Formation of the First Star Clusters and Massive Star Binaries by Fragmentation of Filamentary Primordial Gas Clouds

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Abstract

We perform a set of cosmological simulations of early structure formation incorporating baryonic streaming motions. We present a case where a significantly elongated gas cloud with \( \sim 10^9 \) solar mass \( (M_\odot) \) is formed in a pre-galactic \( (\sim 10^7 M_\odot) \) dark halo. The gas streaming into the halo compresses and heats the massive filamentary cloud to a temperature of \( \sim 10,000 \) Kelvin. The gas cloud cools rapidly by atomic hydrogen cooling, and then by molecular hydrogen cooling down to \( \sim 400 \) Kelvin. The rapid decrease of the temperature and hence of the Jeans mass triggers fragmentation of the filament to yield multiple gas clumps with a few hundred solar masses. We estimate the mass of the primordial star formed in each fragment by adopting an analytic model based on a large set of radiation hydrodynamics simulations of protostellar evolution. The resulting stellar masses are in the range of \( \sim 50–120 M_\odot \). The massive stars gravitationally attract each other and form a compact star cluster. We follow the dynamics of the star cluster using a hybrid \( N \)-body simulation. We show that massive star binaries are formed in a few million years through multi-body interactions at the cluster center. The eventual formation of the remnant black holes will leave a massive black hole binary, which can be a progenitor of strong gravitational wave sources similar to those recently detected by the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO).

Key words: cosmology: theory – dark ages, reionization, first stars – galaxies: high-redshift – methods: numerical – stars: formation – stars: Population III

1. Introduction

Recent detection of gravitational waves from binary black holes (BHs) by the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) opened the new era of gravitational wave (GW) astronomy. The origin and evolution of such binary BHs with masses of several tens of solar masses are largely unknown, but it is thought that they are the remnants of stellar populations formed in low-metallicity environments. It has been also suggested that binary systems consisting of massive primordial stars can be progenitors of gravitational wave sources.

There has been significant progress in the theoretical study of primordial star formation (see Greif 2015 and Barkana 2016 for recent reviews). Three-dimensional simulations with a fully cosmological set-up have been used to study in detail the formation process and physical properties of the first stars, galaxies, and black holes (e.g., Hirano et al. 2014; Wise et al. 2014; Chon et al. 2016). Generating realistic initial conditions is the key for such cosmological simulations. Tseliakhovich & Hirata (2010) identify an important physical effect caused by baryonic supersonic motions relative to dark matter (DM) in the early Universe. The initially supersonic motions quickly decay as the Universe expands, but cause considerable effects on early structure formation (see Fialkov 2014 for a review). The baryon fraction in small-mass dark halos is reduced (Naoz et al. 2013), gas condensation and subsequent star formation are suppressed or delayed (Greif et al. 2011; Stacy et al. 2011), and even the abundance of DM halos is affected (Dalal et al. 2010; Tseliakhovich et al. 2011; Fialkov et al. 2012; Naoz et al. 2012; Bovy & Dvorkin 2013). Several important observational signatures are expected to be imprinted in large-scale structure, such as the large angular-scale fluctuation in the 21 cm intensity distribution (Dalal et al. 2010; McQuinn & O’Leary 2012; Visbal et al. 2012; Barkana 2013; Fialkov et al. 2013; Tanaka et al. 2016, B-mode polarization of the cosmic microwave background (CMB; Ferraro et al. 2012), and the number density of the low-mass satellite galaxies in the Milky Way (Bovy & Dvorkin 2013).

A number of authors have performed cosmological simulations in order to study the impact of the baryonic streaming motions. Maio et al. (2011) and Naoz et al. (2012) studied the formation of small-mass dark halos and their gaseous contents, and O’Leary & McQuinn (2012) and Richardson et al. (2013) studied the formation of star-forming gas clouds. Greif et al. (2011) showed that primordial star formation is delayed significantly and that the so-called minimum halo mass for gas collapse is raised by a factor of a few compared to the case without the streaming motions. The global delay of star formation due to the streaming motions causes both positive and negative feedbacks on the subsequent star formation through fluctuations in the ultraviolet (e.g., Haiman et al. 1996) and X-ray background radiation (e.g., Machacek et al. 2003). The relative motions can cause the spatial offset between the baryon and DM density fluctuations. An intriguing possibility is that gas-deficient DM halos and DM-free gas clumps are formed, of which the latter can evolve into globular clusters, whereas the former can be progenitors of ultra-faint dwarf galaxies (Naoz & Narayan 2014; Popa et al. 2016). Clearly, the early baryonic streams can generate a variety of objects from stars to star clusters and (dark) galaxies. It is thus important to follow the formation of individual early objects in detail using three-dimensional simulations.
We use cosmological hydrodynamics simulations with primordial chemistry and radiation transfer to study in detail the effect of baryonic streaming motions on the formation of the first stars. Earlier in Hirano et al. (2017), we presented several cases where supermassive stars are formed under very large baryonic streaming motions. Primordial supermassive stars with masses $10^4-10^5 M_\odot$ are formed in a manner similar to the turbulent core collapse model of present-day massive star formation (e.g., McKee & Tan 2002). In the present paper, we investigate other cases with low-to-moderate streaming velocities. We find an interesting case where a large filamentary gas cloud is formed, which then fragments to yield multiple gas clouds. Such filament fragmentation has not been seen in previous simulations without baryonic streaming motions, but could actually be one of the characteristic cases with realistic cosmological initial conditions because the streaming velocities assumed in the present study are not very large and correspond only to $2\sigma$ fluctuations. Finally, we follow the dynamical evolution of a cluster of stars formed via the filament fragmentation. We show that close-binary systems of massive stars are formed through multi-body interactions between the cluster member stars.

The rest of the paper is organized as follows. We begin by describing the calculation methods in Section 2. Section 3 shows the results of cosmological simulations with different initial streaming velocities. Section 4 discusses and summarizes the dependence of first star formation on the intrinsically generated streaming velocities.

### 2. Numerical Methodology

We perform a set of cosmological simulations that incorporate the early baryonic streaming motions. We use a hierarchical zoom-in technique to achieve sufficiently high spatial resolution to follow the hierarchical assembly of small-mass dark matter halos and the formation of the star-forming gas cloud within them. The parent cosmological simulation has a volume of $L_{\text{box}} = 10 h^{-1}$ Mpc on a side, in which we select zoom regions with $L_{\text{zoom}} = 0.3 h^{-1}$ Mpc. In the high-resolution regions, the particle masses of dark matter and gas components are $m_{\text{DM}} = 16.4$ and $m_{\text{baryon}} = 3.0 M_\odot$, respectively. We use the publicly available code MUSIC (Hahn & Abel 2011) to generate the cosmological initial conditions at redshift $z_{\text{ini}} = 499$. Note that the initial epoch is chosen so that the high-order perturbations are accurately reproduced. We adopt the standard $\Lambda$-cold dark matter ($\Lambda$CDM) cosmology with total matter density $\Omega_m = 0.3086$, baryon density $\Omega_b = 0.04825$, dark energy density $\Omega_{\Lambda} = 0.6914$ in units of the critical density, Hubble constant $h = 0.6777$, density fluctuation amplitude $\sigma_8 = 0.8288$, and primordial index $n_s = 0.9611$ (Planck Collaboration et al. 2014). The initial ionization fraction is $x_e = 6.88 \times 10^{-4}$ (Seager et al. 1999, 2000; Wong et al. 2008).

The streaming motions are realized in a straightforward manner by simply adding a constant uniform velocity along one axis to the initial conditions of our zoomed simulations. This procedure is valid because the distribution of the streaming velocity is coherent over a length of a few megaparsecs, which is larger than a typical region that contains target first galaxy halos of our interest (Tseliakhovich & Hirata 2010). Furthermore, the initial streaming direction can be set arbitrarily because the cosmological supersonic motion is not correlated with the local overdensity (Ahn 2016). In practice, we introduce the initial relative velocity $v_{\text{bc}}$ ("bc" representing "baryon-cold dark matter") into the otherwise standard initial conditions. We do not consider spatial offset between the two components at $z_{\text{ini}}$ because it is negligibly small at the initial redshift (Naoz et al. 2012). We generate four cosmological initial conditions with the same phase for the density field but with different $v_{\text{bc}}$ normalized by the root-mean-square value, $\sigma_{\text{bc}} = 30 \, \text{km s}^{-1}$, at the epoch of cosmological recombination $z_{\text{rec}} = 1089$. We adopt the following values and dub the four runs as $v_{\text{bc}}/\sigma_{\text{bc}} = 0$ (Run-No), 1 (Low), 2 (Med), and 3 (High). Table 1 summarizes the parameter sets of the cosmological initial conditions. We also refer to the simulations in Hirano et al. (2017), for which the initial density fields are generated with $\sigma_8 = 1.2$ (Run-B) and 2.0 (A).

The cosmological simulations are performed using the parallel $N$-body/smoothed particle hydrodynamics (SPH) code GADGET-2 (Springel 2005) suitably modified for primordial star formation (Yoshida et al. 2007, 2008; Hirano et al. 2015). We employ a hierarchical refinement technique to follow the

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Table 1

| Identifier | $v_{\text{bc}}$ ($\sigma_{\text{bc}}$) | $\sigma_8$ | $z$ | $R_I$ (pc) | $M_{\text{tot}}$ ($10^3 M_\odot$) | $T_{\text{gas}}$ (K) | $f_{\text{gas}}$ | $R_I$ (pc) | $M_t$ ($10^3 M_\odot$) | $a/b - 1$ |
|-----------|------------------|----------|----|----------|-----------------|-----------------|--------------|----------|-----------------|------------|
| Run-No    | 0                | 0.8      | 34.6 | 26       | 0.016           | 1010            | 0.122        | 0.25     | 0.36            | 1          |
| Low       | 1                | 0.8      | 27.9 | 76       | 0.022           | 2880            | 0.119        | 1.25     | 3.0             | 5          |
| Med       | 1                | 0.8      | 20.1 | 293      | 3.35            | 9670            | 0.194        | 20       | 220             | 10         |
| High      | 3                | 0.8      | 17.3 | 464      | 6.28            | 4920            | 0.102        | 79       | 2200            | 4          |
| A         | 3                | 2.0      | 49.4 | 93       | 2.76            | 6220            | 0.086        | 5.0      | 160             | 0          |

Note. Column 1: identification of simulation; Column 2: relative streaming velocity normalized by the root-mean-square value $\sigma_{\text{bc}}$; Column 3: a root-mean-square density fluctuation in a sphere of radius $8 h^{-1}$ Mpc; Column 4: redshift when the gas number density at the collapsing center reaches $n_{\text{crit}} = 10^4 \, \text{cm}^{-3}$; Columns 5 to 8: radius, total mass, gas temperature, and gas fraction at the virial scale; Columns 9 and 10: radius and mass at the Jeans scale; and Column 11: ellipticity of collapsing gas cloud $a/b - 1$, where $a$ and $b$ are the major and minor axes. The second rows for Run-Med and High shows results for when the gas collapse can occur if the collapse suppression via halo mergers were to be ignored. The bottom two are results in Hirano et al. (2017), which leave a supermassive protostar with $\sim 10^5 M_\odot$.

5 O’Leary & McQuinn (2012) suggested setting high initialization redshifts with $z_{\text{ini}} > 200$.  

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gas cloud collapse as in Hirano et al. (2017), with refinement criterion that the local Jeans length is always resolved by 15 times the local smoothing length by progressively increasing the spatial resolution using the particle-splitting technique of Kitsionas & Whitworth (2002). The minimum mass of gas particles becomes $m_{\text{baryon,min}} = 1.6 \times 10^{-4} M_\odot$, which is enough to avoid the artificial delay of gas collapse (Greif et al. 2011). We stop the simulations when the maximum hydrogen number density reaches $n_H = \rho/m_H = 10^{12} \text{cm}^{-3}$, where $m_H$ is the proton mass.

3. Hydrodynamical Simulations

We confirm that the previously known effects of the streaming motions are reproduced in our simulations. Namely, the gas cloud collapse is delayed and the host halo mass increases until the gas cloud finally collapses. Table 1 summarizes the properties of the star-forming gas clouds in our four runs at the respective time when gravitational collapse occurs. In addition to these expected results, we also find significant deformation of the collapsing gas clouds. Figure 1 shows clearly that the cloud appears nearly spherical but is elongated to be filamentary with increasing streaming velocity (from left to right panels).

3.1. Formation of the Star-forming Gas Cloud

A major effect of the streaming velocity on structure formation is the suppression or delay of the gas condensation in small-mass dark matter halos. Figure 2 shows the time variation of the maximum gas density in each run. The collapse epoch is systematically delayed to lower redshifts with increasing streaming velocity. As an example, let us compare Figures 1(b) and 3(d). The gas cloud has already collapsed ($n_H \gtrsim 10^5 \text{cm}^{-3}$) in the former (Run-Low), but the latter (Run-Med) reaches just only $n_H \sim 10 \text{cm}^{-3}$ at similar epochs $z = 27-28$ (see Figure 2). Note that the dark matter distributions are nearly the same at any given epoch in Run-No to Run-High, regardless of the baryonic streaming velocities. Figure 1(c) shows that the halo gas is compressed and vertically elongated at $z = 17.3$. Then the host halo mass is already greater than $10^7 M_\odot$, and its deep gravitational potential can trap the gas streams inflowing from the left in the figure. In Run-High, the gas distribution is highly disturbed within the virial radius of $R_V = 464 \text{pc}$ (Figure 1(d)). The subsequent gravitational collapse of the central gas cloud

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Projected structure of the primordial star-forming cloud in Run-No (at $z = 34.6$), Low (27.9), Med (20.1), and High (17.3): gas number density in a region of 1 kpc on a side (panels (a)-(d)), and gas number density ((e)-(h)) and gas temperature ((i)-(l)) in a region of 100 pc on a side. The direction of the initial supersonic stream between the gas and dark matter components is aligned to the horizontal axis (from left to right) in the figure.}
\end{figure}
proceeds in a dynamical and complicated manner (Figure 1(h)), as has been also reported in Hirano et al. (2017).

The overall impact of the streaming motions weakens with time because the relative velocity decays with decreasing redshift as

$$v_{bc}(z) = v_{bc}^\text{rec} \left(1 + \frac{z}{1 + z_{\text{rec}}} \right). \quad (1)$$

However, in addition to the overall delay of collapse, halo mergers continue disturbing the gas collapse after $z = 25$ in Run-Med and High (Figure 2). A number of minihalos fall in along dark matter “filaments” and are accreted onto the central halo (Figures 3(a)–(c)). Through the dynamical relaxation process, halo mergers prevent the gas from cooling and condensing, until the gas temperature reaches $\sim 10,000$ K and efficient atomic hydrogen cooling operates. To summarize, the fast gas streams delay gas condensation, and hence star formation in small dark halos, and the gas in growing dark halos is kept dynamically “hot” for a few tens of millions of years. Star-forming gas clouds are formed only after the virial halo temperature exceeds the so-called atomic cooling threshold.

With the dynamical effect taken into account, the minimum halo mass for gas cloud formation is significantly larger than in the case without streaming motions. Figure 4 shows that the virial halo masses at the onset of gas collapse (filled symbols) agree well with the cooling threshold (open symbols) derived from the virial halo temperature given by

$$M_{\text{onl}} \approx 4.5 \times 10^5 M_\odot \left(\frac{v_{\text{circ}}}{4 \text{ km s}^{-1}}\right)^3 \left(\frac{1 + z}{21}\right)^{-3/2}, \quad (2)$$

where $v_{\text{circ}} = \sqrt{GM_N/R_V}$ is the circular velocity, $G$ is the gravitational constant, and $M_N$ and $R_V$ are the virial mass and radius (e.g., Barkana & Loeb 2001). Interestingly, a naive model that accounts for the effect of the streaming motions does not reproduce our results. Fialkov et al. (2012) proposed that the increase of the threshold mass can be formulated by using the “effective” velocity

$$v_{\text{circ,fit}}(z) = \sqrt{\frac{v_{\text{circ},0}^2 + \alpha v_{bc}(z)}{2}}. \quad (3)$$

With appropriate choice of the two parameters, $v_{\text{circ},0}$ and $\alpha$, the simulation results of Stacy et al. (2011) and Greif et al. (2011) are reproduced (Fialkov et al. 2012). However, this model does not describe well the results of our simulations (compare crosses and filled symbols in Figure 4). This can be easily seen in Figure 5, where we compare the circular velocities of halos at the onset of gas collapse as a function of $v_{bc}(z)$ (Equation (1)). Data for Run-No and Low can be fitted by $v_{\text{circ,fit}}(z)$ with parameters $v_{\text{circ},0} = 3.7$ km s$^{-1}$ and $\alpha = 3.2–4.7$. Contrastingly, in Run-Med and Run-High, the host halos have grown significantly through mergers to over the estimated cooling threshold mass. We note that the halo circular velocity at $z = 24$ in Run-Med (indicated by the open circle) is actually close to the model prediction. While the gas cloud is contracting at $z = 24$, a series of halo mergers continuously disturb, and the final collapse occurs late at $z = 20$ (see also
indicate the results from the corresponding threshold masses obtained from Equation (2). The crosses indicate the results from the fitting function (Equation (3)) with the parameters $v_{\text{esc},0} = 3.7 \, \text{km s}^{-1}$ and $\alpha = 4.0$. The open and filled diamonds, plotted for comparison, are the results for Run-A and Run-B in Hirano et al. (2017).

The density profile steepens at the Jeans scale, $R_J$, which is determined by the Jeans mass $M_J$ of the collapsing gas cloud. At the Jeans scale, the gas cools efficiently and the Jeans mass is given by

$$M_J \approx 10^3 M_\odot \left( \frac{c_s}{1 \, \text{km s}^{-1}} \right)^3 \left( \frac{n_H}{10^4 \, \text{cm}^{-3}} \right)^{1/2},$$

where $c_s$ is the sound speed of about a few $\text{km s}^{-1}$ in the collapsing primordial cloud. Because the gas clouds are supported by thermal pressure and also by turbulent motions induced by the streaming motions, we evaluate the Jeans mass by replacing $c_s$ with $\sqrt{c_s^2 + v_{\text{esc}}(z)}$, where $v_{\text{esc}}(z)$ is the escape velocity of the host halo. In Run-Med and High with large streaming velocities, the gas fraction tends to be "squashed" vertically with respect to the streaming motions (see Figures 1(g) and (b)). This can be seen typically at low redshifts ($z \sim 15$–25) when the host halos can gravitationally trap the streaming gas efficiently. In Run-A and B of Hirano et al. (2017) with the same initial streaming velocity but in high-density regions, the gas fractions are much lower than the cosmic mean, $f_{\text{gas},V} \approx 0.085$.

3.2. Fragmentation of the Elongated Cloud

We stop the simulations when the gas density at the cloud center reaches $n_H = 10^{12} \, \text{cm}^{-3}$. By the respective final epoch, the host halo has grown to about 10–100 times that in Run-No (Table 1). In such a massive halo, the star-forming cloud is surrounded by a dense gas envelope. We find that the density distribution in Run-No is approximated by a power-law function as $ho \propto R^{-2.2}$ (Omukai & Nishi 1998), but the other cases show strongly enhanced density structure at large radii. The density profile steepens at the Jeans scale, $R_J$ (Table 1), inside which the gas cloud undergoes runaway collapse. At the innermost region, the density profile is similar to the power-law shape of the cloud in Run-No.

Figure 6(a) shows the thermal evolution of the collapsing gas clouds. There are two major radiative cooling processes in the pristine gas. Atomic hydrogen (H) cooling becomes efficient at $T \geq 8000 \, \text{K}$ (Barkana & Loeb 2001), and molecular hydrogen (H$_2$) line emission can further cool the gas down to $T \sim 200 \, \text{K}$. The gas cloud in Run-No cools by H$_2$-cooling when a sufficient amount of hydrogen molecules are formed at $n_H \sim 10^4 \, \text{cm}^{-3}$. In Run-Med and High with large streaming velocities, the gas temperature first reaches $\sim 8000 \, \text{K}$, above which atomic hydrogen cooling becomes efficient, and then the gas cools rapidly.

While condensing in the dark halo, the gas cloud becomes gravitationally unstable when its mass exceeds the Jeans mass, which is given by

$$M_t \approx 10^3 M_\odot \left( \frac{c_s}{1 \, \text{km s}^{-1}} \right)^3 \left( \frac{n_H}{10^4 \, \text{cm}^{-3}} \right)^{1/2},$$

where $c_s$ is the sound speed of about a few $\text{km s}^{-1}$ in the collapsing primordial cloud. Because the gas clouds are supported by thermal pressure and also by turbulent motions induced by the streaming motions, we evaluate the Jeans mass by replacing $c_s$ with $\sqrt{c_s^2 + v_{\text{esc}}(z)}$. Runaway gravitational collapse is triggered when the mass of the collapsing gas cloud increases to $M_t$. The figure shows the Jeans mass and critical mass for gas cooling and collapse for a range of initial streaming velocities. The crosses indicate the results from the fitting function (Equation (3)) with the parameters $v_{\text{esc},0} = 3.7 \, \text{km s}^{-1}$ and $\alpha = 4.7, 4.0, 3.2$, respectively.
CMB temperature effective again, but slowly, when compressional heating becomes brief period of gas condensation, the temperature increases quickly gets to around 250 K owing to compression heating. Thus HD cooling does not become efficient in a primordial cloud, which has cooled by H2 cooling from a highly ionized state with $\sim 10^4$ K (Yoshida et al. 2007). Similar conditions are realized in Run-Med and High (panel b). The necessary HD fraction to cool the gas is estimated to be $f_{\text{HD}}/f_{\text{H2}} \sim 10^{-3}$ at $n_{\text{H}} < 10^6$ cm$^{-3}$. The HD fraction increases in all of our runs, but the gas temperature does not get sufficiently low due to enhanced compressional heating. Thus HD cooling does not become efficient in Run-Med (panel c)), whereas in Run-High, the central core temporarily cools to the CMB temperature floor, $T_{\text{CMB}}(z) = 2.73(1 + z) \approx 50$ K at $z = 17.3$, but quickly gets to around 250 K owing to compression heating.

This overcomes this critical mass (circles in Figure 6(a)). After a brief period of gas condensation, the temperature increases again, but slowly, when compressional heating becomes effective (Figure 6(a)).

The star-forming cloud transforms from spherical to having an elongated structure with increasing streaming velocity (Figures 1(e)–(h)). We find that the filamentary clouds shrink radially at first, while the cloud ellipticity, $a/b - 1$, where $a$ and $b$ is the major and minor axes, is roughly maintained (Table 1). When the contracting filament, with its temperature decreasing owing to radiative cooling, becomes gravitationally unstable, it breaks up into multiple gas clumps.

Collapse and fragmentation of an elongated gas cloud can be well described by self-similar solutions of a cylindrical filament (e.g., Inutsuka & Miyama 1992, 1997). A dense filament becomes unstable to axisymmetric perturbations of wavelength greater than about twice the filament diameter, when the line mass (gas mass per unit length) is close to the equilibrium value $\sim 2\zeta_2^2/G$. On the other hand, if the line mass exceeds the equilibrium value, the whole filament collapses along the major axis without fragmentation. The former case is found in Run-Low, Run-Med, and Run-High in this study, whereas the latter case is realized in Run-B in Hirano et al. (2017), where a large fraction of the initially filamentary cloud with $a/b - 1 = 5$ is finally accreted onto a central protostar.

The cosmological streaming motions delay gas cloud formation but also affect the subsequent evolution of star-forming gas clouds in a complicated manner. The cloud in Run-No collapses nearly spherically, and forms a single protostar at the center (Figure 1(e)). In Run-Low, an elongated structure appears when $n_{\text{H}_{\text{cen}}} \sim 10^3$ cm$^{-3}$ and two fragments with a separation about 10 pc $\sim 2L_J$ (Jeans length) are formed when gravitational instability sets in at $n_{\text{H}_{\text{cen}}} \sim 10^4$ cm$^{-3}$ (Figure 1(f)). In Run-Med and Run-High, large filamentary structures are formed and yield a number of fragments when $n_{\text{H}_{\text{cen}}} \sim 10^3$–$10^6$ cm$^{-3}$. In Figure 7, we show the time evolution of $M_{\text{enc}}/M_J$ in Run-Med. After the first unstable cloud with $\sim 10^5 M_J$ forms when $n_{\text{H}_{\text{cen}}} = 10^3$ cm$^{-3}$, the inner filamentary structure with mass $\sim 10^4 M_J$ becomes highly gravitationally unstable. The densest part the filamentary structure has a density of $\sim 10^6$ cm$^{-3}$, and its collapse occurs just after the so-called loitering point.

### 3.3. Formation of Massive First Star Cluster

What is the final fate of the cluster of massive gas clumps found in Run-Med? An important question is whether most of, if not all, of the fragments collapse to yield stars before the very first star grows and causes radiation feedback effects in its surroundings. The typical evolution timescale from the protostar formation to the zero-age main sequence is $10^4$–$10^5$ years (see Figure 1 in Hirano & Bromm 2017).
should be compared with the free-fall time of a typical cloud (fragment),

\[ t_{\text{ff}} = \sqrt{\frac{3\pi}{32G\rho}} = 5.2 \times 10^4 \text{years} \left( \frac{n_H}{10^6 \text{cm}^{-3}} \right)^{-1/2}. \]  

(5)

Note that the dense fragments can also shield themselves against external radiation. Hence, each gas cloud, or at least its densest part, likely continues contracting even under the influence of radiation from nearby stars forming at the same time. We thus expect that most of the fragments with densities greater than \( \sim 10^5 \text{cm}^{-3} \), as found in our simulations, can actually collapse and form stars before being disrupted significantly by the radiation feedback from the other nearby stars.

Figure 8 shows the fine structure of the filamentary cloud in Run-Med. The bottom panel shows the most massive part, including a few fragments. The region within the density contour with \( n_H = 10^6 \text{cm}^{-3} \) has 5.8 pc in length and 0.2 pc in width. Note the Jeans length \( L_J \simeq 0.4 \text{ pc} \) for \( T = 400 \text{ K} \) and \( n_H = 10^6 \text{cm}^{-3} \). To study further the evolution of the density fluctuations in the filament, we continue the simulation by introducing the technique of Hirano & Bromm (2017). We followed the evolution for 40,000 years after the first clump (CL1) formation, and found that a total of eight clumps were formed in the same filament.

To identify gravitationally unstable fragments in the filament, we perform a series of procedures as follows. We first identify the filament as a cloud of gas particles with densities greater than \( 10^5 \text{cm}^{-3} \).

### Table 2

| CL1  | CL2  | CL3  | CL4  | CL5  | CL6  | CL7  | CL8  |
|------|------|------|------|------|------|------|------|
| \( M_{\text{frag}}/M_\odot \) | 240  | 180  | 400  | 410  | 240  | 280  | 350  | 170  |
| \( M_{\text{star}}/M_\odot \) | 74   | 59   | 111  | 113  | 74   | 84   | 100  | 56   |

**Note.** The gravitationally unstable gas mass around the clump, \( M_{\text{frag}} \), and the stellar mass estimated by a fitting function, \( M_{\text{star}} \) (Equation (17) in Hirano et al. 2014).
1. We define the direction of the filament by a vector pointing from one side of the filament to the other.

2. We divide the filament into a series of bins with a width of $\Delta L = 0.01 \text{ pc}$ along the vector defined in 1 above. Within each bin, the radial center is defined at the maximum density point. We then calculate the radial density profile within the small segment of the filament.

3. We examine if the line segments with gas mass $\Delta M_{\text{cell}}$ are gravitationally unstable by comparing the local line mass, $M_{\text{line}} = \Delta M_{\text{cell}} / \Delta L$, with the critical line mass, $M_{\text{line}, \text{crit}} = 2c_s^2 / G$ (e.g., Inutsuka & Miyama 1992, 1997).

Using the above procedures, we find gravitationally unstable line segments with gas masses $M_{\text{frag}} = M_{\text{line}} / L_{\text{Jeans}} = 170-410 M_\odot$ (e.g., Figure 9 for CL3). These are identified as star-forming gas clouds. We estimate the stellar mass formed in each fragment using a fitting formula derived from the results of a set of first star formation simulations (Equation (17) in Hirano et al. 2014). We assume the mean ratio of rotational energy to gravitational energy ($\beta_{\text{cloud}} = 0.3$). The estimated stellar masses, typically of several tens to a hundred solar masses, are listed in Table 2.

We study the dynamical interaction of the massive stars using the hybrid $N$-body code BRIDGE (Fuji et al. 2007; Sakurai et al. 2017). The eight gas clumps (stars) are replaced with $N$-body particles with positions and velocities that are calculated from those of the original SPH particles. The other SPH particles are converted to $N$-body particles with the same mass and velocity. In the following $N$-body calculations, we consider neither gas drag nor pressure forces from the diffuse gas component within the host halo, which interacts with itself and the star particles only through gravity. At the initial state, there are two multiple systems with four (CL1 to 4) and three (CL5 to 7) stars, and a single star (CL8; Figure 10(a)). Upon starting the $N$-body simulation, the eight stars gather quickly to form a cluster of massive primordial stars, and the whole filament collapses to form a spherical system (Figures 10(b)–(d)).

An important process is the formation of hard binaries. Once a hard binary forms, multi-body interactions continuously occur and the binary becomes even harder. Figure 11 shows the time evolution of the semimajor radius and eccentricity of the hardest binary in the cluster. From $\sim 1$ to $\sim 2.5 \text{ Myr}$, the semimajor axis of the binary gradually decreases owing to repeated stellar encounters, through which the binary eccentricity increases. The hardest binary interacts with the other stars, but the scattered stars remain bound within the host dark matter halo. After $\sim 2.5 \text{ Myr}$, the binary evolution slows down, for the other stars are scattered out of the cluster. At 3 Myr, the hardest binary consisting of CL3 ($111 M_\odot$) and CL6 ($86 M_\odot$) has a semimajor axis of 56.1 au and eccentricity of 0.981 (Figures 10(f) and 11).

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Figure 10. Time evolution of the filament structure during the $N$-body simulation at $t = 0, 0.15, 0.5, 1, 2,$ and 3 Myr. The color-scale shows the gas density distribution in a region of 10 pc on a side, and the dots represent the eight massive stars (CL1 to 8).
In order to see the effect of the assumed stellar mass, we have also performed N-body simulations with a fixed stellar mass. We set $m_{\text{star}} = 30\, M_\odot$ in one case, and $m_{\text{star}} = 100\, M_\odot$ in the other. The two runs show a quite similar evolution of the system and binary formation. We thus conclude that the hard binary formation is not a peculiar result of our N-body simulation with the estimated stellar masses. The precise stellar mass is not important in the star cluster evolution and in the formation of hard binaries.

The formed massive star binary can be a promising progenitor of BH-BH merger (e.g., Figure 2 in Belczynski et al. 2017) like the recently detected GW sources (Abbott et al. 2017). The merger timescale of a black hole binary depends on the separation (Equation (80) in Kinugawa et al. 2014),

$$t_{\text{coal}}(e_0 = 0) = 10\, \text{Gyr} \left( \frac{a_0}{0.2\, \text{au}} \right)^4 \times \left( \frac{M_1}{30\, M_\odot} \frac{M_2}{30\, M_\odot} \frac{M_1 + M_2}{60\, M_\odot} \right)^{-1},$$

where $e_0$ is the initial eccentricity, $a_0$ is the initial semimajor axis, and $M_1$ and $M_2$ are the masses of the primary and secondary stars. There is a strong constraint on the initial separation that allows coalescence within a Hubble time. For dynamically formed binaries with large eccentricities, the coalescence time is given by

$$t_{\text{coal}}(e_0) \sim (1 - e_0)^{7/2} t_{\text{coal}}(e_0 = 0).$$

Here we use Equation (81) in Kinugawa et al. (2014). With $e_0 = 0.9$ and 0.99, the necessary initial separation for merging within a Hubble time is 4.3 and 31 times the critical value for $e_0 = 0$. Figure 11(c) shows the merger timescale calculated using Equation (7). Although the binary separation does not decrease significantly after $\sim 2.5\, \text{Myr}$, the merger timescale periodically falls below the Hubble time because both the separation and eccentricity vary considerably. In principle, one needs to follow the stellar evolution of the binary stars and more complex interaction with gaseous envelope in order to determine the final fate. Our N-body simulations do not provide accurate predictions for when exactly the binaries merge. However, the fact that eccentric close-binaries with separations less than 10 au are formed within a few million years suggests that a fraction of such massive star binaries likely leave massive BH binaries that can coalesce through emission of gravitational waves within a Hubble time.

### 4. Discussions

We study the formation of the first star clusters by performing cosmological hydrodynamic simulations. Our simulations with early baryonic streaming motions show the formation of a massive, elongated filamentary cloud. Gravitational fragmentation of the large filament produces multiple gas clouds in which massive primordial stars of $\sim 100\, M_\odot$ are formed.

The formation of the first star clusters offers an interesting possibility for direct observation. Although the system found in our simulation is small, with a total stellar mass of about a few thousand solar masses, if a larger filament is formed by a similar process, and if more massive and hence luminous star clusters are formed, they may be detected by future telescopes such as the James Webb Space Telescope (Tumlinson et al. 2001; Bromm & Yoshida 2011), especially when the magnification effect by gravitational lensing is utilized (Rydberg et al. 2013). Yet there is a more exciting implication for observations of the first star cluster systems. Our simulations show the formation of a hard binary of massive stars at the center of the star cluster. If the remnant BHs with dozens of solar masses form an eccentric close-binary system, it emits strong gravitational waves with characteristic signatures at the final merger phase (Kinugawa et al. 2014, 2016; Inayoshi et al. 2017). In fact, mergers of massive BHs in the present-day Universe have been already detected (Abbott et al. 2016), and the origin of the massive BHs could be the first stars. Our results in the present paper provide a viable formation path for the massive BH binaries in a low- (zero) metallicity environment. Intriguingly, Abbott et al. (2017) reported that the measured BH spins are likely misaligned. The binary system may have been formed through dynamical interactions in dense clusters, in a similar manner as studied in the present paper.

In our simulations, the baryonic streaming motions produce large filaments with lengths of a few tens of parsecs. Filamentary gas clouds can also be formed in different manners in variants of cosmological models. For example, the formation...
of a large filamentary structure and its fragmentation are found in simulations of warm dark matter cosmology (Gao & Theuns 2007; Gao et al. 2015) and also in a model with axion-like particle dark matter (Hirano et al. 2018). It would be interesting to follow the dynamics of the fragments and possible formation of star clusters in these cosmological models.

Vigorous fragmentation of a primordial gas cloud can occur in a different environment. It is thought that an initially “hot” gas cloud with a temperature of \( \sim 8000\)–10,000 K can be formed in an atomic-cooling halo under the influence of an external Lyman–Werner radiation (Omukai 2001). If the external radiation intensity is below a certain critical value for the complete suppression of hydrogen molecule formation, the thermal evolution of a gas cloud is similar to those found in our simulations (Latif & Volonteri 2015). The combined effects of the baryonic streaming motions and (weak) ultraviolet radiation may well produce the conditions for primordial star cluster formation. Cosmological simulations with realistic initial conditions with the baryonic streaming motions provide the opportunity to explore a variety of formation paths of the first stars, star clusters, and galaxies.

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References

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016, PhRvL, 116, 061102
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017, PhRvL, 118, 221101
Ahn, K. 2016, ApJ, 830, 68
Barkana, R. 2013, PASA, 30, 36
Barkana, R. 2016, PhR, 645, 1
Barkana, R., & Loeb, A. 2001, PhR, 349, 125
Belczyński, K., Klencki, J., Meynet, G., et al. 2017, arXiv:1706.07053
Bovy, J., & Dvorkin, C. 2013, ApJ, 768, 70
Bromm, V., & Yoshida, N. 2011, ARA&A, 49, 373
Chon, S., Hirano, S., Hosokawa, T., & Yoshida, N. 2016, ApJ, 832, 134
Dalal, N., Pen, U.-L., & Seljak, U. 2010, JCAP, 11, 7
Ferraro, S., Smith, K. M., & Dvorkin, C. 2012, PhRvD, 85, 043523
Fialkov, A. 2014, JMPD, 23, 30017
Fialkov, A., Barkana, R., Tseliakhovich, D., & Hirata, C. M. 2012, MNRAS, 424, 1335
Fialkov, A., Barkana, R., Vishal, E., Tseliakhovich, D., & Hirata, C. M. 2013, MNRAS, 432, 2909
Fujii, M., Iwasawa, M., Funato, Y., & Makino, J. 2007, PASI, 59, 1095
Gao, L., & Theuns, T. 2007, Sci, 317, 1527
Gao, L., Theuns, T., & Springel, V. 2015, MNRAS, 450, 45
Greif, T. H. 2015, ComAc, 2, 3
Greif, T. H., White, S. D. M., Klessen, R. S., & Springel, V. 2011, ApJ, 736, 147
Hahn, O., & Abel, T. 2011, MNRAS, 415, 2101
Haiman, Z., Rees, M. J., & Loeb, A. 1996, ApJ, 467, 522
Hirano, S., & Bromm, V. 2017, MNRAS, 470, 898
Hirano, S., Hosokawa, T., Yoshida, N., et al. 2014, ApJ, 781, 60
Hirano, S., Hosokawa, T., Yoshida, N., & Kuiper, R. 2017, Sci, 357, 1375
Hirano, S., Hosokawa, T., Yoshida, N., Omukai, K., & Yorke, H. W. 2015, MNRAS, 458, 568
Hirano, S., Sullivan, J. M., & Bromm, V. 2018, MNRAS, 473, L6
Inayoshi, K., Hirai, R., Kinugawa, T., & Hotokezaka, K. 2017, MNRAS, 468, 5020
Inutsuka, S.-I., & Miyama, S. M. 1992, ApJ, 388, 392
Inutsuka, S.-I., & Miyama, S. M. 1997, ApJ, 480, 681
Kinugawa, T., Inayoshi, K., Hotokezaka, K., Nakauchi, D., & Nakamura, T. 2014, MNRAS, 442, 2963
Kinugawa, T., Nakano, H., & Nakamura, T. 2016, PTEP, 2016, 103E01
Kitson, S., & Whitworth, A. P. 2002, MNRAS, 330, 129
Latif, M. A., & Volonteri, M. 2015, MNRAS, 452, 1026
Machacek, M. E., Bryan, G. L., & Abel, T. 2003, MNRAS, 338, 273
Maio, U., Khochfar, S., Johnson, J. L., & Ciardi, B. 2011, MNRAS, 414, 1145
Mckee, C. F., & Tan, J. C. 2002, Nat, 416, 59
Mcquinn, M., & O’Leary, R. M. 2012, ApJ, 760, 3
Naoz, S., & Narayan, R. 2014, ApJL, 791, L8
Naoz, S., Yoshida, N., & Gnedin, N. Y. 2012, ApJ, 747, 128
Naoz, S., Yoshida, N., & Gnedin, N. Y. 2013, ApJ, 763, 27
O’Leary, R. M., & Mcquinn, M. 2012, ApJ, 760, 4
Omukai, K. 2001, ApJ, 546, 635
Omukai, K., & Nishi, R. 1998, ApJ, 508, 141
Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2014, A&A, 571, A16
Papa, C., Naoz, S., marinacci, F., & Vogelsberger, M. 2016, MNRAS, 460, 1625
Richardson, M. L. A., Scanapieco, E., & Thacker, R. J. 2013, ApJ, 771, 81
Rydberg, C.-E., Zackrisson, E., Lundqvist, P., & Scott, P. 2013, MNRAS, 429, 3658
Sakurai, Y., Yoshida, N., Fujii, M. S., & Hirano, S. 2017, MNRAS, 472, 1677
Schauer, A. T. P., Regan, J., Glover, S. C. O., & Klessen, R. S. 2017, MNRAS, 471, 4878
Seager, S., Sasselov, D. D., & Scott, D. 1999, ApJL, 523, L1
Seager, S., Sasselov, D. D., & Scott, D. 2000, ApJS, 128, 407
Springel, V. 2005, MNRAS, 364, 1105
Stacy, A., Bromm, V., & loeb, A. 2011, ApJL, 730, L1
Tanaka, T. L., O’Leary, R. M., & Perna, R. 2016, MNRAS, 455, 2619
Tseliakhovich, D., Barkana, R., & Hirata, C. M. 2011, MNRAS, 418, 906
Tseliakhovich, D., & Hirata, C. 2010, PhRvD, 82, 083520
Tumlinson, J., Giroux, M. L., & Shull, J. M. 2001, ApJL, 550, L1
Visbal, E., Barkana, R., Fialkov, A., Tseliakhovich, D., & Hirata, C. M. 2012, Natur, 487, 70
Wise, J. H., Demchenko, V. G., Halicek, M. T., et al. 2014, MNRAS, 442, 2560
Wong, W. Y., Moss, A., & Scott, D. 2008, MNRAS, 386, 1023
Yoshida, N., Oh, S. P., Kitayama, T., & Hernquist, L. 2007, ApJ, 663, 687
Yoshida, N., Omukai, K., & Hernquist, L. 2008, Sci, 321, 669