# Computing Implementation of Globular Cluster Simulation for CSST

Zhongmu Li[1,*], Yangyang Deng[1,2] and Tao Xia[1,3]
[1]*Institute of Astronomy, Dali University, Dali 671003, China*
[2]*Yunnan Observatories, Chinese Academy of Sciences, Kunming 650216, China*
[2]*Shanghai Key Lab for Astrophysics, Shanghai Normal University, Shanghai 200234, China*

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Abstract: Direct N-body simulation is hard to implement as the great demand on computational resources. It is strictly relied on the configurations of hardware and software. The direct N-body simulation of star clusters are important for many scientific projects including the China Space Station Telescope (CSST), because star clusters are important celestial bodies of these projects. Such simulation is difficult to be done by normal computers because of the large number of cluster member stars. This paper carries out the direct N-body simulation of three globular cluster models for CSST. The cluster models take various star numbers, binary fractions and chemical compositions. The simulation is realized via employing appropriate environment configuration and an updated code, NbodyCP, which is based on NBODY6++GPU. The photometric data, spatial and physical parameters of three clusters are finally calculated. It is shown that GPU computational technique and the number of binaries dominate the computational efficiency of celestial bodies with a large amount of member stars.

# 1 INTRODUCTION

China Space Station Telescope (CSST) is the largest space-based optical telescope in China. It is expected to put into service in 2024 (Zhan, 2021). As one of the advanced study of CSST, the simulation of star clusters is crucial because it can provide the theoretical guidance and test for observations.

According to cluster age, number and spatial distribution of member stars, star cluster are classified into two types, globular and open clusters. The former contains more than thousands of member stars and the latter one includes only dozens to thousands of member stars. Some globular clusters are thought as the oldest celestial bodies, because they are as old as the universe. It is likely to give some limitation on the cosmic age and reveal the formation and evolution of early universe. Besides, globular clusters are widely distributed in the Milky Way and nearby galaxies (e.g., M31, Large and Small Magellanic Clouds). Therefore, globular cluster is the key object in CSST study. The detailed simulation of globular clusters is required to complete the map of celestial studies.

Due to the large number of member stars and the complex stellar evolution process, the implementation of direct N-body simulation of globular cluster is relatively difficult. As well as the limitation of the configurations and environment of computational resource, it is hard to derive the simulated results of several globular clusters within a short period.

In consequence, this work concentrates on the direct N-body simulation of globular clusters. We compute the simulation of three globular cluster models, from zero age to 13.7 giga year. The model clusters are put in specific nearby galaxies and the stellar magnitudes are transfer to the photometric systems of CSST. Some other physical parameters such as effective temperature and luminosity of member stars are also obtained in the simulation.

# 2 N-BODY SIMULATION

## 2.1 Algorithm and Parallelization

In this work, we apply an improved N-body simulation code, NbodyCP, which is especially designed for calculating star clusters with multiple populations by Prof. Zhongmu Li. The code is based on NBODY6++GPU code (Wang et al, 2015), modified by adding the simulation of multiple stellar



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population and improving the stellar evolution code (Banerjee et al, 2020). The code has also been designed to be used conveniently.

Similar to the descriptions of Wang et al (2015), the combination of the fourth-order Hermite integration and hierarchical time-steps methods is applied to decide the calculating time-steps. In order to decrease the computational time of forces among particles, the Ahmad-Cohen neighbour scheme (Ahmad and Cohen, 1973) is employed. The forces are divided into two types according to the locations of particles away from the neighbour radius. The inner is irregular force (time-step is large) and the outer is regular force (time-step is small). In addition, the members of star clusters include close binaries, triples and higher order systems, which are important parts in dynamical process, requiring the precise solution. The internal evolution processes of these systems are treated differently using the algorithms in Kustaanheimo & Stiefel (1965) (KS) and chain regularization (Mikkola and Aarseth, 1993).

In addition, the hybrid parallelization is used in NbodyCP code to implement the simulation of million particles, similar to that in NBODY6++GPU. In general, the integration of the time-step of KS is calculated by CPU because the time-step distribution is the smallest, then the time-step of irregular force is parallelized by AVX/SSE with OpenMP. The regular force time-step is parallelized by GPUs with OpenMP as well. An adjust block is existed after the calculation of regular force time-step, is parallelized by GPUs. A node is consisted of all the time-step blocks, and numerous nodes constitute the entire code structure (for computer cluster). Therefore, the NbodyCP code is able to simulate the globular clusters in a relatively short period.

## 2.2 Configuration and Environment

The simulation of this work is performed on three servers. Different GPUs are used for computations on these servers. The GPUs on these servers are NVIDIA RTX A6000, NVIDIA GeForce RTX 3090 and NVIDIA GeForce RTX 3080 respectively. The CPUs of the servers are Intel Core i9-10900k and i9-11900k, contain 20 or 16 cores. The basic frequency is 3.7 and 3.5 GHz separately. Other configurations of the three servers, such as operating system, memory, compiler and motherboard, are all the same. Table 1 lists the descriptions of configurations and environments of the three servers.

Table 1: Configurations and environments of different servers.

<table>
<tr><th></th><th>Server 1</th><th>Server 2</th><th>Server 3</th></tr>
<tr><td>GPU</td><td>RTX A6000</td><td>GeForce RTX 3090</td><td>GeForce RTX 3080</td></tr>
<tr><td>CPU</td><td>Core i9-11900k, 3.5 GHz, 16 cores</td><td colspan="2">Core i9-10900k, 3.7 GHz, 20 cores</td></tr>
<tr><td>OS</td><td colspan="3">Ubuntu 20</td></tr>
<tr><td>Memory</td><td colspan="3">4 × 32 GB, DDR4-3200</td></tr>
<tr><td>GPU Compiler</td><td colspan="3">CUDA 11</td></tr>
<tr><td>Basic Compiler</td><td colspan="3">gfortran</td></tr>
<tr><td>Motherboard</td><td colspan="3">TUF GAMING Z590-PLUS WIFI</td></tr>
</table>

## 2.3 Model Input

We build three globular cluster models for our globular cluster simulation. The three cluster models contain 50,000, 100,000 and 100,000 member stars respectively. They are named Model 1, Model 2 and Model 3. Models 1 and 3 contain the initial binary fraction of 0.1, while all member stars in Model 2 are set to be single. As the significant role in cluster dynamical evolution process, initial binary fraction affects the computational efficiency significantly. Note that all binary stars are randomly generated. The metallicities of Models 1 and 2 are $Z = 0.0001$, and that of Model 3 is $Z = 0.0003$, because most globular clusters are detected to be metal-poor. The stellar masses of three models are produced by the initial mass function (IMF) of Kroupa (2001), covering a range from 0.08 to 100 solar masses as described in stellar evolution theory. Star members are set to distribute as the Plummer sphere (Plummer, 1911). The stellar evolutionary process is calculated by the developed BSE code (Banerjee et al, 2020; Hurley et al, 2002). Due to the universe age, the maximum evolution age of cluster models is set to 13.7 giga year. The first 8 rows of Table 2 summary the input parameters of the three star cluster models.

Table 2: Input parameters and computational times of three models. Number, $f_b$, $M_{max}$ and $M_{min}$ indicate star number, binary fraction, upper and lower limits of stellar masses. Age is the simulated physical age of star cluster and t is the time spent in the simulation process. The unit of stellar mass is solar mass.

| | Model 1 | Model 2 | Model 3 |
|---|---|---|---|
| Number | 50,000 | 100,000 | 100,000 |
| $f_b$ | 0.1 | 0.0 | 0.1 |
| $Z$ | 0.0001 | | 0.0003 |
| IMF | Kroupa (2001) | | |
| $M_{max}$ | 100 $M_\odot$ | | |
| $M_{min}$ | 0.08$M_\odot$ | | |
| Stellar evolution code | BSE code (Banerjee et al, 2020; Hurley et al, 2002) | | |
| Spatial distribution | Plummer (1911) | | |
| Age | 13.7 giga year | | |
| t | 8 days and 20 hours | 18 days and 20 hours | 40 days and 4 hours |
| Device | Server 1 | Server 2 | Server 3 |

## 2.4 Results

After the computations of three models, the spatial, kinetic, and evolutionary data of member stars are obtained at different ages from the direct N-body simulation. In detail, the three-dimension position and velocity, stellar radius, core radius, effective temperature, luminosity, stellar type, gravitational acceleration and metallicity are precisely determined in the evolutionary process. In order to derive the data at a fixed time, we develop an interpolation program to obtain the data at a given time. The detailed star distribution and stellar evolution of three cluster models can be tracked well (see examples in Figures 1 and 2) using the simulation data.

The time spent on the simulations of three models are found to be significantly different. As can be seen in the tenth row of Table 2, Model 1 spends 8 days and 20 hours computing the integral process. Model 2 costs more than two times and Model 3 needs about five times of that of Model 1. The comparison of Models 2 and 3 suggests that binary fraction affect a lot on the computing efficiency of cluster simulation, because the largest difference between the two simulations is the number of binaries. Star number affects the computing time significantly as well. Moreover, the minimal investment of time of Model 1 emphasizes the crucial impact on computing power of GPU unit. Although the CPU-computing of Model 1 is weaker than those of Models 2 and 3, the time spent decreases effectively.

# 3 TRANSFORMATION OF MAGNITUDES AND COORDINATES

In order to use the simulated results as a reference for the observation of CSST, the related physical parameters, such as effective temperature, luminosity, mass and metallicity, are utilized to calculate the magnitudes in CSST bands online[1]. Therefore the stellar data is expanded to involve *NUV*, *u*, *g*, *r*, *i*, *z* and *y* magnitudes. Figure 1 displays the example of Hertzsprung-Russell and color-magnitude diagrams (HRDs and CMDs) of Model 1. The evolution times (i.e., ages) are 5 and 13 giga years. Because the HRD and CMD are the ideal criteria of stellar evolutionary computation, the diagrams verify the accuracy of our simulation.

Besides, the simulated cluster center is 0 of a local system in our simulation, so we put three models to some locations of three nearby galaxies (M31, Large and Small Magellanic Clouds) to get more useful mimic clusters. This helps to do some advanced studies easily. The entire process is implemented by the Astropy package[2]. Firstly, the positions and radial velocities of the galaxies are converted from the equatorial coordinate system to the Cartesian coordinate system. Then a three-dimensional coordinate in the range of galaxy radius is randomly generated to be the coordinate of cluster center, avoiding the overlap of cluster position. After that, a linear superposition of the coordinates of galaxies and cluster center is obtained. The combined coordinates are finally converted back to the equatorial coordinate system. Consequently, The right ascensions (RAs), declinations (DECs), proper motions, radial velocities and the distances from the sun to the three model clusters in galaxies M31, Large and Small Magellanic Clouds are derived. Figure 2 exhibits the example of distributions of initial spatial positions and the final parameters that will be observed by CSST. The expansion of cluster scale is also shown in the figure.

[1] https://sec.center/YBC/

[2] https://www.astropy.org/

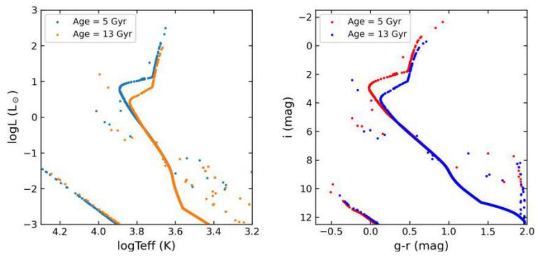


Figure 1. Examples of HRD and CMD for Model 1.

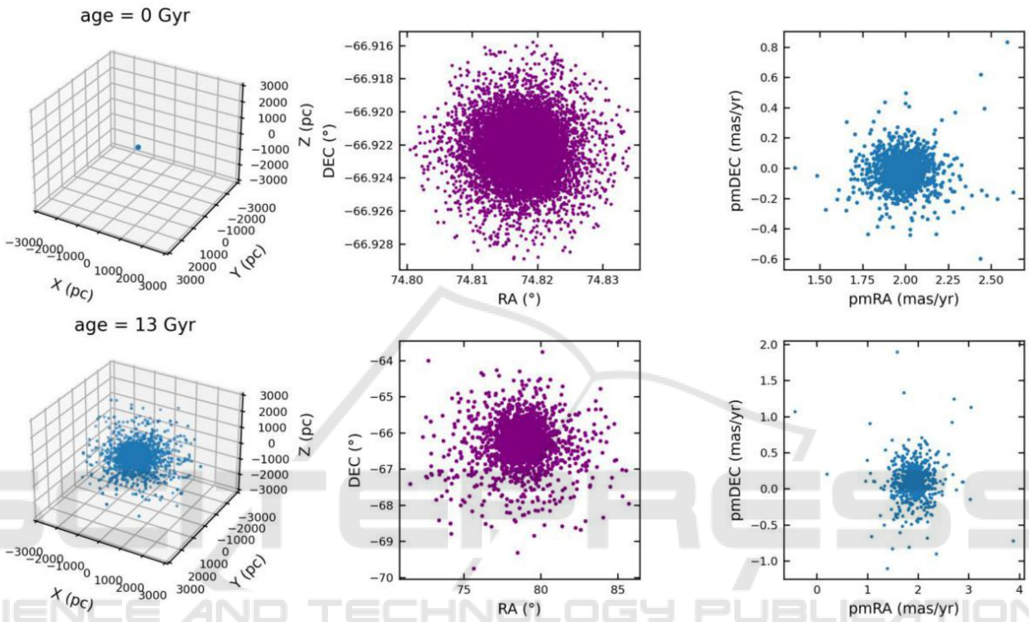


Figure 2. Examples of direct star distributions from N-body simulation, converted coordinates (RA, DEC) and proper motions in RA and DEC. The selected data is from Model 1 which located in Large Magellanic Cloud.



# 4 CONCLUSIONS

This paper describes the direct N-body simulation of three globular cluster models with various numbers of stars, which can be used for the advanced studies of CSST. The simulation is realized on three Linux servers, on which the software and environment configurations are set to be the same. However, the configurations of CPU and GPU are different because of the implementation of algorithms in the code is affected obviously by the hardware.

The NbodyCP code (modified on the basis of NBODY6++GPU by Prof. Zhongmu Li) and an interpolation program are employed to obtain the stellar evolutionary data at every 0.01 giga year. The simulated data is converted to CSST bands and the coordinates are transferred to some locations in three nearby galaxies. As the result, the size of three globular clusters are simulated to expand rapidly. The stellar evolution process is consistent with the previous theory as well.

By comparing the computational time with our previous work (Deng, 2021), the simulated speed of globular clusters has been significantly improved, as the NBODY6++GPU code and GeForce 2080Ti are used in the previous simulation. In addition, the results confirm the important role of binary fraction and GPU computing performance in N-body simulation for a large number of particles. According to the tests, the improvement of CPU basic frequency and the factors above are needed in further simulations.

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