# StellarSim: Modeling Star Cluster Evolution

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## Introduction/Problem Context

- A star cluster is a group of stars that are gravitationally bound to a shared center of mass and typically formed from a single molecular cloud around the same time.
- Significant to astronomers, but difficult to observe directly.
- Clusters change over time due to three main factors:
  - Stars change position due to gravitational interactions.
  - Stars lose or gain mass as they evolve through their life cycles.
  - Some stars escape the cluster when the galaxy's tidal force exceeds the cluster's gravity at a distance called the galactic tidal cutoff.
- Simulations must model three key phenomena: evolution, gravitational interactions, and the tidal cutoff.

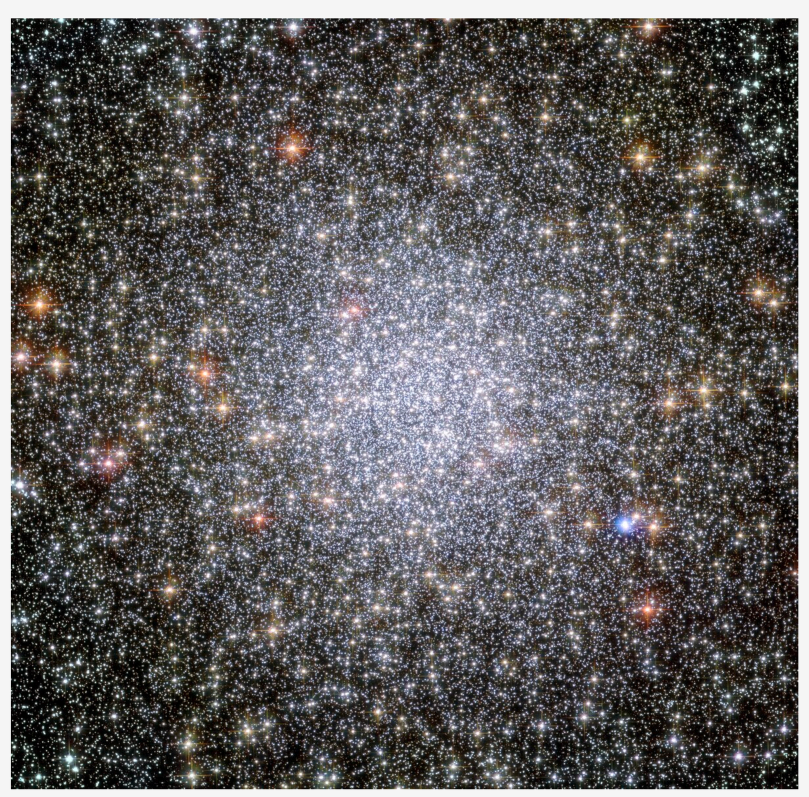

Figure: 47 Tucanae, a star cluster visible with the naked eye

## Technical Background

- **AMUSE:** This project relies on the Astrophysical Multipurpose Software environment (AMUSE), an open-source Python library for astrophysical simulations. [4]
- **N-body Gravitational Solvers:** `Hermite` algorithm calculates gravitational interactions between each star in the cluster at each step, then estimates each star's position for the next step. [1]
- **Stellar Evolution Codes:** `SeBa` code uses predefined evolution tracks to model stellar evolution, tracking changes in star properties like mass, temperature, radius, and luminosity. [5] [7]
- **Tidal Cutoff:** The boundary beyond which stars are no longer bound to the cluster, modeled by finding the radius where the cluster's density approaches zero.

## Prior Work

This project was influenced by previous studies that have simulated star cluster evolution, including:

- **Takahashi and Zwart (2000):** Investigates cluster evolution under galactic tidal forces using N-body simulations. [6]
- **Whitehead et al. (2013):** Explores the AMUSE framework for simulating star clusters, focusing on how different model assumptions affect cluster lifetimes and dissolution modes. [8]

## Methods

**Simulation Parameters:**

- **Number of Stars ($N$):** Typically between 1,000 and 1,000,000 stars in a cluster, but this study focused on clusters of under 10,000 stars. Star masses were determined using the Kroupa initial mass function. [3]
- **Simulation Time ($t_{\text{end}}$):** Star clusters can survive for billions of years, but this study ran simulations that lasted from 100 to 500 Myr.
- **Time Step ($\Delta t$):** The time step for the simulation is set to 0.1 Myr, providing a balance between computational efficiency and accuracy.
- **King Model Parameter ($w_0$):** The initial configuration of the cluster is based on the King model, with the parameter $w_0$, which determines the initial density distribution and the concentration of the cluster. [2].
- **Density Threshold:** A density threshold of $1 \times 10^{-5}$ $M_\odot$ per $pc^3$ is used to determine the gravitational tidal cutoff.

**Tracked Parameters:**

- **Position:** The 3D position of each star $(x, y, z)$ is tracked throughout the simulation, allowing us to observe the movement of the stars and the evolution of the cluster's structure.
- **Mass:** The mass of each star is updated as it evolves, and the total mass of the cluster is tracked to monitor mass loss due to stellar evolution and stars escaping the cluster.
- **Star Type:** The stellar type is tracked over time to capture the star's evolution through different phases.

## Evaluation

The following metrics were used to evaluate the simulation:

- **Mass Loss Over Time:**
  - Track the total mass lost due to stellar evolution and stars escaping the cluster.
  - Monitor the reduction in total mass over the simulation period.
- **Changes in Density Over Time:**
  - Observe how the cluster's density changes as stars evolve and escape.
  - Track changes in the density profile at different radii.
- **Tidal Cutoff (Truncation Radius):**
  - Track the truncation radius where stars become unbound from the cluster.
  - Monitor the number of stars that escape due to tidal forces.

These metrics help assess the cluster's mass, density, and stability throughout the simulation.

## Results

The results of the simulation followed the predicted trends:

- The mass of the cluster decreased over time, consistent with the expected mass loss due to stellar evolution and stars escaping the cluster.
- The truncation radius decreased, reflecting the increasing number of stars that escaped due to tidal forces.
- The density profile of the cluster evolved, showing that mass became less concentrated at the center and more dispersed towards the outskirts.

Further analysis and comparison to other studies are needed to fully evaluate the accuracy of the model, which will be addressed in full detail in the upcoming final paper.

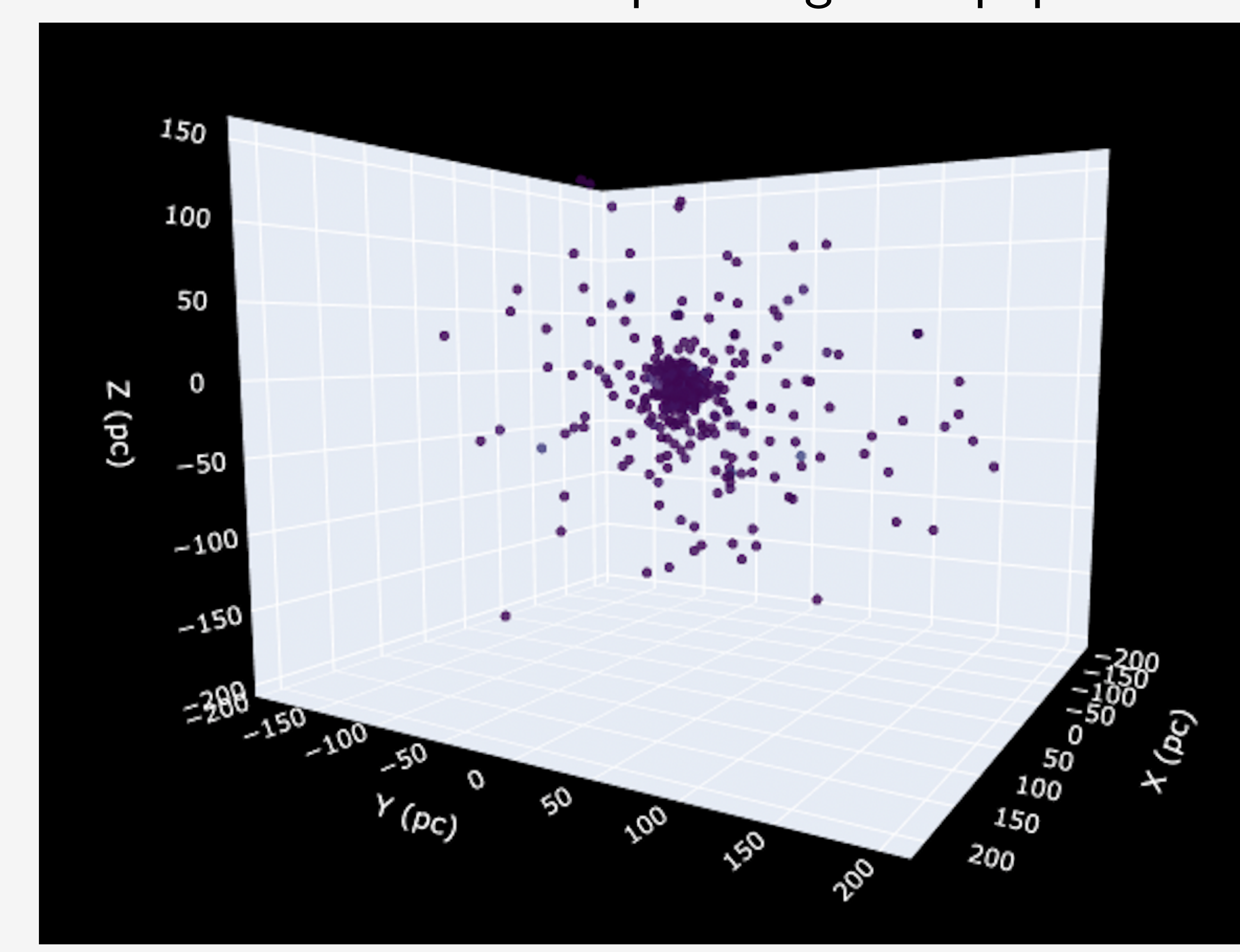


Figure: One frame of a 3D visualization of a star cluster

## Citations


[1] P. Hut, J. Makino, and S. McMillan. "The Effect of Stellar Interactions on the Evolution of Star Clusters". In: *Astrophysical Journal Letters* 443 (1995), pp. L93–L96. DOI: 10.1086/187811.

[2] Ivan R. King. "The structure of star clusters. III. Some simple dynamical models". In: *Astronomical Journal* 71 (1966), p. 64. DOI: 10.1086/109857.

[3] Pavel Kroupa. "On the variation of the initial mass function". In: *Monthly Notices of the Royal Astronomical Society* 322.2 (2001), pp. 231–246. DOI: 10.1046/j.1365-8711.2001.04022.x.

[4] F. I. Pelupessy et al. "The Astrophysical Multipurpose Software Environment". In: *Astronomy and Astrophysics* 557 (2013), A84. DOI: 10.1051/0004-6361/201321188.

[5] S. F. Portegies Zwart and F. Verbunt. "Population Synthesis of High-Mass Binaries". In: *Astronomy and Astrophysics* 309 (1996), pp. 179–186. DOI: 10.1051/aas:1996125.

[6] K. Takahashi and S.F.P. Zwart. "The evolution of globular clusters in the galaxy". In: *The Astrophysical Journal* 535.2 (2000), p. 759. DOI: 10.1086/308842.

[7] S. Toonen, G. Nelemans, and S. F. Portegies Zwart. "Supernova Type Ia Progenitors from Merging Double White Dwarfs: Using a New Population Synthesis Model". In: *Astronomy and Astrophysics* 546 (2012), A70. DOI: 10.1051/0004-6361/201219651.

[8] Alfred J. Whitehead et al. "Simulating Star Clusters with the AMUSE Software Framework. I. Dependence of Cluster Lifetimes on Model Assumptions and Cluster Dissolution Modes". In: *The Astrophysical Journal* 778.2 (Dec. 2013), p. 118. DOI: 10.1088/0004-637X/778/2/118.