Star Clusters and Galactic Chemodynamics: Implosive Formation of Super Star Clusters

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Abstract: We numerically investigate dynamical and chemical properties of star clusters (open and globular clusters, and 'super star clusters', SSC) formed in interacting/merging galaxies. The investigation is two-fold: (a) large-scale (100 pc–100 kpc) SPH simulations on density and temperature evolution of gas in interacting/merging galaxies and (b) small-scale simulations on the effects of the high gas pressure of the ISM on the evolution of molecular clouds. We find that the pressure of ISM in merging galaxies can become higher than the internal pressure of GMCs ($\sim 10^5 k_B$ K cm^{-3}), in particular, in the tidal tails or the central regions of mergers. We also find that GMCs can collapse to form SSCs within an order of 10^7 yr due to the strong compression by the high-pressure ISM in mergers.

Keyword: Galaxy: kinematics and dynamics

1 Introduction

Star clusters (hereafter SC) such as open, globular, and super-star clusters are observed to be relatively 'minor' components (in mass) in luminous galaxies (e.g. the mass ratio of the Galactic GCs to the Galactic luminous disk mass is an order of 0.1%). Therefore, it is generally considered that dynamical evolution of star clusters (e.g. merging or tidal destruction of star clusters) does not influence significantly the evolution of luminous galaxies. However, recent numerical simulations on dynamical evolution of SCs have strongly suggested that this SC dynamic is very important for the formation of galactic nuclei in dwarf irregular or elliptical galaxies and that in ultra-compact dwarf galaxies (Drinkwater et al. 2003) because (a) the time scale of dynamical friction of SCs is relatively short ($\sim 10^9$ yr) and (b) the cross-section of SC merging is also large owing to the larger S_N value (specific frequency of globular clusters) of dwarf galaxies (Bekki et al. 2003). Furthermore, recent HST observations have revealed a significant number of young super star clusters (hereafter SSC) in dwarf irregular galaxies and suggested that physical properties of these SSCs can be correlated with those of their host galaxies (e.g. Billett et al. 2002). These recent numerical and observational results lead the author to investigate (a) how SSCs can be formed in galaxies, (b) how these SSCs dynamically evolve, and (c) whether or not there can be strong physical relationship between structural and chemical properties of SSCs and those of their host galaxies. In this paper, we discuss these problems based on numerical simulations of SSC formation in galaxies. We focus here on SSC formation in major mergers, because recent HST observations discovered many SSCs in interacting/merging galaxies (e.g. Whitmore et al. 1993).

2 A New Two-Fold Numerical Model

Since it is very hard to resolve SSC formation sites (an order of the scale of 1–10 pc) and investigate the formation processes in detail in large-scale (10–100 kpc) galaxy simulations, we adopt the following novel two-fold method for the numerical investigation of SSC formation. Firstly, we investigate time evolution of pressure, temperature, and density of warm interstellar medium (ISM) with the initial temperature of $\sim 10^4$ K and the density of 1 atom cm^{-3}, based on galaxy-scale (larger-scale) SPH simulations of galaxy mergers with total particle number N of $\sim 10^5$. Secondly, we investigate dynamical evolution and star formation histories of GMCs embedded in hot (warm), high-pressure ISM, based on GMC-scale (<100 pc) SPH simulations ($N \sim 4 \times 10^4$). The primary focus here is to investigate how the high-pressure ISM (expected for galaxy mergers) trigger collapse of GMCs and consequently form SSCs within the GMCs. In the second simulations, the data of the ISM surrounding GMCs come from the first simulations: The present simulations are fully self-consistent in the sense that the evolution of GMC under high-pressure ISM is investigated based on physical properties of ISM derived by the large-scale galaxy simulations.

Although the present model can mimic (or corresponds to) the simulations with $N \sim 10^9$, it has both advantages and disadvantages. Firstly, this present study first addresses the GMC evolution under extraordinary physical conditions of surrounding ISM (i.e. very high-pressure of ISM), which previous studies on star cluster formation have not yet investigated (e.g. Bate 1998; Klessen 2001). Secondly, the star formation method adopted here (Jeans instability criteria) is somehow oversimplified so that the total number of stars within a cluster for a given time

scale can be over or underestimated. Thirdly, the external pressure that triggers collapse of ISM is fixed at a certain value during a simulation ($\sim 10^7$ yr). This assumption of constantly high pressure is only reasonable in the central region of a major merger, and could not be reasonable in the tidal tail. Lastly, chemical evolution of gas is only included in the large-scale galaxy simulations (not in the small-scale GMC ones).

2.1 Galaxy Scale

Our numerical methods for modelling chemodynamical evolution of galaxy mergers have already been described by Bekki & Couch (2001) and the details of the adopted TREESPH are given by Bekki (1995, 1997). We accordingly give only a brief review of them here. We construct models of galaxy mergers between gas-rich disks by using the Fall–Efstathiou (1980) model. The total mass and the size of a progenitor exponential disk are M_d and R_d, respectively. From now on, all the masses and lengths are measured in units of M_d and R_d, respectively, unless otherwise specified. Velocity and time are measured in units of $v = (GM_d/R_d)^{1/2}$ and $t_{dyn} = (R_d^3/GM_d)^{1/2}$, respectively, where G is the gravitational constant and assumed to be 1.0 in the present study. If we adopt $M_d = 6.0 \times 10^{10} \, M_\odot$ and $R_d = 17.5$ kpc as fiducial values, then $v = 1.21 \times 10^2$ km s^{-1} and $t_{dyn} = 1.41 \times 10^8$ yr, respectively. The dark-to-disk halo mass ratio and the star-to-gas mass ratio are set equal to 4.0 and 9.0, respectively. Bulge component is not included in the present study. An isothermal equation of state is used for the gas with a temperature of 7.3×10^3 K (corresponding to a sound speed of 10 km s^{-1}). We present the results mostly for merger models with nearly prograde–prograde orbital configurations, parabolic encounters, and a pericentric distance of $0.5R_d$. Numerical results do not depend on the adopted parameters of optimal number of SPH neighborhood particles and the details of the viscosity.

2.2 GMC Scale

We numerically investigate the hydrodynamical effects of high-pressure ISM on a self-gravitating molecular gas cloud in major mergers. The cloud is represented by 20 000 SPH particles and the initial cloud mass (M_{cl}) and size (r_{cl}) are set to be $10^6 \, M_\odot$ and 97 pc, respectively, which are consistent with the mass–size relation observed by Larson (1981). The cloud is assumed to have an isothermal radial density profile with $\rho(r) \propto 1/(r+a)^2$, where a is the core radius of the cloud and set to be $0.2r_{cl}$. An isothermal equation of state for the gas with a sound speed of c_s (set to be 4 km s^{-1}, consistent with the prediction from the virial theorem) is used for models with $M_{cl} = 10^6 \, M_\odot$. Each SPH particle is also subject to the hydrodynamical force of the ISM whose strength depends on the parameters of the ISM (and thus depends on the results of the large-scale galaxy simulations). The ISM is represented by $\sim 20\,000$ SPH particles and an isothermal equation of state with pressure p (or sound velocity of c_h), and density ρ. The ISM particles are uniformly
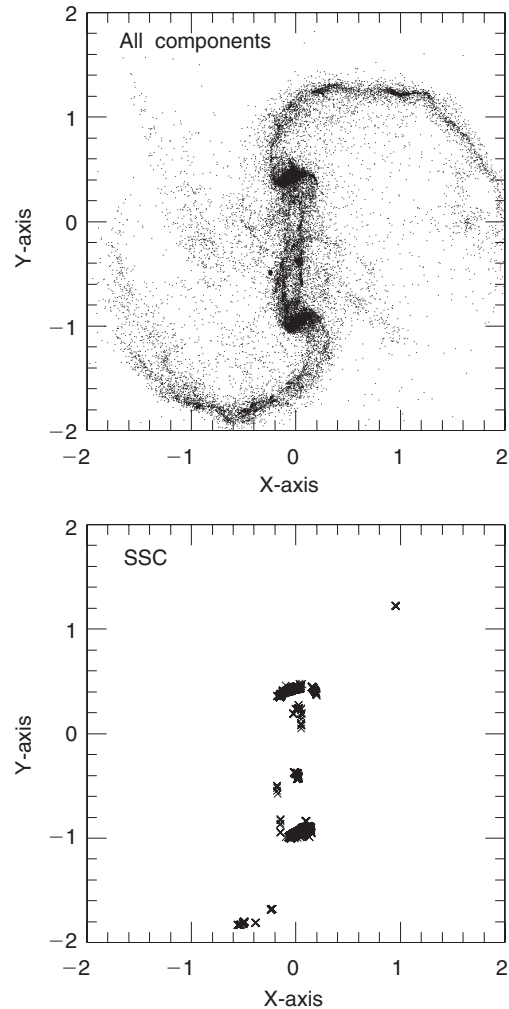

Figure 1 Mass distribution projected onto the x–y plane in the merger model at $T = 0.28$ Gyr for all components (upper) and for formation sites (gas or gas forming SSCs) of SSCs with $P > 10^5 k_B$ (lower). In total, 2667 SSC formation sites with $P > 10^5 k_B$ have been identified prior to this starburst epoch. The scale is given in our units (17.5 kpc), and each of the frames measures 70 kpc on a side.

distributed within a box with size of $6R_{cl}$. A gas particle in a cloud is converted into a collisionless stellar particle if (a) the local dynamical time scale [corresponding to $(4\pi G\rho_i)^{-0.5}$, where G and ρ_i are the gravitational constant and the density of the gas particle, respectively] is shorter than the sound crossing time (corresponding to h_i/c_s, where h_i is the smoothing length of the gas), and (b) the gaseous flow is converging. This method thus mimics star formation due to Jeans instability in gas clouds. In the model without ISM effects, star formation does not occur at all in this star formation method. We mainly show the result of the 'fiducial model' with $\rho = 1$ atom cm^{-3} and $P = 10^5 k_B$ K cm^{-3}, because this model shows the typical behaviour of ISM-induced star formation in a gas cloud.

3 Result I. SSC Formation Sites

Figure 1 clearly demonstrates how the gaseous pressure of the interstellar medium becomes dramatically higher
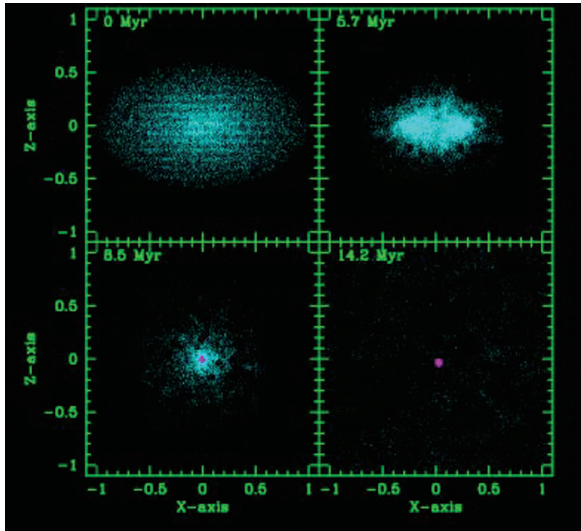
Figure 2 Time evolution of a GMC embedded by high-pressure ISM for gaseous components (cyan) and for new stars formed from the gas (magenta). One frame measures 200 pc on a side. Note that a very compact SSC is formed owing to strong external compression of the GMC by the hot, high-pressure ISM.

Figure 3 Time evolution of star formation rate of the model in Figure 2. Note that the time scale of starburst is less than a few Myr, which is shorter than the lifetime of very massive stars. This implies that supernovae feedback effects are less likely to influence SSC formation.

Figure 4 Final projected surface density distribution of a SSC developed in the model in Figure 2 (in our units). Since the system has not yet relaxed dynamically just after the formation of the SSC, the density profile shows a constant density core.

$(10^4$–$10^5 k_B)$ in some regions of the major merger model at $T = 0.28$ Gyr (starburst phase with the star formation rate of $\sim 75\,M_\odot\,yr^{-1}$) in comparison with the initial disks. Furthermore, gaseous pressure for some fraction of the gas particles (in particular, in the central regions) exceeds the threshold value of $2.0 \times 10^5 k_B$ for globular cluster (SSC) formation (e.g. Jog & Solomon 1992; Harris & Pudritz 1994; Elmegreen & Efremov 1997), essentially because rapid transfer of gas to the central region of the merger and efficient gaseous shock dissipation increase the gaseous density and pressure greatly. These results clearly explain the reason why SSCs can be formed in starbursting galaxies and imply that the formation efficiency of SSCs are much higher in merging galaxies with massive starbursts than in 'normal' disk galaxies. Figure 1 also shows that SSCs are formed not only in the central region, where gas fuelling is more efficient, but also in the outer tidal tails and 'bridges' among the two cores, where the tidal force of the merger forms thin and high-density gaseous layers owing to gaseous shock dissipation. (More details are given in Bekki & Couch 2001.)

4 Result II. Implosive SSC Formation

Figures 2 and 3 describe how a burst of star formation within a gas cloud can be triggered by the external gas pressure of the ISM in the fiducial model. In this model with moderately strong ISM pressure, the high pressure of the ISM can continue to strongly compress the cloud without losing a significant amount of gas from the cloud. As the strong compression proceeds, the internal density and pressure of the cloud can rise significantly. However, the self-gravitational force of the cloud also becomes stronger because the cloud becomes progressively more compact during the ISM's compression. Therefore, the internal
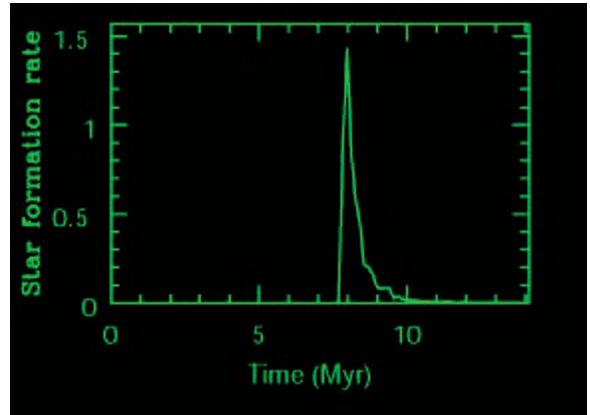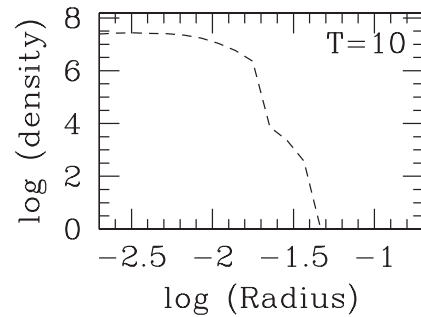
gaseous pressure of the cloud alone becomes unable to support itself against the combined effect of the external pressure from the ISM and the stronger self-gravitational force. As a result of this, the cloud's collapse, initially induced by the high external pressure from the ISM, can continue in a runaway manner.

Due to the rapid, dissipative collapse, the gaseous density of the cloud dramatically rises and consequently star formation begins in the central regions of the cloud. The star formation rate increase significantly to $1.5\,M_\odot\,yr^{-1}$ (8 Myr after the start of the cloud's collapse). About 80% of the gas is converted into stars within 14 Myr to form a stellar system. Because of the 'implosive' formation of stars from strongly compressed gas, the developed stellar system is strongly self-gravitating and compact. This result implies that high external pressure from the ISM is likely to trigger the formation of bound, compact star clusters rather than unbound, diffuse field stars. The final mass distribution of this model is similar to the King profile (with the normalised central potential of 3), but too compact (with the effective radius of ~ 2 pc) to be consistent with the observed effective radius of typical globular clusters (see Figure 4).

5 Conclusions

We first demonstrated that SSCs can be formed from GMCs 'in an implosive manner' for major mergers: Strong external pressure of ISM in mergers can trigger the collapse of GMCs and consequently cause the rapid star formation within the GMCs. The star formation efficiency in the GMCs under strong external pressure is as high as 60–80% (in total cloud mass) so that the developed SSCs can be considered to be bound star clusters (e.g. Hills 1980). The present study suggests that unbound star clusters that are doomed to be destroyed by some external processes (e.g. galactic tidal field and interaction with GMC) can be formed from GMCs embedded by low (normal) pressure ISM whereas SSCs can be formed from GMCs embedded by very high-pressure ISM. The stars initially within unbound star clusters could soon be identified as 'field stars' after the destruction of the clusters. The time scale of SSC formation is very short (a few 10^6 yr, which is shorter than the lifetime of very massive stars, which are responsible for the type II supernovae) so that the energy feedback from supernovae can be much less likely to influence the SSC formation. Although the 'implosive formation scenario' described here can provide a clue to the origin of GCs in general, we have not yet reproduced the observed Fundamental Plane of GCs (in M31 and the Galaxy) and mass–size relation of GCs. Therefore, our future studies will check whether the implosive scenario can explain self-consistently the observed scaling relations of GCs and chemical properties of GCs.

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