STELLAR POPULATIONS IN GAS-RICH GALAXY MERGERS. I. DEPENDENCE ON STAR FORMATION HISTORY

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ABSTRACT

We investigate the nature of stellar populations of major galaxy mergers between late-type spirals with considerably abundant interstellar medium by performing numerical simulations designed to solve both the dynamical and chemical evolution of the mergers in a self-consistent manner. We particularly consider that the star formation history of galaxy mergers is a crucial determinant of the nature of stellar populations of merger remnants, and therefore we investigate how the difference in star formation history between galaxy mergers affects the chemical evolution of galaxy mergers. We found that the rapidity of star formation, which is defined as the ratio of the dynamical timescale to the timescale of gas consumption by star formation, is the most important determinant for a number of fundamental characteristics of stellar populations of merger remnants. The main results obtained in this study are the following.

1. A galaxy merger with more rapid star formation becomes elliptical with larger mean metallicity. This is primarily because, in the merger with more rapid star formation, a smaller amount of metal-enriched gas is tidally stripped away during merging, and, consequently, a larger amount of the gas can be converted to stellar components. This demonstrates that the cause of the color-magnitude relation of elliptical galaxies can be closely associated with the details of merging dynamics that depend on the rapidity of star formation in galaxy mergers.

2. A negative metallicity gradient fitted reasonably well by a power law can be reproduced by a dissipative galaxy merger with star formation. The magnitude of the metallicity gradient is larger for an elliptical galaxy formed by a galaxy merger with less rapid star formation.

3. The absolute magnitude of the metallicity gradient correlates with that of the age gradient in galaxy mergers in the sense that a merger remnant with a steeper negative metallicity gradient is more likely to show a steeper age gradient.

4. The outer part of a stellar population is both older and less metal-enriched than the nucleus in an elliptical galaxy formed by a galaxy merger with less rapid star formation. Moreover, the metallicity of the outer part of the gaseous component for some models with less rapid star formation is appreciably smaller than the stellar metallicity. This result implies that the origin of metal-poor hot gaseous X-ray halos in real elliptical galaxies can essentially be ascribed to the dynamics of dissipative galaxy merging.

5. Irrespective of the rapidity of star formation, the epoch of galaxy merging affects both the mean stellar metallicity and the mean stellar age of merger remnants: later galaxy mergers are more likely to become ellipticals with both younger and more metal-enriched stellar populations. This result reflects the fact that in the later mergers, a larger amount of more metal-enriched interstellar gas is preferentially converted into stars during the later period of star formation triggered by galaxy merging. These five results clearly demonstrate that even the chemical evolution of elliptical galaxies can be strongly affected by the details of dynamical evolution of galaxy merging, which are furthermore determined by the rapidity of star formation of galaxy mergers. In particular, tidal stripping of interstellar gas and the total amount of gaseous dissipation during galaxy merging are demonstrated to play vital roles in determining a number of chemical properties of merger remnants. Based on these results, we adopt a specific assumption of luminosity dependence on rapidity of star formation and thereby discuss how successfully the present merger model can reproduce a number of fundamental chemical, photometric, and spectroscopic characteristics of elliptical galaxies.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: formation — galaxies: interactions — galaxies: stellar content — galaxies: structure

1. INTRODUCTION

Elliptical galaxies have generally been considered to be old, coeval, and homogeneous systems passively evolving after a single initial burst of star formation associated with dissipative galaxy formation. This classical picture of elliptical galaxy formation appears to have been supported by the considerably tight color-magnitude relation of elliptical galaxies (Bower, Lucey, & Ellis 1992; Ellis et al. 1997) and by the relatively small redshift evolution of the photometric properties of elliptical galaxies (Aragón-Salamanca et al. 1993; Franx & van Dokkum 1996). A growing number of recent observational results, however, shed a strong doubt on this long-standing view of elliptical galaxy formation and suggest that there is a great variety of star formation
history among elliptical galaxies in such factors as the epoch of major star formation and the duration and efficiency of star formation (Worthey, Faber, & Gonzalez 1992; Matteuchi 1994; Faber et al. 1995; Bender 1996; Worthey, Trager, & Faber 1996). This tendency of elliptical galaxies to show diversity in star formation history while actually keeping the tightness of the color-magnitude relation is considered to be quite mysterious and thus to provide theoretical models with valuable insight on elliptical galaxy formation. Such a mysterious nature is demonstrated to hold as well for the dynamical and kinematical properties of elliptical galaxies. For example, the considerably small thickness of the fundamental planes of elliptical galaxies implies a rather smaller range of admitted dynamical states of the galaxies (Djorgovski & Davis 1987; Dressler et al. 1987; Djorgovski, Phare, & de Carvalho 1996), whereas the morphological dichotomy between boxy and disky elliptical galaxies (Kormendy & Bender 1996) and the projected density profiles, which systematically depart from de Vaucouleurs $r^{1/4}$ law (Caon, Capaccioli, & D'Onofrio 1993), show that the galaxies consist of a great variety of major orbit families.

These fundamental characteristics, that elliptical galaxies show both diversity and uniformity in their chemical, photometric, and dynamical properties, have imposed some stringent but valuable constraints on any theoretical models of elliptical galaxy formation. What is the most vital in challenging the origin of elliptical galaxy formation in this kind of situation is to investigate whether or not both the chemical and photometric properties and the dynamical and kinematical ones can be reproduced successfully and in a reasonably self-consistent manner by a specific model of galaxy formation. The previous theoretical models addressing this important issue on elliptical galaxy formation are divided basically into two categories, the dissipative galactic collapse model (see, e.g., Larson 1975; Carlberg 1984) and the galaxy merger model (see, e.g., Toomre & Toomre 1972). As suggested by Kormendy & Sanders (1992), these two dominant and apparently competing scenarios for elliptical galaxy formation are now converging; thus it would be crucial to construct one more realistic and sophisticated model of elliptical galaxy formation. Although there are a large number of important studies exploring the origin of elliptical galaxy formation using the dissipative collapse scenario, especially in the context of the nature of stellar populations (see, e.g., Arimoto & Yoshii 1987), we here restrict ourselves to the merger scenario of elliptical galaxy formation.

Recent extensive studies of merger models of elliptical galaxy formation, mostly based upon numerical simulations, appear to have succeeded in resolving most of the outstanding problems related to dynamical and kinematical properties of elliptical galaxies, such as phase space density (Ostriker 1980; Carlberg 1986) and kinematical misalignment (Franx, Illingworth, & de Zeeuw 1991; Barnes 1992), by invoking the inclusion of a bulge component, gaseous dissipation, and a multiplicity of galaxy mergers (Hernquist, Spergel, & Heyl 1993; Weil & Hernquist 1996; Barnes & Hernquist 1996). Although it would be safe to say that galaxy merging between two late-type spirals is one of the most promising candidates in explaining more clearly the origin of elliptical galaxies, at least in the context of their dynamical and kinematical properties, there still remain a number of unresolved and apparently serious problems concerning the merger model (see, e.g., van den Bergh 1995). One of the most crucial problems among these is whether the fundamental characteristics of stellar populations of elliptical galaxies can be reproduced reasonably well by galaxy merging between two late-types spirals. Surprisingly, there are only a few works addressing this critical issue for the merger model, probably because it is considered to be rather difficult to solve the chemical evolution of galaxy mergers in which a number of competing physical processes are expected to affect strongly the chemical evolution of galaxy mergers. White (1980) and Mihos & Hernquist (1994) found that the stellar populations of progenitor disks are not mixed well even by violent relaxation during galaxy merging, and consequently the metallicity gradient of progenitor disks is not drastically washed out. Furthermore, the metallicity gradient of the merger remnant is found not to be fitted by the power law observed in elliptical galaxies (Mihos & Hernquist 1994). Schweizer & Seitzer (1992) discussed whether or not the bluer than expected integrated $UBV$ color of elliptical galaxies with morphologically fine structure can be explained by a secondary starburst induced by major disk-disk galaxy mergers. Kauffmann & Charlot (1997) construct a semianalytic elliptical galaxy formation model that is based upon the hierarchical clustering in a CDM universe and includes rather simple chemical enrichment processes and thereby demonstrates that the color-magnitude relation of elliptical galaxies can be reproduced successfully even in the CDM model of galaxy formation (see also Baugh, Cole & Frenk 1996). Thus, since there are only a few works addressing chemical and photometric properties for the merger model, it is essential to investigate more thoroughly the fundamental chemical and photometric properties of merger remnants, including the cause of the color-magnitude relation (Faber 1973; Visvanathan & Sандage 1977), the age and metallicity gradient (Peleter et al. 1990; Davies et al. 1993), the Mg$_2$-σ relation (Burstein et al. 1988), the age-metallicity relationship in stellar populations (Faber et al. 1995; Worthey et al. 1996), the luminosity dependence of the line ratio [Mg/Fe] (Worthey et al. 1992), the metal-poor gaseous X-ray halo (Matsumoto et al. 1997), and the substantially metal-enriched galactic nuclei at higher redshift (Hamann & Ferland 1993).

What should be recognized foremost in investigating the nature of stellar populations in merger remnants is that a growing number of observational results suggest that the relatively earlier formation of elliptical galaxies have been accumulated. The tightness of the color-magnitude relation in the cluster of galaxies (Bower et al. 1992; Ellis et al. 1996), the relatively small photometric evolution of cluster ellipticals (Aragón-Salamanca et al. 1993), and the redshift evolution of the fundamental plane (Franx & van Dokkum 1996) all suggest the typical formation epoch of elliptical galaxies is earlier than redshift $z = 2$. Furthermore, as is suggested by Kormendy & Sanders (1992), the fact that no galaxy in the K-band survey of Cowie et al. (1994) shows global color resembling that of Arp 220, which is considered to be an ongoing merger and forming elliptical, implies that the formation epoch of elliptical galaxies should be earlier than $z = 1.0$ in redshift. Silva & Bothun (1997) revealed that the fraction of the mass of intermediate-age stellar populations to the total mass in elliptical galaxies with morphologically fine structure is less than 15%. These results imply that, if elliptical galaxies are formed by galaxy merging, the epoch of galaxy merging should be relatively earlier and,
furthermore, that the interstellar medium may be extremely abundant in the precursor disks of merging galaxies compared with that in the present spirals. Recent high-quality imaging using the *Hubble Space Telescope (HST)* has revealed that a larger number of galaxies at faint magnitudes are interacting and/or merging (see, e.g., van den Bergh et al. 1996), indicating that potential candidates for elliptical galaxies formed by galaxy merging are ubiquitous in the higher redshift universe. Hence it is quite reasonable and essential to study the nature of stellar populations of high-redshift galaxy mergers between disk galaxies with gas mass fractions larger than 0.2, which is a typical value for the present late-type spirals, and thereby to confirm whether or not elliptical galaxies can actually be formed by merging galaxies.

The purpose of this paper is to explore the nature of the stellar populations of gas-rich disk mergers, which are considered to occur most frequently in the high redshift universe. We particularly investigate how successfully galaxy mergers between gas-rich spirals can reproduce a number of fundamental chemical, photometric, and spectroscopic properties of elliptical galaxies.

The layout of this paper is as follows. In §2, we summarize numerical models used in the present study and describe in detail methods for analyzing the stellar populations produced by dissipative galaxy mergers with star formation. In §3, we demonstrate how a number of fundamental characteristics of stellar populations in merger remnants are affected by the star formation history of dissipative galaxy mergers. In §4, we discuss how successfully the present merger model can reproduce a number of observational results concerning the chemical, photometric, and spectroscopic properties of elliptical galaxies. In this section, we also point out the advantages and disadvantages of the galaxy merger model in explaining the chemical, photometric, and spectroscopic properties and dynamical and kinematical ones observed in real elliptical galaxies. The conclusions of the present study are given in §5.

2. MODEL

The dynamical evolution of dissipative galaxy mergers with star formation is generally considered to be highly complex principally because a small amount of interstellar gas can drastically change the degree of violent relaxation, the details of the redistribution of angular momentum in gaseous and stellar components, and the total amount of mass transferred to the central region of the merger remnants (Barnes & Hernquist 1992, 1996). Basically, because the transfer and mixing of heavy elements ejected from stellar components are controlled by the above dynamical processes of galaxy merging in a considerably complicated way, we accordingly could not be allowed just to invoke the simple one-zone model in analyzing the chemical and photometric evolution of merging galaxies. Thus, in order to analyze the nature of stellar populations produced in such a complex situation of dissipative galaxy merging, we must solve both the dynamical and the chemical evolution in a self-consistent manner. In the present study, the dynamical evolution of a collisional component (interstellar gas) and a collisionless one (the dark halo and stars) is solved by a specific N-body method; then a number of characteristics of stellar populations at given points in the merger remnants are calculated based on the derived information about the position, velocity, age, and metallicity of each stellar particle. First, in §2.1, we describe the numerical model including the initial conditions of the mergers, the prescriptions for the dissipative process, and the model for star formation. Second, in §2.2, we give the method for analyzing the chemical enrichment process during mergers and the photometric properties of the remnants. Third, in §2.3, we describe the main points of analysis of the present study. Finally, in §2.4, we give values of each parameter in each model.

2.1. Numerical Model

2.1.1. Initial Conditions

We construct models of galaxy mergers betweengas-rich disk galaxies with equal mass by using the Fall & Efstatthiou (1980) model. The total mass and the size of a progenitor disk are $M_d$ and $R_d$, respectively. From now on, mass and length are measured in units of $M_d$ and $R_d$, unless specified. Velocity and time are measured in units of $v = (GM_d/R_d)^{1/2}$ and $T_{\text{dyn}} = (R_d^2/GM_d)^{1/2}$, respectively, where $G$ is the gravitational constant and is 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 $T_{\text{dyn}} = 1.41 \times 10^8$ yr, respectively. In the present model, the rotation curve becomes nearly flat at 0.35 times the radius with the maximum rotational velocity $v_{\text{in}} = 1.8$ in our units. The corresponding total mass $M_{\text{tot}}$ and halo mass $M_h$ are 3.8 and 2.8 in our units, respectively. The radial ($R$) and vertical ($Z$) density profile of a disk are assumed to be proportional to $\exp(R/R_d)$ with scale length $R_0 = 0.2$ and to be proportional to $\exp(-Z/Z_0)$ with scale length $Z_0 = 0.04$ in our units, respectively. The mass density of the halo component is truncated at 1.2 in our units and its velocity dispersion 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 the 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) $Q = 1.0$. This adopted value for the $Q$ parameter is appreciably smaller than the value required for stabilizing the initial disk against the nonaxisymmetrical dynamical instability (e.g., bar instability). The reason for this adoption is that the initial disk is assumed to be composed mostly of interstellar gas, and thus random kinetic energy in the disk is considered to be rather small because of gaseous dissipation in the disk. 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 (see, e.g., Wielen 1977). As is described above, the present initial disk model does not include any remarkable bulge component, and accordingly it corresponds to a "pure" late-type spiral without a galactic bulge. It is highly possible that galactic bulges greatly affect the chemical evolution of galaxy mergers; we, however, investigate this issue in future papers. It is reasonable to consider that the present initial disk with a considerably larger amount of interstellar gas and without pronounced galactic bulges is one of the candidates for precursors of typical elliptical galaxies that are considered to be formed at relatively high redshifts ($z > 2$).

The collisional and dissipative nature of the interstellar medium is modeled by the "sticky-particle" method.
merging galaxies encounter each other parabolically. The set to be 1.0 for all models of pair mergers, meaning that the angular momentum of galaxy mergers. The eccentricity is a free parameter that controls the initial total orbital pericenter distance, represented by is assumed to be a free parameter that controls the epoch of galaxy merging. The size of the two disks, represented by is assumed to be a free parameter. In the simulations of pair mergers between five disks. In all of the simulations of pair mergers, the orbit of the two disks is initially set to be in the \((x, y)\) plane, and the distance between the center of mass of the two disks, represented by \(r_{in}\), is assumed to be a free parameter that controls the epoch of galaxy merging. The pericenter distance, represented by \(r_{p}\), is also assumed to be a free parameter that controls the initial total orbital angular momentum of galaxy mergers. The eccentricity is set to be 1.0 for all models of pair mergers, meaning that the merging galaxies encounter each other parabolically. The spin of each galaxy in a pair merger is specified by two angles, \(\theta_i\) and \(\phi_i\), where the subscript “i” is used to identify each galaxy. \(\theta_i\) is the angle between the \(z\)-axis and the vector of the angular momentum of a disk. \(\phi_i\) is the azimuthal angle measured from the \(x\)-axis to the projection of the angular momentum vector of a disk onto the \((x, y)\) plane. The values of the parameters \(\theta_i\), \(\phi_i\), \(r_{p}\), and \(r_{in}\) for each model are described below. In the simulations of multiple mergers, the initial position of each progenitor disk is set to be distributed randomly within a sphere with radius 6.0 in our units, and the initial 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 kinetic energy to the total potential energy in the system is 0.25. The time when the progenitor disks merge completely and reach dynamical equilibrium is less than 15.0 in our units for most of our models and, in the present calculations, does not depend very strongly on the history of star formation.

2.1.2. Global Star Formation

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 amount of gas \(M_g\) consumed by star formation for each gas particle in each time step is given as

\[
M_g \propto C_{SF} \times (\rho_g / \rho_0)^{\gamma - 1.0},
\]

where \(\rho_g\) and \(\rho_0\) are the gas density around each gas particle and the mean gas density at 0.48 times the radius of an initial disk, respectively. This star formation model is similar to that of Mihos, Richstone, & Bothun (1992). In order to avoid a large number of new stellar particles with different masses, we convert one gas particle into one stellar one according to the following procedure. First, we give each gas particle the probability, \(P_{sf}\), that the gas particle is converted into a stellar one by setting the \(P_{sf}\) to be proportional to the value of \(M_g\) estimated for the gas particle in equation (1). Then we draw a random number to determine whether or not the gas particle is totally converted into one new stellar particle. This method of star formation enables us to control the rapidity of star formation without increasing the number of particles in each simulation and thus allows us to maintain numerical accuracy in each simulation. \(C_{sf}\) in equation (1) is the parameter that controls the rapidity of gas consumption by star formation: the larger \(C_{sf}\) is, the more rapidly the gas particles are converted to new stellar particles. As a result of this, the total amount of gaseous dissipation is also controlled by the parameter \(C_{sf}\): for the models with smaller \(C_{sf}\), more of the kinetic energy of the gas particles is dissipated away by the cloud-cloud collision. This parameter \(C_{sf}\) is meant to be proportional to the ratio of the dynamical timescale of the system to the timescale of gas consumption by star formation. Furthermore, equation (1) states that a large number of stellar particles are created at the regions where the local gas density becomes larger owing to the onset of local Jeans instability. The positions and velocity of the new stellar particles are set to be the same as those of the original gas particles. As described above, in the present study, we do not explicitly include the “threshold density” of star formation, which is demonstrated to be associated with the growth of local gravitational instability with relatively smaller wavelengths, \(\text{that is, the Toomre's } Q \text{ parameter (Kennicutt 1989) for isolated disk galaxies. This is because the threshold criterion, which is derived only for calmy evolving galactic disks, cannot be simply applied to the present merger model, in which the timescale on which the disk can evolve without strong dynamical perturbation is relatively small (less than 10 dynamical times for typical models).}

In the present study, we do not intend to include any “feedback” effects of star formation, such as thermal and dynamical heating of the interstellar medium driven by supernovae, first because such inclusion could prevent us from deducing more clearly the important roles of the rapidity of star formation and second because there still...
remains a great uncertainty concerning the numerical implementation of the feedback effects (Katz 1992; Navarro & White 1993). Accordingly, as described above, “star formation” in this preliminary study means only the formation of collisionless particles and does not literally mean the actual and realistic series of star formation. This kind of modeling for star formation is rather oversimplified in order to address only some important aspects of the roles of star formation in generating the chemical and dynamical characteristics of merger remnants. However, we believe that since the main points of the present study are only the relative global and average characteristics of chemical and photometric properties, even the rather simple model adopted in this study makes it possible to grasp some essential ingredients of the roles of “star formation” in producing a number of important characteristics of stellar populations in merging galaxies. More extensive studies on this subject will be done in future papers by using a more elaborate model of star formation.

All the calculations related to the above dynamical evolution, including the dissipative dynamics, star formation, and gravitational interaction between collisionless and collisional components, have been carried out on the GRAPE board (Sugimoto et al. 1990) at the Astronomical Institute of Tohoku University. The parameter of gravitational softening is set to be fixed at 0.04 in all the simulations. The time integration of the equation of motion is performed by using a second-order leap-frog method. Energy and angular momentum are conserved to within 1% accuracy in a test collisionless merger simulation. Most of the calculations are set to be stopped at $T = 25.0$ in our units unless specified.

2.2. Method for Analysis of Stellar Population

Chemical and photometric properties such as global colors and metallicity gradients in elliptical galaxies depend critically on how the metallicities and ages of stellar components are distributed in the galaxies. Accordingly, we first analyze the distribution of stellar age and that of stellar metallicity in the merger remnant for each model. In the present study, these age and metallicity distributions are calculated based on the age and metallicity assigned to each stellar particle, as described in detail below. The outline for this calculation is as follows. First we derive the distribution of stellar age and that of stellar metallicity by assigning ages and metallicities to stellar particles according to the law of each neighboring gas particle. Accordingly, we first analyze the distribution of stellar age and that of stellar metallicity assigned to each stellar particle, as described in detail below. The outline for this calculation is as follows. First we derive the distribution of stellar age and that of stellar metallicity by assigning ages and metallicities to stellar particles according to the law of each neighboring gas particle. 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 the $R_{\text{chem}}$ and $y_{\text{met}}$ are set to be 0.3 and 0.03, respectively. Furthermore, the time $t_i$ when the new stellar particle is created is assigned to the new stellar particle in order to calculate the photometric evolution of merger remnants, as described below. To verify the accuracy of the above treatment (including numerical code) for the chemical enrichment process, we checked whether or not the following conservation law of chemical enrichment is satisfied for each time step in each test simulation:

$$\sum_{\text{star}} m_z Z_i + \sum_{\text{gas}} m_g Z_i = y_{\text{met}} \sum_{\text{star}} m_z ,$$

where $m_g$, $m_z$, and $Z_i$ are the mass of each gas particle, that of each stellar one, and the metallicity of each particle, respectively, and the summation is done for all the gas or stellar particles. Strictly speaking, the above equation holds when the value of $R_{\text{chem}}$ is 0.0. Thus, in testing the validity of the present code of chemical enrichment, we set the value of $R_{\text{chem}}$ to be 0.0 and then performed a simulation for the test. We confirmed that the above equation is nearly exactly satisfied in our test simulations and that, furthermore, even if $R_{\text{chem}}$ is not 0.0, the difference in the value of total metallicity between the left-hand and right-hand sides in the above equation is negligibly small.

2.2.2. Population Synthesis

It is assumed in the present study that the spectral energy distribution (SED) of a model galaxy is a sum of the SEDs of its stellar particles. The SED of each stellar particle is assumed to be a simple stellar population (SSP) that is a coeval and chemically homogeneous assembly of stars. Thus the monochromatic flux of a galaxy with age $T$, $F_\lambda(T)$, is described as

$$F_\lambda(T) = \sum_{\text{star}} F_{\text{SSP}}, (Z_i, \tau_i) \times m_z ,$$

where $F_{\text{SSP}}, (Z_i, \tau_i)$ and $m_z$ are a monochromatic flux of an SSP of age $\tau_i$ and metallicity $Z_i$, where the subscript “$i$” identifies each stellar particle, and the mass of each stellar particle, respectively. The age of the SSP, $\tau_i$, is defined as $\tau_i = T - t_i$, where $t_i$ is the time when a gas particle converts to a stellar one. The metallicity of the SSP is exactly the same as that of the stellar particle, $Z_i$, and the summation in equation (4) is done for all stellar particles in a model galaxy.

The value of $R_{\text{chem}}$ relative to the typical size of a galaxy could be different between galaxies; accordingly, the value of $R_{\text{chem}}$ is considered to be a free parameter in the present study. The values of $R_{\text{chem}}$ examined most extensively in the present study are 0.4, which is slightly smaller than the effective radius of typical merger remnants in the present study; 0.1; and 0.02, which is the one-half of the gravitational softening length. Next we assign the metallicity of original gas particle to the new stellar particle and increase the metallicity of each neighboring gas particle according to the following equation of chemical enrichment:

$$\Delta M_Z = [Z_i R_{\text{met}} m_z + (1.0 - R_{\text{met}})(1.0 - Z_i)m_z y_{\text{met}}]/N_{\text{gas}} ,$$

where the $\Delta M_Z$ represents the increase of metallicity for each gas particle. $Z_i$, $R_{\text{met}}$, $m_z$, and $y_{\text{met}}$ 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 the $R_{\text{met}}$ and $y_{\text{met}}$ are set to be 0.3 and 0.03, respectively. Furthermore, the time $t_i$ when the new stellar particle is created is assigned to the new stellar particle in order to calculate the photometric evolution of merger remnants, as described below. To verify the accuracy of the above treatment (including numerical code) for the chemical enrichment process, we checked whether or not the following conservation law of chemical enrichment is satisfied for each time step in each test simulation:

$$\sum_{\text{star}} m_z Z_i + \sum_{\text{gas}} m_g Z_i = y_{\text{met}} \sum_{\text{star}} m_z ,$$

where $m_g$, $m_z$, and $Z_i$ are the mass of each gas particle, that of each stellar one, and the metallicity of each particle, respectively, and the summation is done for all the gas or stellar particles. Strictly speaking, the above equation holds when the value of $R_{\text{chem}}$ is 0.0. Thus, in testing the validity of the present code of chemical enrichment, we set the value of $R_{\text{chem}}$ to be 0.0 and then performed a simulation for the test. We confirmed that the above equation is nearly exactly satisfied in our test simulations and that, furthermore, even if $R_{\text{chem}}$ is not 0.0, the difference in the value of total metallicity between the left-hand and right-hand sides in the above equation is negligibly small.
A stellar particle is assumed to be composed of stars whose age and metallicity are exactly the same as those of the stellar particle and the total mass of the stars is set to be the same as that of the stellar particle. Thus the monochromatic flux of the SSP at a given wavelength is defined as

\[ F_{\text{SSP},i}(Z_i, \tau_i) = \int_{M_L}^{M_U} \phi(M) f_j(M, \tau_i, Z_i) dM, \]  

where \( M \) is mass of a star and \( f_j(M, \tau_i, Z_i) \) is the monochromatic flux of a star with mass \( M \), metallicity \( Z_i \), and age \( \tau_i \). \( \phi(M) \) is the initial mass function (IMF) of the stars, and \( M_U \) and \( M_L \) are the upper and the lower mass limits, respectively, of the IMF.

In this paper, we use the \( F_{\text{SSP},i}(Z_i, \tau_i) \) calculated by Tantalo et al. (1996). The characteristics of the SSP of Tantalo et al. (1996) are that (1) all evolutionary phases, from the main sequence to the white dwarf or C-ignition stage, are included and that (2) metallicity \( Z \) ranges from 0.0004 to 0.1 and helium content \( Y \) satisfies the relation \( Y = 2.5Z + 0.230 \). The library of stellar spectra calculated by Kurucz (1992) and the following form of the Salpeter IMF are used in deriving the above \( F_{\text{SSP},i}(Z_i, \tau_i) \):

\[ \phi(M) = \frac{(x - 2)M_i^{x-2}}{1 - (M_i/M_e)^{-2}} M^{-x}, \]

where \( x = 2.35, M_f = 0.15 M_\odot, \) and \( M_U = 120 M_\odot \). In order to estimate the \( F_{\text{SSP},i}(Z_i, \tau_i) \) for stellar particles with arbitrary \( Z_i \) and \( \tau_i \), we assign interpolated values to each stellar particle by using a set of data points tabulated in Table 2 of Tantalo et al. (1996). The mean stellar metallicity \( \langle Z_\star \rangle \) used in the present study is defined as

\[ \langle Z_\star \rangle = \frac{\sum_{\text{star}} Z_i m_i}{\sum_{\text{star}} m_i}. \]

Colors at given radii and radial color gradients are given as follows. First we divide the region ranging from 0.5 to 5.0R_e from a merger remnant into 20 annuli whose inner and outer boundaries are located at distances \( r_j \) and \( r_{j+1} \) from the center of the remnant, respectively. Then the monochromatic flux emitted from the \( j \)th annulus is derived by summing the \( F_{\text{SSP}}(Z_i, \tau_i) \) of all the particles located at \( r_j < R_i < r_{j+1} \), where \( R_i \) is the distance between the position of each stellar particle and the center of the remnant. Color gradients are calculated by using this monochromatic flux for each annulus.

### 2.3. Main Points of Analysis

We consider that \( C_{\text{SF}} \) is the most important parameter in the present study, principally because \( C_{\text{SF}} \) could depend on galactic luminosity. The importance of \( C_{\text{SF}} \) and its possible dependence on galactic luminosity are described in Appendices A and B. In what follows, we mainly investigate how the rapidity of gas consumption by star formation (\( C_{\text{SF}} \)) can determine a number of fundamental chemical, photometric, and spectroscopic properties of merger remnants, and we thereby observe how successfully the present merger model can reproduce the fundamental characteristics of real elliptical galaxies. Since \( C_{\text{SF}} \) is considered to depend on galactic luminosity in the present study, this investigation corresponds to addressing indirectly the origin of the luminosity-dependent characteristics of elliptical galaxies. First, in § 3.1, we investigate the dependence of chemical properties on \( C_{\text{SF}} \). What we investigate most extensively are its effects on the mean stellar and gaseous metallicities, the radial gradients of metallicity and age, the shapes of isochrone contour, and the formation of substantially metal-enriched galactic nuclei in merger remnants. Second we investigate the important roles of four other parameters, the chemical mixing length, the orbital configuration of merging galaxies, the multiplicity of merging galaxies, and the epoch of galaxy merging, in determining the fundamental chemical properties of merger remnants (§ 3.2). This sort of multiparameter study is indispensable for the present study, in which initial physical conditions of galaxy mergers can vary. In this investigation, we confirm whether or not the important roles of the parameter \( C_{\text{SF}} \) derived in § 3.1 also apply in models with different chemical mixing lengths, orbital configurations, multiplicities of mergers, and merging epochs. We also observe how these four parameters modify the \( C_{\text{SF}} \) dependence derived in § 3.2 and what fundamental roles the four parameters play in determining the characteristics of stellar populations. Third, in § 3.3, we investigate the photometric and spectroscopic properties of merger remnants and their dependence on galactic luminosity by adopting a specific relation between \( C_{\text{SF}} \) and galactic luminosity and by assigning the mass and scale to each model using \( C_{\text{SF}} \).

### 2.4. Parameter Values of Each Model

In the present paper, 29 models are investigated; the parameters and a brief summary of the results are given in Table 1. Each model of galaxy merger is labeled, for example, model(first letter) “B1,” according to the orbital configuration and multiplicity of the merging galaxies. Most of models (23 models) are assigned to pair mergers, in models B (the standard models), C, D, E, and F, and only two are assigned to multiple mergers, in model G. For comparison, the isolated evolution of the progenitor disk of a galaxy merger is also investigated and labeled as model A. The values of the orbital parameters, \( \theta_1, \theta_2, \phi_1, \) and \( \phi_2 \), are set to be 30.0, 120.0, 90.0, and 0.0, respectively, for models B and F; 0.0, 120.0, 0.0, and 0.0 for model C; 0.0, 30.0, 0.0, and 0.0 for model D; and 150.0, 150.0, 0.0, and 0.0 for model E. The orbital configurations of models D and E correspond to a nearly prograde merger and a nearly retrograde one, respectively. Model F with \( r_\text{a} = 0.5 \) corresponds to a galaxy merger with small initial orbital angular momentum. The difference between models A1 and A2 and models A3 and A4 is that in models A3 and A4, chemical evolution including star formation is solved but dynamical evolution is not. Accordingly, structural and kinematical properties of the disk are set to be the same between the initial and final states in models A3 and A4.

Columns (1), (2), and (3) in Table 1 denote the model number, the value of the parameter \( C_{\text{SF}} \), and that of \( R_{\text{chem}} \), respectively, for each model. The values of \( r_\text{in} \) and \( r_\text{a} \) are given in columns (4) and (5), respectively. We give the mean gaseous metallicity \( \langle Z'_\star \rangle \), the mean stellar metallicity \( \langle Z_\star \rangle \), and the gas mass fraction \( f_2 \) in columns (6), (7), and (8), respectively. The values of the mean gaseous \( \langle Z_{\text{Sim}} \rangle \) and stellar \( \langle Z_{\star, \text{Sim}} \rangle \) metallicities predicted from the simple one-zone model are presented in columns (9) and (10), respectively. The mean epoch of star formation \( \langle T_\star \rangle \), which is defined as the average of the star formation epochs (\( t_i \)) for all stellar particles in a merger remnant at final state (\( T = 15 \) in our units), is given in column (11). \( T_{\text{Mal}/M=0.6} \) shown in column (12) represents the timescale (in our units).
in which 60% of the initial gas of progenitor disk galaxies has been converted into stellar particles during a simulation. Column (13) gives the magnitude of metallicity gradient, which is defined as \( \Delta \log \langle Z_\ast \rangle/\Delta \log R \) \( (R \) is the distance from the center of remnant) and is measured for the region ranging from 0.5R_{eff} to 5.0R_{eff} \( (R_{eff} \) is the effective radius of each model) in the \( (x, y) \) projection for each model.

### 3. Results

In this section, we observe how the star formation history—in particular, the rapidity of star formation—in galaxy mergers can affect the fundamental characteristics of stellar populations in merger remnants. Before describing the results of merger remnants, we begin by briefly observing the dynamical evolution of an isolated disk galaxy with star formation, which in the present study is considered to be a progenitor of a galaxy merger, and the dependence of star formation history on the parameter \( C_{SF} \) in galaxy mergers. Figure 1 gives snapshots of an isolated disk model with \( C_{SF} = 0.35 \) (model A1) at \( T = 15.0 \), in which about 60% of the initial gas mass is converted into stellar components within 6.5 dynamical times. In the present isolated disk model, a stellar bar develops sufficiently in the central region of the disk only after more than 60% of initial gas mass has been consumed by star formation in the disk. The developed stellar bar is found to possess an exponential density profile along the major axis of the stellar bar, which is the so-called "exponential bar" (see Elmegreen 1996 for a recent review). The initial disk is found to be heated dynamically in the vertical direction of the disk within 15 dynamical times, owing to the dynamical interaction between the background stars, the small gaseous clumps, and the developed stellar bar. Accordingly, the present merger model describes the galaxy mergers between disk galaxies that could be identified with late-type barred galaxies if galaxy merging had not occurred. Figure 2 shows the time evolution of the star formation rate, \( f_s \), for merger models B1 and B5. As is indicated in this figure, star formation during galaxy merging proceeds in such a way that the interstellar gas is consumed by star formation more rapidly for a model with larger \( C_{SF} \). This trend for star formation also holds for model sequences B–G. The dependence of morphology and dynamical structure in merger remnants on \( C_{SF} \) is briefly summarized in Appendices A and B, which can help to understand more deeply the present numerical results. In the following subsections, by using these models of galaxy mergers, we mainly present the dependence of the mean stellar and gaseous metallicities, the radial gradients of age and metallicity, and the shapes of isophotes and isochromes on \( C_{SF} \).

#### 3.1. Dependence of the Chemical Properties on the Rapidity of Star Formation

The chemical, photometric, and spectroscopic properties of galaxies depend basically on how the metallicities and ages of stellar populations of galaxies are distributed. Thus, we begin to observe the distribution of metallicity (\( Z_\ast \)) and the epoch of star formation (\( T_s \)) in the stellar component of a merger remnant and its dependence on \( C_{SF} \). In § 3.1, we demonstrate (1) the dependence of \( Z_\ast - T_s \) distribution on \( C_{SF} \), (2) the dependence of mean \( Z_\ast \) on \( C_{SF} \) and its physical explanation, and (3) the difference in the metallicity distribution of merger remnants between the simple one-zone model and the present chemodynamical one.
3.1.1. Distribution of Stellar Populations

First we describe the results concerning the dependence of the $Z_\mathrm{SF}-T_\mathrm{SF}$ distribution on $C_{\mathrm{SF}}$. Figure 3 shows the distribution of stellar populations on the $Z_\mathrm{SF}-T_\mathrm{SF}$ map for models with $C_{\mathrm{SF}} = 0.35$ and 3.5. The meaning of $T_\mathrm{SF}$ is that the stellar component with smaller $T_\mathrm{SF}$ is born earlier and thus is older. The vertical height in each bin of $Z_\mathrm{SF}$ and $T_\mathrm{SF}$ denotes the number of star particles with $Z_\mathrm{SF}$ and $T_\mathrm{SF}$. In this figure, we can observe that there is an appreciable scatter in the metallicity for a fixed $T_\mathrm{SF}$. This scatter of metallicity for a given $T_\mathrm{SF}$ is one of the characteristics of the chemical evolution of galaxies in which chemical components produced by star formation are less efficiently and less widely mixed into the whole region of galaxies, as has been already pointed out by Steinmetz & Müller (1994) for dissipatively collapsing galaxies. $Z_\mathrm{SF}-T_\mathrm{SF}$ distribution in the model with $C_{\mathrm{SF}} = 3.5$ is shifted toward the larger $Z_\mathrm{SF}$ and smaller $T_\mathrm{SF}$ (is older in age) than in the model with $C_{\mathrm{SF}} = 0.35$, meaning that a larger amount of metal-enriched stars are produced more rapidly in the merger with rapid star formation than in that with gradual star formation. The spread in $T_\mathrm{SF}$ for a fixed $Z_\mathrm{SF}$ is likely to be larger in the model with $C_{\mathrm{SF}} = 0.35$ than in that with $C_{\mathrm{SF}} = 3.5$, whereas $Z_\mathrm{SF}-T_\mathrm{SF}$ distribution is more strongly peaked in the model with $C_{\mathrm{SF}} = 3.5$ than in that with $C_{\mathrm{SF}} = 0.35$. These results imply that, in the model with $C_{\mathrm{SF}} = 0.35$, star formation proceeds less rapidly and more gradually, resulting in smaller metal-enriched stellar populations and larger young stellar populations. This tendency of stellar populations plays an important role in determining the mean metallicity and age, and thus in determining the photometric and spectroscopic evolution of merger remnants, described below.

Second, we observe how the mean stellar metallicity depends on the rapidity of star formation and explain the cause of this dependence. As shown in Figure 4, which describes the time evolution of the mean stellar metallicity ($\langle Z_\ast \rangle$) of each merger remnant, the chemical enrichment proceeds faster and more efficiently in the model with larger $C_{\mathrm{SF}}$ than the model with smaller $C_{\mathrm{SF}}$, and thus the final value of $\langle Z_\ast \rangle$ is larger in the model with larger $C_{\mathrm{SF}}$ than in the model with smaller $C_{\mathrm{SF}}$. The time when $\langle Z_\ast \rangle$ exceeds 0.015 is $T = 0.7$ for the $C_{\mathrm{SF}} = 3.5$ model and $T = 5.0$ for the $C_{\mathrm{SF}} = 0.35$ model, and the asymptotic value of $\langle Z_\ast \rangle$ (the value at $T = 15.0$ in our units) is 0.0237 for the $C_{\mathrm{SF}} = 3.5$ model and 0.0185 for the $C_{\mathrm{SF}} = 0.35$ model. These results clearly demonstrate that, in dissipative galaxy mergers with star formation, the rapidity of star formation is an important factor even for determining the global and average chemical properties of merger remnants. The physical reason for this dependence is that, for a galaxy merger with more rapid star formation, less interstellar gas is tidally stripped away from the system during galaxy merging, principally because more initial gas has already been converted to stellar components before the system suffers more severely from the violently varying gravitational potential of galaxy merging. As a result of this, the gas is consequently metal-enriched to a larger extent and is converted into stellar components during merging. Thus, more metal is shared by stellar components in the remnant of the galaxy merger with more rapid star formation. Moreover, this observed tendency of the dependence of the mean stellar metallicity on $C_{\mathrm{SF}}$ is found to apply to the five standard models (see col. [7] in Table 1 for models B1–B5). These results provide a potential for success in reproducing qualit-
$C_{\text{SF}} = 0.35$

Fig. 3.—Distribution of the stellar metallicity ($Z_*$) and the epoch of star formation ($T_*$) for the model with $C_{\text{SF}} = 0.35$ (model B1; upper panel) and $C_{\text{SF}} = 3.5$ (model B5; lower panel) at $T = 15.0$ in our units. The vertical height of each line represents the total number of stellar particles with a given $Z_*$ and $T_*$. Younger stellar particles have larger values of $T_*$. 

Atively the mass-metallicity relation of elliptical galaxies; if the value of $C_{\text{SF}}$ is larger for a more luminous galaxy merger, then the derived result indicates that a galaxy merger between more luminous spirals is more likely to become an elliptical with a higher stellar metallicity. This furthermore suggests that even the origin of fundamental photometric and spectroscopic properties in elliptical galaxies, such as the color-magnitude relation, is closely associ-
ated with the details of galactic dynamics.

In order to observe more clearly the above strong dynamical coupling between dynamical and chemical evolution, we perform a set of comparative simulations in which the chemical evolution (including star formation) for an isolated galactic disk (models A3 and A4) is solved but the dynamical evolution (gravitational and dissipative dynamics) is not. Accordingly, the density distribution and the kinematical properties in the disk are fixed during the simulations. Since the time evolution of the gas mass fraction is the most fundamental determinant of the mean stellar metallicity in galaxies, by investigating the effects of galactic dynamics on the time evolution of the gas mass fraction and the final gas mass fraction, we observe how the dynamical evolution can affect the chemical evolution in the present merger model. Figure 5 gives the time evolution of the gas mass fraction, \( f_g \), for isolated disks without dynamical evolution (models A3 and A4) and for mergers (models B1 and B5). As shown in the lower panel of Figure 5, the gas mass fraction at \( T = 15.0 \) is not so different between models with different \( C_{SF} \) for isolated disks without dynamical evolution (models A3 and A4), whereas significant difference in the final gas mass fraction can be seen for merger models (models B1 and B5). This result clearly indicates that dynamical evolution itself greatly strengthens the difference in final gas mass fraction between merger models with different \( C_{SF} \). Therefore, chemical evolution in galaxy mergers is demonstrated to be greatly affected by the dynamical evolution of galaxy merging. In the merger model (models B1 and B5), as described before, the total amount of interstellar gas tidally stripped away from the system is determined by the rapidity of star formation (\( C_{SF} \)); accordingly, the final gas mass fraction is strongly affected by the rapidity of star formation. The importance of \( C_{SF} \) in controlling the final gas mass fraction can be seen even in the isolated disk models (models A1 and A2) and can be explained as follows (see the upper panel of Fig. 5). In the model with smaller \( C_{SF} \), nonaxisymmetric structures, such as spiral arms and bars developed in the star-forming disk, can redistribute the mass and angular momentum of the remaining gaseous component more efficiently and for a longer time, principally because a larger amount of the gas has not been yet converted into stellar components. Consequently, a larger amount of the gas is transported outward in the disk, and thus the mean gas density there drops off greatly. As a result of this, only a smaller fraction of the outwardly transported gas can be further converted into stellar components, and thus the mean stellar metallicity is smaller for the model with smaller \( C_{SF} \). This result clearly shows that the redistribution of mass and angular momentum driven by specific nonaxisymmetric structures plays an important role in determining the final gas mass fraction in isolated disks. Thus, although the dynamical mechanisms operating to yield the difference in the final gas mass fraction between models with different \( C_{SF} \) is significantly different between isolated disks (models A1 and A2) and mergers (models B1 and B5), these results say essentially the same thing, that the chemical evolution of galaxies can be greatly affected by mass and angular momentum redistribution driven by global dynamical processes such as the violent relaxation of galaxy merging and mass transfer triggered by the nonaxisymmetric gravitational potential of galaxies. This sort of strong coupling between dynamical and chemical evolu-

![Figure 4](image1.png)

**Fig. 4.**—Time evolution of mean stellar metallicity \( \langle Z_\star \rangle \) for models with \( C_{SF} = 0.35 \) (model B1; open circles) and 3.5 (model B5; open triangles).

![Figure 5](image2.png)

**Fig. 5.**—Time evolution of the gas mass fraction \( f_g \) for isolated disk models A1 and A2 (upper panel, solid lines) and for merger models B1 and B5 (lower panel, solid lines). For comparison, the time evolution of \( f_g \) for isolated disk models without dynamical evolution, models A3 and A4, is presented by dotted lines in each panel. Open circles and triangles denote the model with \( C_{SF} = 0.35 \) and that with \( C_{SF} = 3.5 \), respectively. It should be noted that although the final gas mass fraction at \( T = 15.0 \) is not very different between the two isolated disk models without dynamical evolution (models A3 and A4), it is remarkably different between the isolated disk models (models A1 and A2) and between the merger models (models B1 and B5).
tion is first demonstrated by the present work and by Bekki & Shioya (1997b).

Third, we observe the difference in the chemical evolution of merging galaxies between the simple one-zone model and the present chemodynamical one. Figure 6 describes the metallicity distribution of stellar components for the \( C_{SF} = 0.35 \) and 3.5 models, on each of which the metallicity distribution predicted from the simple model is superimposed. In estimating the distribution of stellar metallicity expected from the simple model for each value of \( C_{SF} \), we use the time evolution of the gas mass fraction obtained for each merger model (models B1 and B5) and then calculate the metallicity distribution according to the standard formulation of the relation between the gas mass fraction and the mean stellar metallicity for the simple model. Since the simple model assumes both instantaneous recycling and instantaneous mixing, it corresponds to the present chemodynamical model with \( R_{chem} = \infty \). We also give the values of the mean stellar and gaseous metallicities expected from the simple model in columns (9) and (10) of Table 1, by adopting the following formulation:

\[
\langle Z_* \rangle = y_{net} \left( 1 + \frac{f_e \ln f_e}{1 - f_e} \right),
\]

\[
Z_{gas} = - y_{net} \ln f_e.
\]  

As shown in Figure 6, the metallicity distribution of the model with larger \( C_{SF} \) is shifted farther to the right than in the model with smaller \( C_{SF} \), which is consistent with the already determined trend that the mean stellar metallicity of merger remnants with larger \( C_{SF} \) is larger than that of the remnants with smaller \( C_{SF} \). Furthermore, it is found that irrespective of the value of \( C_{SF} \), the metallicity distribution is shifted farther to the right in the chemodynamical model than in the simple one and thus that the spread of the distribution is larger in the chemodynamical model. This larger spread results from the fact that, in the present chemodynamical model, the chemical enrichment proceeds preferentially in the gaseous region with higher density where a larger amount of chemically enriched gas is converted into new and more metal-enriched stars. The magnitude of the difference of the distribution is found to be likely to be larger for models with smaller \( C_{SF} \). This result clearly explains why the difference in the mean stellar metallicity between the models with different values of \( C_{SF} \) for the present chemodynamical model is smaller than is expected from the simple model (see cols. [6], [7], [9], and [10] in Table 1). Gaseous metallicity, on the other hand, is found to be smaller in the chemodynamical model compared with that expected from the simple model and is found not to depend on the value of \( C_{SF} \). These differences in the metallicity distribution between the simple model and chemodynamical one lead to the differences in the photometric and spectroscopic properties of merger remnants between these models, as described in detail below.

Thus we demonstrate that dynamical evolution greatly affects the chemical evolution in galaxy mergers, and consequently the chemical evolution is significantly different from that expected from the simple one-zone model. What is particularly important in the present study is that the tidal stripping of interstellar gas during galaxy merging plays a vital role in determining even the global chemical properties of merger remnants. This tidal stripping of interstellar gas is probably more important in galaxy mergers with a larger amount of interstellar gas—for example, in the mergers at higher redshifts or in the mergers between less luminous spirals.

3.1.2. Radial Gradient of Stellar Populations

Here, we first observe how successfully the observed profile of the radial metallicity gradient of elliptical galaxies can be reproduced in merger remnants and how the rapidity of star formation controls the absolute magnitude of the gradient. Observational studies have revealed that the radial metallicity gradients of elliptical galaxies can be fitted reasonably well by a power-law profile and that the magnitudes of the gradients, \( \Delta \log Z_{se} / \Delta \log R \), are on average \(-0.2\) (Peletier et al. 1990; Davies et al. 1993). Mihos & Hernquist (1994) found that collisionless galaxy mergers between spirals with exponential metallicity gradient profiles become ellipticals with metallicity gradient profiles appreciably deviating from power-law profiles, implying that later mergers with less gaseous dissipation cannot reproduce the observed gradients with power-law profiles. Figure 7 gives the radial distribution of stellar and gaseous metallicity for the present merger model with star formation and gaseous dissipation. As shown in this figure, a negative metallicity gradient fitted by a power-law profile is reproduced reasonably well for models with \( C_{SF} = 0.35 \) and 3.5, which indicates that the origin of the metallicity gradients of elliptical galaxies is closely associated with dissipative galaxy merging with star formation. A merger remnant in the \( C_{SF} = 0.35 \) model has larger stellar metallicity in the central part and smaller metallicity in the outer part than does the remnant in the \( C_{SF} = 3.5 \) model, meaning that the metallicity gradient is larger for the model with less rapid star formation. The qualitative explanation for this metallicity gradient trend can be given as follows. In the model with smaller \( C_{SF} \), a larger amount of metal enriched gas can be transferred to the inner region of the remnant owing to less rapid star formation and more gaseous dissipation. In the outer part of this merger, star formation is less likely to proceed efficiently and thus is less likely to form metal-enriched stars because the gaseous density is lower than in the inner part. As a result of this, a relatively larger metallicity gradient is established for the model with smaller \( C_{SF} \). For the model with larger \( C_{SF} \), on the other hand, a larger amount of gas has been converted into metal-enriched stars before the onset of violent relaxation; thus the stellar component in this galaxy merger suffers more severely from chemical mixing driven by violent relaxation owing to less gaseous dissipation. As a result of this, the metallicity gradient is more strongly washed out, and its absolute magnitude becomes smaller. The obtained value of the metallicity gradient is found to be smaller than the value typically observed, \(-0.2\), for most models with \( R_{chem} = 0.4 \). This result indicates that in the present chemodynamical model of galaxy mergers, chemical mixing, controlled basically by the chemical mixing length and the degree of violent relaxation of galaxy merging, is appreciably more efficient than is required to reproduce the observed trend.

Next we observe the dependence of the radial gradient of stellar age on the rapidity of star formation. It has been generally considered that it is difficult to derive the age gradient observationally, since the color gradient is affected both by the metallicity gradient and by the age gradient (i.e., the age-metallicity degeneracy problem). Recently, Faber et al. (1995) and Bressan, Chiosi, & Tantalo (1996) have suc-
F. 6. Distribution of stellar metallicity for models with $C_{\text{SF}} = 0.35$ (model B1; upper panel) and 3.5 (model B5; lower panel) at $T = 15.0$ in our units (solid lines). For comparison, the stellar metallicity distribution predicted from the simple one-zone model for each model is also plotted (asterisks) in the same panel.

The shape of the isochromes and the degree of difference between the isochore and isophote shapes are considered to be observational clues about the origin of the formation and evolution of elliptical galaxies. As is revealed by multi-band photometry (see, e.g., Boroson, Thompson, & Shectman 1983), the shapes of the isochromes are appreciably similar to those of the isophotes in elliptical galaxies. However, in the dissipative collapse model of Larson (1975), the shapes of the isochromes are significantly flatter than those of the isophotes. In the dissipative collapse model of elliptical galaxy formation of Carlberg (1984), the shapes of

![Fig. 6](image)

![Fig. 7](image)

![Fig. 8](image)
isochromes are slightly flatter than the isophotal shapes; Carlberg thus appears to have succeeded in overcoming the disagreement between isochromes and isophotes shapes of Larson's collapse model. Here, we observe whether or not the shapes of the isochromes can match reasonably well those of the isophotes in the present dissipative merger model. Although the color of a galaxy is affected by both the metallicity and the age of its stellar population, we assume that the isometallicity contour is exactly the same as the isochromal contour and that the isodensity contour is the same as the isophotal contour. In Figure 9, we show arbitrary isochromes (solid lines) and isophotes (dotted lines) for the $C_{\text{SF}} = 3.5$ model. We found that the shapes of isochromes are nearly the same as those of isophotes and furthermore that this trend does not depend strongly on the value of $C_{\text{SF}}$. These results suggest that violent relaxation combined with an appreciable amount of gaseous dissipation, which is a specific dynamical process for dissipative galaxy mergers, plays a vital role in producing isochromal shapes that well match the isophotal shapes.

3.2. Fundamental Roles of Other Parameters

In addition to the rapidity of star formation, the chemical mixing length, the orbital configuration of galaxy merging, the multiplicity of a merger, and the epoch of galaxy merging are considered to be fundamental factors in the chemical, photometric, and spectroscopic properties of a galaxy merger. We accordingly observe how and to what extent the above four parameters strengthen or lessen the $C_{\text{SF}}$ dependence of the chemical properties derived in §3.1. Dependence of chemical properties on each of the four parameters is summarized in Figure 10 for the mean stellar metallicity, in Figure 11 for the mean epoch of star formation, in Figure 12 for the stellar metallicity gradient, and in Figure 13 for the radial gradient of the mean epoch of star formation. What should be emphasized in these figures is that although variety in the values of the above four parameters indeed introduces appreciable scatter in the $C_{\text{SF}}$ dependence of chemical properties derived in §3.1, the basic trends in the $C_{\text{SF}}$ dependence derived in §3.1 are not drastically changed. For example, the mean stellar metallicity of a merger remnant is larger in the model with larger $C_{\text{SF}}$ for a given chemical mixing length, orbital configuration, multiplicity, and merging epoch. Accordingly, in §3.2.1–3.2.4, below, we mainly present outstanding results that we could not obtain by varying only the value of $C_{\text{SF}}$, as described in §3.1, and furthermore we describe the fundamental roles specific for each of the above four parameters in determining the chemical properties of merger remnants.

3.2.1. Mixing Length of Chemical Component

It is considered to be highly uncertain how locally and how well metals ejected from stars with different masses and ages can be actually mixed into the interstellar medium in galaxies (see, e.g., Roy & Kunth 1995). Because of this
indicates that if is larger for a model with smaller B6, B7, B8, and B9). This result can be explained as follows. Thus the mean stellar metallicity of merger remnants is likely to be born from the gas with a larger metallicity, and accordingly the redistribution of mass and angular momentum during merging and thus determine the transfer process of chemical components in mergers. We accordingly investigate how the initial inclinations of two progenitor disks (models C, D, and E) and the pericenter distance (model F) can affect the final chemical properties of merger remnants. We found that, for the model with larger in each of the sequences C, D, E, and F, the mean stellar metallicity of the merger remnants is larger, whereas the mean epoch of star formation (\(T_\star\)) is smaller (see Figs. 10 and 11), results which are consistent with those derived in § 3.2 and which thus reinforce the importance of the rapidity of star formation in determining the mean stellar metallicity and the mean stellar age in merger remnants. As shown in Figure 12, both the magnitude of the negative metallicity gradient and that of the age gradient in merger models are distributed with appreciable spread even for a fixed value of \(C_{\text{SF}}\) (= 0.35 and 3.5), suggesting that the spread in the magnitudes of the metallicity and age gradients observed in elliptical galaxies with a given luminosity is caused by the diversity in the orbital configurations of the galaxy mergers. The reason for the relatively larger negative value of the metallicity gradient observed for the model with a nearly prograde-prograde merger (model D2) is probably that the developed prolate stellar bar in the SB0-like merger remnant more efficiently transfers the chemical components into the central region, and, consequently, it enhances the difference in stellar metallicity between the outer and inner regions in the galaxy. This result should be compared with that of Friedli & Benz (1995), in which the rotating stellar bar changes the mass and angular momentum distribution of stars and gas in a galactic disk, and consequently smooths out the already-existing metallicity gradient of the barred galaxy. The difference in the dynamical roles of stellar bars

![Figure 12](image1.png)

**Fig. 12.**—Dependence of the radial gradient of mean metallicity on \(C_{\text{SF}}\). Symbols are as in Fig. 10.

uncertainty, the best way in the preliminary stage of the present study is to vary the values of the chemical mixing length, represented by \(R_{\text{chem}}\), in each model and thereby to examine its importance in determining the chemical properties of galaxies. We found that, irrespective of the value of \(C_{\text{SF}}\), as the value of \(R_{\text{chem}}\) becomes smaller, the mean stellar metallicity becomes larger (see col. [7] in Table 1 for models B6, B7, B8, and B9). This result can be explained as follows. In the model with smaller \(R_{\text{chem}}\) metals produced by star formation in a higher density region can be mixed into the surrounding interstellar gas more locally, and accordingly the metals are more likely to be trapped by the gas only in the higher density region. Consequently, chemical enrichment proceeds more preferentially in the higher density regions, where a larger number of stars are formed; thus, the mean stellar metallicity in the merger is basically determined. As a result of this, a larger number of stars are more likely to be born from the gas with a larger metallicity, and thus the mean stellar metallicity of merger remnants is larger for galaxy mergers with smaller \(R_{\text{chem}}\). This result indicates that if \(R_{\text{chem}}\) is larger for a model with smaller \(C_{\text{SF}}\), the already-obtained \(C_{\text{SF}}\) dependence of the mean stellar metallicity is strengthened (see Fig. 10). We also found that for most models, as the value of \(R_{\text{chem}}\) grows smaller, the negative metallicity gradient becomes steeper (see Fig. 12). This result reflects the fact that chemical enrichment can proceed more preferentially in the higher density (i.e., inner) regions, such as the nuclei of mergers, in the model with smaller \(R_{\text{chem}}\).

The most interesting result derived by varying \(R_{\text{chem}}\) is that for the model with smaller values of \(R_{\text{chem}}\) and \(C_{\text{SF}}\), the mean gaseous metallicity is smaller than the stellar metallicity in the merger remnant (see cols. [6] and [7] in Table 1 for models B6 and B8). This result cannot be obtained until both dynamical and chemical evolution are solved in a self-consistent manner, since the simple one-zone model predicts that the gaseous metallicity is never smaller than the stellar metallicity. Furthermore, this result provides a valuable clue about the origin of the metal-poor hot gaseous halos of elliptical galaxies: the *Advanced Satellite for Cosmology and Astrophysics (ASCA)* has shown that the metallicity of the hot X-ray gaseous halo is appreciably smaller than that of the stellar component of the host elliptical galaxy (see, e.g., Matsumoto et al. 1997). The details of the formation of the metal-poor gaseous halo will be discussed in future papers.

### 3.2.2. Orbital Configuration

Orbital parameters of galaxy merging, such as the initial intrinsic spin of progenitor disks and the pericenter distance of mergers, can affect the degree of violent relaxation and the redistribution of mass and angular momentum during merging and thus determine the transfer process of chemical components in mergers. We accordingly investigate how the initial inclinations of two progenitor disks (models C, D, and E) and the pericenter distance (model F) can affect the final chemical properties of merger remnants. We found that, for the model with larger \(C_{\text{SF}}\) in each of the sequences C, D, E, and F, the mean stellar metallicity of the merger remnants is larger, whereas the mean epoch of star formation (\(T_\star\)) is smaller (see Figs. 10 and 11), results which are consistent with those derived in § 3.2 and which thus reinforce the importance of the rapidity of star formation in determining the mean stellar metallicity and the mean stellar age in merger remnants. As shown in Figure 12, both the magnitude of the negative metallicity gradient and that of the age gradient in merger models are distributed with appreciable spread even for a fixed value of \(C_{\text{SF}}\) (= 0.35 and 3.5), suggesting that the spread in the magnitudes of the metallicity and age gradients observed in elliptical galaxies with a given luminosity is caused by the diversity in the orbital configurations of the galaxy mergers. The reason for the relatively larger negative value of the metallicity gradient observed for the model with a nearly prograde-prograde merger (model D2) is probably that the developed prolate stellar bar in the SB0-like merger remnant more efficiently transfers the chemical components into the central region, and, consequently, it enhances the difference in stellar metallicity between the outer and inner regions in the galaxy. This result should be compared with that of Friedli & Benz (1995), in which the rotating stellar bar changes the mass and angular momentum distribution of stars and gas in a galactic disk, and consequently smooths out the already-existing metallicity gradient of the barred galaxy. The difference in the dynamical roles of stellar bars

![Figure 13](image2.png)

**Fig. 13.**—Dependence of the radial gradient of mean star formation epoch (\(\langle T_\star \rangle\)) on \(C_{\text{SF}}\). Symbols are as in Fig. 10.
between the present study and Friedli & Benz (1995) probably results from the differences in the total amount of gas mass and the strength of dynamical perturbation assumed in the two studies. More detailed studies are required for understanding more clearly the dynamical roles of triaxiality (i.e., barred structure) in determining the chemical gradient of galaxies and their dependences on galaxy types.

3.2.3. Multiple Galaxy Merging

Important roles for multiple mergers between late-type spirals are suggested, for example, in forming field elliptical galaxies (Barnes 1989) and in mitigating the difficulty of pair mergers to produce the observed smaller degree of kinematical misalignment (Weil & Hernquist 1996). We here present the difference in a number of chemical properties of merger remnants between pair mergers and multiple ones (models G1 and G2). The differences found in the present study are the following: first, in multiple mergers, irrespective of \( C_{\text{SF}} \), a larger amount of interstellar gas is stripped away and consequently cannot participate in further star formation. This is because the tidal stripping of interstellar gas is more efficient in multiple mergers owing to the more violent dynamical interaction between merging galaxies and because a smaller amount of mass is transferred to the inner region and thus cannot form the higher density gaseous regions. Second, as a result of this, the merger remnant is finally surrounded by a larger amount of metal-poor gas, which might be the metal-poor gaseous X-ray halo actually observed in elliptical galaxies (see, e.g., Matsumoto et al. 1997). Third, the dependence of chemical properties on \( C_{\text{SF}} \), in particular that of the metallicity gradient, are less discernible in multiple mergers. This is probably because chemical mixing driven by the violent gravitational relaxation of the merger is more effective in multiple mergers. Fourth, in the multiple merger model with \( C_{\text{SF}} = 3.5 \), the stellar population in the central part of the merger remnant is both older and less metal-enriched than is the outer part, which in the present study is a specific characteristic of the chemical properties of multiple mergers with larger \( C_{\text{SF}} \).

This result is reflected in the fact that in the multiple merger model with \( C_{\text{SF}} = 3.5 \), the magnitude of the metallicity gradient for the region \( 0.5R_{\text{eff}} \leq R \leq 5.0R_{\text{eff}} \) (\( R_{\text{eff}} \) is effective radius) is \(-0.07\), whereas it is \(0.19\) for the region \(0.1R_{\text{eff}} \leq R \leq 1.0R_{\text{eff}}\). Actually, Bressan et al. (1996) show that there are a number of galaxies possessing this trend. Since only a relatively small range of parameter space has been investigated in the present study, we can not give here a stronger statement that elliptical galaxies with older and less metal-enriched stellar populations in their central parts are indicative of multiple mergers. Accordingly, a further study to confirm the above result by performing numerical simulations with a larger range of parameter space for multiple mergers and further to investigate the fundamental chemical properties specific to multiple mergers would be useful. Thus, these four results demonstrate that multiplicity in galaxy mergers can also affect a number of chemical properties in the merger remnants (and thus in elliptical galaxies).

3.2.4. Epoch of Galaxy Merging

We here investigate how the difference in the epoch of galaxy merging can affect the fundamental chemical properties of merger remnants by varying the initial separation between two progenitor disks (\( r_{\text{in}} \)) and thereby delaying the epoch of galaxy merging (models B10–B15). We found that a galaxy merger with larger \( r_{\text{in}} \) (later merger) becomes an elliptical galaxy with both a more metal-enriched and a younger stellar population and, furthermore, that this tendency does not depend on the values of \( C_{\text{SF}} \) (see Fig. 14). These results can be explained as follows. In the later galaxy merger (the model with larger \( r_{\text{in}} \)), a larger amount of interstellar gas can continue to be converted into stellar components and become chemically enriched in the progenitor disk for a longer time before the merger. Consequently, new stars (younger stellar populations) are more preferentially born from the more chemically enriched interstellar gas when the later starburst is triggered by the later galaxy merging. As a result of this, stellar populations in the later galaxy merger are both younger and more metal-enriched on average than in the earlier merger. Faber et al. (1995) and Worthey et al. (1996) suggest that if the younger galaxies are actually more metal-rich than older ones, the color-magnitude relation of elliptical galaxies can be equally reproduced without invoking the conventionally accepted mass-metallicity relation of elliptical galaxies. They furthermore suggest that even if there exists outstanding spread in luminosity-weighted age and metallicity among elliptical galaxies, the tightness of the color-magnitude relation can be maintained with a specific assumption that the age and the metallicity \( Z \) satisfy the relation \( \Delta \log \text{age}/\Delta \log Z = -1.5 \) (Worthey’s law). It is remarkable that the above numerical result that a merger remnant with younger stellar populations is more metal-enriched is at least qualitatively consistent with Worthey’s law. Although more extensive observational studies should be accumulated that can confirm whether or not Worthey’s law is universal among elliptical galaxies with different luminosities and environments, we can say however that the nature of the stellar populations of elliptical galaxies is closely associated with the epochs of galaxy merging and thus with the strength of the secondary bursts of star formation during galaxy merging. Specifically, the amount interstellar gas the progenitor disks have and the degree to which the gas has already been metal-enriched before the mergers is crucial in determining the chemical and photo-

![Fig. 14.—Dependence of the mean stellar metallicity \( \langle Z_t \rangle \) on the mean epoch of star formation \( \langle T_s \rangle \) in merger remnants for models with different merging epochs. Open circles and triangles represent the models with \( C_{\text{SF}} = 0.35 \) and 3.5, respectively.](image-url)
metric properties of elliptical galaxies formed by galaxy mergers. Although our numerical study appears to have succeeded in grasping some essential qualities of the dependence of the chemical properties of merger remnants on the epoch of galaxy merging, a larger range of parameter space should be covered by future studies in order to confirm the derived dependence.

Finally, in Figure 15, we give the dependence of the age gradient on the metallicity gradient for all merger models. As shown in this figure, the merger model with a larger metallicity gradient shows a larger age gradient, which is actually observed by Bressan et al. (1996).

3.3. Characteristics of Stellar Populations Dependent on Galactiic Luminosity

We have so far focused mainly on the parameter dependence of the chemical properties of merger remnants and have not described the photometric and spectroscopic properties of the remnants by adopting a specific mass and size for each merger model discussed in §§ 3.1 and 3.2. We here describe the photometric and spectroscopic properties of merger remnants by assuming that the model with $C_{\text{SF}} = 1.0$ corresponds to the galaxy merger between late-type spirals with mass and size equal to the fiducial values of the present study ($M_\odot = 6.0 \times 10^{10}$ $M_\odot$ and $R_\odot = 17.5$ kpc, respectively) and that $C_{\text{SF}} \propto L^{0.55}$ (this assumed relation is plausible; see Appendix A). The assumed relation, $C_{\text{SF}} \propto L^{0.55}$, means that more luminous elliptical galaxies are formed by galaxy mergers with more rapid star formation. For convenience, we consider that for each model, 13 Gyr have passed since the two progenitor galaxies began to merge with a given $r_{\text{in}}$. This means that we do not intend to include any initial age difference between galaxy mergers in this consideration; thus, the derived photometric and spectroscopic properties basically reflect the mean stellar metallicity of the remnants. It should be emphasized here that whether or not the above assumptions on the scaled mass and size of galaxy mergers are actually reasonable and realistic is probably highly uncertain in the present study because of the lack of extensive observational studies of the luminosity dependence of star formation histories of disk galaxies and mergers. Accordingly, the derived luminosity dependence of the photometric and spectroscopic properties of merger remnants reflects only the adopted assumptions, and thus we describe them only in a schematic manner. Although this investigation could not allow us to compare the photometric properties of merger remnants with the observational properties of real elliptical galaxies in a more quantitative way, it enables us to point out in a quantitative way the possible advantages and disadvantages of the present merger model in reproducing the observed photometric properties of real elliptical galaxies. In §§ 3.3.1 and 3.3.2, the luminosity dependences of the mean stellar metallicity, of the metallicity gradient, and of the integrated color of merger remnants are presented.

3.3.1. Chemical Properties

Based upon the results presented in the Figures 10, 11, 12, and 13, we can obtain the following dependence: more luminous elliptical galaxies formed by galaxy merging show (1) larger mean stellar metallicities, (2) smaller central stellar metallicities, and (3) smaller radial gradients of stellar metallicity. The first result appears to agree qualitatively with the mass-metallicity relation implied by the color-magnitude relation of elliptical galaxies (Faber 1973; Visvanathan & Sandage 1977), whereas the second result appears to disagree with the expected luminosity dependence of the central metallicity of elliptical galaxies indicated by the $M_{\text{G}_2}$-$\sigma$ relation (Burstein et al. 1988). It still seems less feasible to determine whether the third result matches the observed luminosity dependence of the stellar metallicity gradient in elliptical galaxies, as described below. Although a number of observational studies that describe the dependence of the metallicity gradient on galactic parameters have been accumulated, a clear trend in the dependence seems unlikely, as described below. Carollo, Danziger, & Buson (1993) reported that the $M_{\text{G}_2}$-index gradient shows a bimodal trend with mass: for less massive galaxies ($M < 10^{11} M_\odot$), the $M_{\text{G}_2}$ gradient increases with increasing mass, whereas for massive galaxies ($M > 10^{11} M_\odot$), there is no obvious pattern in the mass dependence of the gradient. Gonzalez & Gorgas (1996) found that the gradient of the $M_{\text{G}_2}$ index correlates with the central $M_{\text{G}_2}$ index: galaxies with steeper $M_{\text{G}_2}$-index gradients have larger central $M_{\text{G}_2}$ indices. Since the central $M_{\text{G}_2}$ index becomes larger as the mass of galaxy increases, this correlation suggests that massive galaxies are more likely to have steeper metallicity gradients. Furthermore, Peletier et al. (1990) reported that there is no correlation between color gradient, which is a combination of the age and metallicity gradients, and the luminosity of galaxies. Thus, we cannot safely speculate on the cause of the dependence of the metallicity gradient on galactic parameters. We must await further extensive studies that reveal clear trends in the dependence of the metallicity gradient on galactic parameters, in order to compare the derived $C_{\text{SF}}$ dependence of the metallicity gradient in the present study with observational results.

3.3.2. Photometric and Spectroscopic Properties

Figure 16 shows the radial distribution of $U-R$ and $B-R$ colors in the merger remnant for the fiducial model.
show redder color in $V-K$; however, the derived luminosity dependence of the integrated color does not agree reasonably well with the observed color-magnitude relation of elliptical galaxies. What this result actually means depends on whether or not we adopt the conventional point of view regarding the cause of the observed CM relation in elliptical galaxies. In the conventional point of view (Faber 1973; Visvanathan & Sandage 1977), the CM relation reflects the mass-metallicity relation of galaxies (the "metallicity effect"), whereas in the newly proposed view (Faber et al. 1995; Worthey et al. 1996), the CM relation reflects the fact that less luminous elliptical galaxies are progressively younger than more luminous ones (the "age effect"). If we adopt the former view, we should conclude that the above result means that the observed color-magnitude relation (the mass-metallicity relation) would not be reproduced so successfully by the present merger model with $C_{SF} \propto L^{0.55}$. As has already been pointed out by Bekki & Shioya (1997b), even the present merger model, in which any age difference between galaxies and any thermal and dynamical feedback effects of star formation are not included, can reproduce at least qualitatively the observed CM relation if we assume that $C_{SF} \propto L^{0.69}$. However, this assumption, $C_{SF} \propto L^{0.69}$, seems less plausible, since in order to derive it, we must adopt somewhat particular assumptions, for example, that the initial density of the progenitor disk ($\Sigma$) in a merger depends strongly on the galactic luminosity ($L$) in such a way that $\Sigma \propto L^{0.56}$. Therefore, instead of adopting such apparently less realistic assumptions, we should reconsider other fundamental parameters that are important determinants for the chemical evolution of galaxy mergers and that strongly depend on galactic mass and then reinvestigate the luminosity-dependent chemical and photometric properties of merger remnants. On the other hand, if we adopt the latter, fresher, point of view (Faber et al. 1995; Worthey et al. 1996), we should conclude that the derived result for the CM relation does not necessarily disagree with the observed CM relations of elliptical galaxies. In this case, we must await further extensive observational studies that reveal extent to which the age effect and the metallicity effect each actually contribute to the generation of the CM relation and that clarify the relative importance of the two effects in the production of the CM relation. Future studies would be useful to elucidate the cause of the relative importance of each effect in the context of dissipative galaxy merging when the relative contributions of the age effect and the metallicity effect are observationally clarified. Considering these situations, we cannot safely determine how successfully the present merger model has reproduced the CM relation until more extensive observational studies clarify the relative importance of the metallicity effect and the age effect.

Finally, we comment on the difference in the photometric and spectroscopic properties between the simple one-zone model and the present chemodynamical one. As shown in Figure 17, the $V-K$ color is bluer in the simple model than in the chemodynamical one, resulting from the fact that the stellar metallicity in the simple model is smaller than in the chemodynamical model. This implies that the chemical, photometric, and spectroscopic properties derived by adopting the simple one-zone model are not a better approximation, as is tacitly understood, especially when a more quantitative comparison of the theoretical with observational results is required.
4. DISCUSSION

4.1. Outstanding Differences between the Simple One-Zone Model and the Present Chemodynamical One

We present here the two outstanding differences in chemical evolution between the simple one-zone model and the present chemodynamical one, and we then give related implications about the chemical evolution of elliptical galaxies formed by galaxy mergers. First, we stress that even if we discuss the global and mean properties of chemical and photometric evolution of elliptical galaxies formed by galaxy mergers, both chemical and dynamical evolution should be solved in a self-consistent way. As is described in detail in the previous sections, during dissipative galaxy merging with star formation, the chemical enrichment process, which is controlled basically by the violent relaxation of galaxy merging and by gaseous dissipation, is found to proceed in a considerably inhomogeneous way. This aspect of the chemical enrichment process provides a remarkable difference between the simple one-zone model and the present chemodynamical one in that the final gas mass fraction is not the only important determinant for the final stellar metallicity in the present chemodynamical model. As a natural result of this difference, photometric and spectroscopic properties such as the integrated $V-K$ color is observed to be appreciably different in the simple one-zone model and in the present chemodynamical one. Although the difference in the photometric and spectroscopic properties of merger remnants between the two models is not large, we should recognize how the details of the dynamical evolution of forming elliptical galaxies modify the results derived by the simple one-zone model, especially when comparing the theoretical results more precisely with observational results. Furthermore, in the present chemodynamical model, chemical enrichment is found to proceed faster in the higher density region (i.e., the inner region), where star formation occurs more efficiently, than in the lower density region (i.e., the outer region), which strengthens the difference in the degree of chemical enrichment between the higher density (inner) and the lower density (outer) regions ("chemical segregation"). This sort of chemical segregation could give a natural explanation for the difference in photometric and spectroscopic properties between the outer and the central parts of an elliptical galaxy.

Second, we should emphasize the fundamental roles of chemical mixing length in determining a number of chemical properties in merger remnants, such as the mean stellar metallicity and the radial metallicity gradient. Unlike the simple one-zone model, chemical enrichment is assumed to proceed locally in the present merger model. As described in detail in the previous sections, both the radial metallicity gradient and the mean stellar metallicity in merger remnants depend on how locally metals ejected from stellar components can be mixed into interstellar gas: both the mean stellar metallicity and the absolute magnitude of the radial gradient of stellar metallicity are larger for a merger remnant whose chemical components have a smaller mixing length. Moreover, the chemical mixing length is found to determine the amount of heavy elements ejected from stellar components that can be shared by stars or interstellar gas and accordingly affects the formation of a gaseous halo that is less metal-enriched than the stellar components of merger remnants. These results suggest that the rapidity of star formation in mergers is not the only dominant factor in determining the chemical properties of merger remnants; thus, we should investigate the physical relation between the rapidity of star formation and chemical mixing length in galaxies and its dependence on galactic luminosity to develop a clearer understanding of the chemical, photometric, and spectroscopic evolution of galaxy mergers. There still remains much to investigate and understand in the chemical evolution of galaxy mergers.

4.2. On the Origin of the Color-Magnitude Relation

The color-magnitude (CM) relation of elliptical galaxies is considered to be one of the most fundamental relations containing valuable information about formation history of elliptical galaxies. The CM relation is that the integrated color of elliptical galaxies becomes redder as the absolute magnitude of the luminosity decreases (see, e.g., Faber 1973). Although the age difference between elliptical galaxies has been recently demonstrated to play an important role in the reproduction of the CM relation (see, e.g., Worthey et al. 1996), it has been conventionally considered that the mean stellar metallicity is larger for more luminous elliptical galaxies (see, e.g., Tinsley 1978). Larson (1975) originally proposed that this luminosity-dependent mean stellar metallicity observed in elliptical galaxies should essentially be ascribed to the truncation of star formation by the so-called "galactic wind" driven by accumulated thermal energy produced mainly by supernovae during the early stage of dissipative collapse. Although there is a large number of studies to adopt this galactic wind model and to investigate the origin of the CM relation by using the evolutionary method of population synthesis (see, e.g., Arimoto & Yoshii 1987; for a more recent study, see Bressan et al. 1994), only a few studies have addressed the fundamental question about whether or not the merger model of elliptical galaxy formation can also reproduce the mass-metallicity relation. Thus, we begin to discuss this important issue in terms of elliptical galaxy formation by galaxy merging, provided that the color-magnitude relation reflects the mass-metallicity relation in elliptical galaxies.

As described in the previous section, what is remarkable in the present merger model is that even if we do not include the thermal and dynamical feedback effects of type II supernovae on the gasdynamics in merging galaxies, the final gas mass fraction and the mean stellar metallicity in merger remnants depend on the star formation history and thus on galactic luminosity, owing to the tidal truncation of star formation. This mechanism, by which the mass-metallicity relation can be closely associated with the details of the dynamics of galaxy merging, is quite different from that invoked by the classical galactic wind model. This result furthermore implies that there can be a number of ways to reproduce the mass-metallicity relation in elliptical galaxies and thus that the CM relation probably has more profound meanings than we can deduce by invoking only a specific model of elliptical galaxy formation. Here we should note that although our merger model can potentially reproduce at least qualitatively the mass-metallicity relation, more total and successful comparison of our merger model with the mass-metallicity relation required for the reproduction of the CM relation is found to be less promising without applying the less realistic assumption that $C_{\text{SF}} \propto L^{-0.69}$ (Bekki & Shioya 1997b). This result implies either that other physical processes such as the thermal and dynamical
effects of type II supernovae on the galactic dynamics should be further incorporated into the present merger model or that the observed CM relation should not be interpreted so simply in terms of the mass-metallicity relation. Thus one of our further goals is to investigate to what degree the dynamical and thermal effects of supernova-driven energy associated with the burst of star formation during galaxy merging can modify the present results. We should also reexamine the validity of the assumption that the observed CM relation is actually a mass-metallicity relation of elliptical galaxies, as described below.

A growing number of observational and theoretical studies attempting to disprove the age-metallicity degeneracy suggest that the CM relation of elliptical galaxies does not necessarily imply the mass-metallicity relation. Faber et al. (1995) suggest that even if the mean stellar metallicities of elliptical galaxies are the same, the CM relation can be equally well reproduced with the assumption that the effective age of stellar populations is progressively younger for less luminous ellipticals (the age effect). Furthermore, Worthey et al. (1996) demonstrate that even if the typical or luminosity-weighted age of galaxies is considerably spread (more than several Gyr) between elliptical galaxies for a given luminosity, the tightness of the color-magnitude relation can be maintained with a specific relation that younger elliptical galaxies should be more metal-enriched (Worthey’s 3/2 law). This implies that a single-burst model of elliptical galaxy formation, such as the galactic wind model, in which star formation is assumed to be truncated within at most 2 Gyr, cannot be accepted at all for a realistic model of elliptical galaxy formation. Kodama & Arimoto (1996) construct a specific model designed to mimic the age effect in order to check the validity of the above suggestion and to demonstrate that the pure age effect does not convincingly reproduce the tightness of the color-magnitude relation observed in both the present cluster ellipticals and the intermediate redshift cluster ellipticals. It is safe to say here that neither the pure age effect nor the pure metallicity effect (i.e., the mass-metallicity relation) could explain a growing number of findings suggesting the diversity of star formation history in elliptical galaxies. We must await more extensive observational studies that can confirm whether the suspected age spread and Worthey’s 3/2 law, both of which shed new insight on the origin of the CM relation, are robust and do not depend on galactic mass, environment, and redshift. We can say, however, that both the age spread and Worthey’s 3/2 law could naturally be explained by the present merger model in a rather qualitative manner. As is demonstrated in the previous sections, the epoch of galaxy merging can affect both the mean age and the metallicity of merger remnants in the sense that later mergers are more likely to become ellipticals with more metal-enriched and younger stellar populations. This result suggests that Worthey’s 3/2 law can essentially be ascribed to the difference in the epoch of galaxy merging between galaxy mergers. Furthermore, as is predicted by the semianalytical models of galaxy formation based upon the hierarchical clustering scenario with CDM cosmogony (see, e.g., Baugh et al. 1996), it is quite reasonable that the epoch of galaxy merging differs from galaxy to galaxy. Accordingly, the luminosity-weighted ages, which might be dependent on the strength of the secondary starbursts in galaxy merging, can naturally be spread between elliptical galaxies formed by galaxy merging. Thus galaxy merging between late-type spirals, which might have occurred in different epochs, is a promising candidate in explaining the apparent diversity of star formation history observed in real elliptical galaxies and in explaining the tightness of the CM relation of elliptical galaxies.

5. CONCLUSION

The main results obtained in the present study are summarized as follows.

1. Galaxy mergers with more rapid star formation become ellipticals with larger mean stellar metallicities primarily because, in the mergers with more rapid gas consumption, a smaller amount of metal-enriched gas is tidally stripped away during merging and consequently a larger amount of the gas can be converted into stellar components. This result is demonstrated not to depend strongly on other parameters, such as the orbital configuration of the galaxy merger and multiplicity of the mergers. This suggests that the origin of the color-magnitude relation of elliptical galaxies can be closely associated with the details of merger dynamics that depend on the rapidity of star formation (and thus on galactic luminosity) in galaxy mergers.

2. Negative metallicity gradients fitted reasonably well by power-laws can be reproduced by dissipative galaxy mergers with star formation, which is in good agreement with recent observational findings on elliptical galaxies. The absolute magnitude of the metallicity gradient in each merger remnant depends on the orbital configuration of each merging galaxy, suggesting that the observed dispersion in the absolute magnitudes of metallicity gradients for a given luminosity range of elliptical galaxies reflects the diversity in the orbital configuration of the merging galaxies.

3. The absolute magnitude of the metallicity gradient correlates with that of the age gradient in a merger in the sense that a merger remnant with a steeper negative metallicity gradient is more likely to show a steeper age gradient. This result reflects the fact that the degree of violent relaxation and gaseous dissipation during merging strongly affects both the age and the metallicity gradients.

4. The outer part of the stellar population is both older and less metal-enriched than in the nucleus in an elliptical galaxy formed by galaxy mergers with less rapid star formation. Moreover, galaxy mergers with less rapid star formation are more likely to become ellipticals with metal-poor gaseous halos. This result suggests that the formation of the metal-poor X-ray halos actually observed in elliptical galaxies can essentially be ascribed to the dissipative merger of late-type spirals and furthermore provides a clue to the iron-abundance discrepancy problem in elliptical galaxies.

5. The epoch of galaxy merging affects both the mean stellar metallicity and the mean stellar age in merger remnants: later galaxy mergers become ellipticals with both younger and more metal-enriched stellar populations. This result suggests that the cause of Worthey’s 3/2 rule (Worthey et al. 1996), which is invoked in maintaining the tightness of the color-magnitude relation of elliptical galaxies, can be understood in terms of a difference in the epochs of galaxy formation and transformation—that is, the epoch of galaxy merging—between elliptical galaxies.

6. The luminosity dependence of chemical, photometric, and spectroscopic properties in merger remnants, which is derived by adopting a specific assumption of the luminosity
dependence of the rapidity of star formation in galaxy mergers, does not reasonable well match that observed in real elliptical galaxies. This result implies that other fundamental physical processes expected to be dependent on galactic luminosity should be incorporated into the present merger model for more successful comparison with observational trends concerning luminosity-dependent chemical, photometric, and spectroscopic properties of elliptical galaxies.

7. As described above, the details of the gasdynamics of galaxy merging—in particular, the tidal stripping of metal-enriched interstellar gas and the degree of gaseous dissipation during merging, both of which depend on the star formation history of galaxy mergers—are demonstrated to determine even the chemical and photometric properties of the merger remnants. A complete understanding of these relationships cannot be obtained until both chemical and dynamical evolution during galaxy merging are solved numerically in a reasonably self-consistent way.

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**APPENDIX A**

**THE EXPECTED LUMINOSITY DEPENDENCE OF THE PARAMETER C_{SF}**

A1. **THE IMPORTANCE OF C_{SF}**

In the present study, we adopt the assumption that more massive (and luminous) elliptical galaxies are formed by major galaxy merging between more massive (luminous) late-type spirals, and we thereby investigate how differences in the galactic mass (luminosity) of the progenitor disks in a merger can affect the chemical and photometric properties of the merger remnants. It is reasonable and realistic that if the mass of the merger progenitors differs among galaxy mergers, there could be remarkable differences between mergers in the fundamental physical processes related to the chemical evolution of galaxies, such as the duration, strength, and timescale of star formation (the star formation history), the dissipative dynamics of the interstellar gas, the thermal and dynamical effects of accumulated thermal energy driven by supernova events, and the chemical mixing driven by the dynamics of galaxy merging. Accordingly, we should investigate such physical processes expected to be dependent on galactic mass (luminosity) and thereby clarify the relative importance of these processes. Among these, the most extensively examined in previous studies have been the thermal and dynamical “feedback” effects associated with the supernova events, primarily because the ratio of the accumulated thermal energy driven by the supernovae to the total potential energy of galaxies has been considered to depend predominantly on galactic luminosity. Although there are a number of important issues that should be addressed extensively, we here focus on the difference in the star formation history between galaxy mergers with different masses (or luminosity); other important issues will be explored in our future papers.

The adopted working hypothesis that galactic mass predominantly determines the star formation history of elliptical galaxies is quite realistic and reasonable, since a growing number of observational studies support this hypothesis. For example, the line ratio of [Mg/Fe], which can be interpreted as the strength of the past activity of type II supernovae relative to that of the type I supernovae, implies that more luminous elliptical galaxies are more likely to truncate their star formation earlier (see, e.g., Worthey et al. 1992). Furthermore, as is suggested by the analysis of the Hβ line index, the epoch, strength, and duration of the latest star formation of elliptical galaxies all seem quite diverse, implying that the classical single-burst picture of elliptical galaxy formation becomes less attractive (Faber et al. 1995). It should be also emphasized that the B−H color in more luminous disk galaxies, which are considered to be merger precursors of more luminous ellipticals in the present study, is found to be redder than in the less luminous disk galaxies (Wyse 1982; Bothun et al. 1985; Gavazzi & Scodellaro 1996). These lines of observational evidence strongly motivate us to clarify the important role of star formation history in determining the chemical and photometric properties as well as the dynamical and kinematical ones in elliptical galaxies.

In the present paper, we focus particularly on the timescale of gas consumption by star formation relative to the dynamical timescale of galaxy mergers; it should be emphasized here that the timescale of gas consumption by star formation relative to the dynamical timescale, not the timescale of gas consumption by star formation itself, is the important determinant. The reason for this is that the timescale of gas consumption by star formation is the typical timescale within which heavy elements are produced by star formation and mixed into interstellar medium. The dynamical timescale is the typical timescale within which violent relaxation during galaxy merging causes mass and angular momentum redistribution and thus dynamical mixing of heavy elements produced by star formation. Therefore, if the dynamical timescale is much larger than the gas consumption timescale, star formation can proceed quite efficiently before the system reaches dynamical equilibrium, and consequently the larger amount of heavy elements produced by this star formation can suffer more effective dynamical mixing of the heavy elements during galaxy merging. Thus, since the dynamics of galaxy merging can strongly affect even the chemical evolution in the present merger model, the ratio of the above two timescales are expected to be more essential for the chemodynamical evolution of galaxy mergers than the star formation timescale itself. For convenience, the inverse ratio of the timescale of gas consumption by star formation to the dynamical timescale is referred to as the rapidity of star formation and is represented by the parameter C_{SF}. It is C_{SF} that we consider to depend strongly on galactic luminosity; accordingly, in the present study, what we investigate most extensively are the important roles of C_{SF} in determining the fundamental characteristics of elliptical galaxies.

A2. **POSSIBLE LUMINOSITY DEPENDENCE OF C_{SF}**

The expected luminosity (mass) dependence of C_{SF} is described as follows. The parameter C_{SF} is set to be proportional to T_{dyn}/T_{SF}, where T_{dyn} and T_{SF} are the dynamical timescale and the timescale of gas consumption by star formation, respectively.
STRUCTURE AND MORPHOLOGY OF MERGER REMNANTS

Although our main purpose in the present paper is not to determine the dynamical properties of elliptical galaxies, we briefly describe how successfully the present merger model can reproduce the luminosity-dependent dynamical properties of elliptical galaxies. The reason for this is that, since the details of chemical evolution are strongly affected by the dynamical evolution of galaxy mergers in the present merger model, observing the dynamical evolution of dissipative galaxy mergers with star formation would help us to understand more clearly the present results concerning the chemical evolution of galaxy mergers.

B1. DEPENDENCE ON $C_{\text{SF}}$

First we present the morphological, structural, and kinematical properties of merger remnants and their dependence on $C_{\text{SF}}$. As described in detail by Bekki & Shioya (1997a, 1998), galaxy mergers with larger $C_{\text{SF}}$ are found to be likely to become elliptical galaxies less strongly supported by global rotation, less strongly self-gravitating, and with smaller central surface brightness values, larger cores, and boxy isophotal shapes. Figure 18 describes the morphological evolution of the $C_{\text{SF}} = 0.35$ model (model B1). As the dynamical interaction between star-forming disk galaxies becomes stronger, an appreciable amount of metal-enriched gas is tidally stripped away from the disks and finally surrounds the developed elliptical galaxy without contributing to further star formation and chemical enrichment. The developed metal-poor gaseous halo might be observed as the hot and metal-poor X-ray halo of elliptical galaxies that has recently been revealed by ASCA (see, e.g., Matsumoto et al. 1997). The final morphology of the merger remnants depends strongly on the rapidity of star formation represented by $C_{\text{SF}}$, as is shown in Figure 19: a galaxy merger with less rapid star formation becomes a more compact elliptical galaxy. The density profiles of merger remnants are well fitted by an $R^{1/4}$ law; however, the systematic deviation from the $R^{1/4}$ law is also observed to depend on the values of $C_{\text{SF}}$, as shown in Figure 20. Unlike the late galaxy merger in which the gas mass fraction of the precursor disk is less than 0.2, the present merger model, with highly dissipative interstellar gas, succeeds in boosting more significantly the central density of the merger remnant than do isolated disk models (models A1 and A2). This result suggests the problems related to the phase space density of elliptical galaxies (Ostriker 1980; Carlberg 1986) can successfully be resolved in high-redshift galaxy mergers, as has already been indicated by Kormendy & Sanders (1992). These results imply that galaxy mergers with star formation and gaseous dissipation, which might occur most frequently at high redshifts, can naturally explain the fundamental dynamical and kinematical properties of elliptical galaxies (for further details, see Bekki & Shioya 1997a, 1998).

B2. DEPENDENCE ON GALACTIC LUMINOSITY

By adopting a specific assumption about the luminosity dependence of the parameter $C_{\text{SF}}$, we can observe how successfully the present merger can reproduce the luminosity-dependent morphological, structural, and kinematical properties of elliptical
galaxies. Although describing the dynamical properties of elliptical galaxies and their dependence on galactic luminosity is not main purpose of this paper, we briefly discuss them since we will point out the advantages and disadvantages of the present merger model in reproducing both the dynamical and chemical properties of elliptical galaxies described in § 4. Observational results indicate that more luminous elliptical galaxies are likely to be less rotationally supported (Davies et al. 1983), to have a less luminous surface density (Djorgovski et al. 1996) and a smaller phase space density (Carlberg 1986), and to have boxy isophotes (Kormendy & Bender 1996) and larger cores (Kormendy & Djorgovski 1989). If we assume that \( C_{SF} \propto L^{0.57} \), that is, that more luminous elliptical galaxies are formed by galaxy mergers with more rapid star formation, our numerical results are consistent with the above observed trends of the luminosity-dependence of the dynamical properties of elliptical galaxies, at least in a qualitative manner. For example, the present merger model explains that the observed positive correlation of the galactic core radius and luminosity in an elliptical galaxy results from the more luminous ellipticals being formed by major galaxy merging between more luminous spirals. The first reason for this is that, since more luminous spirals initially are more likely to have larger cores (smaller central phase space density) as is implied by Freeman’s law and the relation between galactic luminosity and scale length (see, e.g., McGaugh & de Blok 1997), galaxy mergers between spirals with larger cores are more likely to become ellipticals with larger cores (with smaller central phase space density). The second reason is that more luminous galaxy mergers are less dissipative owing to the more rapid consumption of interstellar gas and consequently become ellipticals with less central concentration. Hence the luminosity-dependent central structure in elliptical galaxies could reflect the luminosity-dependent dynamical structure of disk galaxies and the star formation history of galaxy mergers. Our numerical results imply furthermore that no particular physical process, such as the dynamical heating of the central cores by binary black holes (Ebisuzaki, Makino, & Okumura 1991), is necessarily required for the formation of larger cores in more luminous elliptical galaxies. Thus, our numerical results strongly suggest that the luminosity-dependent dynamical structure of elliptical galaxies can be understood in the context of the star formation history between gas-rich galaxy mergers and the difference in luminosity-dependent dynamical structure of the progenitor disks. This furthermore indicates that the total amount of gaseous dissipation and the degree of violent relaxation during merging, both of which are determined basically by the star formation history of galaxy mergers, are important factors that can affect the luminosity-
Fig. 19.—Snapshots of stellar components in merger remnants projected onto the \((x, z)\) plane at \(T = 20.0\) in our units for models with \(C_{\text{SF}} = 0.35\) (model B1; upper panel) and \(C_{\text{SF}} = 3.5\) (model B5; lower panel).

Fig. 20.—Radial distribution of stellar components projected onto the \((x, y)\) plane for merger remnants (solid lines) in the model with \(C_{\text{SF}} = 0.35\) (model B1) and \(C_{\text{SF}} = 3.5\) (model B5) and for isolated disks (dotted lines) with \(C_{\text{SF}} = 0.35\) (model A1) and \(C_{\text{SF}} = 3.5\) (model A2) at \(T = 15.0\) in our units. Models with \(C_{\text{SF}} = 0.35\) and 3.5 are represented by open circles and open triangles, respectively.

dependent morphological, structural, and kinematical properties of elliptical galaxies. The validity of the suggested point of view that essentially ascribes the luminosity-dependent dynamical structures of elliptical galaxies to the difference in the star formation history between elliptical galaxies formed by dissipative galaxy merging has been also investigated by Bekki & Shioya (1998) in the context of the origin of the fundamental plane of elliptical galaxies. Although more elaborate numerical
studies, including more realistic implementation of star formation and gaseous dissipation, are definitely required for confirming the validity of the results obtained in the present study, the merger scenario that more luminous ellipticals are formed by dissipative and major galaxy merging between more luminous spirals seems likely because it succeeds in reproducing the observed luminosity-dependent dynamical properties of elliptical galaxies.

B3. SELF-CONSISTENCY OF THE PRESENT MERGER MODEL

Our final goal is to construct a more realistic model that can clearly explain both the structural and kinematical properties, such as the origin of the fundamental plane (Djorgovski & Davis 1987; Dressler et al. 1987), the boxy-disky dichotomy (Kormendy & Bender 1996), the surface brightness-effective radius relation (Djorgovski et al. 1996), and the chemical and photometric properties, such as the color-magnitude relation (Faber 1973; Visvanathan & Sandage 1977) and the luminosity-dependent radial gradients of metallicity, age, and color (Peletier et al. 1990; Davies et al. 1993). Therefore, it is essential to discuss how successfully the present merger model has actually reproduced or would reproduce both the dynamical and kinematical properties and the chemical and photometric ones in a self-consistent way. What is most vital in addressing this crucial issue is to try to explain both the luminosity-dependent dynamical and chemical properties of elliptical galaxies. Since the present study is the first step toward the complete understanding of elliptical galaxy formation, we first make only a qualitative comparison of the present results with observations, and then we point out the advantages and disadvantages of the present merger model in reproducing the luminosity-dependent dynamical and chemical properties of real elliptical galaxies. In the following discussions, we adopt the assumption that galaxy mergers with larger $C_{\text{FR}}$ become more luminous elliptical galaxies, mainly because this assumption is realistic and essential for explaining the morphological and kinematical properties of elliptical galaxies formed by galaxy merging (Bekki & Shioya 1997a, 1998).

As is described in detail by Bekki & Shioya (1997a, 1998), more luminous elliptical galaxies formed by dissipative galaxy mergers with star formation are less rotationally supported, less compact, less strongly self-gravitating, and more likely to have boxy isophotal shapes. In the present study, more luminous elliptical galaxies are found to be more likely to be redder in global color than less luminous ones. These findings concerning the luminosity dependence of structural, dynamical, and photometric properties agree at least qualitatively with the observed trends of elliptical galaxies in a self-consistent manner. These results strongly suggest that both the origin of luminosity-dependent dynamical and morphological structure and that of the luminosity-dependent chemical, photometric, and spectroscopic properties in elliptical galaxies are closely associated with the star formation history—in particular, with the rapidity of star formation in galaxy mergers. Furthermore these results imply that dissipative galaxy merging with star formation, which might occur most frequently at higher redshifts, has more advantages in reproducing the nature of elliptical galaxies than we had previously expected.

What we should note here is that the present merger model also has a number of problems concerning the self-consistent reproduction of structural and chemical properties of elliptical galaxies. One of the foremost problems that should be resolved concerns the luminosity dependence of the central surface brightness (or density) and that of the central stellar metallicity in elliptical galaxies. Observational studies have revealed that more luminous elliptical galaxies show both less luminous central (or effective) surface brightness, as is indicated by the Kormendy relation (see, e.g., Djorgovski et al. 1996), and larger central stellar metallicity, as is indicated by the $\text{Mg}_{\text{II}}-\sigma$ relation (Burstein et al. 1988). This fundamental tendency of elliptical galaxies has not yet been reproduced by the present merger model, which predicts that more luminous elliptical galaxies show less luminous central surface brightness (larger cores) but show smaller central stellar metallicity than do less luminous ellipticals. This sort of failure can also be seen in the dissipative collapse models of Larson (1975) and Carlberg (1984), in which elliptical galaxies with larger central stellar metallicity show more luminous central surface brightness (or smaller cores). We consider these apparent failures to be caused, probably, by the ill approximation of the adopted instantaneous recycling, in which chemical enrichment is assumed to proceed considerably faster than dynamical evolution. Actually, for less luminous elliptical galaxies, the instantaneous recycling approximation is expected to give an undesirable result, in which the dynamical timescale of the systems is comparable to or only slightly longer than the typical lifetime of massive stars (a few times $10^7$ yr). Specifically, for less luminous galaxies, dynamical evolution such as the violent relaxation and redistribution of the angular momentum of gas and stars, which plays a vital role in transferring and dynamically mixing chemical components, probably ends earlier, before the onset of efficient chemical enrichment driven by type II supernovae. As a result of this, the dynamical transfer of the newly enriched components into the inner region of galaxies, which determines the magnitude of the central stellar metallicity, is less likely for less luminous elliptical galaxies. This indicates that the ratio of the typical timescale of chemical enrichment (a few times $10^7$ yr) to the dynamical timescale and its luminosity dependence of this ratio are more critical in the chemodynamical evolution of less luminous elliptical galaxies. This importance is probably not properly modeled by the present chemodynamical model; accordingly, the present model, with instantaneous recycling, should be greatly modified to be more realistic. Hence, it is our objective in the future to consider the importance of the ratio of the timescale of chemical enrichment to the dynamical timescale in elliptical galaxy formation and then to investigate again whether or not the remaining problems of the present merger model can be resolved by these more sophisticated models of chemodynamical evolution.

Thus, the present numerical study suggests that a merger remnant with larger central metallicity is more likely to show larger central surface density, which appears to disagree with the observational trend in real elliptical galaxies. This apparent failure of the present merger model accordingly leads us to the conclusion that other important physical processes associated with dissipative galaxy merging, such as the thermal and dynamical feedback effects of star formation, should be included in the future for more successful agreement with observational results. The alternative conclusion is that the instantaneous recycling approximation adopted in the present study may not be appropriate for analyzing both chemical and dynamical evolution in galaxy mergers, especially for less luminous galaxy mergers in which the typical timescale of chemical enrichment is comparable to or larger than the dynamical timescale of the mergers.
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