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FORMATION OF STAR CLUSTERS IN THE LARGE MAGELLANIC CLOUD AND SMALL MAGELLANIC CLOUD. 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 that show that compact, bound star clusters can be formed within the centers of two colliding clouds as a result of strong gaseous shocks, compression, and dissipation, provided that the clouds have moderately large relative velocities (10–60 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 on 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: interactions — galaxies: star clusters — Magellanic Clouds

On-line material: color figures

1. INTRODUCTION

It is well established that several physical properties of the globular clusters and populous young blue clusters in the Large Magellanic Cloud (LMC) 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, Shara, & Zurek 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 in theoretical and numerical works. Fujimoto & Kumai (1997) proposed that oblique cloud-cloud collisions in an interaction between the LMC and the Small Magellanic Cloud (SMC) can result in the formation of binary star clusters revolving around each other. Leon, Bergond, & Vallenari (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, Bica, & Dottori (2000) suggested that the merging of binary clusters could be responsible for the observed flattened shapes of LMC clusters.

Kumai, Basu, & Fujimoto (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 through 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 the closest encounter between the LMC and the SMC (Murai & Fujimoto 1980; Gardiner, Sawa, & Fujimoto 1994; Gardiner & Noguchi 1996). However, because of 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, or (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 twofold: 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 hydrodynamic 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 attempting to explain precisely the observed physical properties of star clusters for the LMC/SMC system in a self-consistent manner. Because this paper is the first step toward a 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 the disky distribution of LMC old star clusters will also be 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 the interacting LMC/SMC is investigated. We then describe the hydrodynamic 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 bulgeless, gas-rich disks with an initial gas mass fraction of 0.1. The 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 ($r_{\rm cl}$) of an individual cloud with a given mass ($M_{\rm cl}$) 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 the total particle number in each simulation is 20,000 for dark matter and 22,000 for disk components.

We focus on the past 1 Gyr evolution of the LMC/SMC (in particular, at the latest SMC pericenter passage), during which time populous young star clusters are known to have formed (e.g., van den Bergh 2000a). Because 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 the SMC 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 at 30 kpc. The pericenter of the orbit (represented by R_p), inclination of the LMC disk with respect to the orbital plane ($\theta_{\rm LMC}$), and that of SMC ($\theta_{\rm SMC}$) 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, $\theta_{\rm LMC} = -15^\circ$, and $\theta_{\rm SMC} = 45^\circ$. 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 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 of Gardiner & Noguchi (1996), which are not only consistent with the observed location and radial velocity of the LMC/SMC system but are 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 the *Hipparcos* data of Kroupa & Bastian (1997), as shown by Yoshizawa & Noguchi (2003). Therefore, the adopted parameter values can be regarded as reasonable, although 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 ($N_{\rm cl}$) between the clouds with masses of $M_{\rm cl}$ during the time interval dt can be written as $N_{\rm cl} = \pi\, dt\, r_{\rm cl}^2 V_{\rm cl} \Phi_{\rm cl}$, where $r_{\rm cl}$, $V_{\rm cl}$, and $\Phi_{\rm cl}$ 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 $M_{\rm cl}$ dependence of $N_{\rm cl}$. Because $V_{\rm cl}$ is highly likely to be independent of $M_{\rm cl}$, the observed relations $\Phi_{\rm cl} \sim M_{\rm cl}^{-1.63}$ and $M_{\rm cl} \sim r_{\rm cl}^2$ imply that $N_{\rm cl} \sim M_{\rm cl}^{-0.63}$. 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 hydrodynamic evolution of two colliding clouds by using a TREESPH code with star formation (Bekki 1997). The initial cloud mass ($M_{\rm cl}$) and size ($r_{\rm cl}$) are set to $10^6\ M_\odot$ and 97 pc, respectively, which are consistent with the observed mass-size relation of 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 $0.2 r_{\rm cl}$. 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 $M_{\rm cl} = 10^6\ M_\odot$. 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 timescale [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] must be shorter than the sound crossing time (corresponding to h_i/c_s, where h_i is the smoothing length of the gas) Second, the gas flow is converging. This method therefore mimics star formation caused by 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 at the x-y plane. The position and the velocity of each cloud is represented by $\boldsymbol{x}_i$ and $\boldsymbol{v}_i$ ($i = 1, 2$), respectively. We generally only show our "standard model," in which $\boldsymbol{x}_1 = (-1.5 r_{\rm cl},$

$-0.5b, 0) = -\boldsymbol{x}_2$, $\boldsymbol{v}_1 = (0.5V_r, 0, 0) = -\boldsymbol{v}_2$, $V_r = 20$ km s^{-1} (or $V_r/c_s = 5$), and $b = 0.5r_{\rm cl}$ ($= 48.5$ 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 $0 \leq b/2r_{\rm cl} \leq 1.20000$ smoothed particle hydrodynamics (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 $M_{\rm cl} = 10^6\ M_\odot$. Therefore, a stellar particle converted from a gas particle does not directly represent an individual star with the same mass and size that are 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–$10^3\ M_\odot$ because of the lower temperature and the higher gas density. Therefore, the stellar particles in our simulations can be regarded as small "subclusters" of stars with a 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 subclusters but also the formation of a single cluster from the merging between these subclusters.

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 the result of the hydrodynamic evolution of gas driven by cloud-cloud collisions in our numerical study. Thus, the adopted assumption of an 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

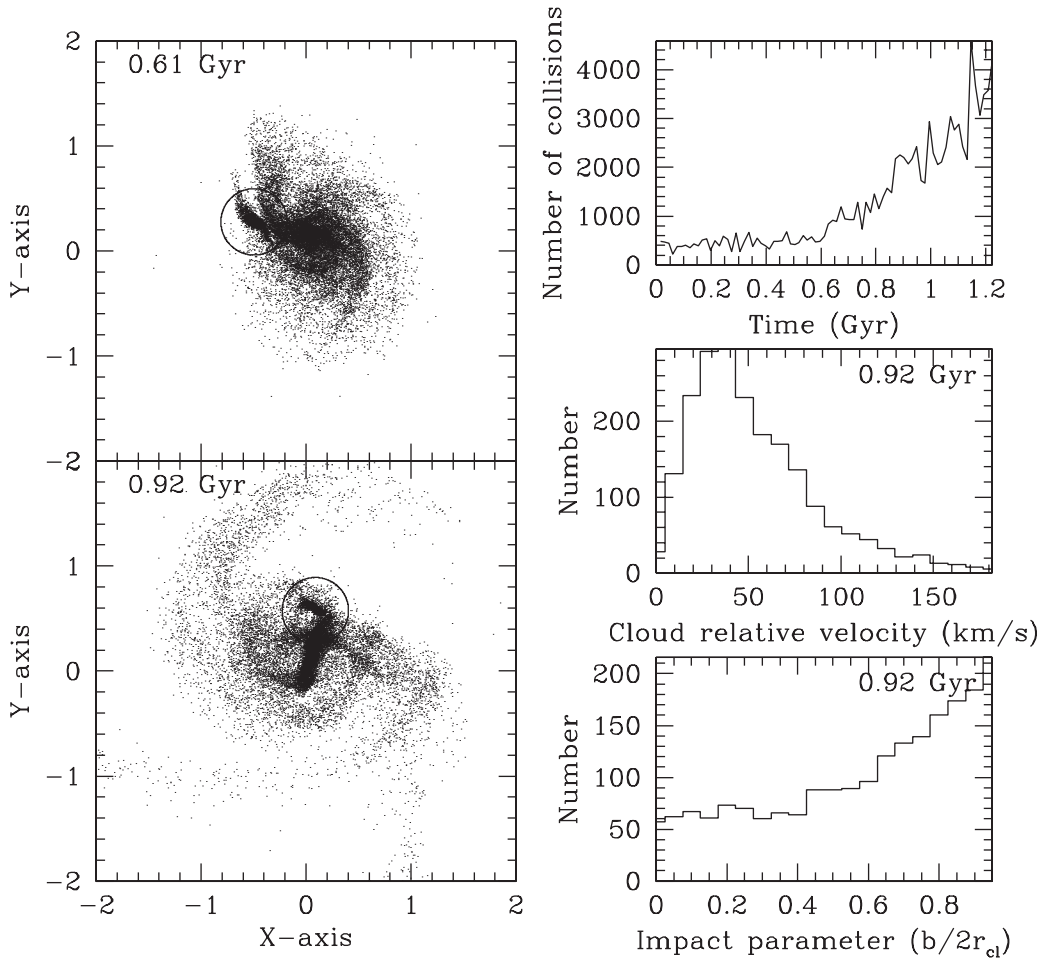


FIG. 1.—*Left*: Mass distributions of two interacting galaxies at $T = 0.61$ Gyr (*top*) and 0.92 Gyr (*bottom*). Here T represents the time that has elapsed since the simulation starts (i.e., the two disks begin to interact with each other). Only stellar and gaseous components are plotted in these panels. Scales are given in units of the LMC 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., $2r_{\rm cl}$).

the SMC passes by the pericenter of the orbit at $T = 0.61$ Gyr (where T represents the time that has elapsed since the two disks begin to interact), the strong tidal force induces nonaxisymmetric 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 more than 4 after the pericenter passage. The cloud-cloud collisions with $V_r \simeq 25$–40 km s^{-1} are most common during the interaction (e.g., $T = 0.92$ Gyr), and we estimate the mean V_r to be 60 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 ($b/2r_{\rm cl} > 0.5$) represent $\sim\frac{2}{3}$ of the total. These results demonstrate that high-speed ($V_r > 50$ km s^{-1}), oblique collisions between two similar clouds are likely in the LMC/SMC interaction, thus confirming the earlier suggestions of Fujimoto & Kumai (1997).

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 among colliding gas clouds in our simulation. Therefore, the proposed large-scale motions with velocities of more than 50–100 km s^{-1} (Kumai et al. 1993; Fujimoto & Kumai 1997) are less likely in the interacting LMC/SMC. The reason for the lower velocities here (V_r of $\simeq$25–40 km s^{-1}, rather than 50–100 km s^{-1}) is that the LMC cloud system is not strongly disturbed by the SMC tidal field because of the small mass ratio of the SMC to the LMC ($\sim$0.1). Our numerical results shown in Figure 1 suggest that if star clusters are formed from cloud-cloud collisions in the 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 among 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 slablike 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 that is considered collapsing through gravitational instability (i.e., Jeans instability in the present study). The Jeans mass ($M_{\rm J}$) 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 subcluster. Because all of these subclusters are formed in the very center of each colliding cloud, the single massive cluster formed in each colliding cloud can be thought of as consisting of numerous small subclusters 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 subclusters. However, we may reasonably assume that these numerous subclusters 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.

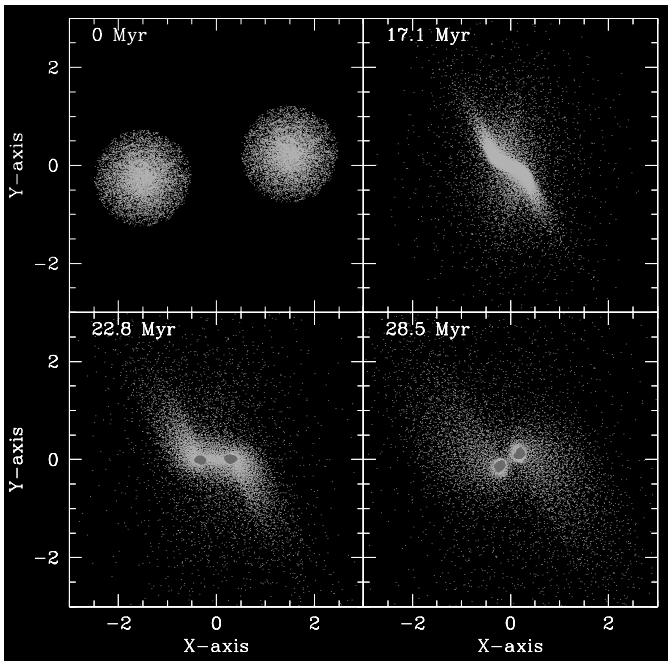


FIG. 2.—Distribution of gas (*light gray*) and new stars formed from gas (*dark gray*) of two colliding clouds in the standard model with $b/2r_{\rm cl} = 0.25$ and $V_r = 20$ km s^{-1} projected onto the *x*-*y* plane, at each time indicated in the top left corner of each panel. One frame measures 583 pc on a side. [*See the electronic edition of the Journal for a color version of this figure.*]

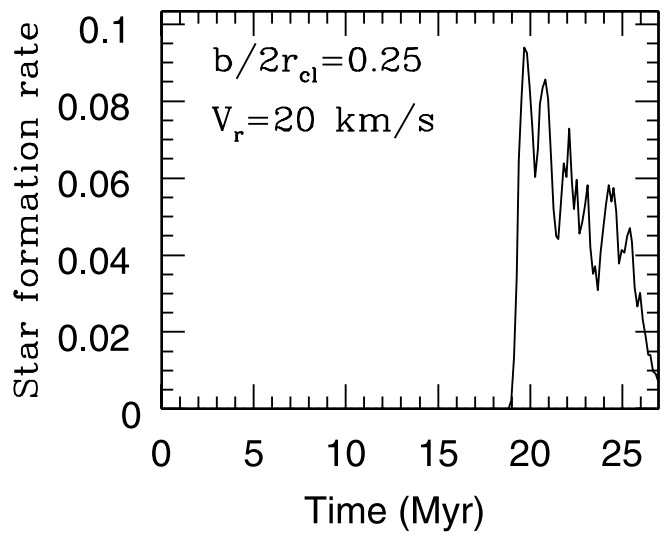


FIG. 3.—Time evolution of the star formation rate of the standard model ($b/2r_{\rm cl} = 0.25$ and $V_r = 20$ km s^{-1}).

The identification of such substructure in our simulations is interesting when one considers recent evidence for the presence of subclustering in young cluster environments. Testi et al. (2000) identified three spatially and kinematically distinct subclusters within Serpens, a nearby (∼300 pc) cloud comprising 500–1500 $M_\odot$ molecular gas and 40–80 $M_\odot$ 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 that then proceed to merge in a bottom-up (hierarchical) fashion. The idea that star formation in stellar clusters proceeds preferentially in subclusters 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. envisaged the formation of star and globular clusters from gravitationally unstable gas with M_J of 10^5–10^6 $M_\odot$ in colliding clouds. Our simulations suggest that a single massive cluster is initially not a single massive cluster but a cluster of numerous small subclusters that are formed from gas with smaller M_J (significantly smaller than 10^5–10^6 $M_\odot$). 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 (and 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 subclusters may quickly merge with one another to form a single massive cluster as a result of 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 the remaining gas is quickly removed during/after the cloud collisions. Such gas removal likely occurs because of 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 $b/2r_{\rm cl} = 0.25$, 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 Fig. 4): First, there is an optimal range of V_r (10–50 km s^{-1}) for star cluster formation. The star cluster formation efficiency drops rapidly as V_r becomes smaller than a threshold value (∼6 km s^{-1}). This occurs because of the much weaker compression and the less efficient shock dissipation of the colliding gas. The star formation efficiency becomes very small for models with large V_r(> 50 km s^{-1}), since the merging of two clouds does occur at all in these models. Second, the star formation efficiency is likely to be higher for models with a smaller impact parameter $b/2r_{\rm cl}$ (in particular, for $V_r < 20$ km s^{-1}). Third, a single cluster rather than a binary cluster is likely to be formed just after the cloud collision in models with smaller $b/2r_{\rm cl}$. 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 $V_r > 60$ km s^{-1} is much less likely

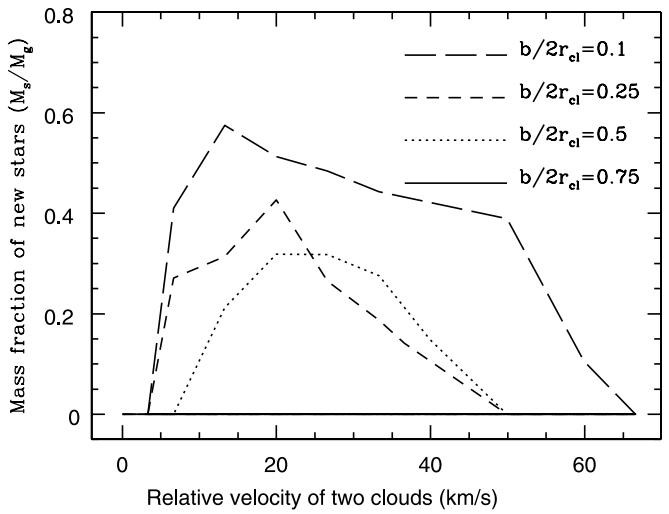


FIG. 4.—Dependence of the mass fraction of new stars within two colliding clouds on the relative velocity of the clouds for a given impact parameter (b). The mass fraction here is defined as M_s/M_g, where M_s and M_g are the total mass of new stars formed before $T = 56$ Myr and initial gas mass of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

for the adopted parameter range of $b/2r_{\rm cl}$. As is shown in Figure 5, the two colliding clouds with $b/2r_{\rm cl} = 0.25$ and $V_r =$ 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_r(>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 $M_\odot$)

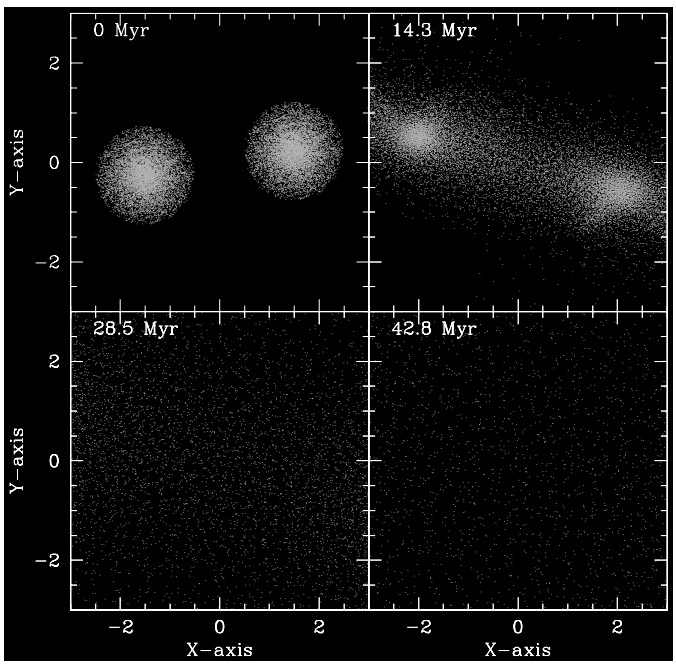


FIG. 5.—Same as Fig. 2, but for the model with $b/2r_{\rm cl} = 0.25$ and $V_r =$ 67 km s^{-1}. Note that no star formation occurs in this large V_r model during the collision of two gas clouds. [*See the electronic edition of the Journal for a color version of this figure.*]

in colliding clouds with very large V_r, 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 in 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_r (or V_r/c_s) strongly suggest that the original proposal of 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 $V_r > 100$ 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 cannot 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 the LMC/SMC are formed from colliding clouds with $V_r > 50$–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 that 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 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 stress here 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_{\rm 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 $M_{\rm J}$ 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 $M_{\rm J} \ll 10^5$–10^6 $M_\odot$). Therefore, a single star cluster with a mass of 10^5–10^6 $M_\odot$ is less likely to form from gravitationally unstable gas with an $M_{\rm J}$ 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 $M_{\rm J}$ 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 an $M_{\rm J}$ of 10^3 $M_\odot$) such that the central region of each colliding cloud may be regarded as "a cluster of subclusters" with the masses of 10^3 $M_\odot$. These subclusters 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 subclusters in the cloud centers, since the $M_{\rm J}$ of the gas is less than 10^5–10^6 $M_\odot$.

Because 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 $M_{\rm cl} = 10^6$ $M_\odot$, we cannot investigate the details of the merging process of these subclusters. 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 ($M_{\rm st}$) and size ($R_{\rm st}$) of young star clusters and globular clusters (e.g., $R_{\rm st} \propto M_{\rm st}^{0.1\pm0.1}$ 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 $r_{\rm cl} \propto M_{\rm cl}^{0.5}$ (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 because of 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 ϵ as the star formation efficiency in colliding gas clouds,

$$\epsilon = \frac{M_{\rm st}}{M_{\rm cl}}. \tag{1}$$

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

$$\frac{R_{\rm st}}{r_{\rm cl}} \simeq \epsilon^{-1}. \tag{2}$$

Based on our simulations, we can write the dependence of ϵ on V_r/c_s as

$$\epsilon \propto \left(\frac{V_r}{c_s}\right)^{\alpha}. \quad (3)$$

Therefore, the dependence of $R_{\rm st}$ on $M_{\rm cl}$ is

$$R_{\rm st} \propto r_{\rm cl}\epsilon^{-1} \propto M_{\rm cl}^{1/2+\alpha/4} \propto M_{\rm st}^{(2+\alpha)/(4-\alpha)}. \quad (4)$$

Here we assume that (1) $r_{\rm cl} \propto M_{\rm cl}^{0.5}$ (Larson 1981), (2) $c_s \propto M_{\rm cl}^{0.25}$ 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 α should be ~ -2 to explain the apparent lack of a mass-radius relation in young clusters (Zepf et al. 1999). Although our simulations suggest that α takes a negative value, they do not enable us to derive a robust value (or range) for α because of our relatively small parameter space. We plan to estimate α 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*

The origin of the flattening of LMC star clusters have been discussed by 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. We have also 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 extensively investigate a set of numerical simulations with a wider range of parameters such as the mass ratio and the density profiles of two colliding 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 of 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. The derived dependence on V_r/c_s provides a new clue to the origin of the observed mass-size relation of young star clusters.

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