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Formation process of the Orion Nebula Cluster

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Abstract. The Orion Nebula Cluster (ONC) is one of the nearest open clusters, which we can directly compare to numerical simulations. We performed a simulation of star cluster formation similar to the ONC using our new N-body/smoothed particle hydrodynamics code, ASURA+BRIDGE. We found that the hierarchical formation of star clusters via clump mergers can explain the observed three peaks in the stellar age distribution as well as the dynamically anisotropic structures of the ONC.

Keywords. methods: n-body simulations, methods: numerical, open clusters and associations: individual (Orion Nebula Cluster)

1. Introduction

The Orion Nebula Cluster (ONC) is one of the nearest open clusters. It is $\sim$ 400 pc away from us (Kounkel et al. 2017), and the age is estimated to be 1–3 Myr (Hillenbrand and Hartmann 1998). Thanks to the distance, we can observe the detailed structures of this cluster. Recent observations have shown that it has three distinct age populations (Beccari et al. 2017). One possible scenario explaining it is the complete ejection of O-stars during the formation of the ONC. Kroupa et al. (2018) suggested that massive stars formed in star clusters suspend star formation until they are completely ejected from the clusters due to binary-single encounters. Once all massive stars are ejected, star formation starts again. The complete ejection of massive stars was examined using N-body simulations (Wang et al. 2019), but the formation of new stars was not included in their study.

2. Simulation

We performed an N-body/smoothed-particle hydrodynamics simulation for the formation of an ONC-like cluster. We used our new code ASURA+BRIDGE (Fujii et al. 2021b,a). In this code, star formation is assumed using a probabilistic formation following a given initial mass function (Hirai et al. 2021). Once massive stars formed more massive than $10\,M_{\odot}$, stellar feedback is switched on. We assumed that individual massive stars form HII regions with a Strömgren radius calculated using local gas density and the photon emission rate. The details of the simulation are described in Fujii et al. (2021a).

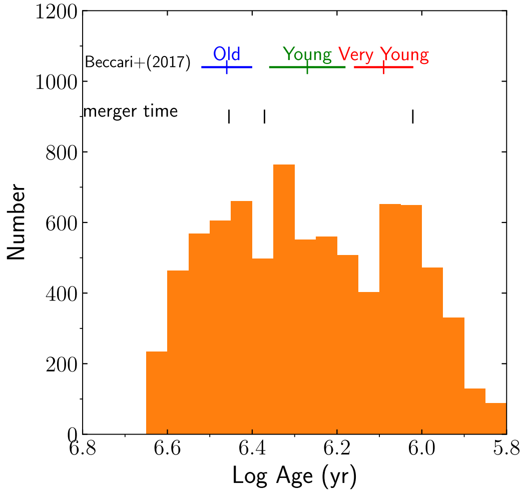

Figure 1. Age distribution of stars in the star cluster at 8.7 Myr. Blue, green, and red bars indicate the three age distributions identified in Beccari et al. (2017). Black lines indicate the merger timings of clumps.

One of the main advantages of ASURA+BRIDGE is that we can integrate stellar orbits without any gravitational softening. In ASURA+BRIDGE, stars are integrated using a direct-tree hybrid integrator, Particle-Particle Particle-Tree (P^3T; Oshino et al. 2011; Iwasawa et al. 2015). We adopted an open-source code, PeTar (Wang et al. 2020a), for the integration of stars. PeTar includes a Slow-Down Algorithmic Regularization (SDAR) scheme for the integration of binaries and multiples (Wang et al. 2020b), which enables us fast and stable integration of star clusters including hard binaries.

For the initial condition, we adopted a uniform spherical molecular cloud with a turbulent velocity field with a mass of $2 \times 10^4 M_\odot$ and a radius of 12 pc. The initial SPH particle mass is 0.01 $M_\odot$, and the softening length for the gas particle is 0.07 pc. We did not use any softening for the star-star interactions to follow the dynamical evolution of star clusters.

3. Results

3.1. *Three Populations in the ONC*

Star formation started after about one initial free-fall time of the cloud ($\sim$5 Myr). Once massive stars are formed, they begin ionizing the surrounding gas. However, not the entire region is immediately ionized. Dense regions continue star formation until enough massive stars are formed. In this simulation, the star formation was terminated at $\sim$9 Myr.

We found that the star cluster evolved via mergers of smaller clumps and that these mergers enhanced the star formation and made the three populations in age. In Figure 1, we present the age distribution of the cluster at 8.7 Myr from the beginning of the simulation, which is the time we assume that the simulated cluster is the closest to the current ONC. We found three peaks in the age distribution and that each peak corresponds to a clump merger. Clump mergers bring dense gas to the clump center with stars, and it enhances the star formation inside the merged cluster. We confirmed this process by analyzing the amount of dense gas in the cluster.

3.2. *Dynamical Structures of the ONC*

We investigated the dynamical structures of our simulated cluster. We found that we observe anisotropic structures in the velocity space only within ~ 0.5 Myr after clump mergers. We followed the three-dimensional velocity structure (velocity dispersions) and virial ratio every 0.05 Myr. We found that the velocity anisotropy and virial ratio increase after clump mergers and drop in ~ 0.5 Myr. Observed high velocity anisotropy ($\sigma_{v_r}/\sigma_{v_\alpha} = 1.44^{+0.21}_{-0.18}$ and $\sigma_{v_\delta}/\sigma_{v_\alpha} = 1.23^{+0.17}_{-0.16}$; Theissen et al. 2021) and virial ratio (0.7 ± 0.3; Kim et al. 2019) of the ONC suggest that the ONC experienced a clump merger in the past 0.5 Myr.

4. Summary

We performed an N-body/SPH simulation of an ONC-like star cluster. In this simulation, we can follow the orbits of individual stars, including their strong dynamical interactions. In our simulation, stellar clump mergers brought dense molecular gas into the forming cluster and enhanced the star formation in the cluster. This process formed three peaks in the age distribution of stars in the cluster at the time similar to the age of the ONC. We also found that clump mergers cause velocity anisotropy similar to that observed in the ONC. The virial ratio also increased after clump mergers.

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