational interactions. This energy can inhibit **core collapse** by maintaining higher energy levels in the core, or in some cases, accelerate mass loss by ejecting lighter stars.

While the influence of binary stars on cluster dynamics is well established, the exact relationship between primordial binary fraction and cluster lifetime remains unclear. Though higher binary fractions are expected to increase stability, they may also lead to increased ejections of ligher stars because of the stars' innately high energy levels. The computational cost of high-resolution N-body simulations, which scale at $O(N^2)$, limits the ability to explore this question fully, however even small scale simulations can show trends that can be generalized to larger numbers of particles.

This study models the effect of varying **primordial binary fractions** on cluster stability using a custom 2D N-body simulation. By comparing structural evolution and mass retention across different binary fractions, the aim is to establish a correlation between binary content and cluster survival time.

Methodology

To examine how primordial binaries influence star cluster longevity, a custom-built N-body simulation was developed in Python. The simulation models self-gravitating particles in two dimensions for increased efficiency. Minimal energy inaccuracy during interactions is maintained by a high calculation rate which was facilitated by the use of specialized mathematical library NumPy.

Integration and Performance. The force on each particle is computed using Newton's law of gravitation:

$$F_g = \frac{Gm_1m_2}{r^2}$$

and force direction from:

$$\theta = \tan^{-1}\left(\frac{y_2 - y_1}{x_2 - x_1}\right)$$

Newton's third law ($F_1 = -F_2$) was used to optimize performance by halving redundant calculations. The simulation scales with $O(N^2)$ complexity, so efficiency improvements were essential to run scenarios with up to 400 particles. No gravitational softening was used, ensuring accurate resolution of close encounters and prevent energy from appearing out of nowhere. Time steps were finely tuned to maintain total energy conservation below 10^{-6}%. All calculations were vectorized using NumPy for computational efficiency and ease of operation.

Initial Conditions. Particles were assigned random positions within a defined cluster radius, with velocity vectors adjusted to achieve a mean center-of-mass velocity of zero. Velocities were normalized using the SoftMax function:

$$\alpha(z) = \frac{e^{z_i}}{\sum_{j=1}^{K} e^{z_j}}$$

to balance directional momentum and stabilize initial conditions. Each simulation started with a total mass of 7000 units and average particle speed of 5 units.

Binary Implementation. Primordial binaries were introduced by pairing a specified fraction of particles (0%, 8%, 16%, 24%) with equal-mass partners in tight circular orbits. Binary pairs were positioned randomly. The binary orbital mechanics were initialized using:

$$v = \sqrt{\frac{Gm}{r}}$$

where r is the separation and m the mass of each binary component. Both binary stars followed simple tangental motion relative to each other.

Simulation Runs. Each scenario was run 10 times with random seeds to average out stochastic effects. The simulations tracked evolution until 50% of the original mass was unbound which was defined as the decay threshold.

Metrics. Cluster evolution was quantified using a predefined radius around the centre of mass. All units were internally consistent and abstract. After a certain threshold manually defined by the user stars are deleted from the simulation. This is in order to speed up computation time by removing stars that will realistically never come back to the cluster. Summary of fixed simulation parameters:

Table: Simulation Parameters

Parameter	Value	Parameter meaning
G	500	The gravitational constant for Newton's law of gravity
Total mass	7000	Total mass of all particles
Cluster radius	400	The radius around the center of mass considered part of the cluster
Collision radius	0.01	The maximum distance where two particles annihilate themselves
Initial particle speed	5	The average particle speed at simulation initialization
Binary fractions tested	0%, 8%, 16%, 24%	Fractions of particles initialized as binaries
Particles per run	250	Number of particles simulated in each run

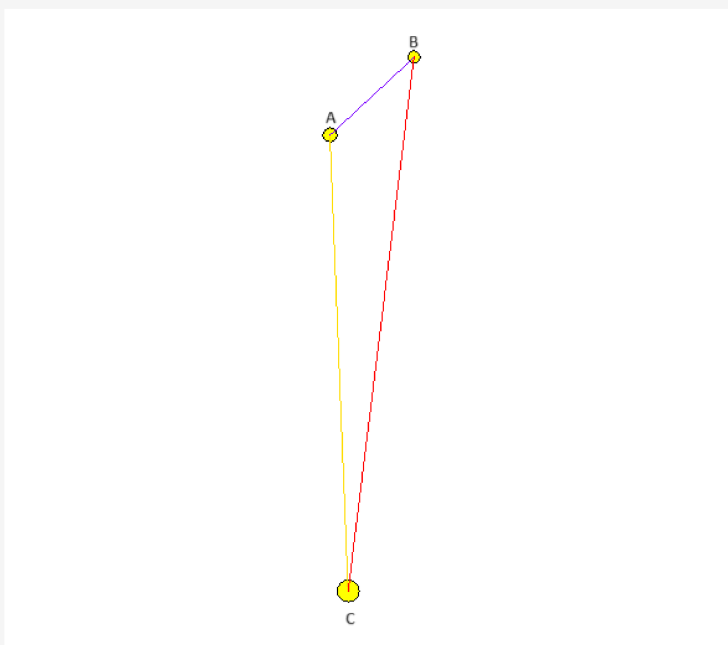

Figure: A development screenshot of forces acting on each particle.

Results: Mass Retention

Mass retention plotted over time shows clusters with higher binary fractions retain mass longer. The 24% binary cluster survives 30,000 units longer than binary-free. Each line is an average of ten different simulations. As you can see random perturbations are still present however my conclusion is consistent with post runs.

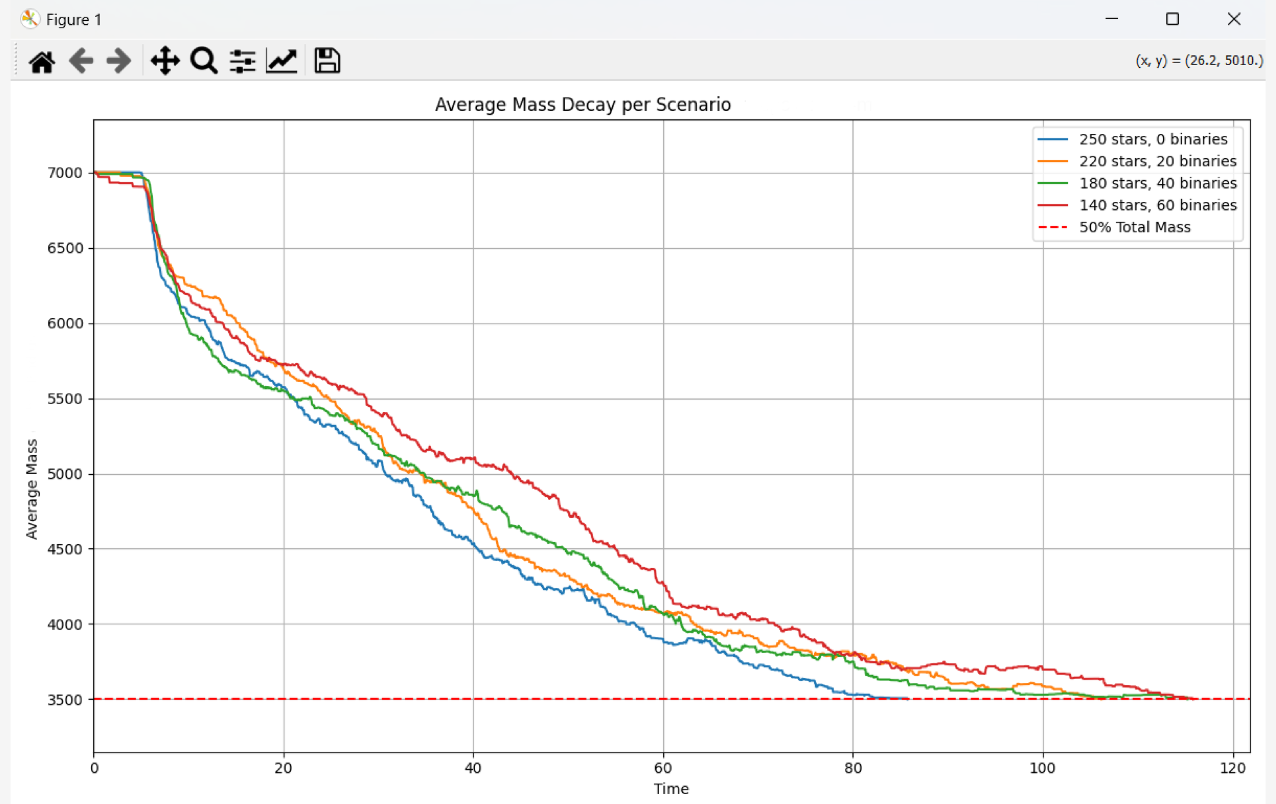

Figure: Mass loss over time for varying binary fractions. Each line represents the average mass of a star system with a certain primordial binary fraction. As shown the half life of such clusters increases with the binary fraction

Results: Core Radius Evolution

Core radius data reveals delayed core contraction with increasing binaries, supporting binary heating effects.

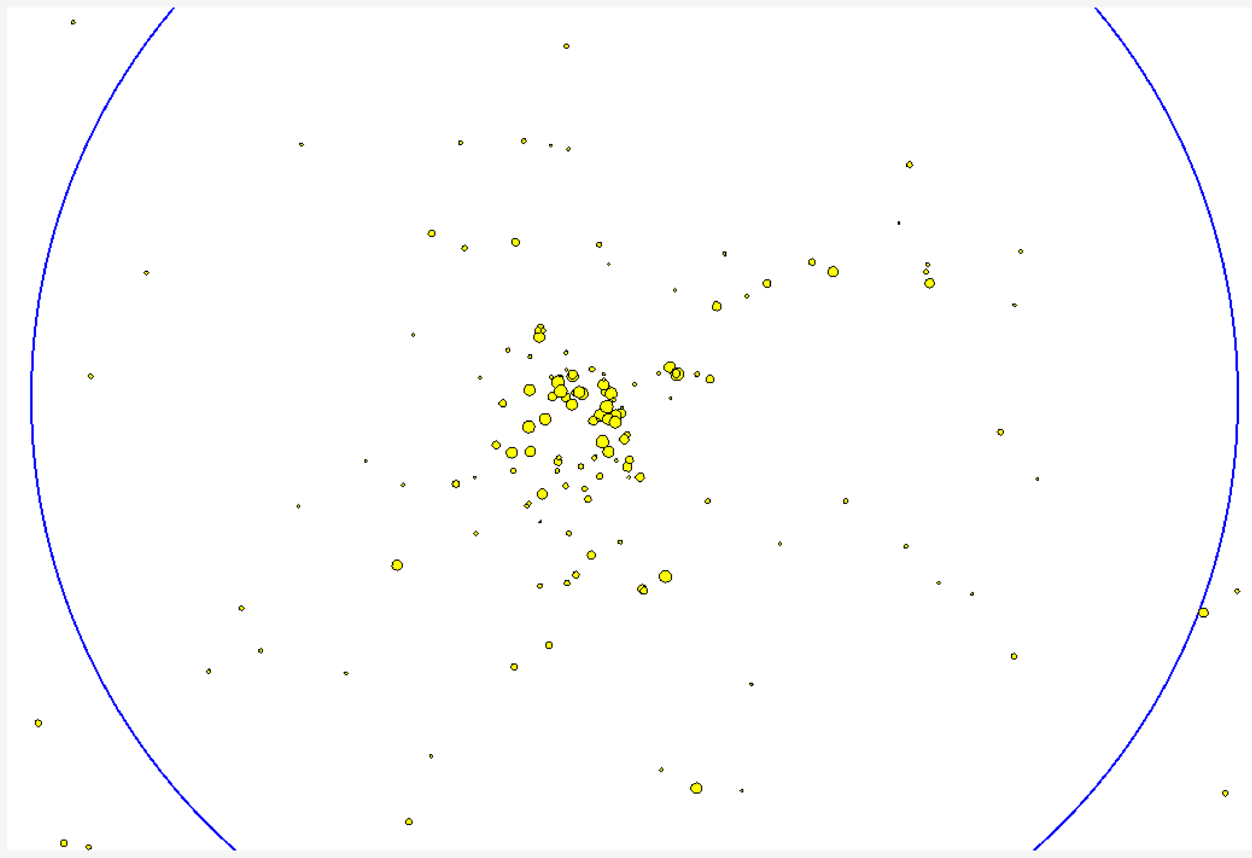

Figure: An image taken of a cluster of 250 single stars 20,000 time units after it was initialized. As you can see a dence core has already formed.

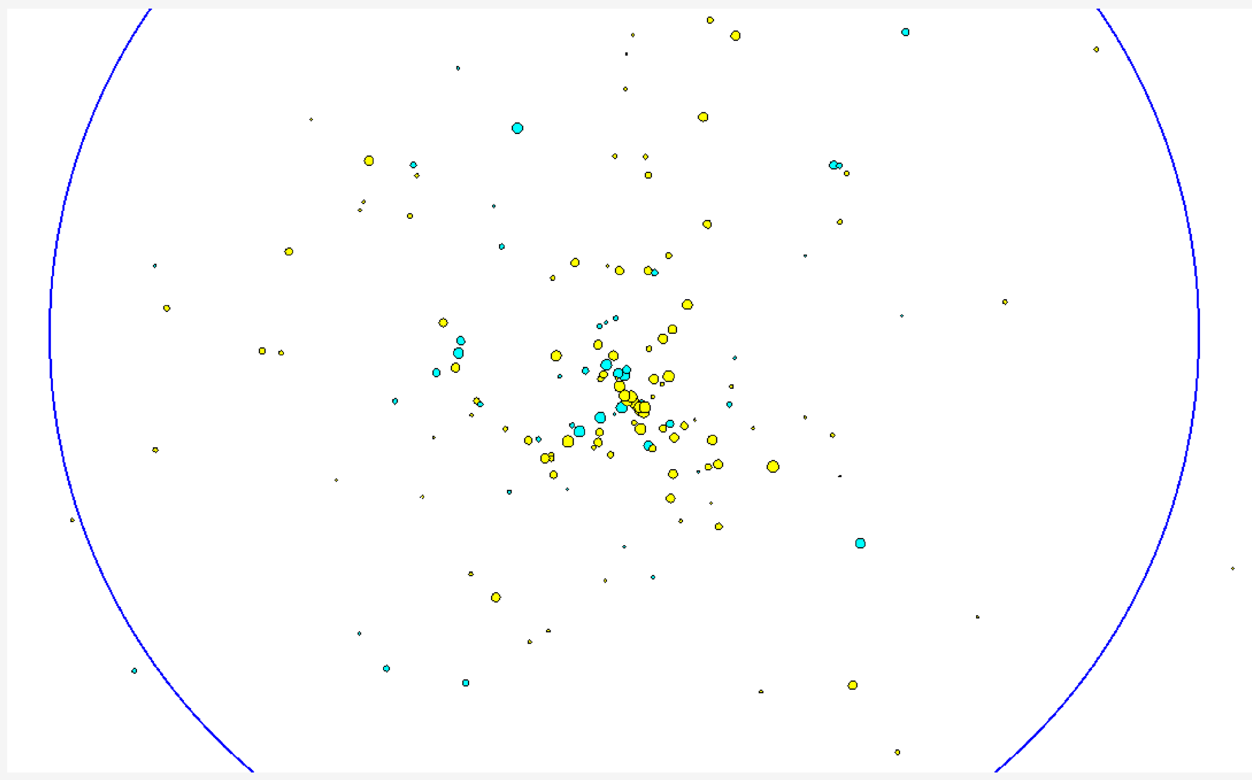

Figure: An image taken of a cluster of 210 single stars and 20 binary pairs 20,000 time units after it was initialized. Note the increased number of stars orbiting far from the center of mass and a less dense core.

Discussion

Primordial binaries act as internal energy sources, delaying collapse and reducing mass loss. No diminishing returns observed up to 24%. Despite simplifications (2D, abstract units), results align with theory and prior studies. A noticeable structural difference between two equal mass clusters with different binary fractions clearly shows how **two-body relaxation** prevents mass segregation and core collapse by maintaining high energy stars on a high orbit above the center of mass. This also shows that the previously mentioned effect outweighs the proposed issue of increased rate of small star ejection. The destruction radius (located 3000 units away from the center of mass) had 8% less objects be deleted when a 24% binary fraction was used.

Conclusion

As shown by this investigation, increasing the binary fraction has a positive effect on the half life of the globular cluster. An increase of 8% leads to around a 5% increase in cluster lifespan. This supports the theory that primordial binary systems provide a **heating** effect helping mitigate **two-body relaxation**. Snapshots of the simulations with different binary fractions at the same simulation step showed that the cluster with binary stars had a significantly increased number of particles outside the dense core, meaning that the process of core collapse is slower in that circumstance. Despite only 250 particles being used in this investigation the information can be generalized to higher numbers of particles.

Code Repository

Gitgub repository:
`https://github.com/Leonid-Elkin/N-body-simulation`
My website: `https://leonid-elkin.github.io/`

Simulation UI Snapshot

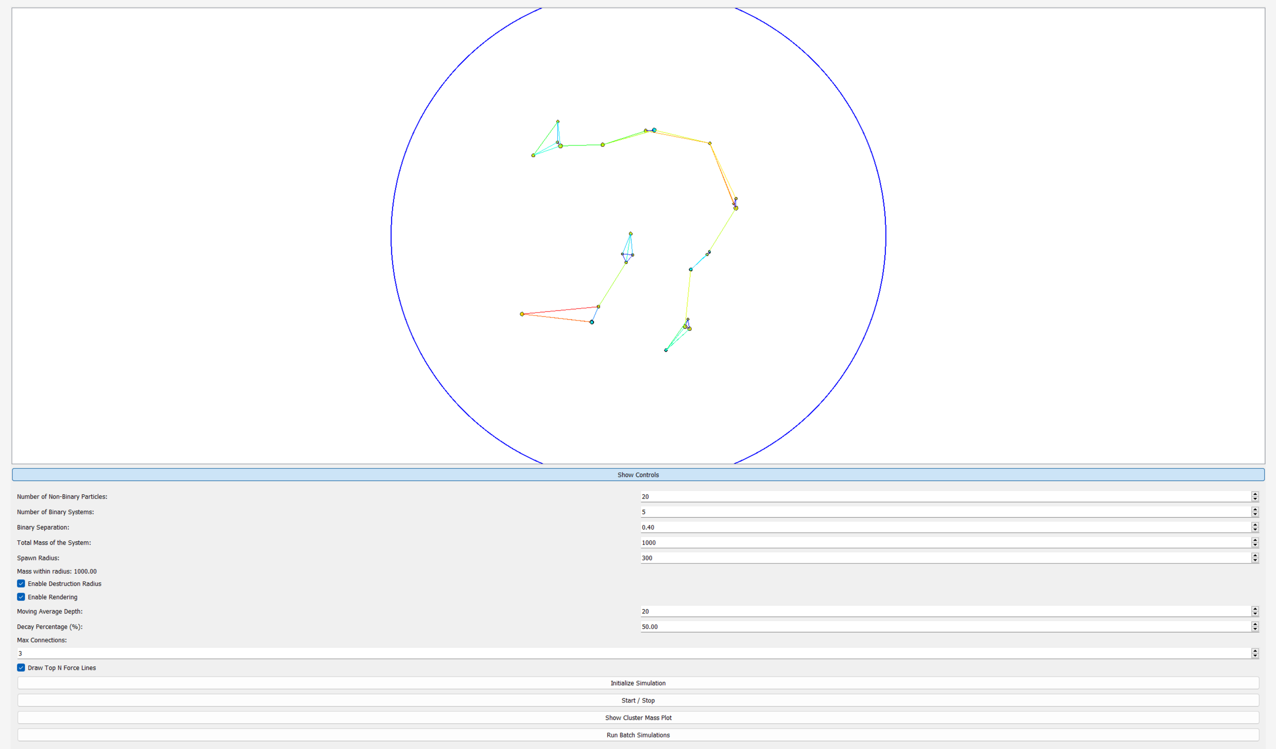

Figure: UI of the simulation