STARBURSTS IN MULTIPLE GALAXY MERGERS
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ABSTRACT

We numerically investigate stellar and gaseous dynamical evolution of mergers among five identical late-type disk galaxies with the special emphasis on star formation history and chemical evolution of multiple galaxy mergers. We found that multiple encounter and merging can trigger repetitive massive starbursts (typically ~100 M☉ yr⁻¹) owing to the strong tidal disturbance and the resultant gaseous dissipation during merging. The magnitude of the starburst is found to depend on initial virial ratio (i.e., the ratio of total kinematical energy to total potential energy) such that the maximum star formation rate is larger for the merger with smaller virial ratio. Furthermore, we found that the time interval between the epochs of the triggered starbursts is longer for the merger with the larger virial ratio. The remnant of a multiple galaxy merger with massive starbursts is found to have a metal-poor gaseous halo that is formed by tidal stripping during the merging. We accordingly suggest that a metal-poor gaseous halo in a field elliptical galaxy is a fossil record of the past multiple merging events for the galaxy.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: formation — galaxies: interactions — galaxies: ISM — galaxies: starburst — galaxies: structure

1. INTRODUCTION

Major galaxy merging between two gas-rich spirals is observationally suggested to play vital roles in the formation and the evolution of galaxies: formation of elliptical galaxies (e.g., Schweizer 1986; Kormendy & Sanders 1992; Bender 1996); quasi-stellar object formation (e.g., Stockton 1997); formation of fine structure of elliptical galaxies (e.g., Schweizer 1997), triggering massive starburst and the resultant formation of ultraluminous infrared galaxies (ULIRGs) (e.g., Sanders et al. 1988; Sanders & Mirabel 1996); and globular cluster formation (e.g., Whitmore & Schweizer 1995). Accordingly, a growing number of theoretical studies have tried to answer the questions related to physical processes of major galaxy merging. These include, for example, the formation of elliptical galaxies (Toomre 1977; Barnes 1988, 1992; Barnes & Hernquist 1992a, 1996; Hernquist 1992, 1993), physical mechanisms for triggering massive starburst (e.g., Mihos & Hernquist 1996; Gerritsen & Ike 1997), and formation and evolution of ULIRGs (e.g., Bekki, Shioya, & Tanaka 1999). In comparison with the above theoretical studies on pair galaxy merging, there are a relatively small number of theoretical studies on the multiple galaxy merging between more than two galaxies, though multiple merging can be important for some aspects of galaxy evolution, such as the evolution of a small group of galaxies (Barnes 1989; Hickson 1997). This is primarily because there are only a few observational results showing unambiguous and direct evidences that multiple galaxy merging is not rare in the universe.

Theoretical studies on multiple galaxy merging can be divided into the following two categories: (1) formation of elliptical galaxies and (2) evolution of a compact group of galaxies. Concerning the first issue, Barnes (1989) first demonstrated that multiple interaction and merging of a compact group (such as Hickson compact groups [HCGs]) results in the formation of a bright elliptical galaxy. Weil & Hernquist (1994) revealed that multiple merging among several stellar disks can successfully reproduce the small angle between rotation and minor axis observed in elliptical galaxies. Weil & Hernquist (1996) furthermore discussed the difference in structural and kinematical properties of merger remnants between pair mergers and multiple ones. Concerning the second issue, most studies have focused on the problems on the timescale within which a compact group of galaxies becomes a single object after successive merging (Carnevali, Cavaliere, & Santangelo 1981; Ishizawa et al. 1983; Barnes 1985; Ishizawa 1986; Mamon 1987, 1990; Navarro, Mosconi, & Lambas 1987; Governato, Bhatia, & Chincarini 1991; Bode, Cohn, & Lugger 1993; Diaferio, Geller, & Ramella 1994; Athanassoula, Makino, & Bosma 1997; Hickson 1997 for a recent review). Barnes (1985) demonstrated that a common dark halo of a compact group can slow down the merging among the member galaxies, and consequently the lifetime of the group can be 5–10 times longer than its apparent crossing time. The roles of a massive background dark halo in delaying the merging timescale of a compact group have been confirmed by several numerical studies (e.g., Navarro et al. 1987). Athanassoula et al. (1997) found that the timescale for which a group of galaxies can merge to form a single massive galaxy can be larger than a Hubble time for some appropriate physical conditions of the group. They therefore suggested that the previously suggested puzzle on the existence of HCGs (i.e., why HCGs can be observable, nevertheless, their crossing times are very short [typically ~0.2 Gyr] and dynamical friction should be so efficient that the galaxies in the groups can all merge in a timescale much smaller than a Hubble time) is not necessarily a problem. Although these previous studies have paid much attention to the structure and kinematics of the remnants of multiple mergers and the merging history, gaseous dynamical process and star formation history, both of which are important for understanding the origin of stellar populations of field elliptical galaxies and thus for their photometric and spectroscopic evolution, have not yet been investigated.

The purpose of this paper is to investigate star formation history and chemical evolution of multiple galaxy mergers among five identical gas-rich spirals. We particularly investigate when and how massive starbursts, which are demon-
strated to occur in (pair) major mergers between two gas-rich spirals (Mihos & Hernquist 1996), are triggered in multiple galaxy merging. We furthermore investigate two-dimensional (projected) distribution of metallicity both for stellar components and for gaseous ones in merger remnants in order to show chemical properties characteristics of the remnants of multiple galaxy merging. Silva & Bothun (1998) investigated the central near-infrared colors of 32 field elliptical galaxies with the sign of recent merging and found that only two of them clearly indicate starburst populations formed a few gigayears ago. Based on these results, Silva & Bothun (1998) have suggested that merging between disk galaxies within the last 3–4 Gyr is not the primary formation mechanism of field elliptical galaxies. These observational results also suggest that although multiple merging could create the rare ULIRGs, it cannot be associated with the formation of field elliptical galaxies at low redshift. Therefore, our multiple merger model can describe only the formation of some ULIRGs (not the formation of field elliptical galaxies at low redshift) in the present study. Star formation history and chemical evolution of multiple mergers have not been investigated at all in previous numerical and theoretical studies. Thus, the present results can provide some implications on the formation and the evolution of galaxies, in particular, on the origin of field elliptical galaxies, the evolution of compact group of galaxies, and the formation of infrared luminous galaxies such as ULIRGs. In the present paper, we furthermore consider that it is important to investigate observationally what fraction of ULIRGs are formed by multiple galaxy merging. This is because the fraction enables us to estimate (though indirectly) the fraction of compact groups that are now evolving from ULIRGs into field elliptical galaxies. We accordingly discuss the fraction of ULIRG and field elliptical galaxies formed by multiple merging in the discussion section.

The layout of this paper is as follows. In § 2, we summarize numerical models used in the present study and describe in detail the methods for solving the star formation history and the chemical evolution of multiple mergers. In § 3, we present numerical results on the time evolution of morphology, star formation history, and chemical properties in multiple mergers. In § 4, we discuss the strength of starbursts triggered in multiple merging and the chemical properties of the merger remnants. The conclusions of the present study are given in § 5.

2. MODEL

Our previous studies (Bekki & Shioya 1998) have already described in detail the initial conditions of merger progenitor disks, the prescriptions of dissipative process, the model for star formation and that for chemical evolution of galaxy mergers, and the numerical method for solving dynamical evolution of stellar and gaseous components. Accordingly, we describe only briefly the merger model in the present study. We consider a multiple merger among five identical gas-rich spiral galaxies without bulges. The disk mass and size are assumed to be exactly the same among disk galaxies in a multiple merger and similar to those of the Galaxy. Each of the disks has an individual dark matter halo, and we do not consider that a common dark halo can envelop a multiple merger composed of five disks in the present study. Although a common dark halo can affect greatly the merging timescale in multiple galaxy merging (Barnes 1985; Athanassoula et al. 1997), we here do not consider this important effect of the common halo.

2.1. Disk Model

We construct models of galaxy mergers between gas-rich disk galaxies with equal mass by using the Fall-Efstathiou model (1980). The total mass and the size of a progenitor disk are \( M_d \) and \( R_d \), respectively. From now on, all mass and length are measured in units of \( M_d \) and \( R_d \), respectively, unless otherwise specified. Velocity and time are measured in units of \( v = (GM_d/R_d)^{1/2} \) and \( t_{dyn} = (R_d^3/GM_d)^{1/2} \), respectively, where \( G \) is the gravitational constant and assumed to be 1.0 in the present study. If we adopt \( M_d = 6.0 \times 10^{10} M_\odot \) and \( R_d = 17.5 \) kpc as a fiducial value, then \( v = 1.21 \times 10^2 \) km s\(^{-1}\) and \( t_{dyn} = 1.41 \times 10^8 \) yr, respectively. In the present model, the rotation curve becomes nearly flat at 0.35 with the maximum rotational velocity \( v_m = 1.8 \) in our units (\( \sim 220 \) km s\(^{-1}\)). The corresponding total mass \( M_\odot \) and halo mass \( M_h \) are 5.0 and 4.0 in our units, respectively. The radial \((R)\) and vertical \((Z)\) density profiles of a disk are assumed to be proportional to \( \exp(-R/R_0) \) with scale length \( R_0 = 0.2 \) and to \( \text{sech}^2(Z/Z_0) \) with scale length \( Z_0 = 0.04 \) in our units, respectively. The velocity dispersion of the halo component at a given point is set to be isotropic and given according to the virial theorem. In addition to the rotational velocity made by the gravitational field of the disk and halo component, the initial radial and azimuthal velocity dispersions are given to the disk component according to the epicyclic theory with Toomre’s parameter (Binney & Tremaine 1987) \( Q = 1.2 \). 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 Milky Way (e.g., Wielen 1977). As is described above, the present initial disk model does not include any remarkable bulge components and accordingly corresponds to “purely” late-type spiral without galactic bulge. Although it is highly possible that galactic bulges greatly affect the chemical evolution of galaxy mergers, we however investigate this issue in our future papers.

2.2. Gas, Star Formation, and Chemical Enrichment

The collisional and dissipative nature of the interstellar medium is modeled by the sticky particle method (Schwarz 1981). We assume that the fraction of gas mass \( f_g \) in a disk is set to be 0.2 initially. The radial and tangential restitution coefficient for cloud-cloud collisions are set to be 1.0 and 0.0, respectively. 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 \( \gamma = 2.0 \) (1.0 < \( \gamma \) < 2.0; Kennicutt 1989) as the controlling parameter of the rate of star formation. The positions and velocity of the new stellar particles are set to be the same as those of original gas particles. Chemical enrichment through star formation during galaxy merging is assumed to proceed both locally and instantaneously in the present study. The fraction of gas returned to the interstellar medium in each stellar particle and the chemical yield are 0.3 and 0.02, respectively. The number of particles for an above isolated galaxy is 5000 for dark halo, 5000 for stellar disk components, and 5000 for gaseous ones. Therefore, in total 75,000 particles are used in a simulation of multiple merging in the present study.
2.3. Initial Conditions of Multiple Mergers

We investigate two different sets of multiple merger models. For one set of models, the initial position of each progenitor disk (i.e., the center of mass of the disk) is set to be distributed randomly within a sphere with the radius of 8.0 in our units (corresponding to 140 kpc), and the initial three-dimensional velocity dispersion of each disk (that is, the random motion of each galaxy in the sphere) is set to be distributed in such a way that the ratio of the total kinematical energy to the total potential energy in the system is \( t_v \). The \( t_v \) is assumed to be a free parameter that controls the degree of dynamical equilibrium (i.e., \( t_v = 0.5 \) corresponds to virial equilibrium), and the results of the models with \( t_v = 0, 0.1, 0.3 \) are described in the present study. For the model with larger \( t_v \), the timescale for which all five disks merge to form a single elliptical galaxy is longer. This set of models is hereafter referred to as the “3D” model. For the other set of models, the initial position of the center of mass of the disk is set to be distributed randomly within a plane (x-y plane). All of the centers of mass of the five disks are located within a circle (on the x-y plane) with the radius of 8.0 in our units (corresponding to 140 kpc). The initial orbital planes of all disks are assumed to be exactly the same as the x-y plane. The initial two-dimensional velocity dispersion of each disk (that is, the random motion of each galaxy in the plane) is set to be distributed in such a way that the ratio of the total kinematical energy to the total potential energy in the system is \( t_v \). The physical meaning of \( t_v \) in this set of models is exactly the same as that for the 3D models. This set of models is hereafter referred to as the “2D” model. The time when the progenitor disks merge completely and reach the dynamical equilibrium is less than 20.0 in our units for most of models. For both sets of models, initial internal spin vectors of five disks are distributed randomly. By comparing the results of the 3D models and those of the 2D ones, we can grasp some essential ingredients of star formation histories of multiple galaxy mergers. We present numerical results of three models with \( t_v = 0, 0.1, 0.3 \) for the two sets of models. The 3D model with \( t_v = 0 \) is referred to as the standard model.

All the calculations related to the above dynamical evolution including the dissipative dynamics, star formation, and gravitational interaction between collisionless and collisional component have been carried out on the GRAPE board (Sugimoto et al. 1990) at Astronomical Institute of Tohoku University. The parameter of gravitational softening is set to be fixed at 0.03 in all the simulations. The time integration of the equation of motion is performed by using the 2-order leap-frog method. Energy and angular momentum are conserved within 1% accuracy in a test collisionless merger simulation. Most of the calculations are set to be stopped at \( T = 20.0 \) in our units unless otherwise specified.

3. RESULT

3.1. The Standard Model

We first describe the results of the standard model, which shows typical behaviors in the star formation history of multiple galaxy mergers. Owing to the initial very small velocity dispersion of galaxies in this model, all five disks rapidly merge to form a single elliptical galaxy within 1.7 Gyr. The detailed morphological, structural, and kinematical properties of remnants of multiple galaxy mergers are given in Barnes (1989) and Weil & Hernquist (1994, 1996). Therefore, we here concentrate on the star formation history and the chemical evolution of multiple mergers. In the following, \( T \) (in units of Gyr) represents the time that has elapsed since the five disks began to merge. For convenience, collisionless stellar components that are initially gaseous and later formed by star formation are referred to as new star(s), whereas those that are initially stellar components at \( T = 0 \) are referred to as old star(s) or simply star(s).

3.1.1. Star Formation History

Figures 1, 2, 3, and 4 show the time evolution of the dark matter halo, star, gas, and new star, respectively, for the standard model. Owing to the lack of a common dark matter halo, the strong dynamical friction drives the five individual halos of disk galaxies to merge very quickly with each other to form a single large halo within \(~1.7\) Gyr. Two equal mass disks first interact strongly with each other at \( T = 0.14 \) Gyr (hereafter in units of Gyr) and consequently forms a long tidal tail at \( T = 0.28 \) (see also Fig. 5). Before these two disks completely merge, another two disks begin to interact with the merging two disks at \( T = 0.4 \). As the merging among these four galaxies proceeds, the long tidal tail formed in the first tidal encounter is destroyed and dispersed into the surrounding intergalactic regions at \( T = 0.62 \). Other weak tidal tails are then developed when the four galaxies finally merge to form a single elliptical galaxy at \( T = 0.62 \). The surviving one-disk galaxy, which is relatively undisturbed in the merger events before \( T < 0.62 \), also finally merges with the previously merged disks and consequently forms a single elliptical galaxy until \( T = 1.69 \). A very long and remarkable tidal tail with the projected length of \(~100\) kpc is developed during this final phase of multiple galaxy merging. In the present model, the morphological properties of tidal tails formed in multiple merging are more complicated and the number of distinct tails is larger compared with the case of pair merging (between only two disks).

As is shown in Figure 6, strong starbursts with the star formation rate of 60–120 \( M_\odot \) yr\(^{-1}\) occur three times during galaxy merging (\( 0 < T < 1.5 \)). The interval between each of the peaks of the star formation (\( T = 0.40, 0.62, \) and 1.00) is about 0.2–0.4 Gyr, which reflects the time interval between each of the strong interaction/merging that occurred in the present model. The derived star formation rate corresponds to that required for explaining the very high infrared luminosity of ULIRGs with dusty starburst (Sanders & Mirabel 1996). This repetitive massive starburst is one of the characteristics of the star formation histories of multiple galaxy merging and thus is in striking contrast to the star formation histories of pair merging: only one or two times are massive starbursts demonstrated to occur in pair mergers (Mihos & Hernquist 1996). The star formation rate does not drop so dramatically between starbursts (i.e., \( 0.4 < T < 0.62 \) and \( 0.62 < T < 1.0 \)) and remains rather high (\( > 10 \) \( M_\odot \) yr\(^{-1}\)) compared with that of the isolated disk model. This is essentially because when the magnitude of a starburst triggered in a merger between two disks becomes small owing to the rapid gas consumption by star formation, another strong interaction and merging begins and then triggers the next starburst(s) in the standard model. Because of the repetitive starbursts, about 75% of the initial gas mass is found to be consumed, as is shown in Figure 6. The total amount of gas is nearly the same as that
derived for pair galaxy mergers (e.g., Mihos & Hernquist 1996).

Although the time evolution of the star formation rate in multiple mergers can be different from that of pair mergers, the physical processes that trigger massive starburst in multiple mergers are nearly the same as those in pairs. As two galaxies first encounter one another in the early phase of multiple merging ($T < 0.4$), the two galaxies are tidally distorted to form strong nonaxisymmetric potential (such as barred potential). This potential acts to torque the interstellar gas of the two disks and consequently drives the rapid inward gas transfer that is indispensable for massive starbursts. Since initial disks are assumed to have no massive bulges in the present model, the triggered starburst can be seen well before the completion of galaxy merging of the two disks. As the galaxies approach very closely to each other and suffer from violent relation in the late phase of multiple merging, the rapidly changing gravitational potential greatly enhances the cloud-cloud collision rate. As a result of this, gaseous energy dissipation becomes very effi-
cient, and consequently a large amount of gas can be fueled to the central starburst regions. These processes have already been given in detail by Mihos & Hernquist (1996). We thus suggest that fundamentally important physical processes of starbursts in multiple galaxy merging can be basically understood in terms of the already clarified mechanism of starbursts in pair mergers.

3.1.2. Chemical Properties

Figure 7 shows age and metallicity distributions for new
stars at $T = 1.69$ when five disks nearly complete the for-
mation of a single elliptical galaxy. Three peaks in the age
distribution can be clearly seen, which reflects the fact that a
massive starburst occurs three times during multiple galaxy
merging. Compared with the peculiar age distribution, only
one peak can be seen in the metallicity distribution, which
means that typical metallicity is not so different between
young starburst components. The peak value of the metal-
llicity distribution is rather high ($\sim 0.05$ corresponding to
2.5 times $Z_\odot$), basically because chemical enrichment in
interstellar gas during starbursts proceeds so rapidly and
efficiently that new stars formed from the enriched gas have
relatively large metallicity. Starbursts triggered by multiple merging thus play vital roles in the formation of metal-rich young stellar populations in elliptical galaxies: dynamical processes such as those triggering starburst are important determinants for chemical evolution of galaxies and thus for the nature of stellar populations of galaxies. As is described above, young stellar components are very metal-rich and have bimodal or multimodal age distribution. This result will provide a clue to the origin of age and metallicity distributions of globular clusters observed in elliptical galaxies and some merging ones (e.g., Whitmore 1997).

Tidal stripping of gaseous components, which causes inhomogeneous chemical mixing, can greatly affect the gaseous chemical evolution during multiple galaxy merging. Figure 8 shows gaseous metallicity distribution of the merger remnant of the standard model for the outer halo region ($R > 17.5$ kpc corresponding to the initial disk size, where $R$ is the distance from the center of mass of the remnant) and for the whole region. The peak value in metallicity distribution both for the outer halo and for the whole region is rather small ($\sim 0.01$). In particular, a significant fraction of gaseous components ($\sim 30\%$) is found to show
subsolary metallicity (less than 0.01) for the outer halo region. These results imply that an elliptical galaxy formed by multiple galaxy merging has the outer metal-poor gaseous halo with the mean metallicity of subsolar. Figures 9 and 10 describe the two-dimensional distribution of metallicity at $T = 1.69$ for stellar components and that for gaseous ones, respectively. Both stellar and gaseous metallicities are larger in the central part than in the outer one, which means that the merger remnant shows negative metallicity gradients in both stellar and gaseous components.

What is most significant in this figure is that the remnant has the metal-poor gaseous halo with the metallicity of $\sim 0.01$ (also relatively metal-poor diffuse stellar halo). The implications of the derived metal-poor gaseous halo are given later in the section of discussion (§ 4).

The details of the formation process of gaseous metallicity gradients are given as follows. In the present chemodynamical model of gas-rich galaxy mergers, metals produced and ejected in star-forming gaseous regions of a multiple merger can be mixed only locally into the surrounding interstellar medium (ISM) ("inhomogeneous chemical mixing"). Accordingly, the metals, which are mostly produced in the central region of the merger, can be mixed preferentially into the ISM in the central region.
where further efficient star formation is expected and thus cannot be mixed so efficiently into the outer region of the merger. Consequently, the ISM of the outer part of the merger remains less metal enriched. Such less metal-enriched ISM in the outer part of the merger is then effectively stripped away from the system during tidal interaction of galaxy merging and finally transferred to the more outer region where metals produced in the central part of the merger are harder to be mixed into. As a natural result of this, the mean metallicity of the ISM remaining in the outer part of the remnant becomes considerably smaller. On the other hand, the ISM initially located in the central part of the merger can be more metal enriched owing to quite efficient star formation there. The formation of gaseous metallicity gradients accordingly reflects the fact that the metals produced by star formation are more efficiently trapped by the ISM in the central part of mergers than by that in the outer part. Thus, the origin of negative metallicity gradients in the gaseous halos of merger remnants is due principally to the inhomogeneous chemical mixing in gas-rich mergers.

The importance of tidal stripping in chemical evolution of galaxy mergers is first investigated by Bekki (1998b) though the range of the parameters for the orbital configu-
Fig. 6.—Time evolution of star formation rate in units of $M_\odot \, \text{yr}^{-1}$ for the standard model. For comparison, the result of the isolated disk model is also given. Note that repetitive massive starburst occurs in the multiple merger model. Note also that initial gas is more rapidly consumed by the triggered starbursts in the merger model than in the disk model.

The time evolution of the gas mass fraction is shown in Fig. 7. For comparison with the isolated disk model, the result of the isolated model is also given. Note that repetitive massive starburst occurs in the multiple merger model. Note also that initial gas is more rapidly consumed by the triggered starbursts in the merger model than in the disk model.

Fig. 7.—Age distribution (upper panel) and metallicity distribution (lower panel) for new stars in the standard model at $T = 1.69 \, \text{Gyr}$. Note that a larger fraction of gas shows subsolar metallicity (less than 0.02) in the outer part of the merger remnant.

3.2. Parameter Dependences

Figure 11 describes the dependence of the time evolution of star formation history and gas mass fraction on the parameter $t_\text{v}$ for the 3D model. We can see the following four clear dependences in this figure. First, irrespective of $t_\text{v}$, strong starbursts with the star formation rate larger than 10 $M_\odot \, \text{yr}^{-1}$ occur in a repetitive way. This is basically because the five disks in a model do not merge with each other at the same time and consequently experience strong dynamical interaction and merging two or three times. Second, the magnitude of the maximum starburst is larger for the model with smaller $t_\text{v}$. The reason for this dependence is described as follows. Owing to the initial smaller velocity dispersion, five disks can interact dynamically with each other in the earlier merger phase when the disks have a larger amount of interstellar gas. As a result of this, a larger amount of gas can be transferred to the central region during multiple merging. Furthermore, a smaller amount of the gas is tidally stripped away from the merger in the model with smaller $t_\text{v}$. Thus, a larger amount of gas accumulated within the central region of the merger can be consumed by the central massive starbursts. Third, the time interval between the first starburst and the last one is longer for the model with larger $t_\text{v}$, which reflects the fact that final merging that produces a single elliptical galaxy occurs later in the model with larger $t_\text{v}$. Fourth, the final gas mass fraction is not so greatly different among the three models, though the strength and the epoch of massive starburst are different between these models: about 70%–75% of initial gas can be consumed by star formation in multiple mergers. This result is very
Two-dimensional distribution of stellar metallicity (including both old stars and new ones) projected onto the x-y plane at $T = 1.69$ Gyr in the standard model. The frame measures 100 kpc on a side and includes 400 bins ($20 \times 20$). For the bin within which no stellar particles are found to be located, any color contours are not given for clarity. As is shown in the color legend of this figure, the metallicity ranges from 0.01 in the outer part to 0.05 in the central one. Note that this merger remnant shows a negative metallicity gradient in stellar components.

similar to that of pair mergers revealed by Mihos & Hernquist (1996).

Figure 12 describes the dependence of the time evolution of star formation history and gas mass fraction on $t_v$ for the 2D model. There are some differences in the $t_v$ dependences between the 2D model and the 3D one. First, the triggered starbursts are a factor of 2–3 stronger in the 2D model than in the 3D model. The first reason for this is that owing to the stronger dynamical friction the five disks can merge at roughly the same time so that the larger amount of gaseous components can collide with each other, dissipate their kinetic energy, be transferred to the central region, and be consumed very efficiently by star formation. The second reason is that if the initial orbits of the five disks in the 2D model are confined in the x-y plane, a smaller amount of gas indispensable for massive starbursts can be stripped away from the merger. Second, the repetitive starburst is not so clearly seen in the 2D model: only the 2D model with $t_v = 0.3$ shows starbursts two times. This result clearly reflects the fact that most of the five disks merge with each other at roughly the same time so that most of the gas can be consumed by the first (and the last) merging in the 2D model. Third, the magnitude of the maximum starburst is not necessarily larger in the model with smaller $t_v$: although the starburst strength is larger in the models with $t_v = 0$ and 0.1 than in that with $t_v = 0.3$, the strength is larger in $t_v = 0.1$ than in $t_v = 0$. This result suggests that in addition to $t_v$
there are some important parameters that control the strength of starbursts in the 2D model. We suggest that in the 2D model orbital configurations of galaxy merging (e.g., whether a merger is a prograde-prograde merger or a retrograde-retrograde one) is also a determinant for the strength of the maximum starburst triggered by multiple galaxy merging.

Figures 13, 14, 15, and 16 summarize the morphological properties of multiple mergers at the epoch of the starburst for the 3D models with $t_v = 0.1$ and $t_v = 0.3$ and the 2D model with $t_v = 0$. The maximum star formation rate is found to range from $\sim 60$ to $\sim 300 M_\odot$ yr$^{-1}$ in the present study. Accordingly, the derived morphological properties are useful and helpful for understanding the nature of infrared

Fig. 13.—Mass distribution at the epoch of massive starburst ($T = 0.59$ Gyr) projected onto the $x$-$y$ plane (upper three frames) and $x$-$z$ plane (lower three frames) in the 3D model with $t_v = 0.1$ for (old) star (left frames), gas (middle frames), and new star (right frames). Each of the six frames measures 192.5 kpc on a side.

Fig. 14.—Same as Fig. 13 but for the 3D model with $t_v = 0.3$ at the final starburst ($T = 1.74$ Gyr)
luminous galaxies and ULIRGs in which star formation rate is required to be the order of $10^{11}-10^{12} \, M_\odot \, yr^{-1}$ for the large infrared luminosity (if the source of the reemission is due mostly to dusty starburst), though the parameter range investigated in the present study is relatively narrow. As is shown in Figure 13, the global morphology of the multiple merger is very complicated particularly for the early epoch of merging (i.e., the first starburst epoch, $T = 0.59$): three long tidal tails, multiple nuclei composed mainly of young stars, and a disk (seen from edge-on view) that is not largely disturbed can be seen at the epoch of maximum starburst. Probably a trend that both few strong tidal tails and an undisturbed disk can be seen in a merger is specific for multiple mergers (i.e., not seen in pair ones). This trend is true for most of the 3D models in the earlier starburst epoch. As is shown in Figure 14, the global morphology at the last starburst epoch ($T = 1.74$) in the merger model with $t_v = 0.3$ does not appear to be so disturbed as that in

**Fig. 15.**—Same as Fig. 14 but for the central region of the merger. Each of the six frames measures 8.75 kpc on a side

**Fig. 16.**—Same as Fig. 13 but for the 2D model with $t_v = 0 \,(T = 0.46 \, Gyr)$
Figures 13 and 16. This is essentially because in the last merging most of the remarkable tidal tails that are formed in the early encounter and merging can be greatly dispersed to form the outer diffuse stellar and gaseous halo. What is remarkable in this model is that although the global morphology of the merger looks like a single elliptical galaxy, the central part of the merger (the central 4.38 kpc) shows two distinct cores composed mostly of new stars (see Fig. 15). The 2D model with $t_e = 0$ is also found to show very complicated tidal tails at the epoch of the maximum starburst (see Fig. 16). What is interesting in this model is that the morphology of young stellar components looks like a tadpole in edge-on view and thus is similar to the morphology of Mrk 273, which is an ULIRG. Thus, morphological properties of multiple mergers at the epoch of their massive starbursts are found to depend on model parameters and thus to be very diverse. Recent observational studies based on the Hubble Space Telescope and large ground-based telescopes have revealed the great difference in structural and morphological properties of ULIRGs (Surace et al. 1998; Dinshaw et al. 1999; Surace, Sanders, & Evans 2000; Scoville et al. 2000) For example, observational studies based on the NICMOS imaging of ULIRGs have found that the morphologies are rather diverse ranging from exponential disks with long tidal tails to only one core with the $R^{1/4}$ law density profiles (e.g., Scoville et al. 2000). The present results imply that the observed diversity in morphological properties of ULIRGs can be partly understood in terms of the difference of physical parameters between multiple mergers.

4. DISCUSSION

4.1. Star Formation History in a Compact Group of Galaxies

The present numerical model has demonstrated that multiple tidal interaction and merging can trigger massive starbursts and the maximum star formation rate can reach $\sim 100 M_\odot yr^{-1}$ that is required for explaining the very large infrared luminosity of typical ULIRGs. Since multiple galaxy merging is suggested to occur naturally in a compact group of galaxies (Barnes 1989; Hickson 1997), we here discuss the derived results in the context of the evolution of galaxies in a compact group of galaxies.

4.1.1. Strength of Starburst

The first problem is whether a massive starburst ($\sim 100 M_\odot yr^{-1}$) can be triggered in some member galaxies during the dynamical evolution of a compact group of galaxies. We here stress that the derived star formation rate is rather overestimated owing to the following two assumptions adopted in the present study. First, for simplicity we assumed that all five disks have the same gas mass fraction ($f_g$) of 0.2. It is suggested that if density-dependent star formation law is applied (i.e., the Schmidt law) the initial gas mass fraction of a merger progenitor disk is a critically important factor for the strong starburst (Bekki 2000). Therefore, if a multiple merger has a few gas-poor disks ($f_g$ much less than 0.2), the strength of the triggered starburst is considerably smaller compared with multiple mergers with all disks being gas-rich (i.e., the mergers investigated in the present study). Second, we assumed that the initial disk mass is the same for all merger progenitor galaxies: the massive starburst is basically triggered by major galaxy merging between equal-mass disks in the present study. Although minor and unequal-mass galaxy merging can trigger the starburst (Mihos & Hernquist 1994), the magnitude of the starburst is rather small compared with major galaxy merging (Bekki 1998a). Therefore, if there is a significant difference in mass between merger progenitor disks, the triggered starburst becomes very small.

Although it is very difficult to discuss what the most probable initial physical conditions of the gas mass fraction and mass ratio of galaxies are for multiple galaxy mergers, we can address this issue by following recent observational results on galaxies in compact groups. Williams & van Gorkom (1988) and Williams, McMahon, & van Gorkom (1991) showed that the cool gas is not confined to the member galaxies of compact groups and accordingly suggested that many compact groups evolved to the point that cool gas contained within individual galaxies can be so efficiently distributed throughout the group (owing to tidal stripping of the gas) that the gas fraction of individual galaxies becomes very small. The fraction of cool interstellar gas estimated from CO-line observation is found to be similar to that of isolated spiral galaxies (Boselli et al. 1996), though this result may be biased by the relatively small size of the compact group of galaxies (Hickson 1997). The fraction of gas-rich late-type disks is demonstrated to be significantly less ($<0.5$) in the compact group than in the field (e.g., Hickson 1982; Sulecic 1987: Hickson, Kindl, & Huchra 1988). These observational results seem to imply that the mean gas mass fraction of galaxies in compact groups is rather small (i.e., the strength of starburst derived in the present study is overestimated). We here stress that the above observational results and their implications are true only for a low-redshift compact group of galaxies and therefore that the gas mass fraction of a merging compact group of galaxies can be very high if the merging can occur at high redshift.

Distribution of relative galaxy luminosity (i.e., the luminosity difference between the brightest galaxy and other member galaxy in a compact group) can provide a clue to the question on the above second assumption (Hickson 1982). Hickson (1982) investigated the difference in galaxy luminosity (indicated in Fig. 3 of Hickson 1982) and found that the difference is larger for a compact group with (first ranked) elliptical galaxies than for that without. Figure 3 in Hickson (1982) clearly showed that there are a significant fraction of compact groups with the difference in magnitude (and, possibly, mass) between member galaxies larger than 2.0 mag, though Hickson (1982) did not clearly mention that. These results imply that multiple major merging is less likely in the evolution of compact groups and thus that the strength of starburst reported by the present study can be overestimated. Thus, these observational results on the above two assumptions seem to imply that compact groups of galaxies are less likely to trigger a massive starburst with the star formation rate of $\sim 100 M_\odot yr^{-1}$. However, considering the smaller number of the detailed observational studies on physical properties of individual galaxies in compact groups, it is fair to say that only a compact group in which the difference in mass between the member galaxies is very small and most of the member galaxies are gas-rich can trigger massive starburst with the star formation rate of $\sim 100 M_\odot yr^{-1}$.

4.1.2. An Evolutionary Link between ULIRGs and Multiple Mergers

The second question is whether a compact group of galaxies can evolve into an ULIRG. Xia & Deng (1997) first
suggested that multiple galaxy merging can be closely associated with the formation of some ULIRGs, based on the observational results of spatial distribution of soft X-ray emission in Mrk 273 and the existence of more than 10 dwarf galaxies within 100 kpc of Mrk 273. Nishiura et al. (1997) discussed whether HCGs can be regarded as precursors of ULIRGs by comparing the K-band luminosity function of the HCGs with that of ULIRGs. Taniguchi & Shioya (1998) suggested that Arp 220, which is a typical ULIRG, is formed by multiple galaxy merging, based on the total number of OH maser sources and its spatial distribution in the central region of Arp 220. Recent morphological studies by the Hubble Space Telescope have found that 22 among 99 ULIRGs in the redshift range 0.05 < z < 0.20 have multiple nuclei (Borne et al. 2000). Based on these new results, Borne et al. (2000) suggested that multiple merging not only plays decisive roles in the formation of ULIRGs but also transforms a compact group of galaxies into a single elliptical galaxy. The idea that ULIRGs are formed by multiple merging is not fundamentally new in the sense that Sanders et al. (1988) have already suggested how dissipative galaxy merging is important for the formation of ULIRGs and Mihos & Hernquist (1996) have already revealed that efficient inward transfer of gas can trigger massive starburst in galaxy mergers: irrespective of whether a merger is a pair or a multiple, essentially important physical processes associated with the formation of starburst is probably the same between the two apparently different mergers. The difference between the model by Sanders et al. (1988) and the multiple merger one by the above authors is only the number of galaxies in merging. Accordingly, it seems to be nearly meaningless to discriminate clearly the two models (pair and multiple merger models). However, we here consider that it is important to investigate observationally what fraction of ULIRGs are formed by multiple galaxy merging. This is because the fraction enables us to estimate (though indirectly) the fraction of compact groups that are now evolving from ULIRGs into field elliptical galaxies.

The observed infrared luminosity of ULIRGs is successfully reproduced by pair mergers (Bekki et al. 1999), and furthermore the diversity in morphological properties between ULIRGs is suggested to reflect the difference in orbital configurations and internal structure between pair mergers (Bekki 2000). The present study on multiple galaxy merging, on the other hand, demonstrated that a multiple merger shows such a high star formation rate that it can be identified as an ULIRG and furthermore that the morphology of the merger at the epoch of massive starburst (i.e., the epoch when the merger can be observed as an ULIRG) is similar to those of some ULIRGs. Numerical results on pair mergers (Bekki et al. 1999; Bekki 2000) and those for multiple ones (i.e., the present study) therefore imply that morphological and photometric properties alone cannot clearly indicate whether an ULIRG is a pair merger or a multiple one. As is suggested by Borne et al. (2000), one of the key observational tests concerning the above question is to investigate whether each of apparent multiple nuclei observed in some ULIRGs (e.g., those shown in Fig. 1 of Borne et al. 2000) is really a galactic nucleus or a super-starburst. Recent high-resolution imaging of some ULIRGs has revealed that most of ULIRGs show compact blue knots of star formation with the number of such knots ranging from 4 to 31 per object (Surace et al. 1998). Surace et al. (1998) furthermore revealed that the range of the knot masses is $10^{-5}$–$10^{9}$ and the upper age limit for the knots in individual galaxies is $3 \times 10^{6}$ yr by using spectral synthesis modeling. The existence of these star-forming blue knots has been confirmed by several other observational studies based on high-resolution optical/near-infrared imaging of ULIRGs (Dinshaw et al. 1999; Surace & Sanders 1999; Scoville et al. 2000). Furthermore, Bekki (2000) demonstrated that most of the morphological properties of ULIRGs can be reproduced by pair mergers at the epoch of the maximum starburst (i.e., the epoch when mergers can be observed as ULIRGs). Accordingly, it is highly possible that ULIRGs with several apparent nuclei appear to be pair mergers with superstarburst knots, though theoretical studies on major mergers have not yet clarified the mechanism for the formation of such massive blue knots observed in ULIRGs. Here it should be noted that Barnes & Hernquist (1992b) have already demonstrated that massive dwarflike objects can be formed in tidal tails of a pair merger. Accordingly, it is not unreasonable to consider that these newly formed objects can be identified as blue knots in ULIRGs. These observational and theoretical results imply that ULIRGs with apparent multiple nuclei are not formed by multiple mergers: a pair galaxy merger both triggers massive starburst and forms several very bright massive star clusters that look like galactic nuclei in optical bands. However, high-resolution multiband studies (in particular, in near-infrared band) on morphological properties of ULIRGs have not been so accumulated yet which can clearly discriminate real galactic nuclei from very bright star clusters. Accordingly, it is fair for us to say that it is still highly uncertain what fraction of ULIRGs are formed by multiple merging.

4.2. Fossil Records of the Past Merging Events in Field Elliptical Galaxies

We have demonstrated that owing to the strong tidal stripping of metal-poor interstellar gas initially within the outer part of disks, an elliptical galaxy formed by multiple galaxy merging can have a metal-poor gaseous halo and show the negative metallicity gradient. There may or may not be recent observational evidences (e.g., those from the Advanced Satellite for Cosmology and Astrophysics [ASCA]) that support the above results. Fe abundance of hot gaseous X-ray halo has been suggested to be appreciably smaller than that of the stellar component in the host field elliptical galaxy (Awaki et al. 1994; Matsushita et al. 1994; Matsu moto et al. 1997; but see Matsushita et al. 1997). Furthermore, the hot X-ray gaseous halo in elliptical galaxies has been suggested to show strong negative metallicity gradients, which implies that some physical mechanisms such as cooling flow, gaseous dissipation, galaxy merging, and dilution from external metal-poor gas play a vital role in the formation of the gaseous metallicity gradients (Loewenstein et al. 1994; Mushotzky et al. 1994; Matsushita et al. 1997). Since the above observationally suggested metal-poor halo and metallicity gradients can be reproduced by the present numerical results, we here propose that the metal-poor gaseous halo is a fossil record of the past multiple merging events for field elliptical galaxies. Multiple galaxy merging can not only transform a compact group of galaxies into an field elliptical galaxy but also form a metal-poor gaseous halo. Therefore, some of field elliptical galaxies can be observed to show a metal-poor gaseous halo.
One of the observational tests to assess the validity of the above proposal is to investigate in detail the two-dimensional distribution of metal-poor gaseous halos in field elliptical galaxies. Metal-poor gas tidally stripped from merger progenitor disks is initially distributed in a very inhomogeneous way owing to the incompleteness of dynamical relaxation of multiple galaxy merging. For a merger (or a merger remnant) with stronger tidal disturbance, the metal-poor gaseous halo can be distributed in a more inhomogeneous way around the merger. Therefore, it is highly possible that a field elliptical galaxy just formed by merging shows a very inhomogeneous distribution of metal-poor gaseous halo. Furthermore, the degree of inhomogeneity in the distribution of metal-poor gaseous halo for merger remnants can depend strongly on how the remnants are dynamically relaxed. Accordingly, we suggest that if future observations discover very inhomogeneous distribution of metal-poor halo in a field elliptical galaxy, the observed halo can be interpreted as a fossil record of the past multiple merging that formed the elliptical. We furthermore suggest that if there is a strong physical correlation between the degree of inhomogeneity in the distribution of metal-poor gaseous halo and that of dynamical relaxation for field elliptical galaxies, the relation strengthens the scenario that some field elliptical galaxies can be formed by multiple merging and evolved from compact groups of galaxies. Since the origin of field elliptical galaxies is still highly uncertain (Bender 1996), future observational studies on the detailed distribution of the metal-poor gaseous halo will provide new and valuable information on the formation and the evolution of field elliptical galaxies.

5. CONCLUSION

We have numerically investigated the star formation history and the chemical evolution of multiple mergers among five identical gas-rich disk galaxies in an explicitly self-consistent manner. The main results of the present study are summarized as follows.

1. We found that repetitive massive starburst with the star formation rate ranging from $\sim 10$ to $\sim 10^2 M_\odot \text{yr}^{-1}$ can occur with the time interval between the starbursts depending on the model parameters. The time interval between the epochs of repetitive starburst is longer for the merger with the larger virial ratio (i.e., the ratio of total kinematical energy to total potential energy).

2. The magnitude of the starburst is found to depend on the initial virial ratio such that the maximum star formation rate is longer for the merger with the larger virial ratio.

3. Initial orbital configurations are also found to be important for the strength of starburst triggered in multiple merging. The 2D model is likely to show stronger starburst than the 3D model during multiple merging.

4. Morphological properties of multiple mergers at the epoch of strong starburst are rather diverse: some mergers show multiple starburst nuclei and very long tidal tails.

5. We also found that chemical evolution during multiple merging proceeds so inhomogeneously that a metal-poor gaseous halo can form in the outer part of the merger remnants. We accordingly suggest that the metal-poor gaseous halo in a field elliptical galaxy is a fossil record of the past multiple merging events for the galaxy.

Multiple merging is suggested to occur in the dynamical evolution of compact groups of galaxies (e.g., Mamon 1987; Barnes 1989; Hickson 1997 for a recent review). These numerical results thus provide some important implications on the evolutionary link among compact groups of galaxies, ULIRGs, and field elliptical galaxies.

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