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Growth of intermediate mass black holes in first star clusters

Yuya Sakurai[1], **Naoki Yoshida**[2,3,4], **Michiko S. Fujii**[5]

[1]School of Physics, Georgia Institute of Technology, Atlanta, GA 30332, US

[2]Department of Physics, School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan

[3]Kavli Institute for the Physics and Mathematics of the Universe (WPI), UT Institute for Advanced Study, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan

[4]Research Center for the Early Universe (RESCEU), School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan

[5]Department of Astronomy, School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
email: yuya.sakurai@physics.gatech.edu

Abstract. We study runaway stellar collisions in primordial star clusters and formation of intermediate mass black holes (IMBHs). Using cosmological simulations, we identify eight atomic-cooling halos in which the star clusters form. We follow stellar and dark matter (DM) dynamics for 3 Myr using hybrid N-body simulations. We find that the runaway stellar collisions occur in all star clusters and IMBHs with masses $\sim 400-1900\,\mathrm{M}_\odot$ form. Performing additional N-body simulations, we explore evolutions of the IMBHs in the star clusters for 15 Myr. The IMBH masses grow via stellar tidal disruption events (TDEs) to $\sim 700-2500\,\mathrm{M}_\odot$. The TDE rates are $\sim 0.3-1.3\,\mathrm{Myr}^{-1}$. DM motions affect the star cluster evolutions and reduce the TDE rates. The IMBHs may subsequently grow to SMBHs by gas supply through galaxy mergers or large-scale gas inflows, or they may remain within or around the clusters.

Keywords. black hole physics, stellar dynamics, stars: kinematics, galaxies: star clusters

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1. Introduction

Recent observations of high-redshift quasars lurking at $z \gtrsim 6$ or the cosmic age $\lesssim 10^9$ yrs reveal existence of supermassive black holes (SMBHs) with masses as massive as $\sim 10^9\,\mathrm{M}_\odot$ (Mortlock *et al.* 2011; Wu *et al.* 2015; Bañados *et al.* 2018). Formation processes of such SMBHs in the early universe are still uncertain. In order to understand origins of the high-redshift SMBHs, researchers consider several SMBH formation models.

An often referred model is a “Pop III BH” model. In this model, a ‘seed’ BH with masses $\sim 100\,\mathrm{M}_\odot$ forms by gravitational collapse of a Pop III star (Heger *et al.* 2003), which forms in a primordial gas cloud and can be as massive as $\sim 100\,\mathrm{M}_\odot$ (Hirano *et al.* 2014). The seed BH subsequently grows to a SMBH in 10^9 yrs if it continues to accrete surrounding gas at a rate as high as the Eddington accretion rate. The gas accretion, however, could be suppressed by radiation feedback (Ciotti & Ostriker 2001; Milosavljević, Couch & Bromm 2009), which delays the BH growth.

To overcome the delay of the BH growth, researchers consider models in which a larger seed BH forms. One of the models is a runaway stellar collision model. In this model, the dense star clusters form in a primordial gas cloud enriched by a small amount of

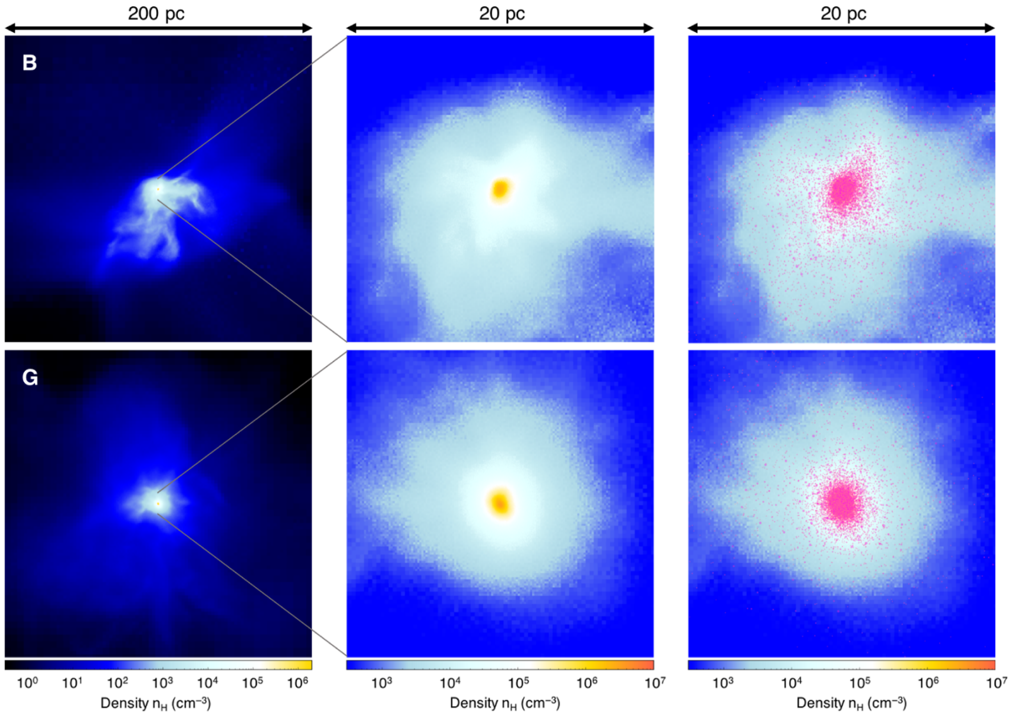

Figure 1. The projected gas density distributions for halo B (top panels) and halo G (bottom panels). In the right panels, stars are overplotted as magenta dots. Source: figure 1 of Sakurai *et al.* (2017), *"Formation of intermediate-mass black holes through runaway collisions in the first star clusters"*, Monthly Notices of the Royal Astronomical Society, 472, 1677.

metal with metallicity $\lesssim 10^4\,Z_\odot$ (Omukai, Schneider & Haiman 2008), forming a massive star with masses $\sim$1000 $M_\odot$ via runaway stellar collisions (Portegies Zwart & McMillan 2002) and leaving an IMBH as a remnant of the star (Katz, Sijacki & Haehnelt 2015). The IMBH can be a seed for the formation of the observed SMBHs.

It is unclear how rare the dense star clusters which result in runaway stellar collisions form in the early universe. It is also uncertain whether in the dense star clusters the IMBHs form and grow to SMBHs. To explore the validity of the runaway stellar collision model, we follow the runaway collision processes and the IMBH formation and growth in the dense star clusters using numerical simulations (Sakurai *et al.* 2017; Sakurai, Yoshida & Fujii 2019).

2. Overview

First of all, we perform 3-D smoothed-particle hydrodynamics (SPH) cosmological simulations using the Gadget-2 code (Springel 2005) to identify eight atomic-cooling halos. The virial masses of the halos are $M_{\rm DM} \sim (1.5-4) \times 10^7\,M_\odot$ and redshifts at the halo formation are $z = 11-20$. The examples of gas density distributions in the halos are shown in the left and the middle panels of Fig. 1.

Assuming that star clusters form from the gas clouds in the halos, we generate stellar distributions in star clusters using a local star formation efficiency parameter and the Salpeter mass function (see the right panels in Fig. 1). We set the minimum mass and the maximum mass of the stellar mass to $3\,M_\odot$ and $100\,M_\odot$ respectively. The obtained star cluster masses are $\sim(5-16) \times 10^4\,M_\odot$ and the number of stars are $\sim(6-20) \times 10^3$.

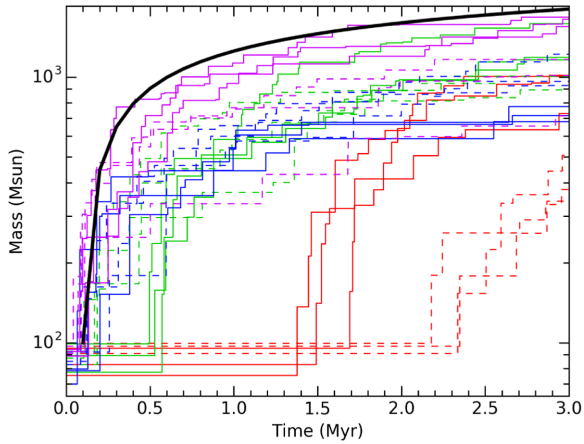

Figure 2. Time evolution of mass growth of the stars which experience the runaway stellar collision processes in the dense star cluster in the N-body simulations. Source: figure 3 of Sakurai *et al.* (2017), *"Formation of intermediate-mass black holes through runaway collisions in the first star clusters"*, Monthly Notices of the Royal Astronomical Society, 472, 1677.

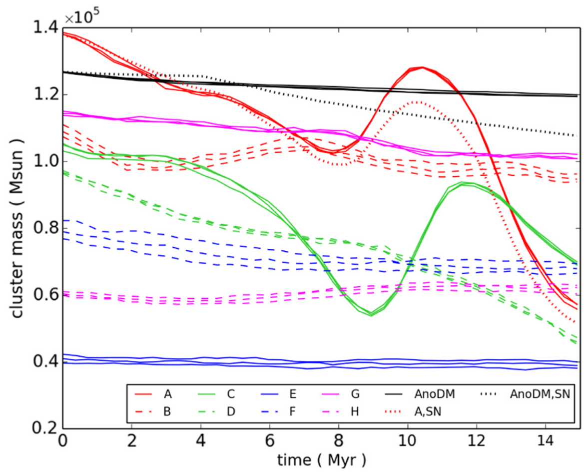

Figure 3. Evolution of bound stellar masses in the star clusters. Source: figure 8 of Sakurai, Yoshida & Fujii (2019), *"Growth of intermediate mass black holes by tidal disruption events in the first star clusters"*, Monthly Notices of the Royal Astronomical Society, 484, 4665.

Using the obtained stellar distributions as initial conditions, we perform hybrid N-body simulations using the BRIDGE code (Fujii *et al.* 2007). In the simulations, we calculate gravity of star particles by a direct method using the sixth-order Hermite integrator (Nitadori & Makino 2008). We also include dark matter (DM) particles and calculate their gravity by a tree method. The star cluster evolutions are followed for 3 Myr.

We find that the runaway stellar collisions occur in all star clusters (see Fig. 2). Massive stars with masses $\sim$400$-$1900 $M_\odot$ form as the results of the runaway stellar collisions. The massive stars will gravitationally collapse to IMBHs at the end of their lifetimes.

To explore subsequent evolution of the IMBHs and discuss their fates, we perform hybrid N-body simulations using the BRIDGE code and follow the stellar and IMBH dynamical motions in the clusters. The evolutions are followed up to 15 Myr. In the simulations, we consider stellar tidal disruption events (TDEs) by the IMBHs.

We find that the masses of the IMBHs in the clusters grow by TDEs to $\sim$700$-$2500 $\mathrm{M}_\odot$ (see figure 2 of Sakurai, Yoshida & Fujii (2019)). The TDE rates by the IMBHs are $\sim$0.3$-$1.3 Myr^{-1}, which are related to the final IMBH masses by the analytic form

$$\dot{N}_{\mathrm{TDE}} \sim 0.3\,\mathrm{Myr}^{-1} \left(\frac{M_{\mathrm{IMBH,f}}}{1000\,\mathrm{M}_\odot} \right)^2 . \tag{2.1}$$

We also show that DM motions affect evolution of the star clusters. In Fig. 3, we plot evolutions of bound stellar masses of the clusters. When DM masses increase within a star cluster, stars in the outer regions of the cluster are accelerated. By the acceleration, stars become unbound from the cluster and the TDE rate in the cluster decreases.

3. Implications

We consider two possible fates of the IMBHs.

- The IMBHs could grow to the observed SMBHs by galaxy mergers or large-scale gas inflows.
- The IMBHs could remain within or around the star clusters. The origins of observed candidate IMBHs (e.g. Maccarone *et al.* 2007) may be explained by the runaway stellar collision scenario.

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