N-body Simulation of a Young Open Cluster

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Abstract. The evolutionary process of young clusters remains unclear. In order to investigate the detailed dynamical evolution of star clusters, this paper simulates a young open cluster to tens of million years, via a reliable N-body simulation code. The dynamical interactions among stars, and stellar evolution of both single and binary stars have been taken into account. The position, velocity, effective temperature, luminosity, radius and mass of each star are finally calculated at different ages. It is shown that the size of simulated cluster increases with time. The size evolution of cluster is found to depend on the initial velocities of stars. Therefore, to determine the initial states of clusters is of key importance in the simulation of star clusters. The parallel computing technique is also tested by this simulation. The result shows that the computation speed is enhanced by six times when taking 8-core parallel computation instead of 1-core computation.

1. Introduction
There are two kinds of star clusters, i.e., globular clusters and open clusters. The simulation of open clusters is relatively easy, because they contain much less stars compared to globular clusters. Such simulation helps understanding the formation and evolution of star clusters. It is also important for studying the stellar populations in clusters, e.g., gravitational wave (GW) sources. Although there have been many simulations for open clusters, the details are usually ignored because most works simulate the clusters in large time ranges such as a few giga years. This makes it difficult to understand the change of distributions of stars in the space when clusters evolve. So does the change of stellar velocities. This paper aims to give a detailed simulation of a young open cluster, with enough time resolution. The basic parameters of each cluster member stars will be given at various ages to show their evolution.

2. Model Inputs and Simulation Code
In this work, a small star cluster with 2500 stars simulated. The star number (N*) is similar to some small observed open clusters. An initial binary fraction of 8% is set for the mock cluster. It will change with the stellar evolution and dynamical interactions (see, e.g., Li & Mao 2018)[1]. Stellar evolution usually makes binary fraction decrease, while dynamical interactions usually make binary fraction increase with time. The masses of stars are randomly given by taking the initial mass function (IMF) of Kroupa (2001) [2] (Kroupa2001). The lower and upper mass limits are set to 0.08 M⊙ and 100 M⊙, respectively. For binaries, the orbital period and eccentricity are given randomly. Because the number of binary stars is very small, only 200, they affect the simulation results slightly. This is similar to most other works. In order to simulate a metal-poor cluster, the metallicity (Z) is fixed to 0.0001. Metallicity can affect stellar evolution significantly, so the evolutionary parameters will be different.
for other metallicities. The Lagrangian radius (R\text{lag}) is calculated from initial masses of stars in this work. This is suitable for a simple test. One can see Table 1 for the model inputs.

**Table 1.** Input parameters of simulation.

| Parameter | Value                     |
|-----------|---------------------------|
| N         | 2500                      |
| N\text{b} | 200                       |
| Z         | 0.0001                    |
| IMF       | Kroupa2001                |
| M\text{low} | 0.08 M\odot            |
| M\text{up} | 100 M\odot               |
| R\text{lag} | Computed from initial mass|

A widely-used star cluster simulation code, a recently updated version of N-body6++GPU (Spurzem 1999)\textsuperscript{3,4} is used in this simulation. The latest version has been used, so it calculates the evolution of stars using the updated BSE code (Hurley et al. 2000\textsuperscript{5}, Banerjee et al. 2019\textsuperscript{6}). The new results on stellar evolution are therefore considered in this simulation. In addition, both single and binary stars are included and evolved in the simulation.

3. Results

The simulation of the mock cluster is finished by one core and eight cores, respectively. The times of 42 and 6.4 minutes are spent. It means that the parallel computing via 8 cores is about 6 times faster than the case of using only a single core. As a result, the space distribution and velocities of stars are computed at different ages. They are introduced as follows.

3.1. Star Distribution and Velocity

Figures 1-3 show the space distribution and velocities of stars at 0, 10.5, 23.7 Myrs. The longer the arrow, the larger the velocity. The direction of each arrow means the direction of velocity. We observe that the size of cluster becomes larger with time. Some stars go away from the cluster center in the evolution. This because these stars have relative large velocities and the centrifugal force is larger than gravity. In addition, the velocities of some stars become larger, under the dynamical interactions. In this case, more and more stars will move from the cluster center. The cluster will be sparser in the future.

![Figure 1](image)

**Figure 1.** Initial star cluster of the simulation. Points are stars of the cluster at zero age. Arrows denote the velocities of stars. The unit of coordinates is pc, and that of velocity is 50m/s. The points with two arrows are binary stars with two components.
Figure 2. Similar to Figure 1, but for the central part of cluster at 10.5 Myr. Note that the outer part is not plotted.

Figure 3. Similar to Figure 1, but for the central part of cluster at 23.7 Myr.

3.2. HR Diagram
Because the members of a cluster are stars, they are different from mass points. These stars will evolve from main sequence to late stages. The evolution of stars can be analyzed via a HR diagram. Figure 4
presents the HR diagrams at 0 and 23.7 Myrs. It is clear that some massive stars leave main sequence at 23.7 Myr. However, the number of such stars is not large. This stems from the IMF of the simulated cluster, in which massive stars are assumed to be much less than others. We do not observed obvious binary stars at the age of 23.7 Myr, because there are only a small fraction of binary stars, and close binary stars have an extreme small fraction.

4. Conclusion

This paper studies the evolution of a small open cluster within the first 23.7Myrs in detail, via an N-body simulation code. It is shown that the size of cluster strongly depends on the initial velocities of stars. If velocities are somewhat large, many stars will go away from the cluster center, and the cluster size will increase with time, as the simulated cluster. Otherwise, if the initial velocities of stars are small, many stars will fall into the cluster center, and the cluster size will decrease with time.

![HR Diagrams](image)

**Figure 4.** HR diagrams at zero age (gray) and 23.7 Myr (red and purple). Effective temperature (Teff) is in K, and luminosity (L) is in solar luminosity.

The stellar evolution of cluster is also studied via the HR diagram, which is the theoretical counterpart of color-magnitude diagram (e.g., Li et al. 2020[7]). It is found that some massive stars leave main sequence within 23.7Myrs. This agrees well with the result of stellar population synthesis studies.

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