FORMATION OF METAL-POOR GASEOUS HALOS IN GAS-RICH GALAXY MERGERS

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ABSTRACT

We numerically investigate the chemodynamical evolution of the interstellar medium (ISM) in gas-rich disk-disk galaxy mergers in order to explore the origin of fundamental chemical properties of halo ISM observed in elliptical galaxies. There are three main results of this chemodynamical study: (1) Elliptical galaxies formed by gas-rich mergers show steep negative metallicity gradients in the ISM, especially in the outer parts of galaxies. This is because chemical evolution of the ISM in mergers proceeds in such an inhomogeneous way that metal enrichment of the ISM is more efficient in the central part of mergers, as a result of the radial inflow of metal-enriched ISM during dissipative galaxy merging, whereas in the outer part, metal enrichment is less efficient because a larger amount of metal-enriched ISM is tidally stripped away from mergers. This result provides a clue to the origin of gaseous metallicity gradients in elliptical halos recently revealed by ASCA. (2) Because of the inhomogeneous chemical evolution of the ISM in mergers, some merger remnants show a mean gaseous metallicity that is discernibly smaller than the mean stellar one. The degree of difference between the mean stellar and gaseous metallicities in a merger remnant depends on chemical mixing length, galactic mass, and the effectiveness of supernova feedback. (3) Elliptical galaxies formed by multiple mergers are more likely to have metal-poor gaseous halo components and steep gaseous metallicity gradients than those formed by pair mergers. This is principally because a larger amount of less metal enriched ISM can be tidally stripped away more efficiently from galaxies in multiple mergers. These three results demonstrate that dynamical evolution of gas-rich galaxy mergers, in particular tidal stripping of less metal enriched ISM during galaxy merging, greatly determines the chemical evolution of the ISM of galaxy mergers. These results furthermore imply that recent ASCA observational results on the mean and radial chemical properties of halo ISM in elliptical galaxies can be understood in terms of the chemodynamical evolution of gas-rich galaxy mergers.

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

1. INTRODUCTION

Recent observational studies by ASCA (Advanced Satellite for Cosmology and Astrophysics) have revealed a number of fundamental chemical properties of the interstellar medium (ISM) of elliptical galaxies, thus providing valuable information about the formation and evolution of elliptical galaxies (e.g., Awaki et al. 1994; Loewenstein et al. 1994; Matsushita et al. 1994; Mushotzky et al. 1994; Matsumoto et al. 1997; Matsushita et al. 1997). For example, the Fe abundance of hot gaseous X-ray halos has been revealed to be appreciably smaller than that of the stellar component in the host elliptical galaxy (Awaki et al. 1994; Matsushita et al. 1994; Matsumoto et al. 1997; but see Matsushita et al. 1997). This smaller gaseous metallicity is considered to be largely inconsistent with the theoretical prediction of the conventional one-zone chemical evolution model (the iron abundance discrepancy problem) and thus has been extensively discussed in theoretical studies (e.g., Renzini et al. 1993; Fujita, Fukumoto, & Okoshi 1996; Arimoto et al. 1997). Furthermore, the hot X-ray gaseous halo in elliptical galaxies has been revealed to show strong negative metallicity gradients, which suggests that some physical mechanisms, such as cooling flow, gaseous dissipation, galaxy merging, and dilution from external metal-poor gas, play a vital role in the formation of the gaseous metallicity gradients (Loewenstein et al. 1994; Mushotzky et al. 1994; Matsushita et al. 1997). Although these ASCA observational results on the mean and radial chemical properties of the ISM can provide some diagnostics for any theory of elliptical galaxy formation, only a few theoretical studies have addressed the origin of the above fundamental characteristics of the chemical properties of the ISM in elliptical galaxies.

The purpose of this paper is to explore the origin of the fundamental chemical properties of the ISM of elliptical galaxies recently revealed by ASCA. We adopt the assumption that elliptical galaxies are formed by gas-rich disk-disk galaxy mergers and investigate whether or not the merger model of elliptical galaxy formation can give a plausible explanation for the origin of the recent observational results of ASCA for the mean and radial chemical properties of the ISM in elliptical galaxies. We particularly investigate how the dynamical mixing of chemical components during galaxy merging, which has not been investigated at all in previous studies, affects the mean and radial chemical properties of the ISM of merger remnants. In the present study, the key physical process associated with the origin of metal-poor gaseous halo and radial gaseous metallicity gradients in elliptical galaxies is demonstrated to be tidal stripping of less metal enriched ISM during galaxy merging. Based on the present numerical results, we point out the disadvantages of the commonly used one-zone models in discussing the metallicity of the ISM of elliptical galaxies, and we stress the importance of dynamical processes of galaxy formation in the chemical enrichment of the ISM in galaxies. The layout of this paper is as follows. In § 2 we summarize numerical models used in the present study. In § 3 we demonstrate how a number of fundamental chemical properties of the ISM in merger remnants are affected by purely dynamical processes of galaxy merging. In
§ 4 we discuss a number of implications for the chemical properties of the ISM in elliptical galaxies, and give conclusions of the present study.

2. MODEL

We mainly investigate a number of fundamental chemical properties of the ISM in ellipticals formed by galaxy mergers between two gas-rich spirals. Fundamental chemical properties of the ISM in galaxy mergers are basically controlled by the star formation histories, which strongly depend on the time evolution of dynamical and kinematical properties such as the local dynamical instability in galaxies (e.g., Kennicutt 1989; Larson 1992). Hence, we numerically solve the time evolution of the chemical evolution of galaxy mergers based on the dynamical evolution of galaxies. Since the details of the chemodynamical model are given in Bekki & Shioya (1998), we only briefly describe this model in the present study. We first describe a numerical model for the dynamical evolution of galaxy mergers, including the structure and kinematics of merger progenitor disks and the star formation law (§ 2.1), and then give the method for analyzing the chemical enrichment process during galaxy merging (§ 2.2).

2.1. A Model of Gas-rich Galaxy Mergers

We construct models of galaxy mergers between gas-rich disk galaxies with equal mass using the model of Fall & Efstathiou (1980). The total mass and size of a progenitor disk are given by $M_d$ and $R_d$, respectively. In this paper, mass and length are measured in units of $M_d$ and $R_d$, respectively, unless otherwise specified. Velocity and time are measured in units of $v = (GM_d/R_d)^{1/2}$ and $t_{\text{dyn}} = (R_d/GM_d)^{1/2}$, respectively, where $G$ is the gravitational constant, assumed to be 1.0 in the present study. Dimensional values for these units in each model are given later. In the present model, the rotation curve becomes nearly flat at 0.35 $R_d$, with maximum rotational velocity $v_{\text{rot}} = 1.8$ in our units. The corresponding total mass, $M_r$, and halo mass, $M_h$, are 3.8 and 2.8 in our units, respectively. The radial ($R$) and vertical ($Z$) density profiles of a disk are assumed to be proportional to $\exp (R/R_0)$ with scale length $R_0 = 0.2$, and $\exp (Z/Z_0)$ with scale length $Z_0 = 0.04$ in our units, respectively. In addition to the rotational velocity generated by the gravitational field of the disk and halo components, initial radial and azimuthal velocity dispersions are given to the disk component according to the epicyclic theory with Toomre's parameter (Binney & Tremaine 1987), $Q = 1.0$. The vertical velocity dispersion at a given radius is set to be 0.5 times the radial velocity dispersion at that point, as is consistent with the observed trend of the Milky Way (e.g., Wielen 1977). The collisional and dissipative nature of the ISM is modeled by the sticky-particle method (Schwarz 1981). The size of the clouds is set to be $5.0 \times 10^{-3}$ in our units in the present simulations. The radial and tangential restitution coefficients for cloud-cloud collisions are set to be 0.5 and 0.0, respectively. We assume that the fraction of gas mass in a disk is 1.0 initially, in order to mimic higher redshift galaxy mergers, which probably have a considerably larger amount of ISM. The reason for this assumption is that recent observational studies, such as those considering the tightness of the color-magnitude relation in the cluster of galaxies (e.g., Bower, Lucey, & Ellis 1992; Ellis et al. 1996), have suggested the relatively higher redshift of typical elliptical galaxy 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 consumed by star formation for each gas particle in each time step, $M_g$, is given by

$$M_g \propto (\rho_g/\rho_0)^{1.0},$$

where $\rho_g$ and $\rho_0$ are the gas density around each gas particle and the mean gas density at 0.48 radius of an initial disk, respectively. Thermal and dynamical (kinematic) heating of the ISM driven by supernovae are found to greatly affect the formation and evolution of galaxies (e.g., Katz 1992; Navarro & White 1993). We here consider the dynamical feedback effects of Type Ia (SNIa) and Type II (SNII) supernovae and neglect the feedback effects of thermal heating on galaxy evolution. The reasons for this omission are, first, that our gaseous model does not solve for the thermal evolution of the ISM, and, second, that such thermal effects are found to be less important than dynamical feedback effects arising from efficient cooling of the ISM (e.g., Katz 1992; Navarro & White 1993). In the present study, 10% of the total energy ejected from SNIa and SNII is assumed to be returned to the ISM to produce velocity perturbations in the ISM. More details of the supernovae feedback effects are given in Bekki & Shioya (1998).

We investigate two different types of merger models, both of which are considered to be promising candidates for describing elliptical galaxy formation (Barnes & Hernquist 1992): pair mergers between two disks and multiple mergers of five disks. The initial orbit conditions of the two merger progenitor disks in the pair-merger model are as follows. The orbit of the two disks in a pair merger is set to be initially in the $x$-$y$ plane. The initial distance between the center of mass of the two disks, the pericenter distance, and the eccentricity of merger orbit are 4.0, 1.0, and 1.0, respectively. The spin of each galaxy in a pair merger is specified by the two angles $\theta_i$ and $\phi_i$, where the suffix $i$ is used to identify each galaxy. The angle between the $z$-axis and the vector of the angular momentum of a disk is given by $\theta_i$. The azimuthal angle measured from $x$-axis to the projection of the angular momentum vector of a disk onto $x$-$y$ plane is given by $\phi_i$. In this model, $\theta_1$, $\theta_2$, $\phi_1$, and $\phi_2$ are set to be $30.0$, $120.0$, $90.0$, and 0.0, respectively. In simulations of multiple mergers, the initial position of each progenitor disk is set to be distributed randomly within a sphere of 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 kinematic energy to the total potential energy in the system is 0.25. The timescale in which the progenitor disks merge completely and reach the dynamical equilibrium of an elliptical galaxy is less than 20.0 in our units for the two models.

All the calculations related to the above dynamical evolution, including the dissipative dynamics, star formation, and gravitational interaction between collisionless and collisional component, have been carried out on the GRAPE board (Sugimoto et al. 1990) at the Astronomical Institute of Tohoku University. The number of particles in the halo and the gaseous components are 10,000 and 20,000 for the pair-merger model, and 25,000 and 25,000 for the multiple-
merger model. The parameter of gravitational softening is fixed at 0.04 in all the simulations. The time integration of the equation of motion is performed 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 $t = 20.0$ in our units (corresponding to a few Gyr), unless otherwise specified.

### 2.2. Chemical Enrichment

Chemical enrichment through star formation during galaxy merging is assumed to proceed locally and inhomogeneously in the present chemodynamical model. We investigate the time evolution of five species of chemical components: H, He, O, Mg, and Fe, as well as the conventional mean metallicity, $Z$. The mean metallicity $Z$ for each $i$th stellar particle is represented by $Z_r$. The total mass of each $j$th $(j = 1, 2, 3, 4,$ and $5)$ chemical component (H, He, O, Mg, and Fe) ejected from each $i$th stellar particle through SNII and SNII at time $t$ is given as

$$ \Delta Z_{i,j}(t) = m_{n,i} Y_{i,j}(t - t_i), $$

where $m_{n,i}$ is the mass of the $i$th stellar particle, $Y_{i,j}(t - t_i)$ is the mass of each $j$th chemical component per unit mass at time $t_i$ and $t_i$ represents the time at which the $i$th stellar particle is born from a gas particle. The $\Delta Z_{i,j}(t)$ is given to neighbor gas particles located within $R_{\text{chem}}$ from the position of the $i$th stellar particle. $R_{\text{chem}}$ is the chemical mixing length, representing the region within which the neighbor gas particles are polluted by metals ejected from stellar particles. The value of $R_{\text{chem}}$ relative to the typical size of a galaxy could differ between galaxies, so the value of $R_{\text{chem}}$ is accordingly considered to be a free parameter in the present study. The value of $R_{\text{chem}}$ examined most extensively in the present study is 0.1, which corresponds to half the scale length of the initial disks. Initial gaseous metallicity for each chemical components is set to be 0.1 solar, which is exactly the same as that of infall gas adopted in the classical chemical evolution models of disk galaxies with gaseous infall. Although we investigate the above six species of chemical components (H, He, O, Mg, Fe, and Z), we only present the results for Fe and Z in the present study.

Since we now consider the time delay between the epochs of star formation and supernovae explosions, the mass of each $j$th chemical component ejected from each $i$th stellar particle through SNII and SNII, which are basically determined by $Y_{i,j}(t - t_i)$, is also strongly time dependent. We estimate the mass-dependent lifetime of stars that becomes SNII or SNII using the mass-age relation given by Bressan et al. (1993). The fraction of close binary stars in SNII relative to SNII (represented by the $A$ parameter in Matteucci & Tornambé 1987) is assumed to be 0.1. The value of $Y_{i,j}(t - t_i)$ further depends on the stellar yields, the IMF profiles, and the upper and lower cutoff masses, $M_{\text{up}}$ and $M_{\text{low}}$. In the present study, we adopt the Salpeter IMF, $\phi(m) \propto m^{-1.35}$, with $M_{\text{up}} = 120 M_\odot$ and $M_{\text{low}} = 0.6 M_\odot$. The reason for this larger $M_{\text{low}}$ is that we do not have stellar yield tables for stars with masses less than 0.6. To calculate the ejected mass of gas and metals in $Y_{i,j}(t - t_i)$, we use stellar yields from Woosley & Weaver (1995) for SNII, from Nomoto, Thielemann, & Yokoi (1984) for SNIa, and from Bressan et al. (1993) and Magris & Bruzual (1993) for low- and intermediate-mass stars. More details of the time dependence of $Y_{i,j}(t - t_i)$ for a given IMF, $M_{\text{up}}$, and $M_{\text{low}}$ are given in Bekki & Shioya (1998).

### 2.3. Model Parameters

By using the above chemodynamical model of gas-rich galaxy mergers, we mainly investigate the following two points concerning the chemical evolution of ISM: (1) the radial chemical properties of ISM ($Z$ and Fe) in merger remnants and (2) the degree of difference in mean metallicity between stellar components and gaseous ones (ISM) in merger remnants. We describe numerical results for five models (models 1, 2, 3, 4, and 5). Model 1 is a pair-merger model with $M_d = 10^{10} M_\odot$ and $R_{\text{chem}} = 0.1$, which shows typical behavior of the chemical evolution of ISM in the present merger model, and thus is referred to as the standard model. Model 2 is a pair-merger model with $M_d = 10^{12} M_\odot$ and $R_{\text{chem}} = 0.1$, which describes the results of more massive galaxy mergers. Model 3 is a pair-merger model with $M_d = 10^{10} M_\odot$ and $R_{\text{chem}} = 0.4$, in which the chemical evolution of ISM is assumed to proceed more globally and homogeneously, because of the larger chemical mixing length. Model 4 is a pair-merger model with $M_d = 10^{10} M_\odot$ and $R_{\text{chem}} = 0.1$, in which the total amount of supernova energy returned to the ISM is 5 times larger than that adopted in model 1 (a model with stronger supernova feedback). Model 5 is a multiple merger model with $M_d = 10^{10} M_\odot$ and $R_{\text{chem}} = 0.1$, in which five disks are assumed to merge with each other to form an elliptical galaxy. The dimensional values of $R_{\text{dyn}}$ (units of the present study) and $R_d$ are $3.0 \times 10^7$ yr and $7.4$ kpc, respectively, as models with $M_d = 10^{10} M_\odot$ and $2.9 \times 10^8$ yr and $74.1$ kpc, respectively, for models with $M_d = 10^{12} M_\odot$. The parameter values for these five models are summarized in Table 1.

### 3. Results

#### 3.1. Inhomogeneous Chemical Evolution of the ISM in Mergers

In the present chemodynamical model of gas-rich galaxy mergers, metals produced in star-forming regions of mergers are assumed to be mixed only locally into the surrounding ISM. This local mixing of chemical components plays a vital role in determining not only radial but also mean chemical properties of the ISM in merger remnants. Figure 1 shows the radial properties of mean gaseous metallicity, $\langle Z \rangle$ and $\langle \text{Fe} \rangle$, in a merger remnant at time $T = 16.0$ $T_{\text{dyn}}$ (corresponding to $\sim 1.4$ Gyr) for model 1 (the standard model). It is clear from Figure 1 that the merger remnant has a steep negative metallicity gradient in the ISM for both $\langle Z \rangle$ and $\langle \text{Fe} \rangle$. Furthermore, gaseous metallicity is found to be considerably smaller ($\sim 0.5$ solar) in the outer part of the merger remnant, which implies that the formation of a metal-poor gaseous halo surrounding the outer part of the galaxy is an inevitable physical process for ellipticals formed by gas-rich galaxy mergers. These results suggest

### Table 1

| Model | $M_d/M_\odot$ | $R_{\text{chem}}$ | Comments |
|-------|--------------|-------------------|----------|
| 1     | $10^{10}$    | 0.1               | standard model |
| 2     | $10^{12}$    | 0.1               | massive disks |
| 3     | $10^{10}$    | 0.4               | larger mixing length |
| 4     | $10^{10}$    | 0.1               | stronger supernova feedback |
| 5     | $10^{10}$    | 0.1               | multiple merger |
that the dynamical evolution of gas-rich galaxy merging greatly affects the chemical evolution of the ISM and thus controls the radial properties of $\langle Z \rangle$ and $\langle Fe \rangle$. The details of the formation process of gaseous metallicity gradients are as follows. In the present chemodynamical model of gas-rich galaxy mergers, metals produced and ejected by SNIa and SNII in star-forming gaseous regions of a merger can be mixed only locally into the surrounding ISM (inhomogeneous chemical mixing). Accordingly, the metals, which are mostly produced in the central region of the merger, are mixed preferentially into the ISM in the central region, where further efficient star formation is expected, and thus they cannot be mixed so efficiently into the outer region of the merger. Consequently, the ISM of the outer part of the merger remains less metal enriched. This less metal enriched ISM in the outer part of the merger is then effectively stripped away from the system during the tidal interaction of galaxy merging and is finally transferred to the more outer region, where it is still more difficult to mix in metals produced in the central part of the merger. As a natural result, the mean metallicity of the ISM remaining in the outer part of the remnant becomes considerably smaller.

On the other hand, the ISM initially located in the central part of the merger will be more metal enriched because of the quite efficient star formation there. The formation of gaseous metallicity gradients accordingly reflects the fact that the metals produced by star formation are more efficiently trapped by the ISM in the central part of mergers than by the ISM in the outer part. Thus, the origin of the negative metallicity gradients in the gaseous halos of merger remnants lies principally in the inhomogeneous chemical mixing in gas-rich mergers.

This inhomogeneous mixing of metals furthermore plays a decisive role in determining mean chemical properties of the ISM in merger remnants. Figure 2 shows the dependence of mean stellar metallicity ($\langle Z_s \rangle$ and $\langle Fe_s \rangle$) on mean gaseous metallicity ($\langle Z \rangle$ and $\langle Fe \rangle$) at times $T = 8.0, 12.0,$ and $16.0 \, T_{\text{dyn}}$ in a galaxy merger for model 1. Mean gaseous and stellar metallicity are measured for the region $R \leq R_{\text{eff}}$ (where $R_{\text{eff}}$ is the effective radius of the remnant), $R \leq 2.5 \, R_{\text{eff}}$, $R \leq 10.0 \, R_{\text{eff}}$, and the whole region in the merger remnant. As shown in Figure 2, $\langle Z_s \rangle$ is larger than $\langle Z \rangle$ for $R \leq R_{\text{eff}}$, whereas $\langle Z \rangle$ is discernibly smaller than $\langle Z_s \rangle$ for the whole region. This result implies that metals produced by star formation can be more homogeneously mixed into the ISM in the inner regions of galaxy mergers. $\langle Fe \rangle$ is also found to be larger than $\langle Fe_s \rangle$ for the above four regions.
Furthermore, the difference in mean stellar and gaseous metallicity depends on the region for which mean metallicity is measured; the difference is larger in the more central regions. Most significant among these results is that mean gaseous metallicity $\langle Z \rangle$ can be smaller than mean stellar metallicity $\langle Z_\ast \rangle$ in merger remnants; classical one-zone chemical evolution models never fail to predict that mean gaseous metallicity will always be larger than (or equal to) mean stellar metallicity (e.g., Arimoto & Yoshii 1987). Thus, the present chemodynamical model suggests that dynamical evolution of galaxy mergers, in particular tidal stripping of less metal-enriched ISM during merging, can determine even the mean chemical properties of the stellar and gaseous components of merger remnants.

The important roles of inhomogeneous chemical mixing of metals in determining mean and radial chemical properties of ISM can be observed even more clearly in a multiple-galaxy merger than in pair mergers. Figure 3 describes radial properties of the mean gaseous metallicity, $\langle Z \rangle$ and $\langle \text{Fe} \rangle$, in a remnant of a multiple-galaxy merger at time $T = 16.0 \ T_{\text{dyn}}$ (corresponding to $\sim 1.4$ Gyr) for model 5. As is shown in Figure 3, the remnant of the multiple-galaxy merger has negative gradients of $\langle Z \rangle$ and $\langle \text{Fe} \rangle$ that are appreciably steeper than those of the pair merger in model 1 (see Fig. 1). The reason for these steeper metallicity gradients is that a larger amount of less metal-enriched ISM can be tidally stripped away from galaxies through the stronger multiple-galaxy interaction, finally surrounding the outer part of merger remnants in multiple mergers. Figure 4 shows the dependence of the mean stellar metallicity ($\langle Z_\ast \rangle$ and $\langle \text{Fe}_\ast \rangle$) on mean gaseous metallicity ($\langle Z \rangle$ and $\langle \text{Fe} \rangle$) at times $T = 8.0$, $12.0$, and $16.0 \ T_{\text{dyn}}$ in a multiple-galaxy merger model (model 5). As a natural result of the stronger tidal stripping of less metal enriched ISM in the multiple-galaxy merger, the gaseous metallicity averaged for the whole region of the merge remnant in model 5 is appreciably smaller than the stellar metallicity. These results thus confirm the importance of the dynamical evolution of galaxy mergers in determining mean and radial chemical properties of the ISM in merger remnants.

**3.2. Parameter Dependence**

Figure 5 shows the dependence of the mean stellar metallicity ($\langle Z_\ast \rangle$ and $\langle \text{Fe}_\ast \rangle$) on the mean gaseous metallicity ($\langle Z \rangle$ and $\langle \text{Fe} \rangle$) at time $T = 16.0 \ T_{\text{dyn}}$ in each merger model (models 1–5). From Figure 5, we can clearly observe the following five points.

1. Irrespective of the model parameters, mean stellar metallicity ($\langle Z_\ast \rangle$ and $\langle \text{Fe}_\ast \rangle$) is smaller than mean gaseous metallicity ($\langle Z \rangle$ and $\langle \text{Fe} \rangle$) in the central part of merger remnants ($R \leq R_{\text{eff}}$). This result implies that for all merger models, metals produced in star-forming regions can be more efficiently and homogeneously mixed into the surrounding ISM in the central part of galaxy mergers.

2. $\langle \text{Fe} \rangle$ is larger than $\langle \text{Fe}_\ast \rangle$ both for the region $R \leq R_{\text{eff}}$ and for the whole region of merger remnants.

3. The mean gaseous metallicity $\langle Z \rangle$ can be smaller than the mean stellar metallicity $\langle Z_\ast \rangle$, particularly for more massive galaxy mergers and multiple-galaxy mergers. This result suggests that some ellipticals with metal-poor gaseous
Small regions in the larger chemical mixing length adopted.

ceeds more homogeneously during galaxy merging because in model 3, chemical mixing of metals progresses as the mean gaseous metallicity in merger remnants, and thus has a negligible effect on the formation of gaseous halos with mean metallicity smaller than stellar.

These five results imply that although certain physical conditions of gas-rich galaxy mergers are required, the mean gaseous metallicity of the ISM can be discernibly smaller than the mean stellar metallicity in some merger remnants.

4. DISCUSSION AND CONCLUSIONS

There is growing observational evidence that suggests strong radial negative gradients in hot X-ray gaseous halos of elliptical galaxies (Loewenstein et al. 1994; Mushotzky et al. 1994; Matsushita et al. 1997). Observational study of NGC 4636 (Matsushita et al. 1997) has revealed a factor of 3–4 difference in the ISM metallicity within ~7.1 $R_{\text{eff}}$. Cooling flows, stellar metallicity gradients actually existing in ellipticals, the long-term chemical evolution of the ISM driven by stellar mass loss or SNIa, and the dilution of metal-enriched ISM by external metal-poor gas are considered to be likely explanations for the origin of gaseous metallicity gradients (e.g., Loewenstein et al. 1994; Mushotzky et al. 1994; Matsushita et al. 1997). These likely explanations are closely associated with either external metal-poor gas or the later chemical evolution of ellipticals. The present study provides an alternative explanation for the origin: the ISM metallicity gradients may be closely associated with intrinsic and dynamical processes of dissipative galaxy merging at the epoch of elliptical formation.

The inhomogeneous and radial-dependent chemical evolution of galaxies is found to play a decisive role in the formation of negative gaseous metallicity gradients of merger remnants. The present numerical results thus imply that the present-day metallicity gradients of hot ISM halos can contain a fossil record of the past dynamical evolution of the ISM of elliptical galaxies at the epoch of their formation.

Negative metallicity gradients derived in the present study are only true for ellipticals of a few Gyr age, primarily because we only solved for a few Gyr evolution of the chemical properties of ISM, but did not solve the later long-term evolution (corresponding to the Hubble time). Thus, we should investigate the following two points in future studies in order to confirm that the proposed explanation for the origin of observed metallicity gradients is actually viable for present-day ellipticals with ages of ~10 Gyr in a more quantitative sense. The first point for investigation is the long-term chemical evolution of the ISM surrounding merger remnants, which could be greatly affected by later and continuous metal enrichment from SNIa and the stellar mass loss of long-lived stars. As has been demonstrated by several previous studies of the long-term hydrodynamical evolution of hot ISM in ellipticals (e.g., David, Forman, & Jones 1991), the effectiveness of thermal heating by SNIa (and partly by long-lived stars) determines the time-evolution radial flow patterns of hot ISM (e.g., either outflow due to effective thermal heating of SNIa or inflow due to efficient cooling). Such later gaseous inflow or outflow, which can transfer metal-enriched ISM, could change the radial metallicity distribution that is initially formed by gas-rich galaxy merging. Accordingly, chemodynamical effects of the later stellar mass loss and supernovae on the radial metallicity distribution should be explored more in detail in our future studies. The second point for
Further investigation is the long-term dynamical evolution of less metal-enriched ISM that is tidally stripped and surrounds merger remnants. The present study predicts that the tidally stripped metal-enriched ISM surrounds the considerable outer part of merger remnants, where external tidal fields from neighboring galaxies and the large-scale gravitational potential of a cluster or group of galaxies can affect dynamical evolution of the stripped ISM. Later dynamical effects of external tidal force can drastically change the initial radial gradients of ISM in merger remnants, so we should also consider these in our future studies. Since radial metallicity gradients of ISM in ellipticals contain valuable information not only on the chemical evolution of the ISM but also on the dynamical evolution of galaxies as a whole, more extensive studies are necessary to better understand the origin of the gradients.

Furthermore, the difference in mean metallicity between stellar and gaseous components derived in the present merger model can be compared with recent observational results from ASCA (Awaki et al. 1994; Matsushita et al. 1994; Matsumoto et al. 1997), which reveal that the abundance of hot gaseous X-ray halo (Fe) is appreciably smaller than that of the stellar component in the host elliptical galaxy. These observational results seem to be consistent with results derived from some merger models of the present study, which imply that metal-poor gaseous components in some elliptical halos can be formed by gas-rich mergers. The most recent result of Matsushita et al. (1997), however, shows that there is not so large difference between mean stellar metallicity (0.74 solar) and mean gaseous metallicity (~1.0 solar) within ~4.0 R_eff of NGC 4636, and furthermore that the gaseous metallicity in the outer part of the halo (for the region 4.7 ≤ R/R_eff ≤ 7.1) is still smaller (~0.37 solar) than the mean stellar metallicity of NGC 4636. Although the metallicity averaged over the whole region of the gaseous halo in NGC 4636 has not yet been clarified, this new observational result suggests the following implications for the inhomogeneous chemical mixing derived in the present study. If the gaseous metallicity averaged over the whole region of the gaseous halo is really larger than the stellar metallicity in NGC 4636, the present numerical result that the mean gaseous metallicity can be smaller than the mean stellar metallicity in some merger remnants is not consistent with observation. In this case, we should consider either that inhomogeneous chemical mixing is not as efficient in real galaxy mergers as the present study predicts, or that the later long-term metal enrichment of ISM resulting from metal ejection from long-lived stars and supernovae (SNIa) can greatly affect the chemical evolution of the ISM after galaxy merging, and thus change the difference of the mean stellar and gaseous metallicities in merger remnants. Alternatively, if the gaseous metallicity averaged over the whole region of the gaseous halo is really smaller than the stellar metallicity, the present study can provide a clue to the origin of this smaller gaseous metallicity in elliptical halos; the origin of metal-poor gaseous halos in ellipticals may be closely associated with past dissipative galaxy merging processes. Since the total number of sample X-ray gaseous halos with a precise estimate of mean metallicity is still small, it is safe for us to say, at least for now, that future, more extensive observational studies and more elaborate theoretical models will assess the validity of the inhomogeneous chemical mixing model derived in the present study.

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

1. Elliptical galaxies formed by gas-rich mergers show steep negative metallicity gradients in the ISM, especially in the outer parts of galaxies. The essential reason for this is that chemical evolution of the ISM in mergers proceeds in such an inhomogeneous way that in the central part of mergers, metal enrichment of the ISM is more efficient, owing to the radial inflow of metal-enriched ISM during dissipative galaxy merging, whereas in the outer parts, metal enrichment is less efficient because of the larger amount of metal-enriched ISM tidally stripped away from mergers. This result provides a clue to the origin of the gaseous metallicity gradients of elliptical halos recently revealed by ASCA.

2. Because of the inhomogeneous chemical evolution of the ISM in mergers, some merger remnants show mean gaseous metallicity discernibly smaller than mean stellar metallicity. The degree of difference in mean stellar and gaseous metallicities in a merger remnant depends on the chemical mixing length, galactic mass, and the effectiveness of supernova feedback.

3. Elliptical galaxies formed by multiple mergers are more likely to have metal-poor gaseous halo components and steep gaseous metallicity gradients than those formed by pair mergers. This is principally because a larger amount of less metal enriched ISM can be tidally stripped away more efficiently from galaxies in multiple mergers.

These three results demonstrate that the dynamical evolution of galaxy mergers can greatly affect the chemical evolution of the ISM of galaxies, which cannot be attained until both the dynamical and chemical evolution of galaxies are solved in an admittedly self-consistent manner. In particular, tidal stripping of less metal enriched ISM during dissipative galaxy merging is found to play a vital role in determining mean and radial chemical properties of the ISM in elliptical galaxies. The present study accordingly implies that the origin of the metal-poor gaseous halo and negative metallicity gradients of the ISM in an elliptical galaxy can be closely associated with gas-rich galaxy merging at the epoch of elliptical galaxy formation.

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Bekki, K., et al. (Awaki 1994; Matsushita 1997), which reveal that the abundance of hot gaseous X-ray halo (Fe) is appreciably smaller than that of the stellar component in the host elliptical galaxy. These observational results seem to be consistent with results derived from some merger models of the present study, which imply that metal-poor gaseous components in some elliptical halos can be formed by gas-rich mergers. The most recent result of Matsushita et al. (1997), however, shows that there is not so large difference between mean stellar metallicity (0.74 solar) and mean gaseous metallicity (~1.0 solar) within ~4.0 R_eff of NGC 4636, and furthermore that the gaseous metallicity in the outer part of the halo (for the region 4.7 ≤ R/R_eff ≤ 7.1) is still smaller (~0.37 solar) than the mean stellar metallicity of NGC 4636. Although the metallicity averaged over the whole region of the gaseous halo in NGC 4636 has not yet been clarified, this new observational result suggests the following implications for the inhomogeneous chemical mixing derived in the present study. If the gaseous metallicity averaged over the whole region of the gaseous halo is really larger than the stellar metallicity in NGC 4636, the present numerical result that the mean gaseous metallicity can be smaller than the mean stellar metallicity in some merger remnants is not consistent with observation. In this case, we should consider either that inhomogeneous chemical mixing is not as efficient in real galaxy mergers as the present study predicts, or that the later long-term metal enrichment of ISM resulting from metal ejection from long-lived stars and supernovae (SNIa) can greatly affect the chemical evolution of the ISM after galaxy merging, and thus change the difference of the mean stellar and gaseous metallicities in merger remnants. Alternatively, if the gaseous metallicity averaged over the whole region of the gaseous halo is really smaller than the stellar metallicity, the present study can provide a clue to the origin of this smaller gaseous metallicity in elliptical halos; the origin of metal-poor gaseous halos in ellipticals may be closely associated with past dissipative galaxy merging processes. Since the total number of sample X-ray gaseous halos with a precise estimate of mean metallicity is still small, it is safe for us to say, at least for now, that future, more extensive observational studies and more elaborate theoretical models will assess the validity of the inhomogeneous chemical mixing model derived in the present study.

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

1. Elliptical galaxies formed by gas-rich mergers show steep negative metallicity gradients in the ISM, especially in the outer parts of galaxies. The essential reason for this is that chemical evolution of the ISM in mergers proceeds in such an inhomogeneous way that in the central part of mergers, metal enrichment of the ISM is more efficient, owing to the radial inflow of metal-enriched ISM during dissipative galaxy merging, whereas in the outer parts, metal enrichment is less efficient because of the larger amount of metal-enriched ISM tidally stripped away from mergers. This result provides a clue to the origin of the gaseous metallicity gradients of elliptical halos recently revealed by ASCA.

2. Because of the inhomogeneous chemical evolution of the ISM in mergers, some merger remnants show mean gaseous metallicity discernibly smaller than mean stellar metallicity. The degree of difference in mean stellar and gaseous metallicities in a merger remnant depends on the chemical mixing length, galactic mass, and the effectiveness of supernova feedback.

3. Elliptical galaxies formed by multiple mergers are more likely to have metal-poor gaseous halo components and steep gaseous metallicity gradients than those formed by pair mergers. This is principally because a larger amount of less metal enriched ISM can be tidally stripped away more efficiently from galaxies in multiple mergers.

These three results demonstrate that the dynamical evolution of galaxy mergers can greatly affect the chemical evolution of the ISM of galaxies, which cannot be attained until both the dynamical and chemical evolution of galaxies are solved in an admittedly self-consistent manner. In particular, tidal stripping of less metal enriched ISM during dissipative galaxy merging is found to play a vital role in determining mean and radial chemical properties of the ISM in elliptical galaxies. The present study accordingly implies that the origin of the metal-poor gaseous halo and negative metallicity gradients of the ISM in an elliptical galaxy can be closely associated with gas-rich galaxy merging at the epoch of elliptical galaxy formation.

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