The Core-Collapse Time of Star Clusters with Mass Functions

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Star clusters dynamically evolve due to two-body relaxation. The relaxation process causes the shrink of the cluster core and the increase of the core density, which are called as core collapse. In the dense core, binaries form. They evolve to hard (tightly bound) binaries via dynamical interactions with the surrounding stars. During this process, the binaries give their energy to the surrounding stars. Once the energy given from the binaries exceed the potential energy of the cluster core, the core bounces. The time until the core bounce is called as core-collapse time [1].

Core-collapse time ($t_{\rm cc}$) is scaled by relaxation time ($t_{\rm rlx}$) and it is known that $t_{\rm cc}$ = 15–20 $t_{\rm rlx}$ for systems with single-mass components. When the stars in a cluster follow a mass function, the core-collapse time is much shorter than that in the case of single components. Using Monte-Carlo simulations, Gürkan et al. (2004) showed that the core-collapse time with a mass function follows $t_{\rm cc} \propto (m_{\rm max}/\langle m \rangle)^{-1.3}$, where $m_{\rm max}$ and $\langle m \rangle$ are the maximum and the mean mass of the cluster stars [2]. The theoretical reason for this relation, however, has not been understood.

We performed direct N-body simulations using sixthorder Hermite scheme, with which we can treat the interactions among binaries and their surrounding stars accurately and investigated the core collapse time of star clusters with mass functions. We found that the corecollapse time follows $t_{\rm cc} \propto (m_{\rm max}/\langle m \rangle)^{-1}$ (see Figure 1). We also found that this relation is obtained from the following equations. We assume that the core collapse proceeds in the dynamical friction time-scale of the most massive stars in the cluster. The dynamical friction time is obtained as

$$t_{\rm df} = \frac{1.91}{\ln \Lambda'} \frac{r^2 \sigma_{\rm 3D}}{G m_{\rm max}} . \qquad (1)$$

Since the relaxation time in the cluster core is written as

$$t_{\rm rc} = \frac{0.065 \sigma_{\rm c,3D}^3}{G^2 \langle m \rangle \rho_{\rm c} \ln \Lambda} , \qquad (2)$$

we obtain the core-collapse time scaled by the relaxation time as

$$\frac{t_{\rm cc}}{t_{\rm rc}} = 29.4 \frac{\ln \Lambda}{\ln \Lambda'} \frac{G r^2 \rho_{\rm c} \sigma_{\rm 3D}}{\sigma_{\rm c,3D}^3} \left(\frac{m_{\rm max}}{\langle m \rangle} \right)^{-1} . \qquad (3)$$

This relation is drawn as dashed line in Figure 1, and the results obtained from our simulations agree with it. In addition, the decrease of the core-collapse time stops at some point, when we adopt a large $m_{\rm max}$, and this phenomenon depends on the number of particles (N). We found that this is because the core-collapse time must be longer than the crossing time of the system. While the crossing time is independent from N, the relaxation time increases with N. With a larger-N, therefore, the system can reach a shorter core-collapse time (see Figure 1). With the simulations, we also found that the core-collapse time is estimated using the binding energy of the binary formed in the cluster core [3].

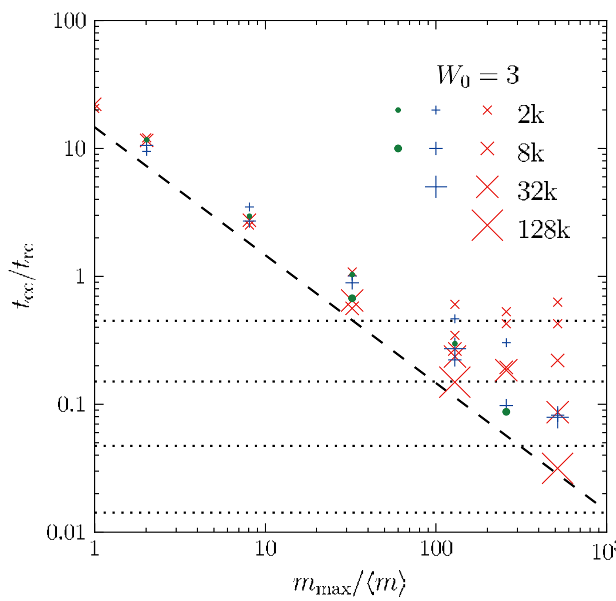

Figure 1: The core-collapse time as a function of the maximum mass of the cluster particles. Color symbols indicate the results obtained from our simulations. Dashed line shows the analytic result obtained from equation (3). Dotted lines indicate the minimum core-collapse time (ten crossing time) for N = 2k, 8k, 32k, and 128k from top to bottom.

References

[1] Heggie, D., Hut, P.: 2003, The Gravitational Million-Body Problem: A Multidisciplinary Approach to Star Cluster Dynamics, by Douglas Heggie and Piet Hut, *Cambridge University Press*.
[2] Gürkan, M. A., Freitag, M., Rasio, F. A.: 2004, *ApJ*, **604**, 632.
[3] Fujii, M. S., Portegies Zwart, S.: 2014, *MNRAS*, **439**, 1003.