TIGHTNESS OF THE COLOR-MAGNITUDE RELATION OF ELLIPTICAL GALAXIES AND THE EPOCH OF MAJOR GALAXY MERGING

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ABSTRACT

We investigate a one-zone chemophotometric evolution model of disk-disk galaxy mergers in order to clarify whether galaxy mergers with a widely spread merging epoch can reproduce reasonably well the observed small scatter of the color-magnitude (C-M) relation in cluster ellipticals at low and intermediate redshift (z < 1). We consider that merger-progenitor disks begin to consume interstellar gas at a moderate rate from z ~ 5 and then merge to form an elliptical with a secondary starburst at z = z_{merge}. We find that even if the epoch of galaxy merging is rather extended (0.3 < z_{merge} < 3.0), the dispersion in the rest-frame U-V color among galaxy mergers is well within the observed one (~0.05 mag at z = 0). We also find that the z_{merge} is required to be within a certain range to keep the observed C-M relation tight at a given z. For example, the required range of z_{merge} in galaxy mergers between Sa disks is 1.3 < z_{merge} < 3.0 for cluster ellipticals at z = 0.895, 0.9 < z_{merge} < 3.0 for z = 0.55, and 0.3 < z_{merge} < 3.0 for z = 0. The main reason for the derived small scatter is that younger stellar populations, which are formed during the secondary starburst of galaxy mergers, are formed preferentially from more metal-enriched interstellar gas. This result reinforces Worthey’s suggestion of 1996 that the age-metallicity conspiracy, which means that younger stellar populations are preferentially more metal-enriched, can operate to keep the tight C-M relation. These numerical results imply that the observed small scatter in the C-M relation at low and intermediate redshift (z < 1) does not necessarily require the coevality of elliptical galaxies in clusters or their formation at high z, which has been conventionally believed in the classical, passive evolution picture.

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

1. INTRODUCTION

Redshift evolution of fundamental physical relations in elliptical galaxies is generally considered to give strong constraints on the formation and evolution of elliptical galaxies. For example, evolution of the color-magnitude (C-M) relation with redshift (z) suggests that elliptical galaxies are old, coeval, and homogeneous systems passively evolving after the single initial burst of star formation associated with dissipative galaxy formation at z > 2.0 (Aragón-Salamanca et al. 1993; Ellis et al. 1997; Stanford, Eisenhardt, & Dickinson 1998). This classical picture of coeval elliptical galaxy formation also appears to be supported by the small redshift evolution of both the mass-to-light ratio (van Dokkum & Franx 1996) and the Mg_{2}-σ relation (Ziegler & Bender 1997). Furthermore, the considerably tight C-M relation (Bower, Lucey, & Ellis 1992) and the Fundamental Plane (e.g., Djorgovski & Davis 1987) at the present epoch, the redshift evolution of the slope, and the zero point of the C-M relation (Kodama & Arimoto 1997; Gladders et al. 1998; Kodama et al. 1998) seem to support the coevality of elliptical galaxy formation.

An increasing number of recent observational results, however, shed strong doubt on this long-standing view of elliptical galaxy formation and suggest that there is great variety of star formation histories among elliptical galaxies, such as the epoch of major star formation and the duration and efficiency of star formation (Worthey, Faber, & Gonzalez 1992; Faber et al. 1995; Worthey, Trager, & Faber 1996). In particular, Faber et al. (1995) suggested that the “apparent age spread,” which is inferred from the combination of line index analyses of elliptical galaxies, amounts to ~ 10 Gyr. Schweizer & Seitzer (1992) found that in merger remnants with morphologically fine structures, the last merging epoch, which corresponds to elliptical galaxy formation, ranges from 4.6 to 8.0 Gyr ago. These observed spreads in “apparent mean age” seem to be inconsistent with the aforementioned coevality of elliptical galaxy formation expected mainly from the redshift evolution of the C-M relation.

The purpose of this paper is to give a plausible answer to the above apparent inconsistency in the epoch of elliptical galaxy formation. We adopt the merger scenario of elliptical galaxy formation (e.g., Toomre & Toomre 1972) and thereby investigate to what degree the difference in the epoch of major galaxy merging (i.e., the epoch of elliptical galaxy formation) can be allowed to preserve the observed small scatter of the C-M relation of cluster ellipticals (~0.05 mag) at z = 0 (Bower et al. 1992), 0.55 (Ellis et al. 1997), and 0.895 (Stanford et al. 1998). We find that, owing to the age-metallicity conspiracy proposed by Worthey et al. (1996), the observed small scatter in the C-M relation can be reproduced reasonably well, even in star-forming galaxy mergers with the widely spread merging epoch. Accordingly, this result reinforces the recent results of Kauffmann & Charlot (1998), in which the tight C-M relation can be successfully reproduced by a merger scenario of elliptical galaxy formation based on a hierarchical clustering scenario. Furthermore, this result implies that the previously suggested interpretation of the tightness of the C-M relation at low and intermediate redshift (z < 1) is not unique and...
Fig. 1.—Time evolution of the fractional mass of stars for Sa models with different $0.3 \leq z_{\text{merge}} \leq 3.0$. For comparison, the results of an isolated Sa model are given by a dotted line. Solid lines, short-dashed lines, and long-dashed lines represent Sa models with $1.0 < z_{\text{merge}} \leq 3.0$, $0.5 < z_{\text{merge}} \leq 1.0$, and $0.0 < z_{\text{merge}} \leq 0.5$, respectively.

thus that the formation epoch of elliptical galaxies can be more widely spread than the classical passive evolution picture predicts. Thus, the above apparent inconsistency in the interpretation of the C-M relation can be due primarily to the fact that previous studies claiming the coevality of elliptical galaxy formation did not so extensively explore the possible variety in star formation histories of elliptical galaxies.

2. MODEL

We adopt a one-zone chemophotometric evolution model of elliptical galaxies formed by major disk-disk galaxy mergers with the merging epoch widely spread, and we thereby investigate to what degree the spread of the merging epoch can be allowed for keeping the observed tightness of the C-M relation in cluster ellipticals at a given redshift. The remarkable differences in model assumptions between the present merger model and previous ones based on a classical, initial-burst picture of elliptical galaxy formation (e.g., Bower et al. 1992; Kodama & Arimoto 1997) are the following: First, the present model allows continuous and moderate star formation of galaxies before the onset of the secondary starburst associated with the elliptical galaxy formation via merger events. Second, in the present model, the epoch of the formation of elliptical galaxies (more accurately, the formation of elliptical morphology) is assumed to be the epoch of the secondary starbursts in mergers. These two differences generate qualitatively different results in the evolution of the C-M relation between the present study and the previous ones based on a classical, initial-burst picture of elliptical galaxy formation. The elliptical galaxy formation with the secondary starburst has been investigated by Kauffmann (1996) in the context of the galaxy formation in the cold dark matter universe and by Charlot & Silk (1994) in the context of the origin of Butcher-Oemler galaxies. We follow the chemical evolution of galaxies by using the model described in Matteucci & Tornambè (1987), which includes metal-enrichment processes of type Ia and II supernovae (SNIa and SNII). We adopt the Salpeter initial mass function (IMF), $\phi(m) \propto m^{-1.35}$, with upper mass limit $M_{\text{up}} = 120 M_\odot$ and lower mass limit $M_{\text{low}} = 0.1 M_\odot$ for most of the models. We also investigate the models with the slope of the IMF, $x$, equal to 1.10, in order to confirm that the results derived for models with the Salpeter IMF can be generalized. The fraction of close binary stars (represented by the $\alpha$ parameter in Matteucci & Tornambè 1987), which controls the frequency of SNIa relative to SNII, is assumed to be 0.1. To calculate the ejected mass of gas and heavy elements, we use stellar yields derived by Woosley & Weaver (1995) for SNII; by Nomoto, Thielemann, & Yokoi (1984) for SNIa; and by Bressan et al. (1993) and Magris & Bruzual (1993) for low- and intermediate-mass stars. We calculate photometric properties of galaxies as follows: The monochromatic flux of a galaxy with age $T$, $F_j(T)$, is described as

$$F_j(T) = \int_0^T F_{\text{SSP},j}(Z, T - t)\psi(t)dt,$$

where $F_{\text{SSP},j}(Z, T - t)$ is a monochromatic flux of a single stellar population (SSP) of age $T - t$ and metallicity $Z$, and $\psi(t)$ is the time-dependent star formation rate described later. In this paper, we use the spectral library GISSEL96, which is the latest version of Bruzual & Charlot (1993).

The star formation history of galaxy mergers is characterized by three epochs. The first is $z_{\text{form}}$, in redshift at which merger progenitor disk galaxies form and begin to consume initial interstellar gas by star formation at a moderate rate, and the value of $z_{\text{form}}$ is fixed at 5.0 for all models. The second is $z_{\text{merge}}$, at which two disks merge with each other and morphological transformation of galaxies (to ellipticals) and the accompanying starbursts happen. The third is $z_{\text{end}}$, at which star formation ceases; it is defined as the epoch at which stellar mass fraction becomes 0.9 in our models. Star formation rates of galaxy mergers during $z_{\text{form}} \leq z < z_{\text{merge}}$, $z_{\text{merge}} \leq z < z_{\text{end}}$, and $z_{\text{end}} \leq z$ are described below.

Throughout the evolution of galaxy mergers, the star formation rate is assumed to be proportional to the gas mass fraction ($f_g$) of galaxies:

$$\psi(t) = kf_g,$$

where $k$ is a parameter that controls the star formation rate. This parameter $k$ is given as follows:

$$k = \begin{cases} k_{\text{disk}}, & z_{\text{form}} \leq z < z_{\text{merge}}, \\ k_{\text{merge}}, & z_{\text{merge}} \leq z < z_{\text{end}}, \\ 0, & z_{\text{end}} \leq z. \end{cases}$$

The parameter values of $k_{\text{disk}}$ investigated in the present study are 0.325 in units of Gyr$^{-1}$, which corresponds to an admittedly plausible star formation rate for Sa disks (e.g., Arimoto, Yoshii, & Takahara 1992), 0.225 for Sb disks, and 0.056 for Sc disks. These values of $k_{\text{disk}}$ are consistent with the timescale of star formation estimated from observations of disk galaxies (e.g., Kennicutt, Tamblyn, & Congdon 1994). The value of $k_{\text{merge}}$ is fixed at 10.0, which is about 2 orders of magnitude larger than that typical values of $k_{\text{disk}}$ adopted in the present study. The strength of the starburst $k_{\text{merge}}$ in the present model is consistent with observational results on starbursts in gas-rich galaxy mergers (e.g., Sanders et al. 1988).
By using the above chemophotometric model, we investigate the evolution of the rest-frame $U-V$ color in galaxy mergers with $z_{\text{merge}} = 0.3, 0.5, 0.7, 0.9, 1.1, 1.3, 1.5, 1.6, 2.0, \text{ and } 3.0$ for each Sa, Sb, and Sc model and $z_{\text{merge}} = 0.1$ for Sb and Sc models. The reason why we do not investigate the merger with $z_{\text{merge}} = 0.1$ for Sa model is that the fractional mass of stars in the Sa disk is larger than 0.9 at $z = 0.1$ (see Fig. 1, dotted line). For comparison, we also investigate the chemophotometric evolution of an isolated disk for Sa, Sb, and Sc models. In the following, the cosmological parameters $H_0$ and $q_0$ are set to be 65 km s$^{-1}$ Mpc$^{-1}$ and 0.05, respectively, which means that the corresponding present age of the universe is 13.8 Gyr.

3. RESULTS

Figure 1 shows the time evolution of the fractional mass of stars for 10 models with $0.3 \leq z_{\text{merge}} \leq 3.0$ in the Sa model. As shown in Figure 1, star formation proceeds at a moderate rate before galaxy merging, then rapidly after the onset of the secondary starbursts of galaxy merging. This continuous star formation before elliptical galaxy formation (before galaxy merging) simply characterizes the star formation history of the present model. Figure 2 describes the time evolution of the rest-frame $U-V$ color for the 10 models (hereafter the $U-V$ color means the rest-frame $U-V$ color). From this figure, we can derive the following two qualitative results: First, the $U-V$ color becomes red within $\sim 2$ Gyr after the secondary starburst of galaxy mergers for each model. The $U-V$ color difference among these models is only $\sim 0.04$ mag. Second, the epoch at which the $U-V$ color becomes red depends on $z_{\text{merge}}$ in such a way that the epoch is earlier for models with larger $z_{\text{merge}}$. These two qualitative results are found to be true for Sb and Sc models. Accordingly, it is clear that, for a given star formation history of merger progenitor galaxies (for Sa, Sb, and Sc models), $z_{\text{merge}}$ is required to be within a certain range for the observed tightness of the $C-M$ relation at a given redshift. We mention that the derived $U-V$ color in our merger models is bluer than that of cluster ellipticals in Bower et al. (1992), owing to the smaller metallicity. The mass-weighted (luminosity-weighted) mean stellar metallicity of our models is about one-half (one-third) of solar metallicity, although approximately solar metallicity is needed to reproduce the observed color. This is essentially because we adopt the Salpeter IMF with $M_{\text{low}} = 0.1 M_\odot$ and the one-zone chemical evolution. If we adopt a shallower slope of the IMF (e.g., $x = 1.10$) or larger values of $M_{\text{low}}$ (e.g., $M_{\text{low}} = 0.6 M_\odot$) and nevertheless use the GISSEL SSP (it is not reasonable to use the GISSEL SSP, since here we do not assume the IMF adopted in GISSEL96), we can reproduce redder color typical for the cluster ellipticals in Bower et al. (1992). However, since the main purpose of the present study is not to successfully reproduce the absolute magnitude of global colors typical for cluster ellipticals, but to explore the origin of the tight $C-M$ relation, it is not unreasonable to discuss the origin of the tight $C-M$ relation by using the merger models with rather bluer colors. In the last paragraph of this section, we will show the $U-V$ color evolution of models with a shallower IMF ($x = 1.10$) and confirm that the tight $C-M$ relation is achieved independent of the adopted IMF.

Figure 3 shows the time evolution of the $U-V$ color for models with $z_{\text{merge}} = 3.0, 1.6, 1.3, 0.9, 0.3$, and 0.1. Here, we introduce the minimum $z_{\text{merge}}$ required to keep the small scatter of the $C-M$ relation at a given redshift ($z = 0.0, 0.55, \text{ and } 0.895$) for Sa, Sb, and Sc models. If the $z_{\text{merge}}$ of galaxy mergers is larger than the minimum value, the color scatter of galaxy mergers at a given redshift can be smaller than the observed one. The minimum $z_{\text{merge}}$ is, for example, 1.3 (1.3, 1.6) at $z = 0.895, 0.9 (0.9, 1.1)$ at $z = 0.55$, and 0.3 (0.1, 0.3) at $z = 0.0$ in Sa (Sb, Sc) models. Accordingly, Figure 3 means, for example, that for Sa models with $1.3 < z_{\text{merge}} < 3.0$, the dispersion of the $U-V$ color is well within the observed dispersion in cluster ellipticals at $z = 0.895 (\sim 0.05 \text{ mag})$. Furthermore, this figure shows that for keeping the tightness of the $C-M$ relation at higher redshift, $z_{\text{merge}}$ should be larger. The gas mass fraction that has already been converted into stars at $z \sim 3.0$ are 0.26 for Sa model. This result suggests that a substantial fraction of initial gas has not necessarily been converted into stars already in higher redshift, which is conventionally required in the passive evolution picture. As shown in Figure 3, these results are true for Sb and Sc models, although the range of the required $z_{\text{merge}}$ depends on the star formation histories of Sa, Sb, and Sc models in such a way that the required $z_{\text{merge}}$ is appreciably larger for Sc models. For example, the minimum $z_{\text{merge}}$ is 1.6 at $z = 0.895$ in Sc models, although it is 1.3 in both Sa and Sb models. Thus, the scatter of the $U-V$ color in galaxy mergers with a wide spread in the merging epoch is found to be rather small, which suggests that the tight $C-M$ relation at low and intermediate redshift does not necessarily require the coevality of elliptical galaxies or their formation at high redshift.

In order to clarify the reason for the small $U-V$ color scatter derived in galaxy mergers with the widely spread

![Fig. 2.—Time evolution of the $U-V$ color for Sa models with different $0.3 \leq z_{\text{merge}} \leq 3.0$. For comparison, the results of an isolated Sa model are given by a dotted line. Solid lines, short-dashed lines, and long-dashed lines represent Sa models with $1.0 < z_{\text{merge}} \leq 3.0, 0.5 < z_{\text{merge}} \leq 1.0,$ and $0.0 < z_{\text{merge}} \leq 0.5$, respectively. The transient decrease of the color represents the epoch of secondary starbursts for each merger model. Note that the $U-V$ color becomes red at the earlier epoch of galaxy evolution for models with larger $z_{\text{merge}}$. We should emphasize here that, because of the adopted Salpeter IMF with $M_{\text{low}} = 0.1 M_\odot$ (which is the only IMF available for photometric and spectroscopic calculation in the GISSEL SSP), the derived color is rather blue compared with that of cluster ellipticals in Bower et al. (1992). ]
ages and metallicities, we can observe the stellar populations characterizing the photometric properties of galaxy mergers (e.g., Faber et al. 1995). Because of the smaller metallicity, the values of [MgFe] in our models are smaller than the observed values (e.g., Faber et al. 1995; Kuntschner & Davies 1997). We note again that this discrepancy might be removed by adopting an IMF with a larger stellar yield or relaxing the one-zone chemical evolution. As shown in each panel of Figure 4, the characteristic metallicity of the galaxy merger with the younger characteristic age (the lower $z_{\text{merge}}$) is larger than that with the older characteristic age (the higher $z_{\text{merge}}$). This is because in the later starburst of galaxy mergers, younger stellar populations are formed preferentially from more metal-enriched interstellar gas. Worthey et al. (1996) have already pointed out that if younger stellar population are more metal-enriched (with Worthey's law of $\Delta$ log age/$\Delta$ log metallicity $= -\frac{1}{2}$), the C-M relation can be kept tight. Accordingly, the small scatter in the present merger model is closely associated with Worthey's "age-metallicity conspiracy." To clarify the effect of metallicity on the small scatter of the $U-V$ color, we calculate the time evolution of the $U-V$ color for "single metallicity" models with $0.3 \leq z_{\text{merge}} \leq 3.0$ in the Sa model. Here "single metallicity" model means a model in which chemical evolution is not solved, but the star formation history is exactly the same as that of a model solving chemical evolution fully. In this model, all stellar populations with different ages in a galaxy have the same metallicity. In this calculation, we set $Z$ to be 0.006, which is a typical value in our models. As shown in Figure 5, the scatter of the $U-V$ color in the "single metallicity" model is appreciably larger than that in the Sa models, described in Figure 2. We also note that the scatter becomes small more slowly in the "single metallicity" model than in models including chemical evolution. This comparative experiment accordingly confirms that the "age-metallicity conspiracy" plays a vital role in keeping the C-M relation tight (compare Figs. 2 and 5). Furthermore, this result provides a qualitative explanation for the reason why the present study allows us to spread the formation epoch of elliptical galaxies (more accurately, the epoch of the secondary starburst), whereas the previous observational ones (Bower et al. 1992; Aragón-Salamanca et al. 1993) do not. This is principally because, in the previous studies, neither variety of star formation in elliptical galaxies nor the effects of chemical enrichment on spectroscopic evolution of galaxies are so fully investigated. Thus it is demonstrated that, owing to the age-metallicity conspiracy, the scatter of the C-M relation observed in cluster ellipticals at low and intermediate redshift can be kept small, even if elliptical galaxies are formed by disk-disk galaxy mergers with the widely spread merging epoch.

Furthermore, Figure 4 shows an interesting behavior in the redshift evolution of the line index on the log [MgFe]--log H$\beta$ diagram. As shown in Figure 4 for the Sa model, the apparent age spread on the log [MgFe]--log H$\beta$ diagram is smaller than the age spread of the merging epoch (the epoch of elliptical galaxy formation) and becomes smaller as the age of burst populations becomes larger. For example, although the time spread between $z_{\text{merge}} = 3$ and $z_{\text{merge}} = 0.3$ is 7.6 Gyr, the apparent age spread in the diagnostic diagram is less than 2 Gyr at $z = 0$. This result suggests that even if the epoch of major galaxy merging is rather spread, the age spread inferred from the log [MgFe]--log H$\beta$...
Diagram of log Hβ vs. log [MgFe] for Sa models with $z_{\text{merge}} = 3.0, 1.3, 0.9, \text{and } 0.3$ (upper panel); for Sb models with $z_{\text{merge}} = 3.0, 1.3, 0.9, \text{and } 0.1$ (middle panel); and for Sc models with $z_{\text{merge}} = 3.0, 1.3, \text{and } 0.3$ (lower panel). In each panel, values of log Hβ and log [MgFe] at $z = 0.00, 0.55, \text{and } 0.895$ are given by filled circles for models keeping the tight C-M relation at $z = 0.895$ (left), 0.55 (center), and 0.0 (right), respectively. For clarity, the results at the same redshift are connected by long-dashed lines. For comparison, the results expected from the SSP of the GISSEL96 are also given by dotted lines with open circles in the same diagram for different ages (3, 7, 11, and 15 Gyr) and metallicities ($Z = 0.004, 0.008, 0.02$). Numbers plotted near open circles represent the age of the SSP in units of Gyr. This diagram can represent the luminosity-weighted mean age and metallicity of stellar populations in galaxies. Note that galaxy mergers dominated by younger stellar populations are more metal-enriched. This result clearly demonstrates that, owing to Worthey's (1996) age-metallicity conspiracy, the C-M relation can be kept tight even in galaxy mergers with a widely different merging epoch.

Lastly, we present the results of models with the slope of the IMF ($x$) equal to 1.10 in order to confirm that the above numerical results for models with smaller stellar yields can be applied to models with larger stellar yields, which can reproduce the observed color of elliptical galaxies with a observational results concerning the log [MgFe]–log Hβ diagram for cluster ellipticals at low redshift (Worthey et al. 1996; Kuntschner & Davies 1997; Mehlert et al. 1998). Kuntschner & Davies (1997) found that in the Fornax Cluster, the age spread inferred from the [MgFe]–Hβ diagram and the C4648–Hα diagram is considerably small among elliptical galaxies. Mehlert et al. (1998) also found that in the Coma Cluster, the age spread among massive elliptical galaxies is rather small. These two results are different from the results of Worthey et al. (1996) and Trager (1997), that both age and metallicity in elliptical galaxies can be rather spread in their samples, which implies that the star formation history of elliptical galaxies is different from cluster to cluster and from environment to environment. Assuming that elliptical galaxies are formed by galaxy mergers, the result in Figure 4 can give the following explanation for the apparent difference in age distribution of galaxies between the above studies: The smaller age scatter inferred from log [MgFe]–log Hβ diagram for clusters of galaxies in Kuntschner & Davies (1997) and Mehlert et al. (1998) reflects the fact that the mean epoch of the last starburst associated with galaxy merging is relatively earlier, whereas the larger scatter in Worthey et al. (1996) reflects the fact that the epoch of the last starburst in elliptical galaxies is more widely spread, owing to the larger spread in the epoch of galaxy merging. Future observational studies will assess the validity of this interpretation about the diversity in the properties of log [MgFe]–log Hβ diagram for elliptical galaxies.
larger metallicity. In this calculation, we also use the GISSEL96, although the IMF of these models is different from that adopted in GISSEL96. Figure 6 clearly demonstrates that even for models with larger stellar yield, the diversity in the epoch of galaxy merging does not introduce large scatter in the $U - V$ color, which implies that the aforementioned age-metallicity conspiracy does not depend on the stellar yield (or, as a result, the stellar metallicity) of galaxies. Assuming that there is a certain relation between the galactic luminosity and the mean stellar metallicity, this result implies that the tightness of global color in a given luminosity in the $C$-$M$ relation can be kept in elliptical galaxies formed by galaxy merging. This accordingly implies that even the slope of the $C$-$M$ relation can be kept after the number increase of elliptical galaxies formed by galaxy merging in the $C$-$M$ relation. Merger progenitor disk galaxies are observationally revealed to have a mass-metallicity relation (Zaritsky, Kennicutt, & Huchra 1994) and a color-magnitude relation similar to those of elliptical galaxies (Peletier & de Grijs 1997). The present study, together with these two observational results, thus predicts that even if a sizable fraction of elliptical galaxies are formed by galaxy mergers, the slope of the $C$-$M$ relation does not evolve so significantly with redshift.

4. DISCUSSION AND CONCLUSIONS

The present study predicts that even if the epoch of major galaxy merging (i.e., the epoch of elliptical galaxy formation) is rather spread, both the tightness and the slope of the $C$-$M$ relation can be kept, owing to the age-metallicity conspiracy originally proposed by Worthey et al. (1996). This result accordingly provides a heuristic explanation for the result of Kauffmann & Charlot (1998), in which the tight $C$-$M$ relation has already been reproduced in the merger scenario of elliptical galaxy formation, based on the hierarchical clustering model. The conclusions derived in the present study, however, seem to be inconsistent with those derived in previous ones on the redshift evolution of the slope, zero point, and tightness of the $C$-$M$ relation of elliptical galaxies (Bower et al. 1992; Aragón-Salamanca et al. 1993; Kodama & Arimoto 1997). In particular, the present numerical results seem to disagree with those of Kodama & Arimoto (1997) and Kodama et al. (1998; see also Gladders et al. 1998), who claim that the considerably less significant evolution of the slope of the $C$-$M$ relation rejects the age spread larger than 1 Gyr among elliptical galaxies. The apparent disagreement between the present study and the previous ones (e.g., Kodama & Arimoto 1997; Kodama et al. 1998) is due essentially to the fact that the previous studies have inevitably overinterpreted the redshift evolution of the $C$-$M$ relation, owing to the ad hoc assumption adopted in the previous studies. Although the previous studies are considerably sensible and valuable, it is important to point out the ad hoc assumptions adopted in the previous studies and thereby clarify the reason why the present conclusions are not consistent with those derived by the previous studies of Kodama & Arimoto (1997) and Kodama et al. (1998). The following are the three ad hoc assumptions that inevitably lead the previous studies to draw the strong and general conclusion that formation of elliptical galaxies (especially in the cores of clusters) are as a whole coeval and occur at high redshift: First, elliptical galaxies are formed by only one initial starburst. Owing to this assumption, the time evolution of global colors of elliptical galaxies depends exclusively on the epoch of the initial burst of star formation (i.e., the epoch of elliptical galaxy formation in the previous study). As a result of this, the age difference between elliptical galaxies (i.e., the difference of the epoch of elliptical galaxy formation in the previous studies) can be more clearly reflected in the redshift evolution of the slope of the $C$-$M$ relation in the previous studies. Accordingly, the observed, less significant evolution of the slope of the $C$-$M$ relation is more likely to be interpreted as evidence that supports the coevality of elliptical galaxy formation. It is certainly reasonable to claim that the observed evolution of the $C$-$M$ relation rejects the "pure age" sequence model, which demands that less luminous ellipticals have a younger age. However, it does not seem to be so reasonable to draw the strong and general conclusion that elliptical galaxies are formed at $z > 2$ only from the redshift evolution of the $C$-$M$ relation. Considering the first ad hoc assumption in the previous studies, what is the more accurate and plausible interpretation of the observed evolution of the $C$-$M$ relation is simply that the formation of stellar populations in some elliptical galaxies in the cores of some clusters (not the formation of galaxies with structural and morphological properties similar to those of ellipticals) can be coeval and occur at higher redshift ($z > 2$). Second, an elliptical galaxy in a cluster of galaxies at higher redshift is a precursor of an elliptical galaxy in a cluster at lower redshift. Third, a cluster of galaxies observed at higher redshift is a precursor of a cluster of galaxies at lower one. These two ad hoc assumptions actually enable us to discuss the origin of elliptical galaxies in a more general way and thus lead us to draw more general conclusions on the formation epoch of elliptical galaxies. However, since there is no observational evidence that can provide the firm physical basis for the above assumptions (at least for now), it is questionable to give any general conclusions on the
coevality of elliptical galaxy formation. Thus, these three assumptions adopted in the previous studies inevitably lead them to provide the strong and general conclusion that formation of elliptical galaxies are coeval and occur at higher redshift.

The present study, on the other hand, does not adopt the above ad hoc assumptions; rather, it relaxes these assumptions. Furthermore, the present study allows instead both continuous and moderate star formation (not strong initial starburst) and the secondary starburst associated with galaxy merging, and it assumes that the epoch of morphological transformation (into ellipticals) does not necessarily coincide with the epoch of galaxy formation (i.e., the epoch when the star formation begins). Consequently, the evolution of the C-M relation in the present study does not depend so strongly on the difference in the formation epoch between elliptical galaxies (i.e., the epoch of major galaxy merging with the secondary starburst). As a result of this, the present merger model predicts that even if the formation epoch of elliptical galaxies (i.e., the epoch of galaxy merging) are rather spread, both the slope and tightness of the C-M relation can be kept. Thus, the essential reason for the aforementioned apparent disagreement on the coevality of elliptical galaxy formation is that the present study does not adopt the above three ad hoc assumptions, whereas the previous studies do. The interpretation of the redshift evolution of the C-M relation in each model can depend strongly on the assumptions adopted by each model. It is safe for us to say that it is not clear, at least now, which of the two different conclusions on the coevality of elliptical galaxy formation is more plausible and reasonable. However, considering the three ad hoc assumptions adopted in the previous studies, what is the more reasonable interpretation on the redshift evolution of the C-M slope is that only stellar populations (not elliptical morphology) in some ellipticals located in the cores of some clusters of galaxies are formed at higher redshift. We should not draw any general conclusions from the redshift evolution of the slope of the C-M relation.

Environmental differences of stellar populations (in particular, the existence of an intermediate-age population) in early-type galaxies have already been indicated by a number of observational studies (e.g., Bower et al. 1990; Rose et al. 1994; Mobasher & James 1996). On the other hand, the tightness and the slope of the C-M relation of early-type galaxies are observationally revealed not to depend so strongly on galaxy environments. These two apparently inconsistent observational results on spectro-photometric properties of elliptical galaxies have given rise to the following question: Why does the C-M relation of early-type galaxies not depend strongly on galaxy environments (e.g., between rich clusters and poor ones), although stellar populations and star formation histories in early-type galaxies probably depend on galaxy environments? To give a plausible answer to this question seems to be important, because the above, apparently inconsistent observational results give us valuable information both on the environmental difference in the details of the physical processes of elliptical galaxy formation and on a certain mechanism for the tight C-M relation. However, no extensive theoretical studies have yet addressed the above important question. The present study has shown that the age-metallcity conspiracy, which is achieved by younger and more metal-enriched stellar populations created in the secondary starburst of galaxy mergers, allows both the apparent age spread of elliptical galaxies and the tightness of the C-M relation. This result seems to provide a clue to the above question. Since the real question concerning the tight C-M relation is not to determine the typical epoch of elliptical galaxy formation but to give a convincing explanation for the reason why the possible diversity in star formation histories of elliptical galaxies can allow the tight C-M relation, more extensive theoretical studies—including a greater variety of star formation histories of elliptical galaxies and their likely dependence on galaxy environments—are certainly valuable for a deeper understanding of the origin of the tight C-M relation.

The present numerical results are consistent with recent observational results, which suggest that coeval elliptical galaxy formation with an initial starburst at higher redshift ($z > 2.0$) is not promising. Kauffmann, Charlot, & White (1996) argued that only about one-third of bright E/S0 galaxies in the sample of Canada-France Redshift Survey were already in the passive evolution phase at $z = 1.0$. Franceschini et al. (1998) found a remarkable absence of early-type galaxies at $z > 1.3$ in the K-band-selected sample of early-type galaxies in the Hubble Deep Field (HDF), which suggests either that early-type galaxies are formed by galaxy merging with less prominent star formation or that dust-polluted interstellar gas obscures forming elliptical galaxies until $z = 1.3$. Zepf (1997) demonstrated that a strong deficit of galaxies with extremely red colors in the HDF means that the formation epoch of typical elliptical galaxies is $z < 5.0$. Sample galaxies in these studies are selected from field ellipticals, which possibly have star formation histories different from those of cluster ellipticals. Accordingly, it might not be plausible to derive strong conclusions on the formation epoch of ellipticals. However, these observational results together with the present results seem to support the merger scenario, which can naturally predict that the epoch of elliptical galaxy formation is rather extended, ranging from high to moderate redshift.

Thus we have succeeded in pointing out that even if the epoch of elliptical galaxy formation (i.e., the epoch of major disk-disk galaxy merging, in this study) is rather widely spread, the tightness of the C-M relation at low and intermediate redshift can be kept reasonably well. This result suggests that the coevality of elliptical galaxy formation, which has been conventionally believed in the classical, passive evolution picture, is not a unique interpretation for the small scatter of the C-M relation. Furthermore, this implies that only the tightness of the C-M relation at a given redshift does not necessarily put strong constraints on the formation epoch of elliptical galaxies. Worthey et al. (1996) have already pointed out that the age-metallcity conspiracy can keep both the tightness of the fundamental plane and that of the C-M relation in elliptical galaxies. The present numerical study, which differs from Worthey’s single stellar population analysis, has confirmed that the proposed age-metallcity conspiracy can actually operate to keep convincingly the tightness of the C-M relation of ellipticals formed by disk-disk galaxy mergers. The present chemophotometric evolution model is, however, not so elaborated and realistic, in that this model neither includes continuous gas accretion/merging expected from a specific cosmology (e.g., Baugh, Cole, & Frenk 1996; Kauffmann & Charlot 1998) nor considers important dynamical effects of galaxy merging on chemical and photometric evolution of
galaxies (Bekki & Shioya 1998). Accordingly, it is the aim of our future study to confirm that the results derived in the present preliminary study can hold, even for more sophisticated and realistic merger models. Furthermore, we should check whether the observed redshift evolution of other fundamental relations—such as the $M_g-\sigma$ relation (Ziegler & Bender 1997), the fundamental plane (van Dokkum & Franx 1996), and the abundance ratio of $\mathrm{[Mg/Fe]}$—can also be reproduced self-consistently by our future merger model.

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