Formation and evolution of the Magellanic Clouds. I. Origin of structural, kinematical, and chemical properties of the Large Magellanic Cloud

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ABSTRACT

We investigate the dynamical and chemical evolution of the Large Magellanic Cloud (LMC) interacting with the Galaxy and the Small Magellanic Cloud (SMC) based on a series of self-consistent chemodynamical simulations. Our numerical models are aimed at explaining the entire properties of the LMC, i.e., the observed structure and kinematics of its stellar halo and disk components as well as the populations of the field stars and star clusters. The main results of the present simulations are summarized as follows.

(1) Tidal interaction between the Clouds and the Galaxy during the last 9 Gyr transforms the initially thin, non-barred LMC disk into the three different components: the central bar, thick disk, and kinematically hot stellar halo. The central bar is composed both of old field stars and newly formed ones with each fraction being equal in its innermost part. The final thick disk has the central velocity dispersion of $\sim 30 \text{ km s}^{-1}$ and shows rotationally supported kinematics with $V_m/\sigma_0 \sim 2.3$.

(2) The stellar halo is formed during the interaction, consisting mainly of old stars originating from the outer part of the initially thin LMC disk. The outer halo shows velocity dispersion of $\sim 40 \text{ km s}^{-1}$ at the distance of 7.5 kpc from the LMC center and has somewhat inhomogeneous distribution of stars. The stellar halo contains relatively young, metal-rich stars with the mass fraction of 2%.

(3) Repetitive interaction between the Clouds and the Galaxy enhances moderately the star formation rate to $\sim 0.4 M_\odot \text{ yr}^{-1}$ in the LMC disk. Most of the new stars ($\sim 90 \%$) are formed within the central 3 kpc of the disk, in particular, within the central bar for the last 9 Gyr. Consequently, the half mass radius is different by a factor of 2.3 between old field stars and newly formed ones.

(4) Efficient globular cluster formation does not occur until the LMC starts interacting violently and closely with the SMC ($\sim 3$ Gyrs ago). The newly formed globular cluster system has a disky distribution with rotational kinematics and its mean metallicity is $\sim 1.2$ higher than that of new field stars because of the pre-enrichment by the formation of field stars prior to cluster formation.

(5) The LMC evolution depends on its initial mass and orbit with respect to the Galaxy and the SMC. In particular, the epoch of the bar and thick disk formation and the mass fraction of the stellar halo depend on the initial mass of the LMC.

Based on these results, we discuss the entire formation history of the LMC, the possible fossil records of past interaction between the Clouds and the Galaxy, and the star formation history of the SMC for the last several Gyr.

Key words: Magellanic Clouds – galaxies:structure – galaxies:kinematics and dynamics – galaxies:halos – galaxies:star clusters

1 INTRODUCTION

Galaxy interaction is generally considered to play a major role not only in controlling formation histories of field
stars and star clusters (e.g., Kennicutt 1998; Ashman & Zepf 1992) but also in transforming galactic morphologies (e.g., Noguchi 1987). The Large and Small Magellanic Cloud (LMC and SMC), which are believed to be interacting with each other, have long been served as an ideal laboratory to study the detail of the tidal effects on structural, kinematical, and chemical properties of galaxies based on the comparison between observations and numerical simulations (e.g., Murai & Fujimoto 1980, hereafter MF; Gardner, Sawa, & Fujimoto 1994, GSF; Gardner & Noguchi 1996, GN; Yoshizawa & Noguchi 2003, YN). Most of previous theoretical and numerical papers on tidal interaction between the Clouds and the Galaxy however have discussed the origin of Magellanic stream and the evolution of the SMC (e.g., Lin & Lynden-Bell 1977, 1982; Mathewson et al. 1987; MF; GSF; GN; YN) rather than the formation and the evolution of the LMC itself. Given the fact that recent observations have raised and confirmed several important questions related to the star formation history, the physical properties of star clusters, and the dynamical properties of the LMC, it is doubtlessly worthwhile to discuss a theoretical model which provides an integrated and systematic understanding of the formation and the evolution of the LMC (Westerlund 1997).

One of the long-standing and remarkable problems related to the star formation history of field stars in the LMC is as to whether there were epochs of dramatic increase in star formation rate of the LMC disk a few or several Gyr ago (e.g., Butcher 1977; Stryker 1983; Bertelli et al. 1992; Olszewski et al. 1996; Gallagher et al. 1996; Vallenari et al. 1996; Holzman et al. 1999). Several authors have recently investigated star formation histories of the different regions of the LMC disk and bar based on the color magnitude diagrams of the field stars derived by Hubble Space Telescope (Ardeberg et al. 1997; Elston et al. 1997; Holzman et al. 1999; Olsen 1999; Smecker-Hane et al. 2002), and revealed that the epoch of enhanced star formation and the degree of the enhancement are different between different regions. For example, Smecker-Hane et al. (2002) found that (1) stellar populations within the LMC bar were formed in the episodes of star formation about 4 – 6 and 1-2 Gyr ago, and (2) these burst populations can account for ~ 25 % and ~ 15 % of the LMC’s stellar mass, respectively. The origin of the observed spatially different star formation histories in the LMC disk is one of key questions related to the LMC evolution (e.g., van den Bergh 2000a).

Several important physical properties of the globular clusters and populous young blue clusters in the LMC are in a stark contrast to those in the Galaxy (e.g., van den Bergh 2000a). These include the more flattened shapes of the LMC clusters (e.g., Geisler & Hodge 1980; van den Bergh & Morbey 1984), the disk distribution of its globular cluster system (e.g., Schommer et al. 1992), possible rotational kinematics of old clusters (e.g., Freeman et al. 1983), 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), and larger sizes at a given galactocentric distance (van den Bergh 2000b). It is unclear whether these differences are understood in terms of the LMC being much more strongly influenced dynamically by other nearby galaxies (i.e., the Galaxy and the SMC) compared with the Galaxy.

Structural and kinematical properties of the LMC have been investigated by many authors concerning different stellar populations and gaseous components (Hartwick & Cowley 1988; Meatheringham et al. 1988; Irwin 1991; Luks & Rohlf 1992; Kunkel et al. 1997; Graf et al. 2000; Olsen & Salyk 2002; Cioni & Hasing 2003; Staveley-smith et al. 2003; Subramanian 2004; See Westerlund 1997 for a review). For example, Caldwell & Coulson (1986) found that the east side of the LMC is closer to us than the west based on photometric observations of carbon stars. Wide-field photometric observations of the LMC disk revealed the exponential scale length of 1.5 kpc (Bothun & Thompson 1988) whereas an exponential disk model that fits to the distribution of field RR Lyrae stars has a scale length of 2.6 kpc (Kinman et al. 1991). Based on observational data of carbon stars by the Deep Near-Infrared Southern Sky Survey (DENIS) and Two Micron All-Sky Survey (2MASS), van den Marel et al. (2002) (hereafter vdMAHS) have recently shown that the LMC has a considerable vertical thickness with V/σ of 2.9±0.9 and a mass of (8.7±4.3)×10^9 M⊙ within 8.9 kpc. The origin of the observed differences in dynamical properties between various populations in the LMC remains unclear, though such differences may well provide some information about physical roles of galaxy interaction in the LMC evolution (Westerlund 1997; van den Bergh 2000a).

Only some theoretical attempts have been made to understand these observed properties of the LMC disk (Pagel et al. 1998; GSF; Weinberg 2000; Kumai et al. 1993), while a growing number of observational results have emerged. Weinberg (2000) first investigated the dynamical effects of the Galactic tidal field on structure and kinematics of the LMC disk. Bekki et al. (2004a) demonstrated that a single or binary star cluster is formed in a cloud-cloud collision triggered by tidal interaction between the LMC and SMC. However, these studies have the following two disadvantages in understanding the LMC evolution in a comprehensive manner. Firstly, these models are not fully self-consistent as they consider either dynamical evolution alone or empirical one-zone chemical evolution. Secondly, the model parameters adopted in these works did not account for the revised knowledge on the structure and kinematics of the LMC as revealed by the latest observations such as DENIS and 2MASS (van den Marel & Cioni 2001; vdMAHS). Thus, the integrated and systematic understanding of structural, kinematical, and chemical properties of the LMC is therefore yet to be obtained.

Thus, the purpose of this paper is to investigate these unresolved problems on the LMC formation and evolution based on chemodynamical simulations with the model parameters (such as LMC’s mass) consistent with the latest observations. In particular, we examine the following five issues: (1) how the star formation history of the LMC is influenced by tidal interaction between the LMC, the SMC, and the Galaxy, (2) whether the stellar halo formation process of the LMC is similar to or different from that of other members of the Local Group of galaxies (e.g., M33, the Galaxy, NGC 3109, and NGC 6822), (3) how we can explain the origin of structure and kinematics of the thin/thick stellar disks of the LMC, (4) how the LMC’s chemical evolution process is associated with the dynamical evolution influenced both
by the Galaxy and the SMC, and (5) whether the origin of the unique nature of the globular clusters and blue populous clusters is understood in terms of the tidal interaction between the Clouds and the Galaxy. Based on these investigations, we attempt to provide a entire history of the LMC for the last $\sim 10$ Gyr.

The layout of this paper is as follows. In §2, we summarize our numerical models used in the present study and describe the methods for analyzing structure and kinematics of the simulated LMC. In §3, we present numerical results on the time evolution of morphology, metallicity distribution, and dynamical properties of the LMC. In §4, we discuss the above five outstanding issues related to formation and evolution of the LMC. The conclusions of the present study are given in §5.

2 MODEL

The present investigation is two-fold. First, we derive the most plausible and realistic orbits of the Clouds with respect to the Galaxy by using a backward integration scheme (MF; GSF; GN). Then we investigate chemodynamical evolution of the LMC on the derived orbit by using a fully self-consistent N-body model of galaxies (Bekki & Shioya 1998, 1999; Bekki & Chiba 2000, 2001). Since our main purpose of this paper is to discuss the origin of structural and kinematical properties of the LMC, we briefly describe the results of the orbital evolution derived from the backward integration scheme in this section. We describe the results of the N-body simulations in the next section §3.

2.1 Derivation of the orbits of the Clouds

2.1.1 The backward integration scheme

We adopt the backward integration scheme originally devised by MF to derive the most reasonable and realistic three dimensional (3D) orbits of the LMC and the SMC around the Galaxy. In calculating the orbital evolution of this triple interacting system, we adopt the most recently derived observational parameters on locations and radial velocities of the Clouds with respect to the Galaxy and masses of the Clouds. In order to derive the orbits of the Clouds, we need to assume model parameters for the following quantities of the Galaxy and the Clouds: (1) the shape of the Galactic potential as a function of the distance $r$ from the Galactic center, in particular, beyond 200 kpc where the Clouds reach at their apocenter passages, (2) gravitational potential of the Clouds, (3) total masses (or mass profiles) of the Clouds, (4) dynamical friction between the Galactic dark halo and the LMC (SMC), and (5) dynamical friction between the LMC and the SMC. The above (3) and (5) are more carefully considered in the present study as described below.

The gravitational potential of the Galaxy $\Phi_G$ is assumed to have the logarithmic potential;

$$\Phi_G(r) = -V_0^2 \ln r,$$

where $r$ and $V_0$ are the distance from the Galactic center and the constant rotational velocity ($= 220 \text{ km s}^{-1}$), respectively. The LMC is assumed to have the Plummer potential;

$$\Phi_{\text{LMC}}(r_L) = -M_{\text{LMC}}/(r_L^2 + a_L^2)^{1/2},$$

where $M_{\text{LMC}}$, $r_L$, and $a_L$ are the total mass of the LMC, the distance from the LMC, and the effective radius, respectively. We adopt the same value of $a_L$ (=3 kpc) as previous numerical studies adopted (e.g., GN). Recent dynamical study of the LMC by vdMAHS showed that the dynamical mass within 8.9 kpc of the LMC is $(8.7 \pm 4.3) \times 10^{9} M_\odot$, which is less than the half of the mass $(2.0 \times 10^{10} M_\odot)$ adopted in previous numerical studies (e.g., GN). Considering this latest and more robust estimation of the dynamical mass of the LMC, we mainly investigate the orbital models with $M_{\text{LMC}} = 10^{10} M_\odot$. The SMC is assumed to have the Plummer potential;

$$\Phi_{\text{SMC}}(r_S) = -GM_{\text{SMC}}/(r_S^2 + a_S^2)^{1/2},$$

where $M_{\text{SMC}}$, $r_S$, and $a_S$ are the total mass of the SMC, the distance from the SMC, and the effective radius, respectively. We adopt the same values of $a_S$ (=3 kpc) and $M_{\text{SMC}}$ (=3.0 $\times 10^{9} M_\odot$) as previous numerical studies adopted (e.g., GN).

We consider the dynamical friction due to the presence of the Galactic dark matter halo both for the LMC-Galaxy interaction and for the SMC-Galaxy one and adopt the following expression (Binney & Tremaine 1987);

$$F_{\text{fric,G}} = -0.428 \ln \Lambda_G \frac{GM^2}{r^2},$$

where $r$ is the distance of the LMC (the SMC) from the center of the Galaxy. The mass $M$ is either $M_{\text{LMC}}$ or $M_{\text{SMC}}$, depending on which Cloud’s orbit (i.e., LMC or SMC) we calculate. We adopt the reasonable value of 3.0 for the Coulomb logarithm $\Lambda_G$ (GSF; GN) both in the orbital calculation of...
the LMC and in that of the SMC. The above equation (4) is essentially the same as that shown in the equation (18) by MF. In addition to the above $F_{h,c,G}$, the dynamical friction between the LMC and the SMC is also considered in the present study. We adopt the following expression;

$$F_{h,c,LS} = -0.428 \ln \Lambda_{LS} \frac{GM_{SMC}^2}{r_{LS}^2},$$

(5)

where $r_{LS}$ and $\Lambda_{LS}$ are the distance between the center of the LMC and that of the SMC and the Coulomb logarithm, respectively. $F_{h,c,LS}$ is assumed to act on the SMC, only when the SMC is within the LMC’s tidal radius $r_1$, within which dark matter halo is gravitationally bound without being stripped from the Galactic tidal field. By using the theoretical model adopted in the equation (4) of GN, $r_1$ is estimated as 13 kpc for the present model. vdMAHS observationally estimated $r_1$ as 15.0 $\pm$ 4.5 kpc based on the newly derived total mass of the LMC. Therefore our choice of $r_1 = 13$ kpc is regarded as a quite reasonable value. For comparison, we investigate the models with $r_1 = 0$ kpc, in which dynamical friction between the Clouds is not included at all.

By integrating equations of the motions of the Clouds toward the past from the present epoch, we investigate orbital evolution of the Clouds for given initial positions and velocities of the Clouds. We adopt the reasonable sets of orbital parameters that are consistent with observations and thus were adopted in previous numerical studies (GN). Figure 1 shows a schematic view of the Galaxy and the Magellanic Clouds and the orbital evolution of the Clouds. The current Galactic coordinate ($b, l$), where $l$ and $b$ are the Galactic longitude and latitude, respectively, is ($-32.89, 280.46$) for the LMC and ($-44.30, 302.79$) for the SMC, and accordingly the current positions ($X, Y, Z$) in units of kpc in the figure are ($-1.0, -40.8, -26.8$) for the LMC and ($13.6, -34.3, -39.8$) for the SMC. The current distance and the Galactocentric radial velocity of the LMC (SMC) is 80 (7) km s$^{-1}$.

| Model | $M_{LMC} \times 10^{10} M_\odot$ | Friction |
|-------|---------------------------------|----------|
| A     | 1.0                             | yes      |
| B     | 1.0                             | no       |
| C     | 2.0                             | yes      |
| D     | 2.0                             | no       |
| E     | 1.0                             | yes      |
| F     | 1.0                             | yes      |
| G     | 1.0                             | yes      |
| H     | 1.0                             | yes      |
| I     | 1.0                             | yes      |
| J     | 1.0                             | yes      |
| K     | 1.0                             | –        |

$(U_L, V_L, W_L)$ (km s$^{-1}$) and $(U_S, V_S, W_S)$ (km s$^{-1}$)

$(-5, -225, 194)$ (40, -185, 171)

$(-5, -225, 194)$ (40, -185, 171)

$(-5, -225, 194)$ (40, -185, 171)

$(-5, -225, 194)$ (40, -185, 171)

$(-5, -225, 194)$ (40, -185, 171)

$(-5, -225, 194)$ (40, -185, 171)

$(-5, -225, 194)$ (40, -185, 171)

$(-5, -225, 194)$ (40, -185, 171)

$(-5, -225, 194)$ (40, -185, 171)

$(-5, -225, 194)$ (40, -185, 171)

Figure 2. The orbital evolution of the Clouds for the last $\sim$ 9 Gyr ($-8.8 \leq T \leq 0$ Gyr) for the best orbital model A. The distance between the Cloud, that between the Galaxy and the LMC, and that between the Galaxy and the SMC are represented by a thick solid line, a thin solid one, and a dotted one, respectively.

The LMC is similar to that of the oldest ones in the Galaxy: We thus investigate the LMC evolution for the last $\sim$ 9 Gyr.

2.1.2 The representative orbits

The current space velocities or $(U, V, W)$ in units of km s$^{-1}$ are the most important parameters that determine the orbital evolution of the Clouds in the present models. They are represented by $(U_L, V_L, W_L)$ for the LMC and by $(U_S, V_S, W_S)$ for the SMC. Eleven representative models with different values of $(U_L, V_L, W_L)$ and $(U_S, V_S, W_S)$ are discussed in the present study, and the Table 1 summarizes the model parameters for these: Model number (column 1), total mass of the LMC represented by $M_{LMC}$ in units of $10^{10} M_\odot$ (2), whether or not the dynamical friction between the Clouds is included (3), $(U_L, V_L, W_L)$ (4), and $(U_S, V_S, W_S)$ (5).

Among these 11 models labeled as A–K, the model A with $(U_L, V_L, W_L) = (-5, -225, 194)$ and $(U_S, V_S, W_S) = (40, -185, 171)$ is considered to be the best orbital model and thus referred to as the “best orbital model” throughout this paper. This is mainly because the Magellanic stream is self-consistently reproduced in previous models for these values. Different observations suggested different values of $(U_L, V_L, W_L)$ and $(U_S, V_S, W_S)$ (e.g., Kroupa & Bastian 1997, KB; vdMAHS). For example, $(U_L, V_L, W_L)$ and $(U_S, V_S, W_S)$ are ($41 \pm 44$, $-200 \pm 31$, $169 \pm 37$) km s$^{-1}$ and ($60 \pm 172$, $-174 \pm 172$, $173 \pm 128$) km s$^{-1}$, respectively, for KB.
The best model accordingly is broadly consistent with the observed data. Figure 2 describes the past $\sim 9$ Gyr orbital evolution of the Clouds in the best orbital model A. Here negative values of the time, $T$, represent the past, with $T = 0$ corresponding to the present epoch. As shown in this figure, the present orbital period of the Clouds about the Galaxy is $\sim 1.5$ Gyr for the adopted gravitational potential and the masses of the Cloud and the Galaxy in the best model. Although the LMC-SMC distance remains very small ($<40$ kpc) over the last 4 Gyr ($T > -4$ Gyr), it cannot keep its binary status beyond $\sim 5$ Gyr: Disintegration of the present-day binary orbit is inevitable in this model.

Figure 3 describes the orbital evolution of the Clouds for the models C and D and thereby shows how the dynamical friction between the Clouds due to the presence of the dark halo of the LMC influences the orbital evolution of the Clouds. The model D with $M_{\text{LMC}} = 2.0 \times 10^{10} M_\odot$ and without dynamical friction between the Clouds is exactly the same as the best model in GN. As shown in this figure, the Clouds can keep its binary status more than $\sim 9$ Gyr in the model D without dynamical friction of the Clouds whereas they cannot in the model C with dynamical friction. This suggests that the models with dynamical friction between the Clouds have difficulties in keeping the binary status of the Clouds for more than several Gyrs. In the Appendix A, we discuss the duration of the LMC/SMC binary status more extensively based on large number of orbital models. Figure 4 summarizes the orbital evolution for the representative models, B, I, J, and F, for which we investigate the LMC evolution in the N-body simulations.

### 2.2 N-body models

#### 2.2.1 The self-gravitating LMC

The LMC is modeled as a fully self-gravitating system and composed of a live dark halo and a thin exponential disk with no bulge. The total mass of the dark halo, that of the disk, and the size of the disk are $M_{\text{dm}}$, $M_d$, and $R_d$, respectively. The mass ratio of the dark halo to the total mass (i.e., $M_{\text{dm}}/M_{\text{LMC}}$) is fixed at 0.7 throughout the paper, which is consistent with the observation by vdMAHS. We adopt the Plummer potential in calculating the orbital evolution of the LMC (§2.1.1) and accordingly we need to adopt the corresponding density profile for the dark matter halo of the LMC in this self-gravitating N-body models for self-consistency. The density profile of the dark halo is described as:

$$
\rho(r_L) = \frac{3 M_{\text{dm}}}{4 \pi a_L^3} \left(1 + \frac{r_L^2}{a_L^2}\right)^{-2.5},
$$

where $r_L$ is the distance from the center of the LMC and the value of $a_L$ is identical with that adopted in the equation (2). Recent cosmological simulations within the framework of the CDM model (Navarro, Frenk & White 1996) have demonstrated the “universal” density distribution (the NFW profile):

$$
\rho(r) = \frac{\rho_0}{(r/r_{\text{NFW}})(1 + r/r_{\text{NFW}})^2},
$$

where $r$, $\rho_0$, and $r_{\text{NFW}}$ are the spherical radius, the central density of a dark halo, and the scale length of the halo,
The radial ($R$) and vertical ($Z$) density profile of the initially thin disk of the LMC are assumed to be proportional to $\exp(-R/R_0)$ with scale length $R_0 = 2.6$ kpc and to sech$^2(Z/Z_0)$ with scale length $Z_0 = 0.2 R_0$, respectively. We adopt the value of 2.6 kpc from Kimman et al. (1991) who investigated spatial distribution of RR Lyrae filed stars that are believed to be old, because our initial stellar disk is assumed to be older than $\sim 9$ Gyr. The circular velocity of the disk becomes a maximum value of $V_\infty$ at $R_L = 5$ kpc from the center of the disk for the adopted dark matter mass profile and $V_\infty$ is 71 km s$^{-1}$. In addition to the rotational velocity made by the gravitational field of disk and halo component, the initial radial and azimuthal velocity dispersion are given to the disk component according to the epicyclic theory with Toomre’s parameter (Binney & Tremaine 1987) $Q = 1.5$. The vertical velocity dispersion at a given radius is set to be 0.5 times as large as the radial velocity dispersion at that point, as is consistent with the observed trend of the Galaxy (e.g., Wielen 1977). In order to compare physical properties of new GCs formed from gas with those of old GCs initially within the LMC disk, we assume that the LMC disk initially contains 100 old GCs and the GC system has a diskly distribution and rotational kinematics. We adopt the GC number of 100 that is much larger than the observed one ($\sim 13$; van den Bergh 2000a), because we need an order of 100 GCs to evaluate structural and kinematical properties of the GC system: Only $\sim 10$ GCs do not allow us to derive the density profile and the rotational properties of the GC system. The assumption on the GC kinematics and structure is consistent with observations of structural and kinematics of old GCs in the LMC (e.g., Freeman et al. 1983; Schommer et al. 1992).

The disk is composed both of gas and stars with the gas mass fraction ($f_\text{g}$) being a free parameter and the gas disk is represented by a collection of discrete gas clouds (corresponding to giant molecular clouds; GMCs) that follow the observed mass-size relationship (Larson 1981). Every pair of two overlapping gas clouds is made to collide with the same restitution coefficient of $f_r$ (Hausman & Roberts 1984). We vary the values of $f_r$ from 0.0 (no dissipation) 1.0 (highly dissipative) and thereby investigate the parameter dependences of the results on $f_r$. We mainly present the results of the models with $f_r = 0.5$ and show some parameter dependences of the present results on $f_r$. Although adopted method of “sticky particles” has been proven to be capable of addressing successfully some aspects of the hydrodynamical interactions in interstellar medium (ISM) for disk galaxies (e.g., Hausman & Roberts 1984; Combes & Gerin 1985), it has some disadvantages in dealing with the more realistic physical processes of the ISM, such as hydrodynamical interaction between the hot interstellar gas (with the temperature of $10^6$ K) and GMCs (e.g., evaporation of GMCs by the hot gas). We discuss this point in §3 for the results that may depend sensitively on the way to treat with ISM.

In order to construct as a realistic gas disk model as possible, we consider the radial dependence of the gas mass fraction $F_\text{g}(r_L)$ in the initial LMC disk. We expect that the inner gas mass fraction in the LMC is smaller than the outer one owing to more rapid consumption of gas in the inner regions with higher gas density. We therefore adopt the following rule;

$$F_\text{g}(r_L) \propto t_{s_f}(r_L) \propto \frac{\Sigma_\text{g}(r_L)}{\Sigma_\text{g}(r_L)} \propto \Sigma_\text{g}^{-\alpha}(r_L), \quad (8)$$

where $r_L$, $t_{s_f}$, $\Sigma_\text{g}$, and $\alpha$ are the distance from the center of the LMC disk, the gas consumption time scale, the initial gas density, the gas consumption rate, and the parameter controlling the radial dependence. Since we adopt the Schmidt law with the exponent of 1.5 for star formation (described below), the reasonable value of $\alpha$ is $\sim 0.5$. According to the value of $F_\text{g}(r_L)$ derived from the above equation (8) at each radius, we determine the reasonable number of

| model no. | orbit type | $\theta$ (degrees) | $\phi$ (degrees) | comments |
|---|---|---|---|---|
| 1 | A | 99 | 257 | fiducial |
| 2 | – | 0 | 0 | isolated LMC |
| 3 | A | 90 | 270 | NFW halo |
| 4 | A | 79 | 257 | NFW halo |
| 5 | A | 109 | 257 | more massive LMC |
| 6 | A | 99 | 257 | more massive LMC |
| 7 | A | 90 | 270 | more massive LMC |
| 8 | B | 99 | 257 | no SMC |
| 9 | C | 99 | 257 | $f_r=0.0$ |
| 10 | D | 99 | 257 | $f_r=0.25$ |
| 11 | E | 99 | 257 | $f_r=0.75$ |
| 12 | F | 99 | 257 | $f_r=1.0$ |
| 13 | G | 99 | 257 | |
| 14 | H | 99 | 257 | |
| 15 | I | 99 | 257 | |
| 16 | J | 99 | 257 | |
| 17 | K | 99 | 257 | |
| 18 | A | 99 | 257 | |
| 19 | A | 99 | 257 | |
| 20 | A | 99 | 257 | |
| 21 | A | 99 | 257 | |
old stellar particles and gaseous ones at each radius and thereby allocate these particles to each radial bin. By assuming that the disk is composed only of gas initially, we determine $F_g(r_L)$ through the equation (8) and derive a reasonable radial distribution of gas and stars. To obtain more realistic initial stellar and gaseous distributions (e.g., with gaseous and stellar spiral arms), a LMC disk with $F_g(r_L)$ is allowed to relax for 10 dynamical time ($\sim 0.7$ Gyr). We then use this disk as an initial LMC disk model in the simulations.

2.2.2 Star formation and chemical evolution

The gas is converted into either field stars or globular clusters (GCs), so that we distinguish the formation process of field stars from that of GCs throughout this paper. Field star formation is modeled by converting the collisional gas particles into collisionless new stellar particles according to the algorithm of star formation described below. We adopt the Schmidt law (Schmidt 1959) with exponent $\gamma = 1.5$ (1.0 $< \gamma < 2.0$, Kennicutt 1998) as the controlling parameter of the rate of star formation. The amount of gas consumed by star formation for each gas particle in each time step is given as:

$$\dot{\rho}_g \propto \rho_g^\gamma,$$

where $\rho_g$ is the gas density around each gas particle. We convert a gas particle into a field star only if the local gas density $\rho$ exceeds the observed threshold gas density of $\sim 3 M_\odot$ pc$^{-2}$ for Magellanic dwarf irregular galaxies (Hunter et al. 1998). These stars formed from gas are called “new stars” (or “young stars”) whereas stars initially within a disk are called “old stars” throughout this paper.

We use the cluster formation criteria derived by previous analytical works (e.g., Kumai et al. 1993) and hydrodynamical simulations with variously different parameters of cloud-cloud collisions on a 1-100pc scale (Bekki et al. 2004a) in order to model GC formation. A gas particle is converted into a cluster if it collides with other high velocity gas (with the relative velocities ranging from 30 km s$^{-1}$ to 100 km s$^{-1}$) and having an impact parameter (normalized to the cloud radius) less than 0.25. Although both binary cluster and single one are formed during high-velocity cloud-cloud collisions (Bekki et al. 2004a), we assume that only one cluster is formed from one event of cloud-cloud collision for simplicity. These GCs formed from gas are called “new GCs” whereas GCs initially within a disk are called “old GCs” throughout this paper.

This model is strongly supported by recent observations (e.g., Zhang et al. 2001) that have revealed that there is a tendency for young clusters to be found in gaseous regions with higher velocity dispersion, where cloud-cloud collisions are highly likely. In the present model, the clusters are not formed in the isolated model (described later) at all. This enables us to investigate how and whether the tidal interaction between the Clouds and the Galaxy triggers the formation of GCs. About an order of 10$^4$ clusters are formed in the models where the LMC interacts with the SMC and the Galaxy. The preset simulations only investigate dynamics with the scale down to $\sim 100$ pc so that it does not allow us to investigate which new clusters with the size of $\sim 10$ pc survive from tidal force of the Galaxy and the Clouds to be observed as GCs at the present time. Therefore, we assume that all clusters formed in the simulations become GCs, and thereby analyze the physical properties of new GCs. The total number of GCs in the simulations may be overestimated in the present model because of this assumption.

Chemical enrichment through star formation and supernovae feedback during the LMC evolution is assumed to proceed both locally and instantaneously in the present study. We assign the metallicity of original gas particle to the new stellar particle and increase the metals of the each neighbor gas particle with the total number of neighbor gas particles equal to $N_{gas}$, according to the following equation about the chemical enrichment:

$$\Delta M_Z = \left( Z_i R_{met} m_s + (1.0 - R_{met}) (1.0 - Z_i) m_s y_{met} \right) / N_{gas}$$

where the $\Delta M_Z$ represents the increase of metal for each gas particle. $Z_i$, $R_{met}$, $m_s$, and $y_{met}$ in the above equation represent the metallicity of the new stellar particle (or that of original gas particle), the fraction of gas returned to interstellar medium, the mass of the new star, and the chemical yield, respectively. The values of $R_{met}$, $y_{met}$, and the initial metallicity are set to be 0.3 and 0.005, and 0.002, respectively. For these values, the final mean metallicity of the inner region of a LMC disk is consistent with the observed one with $[Fe/H] = -0.3 \pm 0.04$ (Luck et al. 1998).

In order to discuss the metallicity distribution of old stars stripped from the LMC disk, we need to assume that the old stellar disk has a metallicity gradient consistent with observations. Friel (1995) has derived the metallicity gradient of the Galactic stellar disk based on the ages and metallicities that are estimated for the Galactic open clusters. Since we do not have any available data on metallicity gradient of open clusters in the LMC, we compromise to use the observed slope of the Galactic metallicity gradient by Friel (1995) for the LMC old stellar disk. We therefore allocate metallicity to each disc star according to its initial position: at $r_L = R_L$, where $r_L$ ($R_L$) is the projected distance in units of kpc from the center of the LMC disk, the metallicity of the star is given as:

$$[m/H]_L = [m/H]_{L=0} + \alpha_d \times R_L.$$  

If we adopt a plausible values of $-0.9$ for the slope $\alpha_d$ (Friel 1995) and the central value of $-0.73$ for $[m/H]_{L=0}$, the mean metallicity of the LMC old disk is $-1.0$ in [Fe/H].

2.3 N-body evolution on the pre-determined orbits

We numerically investigate the evolution of the LMC disk under the gravitational influence by the Galaxy and the SMC for the last $\sim 9$ Gyr (128 dynamical time scales of the LMC) by using the above N-body models of the LMC. We adopt an orbital model (e.g., A) and consider that the LMC (the SMC) in a simulation is always on the predetermined orbit. Based on the orbits of the Clouds derived in the above orbital calculations (i.e., models A – A’), we create a look-up table of positions and velocities of the Clouds at each time step for $-8.8 \leq T \leq 0$ Gyr with the time step width of $1.4 \times 10^6$ yr in each orbital model. The center of mass in the LMC (the SMC) at each time step in a simulation with an orbital model is set to be the same as the location of the LMC (the SMC) at the time step in the look-up table of the orbital model. A fully self-gravitating LMC model is
influenced by the same fixed potential of the Galaxy and the SMC used in the equation (1) and (3), respectively, in a simulation. Since we do not intend to constitute the SMC as a self-gravitating particle system in the present study, possible important physical processes such as direct hydrodynamical interaction between gaseous components of the Clouds and mass-transfer from the SMC to the LMC are not included.

The initial spin of a LMC disk in a model is specified by two angles, $\theta$ and $\phi$, where $\theta$ is the angle between the $Z$-axis and the vector of the angular momentum of a disk and $\phi$ is the azimuthal angle measured from $X$-axis to the projection of the angular momentum vector of a disk onto the $X$–$Y$ plane. We mainly describe the results of the models with $\theta = 99^\circ$ and $\phi = 257^\circ$, because the final structural properties of the LMC disk at $T = 0$ Gyr in this model is broadly consistent with observations in that (1) the simulated LMC disk has a stellar bar with the size of the bar similar to the observed one, (2) the position angle of the simulated bar projected onto the sky is not largely different from the observed one (yet not exactly the same), and (3) the northeast side of the simulated disk is the near side with respect to the Galaxy, which is consistent with the observations by Caldwell & Coulson (1986). The LMC disk precesses and nutates under the tidal torque from the Galaxy during the dynam-

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**Figure 5.** Morphological evolution of old stars and gas seen from the face-on view (referred to as the $x$-$y$ plane) with respect to the LMC disk for the fiducial model.
Formation of the LMC

Weinberg (2000). Therefore it is very hard to choose the initial values of $\theta$ and $\phi$ for which the final internal spin axis of the LMC at $T = 0$ in our simulations is nearly the same as those inferred from observations. Thus, we show the results of the models for which the final structural properties of the LMC are broadly consistent with observations.

We mainly describe the "fiducial model" with the best orbital model/type A, $\theta = 99^\circ$, $\phi = 257^\circ$, $f_g = 0.5$, and $f_r = 0.5$. This is firstly because the parameters of this model are the most reasonably consistent with observations, and secondly because this model shows typical behaviors in dynamical and chemical evolution of the LMC influenced by the Galaxy and the SMC. We also show the results of the representative 21 models thereby discuss the dependences of the results on model parameters such as the orbital types, $\theta$, $\phi$, $f_g$, and $f_r$. The values of these parameters are summarized for each model in the Table 2: Model number (column 1), orbital type (2), $\theta$ in units of degrees (3), $\phi$ in units of degrees (4), and the comments on the models (5).

The initial particle number used in a self-gravitating LMC model is 50000 for the dark matter, 25000 for the old stars, and 25000 for the gas. The total particle number is increased up to $\sim 160000$ owing to the formation of new

Figure 6. The same as Figure 5 but for new stars formed from gas.
field stars and globular clusters. All the simulations have been carried out on GRAPE board (Sugimoto et al. 1990) at the Astronomical Data Analysis Center (ADAC) of the National Astronomical Observatory of Japan. The parameter of gravitational softening is set to be fixed at 0.15 kpc. In the following, in order to show more clearly the morphological and kinematical properties of the simulated LMC, we set the face-one view (edge-on view) of the LMC disk to be always the x-y (x-z) plane by rotating the LMC disk by some degrees at a given time \( T \). Thus it should be noted in the following that the x-y (x-z and y-z) plane is not identical with the X-Y (X-Z and Y-Z, respectively) in the Figure 1.

3 RESULTS

3.1 The fiducial model

3.1.1 Formation of bar and thick disk

Figures 5, 6, and 7 describe the morphological evolution of the LMC for the last \( \sim 9 \) Gyr in the fiducial model. Owing to the smaller mass of the LMC (\( M_{\text{LMC}} = 10^{10} M_\odot \)), the LMC disk is influenced by the strong tidal field of the Galaxy from the early dynamical evolution of the LMC. During the first pericenter passage of the LMC with respect to the Galaxy (\( T \sim -6.8 \) Gyr), two spiral arms composed of old stars and gas are formed within the disk owing to the tidal perturbation from the Galaxy. The distance between the Clouds is larger than \( \sim 100 \) kpc for \( T < -6 \) Gyr so that the SMC does not dynamically influence the LMC in the early dynamical evolution of the LMC. After the first pericenter passage, the bar-like structure composed mostly of old stars is formed in the central region of the disk (\( T = -5.5 \) Gyr).

Formation of field stars starts gradually from the central region of the disk, in particular, from the high density regions of gas along the inner spiral arms of the disk (\( T = -7.1 \) Gyr). As the LMC first passes by the pericenter of its orbit with respect to the Galaxy at \( T = -6.8 \) Gyr, the gaseous regions where field stars are actively forming are shifted from the center to the two remarkable spirals formed by the Galactic tidal perturbation. After the formation of the central bar-like structure (\( T = -5.5 \) Gyr), the gas density within the bar-like structure becomes higher owing to the enhanced rates of cloud-cloud collisions along/within the bar-like structure. As a result of this, the field star formation becomes more efficient within the central bar-like structure. The LMC disk is thus morphologically classified as a barred spiral in the early phase of its evolution (\( T < -5.5 \) Gyr), where the SMC does not dynamically influence the LMC.

As the strong tidal interaction between the Clouds starts (\( T = -3.8 \) Gyr), the stellar bar grows and thus becomes more remarkable compared with the outer stellar disk (\( T = -3.3 \) Gyr). The formation of the stronger bar is associated closely with (1) the tidal perturbation from the SMC and (2) formation of new stars along/within the bar. A significant fraction of old stars (\( \sim 17 \% \)) initially within the outer part of the disk are tidally stripped and field star formation is still ongoing mostly within the bar after the first LMC-SMC encounter. Consequently, most of old and new stars are located in the central bar of the disk at \( T = -2.2 \) Gyr. Tidal interaction between the Clouds and the Galaxy finally results in the formation of an elliptic disk which surrounds the central bar, consists mainly of old stars, and has a major axis misaligned significantly with that of the central bar (\( T = 0 \) Gyr).

As is shown in Figure 7, the initially thin stellar disk is finally transformed into a thick one with the size significantly smaller than its original one owing to the tidal interaction between the Clouds and the Galaxy for the last \( \sim 9 \) Gyr. The strong Galactic tidal field dynamically heats up the stellar disk every time the LMC passes by the pericenter of its orbit with respect to the Galaxy (e.g., \( T \sim -6.8 \) Gyr). The vertical heating by the Galaxy and the resultant thickening of the LMC disk starts from the outer, more fragile part of the disk. After the stellar bar formation (\( T = -5.5 \) Gyr), the disk becomes severely warped and shows a sign of a “banana” shape at \( T = -3.8 \) Gyr. The bending instability following bar formation in tidal galaxy interaction also con-
Fig. 8. The time evolution of the half-mass radius $R_{h}$ and the vertical velocity dispersion ($\sigma_z$) for the fiducial model (solid) and the isolated one (dotted). The value of $R_{h}$ ($\sigma_z$) at each time step, denoted as $R_{h}(T)$ ($\sigma_z(T)$), is normalized to the initial value of $R_{h}(0)$ ($\sigma_z(0)$) at $T = -8.8$ Gyr. Note that $R_{h}$ in the fiducial model dramatically decreases owing to the central new stars efficiently formed during the tidal interaction between the Clouds and the Galaxy. Note also that (1) $\sigma_z$ also significantly increases for $-6 \leq T \leq -2$ Gyr in the fiducial model and (2) the degree of the increase is much more significant in the fiducial model than in the isolated one. These two results suggest that the increase of $\sigma_z$ is not due to the numerical heating caused by small number of stellar particles but due to the tidal heating from the Galaxy and the SMC.

Fig. 9. Time evolution of cloud-cloud collision number (upper), field star formation rate (middle), and globular cluster formation rate (lower) in the fiducial model.
The radial gradients of age (lower) and metallicity (upper) in the LMC disk at $T = 0$ Gyr in the fiducial model.

$\sim 0.4 \ M_\odot \ yr^{-1}$ (averaged for 0.1 dynamical time of the LMC corresponding to $\sim 13$ Myr) owing to the formation of strong, double-armed gaseous arms, where gas density becomes significantly high. The cloud-cloud collision rate is dramatically (more than an order of magnitude) enhanced within $\sim 0.5$ Gyr after the pericenter passage, because the strong Galactic tidal effects increase the velocity dispersion of the gas clouds. However, the cloud-cloud collisions that leads to the formation of GCs in the disk do not occur in this first pericenter passage, just because the tidal perturbation is not strong enough to trigger cloud-cloud collisions with moderately high relative velocities (between 30 and 100 km s$^{-1}$) and small impact parameters ($< 0.25$).

Owing to the rapid gas consumption by formation of field stars during/after the first pericenter passage of the LMC, the formation rate of the field stars does not increase significantly until the strong Galaxy-LMC-SMC tidal interaction begins at $T \sim -3.8$ Gyr. The tidal perturbation from the SMC and the Galaxy triggers the moderately enhanced star formation rate of $\sim 0.1 \ M_\odot$ for $-3.5 < T < -2$ Gyr. During this period, the GC formation also becomes efficient, essentially because the combined tidal effects of the Galaxy and the SMC are strong enough to enhance cloud-cloud collisions required for GC formation in the LMC disk. The peak of the GC formation ($\sim T \sim -2.5$ Gyr) is nearly coincident with that of the field stars for $-3.5 < T < -2$ Gyr. The GC formation also occurs at $T \sim -0.2$ Gyr, when the LMC-SMC distance becomes very small (less than 10 kpc; smaller than the original LMC disk size) so that the LMC collides with the SMC. This final collision between the Clouds around 0.2 Gyr ago could have significant effects in the recent star

formation histories of the LMC, as suggested by previous authors (e.g., GSF).

About 47% of the initial gas is converted into new field stars for the last $\sim 9$ Gyr evolution of the LMC and most of new stars are concentrated in the central bar. Only 0.5% of the gas is converted into GCs, which reflects the fact that the cloud-cloud collisions with moderately high speed (between 30 and 100 km s$^{-1}$) and small impact parameter ($< 0.25$), required for cluster formation, do not occur until the LMC begins to interact violently with the SMC when the two are less than 10 kpc apart ($T = -3.6$ Gyr). Chemical enrichment resulting from the moderately enhanced star formation increases gradually the metallicity of new field stars and GCs. For the fiducial model with the initial gaseous metallicity of 0.002 ([Fe/H] = -1.0), $g_{\text{met}}$ (chemical yield) of 0.005, and $R_{\text{met}}$ of 0.3, the mean metallicity of new field stars within the disk and the halo finally becomes 0.007 (-0.46 in [Fe/H]) at $T = 0$ Gyr (It should be emphasized here that the final metallicity depends strongly on the initial values of the initial metallicity, $g_{\text{met}}$, and $R_{\text{met}}$).

Chemical enrichment proceeds more in the central re-
Figure 12. The age distribution of new stars inside the stellar bar (solid) and outside the bar (dotted) at $T = 0$ Gyr in the fiducial model. A new star is regarded as “inside the bar”, if the distance of the star along the major axis of the bar is less than 5 kpc and if that along the minor axis are is less than 1.5 kpc. For convenience, the normalized number of new stars is shown. The epochs of the pericenter passage of the SMC with respect to the LMC are shown by thick arrows for comparison. Note that the age distribution of new stars inside the bar shows the peak around $\sim 2$ Gyr whereas that outside the bar shows the peak around 6 Gyr.

Figure 13. Radial dependences of line-of-sight-velocity ($V_y$) and velocity dispersion ($\sigma_y$) along with the $x$-axis for old stars (upper) and for new stars (lower) at $T = 0$ Gyr in the fiducial model.

Figure 14. Radial dependences of vertical velocity dispersion ($\sigma_z$) for old stars (thick solid) and new stars (thin solid) with the vertical distance $|z|$ from the disk plane of the LMC less than 1 kpc (upper) and those with $|z|$ less than 7.5 kpc (lower) at $T = 0$ Gyr in the fiducial model. For comparison, the results of the isolated model are also shown by dotted lines.
lar population inside the bar is dominated by new stars that are formed after the Galaxy-LMC-SMC interaction becomes stronger owing to the dynamical coupling of the Clouds. The bump around the ages of $6 - 8$ Gyr in the age distribution inside the bar suggests that some fraction of new stars formed in the early Galaxy-LMC interaction. The age distribution outside the bar, on the other hand, has a peak around 6 Gyr, which means that the stellar population outside the bar is dominated by new stars formed in the early evolution of the LMC, in particular, those formed during the Galaxy-LMC interaction $6 - 7$ Gyr ago. These results in Figures 11 and 12 suggest that (1) the dominant stellar population is significantly different between different regions of the LMC disk and (2) the difference is due essentially to the Galaxy-LMC-SMC interaction which forms a bar and thus drives efficient inner transfer of interstellar gas.

3.1.3 Kinematics

The long-term tidal perturbation from the Galaxy and the SMC to the LMC causes dramatic changes in kinematical properties of the disk that is initially “dynamically cold”. Figure 13 shows that the rotational velocity of old stars (hereafter referred to as $V_{rot}$, and represented as $V_c$ in Figure 13 for convenience) has a peak value of $\sim 50$ km s$^{-1}$ around the central $3 - 4$ kpc and then decreases sharply toward outward from there. The ratio of the maximum value of $V_{rot}$ to $V_m$ (the maximum value of the circular velocity $V_c$ in the initial disk) for old stars is $\sim 0.7$, which implies that azimuthal/ radial velocity dispersion of old stars is significantly increased by the Galaxy-LMC-SMC interaction. $V_{rot}$ decreases outside the central $3 - 4$ kpc much more sharply than expected from the initial mass profile of the LMC. The initial disk shows a decrease by a factor of $\sim 17$% in $V_c$ (and thus $V_{rot}$) for $5 \leq R_L \leq 10$ kpc whereas $V_{rot}$ in the final LMC disk shows a decrease by a factor of $\sim 60$% in $V_{rot}$ for the corresponding region. This clearly indicates that the long-term dynamical heating of the LMC disk by the Galaxy and the SMC changes the shape of the rotation curve of the LMC.

The initial radial profile of azimuthal velocity dispersion of old stars is monotonously decreasing toward the outer region of the LMC disk. As shown in Figure 13, the velocity dispersion $\sigma_\varphi$ (a measure of azimuthal velocity dispersion) shows a large value of $30 - 40$ km s$^{-1}$, which is even larger than the central one of $\sim 20$ km s$^{-1}$, around $7 - 8$ kpc from the center of the disk. This result confirms that the long-term dynamical heating by the Galaxy and the SMC drives the kinematical change of the LMC’s outer disk that is more susceptible to external tidal perturbation. The results of the new stars are essentially the same as those of old ones, except that (1) the velocity dispersion $\sigma_\varphi$ is on average smaller in new stars than in old ones and (2) the maximum $V_{rot}$ is only slightly larger in new stars than in old stars probably because of gaseous dissipation. The asymmetric profiles of $\sigma_\varphi$ and $V_{rot}$ seen both in old stars and in new ones are due partly to the collision between the Clouds at $T \sim -0.2$ Gyr.

Figure 14 shows that the radial gradient of the vertical velocity dispersion $\sigma_z$ of the disk for stars with the vertical distance ($|z|$) from the disk plane equal to or less than 1.5 kpc (i.e., those stars within the thick disk). It is clear from this Figure 14 that $\sigma_z$ of old stars shows a monotonous decrease for $R_L \leq 4$ kpc and begins to increase gradually and slightly toward outward from there, though the profile for $R_L > 4$ kpc is somehow irregular. The outwardly increasing $\sigma_z$ is more remarkable for old stars with $|z| \leq 7.5$ kpc, because these stars include some fraction of old halo stars that form a kinematically hot stellar system around the LMC. The larger $\sigma_z$ in the outer LMC disk means that the scale height also increases with radius for $R_L > 4$ kpc. These results are broadly consistent with recent observational results by Alves & Nelson (2000) and vdMAHS.

$\sigma_z$ is increased by a factor of 2.4 in the center of the disk and a factor of 5.5 at $R_L = 8$ kpc for the old stars with $|z| \leq 1.5$ kpc owing to the long-term tidal interaction between the Galaxy and the Clouds. The radial profiles of $\sigma_z$ for new stars also show such an outwardly increasing $\sigma_z$ for $R_L > 4$ kpc, though the increase is less remarkable compared with that seen in old stars. $\sigma_z$ of new stars is on average lower than that of old stars for nearly every radii, essentially because new stars are formed from gas that dissipates away random kinematical energy yielded by the Galaxy-LMC-SMC interaction. The central “dip” in the radial profile of $\sigma_z$ for new stars is also caused by efficient gaseous dissipation there. Thus Figures 13 and 14 suggest that the outer kinematics of the LMC disk have valuable information on the past interaction history of the LMC with the Galaxy and the SMC.

Figure 15 describes a relation between velocity dispersion of $\sigma_z$ and ages (i.e., so-called “age-dispersion relation”) for new stars of the LMC disk. The isolated model shows the trend of decreasing $\sigma_z$ with decreasing ages, which reflects the fact that a new star formed more recently originates from gas that has experienced a larger amount of gaseous dissipation. This tendency is seen in the disk of the fiducial model for the new stars with the ages older than $\sim 4$Gyr.
Formation of the LMC

Figure 16. The distribution of halo old stars (upper left) and halo new ones (lower left) seen from the edge-on of the LMC disk and the radial dependences of the line-of-sight velocity parallel to the $y$-axis ($V_y$ for halo old stars (upper right) and for halo new stars (lower right) at $T = 0$ Gyr in the fiducial model. Here a star can be classified as a “halo” star either if the projected distance from the center of the LMC disk is less than 7.5 kpc or if the vertical distance from the LMC disk plane is less than 1.5 kpc.

Figure 17. The projected density distribution of halo stars at $T = 0$ Gyr (solid) and at $T = -5$ Gyr (dotted) in the fiducial model. For comparison, the radial distribution of stars in the initial exponential disk is shown by a dashed line for comparison. The definition of “halo stars” is the same as that described in Figure 16. Though the mean $\sigma_z$ is more than a factor of 2 higher in the fiducial model than in the isolated model owing to the dynamical heating by the Galaxy. However, the new stars with the ages younger than $\sim 4$ Gyr show an interesting tendency of $\sigma_z$ slightly increasing with decreasing ages. This is probably because a new star formed more recently originates from gas that is more strongly randomized by the combined tidal effects of the Galaxy and the SMC. The net effect of gaseous dissipation is weaker than that of randomization of gaseous motion by the stronger tidal perturbation from the Galaxy and the SMC for the last $\sim 4$ Gyr. These results imply that the age-dispersion relation in stellar populations of the LMC disk is significantly different from that observed in the Galaxy.

Figure 18. Final radii of halo old stars as a function of the initial radii (upper) and the number distribution of the initial radii of the stars that are regarded as “halo stars” at $T = 0$ Gyr (lower) in the fiducial model. The definition of “halo stars” here is the same as described in Figure 16. The long-dashed and short-dashed lines represent the initial tidal radius $r_t$ (= 13 kpc) and $\sim 3 R_0$ (7.5 kpc), where $R_0$ is the scale radius of the initial LMC disk, respectively. Stars above the dotted line are those for which the final radii are larger than the initial ones (i.e., they are transferred outward due to the tidal effects of the Galaxy and the SMC). For convenience, the normalized number (i.e. number fraction) is shown in the lower panel. Note that most of the halo stars originate from the outer part ($R > 4$ kpc) of the initial LMC disk.
3.1.4 Stellar halo properties

One of the important outcomes of the long-term tidal interaction between the Clouds and the Galaxy is the formation of a stellar halo through the redistribution of old stars initially within the LMC disk. It should also be stressed here that our disk models initially do not include very old (\(\sim 10 - 13\) Gyr), metal-poor ([Fe/H] < -1.6) stellar halo components that the Galaxy is observed to have. Therefore, the halo properties in the present study are dependent totally on those of old stars and new stars stripped from the original disk. Accordingly, direct comparison of the present numerical results with observations is not simply possible, because the LMC stellar halo may contain the old stellar halo that was formed prior to its disk formation. We thus suggest that the present results may well be able to be compared with observational results for halo stars with ages less than \(\sim 9\) Gyr.

As have been shown in Figure 7, some fraction of old stars stripped from the outer part of the disk due to the Galaxy-LMC-SMC interaction are redistributed in the outer halo region of the disk. Figure 16 shows structural and kinematical properties of the stellar halo composed of stars either outside the disk (i.e., \(R_L > 7.5\) kpc) or well above/below the thick disk (i.e., \(|z| > 1.5\) kpc). Although these old halo stars have a relatively homogeneous distribution within the central \(\sim 6\) kpc, they have an elongated distribution for a wider field (\(12\) kpc \(\times 12\) kpc) of view owing to the old stars being now dynamically influenced by the tidal fields of the Galaxy and the SMC. The new stars in the halo also show such an elongated distribution, though it is less remarkable compared with old halo stars. The new halo stars appear to be more flattened compared with old halo ones for the central \(\sim 6\) kpc because of the smaller number of the stars with \(|z| > 4.0\) kpc. Since the mass fraction of the new stars in the halo region is only \(\sim 2\)%, the entire distribution of the halo is determined by old halo stars: The halo has an inner homogeneous distribution and an outer elongated (thus inhomogeneous) one.

As shown in Figure 16, both old and new halo stars show a sign of rotation, in particular, for those within the central 2 kpc, if they are seen from the edge-on view. Although the inner stellar components with a certain amount of rotation should be regarded as parts of the thick disk rather than the halo, the moderately rotating inner halo is regarded as an important characteristic that the stellar halo has if it originates from the outer part of the initially thin stellar disk through the redistribution of the stars during the Galaxy-LMC-SMC interaction. Figure 17 shows that (1) the projected density of the stellar halo at \(T = 0\) Gyr is roughly approximated as an exponential profile with the slope shallower than the original exponential disk for \(R_L > 2\) kpc, (2) the projected density of the stellar halo is on average more than an order of magnitude lower than the original stellar disk and the difference in the density depends strongly on the radius, and (3) the projected density profile changes significantly with time at a given radius and it becomes steeper as the time passes by.

Figure 18 demonstrates that about 75% of old stars in the halo (at \(T = 0\) Gyr) originate from the disk regions with the distances larger than 5 kpc. This is because the tidal stripping of old disk stars and the subsequent redistribution of the stripped stars more efficiently occur during the Galaxy-LMC-SMC interaction. As a natural result of this, the final metallicity distribution function (MDF) in the old halo stars is expected to be significantly different from that of the initial disk. Figure 19 shows a possible MDF of the old halo stars for the fiducial model with an initial negative metallicity gradient (described in the equation (11) in \(\S\)2) and the mean metallicity of [Fe/H] = -1. The MDF in this Figure 19 clearly shows a peak around [Fe/H] = -1.2 \(\sim -1.3\), which is by \(\sim -0.3\) (in dex) lower than that of the initial disk and is by \(\sim -0.4\) (in dex) higher than that of the observed Galactic stellar halo (e.g., Freeman 1987). The derived lower metallicity of the old halo stars is due to the stars originating preferentially from the outer disk regions where the stellar metallicity is lower owing to the negative metallicity gradient.

The derived difference in the MDF between the simulated stellar halo and the observed Galactic stellar halo probably reflects the fact that the formation history of the Galactic stellar halo is significantly different from what is described in this paper (e.g., Bekki & Chiba 2000, 2001). One of the significant differences between the simulated stellar halo and the observed Galactic one is that the simulated halo includes a fraction of relatively metal-rich (\(-1 < [\text{Fe/H}] < -0.3\)) and moderately young stars, though the mass fraction of these populations among the entire halo population is very small (\(\sim 2\)%). These metal-rich halo components result from the tidal stripping of new stars formed the LMC disk in the later phase of the Galaxy-LMC-SMC interaction. Therefore, the detection of such metal-rich, young stars within the LMC halo region in future observations could be an evidence that the Galaxy-LMC-SMC interaction is partly responsible for, at least, some part of the LMC stellar halo.

3.1.5 Properties of GCs

Figure 20 summarizes structural and kinematical properties of old and new GCs in the fiducial model at \(T = 0\) Gyr. As shown in this Figure 20, the final spatial distribution is remarkably different between the old GCs and the new ones. The new GCs has a more compact distribution than the old GCs and most of them are concentrated within the central region.
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Figure 20. The distribution of old GCs projected onto the x-y plane (top left) and onto the x-z one (top right) and that of new GCs projected onto the x-y plane (middle left) and onto the x-z one (middle right) at \( T = 0 \) Gyr in the fiducial model. The bottom panel shows the radial profiles of vertical velocity dispersion (\( \sigma_z \)) for old GCs (thin solid) and for new GCs (thick solid).

Figure 21. Age distributions of field stars (dotted) and clusters (solid) at \( T = 0 \) Gyr in the fiducial model. For convenience, the normalized fraction of stars in each age bin is shown.

\(~3\) kpc. This is essentially because the new GCs form only in the high-density gaseous regions where the cloud-cloud collisions with moderately high speed (between 30 and 100 \( \text{km s}^{-1} \)) and small impact parameter (< 0.25), required for cluster formation, occur. The face-on distribution of the new GCs is fairly elongated with the direction of the elongation nearly parallel to the major axis of the stellar bar: Most of the new GCs are within the stellar bar in the disk. Nearly all of the new GCs is confined within 1 kpc from the LMC disk plane, which reflects the fact that the new GCs originate from the high-density regions in the thin gaseous disk.

The old GCs, on the other hand, show a more wide spread distribution and are not necessarily confined in the central bar region of the disk. The edge-on distribution of the old GCs shows a thick-disk appearance with the two GCs having \( |z| > 3 \) kpc and being able to be regarded as halo GCs. These two halo GCs are initially in the outer stellar disk and thus tidally stripped and subsequently distributed in the halo region. Figure 20 also shows a few differences in the final radial profile of vertical velocity dispersion (\( \sigma_z \)) between the two different GC populations, though the final profiles of \( \sigma_z \) are severely influenced by the tidal perturbation from the Galaxy and the SMC, in particular, from the collision with the SMC around \( T \sim -0.2 \) Gyr (Here the center of mass of field stars is adopted for the estimation of kinematics). \( \sigma_z \) is systematically higher in the old GCs than in the new GCs throughout the disk, because the old GCs experienced for a much longer time (\( \sim 9 \) Gyr) the tidal heating from the Galaxy (and the SMC) than the new GCs all of which are formed relatively recently (\( T < -3.3 \) Gyr).

Figure 21 describes the difference in the age distributions between the new field stars and the new GCs in the disk. It is clear from this figure that all clusters have ages younger than \( \sim 3.3 \) Gyr whereas the field star population show a wide distribution of ages. This result reflects the fact that the field star formation is sensitive to local gas density whereas the cluster formation occurs only when random motion of gas in the LMC becomes significantly large. The mean metallicity of the new GCs at \( T = 0 \) Gyr is by \(-0.08\) dex (in [Fe/H]) higher than that of the new field stars, because chemical enrichment associated with field star formation proceeds efficiently prior to the formation of new GCs (i.e., \( T < \sim -3 \) Gyr) and consequently the new GCs are thus formed from more metal-rich gas. The derived difference suggests that if future observations on the detailed age distribution of field stars for the entire disk region of the LMC reveal the differences in age andmetallicity distributions between field stars and GCs, the difference can be understood in terms of the difference in the formation processes between field stars and GCs during the Galaxy-LMC-SMC interaction.

3.2 Dependences on model parameters

We have described the results of the fiducial model in which the model parameters are consistent with the latest observations and thus the most realistic and reasonable. However, there are still some observational uncertainties in estimating the total mass of the LMC (vdMAHS). Considering this uncertainty, we mainly show the results of the more massive model (model 9) with larger LMC mass (\( M_{\text{LHC}} = 2.0 \times 10^{10} \, M_\odot \)) in this subsection. We also briefly summarize the
3.2.1 LMC mass

The adopted LMC mass $M_{\text{LMC}}$ is consistent with the observation by vdMAHS but smaller than that adopted in most of previous studies with $M_{\text{LMC}} = 2.0 \times 10^{10} \, M_\odot$ (GN). Accordingly, it is important to investigate how the LMC evolution depend on its mass if it has a larger mass. The stellar disk of the more massive LMC in the model 9 (10) is less susceptible to tidal perturbation from the Galaxy and the SMC than that in the fiducial model, because it is more strongly self-gravitating. As a result of this, the SMC in this model does not so strongly influence the LMC disk dynamically even after it dynamically couples with the LMC ($T \sim 6 \, \text{Gyr}$) in comparison with the fiducial model. We summarize our principle results of the more massive LMC model 9 as follows.

1. The formation of a global stellar bar cannot be completed until $T = -0.5 \, \text{Gyr}$. This delayed formation of the stellar bar is due to the stronger self-gravity which prevents the Galactic tidal field from exciting the non-axisymmetric bar instability in the LMC disk. Only spiral arms are excited by the Galactic tidal field in the early dynamical evolution of the LMC. As a natural result of the delayed bar formation, the bending/warping associated with the bar formation occurs around $T = 0 \, \text{Gyr}$ and is accordingly seen in the edge-on view of the LMC at $T = 0 \, \text{Gyr}$ (See Figure 22).

2. As shown in Figure 22, the disk cannot be thickened so much compared with the fiducial model owing to the relatively weak tidal perturbation from the Galaxy. Figure 23 shows that the vertical velocity dispersion ($\sigma_z$) consequently increases very slowly during the Galaxy-LMC-SMC interaction until the last collision between the LMC and the SMC at $T = -0.2 \, \text{Gyr}$. The final $\sigma_z$ is $\sim 2.2$ times larger than the initial value and thus is a factor of 1.4 smaller than that of the fiducial model with a smaller $M_{\text{LMC}} (10^{10} \, M_\odot)$. This result implies that kinematical evolution of the stellar disk of the LMC strongly depends on its mass during the Galaxy-LMC-SMC interaction.

3. The abrupt increases of $\sigma_z$ between $-0.2 < T < 0 \, \text{Gyr}$ seen in Figure 23 is due to the strong tidal perturbation caused by the LMC-SMC collision. There are no significant differences in the evolution of the half-mass radius ($R_h$) between the isolated LMC model 10 and the model 9, because radial mass transfer, which drives a dramatic change of $R_h$, is not efficient both in the isolated model 10 and the model 9.

4. The total mass of old stars stripped from the LMC disk is smaller in the more massive LMC model (model 9) than in the fiducial model, because the LMC is more strongly bounded by self-gravity in the more massive LMC model. As a result of this, the “tidal stream” composed of the stripped stars shown in Figure 24 is less clearly seen in the more massive model. This result implies that projected number density of the Galactic halo stars along the possible tidal

Figure 22. The same as Figure 7 but for the model 9.

Figure 23. The same as Figure 8 but for the model 9.

Figure 24. The final distribution of old stars stripped from the LMC disk in an Aitoff projection (upper) and for the model 9 (lower). The preset locations ($T = \, \text{Gyr}$) of the LMC and the SMC are indicated by a large filled circle and a small filled one, respectively, whereas the locations of the LMC and the SMC $\sim 9 \, \text{Gyr ago}$ ($T = -8.8 \, \text{Gyr}$) are indicated by a large open circle and a small open one, respectively.

Parameter dependences on less important parameters (e.g., orbits of the Clouds and $f_i$).

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stream formed from stars stripped from the LMC stellar disk provides a valuable information of the LMC mass.

(5) The formation efficiency of new field stars (estimated from the fraction of the mass of new stars to the initial gas mass) is similar between the more massive LMC model and the fiducial model (43 % and 47 %, respectively). All of the new GCs are formed only after $T < -3$ Gyr and most of the newly formed GCs have the ages of $< 2$ Gyr in the model 9.

3.2.2 Other parameters
The parameter dependences of the present simulations are summarized as follows.

(1) Final structural and morphological properties of the LMC disk and star formation histories of field stars and GCs do not depend strongly on $\theta$ and $\phi$ (i.e., inclination of the disk) for a reasonable set of these values. For example, mass fraction of gas converted into new field stars range from 40 $\%$ to 47 $\%$ for the models 1, 3, 4, 5, 8 and all these models show a central stellar bar composed both of old field stars and new ones at $T = 0$ Gyr.

(2) The present results do not depend on the shape of the dark matter halo (models 5 and 6), essentially because the model parameters of the NFW halo are chosen such that $V_m$ and the shape of the rotation curve are similar to those of the fiducial model. The epoch of the commencement of the GC formation does not depend on the shape of the dark matter halo, which confirms that the most recent episode of globular cluster formation in the LMC is related to the commencement of strong tidal interactions between the LMC, the SMC and the Galaxy.

(3) The star formation histories of field stars and GCs depend on the orbital evolution of the Clouds (model 11–17), although the final barred morphology is not so different between the models. For example, the formation rate of field stars before $T = -4$ Gyr is significantly higher than that after $T = -4$ Gyr, for the model with the orbital type I (i.e., model 15), in which the LMC-SMC distance does not become so small compared with the fiducial model. As a result of this, the age distribution of new field stars in this model 15 has no peak around $T = -2$ Gyr where the fiducial model shows its secondary peak in the age distribution: The age distribution of field stars provides a fossil record of the Galaxy-LMC-SMC interaction history that is totally determined by the orbits of these three.

(4) The model without the SMC’s tidal effect (model 17) shows much less efficient formation of field stars and GCs compared with the fiducial model with the SMC. For example, the mass fraction of gas converted into new field stars (new GCs) for the last $\sim 9$ Gyr in the model without the SMC is only 62 (17) $\%$ of the fiducial model with the SMC. This result strongly suggests that the tidal perturbation from the SMC plays an important role in the star formation history of the LMC, in particular, in the GC formation.

(5) The dissipative dynamics of interstellar medium during the Galaxy-LMC-SMC interaction also controls the formation histories of field stars and GCs, though it cannot significantly change the age distributions of these stellar populations (models 1 and 18–21 with different $f_r$). In particular, the formation efficiency of GCs (i.e., the total number of new GCs) strongly depends on $f_r$ in the sense that the efficiency is higher in the model with larger $f_r$ (i.e., more dissipative).

4 DISCUSSION

4.1 Born as a pair or different entities?
It remains unclear whether the Clouds were born initially as a primordial pair of galaxies at the epoch of galaxy formation (hereafter referred to as “the primordial binary galaxy model” just for convenience) or formed as different entities at different places and have only recently become a close pair for the first time (“the recent coupling model”). This question is the central core of any problems related to the long-term evolution of the Clouds (\(\sim 10\) Gyr), because strong dynamical interaction between the Clouds significantly influences not only star formation histories but also structure and kinematics of the Clouds if they are strongly coupled. The primordial binary galaxy model has the following two advantages in explaining some physical properties of the Clouds. Firstly, previous numerical studies showed that structural and kinematical properties of the Magellanic stream are self-consistently explained by the models for which the Magellanic Clouds have remained in a binary state for the past 15 Gyr (MF; GSF; GN; YN). Secondly, such a primordial binary galaxy model of the Clouds also naturally explains active star formation about 0.2 Gyr ago in the LMC disk (GSF) and structural properties of the stellar halo and the very recent star formation history of the SMC (GN; YN). MF discussed whether the binary Clouds could be formed from a single protogalaxy via tidal fission \(\sim 15\) Gyr ago. Since these previous studies showed only binary galaxy models that explain the above observational properties of the Cloud and the Magellanic Stream, it is not so clear whether other models for which the duration of the binary state of the Clouds does not exceed \(\sim 15\) Gyr can equally explain physical properties.

In calculating the orbital evolution of the Clouds, the above previous studies adopted the following two assumptions that are not so consistent with the latest observations of LMC’s structure and kinematics (e.g., vdMAHS): (1) the LMC has a mass of $2 \times 10^{10} M_\odot$ and (2) dynamical friction between the Clouds is negligible. The present study has demonstrated that if we adopt more reasonable assumptions as to the above (1) and (2), it is not possible for the Clouds to remain in a binary state for the last 13 Gyr. It has therefore suggested that the LMC and the SMC could have dynamically coupled relatively recently (\(\sim 4\) Gyr ago) for the first time and thus were born not as a binary but as different entities. These results never mean that the primordial binary galaxy models (e.g., MF) can be ruled out, because there are still some uncertainties in the mass estimation of the LMC by vdMAHS. It rather suggests that it depends on the model parameters. In particular, the LMC mass determines how long the Clouds can keep their binary state in their dynamical history: More precise mass estimation of the LMC is doubtless worthwhile for the better understanding of the orbital evolution of the Clouds.

Formation histories of field stars and globular clusters and structural and kinematical properties in the LMC are
observed to be different from those in the SMC (e.g., van den Bergh 1981; 2000). For example, the “age gap” (i.e., only one cluster with the age ranging from \( \sim 13 \) Gyr to \( 3 \) Gyr) observed in LMC’s globular clusters does not exist in SMC’s globular clusters (e.g., Piatti et al. 2002). Since strong tidal perturbation triggers the formation of globular clusters (e.g., Bekki et al. 2002), it is not clear why formation histories of star clusters are different between the two in the primordial binary model, in which the Clouds have been perturbing one another from their initial dynamical state until now.

The observational fact that the age gap is seen only in the LMC can be understood in terms of the recent coupling model as follows. The LMC was formed as a relatively low surface brightness galaxy, being more distant (\( \sim 150 \) kpc, corresponding to the apocenter of its early orbit) from the Galaxy so that the Galactic tidal field alone could not trigger cluster formation efficiently until it first encounters with the SMC. In contrast, the less massive SMC, which is therefore more susceptible to the Galactic tide, was born less distant (\( \sim 100 \) kpc) from the Galaxy, and thus influenced by the Galaxy strongly enough to form globular clusters from the early evolutionary stage (several to \( 10 \) Gyr ago). Thus the difference in cluster formation histories between the Clouds can be due to the differences in the birthplaces and initial masses between the two in the recent coupling model.

Although Magellanic-type galaxies that appear to be pairs of galaxies are not rare (e.g., Freeman 1984), it is not so observationally clear whether these apparently pairs of galaxies were formed \( \text{initially as pairs at the epoch of galaxy formation or have only recently become pairs owing to recent tidal capture or interaction of galaxies (e.g., Helou 1984). It is accordingly difficult for us to derive some hints on the above question as to the binary state of the Clouds from observations on other Magellanic-type pair. Currently available proper motion data for the Clouds has the accuracy of } \sim 3 \text{ mas yr}^{-1} \text{ (corresponding to } \sim 700 \text{ km s}^{-1} \text{ error of a single star for the distance to the Clouds) so that we cannot determine the duration of the LMC-SMC binary state directly from observational data on the proper motion and the radial velocities of the Clouds (e.g., Westerlund 1997). Future astrometric missions with the } \sim 10 \text{ mas accuracy (corresponding to } \sim \text{ a few km s}^{-1} \text{ ) will allow us to derive an unambiguous answer for the problem as to the binary state of the Clouds.}

## 4.2 Stellar halo formation in the LMC and Magellanic-type dwarfs

Old, metal-poor stellar halo populations of a galaxy have long been considered to be “fossil records” which contain valuable information on dynamical and chemical evolution of the galaxy (e.g., Eggen, Lynden-Bell, & Sandage 1962).

Recent numerical simulations based on the currently favored cold dark matter (CDM) theory of galaxy formation have demonstrated that basic physical processes involved in the formation of the stellar halo are described by both dissipative and dissipationless merging of subgalactic clumps and their resultant tidal disruption in the course of gravitational contraction of the Galaxy at high redshift (Bekki & Chiba 2000, 2001). Previous studies also suggested that (1) merging of subgalactic clumps is an essentially important process for the stellar halo formation in disk galaxies like the Galaxy and (2) the physical properties of the halos depend on the details of the merging processes of subgalactic clumps (Bekki & Chiba 2000, 2001). It is, however, unclear (1) whether stellar halos exist in less luminous disk (or irregular/dwarf) galaxies like the LMC and (2) how they are formed in the course of their formation.

The present study has demonstrated that (1) the stellar halo is formed from redistribution (in space) of stars initially within the outer part of the disk in the LMC even if the LMC has \( \text{initially no stellar halo}, \) (2) the developed stellar halo contains some fraction of younger stars, and (3) the spatial distribution of the outer stellar halo is not homogeneous. Accordingly the present study suggests that the formation process of the LMC’s stellar halo differs from the Galactic one in that it is not associated with any merging of subgalactic clumps. The above result (1) furthermore implies that (i) the LMC could either have no or little amount of stellar mass in its halo at the epoch of its formation, even if it is now observed to have the kinematically hot stellar halo (Minniti et al. 2003; Alves 2004), and (ii) it acquired the substantial mass of the halo owing to the strong tidal interaction between the Galaxy and the SMC (This could be true for the SMC, which could suffer more severe tidal perturbation from the Galaxy and the LMC (than the LMC could)). The present results thus raise the following two issues as to the stellar halo formation in less luminous disk galaxies: (1) whether less luminous disk galaxies are formed initially without old stellar halos and (2) if so, why no stellar halos are formed in such galaxies at the epoch of galaxy formation.

Recently the physical properties of old stellar halos in such less luminous galaxies have been investigated, in particular, in dwarf galaxies in the Local Group (e.g., Demers et al. 2003). One of the intriguing results is that NGC 3109, a Magellanic-type dwarf on the outskirts of the Local Group, contains carbon stars nearly exclusively in and near its disk component, whereas NGC 6822, a galaxy with the same morphological type, has an extended intermediate-age halo as well as an old halo. This suggests that the formation of an old stellar halo is strongly suppressed in some of Magellanic-type dwarfs like NGC 3109. The following two mechanisms are considered for suppressing the formation of a stellar halo. One is that while the formation of disk galaxies like NGC 3109 may accompany merging/accretion incidents of subgalactic clumps, if such clumps were totally gaseous without containing old stars, the accretion/merging of gaseous clumps would not leave a diffuse halo component, which originates from tidal disruption of pre-existing stars. The other is that the initial gas distribution in these galaxies were so diffuse that star formation could happen only after the settlement of gas onto the disk plane, whereby the regions with high gas density emerged.

If we adopt the currently favored theory based on hierarchical assembly of CDM (White & Rees 1978), the above second scenario seems less likely, because the CDM model predicts higher overdensities for galaxies embedded in less massive dark halos. Then, if the first scenario is the case, what is the most likely mechanism for the suppression of star formation within subgalactic clumps which end up with less luminous (Magellanic-type dwarf) disk galaxies? One possible mechanism is that thermal and/or kinematic feedback supplied by supernovae significantly suppresses star forma-
tion in subgalactic clumps which end up with less luminous disk galaxies (e.g., Dekel & Silk 1986). In this mechanism, less massive clumps are susceptible to supernova explosions owing to their shallower gravitational potential. Alternatively, the UV background in the Universe suppresses the formation of dwarf galaxies via photoionization effect (e.g., Bullock, Kravtsov & Weinberg 2000), in such a way that less massive galaxies with lower virial temperature may be more affected. We note that these mechanisms are also clues to solving the problem of overabundance in the number of CDM subhalos in the Local Group (Klypin et al. 1999). Better understanding of such suppression effects of galaxy formation may also resolve the current issue of stellar halos in less luminous disk galaxies.

The present study predicts that if the major component of the stellar halo in a less luminous (Magellanic-type dwarf) disk galaxy is formed by tidal interaction with other more luminous galaxies, the disk galaxy has (1) relatively young stellar halo populations, most of which come from the outer disk stars formed before the interaction and (2) the disk has a thick disk formed through the disk heating by tidal interaction. Therefore, future observations on (1) age and metallicity distributions of halo stars in Magellanic-type dwarf disk galaxies and (2) statistical correlations between the presence of the outer stellar halos and that of the faint thick disk components will help us to determine whether the stellar halos in such dwarfs are formed from tidal galaxy interaction rather than from primordial merging/accretion of subgalactic clumps. Heidmann et al. (1972) revealed that the intrinsic flattening in disk galaxies decreases (i.e., less flattened) abruptly from Sm to Im Hubble types. If this less flattened nature is due to disk heating in these dwarf irregulars, it is an observationally interesting question (related to the stellar halo formation via tidal interaction) whether spherical stellar halos are more likely to be observed in Im rather than Sd galaxies. In the stellar halo formation scenario via tidal interaction, the age distribution of halo stars in a galaxy depends strongly on when the galaxy interacted with other galaxy. Therefore, future observations on the age distribution of halo stars will also provide valuable information on the past interaction history of the galaxy.

4.3 Origin of the LMC’s stellar bar

Recently several observational studies have attempted to derive age and metallicity distributions of stellar populations in the bar region of the LMC in order to constrain the star formation history (SFH) in the bar (Elson et al. 1997; Ardelberg et al. 1997; Holzman et al. 1999; Olsen 1999; Smecker-Hane et al. 2002). There however exists some discrepancy in the results of the SFH of the bar between different observations, possibly because authors investigated SFHs of different regions within the bar using different number of stars analyzed (e.g., Smecker-Hane et al. 2002). For example, Elson et al. (1997) investigated photometric properties of ∼ 15800 stars obtained by the HST for the inner LMC disk and found a possible evidence of a later starburst around 1 Gyr ago which may be responsible for the bar formation in the LMC disk. Smecker-Hane et al. (2002) revealed that star formation of the dominant populations in the LMC bar occurred from 4 to 6 and 1 to 2 Gyr ago. Olsen (1999) suggested that the LMC bar region appears to have high levels of star formation activity as long as 5–8 Gyr ago: The LMC bar is dominated by old stellar populations.

The present study has demonstrated that (1) a large fraction of stars (up to 50 %) in the bar are formed during the strong tidal interaction between the Clouds and the Galaxy and have relatively younger ages and (2) there can exist a steep age gradient of stellar populations along with and perpendicular to the bar in the sense that the outer regions of the bar contain only a smaller fraction of young stars. We therefore suggest that the formation of the observed young stellar populations in the LMC bar region (e.g., Elson et al. 1997; Smecker-Hane et al. 2002) is closely associated with the efficient star formation within the bar for the last several Gyr (in particular, ∼ 2 Gyr ago). We also suggest that the observed discrepancy in the SFH of the bar could be due partly to the radial gradient of ages of stellar populations within the bar: The mass fraction of young stars and the mean age of stellar populations for a target field of the LMC bar in previous observations depend strongly on the distance of the field from the center of the LMC.

The present results imply that the LMC bar was formed not spontaneously from global bar instability in the early evolution stage of the LMC but from tidal perturbation by the Galaxy and the SMC. Several numerical studies have already shown that stellar bar can be formed via tidal interaction of disk galaxies for variously different parameters of galaxy interaction (e.g., Noguchi 1987; Byrd & Valtonen 1990). The mass fraction of stars within a disk embedded by a massive dark matter halo must be at least larger than 0.4–0.5 so that the bar is spontaneously formed from global bar instability (e.g., Sellwood & Carlberg 1984). The total visible mass of stars of the LMC with \( L_V = 3.0 \times 10^9 L_\odot \) is ∼ 2.7 × 10^9 M_\odot for M/L_V = 0.9 ± 0.2 whereas the total dynamical mass of the LMC is (8.7 ± 4.3) × 10^9 M_\odot within 8.9 kpc (vdMAHS). Therefore, the spontaneous bar formation in the LMC disk is not likely to occur and thus the bar is likely to have formed relatively recently from external tidal perturbation. Using numerical simulations, Noguchi (1996) demonstrated that stellar bars formed from external tidal perturbation (“tidal bars”) have a relatively flat density profile along the major axis of the bars with “shoulders” (abrupt steepening of the gradient) at the bar ends. We thus suggest that future observational studies on the radial density profile for the young stellar populations of the LMC confirm the bar’s radial profiles characteristic of the tidal bars, if the LMC bar was formed from tidal interaction with the Galaxy and the SMC relatively recently.

4.4 The Age gap problem

Precise estimation of an age of each individual star cluster in the LMC leads to the determination of the cluster age distribution and thus to the better understanding of the star formation history of the LMC (e.g., Searle et al. 1980; Hodge 1983, 1988; Mateo 1988). Differences in spatial distributions between clusters with different ages provide some information on the spatial variation of the star formation history of the LMC (e.g., van den Bergh 1981). The age distribution of the LMC clusters shows a gap extending from 13 to 3 Gyr with only one cluster (ESO 121-SC03) within this gap, which is not seen in the SMC clusters (Jensen et al. 1988; Da Costa 1991; Geisler et al. 1997; Rich et al. 2001; Piatti et al. 2002).
The following three possible scenarios are proposed for explaining the above “age gap” in the LMC clusters. First is that star cluster formation after the initial formation of old globular clusters \( \sim 13 \) Gyr ago (at the epoch of the LMC formation) had been suspended until very recently \( \sim 3 \) Gyr ago. The second scenario is that although cluster formation has ceaselessly continued until now, only star clusters with ages ranging from 13 to 3 Gyr are tidally stripped. Third is that star clusters with ages between 3 and 13 Gyr were preferentially destroyed by the LMC tidal field to become field stars.

For the above second scenario to be viable, the star clusters with ages between 3 and 13 Gyr should be formed preferentially in the outer LMC’s halo, where tidal stripping of the clusters by the Galaxy is very efficient in this scenario. Given the possible observational evidence that both young \(< 3 \) Gyr old) and old \( \sim 13 \) Gyr clusters show diskily distributions (e.g., Schommer et al. 1991; van den Bergh 2000), it is unclear why only clusters with ages between 3 and 13 Gyr are formed in the outer halo region of the LMC. Therefore the second scenario is regarded as rather less likely one. Regarding the third scenario, it could be possible for clusters with ages between 3 and 13 Gyr to be preferentially destroyed, only if they have typically lower densities and masses compared with other LMC clusters. Since no previous theoretical models predicted age dependences of structural properties of globular clusters (e.g., Harris 1991 and reference therein), the third scenario is equally less likely one.

Thus, if the first scenario is only a reasonable one, the essence of the problem related to the above “age gap” in the LMC clusters is what mechanism is responsible for the abrupt reactivation of cluster formation in the LMC \( \sim 3 \) Gyr. Using numerical simulations, Bekki et al. (2004b) first discussed this problem in the context of mutual tidal interaction between the Clouds and the Galaxy. Bekki et al. (2004b) and the present study have proposed that the epoch of reactivation of cluster formation corresponds to the commencement of strong tidal interaction between the LMC and the SMC, which disturbs the LMC gas disk, enhances cloud-cloud collision rate, and consequently triggers cluster formation. In this scenario, the tidal interaction between the LMC and the Galaxy alone cannot increase so dramatically the number of cloud-cloud collisions leading to cluster formation between 13 and 3 Gyr ago.

The above scenario could be just one of promising scenarios explaining the origin of the age gap, we accordingly point out two possible alternative scenarios below. Byrd et al. (1994) numerically investigated the orbital evolution of the Clouds and Leo I and thereby proposed a scenario that the Cloud left M31 \( \sim 10 \) Gyr ago and were tidally captured by the Galaxy several Gyr ago. Although they did not discuss their results in terms of the age gap of the LMC clusters, it is not unreasonable to expect that the cluster formation could be suddenly triggered by the strong Galactic tidal force when the LMC first experienced the pericenter passage with respect to the Galaxy. One of the alternative scenarios is thus that the origin of the age gap is closely associated with the first pericenter passage of the LMC that once belonged to M31. In this scenario, Byrd et al. (1994) showed that the epoch of the first pericenter passage is ranging from 4.6 Gyr to 12.2 Gyr ago for a relatively narrow parameter space of the orbital evolution. Therefore it remains less clear whether LMC’s first pericenter passage is not \( \sim 6 \) Gyr ago but \( \sim 3 \) Gyr ago. Numerical studies with more variously different yet reasonable initial orbital parameters of the LMC and with more realistic mass models of the Local Group will thus assess the viability of this scenario.

The other alternative scenario is that \( \sim 3 \) Gyr ago corresponds to the epoch when the LMC’s disk gas begins to interact with the Galactic halo plasma and form clusters owing to bow-shocked induced star formation in the LMC disk, de Boer et al. (1998) pointed out that a shock induced by the ram pressure of the halo plasma can induce star formation in the LMC for a reasonable set of parameters of halo gaseous density and temperature and the relative velocity of the LMC with respect to the Galaxy. Hydrodynamical simulations demonstrated that ram pressure of the intracluster/intragroup medium strongly compresses a self-gravitating gas cloud within a short time scale \( \sim 10^7 \) yr, dramatically increasing the central gas density, and consequently causing efficient formation of a compact star cluster within the cloud (Bekki & Couch 2003). Although these two works suggest that cluster formation via ram pressure of the Galactic halo plasma is possible, it is not clear why cluster formation via ram pressure becomes possible for the first time only \( \sim 3 \) Gyr ago, given the fact that the LMC had experienced several pericenter passages before 3 Gyr ago.

One of the possible reason for the sudden interaction between the LMC gas and the Galactic halo gas \( \sim 3 \) Gyr ago is that dynamical friction from the Galactic dark matter halo causes the orbital decay of the LMC so slowly that the LMC cannot approach so closely the outer edge of the Galactic hot plasma until recently \( \sim 3 \) Gyr ago. There could be more reasonable scenarios for the age gap problem other than the three discussed above. The age gap reflects the complicated interaction history between the Clouds and the Galaxy, which depends almost exclusively the details of the orbital evolution of the Clouds. This emphasizes the importance of proper motion measurement with the accuracy of an order of \( \mu \)as for the Clouds in clarifying the origin of the age gap of the LMC clusters.

5 CONCLUSIONS

We have performed numerical simulations for the dynamical and chemical evolution of the LMC interacting with the Galaxy and the SMC for the last 9 Gyr. The main results are summarized as follows.

(1) Tidal interaction between the Clouds and the Galaxy plays a major role not only in the morphological transformation of the LMC disk but also in the formation history of field stars and star clusters. The interaction transforms the initially thin, non-barred LMC disk into the three different components; the thick disk, bar, and kinematically hot stellar halo. The central bar formed during the tidal interaction is composed both of old field stars and newly formed ones with each fraction being equal in the innermost part. The final thick disk has the velocity dispersion of \( \sim 30 \) km s\(^{-1}\) and shows rotationally supported kinematics with \( V_\text{circ}/\sigma_0 \sim 2.3 \). The outer stellar disk \( (R_\text{e} > 5 \) kpc\) surrounding the central bar is highly elliptic resulting from the tidal interaction between the Galaxy and the SMC.
(2) The stellar halo is formed during the interaction as a result of redistribution of stars initially within the outer part of the thin LMC disk. The stellar halo is thus composed mainly of old stars originating from the outer part of the initially thin LMC disk. The outer halo shows velocity dispersion of ~ 40 km s\(^{-1}\) at the distance of 7.5 kpc from the LMC center and has somewhat inhomogeneous distribution of stars. The stellar halo contains relatively young, metal-rich stars with the mass fraction of 2% in the halo. Therefore the MDF of the halo is determined by the old stars and shows a peak around \([\text{Fe/H}] \sim -1.3\) for a reasonable set of parameters of the initial MDF in the stellar disk of the LMC.

(3) Star formation rate in the LMC disk is moderately and repeatedly enhanced owing to the repetitive interaction between the Clouds and the Galaxy. The star formation rate increases from \(\sim 0.1\) \(M_\odot\) yr\(^{-1}\) to \(\sim 0.4\) \(M_\odot\) yr\(^{-1}\) at the first pericenter passage of the LMC with respect to the Galaxy about 7 Gyr ago. The star formation rate also becomes moderately high when the Cloud begins to interact violently (with the LMC-SMC pericenter of less than 10 kpc) about \(\sim 3.5\) and 2 Gyr ago. Most of the new stars (~90%) are formed within the central 3 kpc, in particular, within the bar for the last 9 Gyr. Consequently, the half mass radius is different by a factor of 2.3 between old field stars and newly formed ones. These structural differences between field stars with difference ages are characteristic of the LMC disk under tidal interaction with the Galaxy and the SMC.

(4) Efficient GC formation does not occur until the LMC starts interacting violently and closely with the SMC (~4 Gyrs ago). This is due to the fact that cloud-cloud collisions with moderately high relative speed \((30 \leq V_{\text{rel}} \leq 100\) km s\(^{-1}\)) and with small impact parameter \((b < 0.25)\) required for GC formation occurs the most frequently when both the SMC and the Galaxy dynamically influence the LMC's disk strongly. The newly formed GC system has a disk distribution with rotational kinematics and its mean metallicity is \(\sim 1.2\) higher than that of new field stars because of the pre-enrichment by the formation of field stars prior to cluster formation.

(5) About 15(20) % of the field stars (gas) initially within the LMC disk are tidally stripped to form a great stellar (gaseous) circle of a relic stream around the Galaxy during the last 9 Gyr evolution of the LMC. The great stellar circle shows inhomogeneity in some parts and is composed only of metal-poor old stars. The unique distributions of distance and radial velocity in the tidal stream may well enable us to pick out the stream among the Galactic halo stars. The stellar total mass of the tidal stream depends on the initial mass of the LMC (i.e., smaller for the larger LMC mass), so that the stellar number density along the stream provides valuable information on the LMC mass.

(6) The LMC evolution depends on its initial mass and orbit with respect to the Galaxy and the SMC. In particular, the epoch of the bar and the thick disk formation is determined by the LMC mass in such a way that the stellar bar and the thick disk are formed later in the model with a larger LMC mass. The mass fraction of the stellar halo is smaller for the model with a larger LMC mass. These are essentially because the LMC with a larger mass is more strongly bounded by its self-gravity so that the tidal perturbation from the Galaxy and the SMC does not so significantly influence the dynamical evolution of the LMC.

Based on these results, we have discussed the origin of the stellar halo in less luminous late-type galaxies such as the Clouds, the formation of LMC's stellar bar and thick disk, the origin of the age gap of the LMC globular clusters, and the difference in formation histories of field stars and globular clusters between the LMC and the SMC. It has been also pointed out that future proper motion measurements of the Clouds with \(\sim 10\) mas accuracy (Perryman et al. 2001) to estimate their past 3D orbits in an unprecedentedly precise manner will provide us invaluable information on the complicated interplay between dynamical evolution of the LMC and its star formation history.

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APPENDIX A: STATISTICS ON THE DURATION OF THE LMC-SMC BINARY STATUS

As suggested by Bekki et al. (2004b) and the present study, the epoch when the LMC and the SMC become dynamically coupled (i.e., when the pericenter distance of the LMC-SMC orbit is as small as 10 kpc) is a critical moment for the LMC, because the combined tidal effect of the Galaxy and the SMC starts influencing significantly the LMC evolution at the coupled (i.e., when the pericenter distance of the LMC-SMC orbit is as small as 10 kpc) is a critical moment for the LMC, because the combined tidal effect of the Galaxy and the SMC starts influencing significantly the LMC evolution after the dynamical coupling. It is thus important to investigate when they are the most likely to become coupled during their dynamical evolution. Although the proper motion of the Clouds have been already derived by several authors (e.g., KB; vdMAHS), the measurement error in these observational studies is so large that precise estimation of current velocity components ($U_\star, V_\star, W_\star$) and ($U_S, V_S, W_S$) within an error of $\sim$ a few km s$^{-1}$ cannot be made directly
from the observations. As shown in previous studies on the orbital evolution of the Clouds (e.g., MF), only a velocity difference of \( \sim 5 \) km s\(^{-1}\) can cause a significant difference in the orbital evolution and thus in the binary status of the Clouds. Thus currently available data alone do not allow us to make a robust conclusion on the duration of the LMC-SMC binary status.

Therefore we here make a statistical argument on the duration of the LMC-SMC binary status by investigating every possible orbits of the Clouds for a set of reasonable parameters of gravitational potential for the Galaxy and the Clouds. Using the backward integration scheme (MF) and the models for gravitational potential and dynamical friction adopted in this study for the Galaxy and the Clouds (i.e., the equation (1) - (5)), we first calculate the orbital evolution of the Clouds for each model with a given set of parameters for their initial velocities. Then we estimate the epoch when the LMC-SMC binary distance is for the first time larger than 50 kpc that is adopted by previous numerical studies (MF; GSF) for the threshold of the binary status.

Initial velocity components of \( U_L \) and \( V_L \) (\( U_S \) and \( V_S \)) for the LMC (the SMC) range from \(-320\) km s\(^{-1}\) to 320 km s\(^{-1}\) in the orbital investigation. \( W_L \) (\( W_S \)) is derived from given \( U_L \) and \( V_L \) (\( U_S \) and \( V_S \)) in the LMC (the SMC) so that the radial velocity of the LMC (the SMC) is consistent with the observed radial velocity of the LMC (the SMC). We survey the LMC-SMC binary orbit every 3.2 km s\(^{-1}\) in the range of \((U_L, V_L, W_L)\)-space (\((U_S, V_S, W_S)\)-space) and thus the total number of the orbits investigated in this study is an order of \((10^2 \times 10^2) \times (10^2 \times 10^2) = 10^8\). Such a numerous number of orbital investigation enable us to provide a statistical argument on the duration of the LMC-SMC binary status.

We adopt the four different orbital models with different \( M_{\text{LMC}} \) and with or without dynamical friction: Model 01 with \( M_{\text{LMC}} = 10^{10} \, M_\odot \) and with dynamical friction, Model 02 with \( M_{\text{LMC}} = 10^{10} \, M_\odot \) and without dynamical friction, Model O3 with \( M_{\text{LMC}} = 2 \times 10^{10} \, M_\odot \) and with dynamical friction, and Model O4 with \( M_{\text{LMC}} = 2 \times 10^{10} \, M_\odot \) and without dynamical friction. We investigate not only the models with \( M_{\text{LMC}} \) consistent with observations (i.e., O1 and O2) but also those with \( M_{\text{LMC}} \) significantly larger than the observed one (vdMAHS), because we intend to compare the present results with previous ones (e.g., GN) in which \( M_{\text{LMC}} \) is assumed to be \( 2 \times 10^{10} \, M_\odot \).

Based on the above models, we search for the models which meet the following two requirements/conditions: (C1) The current velocities are broadly consistent with those derived from the latest observations, and (C2) the Clouds can keep its binary status for the Hubble time (\(~ 13 \) Gyr). We first determine the models satisfying the above condition C1 by selecting the models with each of the current velocities

| Table A1. Orbit models |
|-----------------------|
| orbit model | \( F_{\text{bin},1}(\%) \) | \( F_{\text{bin},2}(\%) \) | \( t_{\text{bin},1}(\text{Gyr}) \) | \( t_{\text{bin},2}(\text{Gyr}) \) |
| A | 0 | 5.5 \times 10^{-4} | 4.29 | 1.15 |
| B | 0 | 1.1 \times 10^{-2} | 4.42 | 1.10 |
| C | 16.7 | 4.1 \times 10^{-3} | 6.25 | 1.23 |
| D | 43.8 | 4.6 \times 10^{-2} | 8.88 | 1.26 |

\( M_{\text{MC}}=10^{10} \, M_\odot \) | \( [v_{\text{MC}}] \leq 10 \) km s\(^{-1}\) |
|-----------------------|
| Number fraction |

\( M_{\text{MC}}=2 \times 10^{10} \, M_\odot \) | \( [v_{\text{MC}}] \leq 10 \) km s\(^{-1}\) |
|-----------------------|
| Number fraction |

Figure A1. The distributions of \( t_{\text{bin}} \), duration of binary status of the Clouds for the models with \( M_{\text{LMC}} = 10^{10} \, M_\odot \) (upper) and those with \( M_{\text{LMC}} = 2 \times 10^{10} \, M_\odot \) (lower). \( t_{\text{bin}} \) represents the duration of binary status of the Clouds and the definition of the binary status is given in the main text. For comparison, the results are shown for models with (solid) and without (dotted) dynamical friction between the Clouds in each panel. For convenience, the normalized number of models is given for each bin of the LMC-SMC binary duration. Here only the models in which each component of the current velocities of the Clouds \((U_L, V_L, W_L)\) and \((U_S, V_S, W_S)\) is within \( \pm 10 \) km s\(^{-1}\) of the corresponding component in the model.

Figure A2. The same as Figure A1 but for the models with the current velocities of the Clouds similar to those obtained from Hipparcos data (KB).
(e.g., \( U_L \)) within an error of 10 km s\(^{-1}\) of the observationally inferred one among all models. We then search for the models satisfying the above condition C2 among those satisfying the above condition C1 based on the backward integration of the Clouds’ orbits. In the first selection process, we check whether the current velocities in each model are consistent either with those adopted by GN or with those by KB.

We mainly investigate (1) number fraction of orbits \( F_{\text{bin}} \) satisfying the above two conditions among all possible ones and (2) mean duration of the LMC-SMC binary status \( t_{\text{bin}} \) for each of the four models, O1, O2, O3, and O4. The number fraction of orbital models in which the above condition C1 is satisfied and the current velocities are within an error of 10 km s\(^{-1}\) of those by GN (KB) is represented by \( F_{\text{bin},1} \) \( (F_{\text{bin},2}) \). The mean duration of the LMC-SMC binary status for orbits with the current velocities within an error of 10 km s\(^{-1}\) of those by GN (KB) is represented by \( t_{\text{bin},1} \) \( (t_{\text{bin},2}) \). The Table A1 summarizes the results of the orbital investigation: Model number (column 1), \( F_{\text{bin},1} \) (2), \( F_{\text{bin},2} \) (3), \( t_{\text{bin},1} \) (4), and \( t_{\text{bin},2} \) (5).

Figure A1 shows the distribution of \( t_{\text{bin},1} \) of orbits in which the current velocities are within an error of 10 km s\(^{-1}\) of those by GN for the O1 – O4 models. It is clear from this figure that (1) the Clouds can keep their binary state for only less than 7 Gyr (i.e., the Clouds becomes disintegrated until \( T = -7 \text{ Gyr} \)) in the models O1 and O2, (2) they are the most likely to keep their binary status for \( \sim 4 \text{ Gyr} \) in the models O1 and O2, (3) \( t_{\text{bin},1} \) is the most likely to be \( \sim 2 \text{ Gyr} \) for the O3 model, and (4) the Clouds are the most likely to be able to keep their binary status for the Hubble time only if the LMC has a large mass of \( 2.0 \times 10^{10} M_\odot \) without dynamical friction between the Clouds. These results imply that the Clouds are very hard to keep their binary status for the Hubble time if a reasonable sets of assumptions \((M_{\text{LMC}} = 10^{10} M_\odot \) and inclusion of the dynamical friction between the Clouds) are made for the orbital calculations.

Figure A2 shows the distribution of \( t_{\text{bin},2} \) for orbital models in which the current velocities are within an error of 10 km s\(^{-1}\) of those by KB for the O1 – O4 models. As shown in this Figure A2, the Clouds are the most likely to be able to keep their binary status for less than 1 Gyr, irrespectively of the LMC mass and whether or not the dynamical friction between the Clouds is included in the orbital calculations. The more massive LMC has a higher probability of keeping the LMC-SMC binary status (i.e., larger \( F_{\text{bin},2} \)) for the Hubble time in these models with and without dynamical friction (See the Table A1). The results shown in Figure A1 and A2 thus strongly suggest that the probability of Clouds keeping their binary status is very low.
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