

Formation of globular clusters induced by external ultraviolet radiation – II. Three-dimensional radiation hydrodynamics simulations

Makito Abe,¹* Masayuki Umemura¹ and Kenji Hasegawa²

¹Center for Computational Sciences, University of Tsukuba, Ten-nodai, 1-1-1 Tsukuba, Ibaraki 305-8577, Japan

²Graduate School of Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8602, Japan

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ABSTRACT

We explore the possibility of the formation of globular clusters (GCs) under ultraviolet (UV) background radiation. One-dimensional spherical symmetric radiation hydrodynamics (RHD) simulations by Hasegawa et al. have demonstrated that the collapse of low-mass ($10^{6-7} M_{\odot}$) gas clouds exposed to intense UV radiation can lead to the formation of compact star clusters like GCs if gas clouds contract with supersonic infall velocities. However, three-dimensional effects, such as the anisotropy of background radiation and the inhomogeneity in gas clouds, have not been studied so far. In this paper, we perform three-dimensional RHD simulations in a semicosmological context, and reconsider the formation of compact star clusters in strong UV radiation fields. As a result, we find that although anisotropic radiation fields bring an elongated shadow of neutral gas, almost spherical compact star clusters can be procreated from a ‘supersonic infall’ cloud, since photodissociating radiation suppresses the formation of hydrogen molecules in the shadowed regions and the regions are compressed by UV heated ambient gas. The properties of resultant star clusters match those of GCs. On the other hand, in weak UV radiation fields, dark-matter-dominated star clusters with low stellar density form due to the self-shielding effect as well as the positive feedback by ionizing photons. Thus, we conclude that the ‘supersonic infall’ under a strong UV background is a potential mechanism to form GCs.

Key words: hydrodynamics – radiative transfer – globular clusters: general – galaxies: dwarf – galaxies: formation.

1 INTRODUCTION

According to the concordant cosmology, the formation of low-mass subgalactic objects are thought to have been the prime mode of the star formation in the early Universe. Considering the fact that stars are born in the form of star clusters in present-day galaxies (e.g. Meurer et al. 1995; Lada & Lada 2003; Fall, Chandar & Whitmore 2005), it is of great importance to explore the formation of star clusters in such subgalactic objects, to reveal the structure formation history in the Universe. Globular clusters (GCs) are significant tracers of early star formation history, since they are low-metal, oldest star clusters in the Universe. GCs are relatively massive ($10^{4-6} M_{\odot}$) and stellar-dominated systems in which stars are tightly distributed in colour–magnitude diagram. Thus, GCs are thought to be of a single stellar population. Their ages can be evaluated by isochrone fitting. Although there are some uncertainties in the distances to GCs, the metallicity, and the stellar evolution models, the typical age is evaluated to be $\gtrsim 10$ Gyr with an uncertainty of \sim Gyr (e.g.

Krauss & Chaboyer 2003; Dotter et al. 2007; VandenBerg et al. 2013). Recently, Planck Collaboration XLVII (2016) have reported the reionization redshift as $7.8 < z_r < 8.8$ from the Thomson scattering optical depth of the cosmic microwave background (CMB). Based on the comparison between ages of GCs and the reionization epoch, most of old GCs seem to have formed under the influence of ultraviolet (UV) background radiation fields after the cosmic reionization.

The internal dynamics of GCs is quite distinctive from other systems with comparable luminosities such as dwarf spheroidal galaxies (dSphs). GCs are very compact systems, the half-light radii (r_h) of which are around 1–10 pc, regardless of their luminosity (McConnachie 2012). The velocity dispersions (σ) of GCs are as high as 10 km s^{-1} , and show steep dependence on luminosity (L) as $\sigma \propto L^{1/2}$ (e.g. McLaughlin 2000; Drinkwater et al. 2003; Hasegawa et al. 2005; Forbes et al. 2008), which is insensitive to their radii and masses. These characteristic features of GCs imply that they formed in their inherent environments.

The formation scenarios for GCs have been proposed by many authors, but still under debate. For instance, Kravtsov & Gnedin (2005) have performed high-resolution cosmological simulations to

* E-mail: mabe@ccs.tsukuba.ac.jp

explore the formation of GCs in a Milky Way (MW)-sized galaxy. They have found that cold metal-poor gas is supplied to the centre of the galaxy by direct gas accretion along dark matter (DM) filaments during minor mergers of smaller galaxies. The collisions of accreting gas spawn dense molecular clouds, which may be able to evolve to GCs. Although the spatial resolution of the simulations was not sufficient to resolve the internal structure of each star cluster, their result suggests that GCs possibly form in the cosmological context. The formation of giant molecular clouds can be expected also in major mergers of galaxies. Saitoh et al. (2009) have performed N -body/smoothed particle hydrodynamics (SPH) simulations of major mergers to explore the evolution of the interstellar medium (ISM). As a result, they have shown that the formation of GC-sized massive star clusters is triggered at high dense filamentary regions compressed by shocks. Besides, some high-resolution cosmological N -body simulations have revealed that the radial distribution of subhaloes originating from relatively rare peaks resembles the distribution of the Galactic GCs (Diemand, Madau & Moore 2005; Moore et al. 2006). This result implies that GCs may stem from DM subhaloes, but GCs are usually observed as stellar-dominated systems. To reconcile this inconsistency, Saitoh et al. (2006) have shown, using a semicosmological hydrodynamic simulation, that the tidal force by a host galaxy effectively strips DM haloes surrounding the star clusters. However, no previous work has succeeded in accounting for the characteristic internal properties of GCs.

As stated above, the formation of GCs is likely to be intimately related to the UV background radiation. Many observations have shown that cosmic reionization took place around the GC formation epoch. For instance, Umemura, Nakamoto & Susa (2001) have estimated the reionization epoch to be $6 < z_r < 10$, by confronting the radiative transfer simulations on reionization to Ly α absorption systems seen in high- z quasar spectra. Also, Fan, Carilli & Keating (2006) have estimated neutral hydrogen fractions at $z \sim 5$ –6 from quasi-stellar object (QSO) Ly α absorption lines and concluded that reionization is almost completed by $z \gtrsim 6$. Besides, gamma-ray bursts (GRBs) are also available to probe neutral hydrogen at high redshifts, because of their cosmological distances. Totani et al. (2006) have analysed the Ly α damping wing in the optical afterglow spectrum of GRB 050904 at $z = 6.3$, and concluded that a large fraction of intergalactic hydrogen seems to be ionized at $z = 6.3$. Ouchi et al. (2010) have investigated the evolution of high- z Ly α luminosity functions, and constrained the neutral hydrogen fraction in the intergalactic space as $f_{\text{H I}} < 0.2$ at $z = 6.6$.

UV radiation ionizes gas clouds and heats them up to $T \sim 10^4$ K. As a result, the gravitational contraction of clouds is suppressed if their virial temperatures are lower than $\sim 10^4$ K. Moreover, UV photons dissociate H₂ molecules that are the most important coolant at $T \lesssim 10^4$ K under metal-poor environments in the early Universe. Thus, in order for stars to form in the low-mass gas clouds exposed to UV background radiation, the clouds should be self-shielded from a UV background (Tajiri & Umemura 1998). Hasegawa, Umemura & Kitayama (2009b, hereafter HUK09) have performed spherically symmetric radiation hydrodynamics (RHD) simulations to explore the possibility of the star cluster formation under UV background radiation. As a result, they have found that the star cluster formation processes branch off into three paths according to the timing of the self-shielding. If the self-shielding occurs in the stage of supersonic contraction of a cloud, it leads to the formation of very compact star clusters like GCs (the details of physical processes are described in Section 2). However, in the simulations by HUK09, only isotropic irradiation of UV was investigated. In realistic situations,

we should consider three-dimensional effects. First, background radiation fields are usually expected to be anisotropic. Under an anisotropic UV background, the self-shielded regions also become anisotropic. Hence, the contraction of clouds is thought to proceed in a different fashion from the spherical symmetric collapse. Furthermore, if the density distributions in clouds are inhomogeneous, the self-shielding is subject to shadowing effects. In the context of the cosmic reionization, Nakamoto, Umemura & Susa (2001) have shown, by six-dimensional radiative transfer simulations, that the reionization process in an inhomogeneous media is considerably delayed compared to a homogeneous medium case due to the shadowing effects. Such inhomogeneity also increases an effective recombination rate in gas clouds, since the local recombination rate is proportional to the square of density (Madau, Haardt & Rees 1999). These three-dimensional radiation hydrodynamic effects may bring significant impacts on the star formation in the early Universe.

In this paper, we perform three-dimensional RHD (3D-RHD) simulations, where the six-dimensional radiative transfer is coupled with 3D hydrodynamics, and investigate how the three-dimensional effects have impacts on the formation processes of star clusters under UV background radiation. This paper is organized as follows. In Section 2, the physical models of star cluster formation are described based on HUK09. Section 3 is devoted to the numerical method of the present study. The numerical results are presented in Section 4, where the evolution of gas clouds exposed to external UV radiation and resultant stellar dynamics are shown. Also, we compare the properties of simulated star clusters to those of velocity dispersion-supported systems such as GCs, dSphs, and ultracompact dwarfs (UCDs). Finally, we discuss and conclude our results in Sections 5 and 6, respectively. Throughout this paper, we assume a cold dark matter (CDM) cosmology neglecting the dark energy, since it is less important in the early Universe. We work with cosmological parameters: $\Omega_{\text{M}} = 1.0$, $h = 0.6777$, and $\Omega_{\text{b}} = 0.1564$ (Planck Collaboration XVI 2014).

2 PHYSICAL MODEL

To review the basic physics, we suppose a spherical gas cloud purely composed of hydrogen and exposed to external isotropic background radiation. The external UV radiation ionizes neutral hydrogen and raises the temperature up to $\sim 10^4$ K. Thus, if a cloud is totally ionized, the system with the mass less than the Jeans mass at 10^4 K, $M_{\text{J}} (T = 10^4 \text{ K})$, is hindered from collapsing owing to raised thermal pressure. Furthermore, the primary coolant in the temperature range of $T \sim 10^{3-4}$ K is H₂ molecules for the metal-poor gas with the metallicity of $Z/Z_{\odot} \leq 10^{-2}$ (Susa & Umemura 2004). The Lyman–Werner band UV radiation dissociates H₂ molecules, so that stars cannot be born in the cloud. Therefore, in order for star clusters to form, the cloud should be self-shielded from ionizing and dissociating UV radiation. Tajiri & Umemura (1998) have studied the condition for the self-shielding by solving radiative transfer in the spherical symmetric geometry. Assuming power-law UV background radiation intensity $I_{\nu} = 10^{-21} \times I_{21} (v/v_{\text{L}})^{-1} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ Hz}^{-1}$, where v_{L} indicates the Lyman limit frequency and I_{21} is the intensity at the Lyman limit frequency in units of $10^{-21} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ Hz}^{-1}$, they have shown that the critical number density n_{crit} required for being shielded against the ionizing background radiation is given by

$$n_{\text{crit}} = 1.40 \times 10^{-2} \text{ cm}^{-3} \left(\frac{M}{10^8 M_{\odot}} \right)^{-1/5} I_{21}^{3/5}, \quad (1)$$

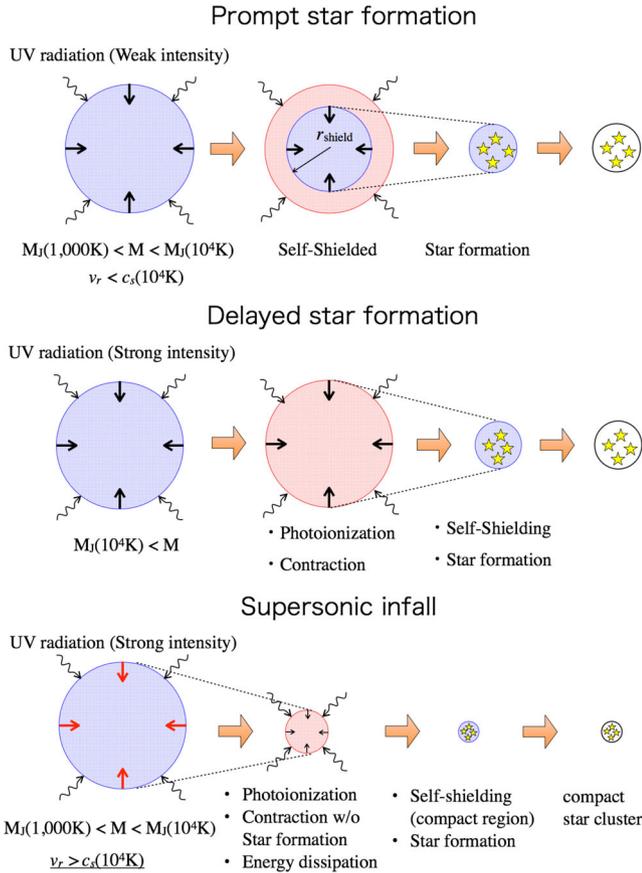


Figure 1. Schematic views for the formation scenarios of star clusters proposed by HUK09. The upper, middle, and bottom panels represent the ‘prompt star formation’, ‘delayed star formation’, and ‘supersonic infall star formation’ scenarios, respectively. In each panel, the red shaded region represents the photoionized gas, while the blue shaded denotes the self-shielded neutral regions. Red arrows denote the infall velocity exceeding the sound speed of photoionized gas ($\sim 10 \text{ km s}^{-1}$).

or the corresponding critical radius is

$$r_{\text{crit}} = 4.10 \text{ kpc} \left(\frac{M}{10^8 M_{\odot}} \right)^{2/5} I_{21}^{-1/5}, \quad (2)$$

where M is the total mass of the cloud. The self-shielded regions inside the shielding radius (r_{shield}) can gravitationally contract, even if the mass ($M < M_J$) is less than M_J (10^4 K). Also, if the interior mass is massive enough to produce H_2 molecules ($T_{\text{vir}} > 10^3 \text{ K}$) and also the dissociating UV radiation is shielded (Draine & Bertoldi 1996), stars can form in the cloud. Thus, the star cluster formation under a UV background is regulated by the self-shielding condition.

In the followings, we briefly describe three branches of the star cluster formation regulated by the self-shielding, based on HUK09. The schematic views for the formation scenarios of star clusters are presented in Fig. 1.

2.1 Prompt star formation

When the cloud mass M is in the range of M_J (10^3 K) $< M < M_J$ (10^4 K) and incident UV intensity is relatively weak (i.e. the cloud radius is smaller than r_{crit}), the self-shielded region promptly forms inside the cloud. As a result, the star formation is initiated in the self-shielded region, while the outer region is conversely evaporated by photoheating. This branch is called ‘prompt star forma-

tion’, which is the basic mechanism for the formation of low-mass galaxies during cosmic reionization (e.g. Susa & Umemura 2004).

In this case, stars can begin to form at an early stage of the contraction. Hence, the gas is effectively converted to stars without dissipating a large amount of kinetic energy. As a result, diffuse stellar systems tend to form. HUK09 have shown that the resultant star clusters mimic dSphs on the σ – L plane.

2.2 Delayed star formation

When the cloud mass exceeds the Jeans mass of photoionized gas, i.e. $M > M_J$ (10^4 K), the cloud can collapse, even if it is totally ionized by strong UV radiation. Although the cloud can keep shrinking, stars are never born before the cloud is self-shielded. Hence, the star formation tends to be delayed compared to no or weak UV cases. This mechanism is called ‘delayed star formation’.

In this case, the gas cloud can collapse without mass loss, but some amount of the kinetic energy is dissipated. As a result, the systems formed via the ‘delayed star formation’ exhibit relatively high velocity dispersions.

2.3 Supersonic infall star formation

Finally, we argue the case that the cloud mass is in the range of M_J (10^3 K) $< M < M_J$ (10^4 K), and strong UV is irradiated to the cloud. If the cloud radius is larger than the critical radius r_{crit} , the bulk of the cloud are ionized. In this case, the cloud cannot collapse due to the thermal pressure of ionized gas. However, HUK09 have shown that the cloud can collapse if the cloud contracts with infall velocity exceeding the sound speed of ionized gas. The contraction continues until the self-shielding effects work, and eventually stars can form in the self-shielded regions. This branch is called ‘supersonic infall star formation’. In this case, the star-forming regions become very compact, and the infall velocity is strongly decelerated due to the thermal pressure. As a result, the star clusters formed via the ‘supersonic infall’ can be as compact as GCs.

Also, HUK09 have argued the probability of such ‘supersonic infall’ in the context of the CDM cosmology. They have found that the ‘supersonic infall’ under a strong UV background can occur at redshift $z \gtrsim 15$ in density peaks higher than the standard deviation of density fluctuations.

3 METHOD

We perform 3D-RHD simulations to investigate the multidimensional effects in the formation of star clusters under UV background radiation. In the simulations, we consistently solve three-dimensional hydrodynamics, non-equilibrium chemistry, the transfer of UV photons, and the gravitational force.

3.1 Three-dimensional hydrodynamics

We solve hydrodynamics by SPH method, utilizing the code based on Hasegawa, Umemura & Susa (2009a) and Hasegawa & Umemura (2010) that have been developed to solve hydrodynamics coupled with the radiative transfer of UV photons.

We set the smoothing length h so that the mass enclosed in the sphere with the radius h is held constant. At every time step, the smoothing length of each SPH particle is iteratively determined to satisfy the above condition (Price & Monaghan 2007). As for the gravitational force calculation, we adopt the Barnes–Hut TREE algorithm to reduce the numerical cost (Barnes & Hut 1986), setting the opening angle to be $\theta = 0.5$.

3.2 Chemical reactions and three-dimensional ray-tracing

In the simulations, we solve primordial chemical networks regarding six species, i.e. e^- , H^+ , H , H^- , H_2 , and H_2^+ . We neglect cooling processes by metals, because the major coolant in the temperature range of $T \sim 10^{3-4}$ K is H_2 as long as the metallicity is $Z/Z_\odot \leq 10^{-2}$ (Susa & Umemura 2004). This is a reasonable approximation for the present study, since we focus on the star formation under metal-poor environments in the early Universe.

For the $H\text{ I}$ photoionization process, we assume the on-the-spot approximation (Spitzer 1978), in which ionized photons emitted from the recombination to the ground state of hydrogen are assumed to be absorbed on the spot. In this case, the solution of the radiative transfer equation is simply given by $I_\nu(\tau_\nu) = I_0 \exp(-\tau_\nu)$, where I_0 and τ_ν are, respectively, the intensity of a UV source and the optical depth at a frequency ν . We integrate the optical depth between a UV source and a target SPH particle by the same way as RSPH method (Susa 2006), and evaluate the photoionization and photoheating rates. To calculate H_2 photodissociation rates, we adopt the self-shielding function derived by Draine & Bertoldi (1996). Using the self-shielding function, the photodissociating radiation flux is given by

$$F = F_0 f_{\text{sh}}(N_{\text{H}_2,14}), \quad (3)$$

where F_0 is the flux without the self-shielding, $N_{\text{H}_2,14}$ is the H_2 column density normalized by 10^{14} cm^{-2} , and f_{sh} is

$$f_{\text{sh}}(x) = \begin{cases} 1, & (x \leq 1), \\ x^{-3/4}, & (x > 1). \end{cases} \quad (4)$$

The H_2 column density is also evaluated by RSPH method. We should mention that the dependence of the H_2 self-shielding on the column density is weaker than that of the $H\text{ I}$ shielding, and hence photodissociating photons are more permeable than ionizing photons, leading to deeper suppression on the star formation. The photodetachment of H^- and the photodissociation of H_2^+ are also considered with the optically thin approximation because of their very small fractions. The cross-sections for these processes are taken from Tegmark et al. (1997) and Stancil (1994).

3.3 Set-up

In each run, we consider a low-mass gas cloud with the initial baryonic mass of $10^6 \leq M \leq 10^7 M_\odot$ in a DM halo that collapses at a redshift of $6 \leq z_c \leq 12$. As for the initial chemical composition, we refer to the cosmological pre-reionization values derived by Galli & Palla (1998). We assume the initial temperature to be $T = 100$ K referring to Iliev et al. (2006, 2009). We start each simulation from the stage when a cloud reaches the maximum expansion. The maximum expansion redshift z_{max} is related to the collapse redshift z_c as $(1 + z_{\text{max}}) = 2^{2/3}(1 + z_c)$. The maximum expansion radius is given by

$$r_{\text{max}} = \left(\frac{4M}{3\pi^3 \rho_{c0}} \right)^{1/3} (1 + z_{\text{max}})^{-1}, \quad (5)$$

where ρ_{c0} is the cosmic critical density at the present-day. In the mass range we consider, the mass resolution is set to be roughly the same. In the present simulations, we use 2^{15-18} SPH particles according to the cloud mass. Thus, the SPH particle mass is $m_{\text{SPH}} \approx 40 M_\odot$ and the effective mass resolution of hydrodynamics is $\approx 4000 M_\odot$ (Bate & Burkert 1997; Bate, Bonnell & Bromm 2003). This mass resolution allows us to pursue the local Jeans instability of primordial gas up to $\sim 10^5 \text{ cm}^{-3}$ (e.g. Omukai et al.

2005). The number of DM particles is set to be the same as that of SPH particles, and the DM particle mass corresponds to $m_{\text{DM}} \approx m_{\text{SPH}}(\Omega_{\text{M}} - \Omega_{\text{b}})/\Omega_{\text{b}}$. The initial density profiles of gas and DM are assumed to be in the form of $\delta(r) = \delta_0 \sin(\lambda r)/(\lambda r)$ (Kitayama et al. 2001), where λ is defined as $\lambda r_{\text{max}} = \pi$. We set δ_0 so that the averaged overdensity within r_{max} is equivalent to 4.55, which is the value derived from the analytic spherical collapse model. We also add inhomogeneity to the cloud. We generate random-Gaussian density fields, where the power spectrum of density fluctuations obeys $P(k) = A_{\text{amp}} k^p$ for the wavenumber k . We use the same method as Braun, Dekel & Shapiro (1988) to generate the random-Gaussian density fields. We set the power-law index $p = -3$ to mimic scale-free density fluctuations of CDM. The amplitude A_{amp} is related to the initial clumping factor $C = \langle n^2 \rangle / \langle n \rangle^2$. In SPH simulations, the clumping factor can be evaluated by the simple formula

$$C = \frac{\sum_i m_i \rho_i^{-1} \sum_j m_j \rho_j}{(\sum_k m_k)^2}, \quad (6)$$

where ρ_i and m_i are the density and mass of the i th particle, respectively (Springel & Hernquist 2003). The initial clumping factor is $C = 1.7$ in all of the runs in this paper.

Also, we specify the epoch of the irradiation of external UV radiation z_{UV} , which are greater than $z = 6$, according to the reionization epoch suggested by observations. As for the intensity of UV background, we define the critical number of incident ionizing photons per unit time \dot{N}_{crit} , which is required to ionize the entire volume of gas cloud $V_{\text{UV, in}}$. \dot{N}_{crit} is given by a following formula (Madau et al. 1999):

$$\dot{N}_{\text{crit}} = \langle n \rangle^2 \alpha_{\text{B}}(T) C V_{\text{UV, in}}, \quad (7)$$

where $\alpha_{\text{B}}(T)$ is the case B recombination coefficient of hydrogen, $\alpha_{\text{B}} = 2.59 \times 10^{-13} \text{ cm}^{-3} \text{ s}^{-1}$ at $T = 10^4$ K. We specify the number of incident UV photons \dot{N}_{ion} in units of \dot{N}_{crit} . In our simulations, $\dot{N}_{\text{ion}}/\dot{N}_{\text{crit}} = 10$ or 0.1 are assumed so that we can explore the dependence on the strength of UV background radiation. Also, in some models, we consider the finite time over which the luminosity rises up to \dot{N}_{ion} . Here, we simply assume the linear rising of the luminosity, i.e. $\dot{N}(t) = \dot{N}_{\text{ion}}/t_{\text{rise}} \times t$, where t_{rise} denotes the rising time, and after t_{rise} the luminosity is set to be constant, $\dot{N}(t) = \dot{N}_{\text{ion}}$. In this paper, we examine three cases of t_{rise} as 1, 10, and 100 Myr. To investigate the effect of the anisotropy of radiation fields, we adopt two extreme cases: the one-sided or isotropic background radiation. In each run with a one-sided radiation field, we place only one ionizing source. The direction towards the source is referred to as the x -direction. On the other hand, in each run with an isotropic radiation field, we isotropically distribute 18 sources around a gas cloud. Note that the luminosity per one source in the one-sided radiation field case is 18 times higher than that in the isotropic radiation field case if $\dot{N}_{\text{ion}}/\dot{N}_{\text{crit}}$ is the same. As a UV spectrum, we assume the blackbody type with the effective temperature of $T_{\text{eff}} = 10^5$ K, since young massive stars are generally thought to be dominant ionizing sources during the reionization epoch.

3.4 Star formation and dynamical evolution

We incorporate the star formation in self-shielded, cooled regions. Here the following star formation criteria are employed: (1) $\nabla \cdot \mathbf{v} < 0$, (2) $y_{\text{H}_2} \geq 5 \times 10^{-4}$, and (3) $T \leq 5000$ K, where \mathbf{v} , y_{H_2} , and T are the local velocity, the H_2 fraction, and the gas temperature, respectively. In particular, the condition (2) is never satisfied unless

Table 1. Numerical parameters in all runs.

z_c	Radiation field	Formation	z_{UV}	M_{ini} ($10^6 M_\odot$)	$\dot{N}_{ion}/\dot{N}_{crit}$	t_{rise} (yr)
6	One-sided/isotropic	Supersonic	6.8	2.5	10	Instant
6	One-sided/isotropic	Supersonic	6.9	5.0	10	Instant
9	One-sided/isotropic	Supersonic	10.3	2.5	10	Instant
9	One-sided/isotropic	Supersonic	10.5	5.0	10	Instant
12	One-sided/isotropic	Supersonic	13.8	2.5	10	Instant
12	One-sided/isotropic	Supersonic	14.0	5.0	10	Instant
9	One-sided	Supersonic	10.5	5.0	10	10^6
9	One-sided	Supersonic	10.5	5.0	10	10^7
9	One-sided	Supersonic	10.5	5.0	10	10^8
9	One-sided	Supersonic	10.5	10.0	10	Instant
12	One-sided	Supersonic	14.0	10.0	10	Instant
6	One-sided	Prompt	8	2.5	0.1	Instant
6	One-sided	Prompt	8	5.0	0.1	Instant
9	One-sided	Prompt	8	1.0	0.1	Instant
9	One-sided	Prompt	12	2.5	0.1	Instant
9	One-sided	Prompt	12	5.0	0.1	Instant
9	One-sided	Prompt	12	10.0	0.1	Instant
12	One-sided	Prompt	15.9	1.0	0.1	Instant
12	One-sided	Prompt	15.9	2.5	0.1	Instant
12	One-sided	Prompt	15.9	5.0	0.1	Instant

the gas is shielded against ionizing and dissociating photons. Thus, this is an essential condition that regulates the star formation.

We consider the time-scale in which a gas particle is converted into a collisionless star particle. At every time step, we search gas particles satisfying the above criteria, and convert them to collisionless stellar particles stochastically as follows. The star-forming time-scale is expected to be controlled by the local free-fall time-scale $t_{ff} = \sqrt{3\pi/32G\rho_{gas}}$, where ρ_{gas} is the local gas density. Using the free-fall time t_{ff} , we describe the star formation rate (SFR) as

$$\frac{d\rho_*}{dt} = c_* \frac{\rho_{gas}}{t_{ff}}, \quad (8)$$

where ρ_* is the local stellar density, and c_* is the dimensionless parameter to control star formation efficiency. We can determine the probability p_* that SPH particles of $m_{gas} = N_{neighbour}m_{SPH}$ are converted to stellar particles of $m_* = \alpha_* \times m_{gas}$ ($0 < \alpha_* < 1$) during the time interval Δt :

$$p_* = \alpha_*^{-1} \left[1 - \exp\left(-c_* \frac{\Delta t}{t_{ff}}\right) \right]. \quad (9)$$

In this paper, we assume $\alpha_* = 0.3$ (Okamoto et al. 2003) and $c_* = 1.0$. Here, c_* is an artificial parameter to control the star formation efficiency (SFE) in the numerical simulations. However, as shown by Susa & Umemura (2004), the final stellar mass fractions are expected to be almost independent of c_* , since the SFE is essentially regulated by the self-shielding. We continue each run until stars formed in the cloud are settled in the quasi-steady state. The parameter sets in this work are summarized in Table 1.

4 RESULTS

4.1 Evolution of gas clouds

4.1.1 Supersonic infall

First, we see the evolution of a cloud infalling with supersonic speed under a strong UV background, and investigate the dependence on the anisotropy of UV background radiation. The cloud evolution under an isotropic UV background is shown in Fig. 2 for a run

with $M_{ini} = 5 \times 10^6 M_\odot$, $z_c = 9$, $z_{UV} = 10.5$, and $\dot{N}_{ion}/\dot{N}_{crit} = 10$, where the distributions of H_2 fraction, temperature, and H I fraction are presented. As we can see, although the outer envelope is evaporated, H_2 molecules in the central region are produced abundantly, which allow the star formation. On the other hand, Fig. 3 shows the evolution of a gas cloud exposed to one-sided background radiation. In this case, the shaded regions appear on the opposite side of the ionizing source owing to the shadowing effect. Accordingly, H_2 molecules form in an elongated region.

To understand the evolution in more detail, we show the temperature, H_2 fraction, and velocity profiles along the x -axis through the centre of the cloud in Fig. 4, where the blue points show the results for isotropic UV background radiation and the red points for one-sided UV radiation. At the initial epoch, the infall velocity exceeds 10 km s^{-1} , which roughly corresponds to the sound speed of the photoionized gas. Owing to such a high infall velocity, the ionized gas with $\sim 10^4 \text{ K}$ can keep contracting even after the UV irradiation. As shown in Fig. 4, the temperature and H_2 molecule distributions are obviously different between isotropic and one-sided background radiation. For isotropic background, only the central region is self-shielded from ionizing radiation and the temperature can keep below 10^4 K at 0.4 Myr, and cools down to $< 10^3 \text{ K}$ due to H_2 molecules at 9.4 Myr. In the case of one-sided background radiation, the temperature is below 10^4 K on the opposite side of the UV source at 0.4 Myr, whereas at 9.4 Myr the temperature is raised by the weak ionization due to the reduction of shadowing effect caused by the shrink of the core. Then, the weak ionization enhances the H_2 molecule formation, since free electrons are the catalyst of H_2 formation through the H^- process. Also, the velocity profile for one-sided background radiation shows the weak expansion of cloud envelope, which leads to the mass loss from the system. The impacts of such three-dimensional shadowing effects on the star formation are argued in Section 4.1.3 later on.

4.1.2 Prompt star formation

Here, we consider the evolution of a cloud infalling with subsonic speed under weak UV background radiation. Fig. 5 shows the time

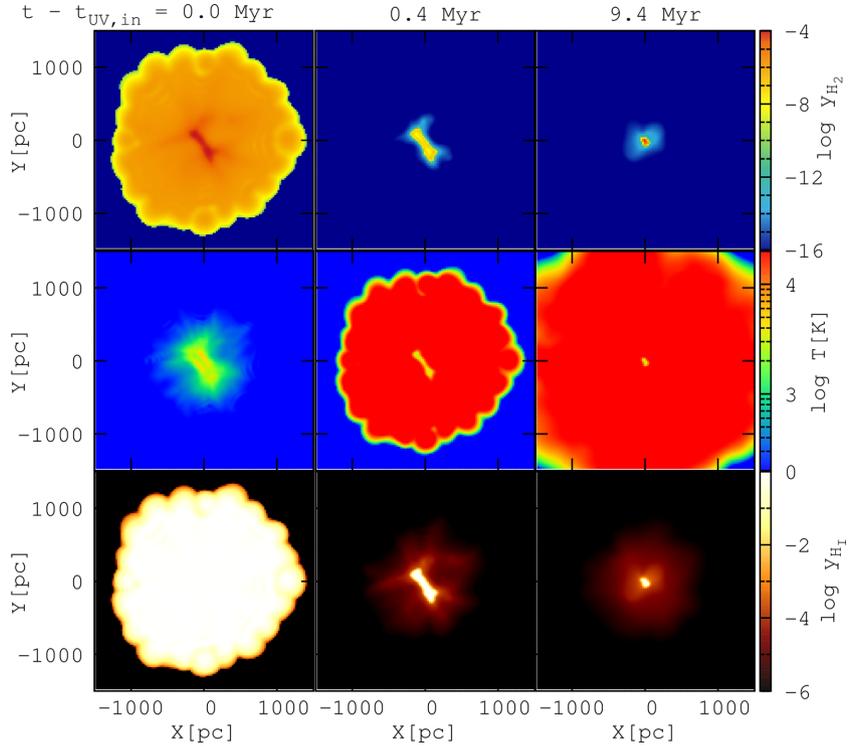


Figure 2. Time evolution of H_2 fraction (top panels), temperature (middle panels), and $H\text{ I}$ fraction distributions (bottom panels) on the x - y plane in the case of the isotropic background radiation. The parameters are $M_{\text{ini}} = 5 \times 10^6 M_{\odot}$, $z_c = 9$, $z_{UV} = 10.5$, and $\dot{N}_{\text{ion}}/\dot{N}_{\text{crit}} = 10$. From left to right, the distributions are shown at the UV irradiation epoch, 0.4 Myr later and 9.4 Myr later, respectively.

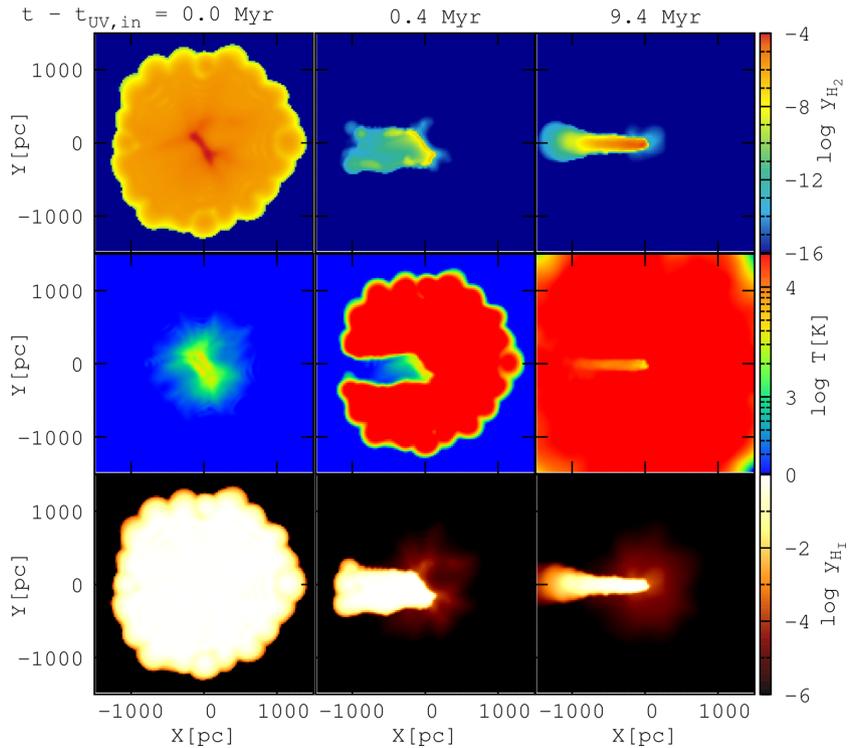


Figure 3. Same as Fig. 2, but for the case of the one-sided background radiation.

evolution of the H_2 distributions in the run with $M_{\text{ini}} = 5 \times 10^6 M_{\odot}$, $z_c = 9$, $z_{UV} = 12$, and $\dot{N}_{\text{ion}}/\dot{N}_{\text{crit}} = 0.1$. Fig. 6 presents the temperature, H_2 fraction, and velocity profiles along the x -axis through the cloud centre. Since this cloud is irradiated by external radiation

at an earlier phase of its contraction compared to the run shown in Section 4.1.1, the infall velocity is lower than the sound speed of photoionized gas at the moment of the irradiation. Hence, the ionized gas inevitably evaporates, and the self-shielded regions can

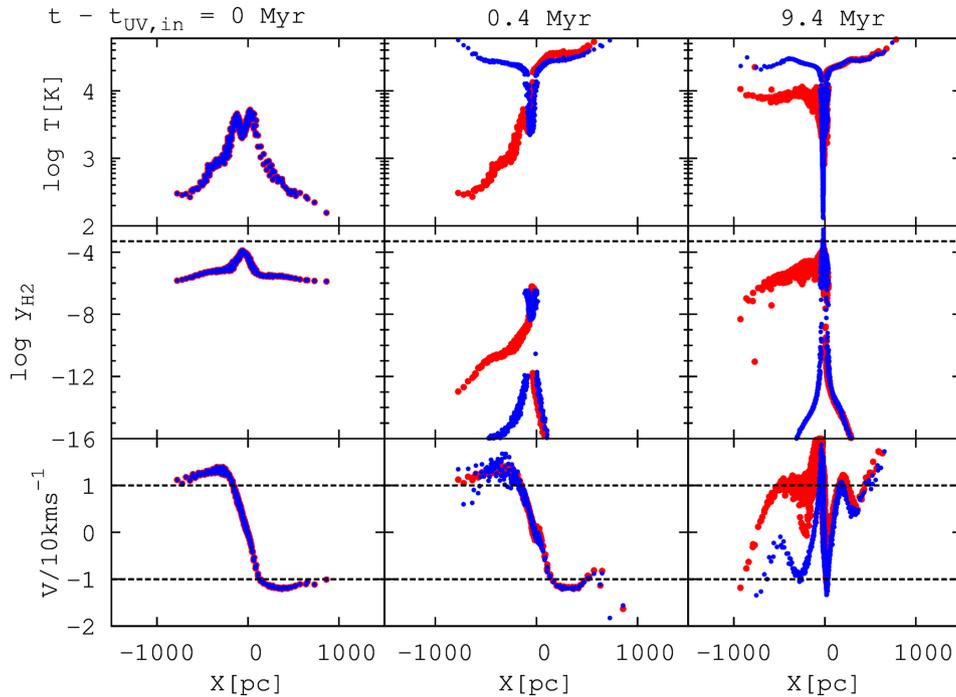


Figure 4. Temperature T (top), H_2 fraction (middle), and velocity (bottom) along the x -axis through the centre of the cloud. The red and blue points, respectively, indicate the quantities in the one-sided and isotropic background radiation cases. A dashed line in the middle panel at each epoch indicates the star formation criteria of $y_{\text{H}_2} = 5 \times 10^{-4}$. Two dashed lines in the bottom panel correspond to the infall velocity of 10 km s^{-1} , which is roughly the sound speed of photoionized gas. The parameters (M_{ini} , z_c , z_{UV} , and $\dot{N}_{\text{ion}}/\dot{N}_{\text{crit}}$) and the time sequence are the same as those in Fig. 2.

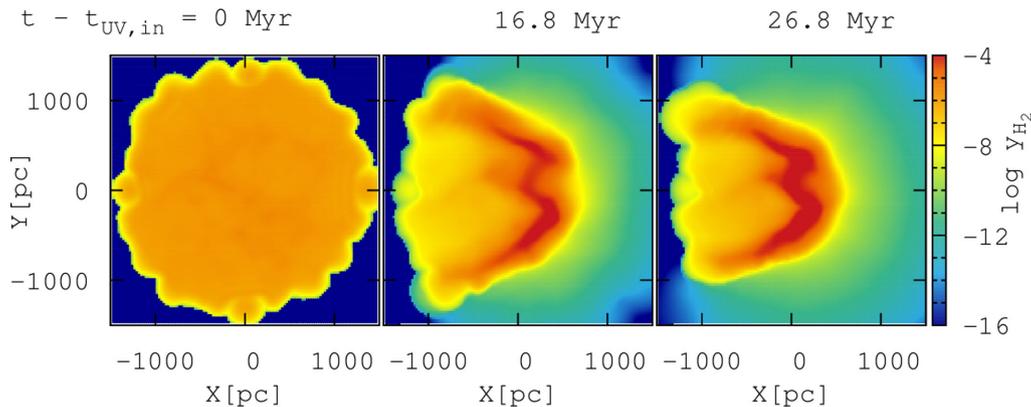


Figure 5. Time evolution of H_2 distributions in the run with $M_{\text{ini}} = 5 \times 10^6 M_{\odot}$, $z_c = 9$, $z_{\text{UV}} = 12$, and $\dot{N}_{\text{ion}}/\dot{N}_{\text{crit}} = 0.1$ on the x - y plane. The left-hand, centre, and right-hand panels correspond to the distributions at 0, 16.8, and 26.8 Myr after the UV irradiation, respectively.

collapse. One of the notable phenomena in this case is the positive feedback by ionizing photons. As shown in Fig. 6, H_2 molecules are efficiently formed around the ionization front. This is caused by the increase of free electrons that act as the catalyst for the H_2 formation. The enhanced H_2 formation induces the formation of stars at the positive feedback region (Ricotti, Gnedin & Shull 2002), and simultaneously protects the central region of the cloud from photodissociating radiation (Hasegawa, Umemura & Susa 2009a; Susa, Umemura & Hasegawa 2009). As a result, the ‘prompt star formation’ proceeds in the cloud, as proposed by HUK09.

4.1.3 Star formation history

As described in Section 4.1.1, the ionization and thermal properties in 3D-RHD calculations are quite different from those in 1D-RHD

calculations. In particular, the difference of self-shielding between the one-sided and isotropic background radiation is noticeable. Furthermore, even though background radiation is isotropic, the H_2 distributions become more complicated owing to the inhomogeneous density fields in the cloud (e.g. the central column of Fig. 2). Therefore, it is expected that the star formation proceeds in a different fashion from that in the 1D-RHD calculations.

To elucidate the three-dimensional effects, we first scrutinize the star formation history in each model. In Fig. 7, the positions where gas particles are converted to star particles are shown. In the runs of the ‘supersonic infall’, we find that most stars form within several 10 pc from the centre of the cloud after the UV irradiation (the red and blue lines in Fig. 7). This is due to the compactness of self-shielded regions formed by the strong UV background. We emphasize that the star-forming regions can be compact eventually

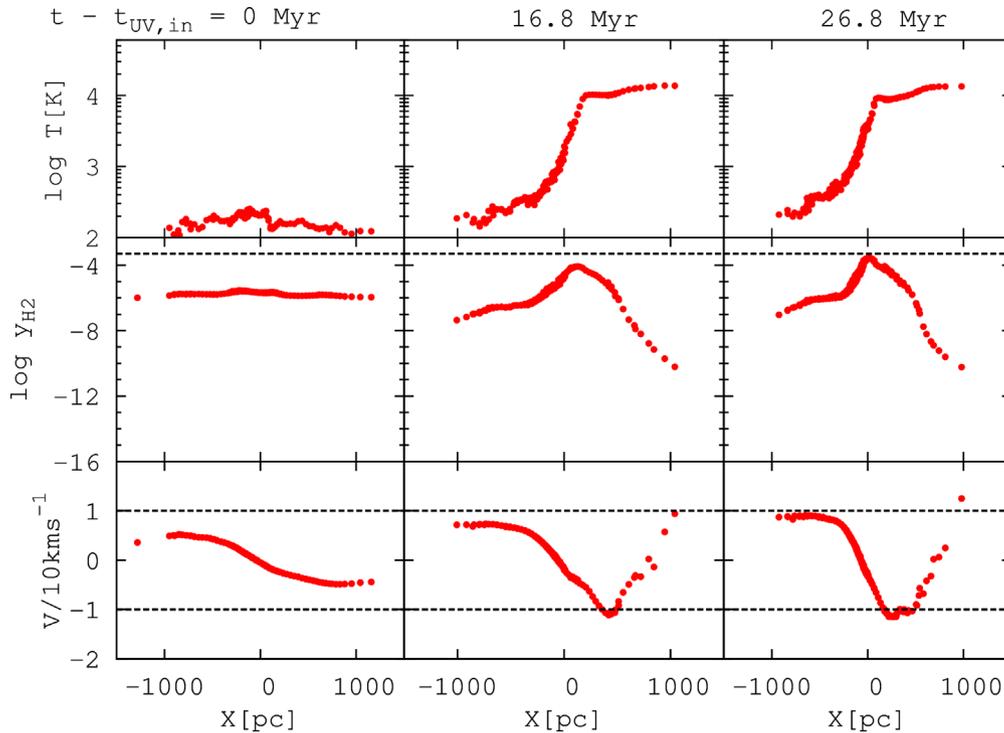


Figure 6. Same as Fig. 4, but for the cloud shown in Fig. 5. From left to right, the three panels, respectively, represent a cloud at the moment of 0, 16.8, and 26.8 Myr after the UV irradiation.

even in the runs of anisotropic background radiation despite the extended shaded regions (e.g. Fig. 3). This can be understood as follows. Although the shaded regions are immediately formed after the UV irradiation (e.g. low-temperature regions in Fig. 4), the photoheated gas surrounds the shaded regions as time goes on, as shown by the temperature map in Fig. 3. The broad shaded regions composed of cold gas are compressed by the photoheated gas. But, photodissociating UV photons suppress H_2 formation, and therefore stars cannot form in the shaded neutral regions until they are shoved by the hot gas towards the central part of the cloud and eventually shielded from photodissociating radiation (Fig. 4). As a result, the star-forming regions become compact, even though the shaded regions are originally extended.

However, the star formation history can be delayed by the anisotropy of UV background. We show the SFR as a function of time in Fig. 8. The typical duration of star formation in the ‘supersonic infall’ runs is less than 10 Myr. Needless to say, such a short duration seems favourable to explain the single stellar population in GCs. Comparing the durations in the one-sided and isotropic UV background, we can see the typical duration in the one-sided UV background is slightly longer. Such delay is mainly caused by the star formation originating in the shaded regions. As already shown, the gas in the shaded regions is never photoevaporated, but is pushed inward by photoionized gas. The relatively slow infall of the shaded regions results in lengthening the duration of the star formation.

The star formation in the ‘prompt star formation’ model proceeds in a completely different fashion. In this case, the cloud is self-shielded promptly and the star formation begins shortly after the gravitational collapse. As shown by the green solid lines in Fig. 7, the star formation sites range from ~ 1 pc up to several 100 pc. The broad distributions in the ‘prompt star formation’ originate in not only the extension of the self-shielded regions but also the

positive feedback through H_2 formation around an ionization front, as mentioned in the previous section. Actually, the distributions of stars in the ‘prompt star formation’ are more extended than the distributions of stars formed prior to the UV irradiation, as indicated by the black lines in Fig. 7. Also, the star formation history is quite different from that in the ‘supersonic infall’. As shown in Fig. 8, the star formation in the ‘prompt star formation’ model continues over ~ 100 Myr. The long-term star formation is attributed to abundant material of self-shielded regions. Besides, stars can be induced by the positive feedback by ionizing photons in an earlier phase than a UV-free case.

4.2 Stellar dynamics

Here, we pursue the stellar dynamics until the simulated star clusters accomplish the quasi-steady state. In this section, we describe the resultant features of the simulated star clusters.

4.2.1 Properties of simulated star clusters

Fig. 9 shows the cumulative mass profiles of the simulated star clusters. Obviously, the star clusters formed via ‘supersonic infall’ become stellar dominated in the main body of ~ 10 pc (red and blue line). On the other hand, the star clusters formed through ‘prompt star formation’ are dominated by DM (green line). The difference of the profiles reflects the way of contraction and star formation processes. In the ‘prompt star formation’, stars form at an early phase of the cloud contraction without strong kinetic energy dissipation. Consequently, diffuse star clusters tend to form. In contrast, in the ‘supersonic infall’, the thermal pressure enhanced by strong UV radiation dissipates the kinetic energy of contraction before stars are formed there. As a result, the formed star clusters tend to be compact and stellar dominated. We here emphasize again that the

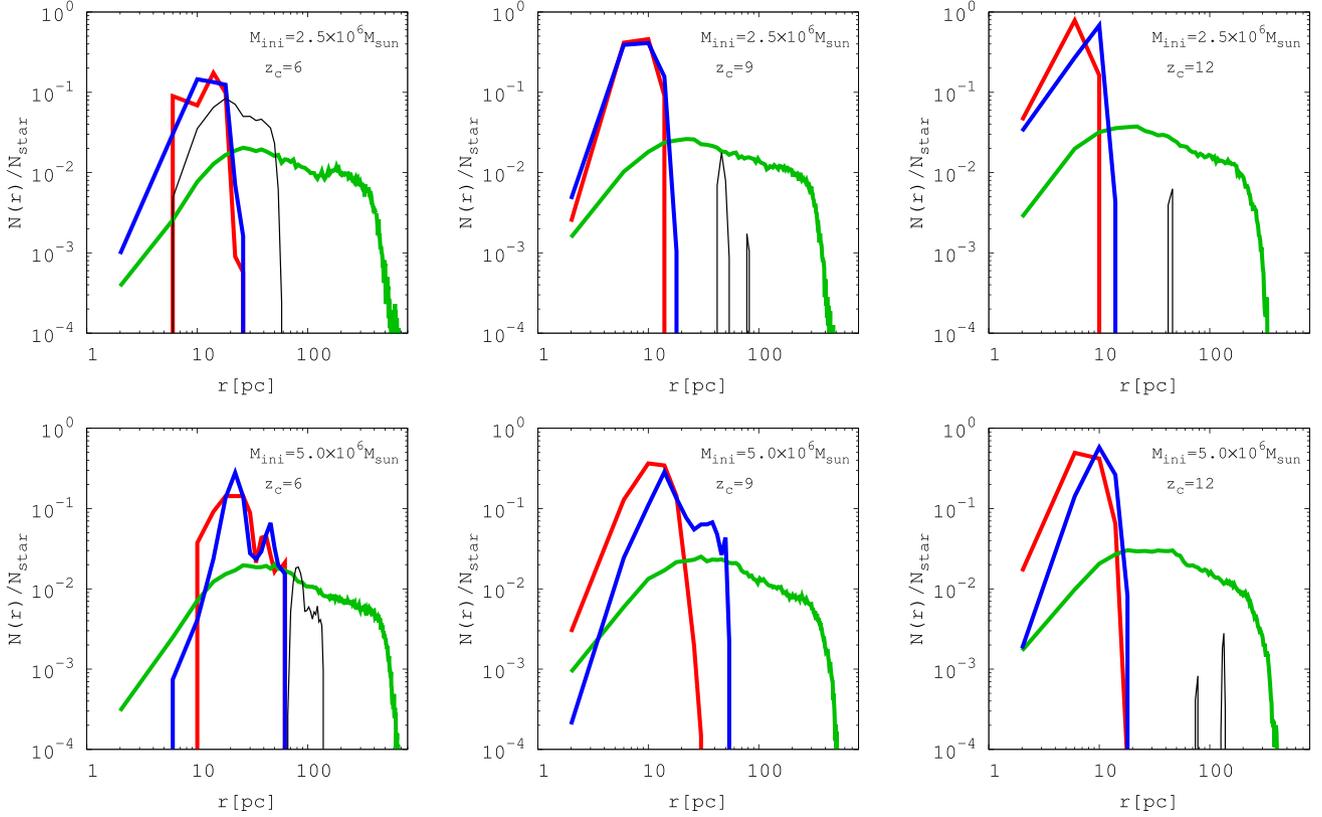


Figure 7. The distributions of the positions where SPH particles are converted to star particles. The horizontal axis denotes the distance from the centre of mass in units of pc, and the vertical axis does the number of formed stars normalized by the total number of stars. The upper three panels are the results for the cloud mass $M_{\text{ini}} = 2.5 \times 10^6 M_{\odot}$, and the lower panels those for $M_{\text{ini}} = 5 \times 10^6 M_{\odot}$. From left to right, the panels show the models of $z_c = 6, 9,$ and $12,$ respectively. Each panel represents the results of ‘supersonic infall’ under a strong one-sided background with $\dot{N}_{\text{ion}}/\dot{N}_{\text{crit}} = 10$ (red lines) and a strong isotropic UV background with $\dot{N}_{\text{ion}}/\dot{N}_{\text{crit}} = 10$ (blue lines), and the results of ‘prompt star formation’ under a weak one-sided UV background with $\dot{N}_{\text{ion}}/\dot{N}_{\text{crit}} = 0.1$ (green lines). Thin black lines in each panel show the distributions for star particles formed before UV irradiation.

properties of such compact star clusters are hardly affected by the anisotropy of radiation.

To quantify the structure of the star clusters, we fit the stellar density profiles by the Plummer model, which is known to be a good model for representing GC density profiles. The Plummer density profile is given by

$$\rho(r) = \frac{3M_*}{4\pi b^3} \left(1 + \frac{r^2}{b^2}\right)^{-5/2}, \quad (10)$$

where M_* denotes the total stellar mass of a cluster and b denotes the Plummer scale length that corresponds to the core radius of the cluster. The core radii fitted for all of the simulated clusters are listed in Table 2. As seen in Table 2, the core radii of the star clusters formed via ‘supersonic infall’ are well concordant with the core radii of $\lesssim 1$ pc observed in GCs (e.g. Kormendy 1985). Also, the difference between the one-sided and isotropic UV background is small. On the other hand, the typical core sizes of the clusters formed via ‘prompt star formation’ are much larger than 10 pc.¹

¹ We should note that the core radii change as the clusters dynamically evolve via the two-body relaxation. To make more precise comparison between the simulated clusters and observed GCs, the effects of two-body relaxation should be carefully incorporated in the collisional N -body simulations, which will be explored elsewhere.

4.2.2 Comparison to observations

In this section, we attempt to compare the simulated star clusters to observations. For the comparison, the V -band magnitude M_V of the simulated clusters is derived by assuming the typical mass-to-light ratio for GCs as $M_{\text{GC}}/L_V = 2$ (Pryor & Meylan 1993).

Fig. 10 shows the resultant half-mass radii r_h for the stellar components of the simulated clusters as a function of M_V . Those of the observed GCs, dSphs, and UCDs are also plotted in the figure. We find that the star clusters formed through ‘supersonic infall’ exhibit $r_h \sim 1\text{--}10$ pc, as observed GCs show. The compactness originates in their compact star-forming regions as well as strong kinetic energy dissipation. The result indicates that strong UV radiation is one of the keys to reproduce small half-mass radii of GCs. In contrast, the star clusters formed via ‘prompt star formation’ are never distributed around the observed GCs on the $r_h\text{--}M_V$ plane. The half-mass radii of the ‘prompt star formation’ star clusters are higher by an order of magnitude than those of the ‘supersonic infall’ star clusters at any M_V .

In Fig. 11, we compare the mass-to-light ratios M_{dyn}/L_V of the simulated clusters with those of GCs. We define the dynamical mass M_{dyn} by the total mass within the half-mass radius $M_*(r < r_h) + M_{\text{DM}}(r < r_h)$. As shown in Fig. 11, the mass-to-light ratios of the star clusters formed via ‘supersonic infall’ are consistent with those of GCs. On the other hand, the mass-to-light ratios of the star clusters in the ‘prompt star formation’ are typically ~ 10 , which are considerably higher than those of GCs. In other words, the star

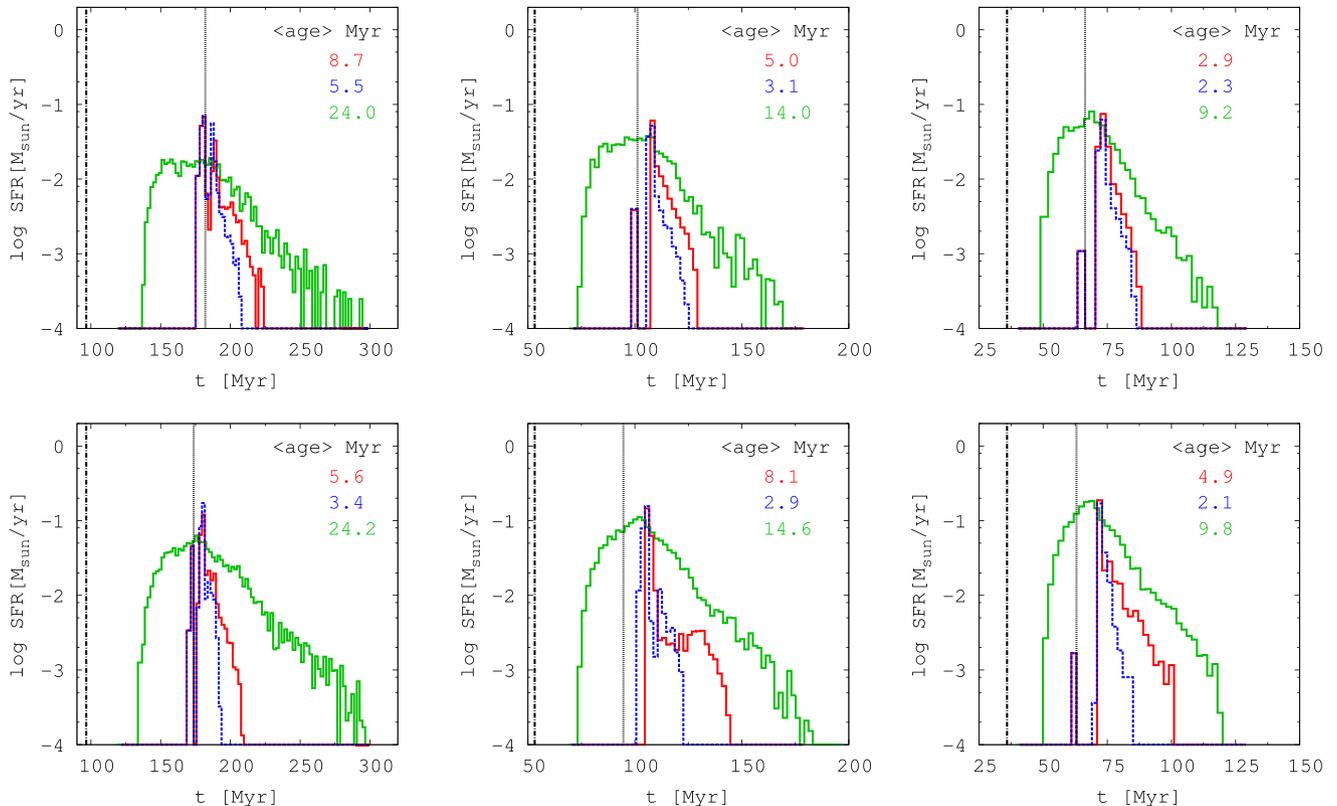


Figure 8. The SFR in units of $M_{\odot} \text{yr}^{-1}$ as a function of time (Myr) for each model presented in Fig. 7. The red solid lines represent the runs of ‘supersonic infall’ under a one-sided UV background, while the blue dashed lines represent those under an isotropic UV background. The green solid lines denote the runs of ‘prompt star formation’. The vertical dotted lines in each panel indicate the epoch of the UV irradiation for the ‘supersonic infall’, while the vertical dot-dashed lines indicate the epoch of the UV irradiation for the ‘prompt star formation’. Also, in each panel, the age dispersions of all stars for each model are inserted.

clusters formed through ‘prompt star formation’ inevitably become DM-dominant systems. They seem to belong to the class of dSphs rather than stellar-dominated systems such as GCs or UCDS.

In Fig. 12, we show the central velocity dispersions σ_0 of the simulated star clusters as a function of M_V and compare them with observations. As seen in Fig. 12, the star clusters in the ‘supersonic infall’ result in higher velocity dispersions than those in the ‘prompt star formation’ at given M_V . As for the ‘prompt star formation’, some clusters show high velocity dispersions of $\sim 10 \text{ km s}^{-1}$, but they are mainly determined by DM potential rather than stars. According to the virial theorem, a velocity dispersion is roughly expressed by using the total mass M and the half-mass radius r_h of a star cluster as

$$\sigma_0 \sim \sqrt{\frac{GM}{r_h}}. \quad (11)$$

If $M \propto r_h^3$ and $L \propto M$ are assumed, equation (11) gives the relation of $\sigma_0 \propto L^{1/3}$. Observed GCs, however, show the relation like $\sigma_0 \propto L^{1/2}$ (Haeghan et al. 2005). These two relations are shown in Fig. 12. The velocity dispersions of the star clusters formed through ‘supersonic infall’ do not satisfy $\sigma_0 \propto L^{1/3}$, but exhibit higher values as those of GCs. However, it is not clear whether the simulated clusters obey the relation of $\sigma \propto L^{1/2}$, since the number of the sample simulated clusters is not enough. The relation of $\sigma_0 \propto L^{1/2}$ is satisfied, only if the size of the system is almost independent of the mass. The half-mass radii of the present cluster samples

slightly depend on the stellar mass in Fig. 10. To argue σ_0 - M_V relation more quantitatively, probably we should consider carefully other processes such as tidal stripping by host galaxies and internal feedback, which are discussed below in Section 5. These additional processes seem to be important to reproduce low-mass GCs as well that are not presented in this work. Although the simulations of such additional effects will be left for the future work, the properties of the simulated star clusters on the diagrams in Figs 10–12 match those shown in 1D simulations by HUK09. We emphasize that the combination of strong UV background radiation and ‘supersonic infall’ provides a potential mechanism for the formation of compact star clusters as observed GCs.

5 DISCUSSION

5.1 Formation sites of globular clusters

As we have seen in the previous sections, strong UV background radiation is one of the essential conditions to produce GC-like compact star clusters. In addition, we can recognize in Figs 10–12 that the time-scale t_{rise} of UV intensity rise is a significant factor for the cluster formation. If $t_{\text{rise}} \lesssim 10 \text{ Myr}$, then the background UV intensity reaches the maximum value before the cloud undergoes the extensive star formation. As a result, the evolution of gas clouds differs little from the case of constant UV background, resulting in the ‘supersonic infall’. On the other hand, if the rise of the

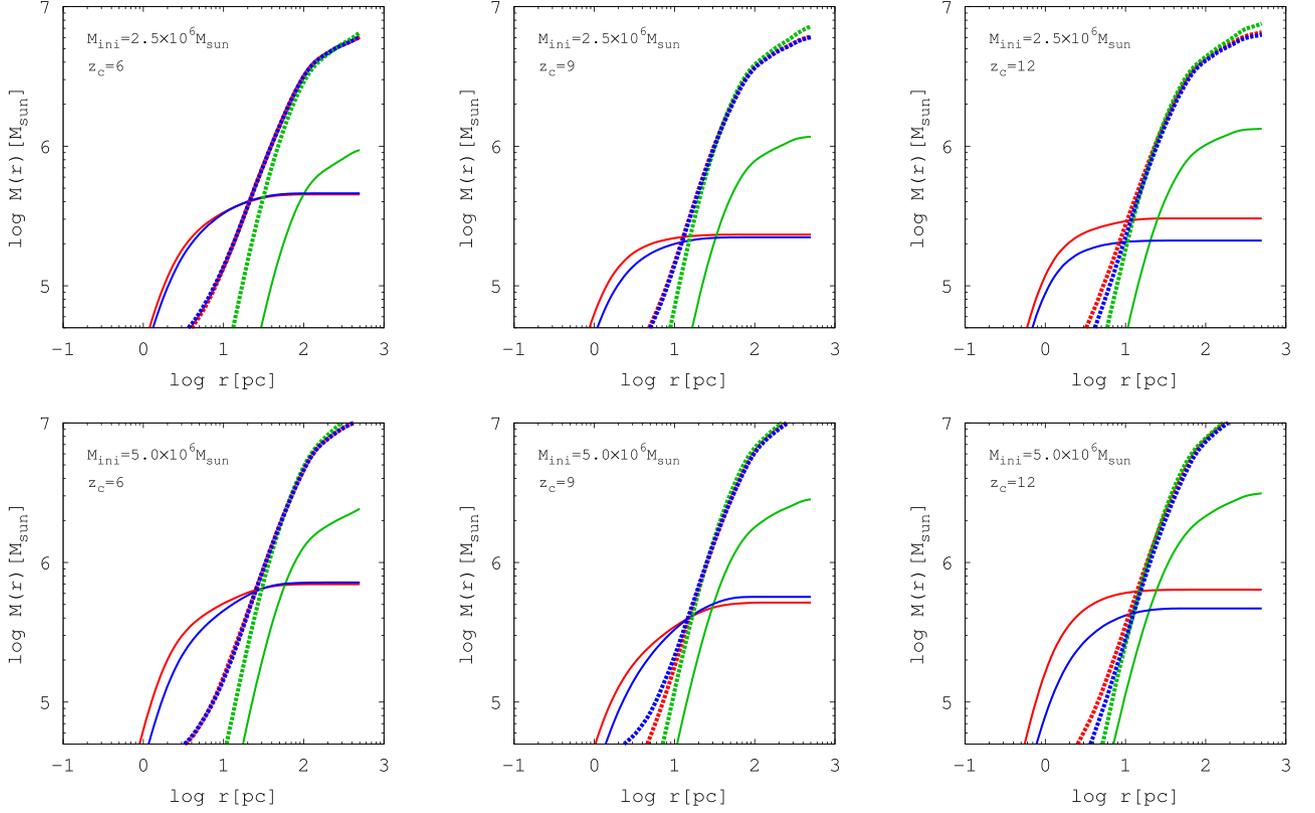


Figure 9. Mass distributions of stellar and DM components as a function of radii for each model presented in Fig. 7. The horizontal axis is the distance r from the stellar density peak in units of pc, while the vertical axis is the cumulative mass contained within r . The solid and dotted lines, respectively, denote the stellar and DM components. The red and blue lines, respectively, correspond to the one-sided and isotropic UV background in the ‘supersonic infall’ model. The green lines denote the ‘prompt star formation’ model.

Table 2. The core radii of simulated star clusters.

z_c	M_{ini} ($10^6 M_{\odot}$)	t_{rise} (yr)	Supersonic/one-sided			Supersonic/isotropic			Prompt star formation		
			b (pc)	M_{core}^a ($10^5 M_{\odot}$)	M_*/M_{ini}^b	b (pc)	M_{core} ($10^5 M_{\odot}$)	M_*/M_{ini}	b (pc)	M_{core} ($10^5 M_{\odot}$)	M_*/M_{ini}
6	2.5	Instant	1.7	0.93	0.18	1.8	0.85	0.18	55.9	2.0	0.40
6	5.0	Instant	1.6	1.5	0.14	2.0	1.3	0.14	46.7	4.8	0.53
9	2.5	Instant	0.94	0.57	0.093	1.0	0.47	0.089	33.7	2.3	0.49
9	5.0	Instant	1.4	0.85	0.10	1.8	0.77	0.11	30.4	5.0	0.60
9	5.0	10^6	1.5	0.85	0.12	–	–	–	–	–	–
9	5.0	10^7	2.4	1.6	0.23	–	–	–	–	–	–
9	5.0	10^8	6.7	16.8	0.42	–	–	–	–	–	–
12	2.5	Instant	0.78	0.83	0.12	0.76	0.60	0.084	22.2	2.5	0.55
12	5.0	Instant	1.0	1.7	0.13	1.2	1.1	0.093	21.0	5.0	0.64
9	1.0	Instant	–	–	–	–	–	–	32.6	0.58	0.32
9	10.0	Instant	2.1	3.2	0.20	–	–	–	25.8	8.6	0.69
12	1.0	Instant	–	–	–	–	–	–	25.0	0.83	0.41
12	10.0	Instant	1.7	4.4	0.30	–	–	–	–	–	–

^aStellar mass within the scale length b in units of $10^5 M_{\odot}$.

^bThe ratio of total stellar mass to the initial gas mass.

background UV is as slow as $t_{\text{rise}} > 10$ Myr, the ‘prompt star formation’ proceeds instead of ‘supersonic infall’, since the self-shielding is effective in an early phase of contraction. Consequently, the results deviate from ‘supersonic infall’, as shown by grey diamonds in Figs 10–12. Therefore, the rise of UV radiation should be faster than the cloud contraction to form GCs. We argue the formation sites of GCs from viewpoints of UV radiation intensity and its variation time-scale.

For the purpose, we first evaluate the photon number flux required. We define F_{ion} as

$$F_{\text{ion}} \equiv \frac{\dot{N}_{\text{ion}}}{\pi r_{\text{UV,in}}^2}, \quad (12)$$

where $r_{\text{UV,in}}$ denotes the radius of a cloud at the irradiation epoch. Although this estimation is higher by a factor of 2–4 than the flux we actually assumed in the simulations, we make an order

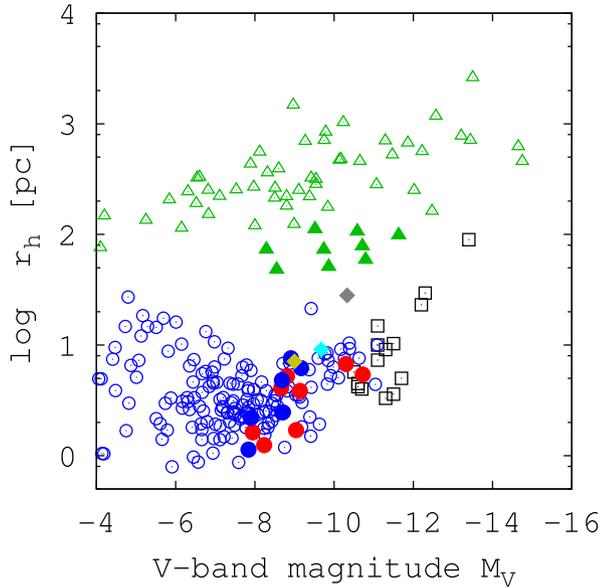


Figure 10. Half-mass radii r_h of star clusters as a function of absolute V-band magnitude M_V . The filled red and blue circles indicate the star clusters formed through ‘supersonic infall’ in the one-sided and isotropic UV background, respectively. The filled diamonds represent the star clusters formed in the time-evolving one-sided UV background, and the colours of yellow, cyan, and grey correspond to the linear rising time of $t_{\text{rise}} = 10, 10,$ and 100 Myr, respectively. The filled green triangles are the star clusters formed via ‘prompt star formation’. The open circles, triangles, and squares denote the observed GCs, dSphs, and UCDs, respectively. The observational data for GCs are taken from the MW GCs catalogue of Harris (1996) and NGC 5218 GCs catalogue of Martini & Ho (2004). Those for dSphs are taken from McConnachie (2012), and for UCDs are taken from Drinkwater et al. (2003) and Mieske et al. (2008). The thick solid line indicates a relationship of $\sigma \propto L^{1/3}$.

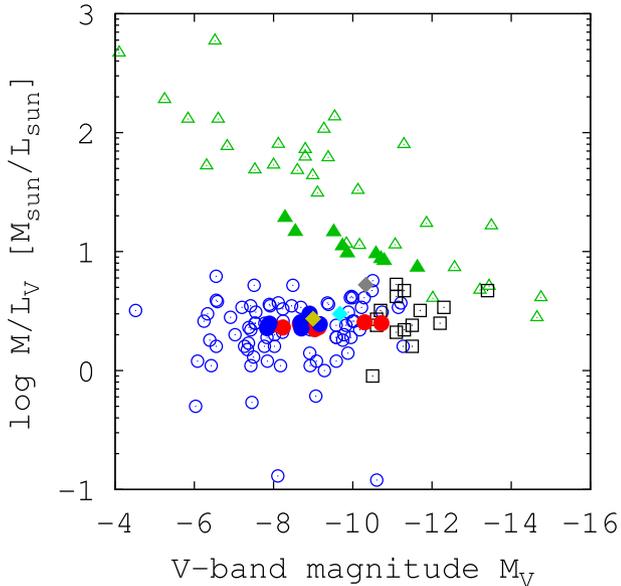


Figure 11. Mass-to-light ratios M/L_V as a function of absolute V-band magnitude M_V . The meanings of the symbols are the same as in Fig. 10. The observational data for GCs are taken from MW GCs, LMC GCs, SMC GCs, Fornax GCs, NGC 5218 GCs, and M31 GCs, compiled by HUK09. The observational data for dSphs are taken from McConnachie (2012). As for UCDs, the data are taken from Drinkwater et al. (2003) and Mieske et al. (2008).

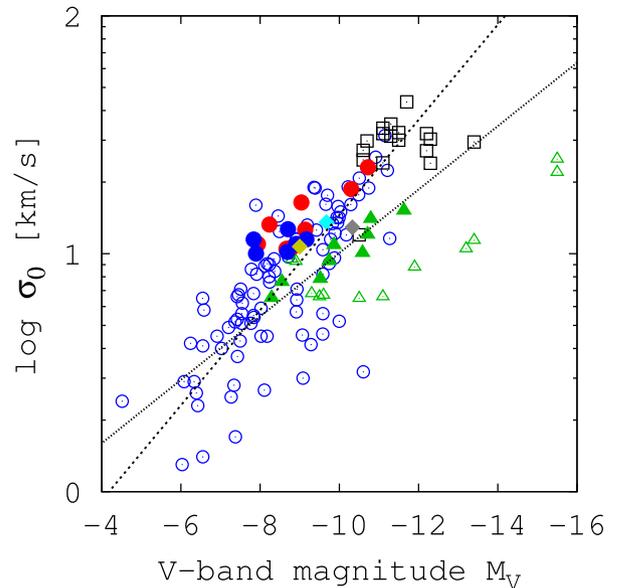


Figure 12. Central velocity dispersions σ_0 as a function of absolute V-band magnitude. The meanings of the symbols are the same as Fig. 10. The observational data for GCs and UCDs are taken from the literatures shown in Fig. 11. The observational data for dSphs are taken from Mateo (1998). The dotted line represents the best-fitting relation of $\sigma \propto L^{1/2}$ for GCs derived by Hasegan et al. (2005). The solid line indicates a relation of $\sigma \propto L^{1/3}$.

Table 3. Ionizing photon flux required for supersonic infall star formation.

z_c	z_{UV}	M_{ini} ($10^6 M_{\odot}$)	F_{ion} (photons $\text{cm}^{-2} \text{s}^{-1}$)
6	6.8	2.5	7.3×10^8
6	6.9	5.0	7.6×10^8
9	10.3	2.5	1.8×10^9
9	10.5	5.0	4.5×10^8
9	10.5	10.0	1.4×10^9
12	13.8	2.5	3.3×10^9
12	14.0	5.0	2.2×10^9
12	14.0	10.0	4.0×10^9

estimation here with this evaluation. We summarize the evaluated fluxes using equation (12) in Table 3. This shows that the required ionizing photon number flux is of the order of $\sim 10^9$ photons $\text{cm}^{-2} \text{s}^{-1}$, which roughly corresponds to $J_{21} \sim 100$ – 1000 , where J_{21} is the mean intensity at the hydrogen Lyman limit frequency in units of 10^{-21} erg $\text{cm}^{-2} \text{s}^{-1} \text{Hz}^{-1} \text{sr}^{-1}$. This value seems to be much higher than J_{21} expected for the global UV background radiation during the epoch of reionization. Thus, we consider the possibilities of local sources.

The first possibility is Population III (Pop III) stars. The Λ CDM cosmology predicts that Pop III stars form in low-mass minihaloes with the masses of $\sim 10^{5-6} M_{\odot}$, which collapse typically at $z \sim 10$ – 30 (e.g. Tegmark et al. 1997; Yoshida et al. 2003). Although the initial mass spectrum of Pop III stars is still controversial, several theoretical studies have shown that Pop III stars are typically massive as $\sim 100 M_{\odot}$ (e.g. Nakamura & Umemura 2001; Hirano et al. 2014, 2015; Susa, Hasegawa & Tominaga 2014). Therefore, strong UV radiation can be expected in the vicinity of a Pop III halo. If we assume a Pop III star with the mass of 100 – $1000 M_{\odot}$ and the ionizing photon emissivity of 10^{50-51}s^{-1} (Schaerer 2002), the

ionizing photon number flux is $\sim 10^{8-9} \text{ cm}^{-2} \text{ s}^{-1}$ at 100 pc, which roughly corresponds to the virial radius of a minihalo. Thus, the ionizing photon number flux to allow the formation of compact star clusters can be easily accomplished if a Pop III star as massive as $>100 M_{\odot}$ forms at ≈ 100 pc from a collapsing cloud. Also, the Kelvin–Helmholtz time-scale of a Pop III star with $\approx 100 M_{\odot}$ is $\sim 10^5$ yr (O’Shea & Norman 2007), and therefore the star reaches the main sequence faster than the cloud contraction. However, the lifetime of a Pop III star is a few 10^6 yr. Thus, the formation of GCs by Pop III radiation is realized only for clouds contracting within 10^6 yr. We note that the ionizing photon number flux possibly changes with time according to the stellar motion, if the Pop III star formation takes place during the hierarchical merging process (e.g. Johnson, Greif & Bromm 2008). The variation time-scale of UV radiation is thought to be roughly the infall time-scale in the GC–host halo, which is ~ 100 Myr. Since this time-scale is longer than the cloud contraction time, the variation of UV radiation due to the virial motion does not affect the cloud evolution.

The second possibility is young star-forming galaxies, e.g. Lyman α emitters (LAEs). Wise & Cen (2009) have numerically simulated the high- z young dwarf galaxies and traced the star formation histories. They have shown that the starburst rises up within a few times 10 Myr and the burst-phase continues for ~ 100 Myr, if the virial masses of the halo are as massive as $10^9 M_{\odot}$. Although the SFR varies with the time-scale of ≤ 10 Myr, the luminosity changes are within a factor of 3. Hence, the time-scale condition for the formation of compact star clusters is likely to be satisfied. Recently, Yajima et al. (2014) have calculated the emissivities of ionizing photons of young star-forming galaxies. According to their result, the ionizing photon number emissivities of the galaxies at $z > 6$ correspond to $\sim 10^{52-53} \text{ s}^{-1}$, which is translated into the ionizing photon number flux of $\sim 10^9 \text{ cm}^{-2} \text{ s}^{-1}$ at 1 kpc from the galactic centre. Thus, if the star-forming regions in LAEs are as compact as ~ 1 kpc, compact star clusters may form in subhaloes of the LAEs.

The third possibility is active galactic nuclei (AGN). Recent studies have pointed out the possibility that high- z quasars and faint AGN bring large contribution to cosmic reionization (Glikman et al. 2011; Giallongo et al. 2015; Madau & Haardt 2015; Yoshiura et al. 2016). Therefore, it is reasonable to consider UV radiation from AGN. As for faint AGN, their typical luminosity is $10^{43} \text{ erg s}^{-1}$ in the range of 2–10 keV (Giallongo et al. 2015). If we assume a simple power law of the spectrum energy distribution as $L_{\nu} \propto \nu^{-1}$, the ionizing photon number emitted by the AGN \dot{N}_{ion} is roughly estimated as $\sim 10^{53} \text{ s}^{-1}$. Thus, even a faint AGN provides the ionizing photon number flux at 1 kpc away as $\gtrsim 10^9 \text{ photons cm}^{-2} \text{ s}^{-1}$. Several authors have argued that the duty cycle of the AGN activity is in the time-scale of 10^8 Myr (e.g. Haehnelt, Natarajan & Rees 1998), which is comparable to the Eddington time-scale. If the mass accretion on to a central black hole is driven by a nuclear starburst, the accretion time-scale can be as short as 10^7 yr (Umemura, Fukue & Mineshige 1997). If this gives the rise time of luminosity, then the situation is favourable for the ‘supersonic infall’. Therefore, we can expect the formation of compact star clusters, if the rise time of the AGN luminosity is shorter than 10 Myr.

5.2 Effect of tidal field

As shown in Section 4.2.2, low-mass ($\lesssim 10^5 M_{\odot}$) GCs are not formed in our simulations. Here, we assess the effect of tidal stripping by host galaxies, which might work so as to reduce the masses of GCs. Assuming a host galaxy as a point mass for simplicity, the

tidal radius r_t of a star cluster orbiting a host galaxy is roughly given by

$$\frac{Gm(r < r_t)}{r_t^2} \sim 2 \frac{GM_{\text{gal}}m(r < r_t)r_t}{r_{\text{gal}}^3}, \quad (13)$$

where $m(r < r_t)$, M_{gal} , and r_{gal} denote the cumulative cluster mass within the tidal radius r_t , the host galaxy mass, and the distance from the galactic centre to the cluster, respectively. Supposing a high- z low-mass galaxy of $M_{\text{gal}} = 10^9 M_{\odot}$ and $r_{\text{gal}} = 0.3\text{--}1$ kpc and using the simulated mass profiles (Fig. 9), the tidal radii are estimated to be a few $\times 10$ pc to ~ 100 pc. This estimation implies that the star-dominant parts of the compact star clusters likely to gradually lose their masses in the tidal fields according as the two-body relaxation proceeds, while the diffuse DM components would be totally stripped away as shown by Saitoh et al. (2006). Furthermore, the variety of the orbits of star clusters possibly leads to the variety of mass-loss rates of the clusters. Hence, it seems important to take the tidal stripping into consideration for more quantitative comparison between simulations and observations.

5.3 Internal feedback processes

Throughout this paper, we have concentrated on the impacts of the external background radiation but neglected internal feedback processes. Actually, stars formed in self-shielding regions are expected to emit UV radiation, which ionizes the self-shielded regions internally. Besides, Type II supernova (SN) explosions pose dynamical impacts on the gas in the star-forming regions. These internal feedbacks may play a significant role to regulate the subsequent star formation (e.g. Kitayama et al. 2004; Kitayama & Yoshida 2005; Hasegawa & Semelin 2013).

Kitayama et al. (2004) have explored the impact of the internal UV radiation feedback by a massive Pop III star in a low-mass halo with $10^6 M_{\odot}$, and found that the feedback reduces the ambient gas density by photoevaporation and suppresses the subsequent star formation. In our simulations, the mass resolution is $\sim 10^3 M_{\odot}$ (Section 3), which correspond to the mass of stars formed simultaneously. Then, the emitted ionizing photon number is evaluated as $\sim 10^{50} \text{ s}^{-1}$ by utilizing STARBURST99 (Leitherer et al. 1999) assuming an instantaneous starburst model for $Z/Z_{\odot} = 0.02$ and the Salpeter initial mass function (IMF). Therefore, the argument by Kitayama et al. (2004) is partially applicable to our simulations, and the subsequent star formation in the gas clouds is expected to be suppressed by the internal UV feedback. However, in the present situation, UV radiation from stars surrounding the cloud centre might positively work to compress the central star-forming region. Since such a complicated behaviour is expected, it is hard to assess how much the internal UV feedback quantitatively affects our results, before the internal UV feedback is actually incorporated. On the other hand, we expect that SN feedbacks are unlikely to affect the formation of compact star clusters, since the star formation is quickly quenched by ~ 5 Myr (see Fig. 8).

6 SUMMARY

In this paper, we have performed three-dimensional radiation hydrodynamic simulations to explore the star cluster formation under UV background radiation. In particular, we have paid attention on three-dimensional effects that were not studied in the previous 1D-RHD calculations by HUK09. We have shown that low-mass clouds with masses of $2.5 \times 10^6\text{--}10^7 M_{\odot}$ can collapse to form stars even under

strong UV background radiation if they are contracting with supersonic velocities. As a result, we have demonstrated that the mechanism proposed by HUK09 does work, even if three-dimensional effects are incorporated.

In the case that UV background radiation is extremely anisotropic, i.e. a cloud is irradiated by UV radiation from one side, shaded neutral regions emerge on the opposite side of the UV source. However, the shaded regions are shoved by surrounding UV heated gas towards the centre of the cloud. Consequently, the gas components are converted to the stellar component at the central compact regions in the cloud (~ 10 pc), regardless of the anisotropy of the background UV radiation. Although the anisotropy of the background radiation slightly affects the star formation histories, the duration of star formation becomes as short as ~ 10 Myr and the stellar age dispersion is less than 10 Myr. Hence, the star clusters formed via ‘supersonic infall’ tend to be of the single stellar population, which is favourable to reproduce the feature of GCs.

We have pursued the stellar dynamics of simulated star clusters, and shown that the star clusters formed via ‘supersonic infall’ become compact, stellar-dominated systems, owing to the compactness of self-shielded regions as well as the strong dissipation of the cloud contraction energy. We have found that the half-mass radius, mass-to-light ratio, and velocity dispersion of simulated star clusters are similar to observed GCs. The results are not affected by the time evolution of the background UV intensity, as long as the rise time of UV intensity is shorter than 10 Myr. We have also confirmed that no GC-like star clusters can form if the ‘prompt star formation’ occurs. In the ‘prompt star formation’, stars begin to form at an earlier phase of the cloud contraction due to the prompt self-shielding and the formation of abundant H_2 molecules around an ionization front. As a consequence of the weak energy dissipation, the star clusters become diffuse, DM-dominated systems, which are clearly distinguished from GCs. Hence, we conclude that the intensity of UV background radiation significantly regulates the properties of the star clusters, and the ‘supersonic infall’ under a strong UV background seems to be a potential scenario for the formation of GCs, as proposed in HUK09.

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