Star Clusters: From the Milky Way to the Early Universe
Proceedings IAU Symposium No. 351, 2019
A. Bragaglia, M. Davies, A. Sills & E. Vesperini, eds.

doi:10.1017/S1743921319007634

Inter-cluster velocity structures of star cluster complexes

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Abstract. Star clusters are often born as star-cluster systems, which include several stellar clumps. Such star-cluster complexes could have formed from turbulent molecular clouds. Since Gaia Data Release 2 provided us high quality velocity data of individual stars in known star-cluster complexes, we now can compare the velocity structures of the observed star-cluster complexes with simulated ones. We performed a series of N-body simulations for the formation of star-cluster complexes starting from turbulent molecular clouds. We measured the inter-cluster velocity dispersions of our simulated star-cluster complexes and compared them with the Carina region and NGC 2264. We found that the Carina region and NGC 2264 formed from molecular clouds with a mass of $\sim 4 \times 10^5 M_\odot$ and $\sim 4 \times 10^4 M_\odot$, respectively. In our simulations, we also found that the maximum cluster mass ($M_{\rm c,max}$) in the complex follows $M_{\rm c,max} = 0.20 M_{\rm g}^{0.76}$, where $M_{\rm g}$ is the initial gas mass.

Keywords. stellar dynamics, methods: n-body simulations, open clusters and associations: general

1. Introduction

Star clusters are often born in a system of star clusters so-called star-cluster complexes. The Carina region is one of the biggest star-cluster complexes. Thanks to Gaia Data Release 2, the astrometric date of star-cluster complexes are now available (Gaia Collaboration 2018). Kuhn *et al.* (2019) identified stellar clumps in some star-cluster complexes and showed the individual velocity of each clump. With this data, we can calculate the inter-cluster velocity dispersion of the observed star-cluster complexes.

The inter-cluster velocity structure seems to have information of their parental molecular clouds and their kinematics, if the complex were formed from giant molecular clouds with turbulence. In Fujii & Portegies Zwart (2015), Fujii (2015), and Fujii & Portegies Zwart (2016), we have shown that star-cluster complexes can form in turbulent molecular clouds using hydrodynamic and N-body simulations and that the resulting clusters have information of their parental clouds. Using the results, we can estimate the parental molecular clouds of observed star-cluster complexes by comparing their kinematical information such as inter-clump velocity dispersion with simulations.

2. Methods

The simulations were performed by the following three steps. In the first step, we performed smoothed-particle hydrodynamics (SPH) simulations of turbulent molecular clouds. The initial condition was set up using AMUSE (Pelupessy *et al.* 2013). We adopted a homogeneous sphere with a turbulent velocity field for the initial conditions. We changed the gas mass from 4×10^4 to $1 \times 10^6 M_\odot$. We also adopted an initial density of $\sim$100 and $\sim$1000 cm^{-3} (10 and 100 $M_\odot\,\mathrm{pc}^{-3}$). All the initial conditions are

Table 1. Initial Conditions of Molecular Clouds.

Model	$N_{\rm Run}$	$M_{\rm MC}(10^3 M_\odot)$	$R_{\rm MC}$ (pc)	ρ ($M_\odot$ pc^{-3})
m1M-d100	1	1000	13.3	100
m400k-d100	3	400	10.0	100
m40k-d100	10	40	4.6	100
m400k-d10	3	400	21.0	10
m100k-d10	6	100	13.3	10

summarized in Table 1, and they are the same as those in Fujii & Portegies Zwart (2016) and Fujii (2019). Here, we set the sum of the kinetic and potential energies of the models to be zero. For less massive models, we performed several runs for a set of the mass and density changing the random seed for the turbulence because the resulting gas structure largely changes depending on the random seed.

We performed the SPH simulations using Fi (Pelupessy *et al.* 2004) in AMUSE. We stopped the simulations at around the initial free-fall time. As the second step, we convert some gas particles to stellar particles. We chose gas particles to form stellar particles following a local star formation efficiency ($\epsilon_{\rm loc}$) depending on the local gas density (ρ);

$$\epsilon_{\rm loc} = \alpha_{\rm sfe} \sqrt{\frac{\rho}{100\,(M_\odot {\rm pc}^{-3})}}, \tag{2.1}$$

where $\alpha_{\rm sfe}$ is a coefficient which controls the star formation efficiency and a free parameter in our simulations. We adopt $\alpha_{\rm sfe} = 0.02$. Resulting global SFE measured for the entire system was several percent, but the local SFE for dense regions reaches $\sim$30 %. In dense regions, the local SFE exceeds 0.5 and reaches 1.0 in the densest regions.

We converted the chosen gas particles to stellar particles. In this process the position and velocity of gas particles are taken for the stellar particles. The stellar masses are randomly drawn from Salpeter mass function with an upper- and lower-mass cut-off of 0.3 and 100 $M_\odot$, respectively. The mean mass of the stellar particles is 1 $M_\odot$, and this is the same as the mass of gas particles. Thus, the mass is globally conserved before and after star formation.

For the third step, we removed all gas particles assuming an instantaneous gas expulsion and continued N-body simulations with stellar particles only. We used a sixth-order Hermite code (Nitadori & Makino 2008) with block timesteps for this calculation.

3. Results

At 0.5 and 2 Myr, we interrupted the simulations and measured the inter-clump velocity dispersion. In order to measure the inter-clump velocity dispersions, we first detected clumps using a clump finding method, HOP Eisenstein & Hut (1998), in AMUSE. We obtained the number of clumps and inter-clump velocity dispersions of our models as well as the mass of the most massive clump (cluster). We performed several runs for one model but with a different random seed for the initial turbulence. This results in different number of clumps and the mass of the most massive clump. However, we found a relation between the initial gas mass ($M_{\rm g}$) and the mass of the most massive clump ($M_{\rm c,max}$); $M_{\rm c,max} = 0.20 M_{\rm g}^{0.76}$ (Fujii & Portegies Zwart 2015). This result is consistent with the observed relation (Hughes *et al.* 2013).

Comparing the mass of the most massive clump and inter-clump velocity dispersion with observations, we found that the Carina region is consistent with our model with an initial gas mass of $4 \times 10^5 M_\odot$ and density of $\sim$100 cm^{-3}. The inter-clump velocity dispersion of this model was 2.9 ± 0.3 km s^{-1}, while that of the Carina region is 2.35 km s^{-1} (Kuhn *et al.* 2019). The most massive cluster of the Carina region is Trumpler 14, and

https://doi.org/10.1017/S1743921319007634 Published online by Cambridge University Press

the mass is $4.3^{+3.3}_{-1.5} \times 10^3 M_\odot$ (Sana *et al.* 2010). The mass of the most massive clump in this model was $3.3 \pm 1.9 \times 10^3 M_\odot$.

We also compared our models with NGC 2264 and found that our model with an initial gas mass of $4 \times 10^4 M_\odot$ and density of $\sim$1000 cm^{-3}. The resulting inter-cluster velocity dispersion was 1.4 ± 0.4 km s^{-1} and the mas of the most massive clump was $3.4 \pm 2.4 \times 10^2 M_\odot$. The observed inter-cluster velocity dispersion of NGC 2264 is 0.99 km s^{-1} (Kuhn *et al.* 2019).

4. Summary

We performed a series of N-body simulations of star-cluster complexes following SPH simulations of turbulent molecular clouds. We compared the simulated star-cluster complexes with the observations of the Carina region and NGC 2264. We found that our model with an initial gas mass of $4 \times 10^5 M_\odot$ is consistent with the inter-clump velocity dispersion and the mass of the most massive clump (cluster) in the region. For NGC 2264, our simulation suggested an initial gas mass of $4 \times 10^4 M_\odot$ (Fujii 2019). In addition, our results suggest that the mass of the most massive clump in the system depends on the mass of the molecular cloud. We found the mass of the most massive cluster ($M_{\rm c,max}$) follows $M_{\rm c,max} = 0.20 M_{\rm g}^{0.76}$, where $m_{\rm g}$ is the mass of the parental molecular cloud. This relation is consistent with observations (Fujii & Portegies Zwart 2015).

In these simulations, we assumed an instantaneous gas expulsion. However, the amount of gas in the observed star-cluster complexes are not negligible. In order to perform star cluster simulations without gravitational softening length, we are developing a tree-direct hybrid N-body/SPH code ASURA-BRIDGE based on a tree-direct hybrid scheme, BRIDGE (Fujii *et al.* 2007). This code is developed from N-body/SPH code ASURA (Saitoh & Makino 2013). In this new code, all stellar particles are copied from N-body/SPH code to Hermite code and the stellar particles are integrated using sixth-order Hermite code. In each fixed time step, the stellar particles are kicked using the force from gas particles. With this scheme, we can integrate stellar particles without a gravitational softening among stellar particles and treat the dynamical formation of binaries and close encounters of stars. With this code, we will be able to investigate the dynamical evolution of star clusters embedded in gas clouds such as the formation of runaway stars in young massive clusters (Fujii & Portegies Zwart 2011) and the formation of first star clusters (Sakurai *et al.* 2017). We will report new results with this code in the near future.

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