Formation of star clusters in the LMC and SMC. I. Preliminary results on cluster formation from colliding gas clouds

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ABSTRACT

We demonstrate that single and binary star clusters can be formed during cloud-cloud collisions triggered by the tidal interaction between the Large and Small Magellanic clouds. We run two different sets of self-consistent numerical simulations which show that compact, bound star clusters can be formed within the centers of two colliding clouds due to strong gaseous shocks, compression, and dissipation, providing the clouds have moderately large relative velocities ($10 - 60 \text{ km s}^{-1}$). The impact parameter determines whether the two colliding clouds become a single or a binary cluster. The star formation efficiency in the colliding clouds is dependent upon the initial ratio of the relative velocity of the clouds to the sound speed of the gas. Based on these results, we discuss the observed larger fraction of binary clusters, and star clusters with high ellipticity, in the Magellanic clouds.

Subject headings: galaxies: interaction — galaxies: star clusters — Magellanic Clouds

1. Introduction

It well established that several physical properties of the globular clusters and populous young blue clusters in the Large Magellanic Cloud (LMC) are differ markedly from those
of clusters in the Galaxy (e.g., van den Bergh 2000a). These properties include the more flattened shapes of the LMC clusters (e.g., Geisler & Hodge 1980; van den Bergh & Morbey 1984), the disky distribution of its globular cluster system (e.g., Schommer et al. 1992), a larger fraction of apparently binary clusters or physical cluster pairs in the LMC (Bhatia & Hatzidimitriou 1988; Bhatia et al. 1991; Dieball & Grebel 1998), a possible “age/metallicity gap” (e.g., Da Costa 1991; Olszewski et al. 1991; Geisler et al. 1997; Sarajedini 1998; Rich et al. 2001), larger sizes at a given galactocentric distance (van den Bergh 2000b), and the presence of a significant number of massive young to intermediate age clusters in the LMC (e.g., van den Bergh 1981, 2000a).

The higher fraction of binary clusters in the LMC, in particular, has attracted much attention from theoretical and numerical works. Fujimoto & Kumai (1997) proposed that oblique cloud-cloud collisions in an interaction between the LMC and the Small Magellanic Cloud (hereafter, SMC) can result in the formation of binary star clusters revolving around each other. Leon et al. (1999) proposed a different scenario in which the tidal capture of clusters in a group (where tidal encounters are expected to be more common) could be associated with the formation of the LMC binary clusters. de Oliveira et al. (2000) suggested that merging of binary clusters can be responsible for the observed flattened shapes of LMC clusters.

Kumai et al. (1993) and Fujimoto & Kumai (1997) pointed out that if interstellar gas clouds are in large-scale disorganized motions with velocities of more than $50 - 100$ km s$^{-1}$ in the interacting LMC/SMC system, then they may collide with one another to form compact star clusters due to strong shock compression. This idea is supported by the coincidence between the observationally inferred two “burst” epochs ($\sim 100$ Myr and $1 - 2$ Gyr ago of cluster formation after the initial LMC collapse phase) (e.g., Girardi et al. 1995) and the theoretically predicted epochs of closest encounter between the LMC and the SMC (Murai & Fujimoto 1980; Gardiner et al. 1994; Gardiner & Noguchi 1996). However, due to the lack of extensive numerical studies of this scenario, these authors did not address (1) whether the high-speed, oblique cloud-cloud collisions, which are central to the scenario of Kumai et al. (1993), are present in the LMC/SMC interaction and (2) how star formation efficiency may increase in the colliding clouds such that compact and bound star clusters rather than unbound field stars will be formed.

In this paper, by using numerical simulations, we demonstrate that the star formation efficiency of colliding gas clouds in interacting galaxies can significantly increase, resulting in the formation of compact stellar systems. This numerical investigation is two-fold: We first derive the most probable impact parameter and the relative velocity of two colliding clouds in a large-scale dynamical simulation of the interacting LMC/SMC. We then investigate
the hydrodynamical evolution and star formation processes of colliding clouds, based on
the most probable parameter values for cloud-cloud collision derived in our first set of
simulations. Here we describe the formation of star clusters in colliding clouds in a general
way, rather than attempt to explain precisely the observed physical properties of star
clusters for the LMC/SMC system in a self-consistent manner. Since this paper is the first
step toward the better understanding of star cluster formation in the LMC-SMC system,
the numerical models are somewhat idealized and lack realism in some areas. In future
papers, we will describe the formation processes, structure and kinematics, and chemical
properties of star clusters formed from cloud-cloud collisions, using a more sophisticated
simulation. The origin of disky distribution of LMC old star clusters will be also discussed
in our future papers in terms of recent cosmological simulations of globular clusters (e.g.,
Kravtsov & Gnedin 2003).

2. Models

We first describe the disk galaxy models in which the dynamical evolution of gas clouds
in interacting LMC/SMC is investigated. We then describe the hydrodynamical models for
the evolution of colliding gas clouds with star formation in the LMC/SMC system.

2.1. Tidal interaction in the LMC/SMC system

We model LMC and SMC as bulge-less, gas-rich disks with an initial gas mass fraction
of 0.1. They Magellanic Clouds are modeled in a fully self-consistent way by using the
Fall-Efstathiou (1980) model, with the exponential density profile for the disks and halo
dark matter-to-disk mass fraction equal to 4. The total galactic mass and the disk size for
the LMC (SMC) are assumed to be \(2.0 \times 10^{10} \, M_\odot\) (\(2.0 \times 10^9 \, M_\odot\)) and 7.5 kpc (2.4 kpc),
respectively. In order to investigate the nature of cloud-cloud collisions in the interacting
LMC/SMC, we adopt the “sticky particle method” (e.g., Hausman & Roberts 1984) in
which the interstellar medium is described as an ensemble of discrete gas clouds. The size
\((r_{cl})\) of an individual cloud with a given mass \((M_{cl})\) is chosen such that the cloud satisfies
the observed mass-size relation of gas clouds (Larson 1981). All calculations related to
self-gravitating gas clouds and stellar components were carried out on GRAPE systems
(Sugimoto et al. 1990) and total particle number in each simulation is 20000 for dark
matter and 22000 for disk components.

We focus on the past 1 Gyr evolution of the LMC/SMC (in particular, at the latest
SMC’s pericenter passage), during which time populous young star clusters are known to have formed (e.g., van den Bergh 2000a). Since the tidal effect on the LMC/SMC system due to the Galaxy is small compared to that from the interaction between the Magellanic Clouds themselves at SMC’s pericenter passage (Gardiner & Noguchi 1996), we do not explicitly include the gravitational effect of the Galactic dark matter halo. Guided by the earlier numerical results of tidal interaction between the Galaxy, the LMC, and the SMC (Gardiner et al. 1994; Gardiner & Noguchi 1996), we choose a plausible set of orbital parameters for the LMC/SMC. The apocenter radius of the interaction (for the last 1 Gyr) is set to be 30 kpc. The pericenter of the orbit (represented by $R_p$), inclination of the LMC’s disk with respect to the orbital plane ($\theta_{\text{LMC}}$), and that of SMC ($\theta_{\text{SMC}}$) are assumed to be free parameters. Although we investigated a number of models with different parameter values, we present the results of the model with $R_p = 3.75$ kpc, $\theta_{\text{LMC}} = -15^\circ$, and $\theta_{\text{SMC}} = 45^\circ$. We choose this set of parameters since they exhibit behavior characteristic of cloud-cloud collisions (e.g., distribution of relative velocity of clouds) in the present study.

The most important parameter of this model, involving interacting galaxies with a mass ratio of 0.1, is the pericenter of the SMC. If the pericenter distance is large (e.g. 15 kpc, which is twice the LMC’s disk size), the frequency of cloud-cloud collisions is not enhanced significantly in the simulation, and the star formation rate is not significantly increased in the simulated LMC disk. Accordingly, the parameter of the pericenter should be carefully chosen. We base the parameter values of the LMC/SMC orbital properties on the early numerical simulations by Gardiner & Noguchi (1996), which are not only consistent with the observed location and radial velocity of the LMC/SMC system but also successful in reproducing the observed physical properties of the Magellanic stream. The orbital parameters in the present study (and thus in Gardiner & Noguchi 1996) are broadly consistent with HIPPARCOS data by Kroupa & Bastian (1997), as shown by Yoshizawa & Noguchi 2003. Therefore, the adopted parameter values can be regarded as reasonable, though the exact orbital properties of the LMC/SMC system have not been observationally determined (thus the orbital parameters should be still free parameters).

It is possible that introducing a mass spectrum on clouds instead of a single mass for all clouds affects the results shown in this paper. The total number of cloud-cloud collisions ($N_{\text{cl}}$) between the clouds with masses of $M_{\text{cl}}$ during the time interval $dt$ can be written as $N_{\text{cl}} = \pi \times dt \times r_{\text{cl}}^2 \times V_{\text{cl}} \times \Phi_{\text{cl}}$, where $r_{\text{cl}}$, $V_{\text{cl}}$, and $\Phi_{\text{cl}}$ are the cloud radius, typical cloud velocity, and number density of gas clouds. By assuming that the number density for a given volume is proportional to the cloud number function observed in the Galaxy (e.g., Harris & Pudritz 1994) and adopting the Larson’s mass-size relation (1981), we can derive the $M_{\text{cl}}$ dependence of $N_{\text{cl}}$. Since $V_{\text{cl}}$ is highly likely to be independent on $M_{\text{cl}}$, the observed relations $\Phi_{\text{cl}} \sim M_{\text{cl}}^{-1.63}$ and $M_{\text{cl}} \sim r_{\text{cl}}^{-2}$ imply that $N_{\text{cl}} \sim M_{\text{cl}}^{-0.63}$. This derived relation
suggests that (1) cloud-cloud collision rates are larger for the clouds with smaller masses and (2) larger clouds can more frequently collide with smaller clouds. Therefore a spectrum of cloud masses is expected to lead to a larger number of low mass clusters.

2.2. Star formation in colliding gas clouds

Next we investigate the hydrodynamical evolution of two colliding clouds by using a TREESPH code with star formation (Bekki 1997). The initial cloud mass ($M_{\text{cl}}$) and size ($r_{\text{cl}}$) are set to be $10^6 M_\odot$ and 97 pc, respectively, which are consistent with the observed mass-size relation by Larson (1981), and therefore with the large-scale simulations described in §2. A gas 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 $0.2 r_{\text{cl}}$. An isothermal equation of state with a sound speed of $c_s$ is used for the gas, and $c_s$ is set to 4 km s$^{-1}$ for models with $M_{\text{cl}} = 10^6 M_\odot$. We choose this value of $c_s$ guided by the virial theorem and Larson’s mass-size relation. A gas particle in a given cloud is converted into a collisionless stellar particle if two conditions are met: First, the local dynamical time scale (corresponding to $(4\pi G \rho_i)^{-0.5}$, where $G$ and $\rho_i$ are the gravitational constant and the density of the gas particle, respectively) must be shorter than the sound crossing time (corresponding to $h_i/c_s$, where $h_i$ is the smoothing length of the gas) Secondly, the gas flow is converging. This method therefore mimics star formation due to the Jeans instability in gas clouds.

The initial orbital plane of the two colliding clouds with relative velocities of $V_r$ and impact parameter of $b$ is set to be the $x$-$y$ plane. The position and the velocity of each cloud is represented by $\vec{x}_i$ and $\vec{v}_i$ ($i = 1, 2$), respectively. We generally only show our “standard model” in which $\vec{x}_1 = (-1.5 r_{\text{cl}}, -0.5 b, 0) = -\vec{x}_2$, $\vec{v}_1 = (0.5 V_r, 0, 0) = -\vec{v}_2$, $V_r = 20$ km s$^{-1}$ (or $V_r/c_s = 5$), and $b = 0.5 r_{\text{cl}}$ (48.5 pc), since this model describes the typical behavior of star cluster formation in colliding clouds in our simulations. Using the most probable values of $V_r$ and $b$ derived from our large-scale simulations, we investigate the parameter dependencies of formation processes of star clusters on $V_r$ and $b$ for $0 \leq V_r \leq 67$ km s$^{-1}$ and $0 \leq b/2 r_{\text{cl}} \leq 1$. 20000 SPH particles are used in a simulation.

Because our adopted total particle number is limited, the resolution of the simulation is at most $10^2 M_\odot$ in mass and $\sim 1$ pc in scale for the models with $M_{\text{cl}} = 10^6 M_\odot$. Therefore, a stellar particle converted from a gas particle does not represent directly an individual star with a mass and size the same as that observed. Most of the stars in our simulations are formed in the very center of a gas cloud, where the Jeans mass of the gas is of order $10^2 - 10^3 M_\odot$ due to the lower temperature and the higher gas density. Therefore, the
stellar particles in our simulations can be regarded as small “sub-clusters” of stars with the mass of $10^2 - 10^3 \, M_\odot$. Our future higher-resolution simulations with the total (gaseous) particle number of more than $10^6$ will enable us to address not only the physical properties of the sub-clusters, but also the formation of a single cluster from the merging between these sub-clusters.

We choose an initial gas temperature (sound speed for isothermal gas) guided by the virial theorem for a gas cloud with a given mass and size. In other words, the value of $c_s$ is chosen such that an isolated gas cloud (not merging with another cloud) is unable to collapse spontaneously. Accordingly, the isolated gas model cannot form stars in its central regions, and the fragmentation of such gas clouds does not occur. This ensures that if star formation occurs in colliding clouds, it is purely a result of the hydrodynamical evolution of gas driven by cloud-cloud collisions in our numerical study. Thus, the adopted assumption of isothermal equation of state and a higher initial gas temperature (corresponding to the virial temperature of the gas) can help us to better interpret the derived results of our numerical simulations. However, the reader should note that this prescription is not as physically realistic as including heating and cooling sources in the gas.

3. Results

3.1. The probability of high-speed, oblique cloud-cloud collisions

Figure 1 shows how the frequency of cloud-cloud collisions can be enhanced and, which type of cloud-cloud collisions most frequently occur, during the LMC/SMC interaction. As the SMC passes by the pericenter of the orbit at $T = 0.61 \, \text{Gyr}$ (where $T$ represents the time that has elapsed since the two disks begin to interact), the strong tidal force induces non-axisymmetric structures (i.e., bars and spiral arms) in the disks of both the LMC and SMC. The large-scale tidal force randomizes the motion of the clouds during the interaction, and consequently the cloud-cloud collision rate is increased by a factor of $> 4$ after the pericenter passage. The cloud-cloud collisions with $V_c \simeq 25 - 40 \, \text{km s}^{-1}$ are the most common during the interaction (e.g., $T = 0.92 \, \text{Gyr}$), and we estimate the mean $V_c$ to be $60 \, \text{km s}^{-1}$. The impact parameter represented by $b$ (Binney & Tremaine 1987) for cloud-cloud collisions can be widely distributed during the tidal interaction, although collisions with larger values ($b/2r_{cl} > 0.5$) represent $\sim 2/3$ of the total. These results demonstrate that high-speed ($V_c > 50 \, \text{km s}^{-1}$), oblique collisions between two similar clouds are likely in the LMC/SMC interaction, thus confirming the earlier suggestions by Fujimoto & Kumai (1998).
However, it should be stressed here that colliding gas clouds with relative velocities of more than $50 - 100$ km s$^{-1}$ are not particularly common amongst colliding gas clouds in our simulation. Therefore, the proposed large-scale motions with velocity of more than $50 - 100$ km s$^{-1}$ (Kumai et al. 1993; Fujimoto & Kumai 1997) are less likely in interacting LMC/SMC. The reason for the lower velocities here ($V_r$ of $\simeq 25 - 40$ km s$^{-1}$, rather than $50 - 100$ km s$^{-1}$) is that the LMC’s cloud system is not strongly disturbed by the SMC tidal field due to the small mass ratio of the SMC to the LMC ($\sim 0.1$). Our numerical results shown in Figure 1 suggest that if star clusters are formed from cloud-cloud collisions in interacting LMC/SMC, then the clusters formed from clouds with relative velocities of more than $50 - 100$ km s$^{-1}$ constitute only a minor population amongst the ensemble of young clusters in the LMC/SMC systems. The pros and cons of the original collisional formation model of star clusters in the LMC/SMC system (Kumai et al. 1993) are discussed in detail later.

3.2. The formation of star clusters in colliding gas clouds

Figures 2 and 3 illustrate how star clusters are formed in two colliding clouds in our standard model. Strong gas compression and dissipation during the collision leads to an elongated slab-like structure formed at around $T = 17.1$ Myr, where $T$ represents the time elapsed since the two clouds began to collide. As the dissipative merging proceeds, the density of gas becomes very high in the shocked regions which are originally the central regions of the two clouds ($T = 22.8$ Myr). Two compact clusters are formed in these high-density gas regions and begin to orbit each other ($T = 22.8$ Myr). This result implies that the orbital angular momentum of the two gas clouds is efficiently converted into that of the binary star clusters during the dissipative cloud-cloud collision. The star formation is akin to an instantaneous “starburst” with a maximum star formation rate of $0.095 \ M_\odot$ yr$^{-1}$, and 40% of the gas is converted into stars within 10 Myr.

A stellar particle is assumed to be formed from each gas cloud which is considered to be collapsing due to gravitational instability (i.e., Jeans instability in the present study). The Jeans mass ($M_J$) of gas in the central regions of colliding clouds is estimated to be $\sim 10^3 \ M_\odot$, and, as such, each stellar particle can be regarded as representing a small “sub-cluster”. Since all of these sub-clusters are formed in the very center of each colliding cloud, the single massive cluster formed in each colliding cloud may be thought of as consisting of numerous small sub-clusters in the early stages of massive cluster formation. Unfortunately, because of the limited resolution of the present simulation, we cannot investigate the subsequent dynamical evolution of these sub-clusters. However, we may reasonably assume that these
numerous sub-clusters will finally merge with one another and consequently erase all of
the substructures inside the cluster. In fact, we do not observe any new stellar particles
escaping from the parent clouds because they are initially in the deepest potential well (i.e.,
the center of the clouds). Thus a single star cluster with a very smooth and homogeneous
mass distribution would finally form.

The identification of such substructure in our simulations is interesting when one
considers recent evidence for the presence subclustering in young cluster environments.
Testi et al. (2000) identified three spatially and kinematically distinct subclusters within
Serpens, a nearby (∼300 pc) cloud comprising of 500-1500 M☉ molecular gas and 40–80M☉
young stellar objects (Giovannetti et al. 1998). Our simulations support the idea that the
characteristic Jeans scale in cloud-cloud collisions gives rise to several subclusters which
then proceed to merge in a bottom-up (hierarchical) fashion. The idea that star formation
in stellar clusters proceeds preferentially in "sub-clusters" of enhanced stellar density was
suggested by Clarke, Bonnell & Hillenbrand (2000).

The formation process described in our simulations differs in important ways from that
proposed originally by Kumai et al. (1993). Kumai et al. (1993) envisaged the formation
of star and globular clusters from gravitationally unstable gas with $M_j$ of $10^5 \sim 10^6$ M☉
in colliding clouds. Our simulations suggest that a single massive cluster is initially not a
single massive cluster but a cluster of numerous small “sub-clusters” that are formed from
gas with smaller $M_j$ (significantly smaller than $10^5 \sim 10^6$ M⊙). These clusters are born in
the very centers of colliding clouds, and may finally form a single massive cluster. Previous
theoretical works argue that the very low $M_j$ (thus very small cluster mass) in the shocked
gas layer is a serious problem for the cloud-cloud collision model of star cluster formation
(e.g., Kumai et al. 1993). The present numerical results suggest that this Jeans mass
problem may not be so important. The incipient sub-clusters may quickly merge with one
another to form a single massive cluster due to their compact distribution in the central
regions of the colliding clouds.

We may speculate that the long-term evolution of binary clusters, of which a detailed
discussion is beyond the scope of this paper, may depend on whether or not the remaining
gas is quickly removed during/after the cloud collisions. Such gas removal likely occurs due
to the thermal and dynamical effects of young OB stars and type II supernovae. We confirm
that if the remaining gas is not removed from the remnant of the cloud-cloud collision in
our standard model, the binary cluster eventually merges to form a single cluster because
of efficient dynamical friction between the cluster and the low-density gas. In the models
with $b/2r_{cl} = 0.25$, the developed binary clusters coalesces into a single cluster within 0.2
Gyr, for $V_r < 27$ km s⁻¹.
The parameter dependencies are summarized as follows (see Figure 4). Firstly, there is an optimal range of $V_t$ ($10 - 50$ km s$^{-1}$) for star cluster formation. The star cluster formation efficiency rapidly drops as $V_t$ becomes smaller than a threshold value ($\sim 6$ km s$^{-1}$). This occurs because of the much weaker compression and less efficient shock dissipation of the colliding gas. The star formation efficiency becomes very small for models with large $V_t$ ($> 50$ km s$^{-1}$), since the merging of two clouds does occur at all in these models. Secondly, the star formation efficiency is likely to be higher for models with a smaller impact parameter $b/2r_{cl}$ (in particular, for $V_t < 20$ km s$^{-1}$). Thirdly, a single cluster rather than a binary cluster is likely to be formed just after the cloud collision in models with smaller $b/2r_{cl}$. Finally, regardless of model parameters, the star clusters possess flattened shapes just after their formation. Our derived higher star formation efficiency can be responsible for the bound cluster formation after gas removal (e.g., Geyer & Burkert 2001).

The present study suggests that the formation of star clusters in colliding gas clouds with $V_t > 60$ km s$^{-1}$ is much less likely for the adopted parameter range of $b/2r_{cl}$. As is shown in Figure 5, the two colliding clouds with $b/2r_{cl} = 0.25$ and $V_t = 67$ km s$^{-1}$ do not show any star-formation in their central regions for 43 Myr evolution. This is essentially a result of the oblique collision of two clouds with larger $V_t$ ($> 60$ km s$^{-1}$), they simply graze each other and soon become well separated without forming strongly shocked and compressed gaseous regions conducive to star formation. Therefore it appears that the formation of a thick gaseous layer (with $M_J$ of $10^5 - 10^6 M_\odot$) in colliding clouds with very large $V_t$ as proposed by Kumai et al. 1993 is unlikely. Our results imply that the formation of star clusters in colliding clouds is more complex than suggested by the previous analytical works of Kumai et al. (1993) and Fujimoto & Kumai (1997).

4. Discussions

4.1. Comparison with previous works

The dependencies of star cluster formation efficiency on $V_t$ (or $V_t/c_s$) strongly suggest that the original proposal by Kumai et al. (1993) on collisional cluster formation should be significantly modified. Kumai et al. (1993) adopted the following two assumptions to investigate the formation processes of star clusters in the LMC/SMC system: (1) The relative velocity of two interacting clouds is likely to be more than 50-100 km s$^{-1}$ and (2) Colliding two gas clouds with such a large relative velocity can form a compressed (shocked) gas layer, where star formation can proceed. Based on these two assumptions, they claimed that the observed differences in cluster formation efficiency between the Galaxy and the LMC/SMC system is due to large-scale random motions with velocities in the Magellanic
Clouds, which is not seen in the present-day Galaxy.

We find that the most likely relative velocities ($V_r$) of colliding clouds in the interacting LMC/SMC system is not 50-100 km s$^{-1}$ but rather 25 – 40 km s$^{-1}$ for a reasonable set of parameters for the gas clouds. We have also found that only a minor fraction of colliding gas clouds have $V_r$ more than 100 km s$^{-1}$. The principal reason for these lower velocities than those expected by Kumai et al. (1993) is that the mass ratio of the SMC to the LMC is small enough ($\sim 0.1$) that the tidal interaction between the two can not strongly disturb the LMC gas clouds. These results imply that (1) the above first assumption adopted by Kumai et al. (1993) is invalid and (2) if star clusters in LMC/SMC are formed from colliding clouds with $V_r$ more than 50-100 km s$^{-1}$, these clusters will be a minority among the young star clusters.

Our simulations have showed that if $V_r > 60$ km s$^{-1}$, the star formation efficiency in colliding clouds becomes very small (therefore any bound star clusters are much less likely to be formed). This is because models with $V_r > 60$ km s$^{-1}$, result in colliding clouds which just graze with each other and then become well separated without forming a strongly shocked gas layer. Unless the collision of such gas clouds is close to a head-on, the clouds cannot form a bound star cluster. The optimal range of $V_r$ in our simulations suggests that the formation of young star clusters in the LMC/SMC system (but not in the Galaxy) are a result the enhanced rates of cloud-cloud collisions with more moderate relative velocities ($V_r \sim 10 – 50$ km s$^{-1}$). We here stress that this optimal value is true for the clouds with the adopted size-mass relation Larson (1981), masses and sizes in the present study.

Kumai et al. (1993) and Fujimoto & Kumai (1997) found that if gas clouds make a head-on collision with $V_r$ of $\sim 100$ km s$^{-1}$, the Jeans mass ($M_J$) of the compressed thin gas layer becomes about $10^5 – 10^6 M_\odot$, depending on the sound velocity of the gas layer. The origin of their derived $M_J$ for star cluster formation is their larger adopted value of $V_r$. The present study has demonstrated that star clusters are less likely to be formed in colliding clouds with $V_r \sim 100$ km s$^{-1}$ (also $M_J << 10^5 – 10^6 M_\odot$). Therefore, a single star cluster with mass of $10^5 – 10^6 M_\odot$ is less likely to form from gravitationally unstable gas with $M_J$ of $10^5 – 10^6 M_\odot$ in colliding clouds with $V_r \sim 100$ km s$^{-1}$.

Our simulations show that star formation starts from the very center of colliding clouds, where $M_J$ is estimated to be $10^3 M_\odot$ for our adopted isothermal equation of state. Stars can continue to form in the high-density gas at the cloud center (with $M_J$ of $10^3 M_\odot$) such that the central region of each colliding cloud may be regarded as “a cluster of sub-clusters” with the masses of $10^3 M_\odot$. These “sub-clusters” are all located in the very center of the colliding cloud, and consequently may quickly merge with one another to form a single massive cluster. Thus, massive clusters ($10^5 – 10^6 M_\odot$) may result from the
merging of numerous small sub-clusters in the cloud centers since $M_J$ of the gas is less than $10^5 - 10^6 \, M_\odot$.

Since the resolution of the present simulation is at most $\sim 10^2 \, M_\odot$ in mass and $\sim 1$ pc in size for models with $M_{cl} = 10^6 \, M_\odot$, we can not investigate the details of the merging process of these sub-clusters. It is necessary to represent such a small cluster not as a single stellar particle, but as a collection of stellar particles (with the total number of $10^2 - 10^3$), to allow a rigorous investigation of the structural and kinematical properties of the remnants of multiple mergers between numerous small clusters. We leave to a future numerical study, with the total particle numbers of more than $10^6$, to confirm (1) whether such small clusters are first formed in the central regions of colliding clouds and (2) how these clusters can merge with one another to form a single massive cluster.

### 4.2. Origin of the observed mass-size relation of star clusters

We have found that the star formation efficiency in colliding gas clouds becomes smaller in the model with larger $V_r$ (or $V_r/c_s$) for $V_r > 30$ km s$^{-1}$. This result provides a new clue to the origin of the observed mass-size relation of star and globular clusters. There is observational evidence suggesting only a weak correlation between the mass ($M_{st}$) and size ($R_{st}$) of young star clusters and globular clusters (e.g., $R_{st} \propto M_{st}^{0.1 \pm 0.1}$ for young clusters; Zepf et al. 1999). Ashman & Zepf (2001) pointed out that if star clusters and globular clusters are formed from molecular gas clouds with the observed size-mass relation of $r_{cl} \propto M_{cl}^{0.5}$ (Larson 1981), then the star formation efficiency should be lower in smaller gas clouds to reproduce the observed mass-radius relation. The sound velocity and gas temperature are smaller in smaller self-gravitating gas clouds (Larson 1981). However, $V_r$ is controlled by global galactic dynamics and therefore is independent of gas cloud mass. Our results suggest that star formation efficiency is lower for smaller gas clouds due to the larger $V_r/c_s$ (for $V_r > 30$ km s$^{-1}$). We note that the origin of the observed scaling relation of star clusters could be closely associated with the star formation efficiency dependent on $V_r/c_s$ in colliding clouds.

Following the simple analytic argument by Ashman & Zepf (2001), we can discuss this point in a more quantitative manner. First we define $\epsilon$ to be the star formation efficiency in colliding gas clouds;

$$\epsilon = \frac{M_{st}}{M_{cl}}.$$ 

(1)

We then assume that the size of a cluster depends upon the star formation efficiency of the
cluster’s progenitor cloud such that (e.g., Hills 1980);

\[ \frac{R_{\text{st}}}{r_{\text{cl}}} \simeq \epsilon^{-1}. \]  

(2)

Based on our simulations, we can write the dependence of \( \epsilon \) on \( V_r/c_s \) as follows;

\[ \epsilon \propto \left( \frac{V_r}{c_s} \right)^\alpha. \]  

(3)

Therefore, the dependence of \( R_{\text{st}} \) on \( M_{\text{cl}} \) is:

\[ R_{\text{st}} \propto r_{\text{cl}}\epsilon^{-1} \propto M_{\text{cl}}^{1/2+\alpha/4} \propto M_{\text{st}}^{2+\alpha/4}. \]  

(4)

Here we assume that (1) \( r_{\text{cl}} \propto M_{\text{cl}}^{0.5} \) (Larson 1981), (2) \( c_s \propto M_{\text{cl}}^{0.25} \) predicted from the virial theorem and Larson’s relation above, and (3) \( V_r \) does not depend on initial cloud mass. It is clear from the above equation that \( \alpha \) should be \( \sim -2 \) to explain the apparent lack of a mass-radius relation in young clusters (Zepf et al. 1999). Although our simulations suggest that \( \alpha \) takes a negative value, they do not enable us to derive a robust value (or range) for \( \alpha \) because of our relatively small parameter space. We plan to estimate \( \alpha \) in more sophisticated future simulations with a much wider parameter space of colliding gas clouds.

### 4.3. Formation of highly flattened star clusters in LMC/SMC

Origin of the flattening of LMC star clusters have been discussed in several authors (e.g., Frenk & Fall 1982; Kontizas et al. 1989). de Oliveira et al. (2000) investigated star cluster encounters in their purely collisionless simulations, and found that binary clusters can merge with each other to form a single cluster with higher ellipticity. They also showed that if the mass ratio of two merging clusters with orbital eccentricities of 0.6 – 0.9 (i.e., a bound orbit) is close to 0.1 (“minor merging”), the merger remnant shows an ellipticity consistent with observations of LMC clusters. The present study has demonstrated that binary clusters can be formed from cloud-cloud collisions. Our study, and that of de Oliveira et al. (2000), suggest that the observed globular and populous clusters with higher ellipticity in the Magellanic Clouds may originate from the merging of binary clusters formed from cloud-cloud collisions. These two studies also imply that the difference in the shapes of clusters between the Galactic halo/disk globular clusters and the young Magellanic Cloud clusters may be due to the fact that only LMC/SMC clusters have experienced the past merging of star clusters.

It is, however, unclear whether binary clusters with the mass ratio of \( \sim 0.1 \) can actually be formed in colliding gas clouds. All of our models involve “major mergers” of
two clouds such that the incipient star clusters in the centers of the two clouds have similar masses. Also, we have only investigated the collision of two gas clouds with identical radial density profiles. This does not allow us to predict the final mass ratio of two clusters formed from unequal-density mergers of gas clouds. We need to investigate extensively a set of numerical simulations with a wider range of parameters such as the mass ratio and the density profiles of colliding two clouds in order to confirm whether a binary cluster formed from a cloud-cloud collision has the mass ratio of \( \sim 0.1 \). Our future more sophisticated simulations including chemical evolution, magnetic fields, dynamical evolution of hierarchical/fractal structures within a cloud, and feedback effects from massive stars and supernovae will address the origin of flattened shapes of LMC/SMC clusters in a more quantitative way.

5. Conclusions

We have used two different sets of numerical simulations to understand the origin of the physical properties of star clusters in the Magellanic Clouds. Although the present model of star cluster formation in colliding two clouds is simplified in a number of areas, we have revealed some essential aspects of star cluster formation in colliding gas clouds.

The main conclusions are summarized as follows.

(1) An oblique collision between two identical clouds can be significantly enhanced during the tidal interaction between the LMC and the SMC. Cloud-cloud collisions with radial velocities (\( V_r \)) of \( 25 - 40 \) km s\(^{-1} \) are most common in our models. These results imply that the origin of young star clusters in the LMC/SMC systems may stem from the enhanced collision rates of gas clouds with moderately large relative velocities. Our results also suggest that the original proposal by Kumai et al. (1993) on collisional cluster formation should be modified.

(2) Compact, bound star clusters can be formed in the centers of colliding gas clouds as a result of strong gas shocks, compression, and dissipation during the collision. The initial impact parameter of two colliding clouds determines whether the star clusters form a single cluster, a binary cluster, or two isolated star clusters. For example, for a smaller impact parameter, the incipient clusters soon merge with each other to form a single, more massive cluster.

(3) Star formation efficiency in colliding clouds depends on the initial ratio of the relative velocity of the clouds to the sound speed of the gas (\( V_r/c_s \)). This dependency is in the sense that the star formation efficiency is lower for models with larger \( V_r/c_s \).
derived dependence on $V_t/c_s$ provides a new clue to the origin of the observed mass-size relation of young star clusters.

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Fig. 1.— *Left*: Mass distributions of interacting two galaxies at $T = 0.61$ Gyr (upper) and 0.92 Gyr (lower). Here $T$ represents the time that has elapsed since the simulation starts (i.e., the two disks begin to interact with each other). Only stellar and gaseous components are plotted in these panels. Scales are given in units of the LMC’s disk size, and so each frame measures 30 kpc on a side. The center of the small circle represents the position of the SMC and the circle size is equal to the disk size of the SMC. *Right*: Time evolution of cloud-cloud collision rate in the interacting galaxies (top), the number distribution of the relative velocity of colliding two clouds (middle), and that of the impact parameter of the two colliding clouds (bottom) for the interacting galaxies at $T = 0.92$ Gyr. The impact parameter ($b$) is given in units of the diameter of a cloud (i.e., $2r_{cl}$).

Fig. 2.— Distribution of gas (cyan) and new stars formed from gas (magenta) of colliding two clouds in the standard model with $b/2r_{cl} = 0.25$ and $V_r = 20$ km s$^{-1}$ projected onto the $x$-$y$ plane, at each time indicated in the upper left corner of each panel. One frame measures 583 pc on a side.

Fig. 3.— Time evolution of the star formation rate of the standard model ($b/2r_{cl} = 0.25$ and $V_r = 20$ km s$^{-1}$).

Fig. 4.— Dependence of the mass fraction of new stars within two colliding clouds on the relative velocity of the clouds for a given impact parameter ($b$). The mass fraction here is defined as $M_s/M_g$, where $M_s$ and $M_g$ are the total mass of new stars formed before $T = 56$ Myr and initial gas mass of the clouds, respectively. The results are shown for $b/2r_{cl} = 0.1$ (long dash), 0.25 (short dash), 0.5 (dotted), and 0.75 (solid). Note that there is an optimal range ($10 - 50$ km s$^{-1}$) for the efficient star (or star cluster) formation in colliding clouds.

Fig. 5.— The same as Figure 2 but for the model with $b/2r_{cl} = 0.25$ and $V_r = 67$ km s$^{-1}$. Note that no star formation occurs in this large $V_r$ model during the collision of two gas clouds.
$b/2r_{\text{cl}} = 0.25$

$V_r = 20 \text{ km/s}$
