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 considerably abundant in interstellar medium by performing numerical simulations designed to solve both the dynamical and chemical evolution in a self-consistent manner. We particularly consider that the star formation history of galaxy mergers is a crucial determinant for the nature of stellar populations of merger remnants, and therefore 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 time-scale to the time-scale of gas consumption by star formation, is the most important determinant for a number of fundamental characteristics of stellar populations of merger remnants. Main results obtained in this study are the following five. (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 component. This result demonstrates that the origin of the color-magnitude relation of elliptical galaxies can be closely associated with the details of merging dynamics which depends on the rapidity of star formation in galaxy mergers. (2) Negative metallicity gradient fitted reasonably well by power-low can be reproduced by dissipative galaxy mergers with star formation. The magnitude of metallicity gradient is larger for an elliptical galaxy formed by galaxy merging with less rapid star formation. (3) Absolute magnitude of metallicity gradient correlates with that of age gradient in galaxy mergers in the sence that a merger remnant with steeper negative metallicity gradient is more likely to show steeper age gradient. (4) The outer part of stellar populations is both older and less metal-enriched than nuclei in an elliptical galaxy formed by galaxy merging with less rapid star formation. Moreover, the metallicity of the outer part of gaseous component for some models with less rapid star formation is appreciably smaller than that of stellar one. This result implies that the origin of metal-poor hot gaseous X-ray halo in real elliptical galaxies can be essentially ascribed to the dynamics of dissipative galaxy merging. (5) Irrespectively of the rapidity of star formation, the epoch of galaxy merging affects both the mean stellar metallicity and 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 younger stars in the later 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 is furthermore determined by the rapidity of star formation of galaxy mergers. In particular, tidal stripping of interstellar gas and total amount of gaseous dissipation during galaxy merging are demonstrated to play a vital role in determining a number of chemical properties of merger remnants. Based upon these results, we adopt a specific assumption of the luminosity dependence of the 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– interaction – galaxies: structure

1. Introduction

Elliptical galaxies have been generally considered to be old, coeval and homogeneous systems passively evolving after the 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 relatively smaller redshift evolution of 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 great variety of star formation history between elliptical galaxies, such as the epoch of major star formation, 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 that elliptical galaxies show diversity in star formation history and nevertheless can actually keep the tightness of the color-magnitude relation is considered to be quite mysterious and thus to provide any theoretical models with a valuable insight on the elliptical galaxy formation. Such kind of mysterious nature observed in elliptical galaxies is demonstrated to hold equally for the dynamical and kinematical properties of elliptical galaxies. For example, considerably small thickness of the fundamental plane of elliptical galaxies implies a rather smaller range of admitted dynamical state of the galaxies (Djorgovski & Davis 1987; Dressler et al. 1987 ; Djorgovski, Pahre, & de Carvalho 1996) whereas the morphological dichotomy between boxy-disky elliptical galaxies (Kormendy & Bender 1996) and the projected density profile systematically departing from de Vaucouleurs $R^{1/4}$ law (Caon, Capaccioli, & D'Onofrio 1993) show a great variety of major orbit families consisting the galaxies. 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 dynamical and kinematical ones can be reproduced successfully by a specific model of galaxy formation in a reasonably self-consistent manner. The previous theoretical models addressing this important issue on elliptical galaxy formation are divided basically into two categories: The dissipative galactic collapse model (e.g., Larson 1976; Carlberg 1984) and the galaxy merger model (e.g., Toomre & Toomre 1972). As is 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 along the dissipative collapse scenario, especially in the context of the nature of stellar populations (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 the phase space density (Ostriker 1980; Carlberg 1986) and kinematical misalignment (Franx, Illingworth, & de Zeeuw 1991; Barnes 1992), by invoking the inclusion of bulge component, gaseous dissipation, and multiplicity of galaxy merging (Hernquist, Spergel, & Heyl 1993; Weil & Hernquist 1996; Barnes & Hernquist 1996). Although it would be safe to say that the galaxy merging between two late-type spirals is one of the most promising candidates explaining more clearly the origin of elliptical galaxies at least in the context of the *dynamical and kinematical properties*, however, there still remain a number of unresolved and apparently serious problems concerning the merger model (e.g., van den Bergh 1995). One of the most crucial problems among these is on 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 so well even by the violent relaxation during galaxy merging and consequently the metallicity gradient of progenitor disks is not so drastically washed out. The metallicity gradient of merger remnant is furthermore found not to be fitted by power law observed in elliptical galaxies (Mihos & Hernquist 1994). Schweizer & Seitzer (1992) discussed whether or not the bluer integrated UBV color of elliptical galaxies with morphologically fine structure can be explained by secondary starburst induced by major disk-disk galaxy mergers. Kauffmann & Charlot (1997) construct a semi-analytic model of elliptical galaxy formation, which is based upon the hierarchical clustering in CDM universe and includes rather simple chemical enrichment process, and thereby demonstrate that the origin of 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 for the merger model to investigate more throughly the fundamental chemical and photometric properties of merger remnants, including the origin of color-magnitude relation (Faber 1973; Visvanathan & Sandage 1977), age and metallicity gradient (Peletier et al. 1990; Davies et al 1991), $\mathrm{Mg}_2 - \sigma$ relation (Burstein et al. 1988), age-metal-conspiracy in stellar populations (Faber et al. 1995; Worthey et al. 1996), luminosity dependence of the line ratio [Mg/Fe] (Worthey et al. 1992), 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 glowing number of observational results have been accumulated which suggest the relatively earlier formation of elliptical galaxies. Tightness of the color-magnitude relation in the cluster of galaxies (Bower et al. 1992, Ellis et al 1996), relatively smaller 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 2 in redshift. Furthermore, as is suggested by Kormendy & Sanders (1992), the fact that no galaxy in the K-band survey of Cowie et al. (1994) shows the global color resembling that of the Arp 220, which is considered to be ongoing mergers and forming ellipticals, implies that the formation epoch of elliptical galaxies should be earlier than 1.0 in redshift. Silva & Bothun (1997) revealed that the fraction of mass of stellar populations with intermediate age to total mass in elliptical galaxies with morphologically fine structure is less than 15 percent. 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 precursor disks of galaxy mergers may be extremely abundant in interstellar medium compared with the present spirals. Recent high quality imaging using *Hubble Space Telescope* (*HST*) has revealed that a larger number of galaxies at faint magnitude are interacting/merging galaxies (e.g., van den Bergh et al. 1996), indicating furthermore that the potential candidate for elliptical galaxies formed by galaxy merging are ubiquitous in higher redshift universe. Hence it is quite reasonable and essential to study the nature of stellar populations of higher redshift galaxy mergers between disk galaxies with the gas mass fraction larger than 0.2, which is a typical value of the present late-type spirals, and thereby to confirm whether or not elliptical galaxies can be formed *actually* by galaxy merging.

The purpose of this paper is to explore the nature of the stellar populations of a gas-rich disk merger which is considered to be occurred the 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 merging. 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 galaxy mergers in explaining both the chemical, photometric, and spectroscopic properties and dynamical and kinematical ones in real elliptical galaxies. The conclusions of the present study are given in §5.

2. Model

Dynamical evolution of dissipative galaxy mergers with star formation is generally considered to be highly complex principally because only a smaller amount of interstellar gas can drastically change the degree of violent relaxation, the details of redistribution of angular momentum in gaseous and stellar component, and the total amount of mass transfered to the central region of merger remnants (Barnes & Hernquist 1992, 1996). Basically the transfer and mixing of heavy elements ejected from stellar component are controlled by the above dynamical processes of galaxy merging in a considerably complicated way, we accordingly could not be allowed simply 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 dynamical and chemical evolution in a admittedly self-consistent manner. In the present study, dynamical evolution of collisional component (interstellar gas) and collisionless one (dark halo and stars) is solved by a specific N-body method and 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. Firstly we describe the numerical model including the initial conditions of the mergers, the prescriptions of dissipative process, and the model for star formation in §2.1. Secondly we give the method for analyzing the chemical enrichment process during mergers and the photometric properties of the remnants in §2.2. Thirdly, we describe the main points of analysis of the present study in §2.3. Lastly, we give values of each parameter in each model in §2.4.

2.1. Numerical model

2.1.1. Initial conditions

We construct models of galaxy mergers between gas-rich disk galaxies with equal mass by using Fall-Efstathiou model (1980). The total mass and the size of a progenitor disk are $M_{\rm d}$ and $R_{\rm d}$, respectively. From now on, all the mass and length are measured in units of $M_{\rm d}$ and $R_{\rm d}$, respectively, unless specified. Velocity and time are measured in units of $v = (GM_{\rm d}/R_{\rm d})^{1/2}$ and $t_{\rm dyn} = (R_{\rm d}^3/GM_{\rm d})^{1/2}$, respectively, where G is the gravitational constant and assumed to be 1.0 in the present study. If we adopt $M_{\rm d} = 6.0 \times 10^{10}$ $\rm M_{\odot}$ and $R_{\rm d} = 17.5$ kpc as a fiducial value, then $v = 1.21 \times 10^2$ km/s and $t_{\rm dyn} = 1.41 \times 10^8$ yr, respectively. In the present model, the rotation curve becomes nearly flat at 0.35 radius with the maximum rotational velocity $v_{\rm m} = 1.8$ in our units. The corresponding total mass $M_{\rm t}$ and halo mass $M_{\rm h}$ 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 $\exp(R/R_0)$ with scale length

$R_0 = 0.2$ and to $\mathrm{sech}^2(Z/Z_0)$ with scale length $Z_0 = 0.04$ in our units, respectively. The mass density of 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 disk and halo component, the initial radial and azimuthal velocity dispersion are given to disk component according to the epicyclic theory with Toomre's parameter (Binney & Tremaine 1987) $Q = 1.0$. This adopted value for Q parameter is appreciably smaller compared with the value required for stabilizing the initial disk against the non-axisymmetric 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 smaller because of gaseous dissipation in the disk. The vertical velocity dispersion at given radius are set to be 0.5 times as large as the radial velocity dispersion at that point, as is consistent with the observed trend of the Milky Way (e.g., Wielen 1977). As is described above, the present initial disk model does not include any remarkable bulge component, and accordingly corresponds to 'purely' late-type spiral without galactic bulge. Although it is highly possible that galactic bulges greatly affect the chemical evolution of galaxy mergers, we however investigate this issue in our future papers. It could be reasonable to consider that the present initial disk with a considerably larger amount of interstellar gas and without pronounced galactic bulges is one of candidates of precursors of typical elliptical galaxies which are considered to be formed at relatively higher redshift ($z > 2$).

The collisional and dissipative nature of the interstellar medium is modeled by the sticky particle method (Schwarz 1981). It should be emphasized here that this discrete cloud model can at best represent the *real* interstellar medium of galaxies in a schematic way. As is modeled by McKee & Ostriker (1977), the interstellar medium can be considered to be composed mainly of 'hot', 'warm', and 'cool' gas, each of which mutually interacts hydrodynamically in a rather complicated way. Actually, these considerably complicated nature of interstellar medium in disk galaxies would not be so simply modeled by the 'sticky particle' method in which gaseous dissipation is modeled by ad hoc cloud-cloud collision: Any existing numerical method probably could not model the *real* interstellar medium in an admittedly proper way. In the present study, as a compromise, we only try to address some important aspects of hydrodynamical interaction between interstellar medium in disk galaxies and in dissipative mergers. More elaborated numerical modeling for real interstellar medium would be necessary for our further understanding of dynamical evolution in dissipative galaxy mergers. To mimic the galaxy mergers which are occurred at higher redshift and thus very dissipative because of a considerably larger amount of interstellar gas in the progenitor disks, we assume that the fraction of gas mass in a disk is set to be 1.0 initially. Actually, the gas mass fraction in precursor disks of a merger is different between galaxy mergers and depends on the epoch of the merging. Although this difference probably could yield a great variety of chemical and dynamical structures in merger remnants, we do not intend to consider this important difference for simplicity in the present paper and will address in our future paper. The size of the clouds is set to be 3.5×10^{-3} in our units in the present simulations. The radial and tangential restitution coefficient for cloud-cloud collisions are set to be 0.5 and 0.0, respectively. The number of particles of halo and the gaseous component for an above isolated galaxy are 5000 and 10000, respectively.

Numerical simulations of galaxy mergers are divided into two categories in the present study: Pair mergers between two disks with a parabolic encounter, and multiple mergers between five disks. In all of the simulations of pair mergers, the orbit of the two disks is set to be initially in the xy plane and the distance between the center of mass of the two disks, represented by $r_{\rm in}$, is assumed to be the free parameter which controls the epoch of galaxy merging. The pericenter distance, represented by $r_{\rm p}$, is also assumed to be the free parameter which 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 encounter of galaxy merging is parabolic. The spin of each galaxy in a pair merger is specified by two angle θ_i and ϕ_i, where suffix i is used to identify each galaxy. θ_i is the angle between the z axis and the vector of the angular momentum of a disk. ϕ_i is the azimuthal angle measured from x axis to the projection of the angular momentum vector of a disk on to xy plane. The value of each parameter, θ_i, ϕ_i, $r_{\rm p}$ and $r_{\rm in}$ for each model is described later. 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 kinematical energy to the total potential energy in the system is 0.25. The time when the progenitor disks merge completely and reach the dynamical equilibrium is less than 15.0 in our units for most of models and does not depend so strongly on the history of star formation in the present calculations.

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 consumed by star formation for each gas particle in each time step, $\dot{M}_{\rm g}$, is given as:

$$\dot{M}_{\rm g} \propto C_{\rm SF} \times (\rho_{\rm g}/\rho_0)^{\gamma-1.0} \tag{1}$$

where $\rho_{\rm g}$ and ρ_0 are the gas density around each gas particle and the mean gas density at 0.48 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 mass, we convert one gas particle into one stellar one according to the following procedure. First we give each gas particle the probability, $P_{\rm sf}$, that the gas particle is converted into stellar one, by setting the $P_{\rm sf}$ to be proportional to the $\dot{M}_{\rm g}$ in equation (1) estimated for the gas particle. Then we draw the random number to determine whether or not the gas particle is totally converted into one new star. This method of star formation enables us to control the rapidity of star formation without increase of particle number in each simulation thus to maintain the numerical accuracy in each simulation. The $C_{\rm SF}$ in the equation (1) is the parameter that controls the rapidity of gas consumption by star formation: The larger the $C_{\rm SF}$ is, the more rapidly the gas particles are converted to new stellar particles. As a result of this, total amount of gaseous dissipation is also controlled by this parameter $C_{\rm SF}$: The more amount of kinetic energy of gas particles is dissipated away by cloud-cloud collision for the models with smaller $C_{\rm SF}$. This parameter $C_{\rm SF}$ is meant to be proportional to the ratio of dynamical time-scale of the system to the time-scale of gas consumption by star formation. Furthermore the equation (1) states that a larger number of stellar particles are created at the regions where the local gas density become 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 original gas particles. As is 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 wavelength, that is, the Toomre's Q parameter (Kennicutt 1989), for isolated disk galaxies. This is because the threshold criterion, which is derived only for calmly evolving galactic disks, would not so simply be applied to the present merger model, in which the time-scale that the disk can evolve without strong dynamical perturbation is relatively smaller (less than 10 dynamical time 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 interstellar medium driven by supernovae, firstly because such inclusion could prevent us from deducing more clearly the important roles of the rapidity of star formation and secondly because there still remains a great uncertainty concerning the numerical implementation of the 'feedback effects' (Katz 1992; Navarro & White 1993). Accordingly, as is described above, the 'star formation' in this preliminary study only means 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 so that we can only address some important aspects of the roles of star formation in generating chemical and dynamical characteristics of merger remnants. However, we believe that since the main points of the present study are only the relatively 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 our future papers by using more elaborated model for star formation.

All the calculations related to the above dynamical evolution including the dissipative dynamics, star formation, and gravitational interaction between collisionless and collisional component have been carried out on the GRAPE board (Sugimoto et al. 1990) at Astronomical Institute of Tohoku University. The parameter of gravitational softening is set to be fixed at 0.04 in all the simulations. The time integration of the equation of motion is performed by using 2-order leap-flog method. Energy and angular momentum are conserved within 1 percent 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 gradient in elliptical galaxies depend critically on how the metallicity and age of stellar component are distributed in the galaxies. Accordingly, we first analyze the distribution of stellar age and that of stellar metallicity in merger remnant for each model in order to grasp the characteristics of stellar population in merger remnants. In the present study, these age and metallicity distribution are calculated based on the age and metallicity assigned to each stellar particle, as described in detail later. The outline for this calculation is as follows. First we derive the distribution of stellar age and that of stellar metallicity by assigning age and metallicity to stellar particles according as the law of chemical enrichment applied to this study. Next, by using the stellar population synthesis method, we calculate the photometric and spectroscopic properties based on the derived distribution of age and metallicity in merger remnant.

2.2.1. Chemical enrichment

Chemical enrichment through star formation during galaxy merging is assumed to proceed both locally and instantaneously in the present study. The model for analyzing metal enrichment of each gas and stellar particle is as follows. First, as soon as a gas particle is converted into a new stellar one by star formation, we search neighbor gas particles locating within $R_{\rm che}$ from the position of the new stellar particle and then count the number of the neighbor gas particles, $N_{\rm gas}$. This $R_{\rm che}$ is referred to as chemical mixing length in the present paper, and represents the region within which the neighbor gas particles are polluted by metals ejected from the new stellar particle. The value of $R_{\rm che}$ relative to the typical size of a galaxy could be different between galaxies, accordingly the value of $R_{\rm che}$ is considered to be free parameter in the present study. The values of $R_{\rm che}$ examined the 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 half of the gravitational softening length. Next we assign the metallicity of original gas particle to the new stellar particle and increase the metals of the each neighbor gas particle according to the following equation about the chemical enrichment:

$$\Delta M_{\mathrm{Z}} = \{Z_i R_{\mathrm{met}} m_{\mathrm{s}} + (1.0 - R_{\mathrm{met}})(1.0 - Z_i) m_{\mathrm{s}} y_{\mathrm{met}}\}/N_{\mathrm{gas}} \tag{2}$$

where the ΔM_{Z} represents the increase of metal for each gas particle. Z_i, R_{met}, m_{s}, and y_{met} in the above equation represent the metallicity of the new stellar particle (or that of original gas particle), the fraction of gas returned to interstellar medium, the mass of the new star, and the chemical yield, respectively. The value of the R_{met} and that of y_{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 is described later. To verify the accuracy of the above treatment (including numerical code) for 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:

$$\sum_{\mathrm{star}} m_{\mathrm{s}} Z_i + \sum_{\mathrm{gas}} m_{\mathrm{g}} Z_i = y_{\mathrm{met}} \sum_{\mathrm{star}} m_{\mathrm{s}} \tag{3}$$

where m_{g}, m_{s}, 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 ($\sum$) is done for all the gas particles or stellar ones. Strictly speaking, the above equation holds when the value of R_{met} is 0.0. Thus, in testing the validity of the present code of chemical enrichment, we set the value of R_{met} to be 0.0 and then perform a simulation for the test. We confirmed that the above equation is nearly exactly satisfied in our test simulations and furthermore that even if the R_{met} is not 0.0, the difference in the value of total metallicity between the left and right side 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 SED of 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

$$F_\lambda(T) = \sum_{\mathrm{star}} F_{\mathrm{SSP},\lambda}(Z_i, \tau_i) \times m_{\mathrm{s}} \ , \tag{4}$$

where $F_{\mathrm{SSP},\lambda}(Z_i, \tau_i)$ and m_{s} are a monochromatic flux of SSP of age τ_i and metallicity Z_i, where suffix i identifies each stellar particle, and mass of each stellar particle, respectively. The age of SSP, τ_i, is defined as $\tau_i = T - t_i$, where t_i is the time when a gas particle convert to a stellar one. The metallicity of SSP is exactly the same as that of the stellar particle, Z_i, and the summation ($\sum$) in equation (4) is done for all stellar particles in a model galaxy.

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 SSP at a given wavelength is defined as

$$F_{\mathrm{SSP},\lambda}(Z_i, \tau_i) = \int_{M_L}^{M_U} \phi(M) f_\lambda(M, \tau_i, Z_i) dM \ , \tag{5}$$

where M is mass of a star, $f_\lambda(M, \tau_i, Z_i)$ is a monochromatic flux of a star with mass M, metallicity Z_i and age τ_i. $\phi(M)$ is a initial mass function (IMF) of stars and M_U, M_L are upper and lower mass limit of IMF, respectively.

In this paper, we use the $F_{\mathrm{SSP},\lambda}(Z_i, \tau_i)$ calculated by Tantalo et al. (1996). The characteristics of Tantalo et al. (1996)'s SSP are (1) all evolutionary phase, from the main sequence to the white dwarf or C-ignition stage, are included and (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 $F_{\mathrm{SSP},\lambda}(Z_i, \tau_i)$:

$$\phi(M) = \frac{(x-2)M_L^{x-2}}{1-\left(\frac{M_L}{M_U}\right)^{x-2}} M^{-x} \ , \tag{6}$$

where $x = 2.35$, $M_L = 0.15 M_\odot$ and $M_U = 120 M_\odot$. In order to estimate the $F_{\mathrm{SSP}}(Z_i, \tau_i)$ for stellar particles with arbitrary Z_i and τ_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 $< Z_* >$ used in the present study is defined as

$$< Z_* > \ = \ \frac{\sum\limits_{\mathrm{star}} Z_i m_{\mathrm{s}}}{\sum\limits_{\mathrm{star}} m_{\mathrm{s}}} \ . \tag{7}$$

Colors at given radius and radial color gradients are given as follows. First we divide the region ranging from 0.5 R_e to 5.0 R_e of a merger remnant into 20 annulus whose inner and outer boundary are located at the distance r_j and r_{j+1} from the center of the remnant, respectively. Then the monochromatic flux emitted from the jth annulus is derived by summing the $F_{\mathrm{SSP}}(Z_i, \tau_i)$ of all the particles locating 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 the C_{SF} is the most important parameter in the present study, principally because the C_{SF} could depend on galactic luminosity. The importance of the C_{SF} and its possible dependence on galactic luminosity are described in the Appendix section. In what follows, we mainly investigate how the rapidity of gas consumption by star formation (C_{SF}) can determine a number of fundamental chemical, photometric, and spectroscopic properties of merger remnants, and thereby observe how successfully the present merger model can reproduce the fundamental characteristics of real elliptical galaxies. Since the $C_{\rm SF}$ 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 we investigate the dependence of chemical properties on the $C_{\rm SF}$, which is the most important parameter in the present study, in §3.1. What we investigate the most extensively in this investigation are on the mean stellar and gaseous metallicity, radial gradients of metallicity and age, shapes of isochrome contour, and the formation of substantially metal-enriched galactic nuclei, in merger remnants. Second we investigate the important roles of other four parameters, the chemical mixing length, orbit configuration of galaxy merging, multiplicity of galaxy merging, and the epoch of galaxy merging, in determining the fundamental chemical properties of merger remnants (§3.2). This sort of multi-parameter study is indispensable for the present study, in which initial physical conditions of galaxy mergers can be variously different. In this investigation, we confirm whether or not the important roles of the parameter $C_{\rm SF}$ derived in §3.1 can be equally seen in the models with different chemical mixing length, orbit configuration, multiplicity of mergers, and merging epoch. We also observe how these four parameters modify the $C_{\rm SF}$ dependence derived in §3.2 and what fundamental roles the four parameters play in determining the characteristics of stellar populations. Third we investigate the photometric and spectroscopic properties of merger remnants and their dependence on the galactic luminosity, by adopting a specific relation between the $C_{\rm SF}$ and galactic luminosity and by assigning the mass and scale to each model with $C_{\rm SF}$, in §3.3.

2.4. Parameter values of each model

In the present paper, totally 29 models are investigated, and the parameters and brief summary of the results are given in Table 1. Each model of galaxy merger is labeled, for example, as Model B1, according to the orbit configuration of galaxy merging and multiplicity of the merging. Most of models (23 models) are assigned to pair mergers in Model B (standard models), C, D, E, and F and only two are assigned to multiple mergers in Model G. For comparison, the isolated evolution of a progenitor disk of a galaxy merger is also investigated and labeled as Model A. The values of orbit parameters, θ_1 θ_2, ϕ_1, and ϕ_2 are set to be 30.0, 120.0, 90.0, and 0.0, respectively, for Model 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, 150.0, 150.0, 0.0, and 0.0 for Model E. Orbit configuration of Model D and that of Model E correspond to nearly prograde merger and nearly retrograde one, respectively. The Model F with $r_{\rm p}$ = 0.5 corresponds to the galaxy merger with smaller initial orbital angular momentum. The difference between the Model A1 (2) and Model A3 (4) is that in the Model A3 (4), 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 state and final one in the models, Model A3 and A4.

First, second and third column in the Table 1 denote the model number, value of the parameter $C_{\rm SF}$, and that of $R_{\rm che}$, respectively, for each model. The values of $r_{\rm in}$ and $r_{\rm p}$ are given in the fourth and fifth column, respectively. We give the mean gaseous metallicity ($< Z >$), the mean stellar metallicity ($< Z_{*} >$), the gas mass fraction $f_{\rm g}$ in the sixth, seventh, and eighth column, respectively. The values of the mean gaseous ($< Z_{\rm Sim} >$) and stellar ($< Z_{*,{\rm Sim}} >$) metallicity predicted from the Simple one-zone model are presented in the ninth and tenth column, respectively. The mean epoch of star formation ($< T_{*} >$), which is defined as the average of star formation epoch (t_i) for all stellar particles in a merger remnant at final state (T = 15 in our units), is given in the eleventh column. $T_{M_{*}/M=0.6}$ shown in the twelves column represents the time-scale (in our units) that 60 percent of initial gas of progenitor disk galaxies has been converted into stellar particles during a simulation. The thirteenth column gives the magnitude of metallicity gradient which is defined as $\Delta \log < Z_{*} > / \Delta \log R$ (R is the distance from the center of merger remnant.) and measured for the region ranging from $0.5R_{\rm eff}$ to $5.0R_{\rm eff}$ ($R_{\rm eff}$ is the effective radius of each model.) in the xy projection for each model.

EDITOR: PLACE FIGURE 1 HERE.

EDITOR: PLACE FIGURE 2 HERE.

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 mergers remnants. Before describing the results of merger remnants, we begin to briefly observe the dynamical evolution of an isolated disk galaxy with star formation, which is considered to be a progenitor of a galaxy merger in the present study, and the dependence of star formation history on the parameter $C_{\rm SF}$ in galaxy mergers. Figure 1 gives snapshots of an isolated disk model with $C_{\rm SF} = 0.35$ (Model A1) at $T = 15.0$, in which about 60 percent of initial gas mass is converted into stellar component within 6.5 dynamical time. In the present isolated disk model, a stellar bar sufficiently develops in the central region of the disk only after more than 60 percent of initial gas mass has been consumed by star formation in the disk. The developed stellar bar is found to possess 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 time 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 been occurred. Figure 2 is the time evolution of star formation rate, f_g, for each merger model, Model B1 and B5. As is indicated in this figure, the star formation during galaxy merging proceeds in such a way that the interstellar gas is consumed by star formation more rapidly for the model with larger $C_{\rm SF}$. This trend of star formation holds for other model sequences Model B $\sim$ G. The $C_{\rm SF}$ dependence of morphology and dynamical structure in merger remnants is briefly summarized in the Appendix section, which can help to understand more deeply the present numerical results. By using these models of galaxy mergers, we mainly present the $C_{\rm SF}$ dependence of mean stellar and gaseous metallicity, radial gradients of age and metallicity, and the shapes of isophotes and isochromes, in the following subsections.

EDITOR: PLACE FIGURE 3 HERE.

EDITOR: PLACE FIGURE 4 HERE.

3.1. Dependence of the chemical properties on the rapidity of star formation

Chemical, photometric, and spectroscopic properties of galaxies depend basically on how the metallicity and age of stellar populations of galaxies are distributed. Thus, we begin to observe the distribution of metallicity (Z_*) and the epoch of star formation (T_*) in the stellar component of merger remnants and its dependence on $C_{\rm SF}$. In this subsection §3.1, we present the following three results: (1) Dependence of $Z_* - T_*$ distribution on $C_{\rm SF}$, (2) Dependence of mean Z_* on $C_{\rm SF}$ and its physical reason, 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 $Z_{*} - T_{*}$ distribution on $C_{\rm SF}$. Figure 3 shows the distribution of stellar populations on the $Z_{*} - T_{*}$ map for model with $C_{\rm SF}$ = 0.35 and for 3.5, respectively. The meaning of the T_{*} is that the stellar component with smaller T_{*} is born earlier thus *older*. The vertical hight in each bin of Z_{*} and T_{*} denotes the number of star particles with Z_{*} and T_{*}. In this figure, we can observe that there is an appreciable scatter in the metallicity for a fixed T_{*}. This scatter of metallicity for a given T_{*} is one of the characteristics of 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. $Z_{*} - T_{*}$ distribution in the model with $C_{\rm SF} = 3.5$ is shifted toward the larger Z_{*} and smaller T_{*} (older in age) than in the model with $C_{\rm SF} = 0.35$, 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 one. Spread in T_{*} for a fixed Z_{*} is more likely to be larger in the model with $C_{\rm SF} = 0.35$ than in that $C_{\rm SF} = 3.5$ whereas $Z_{*} - T_{*}$ distribution is more strongly peaked in the model with $C_{\rm SF} = 3.5$ than in that $C_{\rm SF} = 0.35$. These results imply that in the model with $C_{\rm SF} = 0.35$, star formation proceeds less rapidly and more gradually, resulting in a smaller amount of metal-enriched stellar populations and a larger amount of younger stellar populations. This tendency of stellar populations plays an important role in determining the mean metallicity and age, and thus the photometric and spectroscopic evolution of merger remnants, as is described later.

Second, we observe how the mean stellar metallicity depends on the rapidity of star formation and explain the origin of the dependence. As is shown in Figure 4, which describes the time evolution of mean stellar metallicity ($< Z_* >$) of each merger remnant, the chemical enrichment proceeds faster and more efficiently in the model with larger $C_{\rm SF}$ than the model with smaller $C_{\rm SF}$, and thus the final value of $< Z_* >$ is larger in the model with larger $C_{\rm SF}$ than the model with smaller $C_{\rm SF}$: The time when $< Z_* >$ exceeds 0.015 is $T = 0.7$ for the model with $C_{SF} = 3.5$ and $T = 5.0$ for the model with $C_{SF} = 0.35$, and the asymptotic value of $< Z_* >$ (the value at $T = 15.0$ in our units) is 0.0237 for the model with $C_{SF} = 3.5$ and 0.0185 for the model with $C_{SF} = 0.35$. This result clearly demonstrates 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 can be explained as follows. For a galaxy merger with more rapid star formation, less amount of interstellar gas is tidally stripped away from the system during galaxy merging principally because more amount of initial gas has been already converted to stellar component before the system suffers more severely from violently varying gravitational potential of galaxy merging. As a result of this, more amount of the gas is consequently metal-enriched to a larger extent and converted into stellar component during merging. Thus, more amount of metals is shared by stellar component in the remnant of the galaxy merger with more rapid star formation. Moreover this observed tendency of the C_{SF} dependence of mean stellar metallicity is found to be applied to the five standard models (See the seventh column in the Table 1 for Model B1 $\sim$ B5.). These results provide a potential success of reproducing qualitatively the mass-metallicity relation of elliptical galaxies: If the value of the C_{SF} is larger for more luminous galaxy merger, then the derived result indicates that galaxy mergers between more luminous spirals are more likely to become ellipticals with larger stellar metallicity. This furthermore suggests that even the origin of fundamental photometric and spectroscopic properties such as the color-magnitude relation in elliptical galaxies are closely associated with the details of galactic dynamics.

EDITOR: PLACE FIGURE 5 HERE.

In order to observe more clearly the above strong dynamical coupling between dynamical evolution and chemical one, we perform a set of comparative simulations in which chemical evolution (including star formation) is solved but the dynamical one (gravitational and dissipative dynamics) is not for an isolated galactic disk (Model A3 and A4). Accordingly, the density distribution and kinematical properties in the disk are fixed during the simulations. Since the time evolution of the gas mass fraction is the most fundamental determinant for the mean stellar metallicity in galaxies, by investigating the effects of galactic dynamics on the time evolution of gas mass fraction and the final gas mass fraction, we observe how the dynamical evolution can affect the chemical one in the present merger model. Figure 5 gives the time evolution of gas mass fraction, f_{g}, for isolated disks *without dynamical evolution* (Model A3 and A4) and for mergers (Model B1 and B5). As is shown in the lower panel of this 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 (Model A3 and A4) whereas significant difference in the final gas mass fraction can be seen for mergers (Model B1 and B5). This result clearly indicates that dynamical evolution itself greatly strengthens the difference of final gas mass fraction between merger models with different C_{SF}. Therefore the chemical evolution in galaxy mergers is demonstrated to be greatly affected by the dynamical evolution of galaxy merging. In the merger model (Model B1 and B5), as is 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. This sort of importance of the rapidity of star formation (C_{SF}) in controlling the final gas mass fraction can be seen even in the isolated disk models (Model A1 and A2), and can be explained as follows (See the upper panel of the Figure 5.). In the model with smaller $C_{\rm SF}$, non-axisymmetric 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 times principally because a larger amount of gas has not been yet converted into stellar component. Consequently, a larger amount of the gas is transported outwardly in the disk and thus the mean gas density there is greatly dropped off. As a result of this, only a smaller fraction of the outwardly transported gas can be further converted into stellar component, and thus the mean stellar metallicity is smaller for the model with smaller $C_{\rm SF}$. This result clearly shows that the redistribution of mass and angular momentum driven by specific non-axisymmetric 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 rapidity of star formation is significantly different between isolated disks (Model A1 and A2) and mergers (Model B1 and B5), however these results say essentially the same thing: Chemical evolution of galaxies can be greatly affected by mass and angular momentum redistribution driven by global dynamical process such as the violent relaxation of galaxy merging and mass-transfer triggered by non-axisymmetric gravitational potential of galaxies. This sort of strong coupling between dynamical evolution and chemical one is first demonstrated by the present work and Bekki & Shioya (1997c).

EDITOR: PLACE FIGURE 6 HERE.

Third, we observe the difference in chemical evolution of merging galaxies between the Simple one-zone model and the present chemodynamical one. Figure 6 describes the metallicity distribution of stellar component for the model with $C_{\rm SF} = 0.35$ and for 3.5, 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 model, we use the time evolution of gas mass fraction obtained for each merger model (Model B1 and B5), and then calculate the metallicity distribution according to the standard formulation on the relation between gas mass fraction and mean stellar metallicity for the Simple model. Since the Simple model assumes both instantaneous recycling and instantaneous mixing, the Simple model corresponds to the present chemodynamical model with $R_{\rm che}$ equal to infinity. We also give the values of mean stellar and gaseous metallicity expected from the Simple model in the ninth and tenth column of the Table 1, by adopting the following formulation:

$$< Z_{*} > \; = \; y_{\rm met} \left(1 + \frac{f_g \ln f_g}{1 - f_g} \right) \quad , \tag{8}$$

$$Z_{\rm gas} \; = \; -y_{\rm met} \ln f_g \quad . \tag{9}$$

As is shown in Figure 6, the metallicity distribution of the model with larger $C_{\rm SF}$ is shifted to righter side than the model with smaller $C_{\rm SF}$, which is consistent with the already obtained trend that the mean stellar metallicity of merger remnants with larger $C_{\rm SF}$ is larger than that of the remnants with smaller $C_{\rm SF}$. Furthermore, it is found that irrespectively of the values of $C_{\rm SF}$, the metallicity distribution is shifted to the righter direction 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 more likely to be larger for models with smaller $C_{\rm SF}$. This result clearly explains the reason why the difference in the mean stellar metallicity between the models with different values of $C_{\rm SF}$ for the present chemodynamical model is smaller than expected from the Simple model (See the sixth, seventh, ninth, and tenth column in the 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 not to depend on the values of $C_{\rm SF}$. These differences in the metallicity distribution between the Simple model and chemodynamical one results in the difference between these model in the photometric and spectroscopic properties of merger remnants, as is described in detail later.

Thus we demonstrate that dynamical evolution of galaxy merging greatly affects the chemical evolution in galaxy mergers, and consequently the chemical evolution in mergers 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 play 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 redshift or in the mergers between less luminous spirals.

EDITOR: PLACE FIGURE 7 HERE.

EDITOR: PLACE FIGURE 8 HERE.

3.1.2. Radial gradient of stellar populations

Here, we first observe how successfully the observed profile of 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 gradient of elliptical galaxies can be fitted reasonably well by the power-low profile and that the magnitude of the gradients, $\Delta \log Z_{*}/\Delta \log R$, are -0.2 on average (Peletier et al. 1990; Davies et al. 1991). Mihos & Hernquist (1994) found that the collisionless galaxy mergers between spirals with exponential profile of metallicity gradient become ellipticals with the metallicity gradient profile appreciably deviating from power-low profile, implying that the later mergers with less amount of gaseous dissipation can not reproduce the observed gradient with power-low profiles. Figure 7 gives the radial distribution of stellar and gaseous metallicity for the present merger model with star formation and gaseous dissipation. As is shown in this figure, negative metallicity gradient fitted by power-low profile is reproduced reasonably well for model with $C_{\rm SF}$ = 0.35 and 3.5, which indicates that the origin of the metallicity gradients of elliptical galaxies are closely associated with dissipative galaxy merging with star formation. A merger remnant in the model with $C_{\rm SF}$ = 0.35 has larger stellar metallicity in the central part and smaller metallicity in the outer part than the remnant in the model with $C_{\rm SF}$ = 3.5, meaning that the metallicity gradient is larger for the model with less rapid star formation. The qualitative explanation for this trend of metallicity gradients can be given as follows. In the model with smaller $C_{\rm SF}$, 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 amount of gaseous dissipation. In the outer part of the merger with smaller $C_{\rm SF}$, star formation is less likely to proceed efficiently and thus less likely to form metal-enriched stars because of the lower gaseous density in the outer part. As a result of this, a relatively larger metallicity gradient is established for the model with smaller $C_{\rm SF}$. For the model with larger $C_{\rm SF}$, 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 the galaxy merger suffers more severely from chemical mixing driven by violent relaxation owing to less amount of gaseous dissipation. As a result of this, the metallicity gradient is more strongly washed out and consequently the absolute magnitude of it becomes smaller for model with larger $C_{\rm SF}$. The obtained value of metallicity gradient is found to be smaller than that of the typical value of observation, -0.2, for most of models with $R_{\rm che}$ = 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 required for reproducing 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 metallicity gradient and by age gradient (i.e., the age-metallicity degeneracy problem). Recently, Faber et al. (1995) and Bressan et al. (1996) have succeeded in breaking the degeneracy by using the combination of line strength indices, Hβ and [MgFe]. Faber et al. (1995) furthermore found that outer parts of elliptical galaxies are more likely to be both older and more metal-poor than nuclei. This observational trend is found to be reproduced more successfully in the model with smaller $C_{\rm SF}$ for the present merger model, suggesting that such a trend of age and metallicity gradient of elliptical galaxies is just one of the evidences that an elliptical galaxy is formed by galaxy merging. Figure 8 describes the radial gradient of mean epoch of star formation, $< T_{*} >$, which corresponds to the age gradient in merger remnants. As is shown in Figure 8, the age gradient is more discernibly seen in the model with $C_{\rm SF}$ = 0.35 than the model with $C_{\rm SF} = 3.5$, primarily because in the model with $C_{\rm SF} = 0.35$, the star formation proceeds more gradual and more later in the inner region of the merger remnant. Since it is found that the stellar metallicity is larger for the central region than for the outer region of a merger remnant, this result means that in the model with $C_{\rm SF}$ = 0.35, the inner part of the merger remnant show both younger age and a larger degree of chemical enrichment whereas in the model with $C_{\rm SF} = 3.5$, the inner part of the merger remnant show both slightly older age and a slightly larger degree of chemical enrichment. Interestingly, the result for the model with $C_{\rm SF} = 3.5$ can be seen also in the result of Bressan et al. (1996), which describes that there are a number of elliptical galaxies whose nucleus are both older and more metal-enriched. Thus, the rapidity of star formation is demonstrated to determine both the profiles and the magnitude of the metallicity (and age) gradients in galaxy mergers: Both the metallicity gradient and the age one in the model with rapid star formation are shallower than that with less rapid star formation.

EDITOR: PLACE FIGURE 9 HERE.

3.1.3. The shape of isochromes

The shape of isochromes and the degree of the difference between the isochromes and isophotes shapes are considered to be observational clues about the origin of the formation and evolution of elliptical galaxies. As is revealed by the observation of multi-band photometry (e.g. Boroson et al. 1983), the shapes of isochromes are appreciably similar to those of isophotes in elliptical galaxies. In the dissipative collapse model of Larson (1975), the shapes of isochromes are significantly flatter than those of isophotes, which is not in agreement with the above observation. In the Carlberg (1984)'s dissipative collapse model of elliptical galaxy formation, the shapes of isochromes are slightly flatter than the isophotal shapes and thus appears to have succeeded in overcoming the disadvantage of the Larson's collapse model regarding the difference between isochromes and isophotes shapes. Here, we observe whether or not the shape of isochromes can match reasonably well with that of isophotes in the present dissipative merger model. Although the color of a galaxy is affected by both metallicity and age of stellar populations, we assume that the iso-metallicity contour is exactly the same as the isochromes one and that the iso-density contour is also the same as the isophote one. In Figure 9, we show arbitrary isochromes (solid line) and isophotes (dotted line) for the model with $C_{\rm SF} = 3.5$. We found that the shapes of isochromes are nearly the same as those of isophotes and furthermore that this trend is not dependent so strongly on the $C_{\rm SF}$. 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 the shape of isochromes which can match well with the isophotal shape.

EDITOR: PLACE FIGURE 10 HERE.

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3.2. Fundamental roles of other parameters

In addition to the rapidity of star formation, chemical mixing length, the orbit configuration of galaxy merging, the multiplicity of a merger, and the epoch of galaxy merging are considered to be fundamental factors for chemical, photometric, and spectroscopic properties. We accordingly observe how and to what extent the above four parameters strengthen or lessen the $C_{\rm SF}$ dependence of chemical properties derived in §3.1. Dependence of chemical properties on the four parameters is summarized in Figure 10 for mean stellar metallicity, Figure 11 for mean epoch of star formation, Figure 12 for stellar metallicity gradient, Figure 13 for radial gradient of 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 $C_{\rm SF}$ dependence of chemical properties derived in §3.1, however, the basic trends in the $C_{\rm SF}$ dependence derived in §3.1 is not so drastically changed. For example, the mean stellar metallicity of a merger remnant is larger in the model with larger $C_{\rm SF}$ for a give chemical mixing length, orbit configuration, multiplicity, and merging epoch. Accordingly, in the following parts (§3.2.1 $\sim$ 3.2.4), we mainly present outstanding results which we could not obtain only by varying the value of $C_{\rm SF}$ in the previous subsection §3.1, and furthermore we describe the fundamental roles specific for 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 interstellar medium in galaxies (e.g., Roy & Kunth 1995). Because of this uncertainty, it is the best way in the preliminary stage of the present study to vary the values of the chemical mixing length, represented by $R_{\rm che}$, in each model and thereby to examine its importance in determining chemical properties of galaxies. We found that irrespective of the values of $C_{\rm SF}$, as the values of $R_{\rm che}$ becomes smaller, the mean stellar metallicity becomes larger (See the seventh column in the Table 1 for Model B6, 7, 8, and 9). This result can be explained as follows. In the model with smaller $R_{\rm che}$, metals produced by star formation in higher density region can be mixed into the surrounding interstellar gas more locally, and accordingly the metals are more likely to be trapped only by the gas in the higher density region. Consequently, chemical enrichment proceeds more preferentially in the higher density regions, where a larger number of stars are formed and 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 $R_{\rm che}$. This result indicates that if the $R_{\rm che}$ is larger for the model with smaller $C_{\rm SF}$, the already obtained $C_{\rm SF}$ dependence of mean stellar metallicity is strengthened (See Figure 10.). We also found that for most models, as the values of $R_{\rm che}$ is smaller, the negative metallicity gradient becomes steeper (See Figure 12). This result reflects the fact that the chemical enrichment can proceed more preferentially in the higher density (i.e., inner) region such as the nuclei of mergers in the model with smaller $R_{\rm che}$.

What is the most interesting result derived by varying the $R_{\rm che}$ is that for the model with smaller $R_{\rm che}$ and $C_{\rm SF}$, the mean gaseous metallicity is smaller than the stellar one in the merger remnant (See the sixth and seventh column in the Table1 for Model B6 and B8). This result can not be obtained until both dynamical and chemical evolution are solved in a admittedly self-consistent manner, since the Simple one-zone model predicts that the gaseous metallicity is never smaller than the stellar one. Furthermore, this result provide a valuable clue about the origin of metal-poor hot gaseous halo of elliptical galaxies: The X-ray satellite *ASCA* (*Advanced Satellite for Cosmology and Astrophysics*), the metallicity of the hot X-ray gaseous halo is appreciably smaller than that of the stellar component of the host elliptical galaxy (e.g., Matsumoto et al. 1997). The details of the formation of metal-poor gaseous halo will be discussed in our future papers.

3.2.2. Orbit configuration

Orbit parameters of galaxy merging such as the initial intrinsic spin of progenitor disks and pericenter distance of mergers can affect the degree of violent relaxation and the redistribution of mass and angular momentum during merging, thus determine the transfer process of chemical component in mergers. We accordingly investigate how the initial inclinations of two progenitor disks (Model C, D, and E) and pericenter distance

(Model F) can affect the final chemical properties of merger remnants. We found that for the model with larger $C_{\rm SF}$ in each model sequence, Model C, D, E and F, the mean stellar metallicity of merger remnants is larger whereas the mean epoch of star formation ($< T_{*} >$) is smaller (See Figures 10 and 11.), which is consistent with the results derived in §3.2 and thus reinforces the importance of the rapidity of star formation in determining the mean stellar metallicity and mean stellar age in merger remnants. As is shown in Figure 12, both the magnitude of negative metallicity gradient and that of age gradient in merger models are distributed with appreciable spread even for a fixed value of $C_{\rm SF}$ (=0.35 and 3.5), suggesting that the spread in the magnitude of metallicity and age gradient observed in elliptical galaxies with a given luminosity is due to the diversity in orbit configuration of galaxy merging. The origin of the relatively larger negative value of metallicity gradient observed for model with 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 component into the central region, and consequently enhances the difference in stellar metallicity between outer and inner region in the galaxy. This result should be compered with the result 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 smoothes out the already existing metallicity gradient of the barred galaxy. The difference in the dynamical roles of stellar bars between the present study and that of 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

Multiple mergers between late-type spirals are suggested to play important roles, 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 (Model G1 and G2). The differences obtained in the present study are the following four: First, irrespectively of $C_{\rm SF}$, a larger amount of interstellar gas is stripped away and consequently can not participate further star formation in multiple mergers than in pair mergers. This is firstly because the tidal stripping of interstellar gas is more efficient in multiple mergers owing to the more violent dynamical interaction between galaxy mergers and secondly because a smaller amount of mass can be transferred to the inner region and thus can not form the higher density gaseous regions in multiple mergers. Second, as a result of this, a larger amount of metal-poor gas finally surrounds the merger remnant in multiple mergers, which might be observed as the metal-poor gaseous X-ray halo as is actually observed in elliptical galaxies (e.g., Matsumoto et al. 1997). Third, the $C_{\rm SF}$ dependence of chemical properties in pair merger remnants, in particular, the $C_{\rm SF}$ dependence of metallicity gradient, are less discernable in multiple mergers. This is probably because chemical mixing driven by violent gravitational relaxation of galaxy merging is more effective in multiple mergers. Fourth, in the multiple merger model with $C_{\rm SF} = 3.5$, the stellar populations in the central part of the merger remnant is both older and less metal-enriched than the outer part, which is a specific characteristic of chemical properties for multiple mergers with larger $C_{\rm SF}$ in the present study. This result is reflected in the fact that in the multiple merger model with $C_{\rm SF} = 3.5$, the magnitude of metallicity gradient for the region, $0.5R_{\rm eff} \le R \le 5.0R_{\rm eff}$ ($R_{\rm eff}$ is effective radius.), is -0.07 whereas it is 0.19 for the region, $0.1R_{\rm eff} \le R \le 1.0R_{\rm eff}$. Actually, Bressan et al. (1996) show that there are a number of galaxies possessing the same trend as is described above. Since only a relatively smaller range of parameter space has been investigated in the present study, we could not here give a stronger statement that the elliptical galaxies with older and less metal-enriched stellar populations in the central part of the galaxies are indicative of multiple mergers. Accordingly, it would be our further study to confirm the above result by performing numerical simulations with a larger range of parameter space for multiple mergers and furthermore to investigate what is the fundamental chemical properties specific for multiple mergers. Thus, these four results demonstrate that the multiplicity in galaxy mergers can also affect a number of chemical properties in merger remnants (thus in elliptical galaxies).

EDITOR: PLACE FIGURE 14 HERE.

EDITOR: PLACE FIGURE 15 HERE.

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 disk ($r_{\rm in}$) and thereby delaying the epoch of galaxy merging (Model B10 $\sim$ 15). We found that a galaxy merger with larger $r_{\rm in}$ (later merger) becomes an elliptical galaxy with both more metal-enriched and younger stellar populations and furthermore that this tendency does not depend on the values of $C_{\rm SF}$ (See the Figure 14.). These results can be explained as follows: In the later galaxy merger (the model with larger $r_{\rm in}$), a larger amount of interstellar gas can continue to be converted into stellar component and chemically enriched in the progenitor disk for a longer time, since the merging epoch is delayed. Consequently, new stars (younger stellar populations) are more preferentially born from 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 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 believed mass-metallicity relation of elliptical galaxies. They furthermore suggest that even if there exists outstanding spread in the 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 metallicity, Z, satisfies the relation, $\Delta \log \mathrm{age}/\Delta \log Z$ = -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 the Worthey's law. Although more extensive observational studies should be accumulated which can confirm whether or not the Worthey's law is universal among elliptical galaxies with different luminosity and with different environment, we can say however that the nature of stellar populations of elliptical galaxies is closely associated with the epoch of galaxy merging and thus with the strength of the secondary burst of star formation during galaxy merging. Specifically, it is crucial for chemical and photometric properties of elliptical galaxies formed by galaxy merging how much amount of interstellar gas the progenitor disks still have and to what degree the gas has been already metal-enriched just before galaxy merging. Although our numerical study appears to have succeeded in grasping some essential ingredients concerning 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 our future studies in order to confirm the derived dependence.

Finally in this subsection §3.2, we give the dependence of age gradient on metallicity one for all merger models in Figure 15. As is shown in this Figure 15, the merger model with larger magnitude of metallicity gradient show the larger magnitude of age gradient, which is actually observed in Bressan et al. (1996).

EDITOR: PLACE FIGURE 16 HERE.

EDITOR: PLACE FIGURE 17 HERE.

3.3. Characteristics of stellar populations dependent on galactic luminosity

We have so far focused mainly on the parameter dependence of chemical properties of merger remnants and did not intend to describe the photometric and spectroscopic properties of the remnants by adopting a specific mass and size for each merger model in the previous subsections (§3.1 and 3.2), We here describe photometric and spectroscopic properties of merger remnants by assuming that the model with $C_{\rm SF}$ = 1.0 corresponds to the galaxy merger between late-type spirals with mass and size equal to the fiducial values of the present study ($M_{\rm d}$ = 6.0 × 10^{10} $\rm M_{\odot}$ and $R_{\rm d}$ = 17.5 kpc, respectively) and that $C_{\rm SF} \propto L^{0.55}$ (This assumed relation is plausible, see the Appendix A.). The assumed relation, $C_{\rm SF} \propto L^{0.55}$, means that more luminous elliptical galaxies are formed by galaxy merging with more rapid star formation. For convenient, we consider that for each model, 13 Gyr have passed since the two progenitor galaxies began to merge with a given r_{in}. This means that we do not intend to include any *initial* age difference between galaxy mergers in this consideration, thus means that 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 on the luminosity dependence of star formation histories of disk galaxies and mergers. Accordingly, the derived luminosity dependence of photometric and spectroscopic properties of merger remnants only reflect 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 ones of real elliptical galaxies in a more quantitive way, however, it enable 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 the following parts (§3.3.1 and 3.3.2), luminosity dependence of mean stellar metallicity, metallicity gradient, and integrated color of merger remnants are mainly 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 metallicity, (2) smaller central stellar metallicity, and (3) smaller radial gradient 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 Mg_2 - σ relation (Burstein et al. 1988). It still seems less feasible to determine whether the third result matches with the observed luminosity dependence of stellar metallicity gradient in elliptical galaxies, as is described below. Although a number of observational studies have been accumulated which describe the dependence of the metallicity gradient on galactic parameters, however, the clear trend in the dependence seems less likely, as is described below. Carollo et al. (1992) reported that Mg_2 index gradient shows a bimodal trend with mass: For less massive galaxies ($M < 10^{11} M_{\odot}$), the Mg_2 gradient increase with increasing mass whereas for massive galaxies ($M > 10^{11} M_{\odot}$), there is no obvious pattern in mass dependence of the gradient. Gonzalez & Gorgas (1996) found the gradient of Mg_2 index correlates with the central Mg_2 index: Galaxies with steeper gradient of Mg_2 index have larger central Mg_2 index. Since central Mg_2 index becomes larger as the mass of galaxy increases, this correlation suggests that massive galaxies are more likely to have steeper metallicity gradient. Furthermore, Peletier et al. (1990) reported that there is no correlation between color gradient, which is a combination of age and metallicity gradients, and the luminosity of galaxies. Thus, it is safe for us to say that we could not here give any implications on the origin for the dependence of metallicity gradient on the galactic parameters. We must wait further extensive studies which reveal clear trends in the dependence of metallicity gradient on the galactic parameters, in order to compare the derived $C_{\rm SF}$ dependence of metallicity gradient in the present study with the observational results.

3.3.2. Photometric and spectroscopic properties

Figure 16 is the radial distribution of $U - R$ and $B - R$ color in the merger remnant for the fiducial model with $C_{\rm SF} = 1.0$. The observed color gradient in this model is principally due to the metallicity gradient of the merger remnant, since the age difference between outer part and inner one in the merger remnant is less than 1 Gyr. We found that this relatively shallower color gradient is more discernibly seen in more luminous merger remnants (mergers with rapid star formation). Figure 17 describes the color-magnitude (CM) relation derived for 25 models. In order to observe the difference in the photometric properties (mean color) between the Simple one-zone model and the present chemodynamical one, we calculate the photometric properties expected from the Simple model for the five standard models (Model B1 $\sim$ 5) by using the star formation history obtained for the five models. The derived results of the Simple one-zone model are plotted in the same figure for five models. As is shown in Figure 17, more luminous merger remnant (corresponding to the galaxy merger with larger $C_{\rm SF}$) show the redder color in the $V-K$, 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 origin of the observed CM relation of elliptical galaxies. In the conventional points of view (Faber 1973; Visvanathan & Sandage 1977), the CM relation reflects the mass-metallicity relation of galaxies ('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 ('age effect'). If we adopt the former conventional point of view, we should conclude as follows. The above result means that the observed color-magnitude relation (mass-metallicity relation) could not be reproduced so successfully by the present merger model with $C_{\rm SF} \propto L^{0.55}$. As has been already pointed out by Bekki & Shioya (1997c), 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 $C_{\rm SF} \propto L^{1.69}$. However, this assumption $C_{\rm SF} \propto L^{1.69}$ seems less plausible, since, for deriving the $C_{\rm SF} \propto L^{1.69}$, we must adopt somewhat particular assumptions, for example, that the initial density of the progenitor disk (Σ) in a merger depends strongly on the galactic luminosity (L) in such a way that $\Sigma \propto L^{4.56}$. Therefore, instead of adopting such apparently less realistic assumptions, we should reconsider other fundamental parameters that are important determinant for chemical evolution of galaxy mergers and strongly depend on the galactic mass, and then again investigate the luminosity dependent chemical and photometric properties of merger remnants. On the other hand, if we adopt the latter fresh point of view (Faber et al. 1995; Worthey et al. 1996), we should conclude as follows. The derived result on the CM relation does not necessarily disagree with the observed CM relation of elliptical galaxies. In this case, we must wait further extensive observational studies which reveal to what extent each 'age effect' and 'metallicity effect' actually contributes to the generation of the CM relation and clarify the relative importance of the two effects in the reproduction of the CM relation. It would be our future studies to elucidate the origin of the relative importance in the context of dissipative galaxy merging, when the relative contribution of the two 'age effect' and 'metallicity effect' are observationally clarified. Considering these situations, it is safe for us to say that we can not determine how successfully the present merger model has reproduced the CM relation until more extensive observational studies clarify the relative importance of the two 'metallicity effect' and 'age effect'.

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

4. Discussion

4.1. Outstanding difference between the Simple one-zone model and the present chemodynamical one

We here present the two outstanding differences in chemical evolution between the Simple one-zone model and the present chemodynamical one, and then give the related implications on 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 an admittedly self-consistent way. As is described in detail in the previous sections, chemical enrichment process during dissipative galaxy merging with star formation, which is controlled basically by the violent relaxation of galaxy merging and gaseous dissipation, is found to proceed in a considerably inhomogeneous way. This nature of chemical enrichment process provides a remarkably difference between the Simple one-zone model and the present chemodynamical one in that the final gas mass fraction is not only the 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 color in $V-K$ is observed to be appreciably different between the Simple one-zone model and the present chemodynamical one. Although the difference in the photometric and spectroscopic properties of merger remnants between the two models is not so large, however, we should recognize how the details of 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 the observational ones. Furthermore, in the present chemodynamical model, chemical enrichment is found to proceed faster in the higher density region (i.e., inner region) where star formation occurs more efficiently than in the lower density one (i.e., outer region), which strengthens the difference in the degree of chemical enrichment between the higher density (inner) region and the lower (outer) one ('chemical segregation'). This sort of chemical segregation could give a natural explanation for the origin of the difference in the photometric and spectroscopic properties between the outer and the central part in 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 radial metallicity gradient. Unlike the Simple one-zone model, chemical enrichment is assumed to proceed *locally* in the present merger model. As is described in detail in the previous sections, both radial metallicity gradient and mean stellar metallicity in merger remnants depend on how locally metals ejected from stellar component can be mixed into interstellar gas: Both mean stellar metallicity and the absolute magnitude of radial gradient of stellar metallicity are larger for the merger remnant with smaller mixing length of chemical component. Moreover, the chemical mixing length is found to determine how much amount of heavy elements ejected from stellar component can be shared by stars or interstellar gas, accordingly to affect the formation of gaseous halo which is less metal-enriched than stellar component of merger remnants. These results suggest that the rapidity of star formation in mergers is not only the dominant factor which determines the chemical properties of merger remnants, thus that we should investigate the physical relation between the rapidity of star formation and chemical mixing length in galaxies and its dependence on galactic luminosity for more clear understanding of the chemical, photometric, and spectroscopic evolution of galaxy mergers. There still remains a wide room for investigating and understanding the chemical evolution of galaxy mergers.

4.2. On the origin of 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 describes that the integrated color of elliptical galaxies becomes redder as the absolute magnitude of the luminosity decrease (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 (e.g., Worthey et al. 1996), it has been conventionally considered that the mean stellar metallicity is larger for more luminous elliptical galaxies (e.g., Tinsley 1978). Larson (1974) originally proposed that this luminosity-dependent mean stellar metallicity observed in elliptical galaxies is essentially ascribed to when star formation is entirely truncated owing to the so-called 'galactic wind' driven by accumulated thermal energy produced mainly by supernovae in 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 evolutionary method of population synthesis (e.g., Arimoto & Yoshii 1987, more recently, Bressan et al. 1994), however, only a few studies have addressed the fundamental question about wether 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 is 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 gas dynamics in merging galaxies, final gas mass fraction and 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 that the mass-metallicity relation can be closely associated with the details of 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 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 have a potential success in reproducing at least qualitatively the mass-metallicity relation, more totally 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 appealing the less realistic assumption that $C_{\rm SF} \propto L^{1.69}$ (Bekki & Shioya 1997c). 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 mass-metallicity relation. Thus it is one of our further study to investigate to what degree the dynamical and thermal effects of supernovae-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 mass-metallicity relation of elliptical galaxy, as is described below.

A growing number of observational and theoretical studies aiming at breaking the 'age-metallicity degeneracy' suggest that the CM relation of elliptical galaxies does not necessary mean the mass-metallicity relation. Faber et al. (1995) suggest that even if the mean stellar metallicity between elliptical galaxies are the same with each other, the CM relation can be equally reproduced with the assumption that the effective age of stellar populations is progressively younger for less luminous ellipticals ('age effect'). Furthermore, Worthey et al. (1996) demonstrate that even if the typical or luminosity-weighted age of galaxy 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 (the Worthey's 3/2 law). This result implies that single burst model of elliptical galaxy formation such as the galactic wind one, in which star formation is assumed to be truncated at most within 2 Gyr, can not 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 demonstrate that the pure 'age effect' is not convincing for reproducing both the tightness of the color-magnitude relation observed in the present cluster ellipticals and that in the intermediate redshift cluster ellipticals. It is safe to say here that neither the pure 'age effect' nor the pure 'metallicity effect' (i.e., mass-metallicity relation) could explain a growing number of evidences suggesting the diversity of star formation history in elliptical galaxies. We must wait more extensive observational studies which can confirm whether the suspected age spread and the Worthey's 3/2 law, both of which shed new insight on the origin of the CM relation, are robust and does not depend on the galactic mass, environment, and redshift. We can say, however, that both the age spread and the Worthey's 3/2 law could be naturally 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 metallicity of merger remnants in the sence that later mergers are more likely to become ellipticals with more metal-enriched and younger stellar populations. This result suggests that the Worthey's 3/2 law can be essentially ascribed to the difference in the epoch of galaxy merging between galaxy mergers. Furthermore, as is predicted by the semi-analytical models of galaxy formation based upon the hierarchical clustering scenario with CDM cosmogony (e.g., Baugh et al. 1996), it is quite reasonable that the epoch of galaxy merging differs from galaxies to galaxies. Accordingly the luminosity weighted ages, which might be dependent on the strength of the secondary starbursts in galaxy merging, can be naturally spread between elliptical galaxies formed by galaxy merging. Thus galaxy merging between late-type spirals, which might be occurred in variedly different epoch, is a promising candidate that can explain the apparent diversity of star formation history observed in real elliptical galaxy and nevertheless can explain the tightness of the CM relation of elliptical galaxies.

5. Conclusion

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 metallicity, 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 component. This result is demonstrated not to depend so strongly on the other parameters such as the orbit configuration of galaxy merging and multiplicity of the mergers. These results suggest that the origin of the color-magnitude relation of elliptical galaxies can be closely associated with the details of merging dynamics which depends on the rapidity of star formation (thus on the galactic luminosity) in galaxy mergers.

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

(3) Absolute magnitude of metallicity gradient correlates with that of age gradient in a merger in the sence that a merger remnant with steeper negative metallicity gradient is more likely to show steeper age gradient. This result reflects the fact that the degree of violent relaxation and gaseous dissipation during merging strongly affect both the age

gradient and metallicity one.

(4) The outer part of stellar populations is both older and less metal-enriched than nuclei in an elliptical galaxy formed by galaxy merging with less rapid star formation. Moreover galaxy mergers with less rapid star formation are more likely to become ellipticals with metal-poor gaseous halo. This result suggests that the formation of metal-poor X-ray halo actually observed in elliptical galaxies can be essentially ascribed to the dissipative galaxy merging between late-type spirals, and furthermore provides a clue to a solution for 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 origin 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 the difference in the epoch of galaxy formation and transformation, that is, the epoch of galaxy merging, between elliptical galaxies.

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

(7) As is described in the above (1) - (6), the details of gas dynamics 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 merger remnants. These results can not be obtained until both the chemical and dynamical evolution during galaxy merging are solved numerically in a reasonably self-consistent way.

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A. The expected luminosity dependence of the parameter $C_{\rm SF}$

A.1. The importance of $C_{\rm SF}$

In the present study, we adopt the assumption that more massive (luminous) elliptical galaxies are formed by galaxy *major* merging between more massive (luminous) late-type spirals, and thereby investigate how the difference of galactic mass (luminosity) of progenitor disks in a merger can affect the chemical and photometric properties of merger remnants. It is reasonable and realistic that if the mass of merger progenitor is different between 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, time-scale of star formation (star formation history), dissipative dynamics of interstellar gas, thermal and dynamical effects of accumulated thermal energy driven supernovae 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, what has been the most extensively examined in the previous studies is the thermal and dynamical 'feedback' effects associated with the supernovae 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 which should be addressed extensively, we here focus on the difference in the star formation history between galaxy mergers with different mass (or luminosity), and thus 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 (e.g., Worthey et al. 1992). Furthermore, as is suggested by the analysis of Hβ line index, the epoch, the strength, and the duration of the latest star formation of elliptical galaxies 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 the less luminous one (Wyse 1982; Bothun et al. 1985; Gavazzi & Scodeggio 1996). These lines of observational evidences strongly motivate us to clarify the important roles of star formation history in determining the chemical and photometric properties as well as dynamical and kinematical ones in elliptical galaxies.

In the present paper, we focus particularly on the time-scale of gas consumption by star formation *relative to the dynamical time − scale* of galaxy mergers: It should be emphasized here that the time-scale of gas consumption by star formation is not considered to be an important determinant but the time-scale of gas consumption by star formation *relative to the dynamical time-scale* is to be an important determinant. The reason for this consideration is explained as follows. The time-scale of gas consumption by star formation is the typical time-scale within which heavy elements are produced by star formation and mixed into interstellar medium. The dynamical time-scale is the typical time-scale within which violent relaxation during galaxy merging cause the mass and angular momentum redistribution and thus the dynamical mixing of heavy elements produced by star formation. Therefore, if the dynamical time-scale is much larger than the gas consumption time-scale, star formation can proceed quite efficiently before the system reach the dynamical equilibrium, and consequently the larger amount of heavy elements produced by the 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 time-scales are expected to be more essential for the chemodynamical evolution of galaxy mergers. For convenient, the inverse ratio of the time-scale of gas consumption by star formation to the dynamical time-scale is referred to as the rapidity of star formation and represented by the parameter $C_{\rm SF}$. It is the $C_{\rm SF}$ that we consider to depend strongly on the galactic luminosity, accordingly, we investigate the most extensively the important roles of $C_{\rm SF}$ in determining fundamental characteristics of elliptical galaxies in the present study.

A.2. A possible luminosity dependence of $C_{\rm SF}$

The expected luminosity (mass) dependence of $C_{\rm SF}$ is described as follows. The parameter $C_{\rm SF}$ is set to be proportional to $T_{\rm dyn}/T_{\rm SF}$, where $T_{\rm dyn}$ and $T_{\rm SF}$ are the dynamical time-scale and the time-scale of gas consumption by star formation, respectively. We here define the mass of a galactic disk, the total mass of luminous and dark matter, and size of the progenitor as M_d, M_t, and R_d, respectively. We consider here that gas mass in a disk is equal to M_d for simplicity. The $T_{\rm dyn}$ is given as

$$T_{\rm dyn} \propto R_d^{3/2} M_t^{-1/2} \tag{A1}$$

Provided that the coefficient in the Schmidt law is not dependent on the galactic mass (or luminosity), we can derive $T_{\rm SF}$ as follows.

$$T_{\rm SF} \propto \Sigma^{1-\gamma} \ , \tag{A2}$$

where Σ is the surface density of the gas disk. The parameter γ is the exponent of Schmidt law, which is the same as that used in previous subsections. Assuming the Freeman's law and the constant ratio of R_d to the scale length of exponential disk, we derive

$$\Sigma \propto M_d R_d^{-2} \sim {\rm const.} \tag{A3}$$

Assuming that the degree of self-gravity of a galactic disk is described as

$$M_t \propto M_d^{(1-\beta)} \quad , \tag{A4}$$

then we can derive

$$C_{\rm SF} \propto M_d^{1/4+\beta/2} \quad . \tag{A5}$$

Since β is considered to have positive value ($\beta = 0.6$: Saglia 1996), this relationship predicts that $C_{\rm SF}$ becomes larger as M_d increases. Furthermore, if we assume the constant mass to light ratio for luminous matter, we can obtain the luminosity dependence of $C_{\rm SF}$. In this case, the dependence is described as $C_{\rm SF} \propto L_d^{0.55}$, where $L_d^{0.55}$ is disk luminosity, for $\beta = 0.6$. Alternatively, if we adopt the observed trend that more luminous disks have large surface density, such as $\Sigma \propto M_d$ (McGaugh & Blok 1997), we can obtain $C_{\rm SF} \propto M_d^{1/2+\beta/2}$. Thus, these simple theoretical arguments suggest that larger (or more luminous) disk galaxies are more likely to have larger values of $C_{\rm SF}$.

EDITOR: PLACE FIGURE 18 HERE.

EDITOR: PLACE FIGURE 19 HERE.

EDITOR: PLACE FIGURE 20 HERE.

B. Structure and morphology of merger remnants

Although our main purpose of the present paper is not concerned with 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 in the present merger model, the details of chemical evolution are strongly affected by the dynamical evolution of galaxy mergers, observing the dynamical evolution of dissipative galaxy merging with star formation would help us to understand more clearly the present results on chemical evolution of galaxy mergers.

B.1. Dependence on $C_{\rm SF}$

First we present morphological, structural, and kinematical properties of merger remnants and their dependence on $C_{\rm SF}$. As is described in details by Bekki & Shioya (1997a, b), the galaxy mergers with larger $C_{\rm SF}$ are found to be more likely to become elliptical galaxies with less strongly supported by global rotation, less strongly self-gravitating, smaller central surface brightness, larger cores, and boxy isophotal shape. Figure 18 describes the morphological evolution of the model with $C_{\rm SF} = 0.35$ (Model B1). As the dynamical interaction between star-forming disk galaxies becomes stronger, an appreciably amount of metal enriched gas is tidally stripped away from the disks and finally surrounds the developed elliptical galaxy without 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, which has been recently revealed by the *ASCA* (e.g., Matsumoto et al. 1997). The final morphology of merger remnants depends strongly on the rapidity of star formation represented by the $C_{\rm SF}$, 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 $R^{1/4}$ law, however, the systematical deviation from the $R^{1/4}$ law is also observed depending on values of $C_{\rm SF}$, as is 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 nature of interstellar gas succeeds in boosting up more significantly the central density of merger remnant compared with isolated disk models (Model A1 and A2). This result suggests the problems related to phase space density of elliptical galaxies (Ostriker 1980; Carlberg 1986) can be successfully resolved in high-redshift galaxy mergers, as has been already indicated by Kormendy & Sanders (1992). These results imply that galaxy mergers with star formation and gaseous dissipation, which might be occurred the most frequently at higher redshift, can naturally explain the fundamental dynamical and kinematical properties of elliptical galaxies (For further details, see Bekki & Shioya (1997a, b).).

B.2. Dependence on galactic luminosity

By adopting a specific assumption on the luminosity dependence of the parameter $C_{\rm SF}$, 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, however, we beforehand and briefly discuss them, since we will point out advantages and disadvantages of the present merger model in reproducing *both* dynamical properties and chemical ones of elliptical galaxies in the section §4. Observational results indicate that more luminous elliptical galaxies are more likely to be less rotationally supported (Davies et al. 1983), possess less luminous surface densify (Djorgovski et al. 1996) and smaller phase space density (Carlberg 1986), have boxy isophote (Kormendy & Bender 1996) and larger cores (Kormendy & Djorgovski 1989). If we assume that $C_{\rm SF} \propto L^{0.55}$, that is, 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 $luminosity - dependent$ dynamical properties of elliptical galaxies at least in a qualitative manner. For example, the observed trend that the galactic core radius is more likely to be larger for the more luminous elliptical galaxy can be naturally explained by the present merger model that more luminous ellipticals are formed by galaxy *major* merging between more luminous spirals. The first reason for this is that since more luminous spirals *initially* are more likely to have larger 'cores' (or smaller central phase space density) as is implied by the Freeman's law and the relation between galactic luminosity and scale-length (e.g., McGaugh and Blok 1997), galaxy mergers between spirals with larger cores are more likely to become ellipticals with larger cores (or 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 degree of 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 any particular physical processes such as the dynamical heating of the central cores by binary black holes (Ebisuzaki, Makino, & Okumura 1991) are not 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 difference in luminosity-dependent dynamical structure of progenitor disks and the star formation history between gas-rich galaxy mergers. This furthermore indicates that 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 which can affect the luminosity-dependent morphological, structural, and kinematical properties of elliptical galaxies. The validity of the suggested point of view that luminosity-dependent dynamical structures of elliptical galaxies are essentially ascribed to the difference in the star formation history between elliptical galaxies formed by dissipative galaxy merging has been also investigated by (Bekki & Shioya 1997b) in the context of the origin of the fundamental plane of elliptical galaxies.

Although more elaborated 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 in the context of the reproduction of the observed luminosity-dependent dynamical properties of elliptical galaxies.

B.3. Self-consistency of the present merger model

Our final goal is to construct a more realistic model which can clearly explain both the structural and kinematical properties, such as the origin of the fundamental plane (Djorgovski & Davis 1987; Dressler et al. 1987), boxy-disky dichotomy (Kormendy & Bender 1996), and 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 luminosity-dependent radial gradient of metallicity, age, and color (Peletier et al. 1990; Davies et al. 1991). 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 chemical and photometric ones in a self-consistent way. What is the 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 observational one, then we point out the advantages and disadvantages of the present merger model in reproducing both the $luminosity-dependent$ dynamical and chemical properties of real elliptical galaxies. In the following discussions, we adopt the assumption that galaxy mergers with larger $C_{\rm SF}$ 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, b).

As is described in details by Bekki & Shioya (1997a, b), more luminous elliptical galaxies formed by dissipative galaxy merging with star formation are less rotationally supported, less compact, less strongly self-gravitating, and more likely to have boxy isophotal shape. 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 obtained results 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 be the most frequently occurred in higher redshift, has a number of advantages in reproducing the nature of elliptical galaxies than we have 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 problems that should be foremost resolved is on 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 (e.g., Djorgovski et al. 1996), and the larger central stellar metallicity, as is indicated by Mg_2 - σ relation (Burstein et al. 1988). This fundamental tendency of elliptical galaxies has not yet be reproduced by the present merger model, because the present model predicts that more luminous elliptical galaxies show less luminous central surface (and larger cores) brightness but the smaller central stellar metallicity compared with less luminous ones. This sort of failure can be seen also 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 are probably due to the ill approximation of the adopted instantaneous recycling, in which chemical enrichment is assumed to proceed considerably faster than the dynamical evolution. Actually the instantaneous recycling approximation is expected to give an undesirable result to less luminous elliptical galaxies, in which the dynamical time-scale of the systems is comparable or only slightly larger than the typical life-time of massive stars (a few 10^7 yr). Specifically, for less luminous galaxies, dynamical evolution such as the violent relaxation and redistribution of angular momentum of gas and stars, which plays a vital role in transferring and mixing dynamically chemical components, probably finishes earlier before the onset of efficient chemical enrichment driven by type II supernovae. As a result of this, the dynamical transfer of chemically enriched components into the inner region of galaxies, which determines the magnitude of the central stellar metallicity, are less likely for less luminous elliptical galaxies. This indicates the ratio of the typical time-scale of chemical enrichment (a few 10^7 yr) to the dynamical time-scale and its luminosity dependence are more essential for the chemodynamical evolution of less luminous elliptical galaxies. This kind of chemical evolution expected for less luminous ellipticals (mergers) is probably not modeled by the present chemodynamical model in a proper way, accordingly the present model with instantaneous recycling should be greatly modified to a more realistic one. Hence, it is our future and essential study to consider the importance of the ratio of the time-scale of chemical enrichment to the dynamical time-scale in elliptical galaxy formation and then to investigate again whether or not the remaining problem of the present merger model can be resolved in the more sophisticated models of chemodynamical evolution.

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

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Fig. 1.— Snapshots of an isolated disk model with $C_{\rm SF} = 0.35$ (Model A1) projected onto xy plane (upper) and onto xz plane (lower) at $T = 15.0$ in our units for stellar component (new stars). Note that a stellar bar forms in the central part of the disk.

Fig. 2.— Time evolution of star formation rate in units of $M_{\rm d}/t_{\rm dyn}$ for merger model with $C_{\rm SF} = 0.35$, Model B1 (open circles) and 3.5, Model B5 (open triangles). $M_{\rm d}$ and $t_{\rm dyn}$ denote the initial mass of a progenitor disk and the dynamical time of the disk, respectively.

Fig. 3.— Distribution of the stellar metallicity (Z_{*}) and the epock of star formation (T_{*}) for the model with $C_{\rm SF} = 0.35$ (Model B1, upper) and 3.5 (Model B5, lower) 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_{*}.

Fig. 4.— Time evolution of mean stellar metallicity ($< Z_{*} >$) for model with $C_{\rm SF} = 0.35$, Model B1 (open circles) and 3.5, Model B5 (open triangles).

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

Fig. 6.— Distribution of stellar metallicity for models with $C_{\rm SF} = 0.35$, Model B1, (upper) and 3.5, Model B5 (lower) 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 by asterisks ($*$) in the same panel.

Fig. 7.— Radial gradient of stellar metallicity (solid line) and that of gaseous one (dotted line) for the model with $C_{\rm SF} = 0.35$, Model B1 (open circles), and 3.5, Model B5 (open triangles) at $T = 15.0$ in our units.

Fig. 8.— Radial gradient of the mean epoch of star formation ($< T_* >$) for the models with $C_{\rm SF} = 0.35$, Model B1 (open circles), and $C_{\rm SF} = 3.5$, Model B5 (open triangles) at $T = 15.0$. This figure describes the age gradiant in each merger remant.

Fig. 9.— The shapes of isophotes contours (solid line) and isochromes ones (dotted line) projected onto xy plane for the central region of merger remant (within $R \leq 1.0$ in our units) at $T = 15.0$ in Model B2.

Fig. 10.— Dependence of final mean stellar metallicity (at $T = 15.0$ in our units) on the $C_{\rm SF}$ for standard models, Model B1 $\sim$ B5 (filled circles), for models with different chemical mixing length, Model B6 $\sim$ B9 (open circles), for models with different epock of galaxy merging, Model B10 $\sim$ B15 (open triangles), for models with different orbit configuration, Model C1, C2, D1, D2, E1, E2, F1 and F2 (open squares), and for multiple mergers, Model G1 and G2 (crosses).

Fig. 11.— The same as Figure 10 but for the dependence of mean epoch of star formation ($< T_* >$).

Fig. 12.— The same as Figure 10 but for the dependence of radial gradient of stellar metallicity.

Fig. 13.— The same as Figure 10 but for the dependence of radial gradient of mean star formation epoch ($< T_* >$).

Fig. 14.— Dependence of the mean stellar metallicity ($< Z_* >$) on the mean epoch of star

formation ($< T_* >$) in merger remants for models with different merging epochs. Open circles and triangles represent the models with $C_{\rm SF} = 0.35$ and 3.5, respectively.

Fig. 15.— The dependence of the radial gradient of the mean epoch of star formation ($< T_* >$) on that of stellar metallicity ($< Z_* >$) for all merger models. The notation of each mark is exactly the same as that presented in the Figure 10.

Fig. 16.— Radial distribution of the integrated color, $U-R$ (solid line) and $B-R$ (dotted) at 13 Gyr for the fiducial model with $C_{\rm SF} = 1.0$.

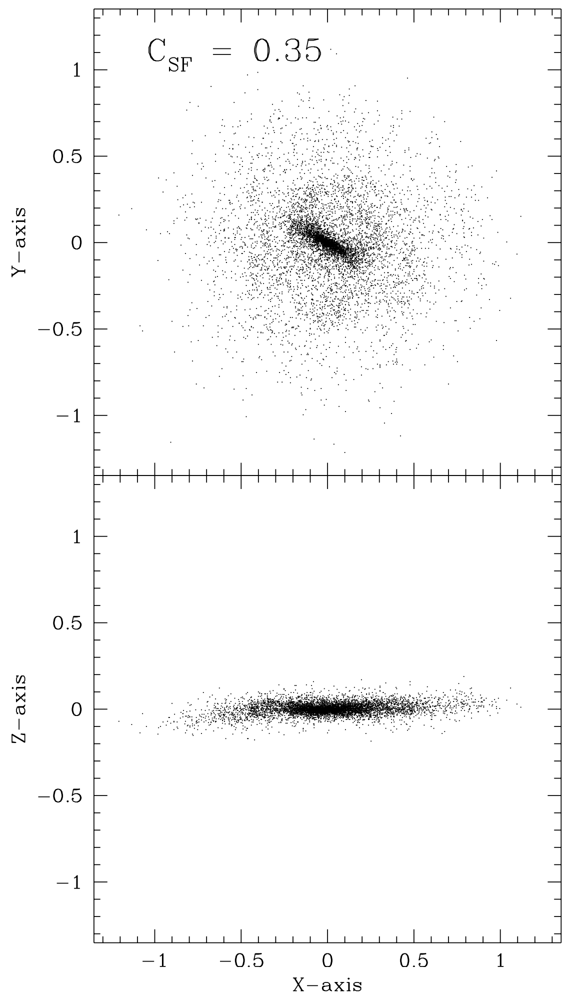
Fig. 17.— Color-magnitude relation for all merger models at 13 Gyr. The notation of each mark is exactly the same as that presented in the Figure 10. For comparison, the integrated global color expected from the Simple one-zone model is also plotted by asterisks for five standard models with different $C_{\rm SF}$ (Model B1 $\sim$ B5) in the same figure. A solid line represents the observed color-magnitude relation derived from Bower et al. (1992).

Fig. 18.— Morphological evolution of a galaxy merger with $C_{\rm SF} = 0.35$ (Model B1) projected onto xy plane for halo (top), interstellar gas (middle) and new stellar component (bottom). T indicates the time in our units. Note that an appreciable amount of interstellar gas is tidally stripped away during merging to form gaseous halo.

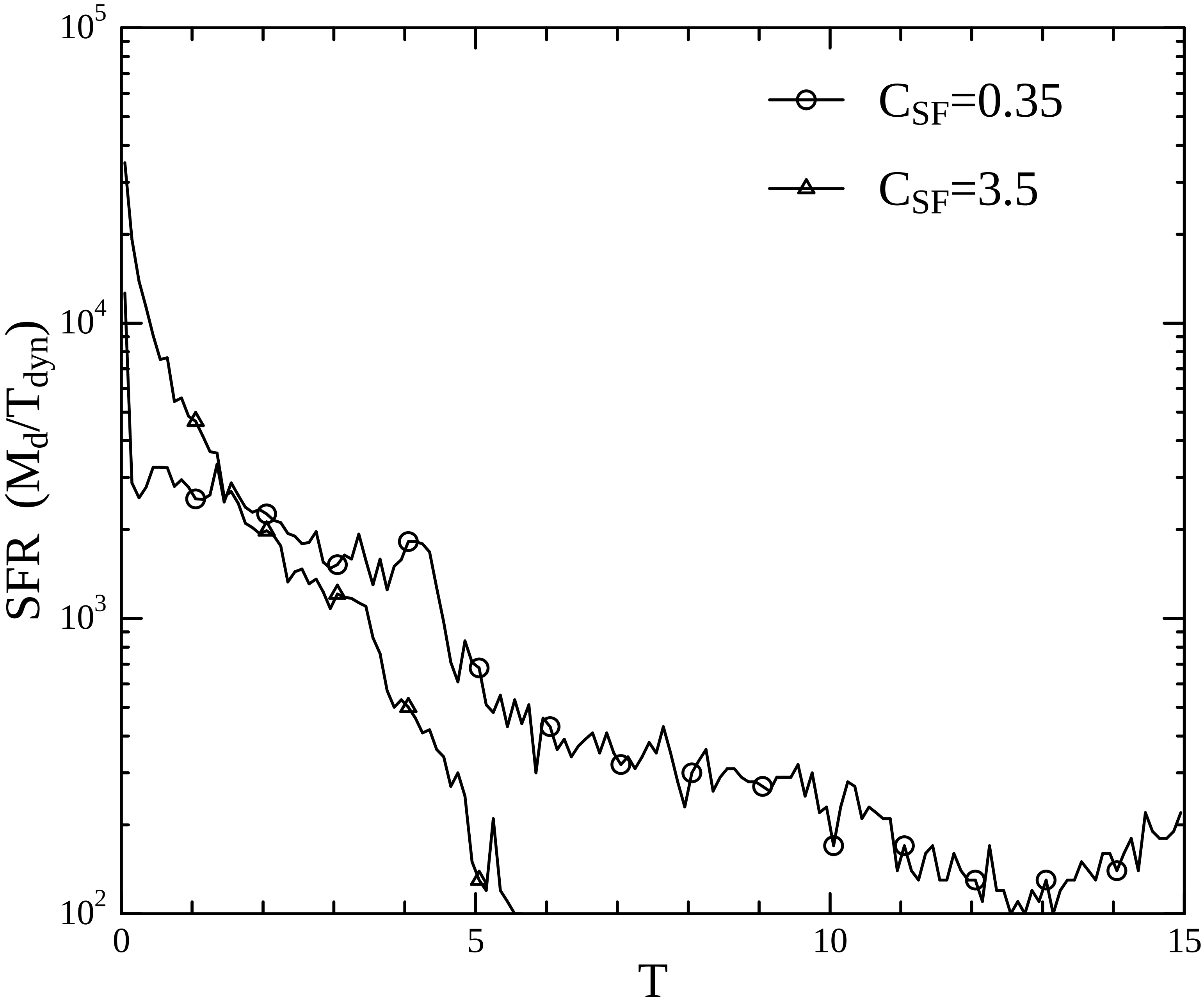
Fig. 19.— Snapshots of stellar component in merger remnants projected onto xz plane at $T = 20.0$ in our units for model with $C_{\rm SF} = 0.35$, Model B1 (upper), and $C_{\rm SF} = 3.5$, Model B5 (lower).

Fig. 20.— Radial distribution of stellar component projected onto xy plane for merger remnants (solid lines) in the model with $C_{\rm SF} = 0.35$ (Model B1) and $C_{\rm SF} = 3.5$ (Model B5) and for isolated disks (dotted ones) with $C_{\rm SF} = 0.35$ (Model A1) and $C_{\rm SF} = 3.5$ (Model A2) at T =15.0 in our units. Models with $C_{\rm SF} = 0.35$ and those with $C_{\rm SF} = 3.5$ are represented

by open circles and by open triangles, respectively.

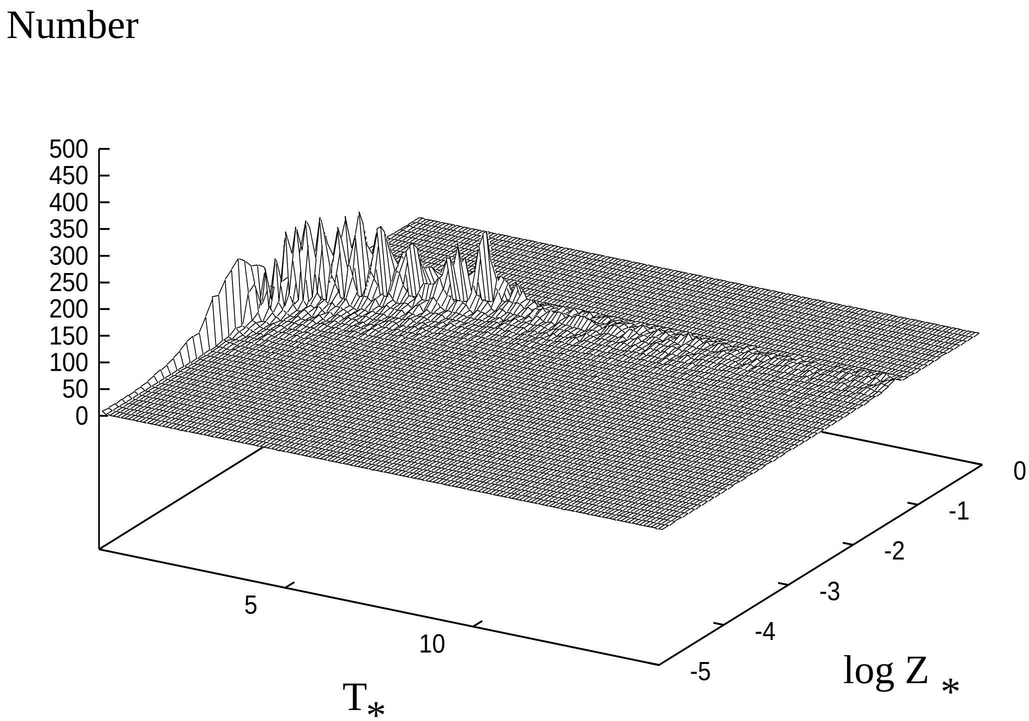


C_{SF} = 0.35
Y−axis
Z−axis
X−axis
1
0.5
0
−0.5
−1

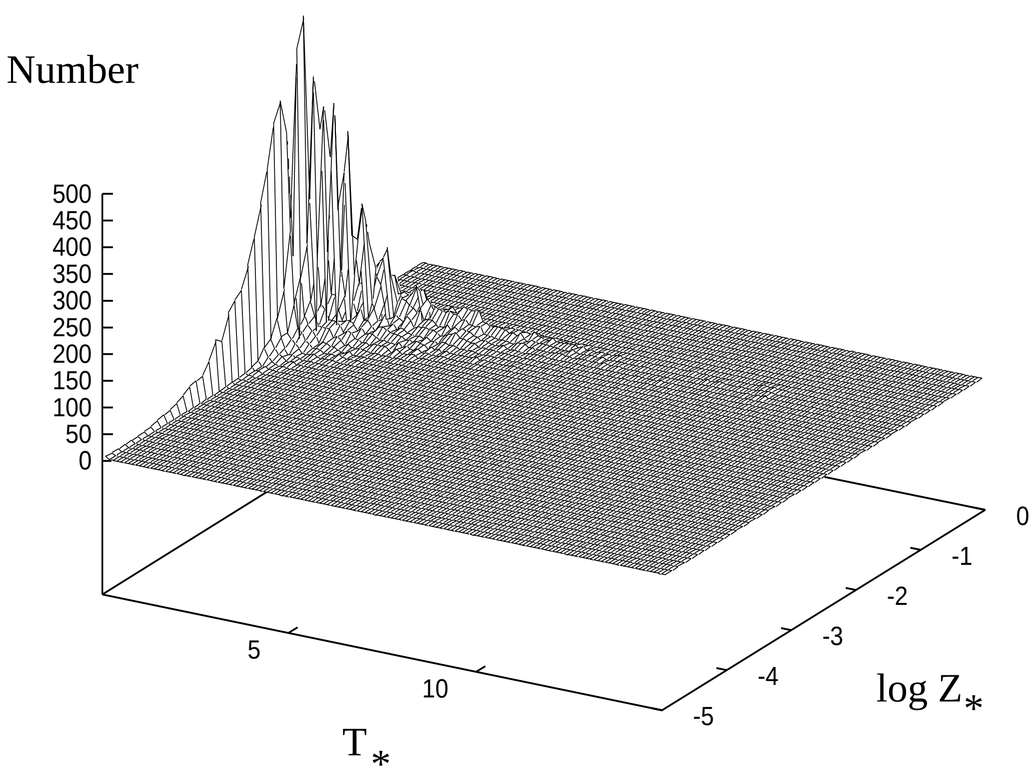


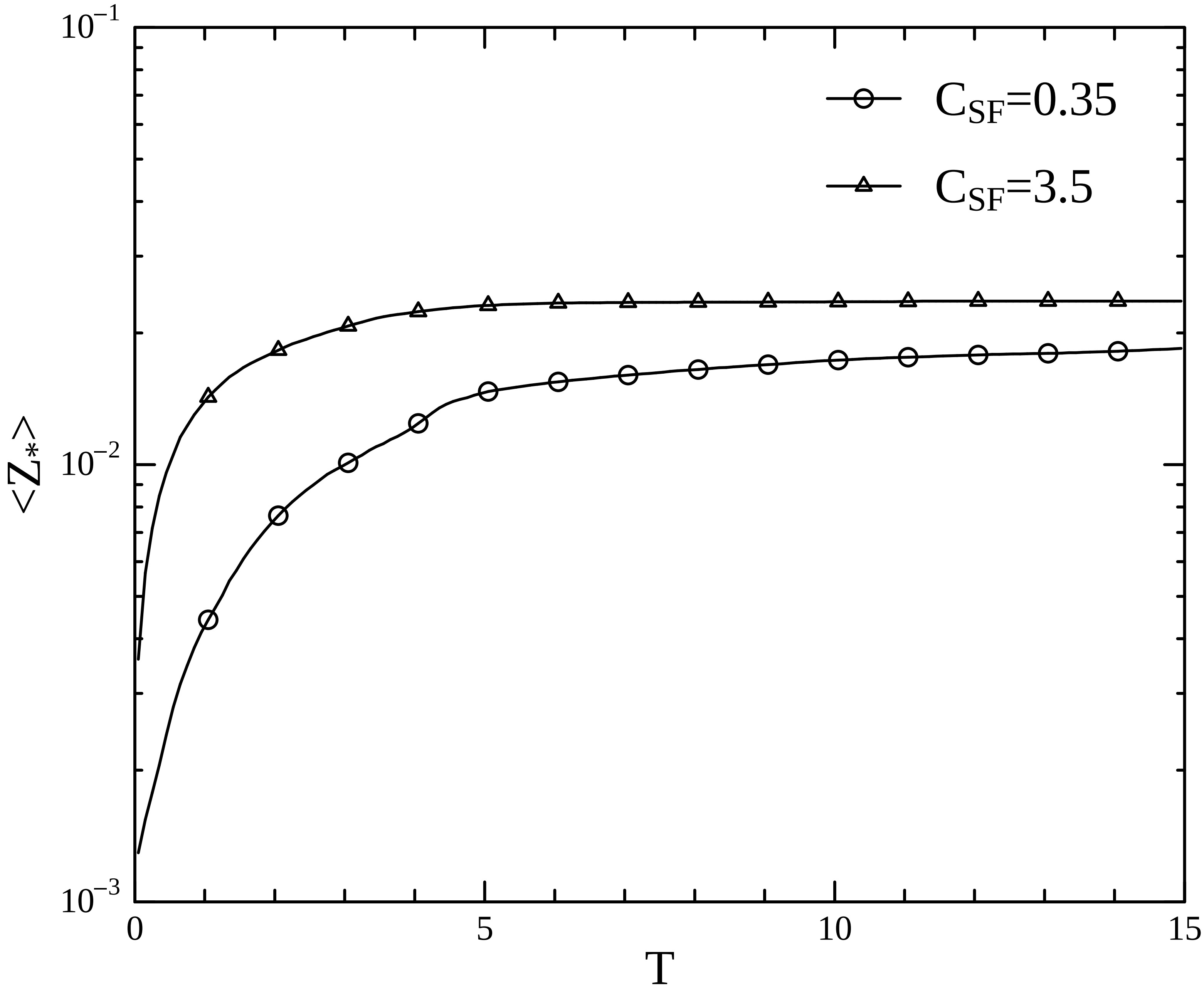
C_{SF}=0.35
C_{SF}=3.5
SFR (M_d/T_{dyn})
T
10^5
10^4
10^3
10^2
0
5
10
15

(a) $C_{SF} = 0.35$

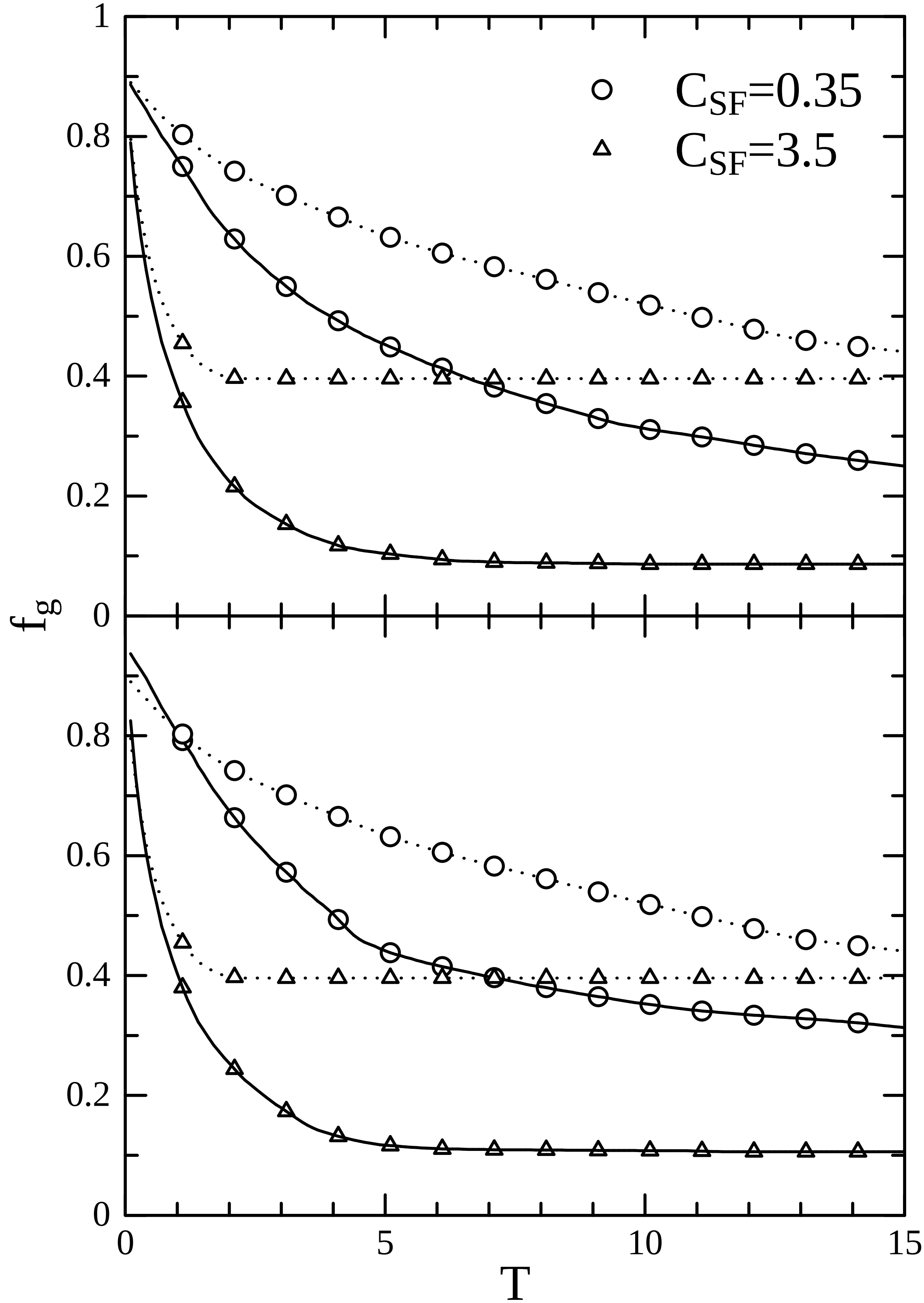


(b) $C_{SF} = 3.5$

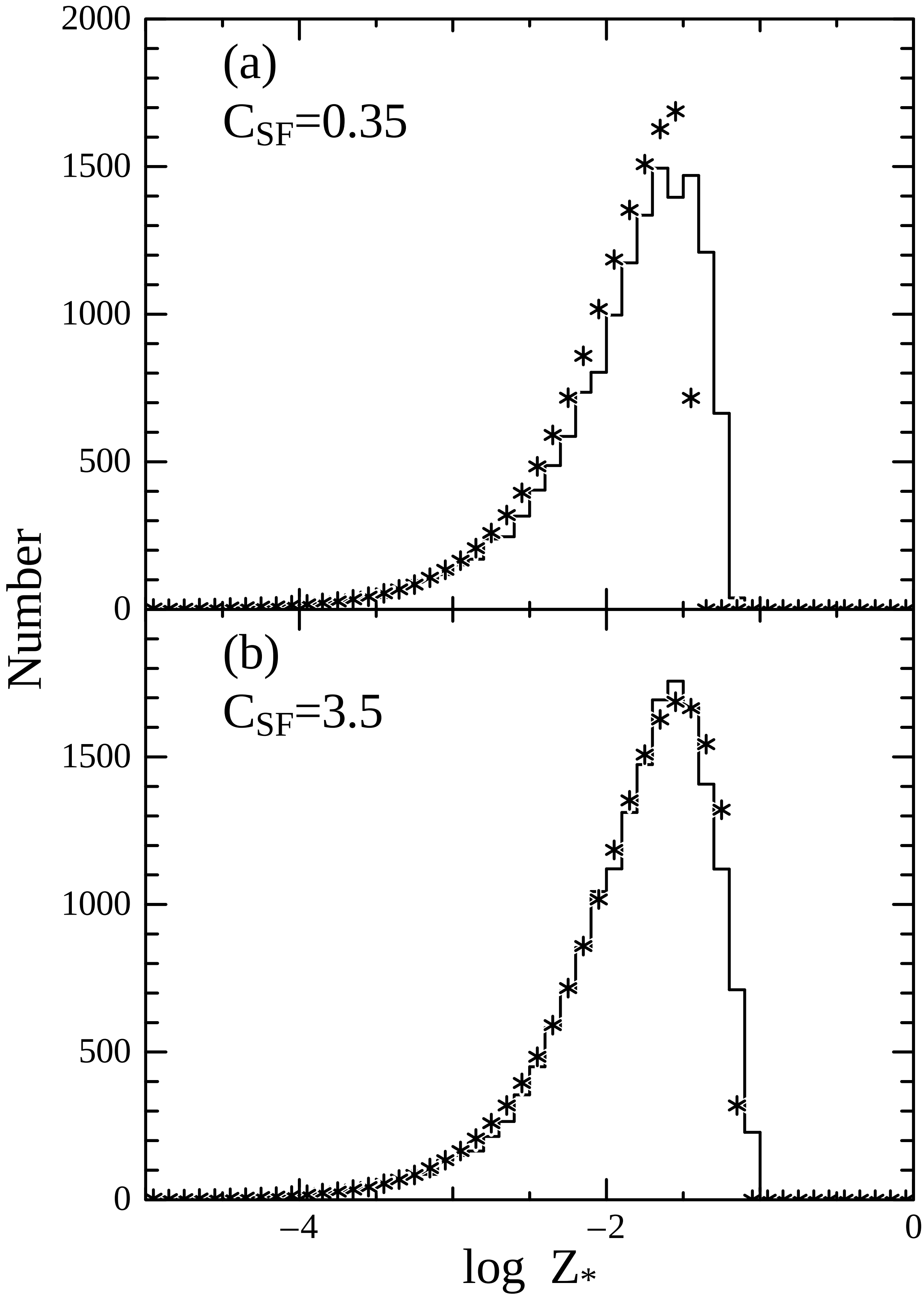




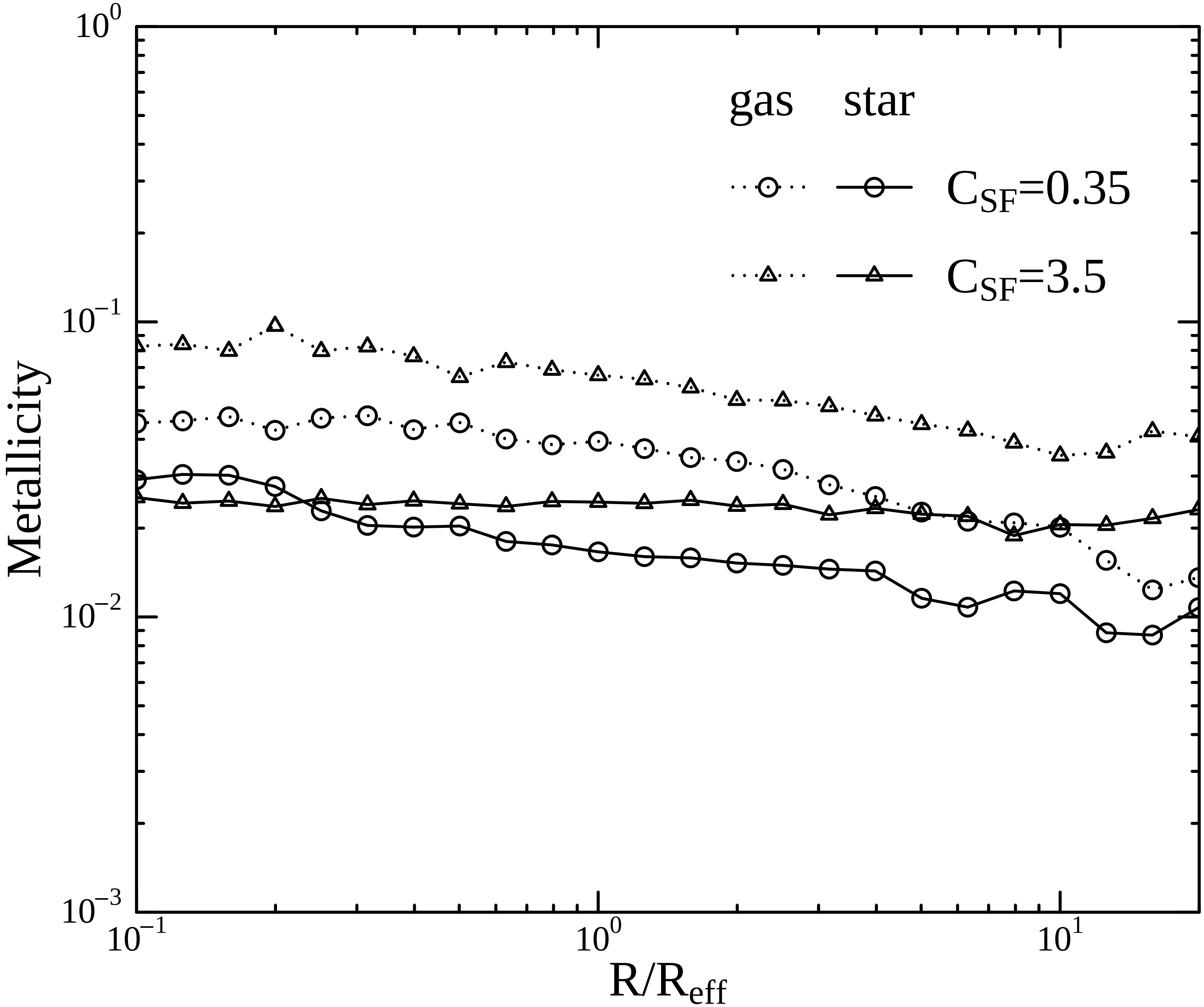
C_{SF}=0.35
C_{SF}=3.5
10^{-1}
10^{-2}
10^{-3}
$\langle Z_* \rangle$
0
5
10
15
T



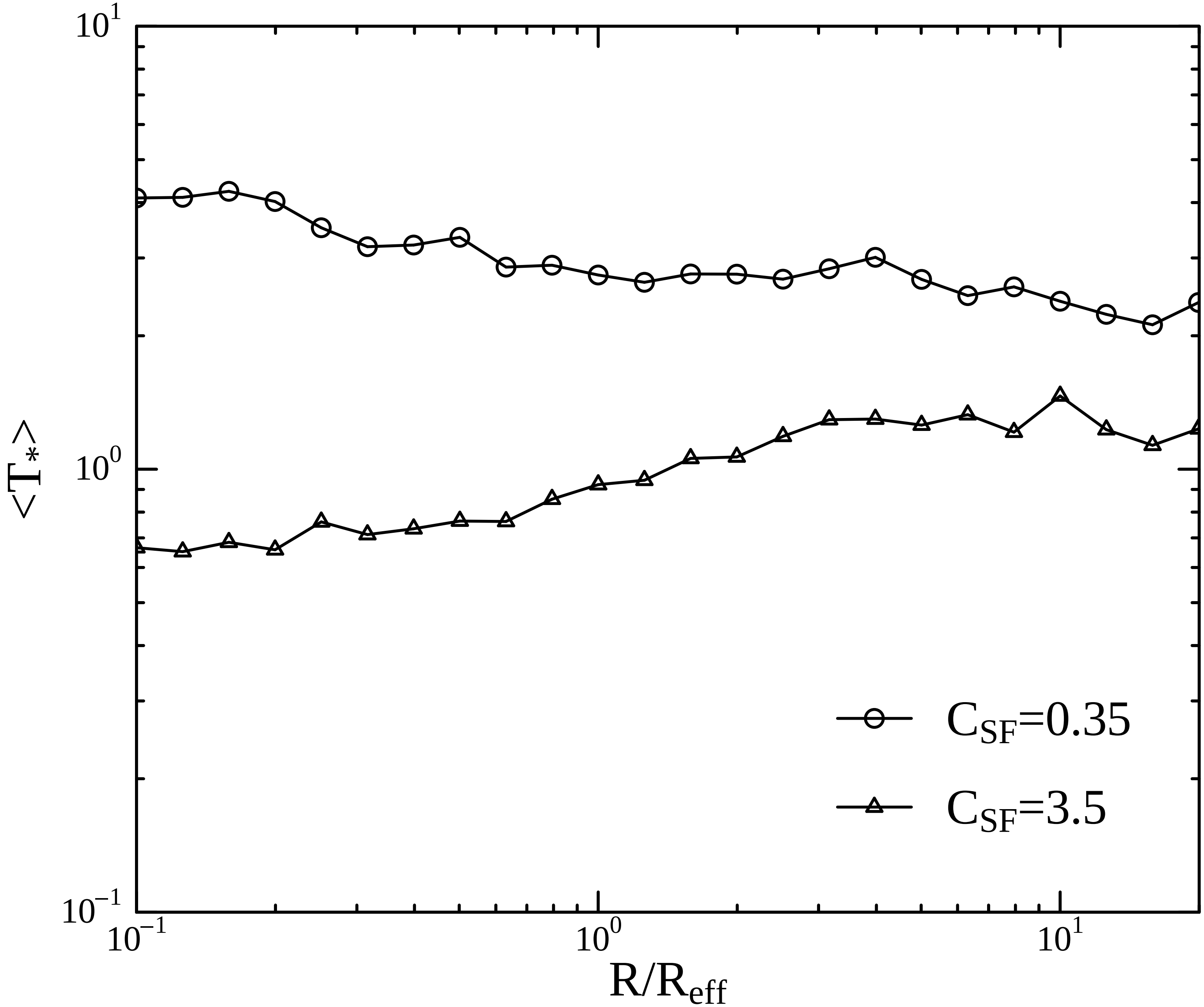
C_SF=0.35
C_SF=3.5
f_g
T
0
0.2
0.4
0.6
0.8
1
5
10
15



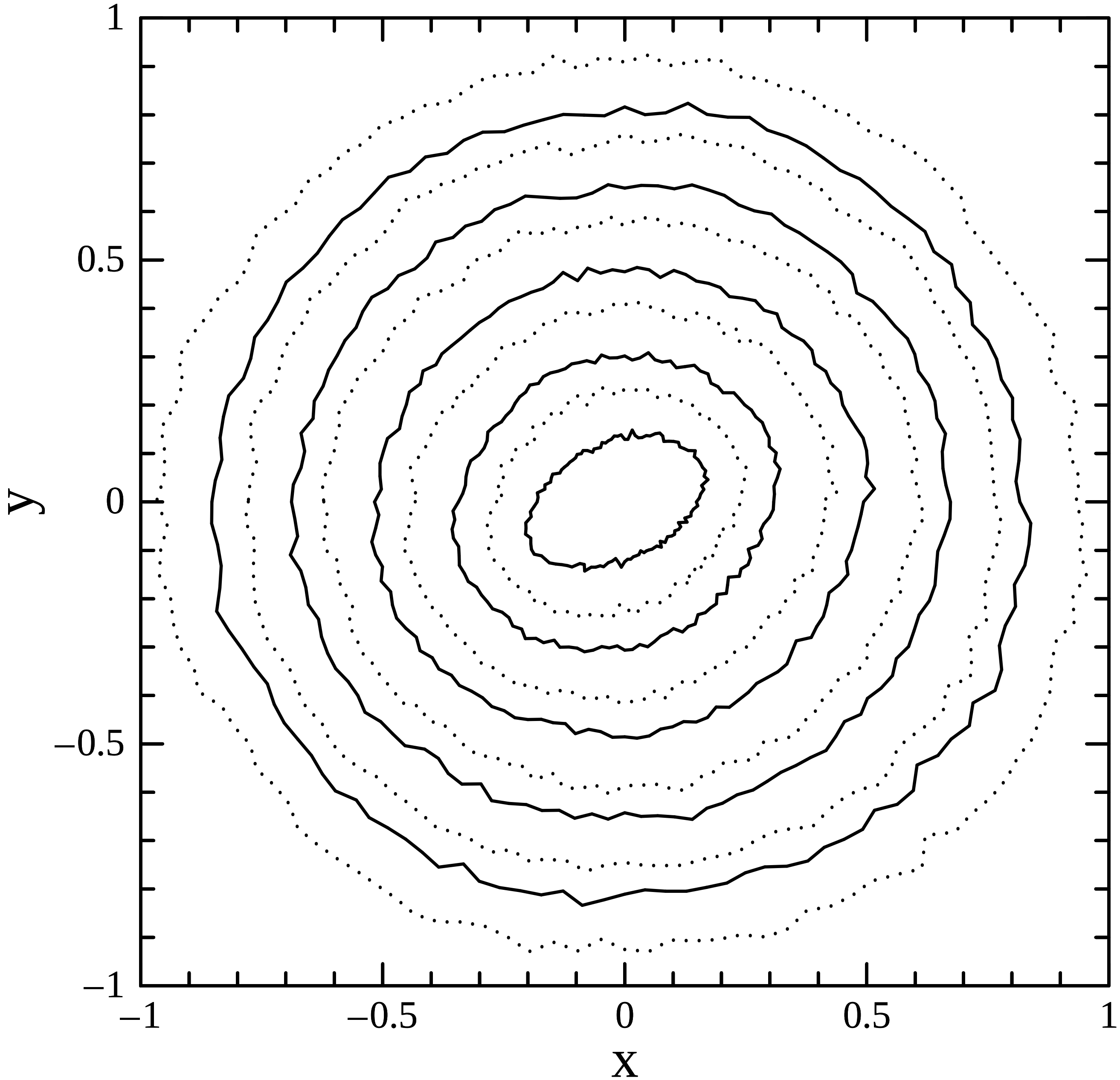
2000
1500
1000
500
0
(a)
C_{SF}=0.35
1500
1000
500
0
(b)
C_{SF}=3.5
Number
−4
−2
0
log Z_*



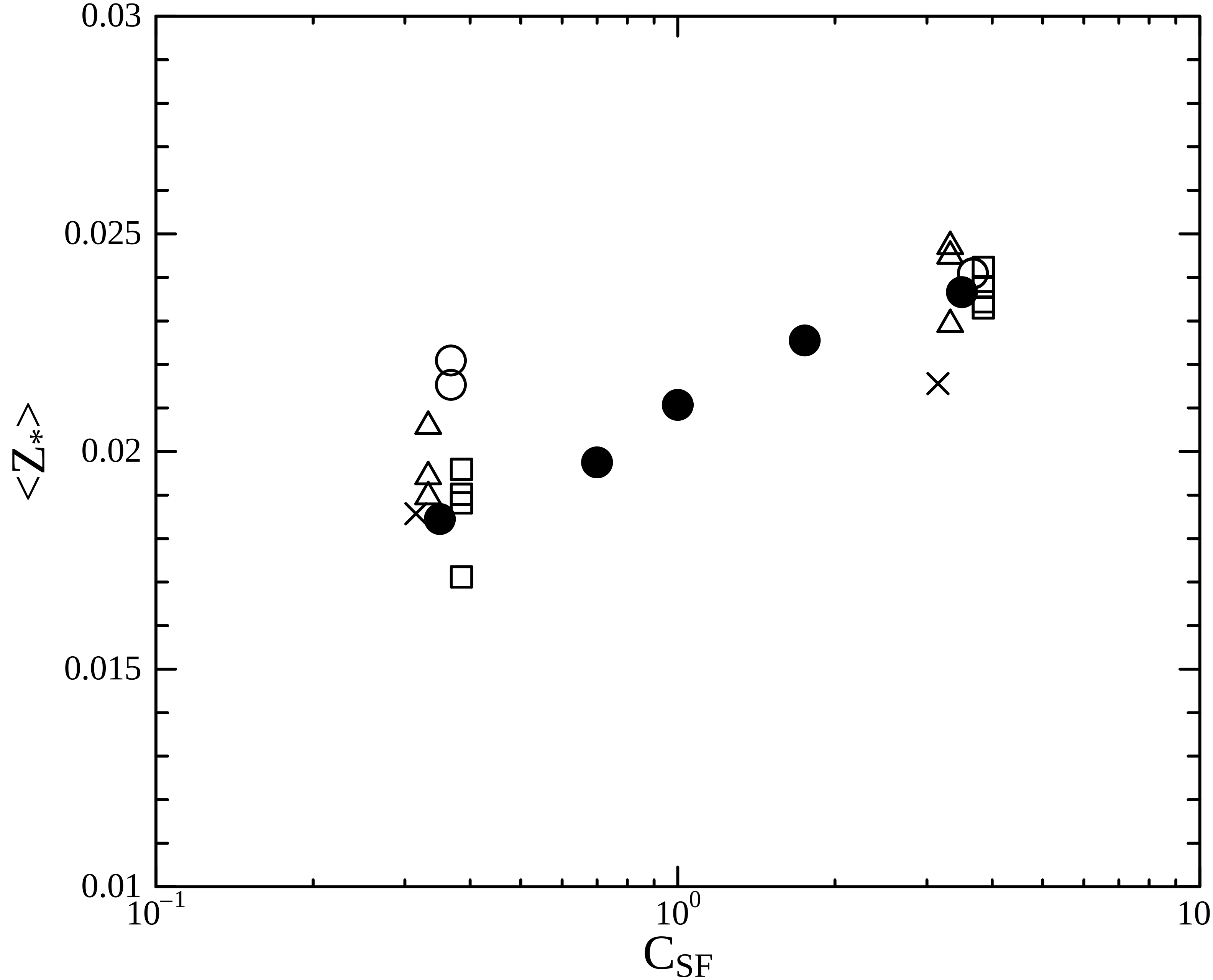
gas star
C_{SF}=0.35
C_{SF}=3.5
Metallicity
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-1}
10^0
10^1
R/R_{eff}

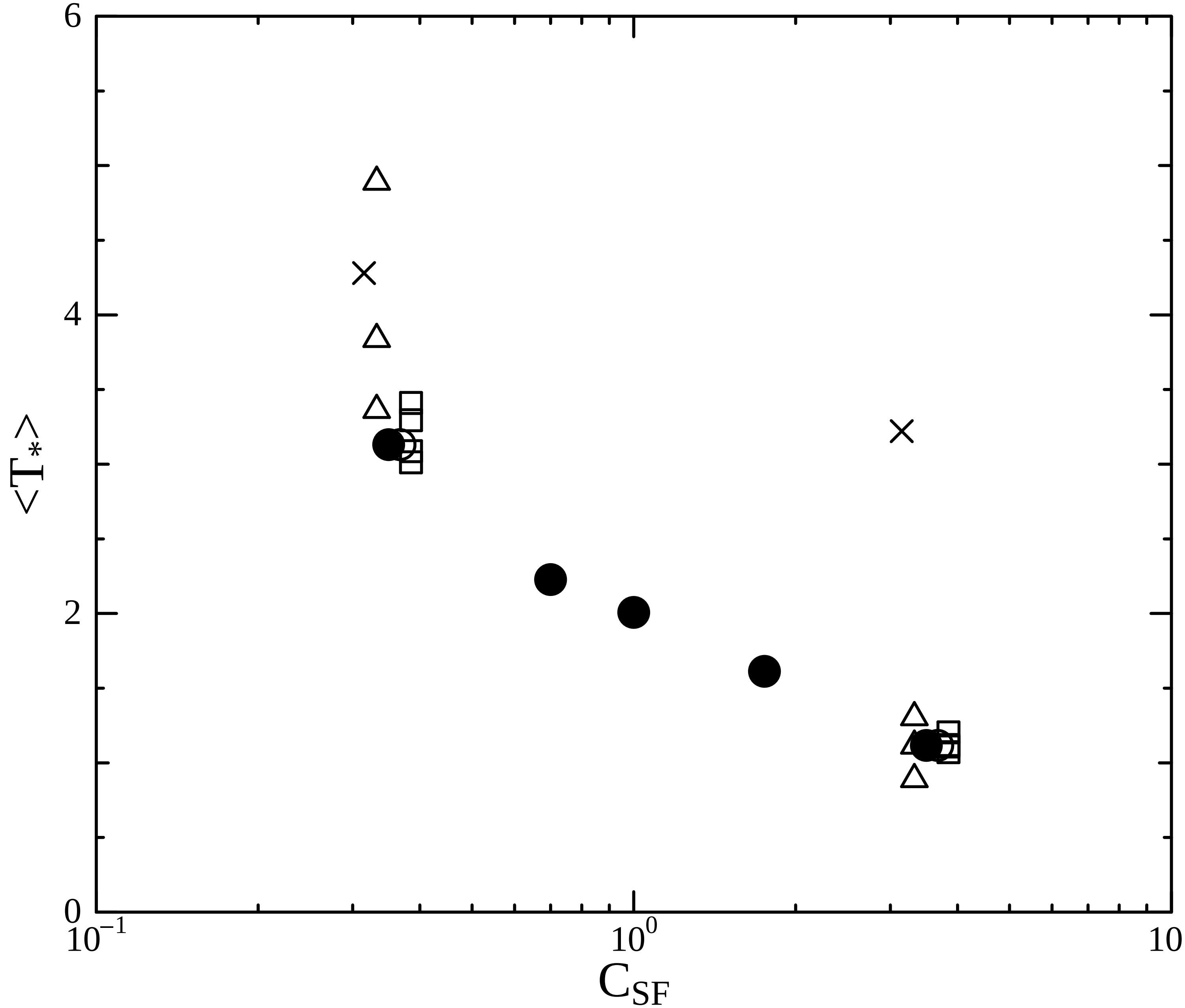


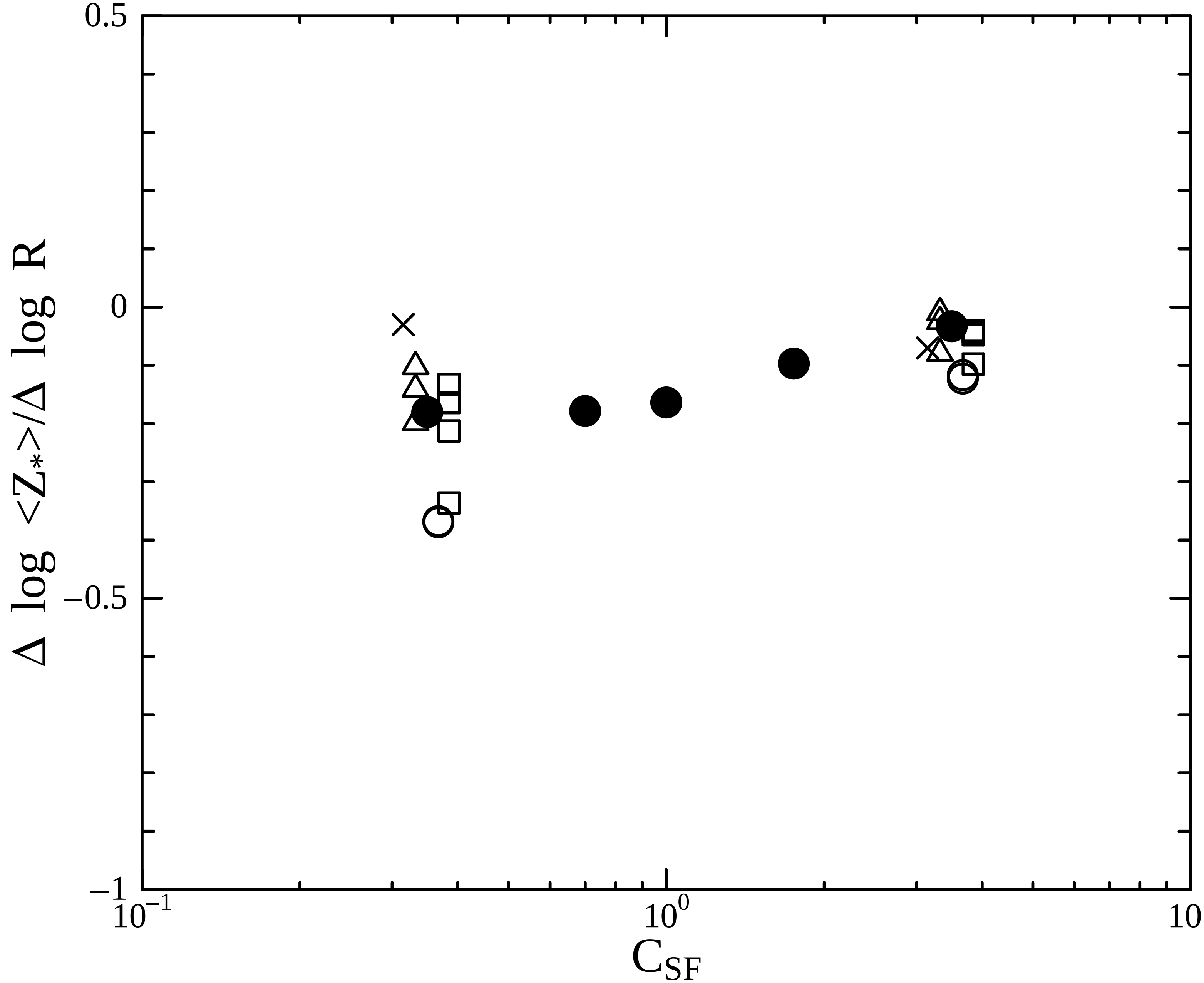
10^1
10^0
10^{-1}
$\langle T_* \rangle$
10^{-1}
10^0
10^1
R/R_{eff}
C_{SF}=0.35
C_{SF}=3.5



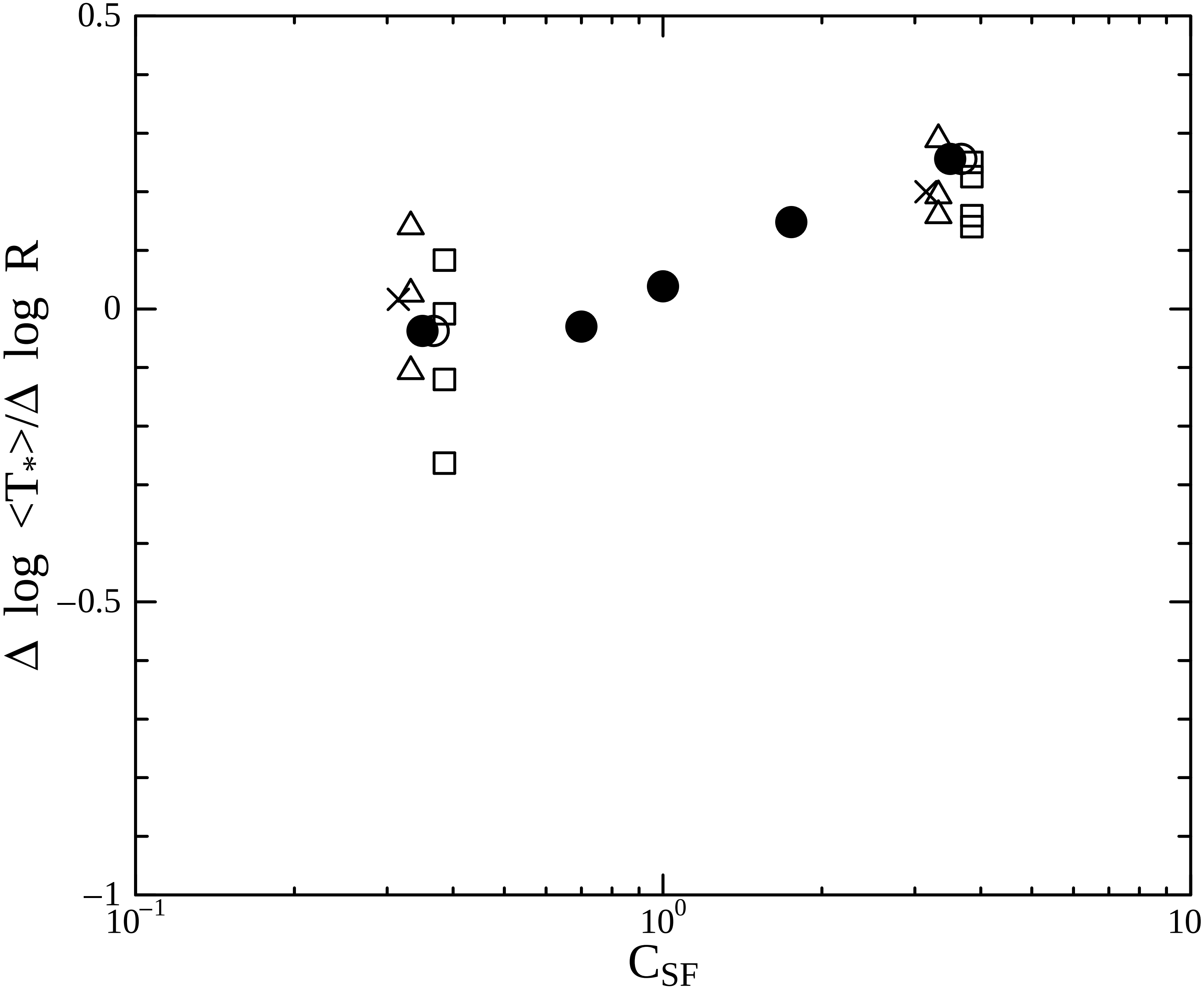
1
0.5
0
−0.5
−1
−1
−0.5
0
0.5
1
x
y

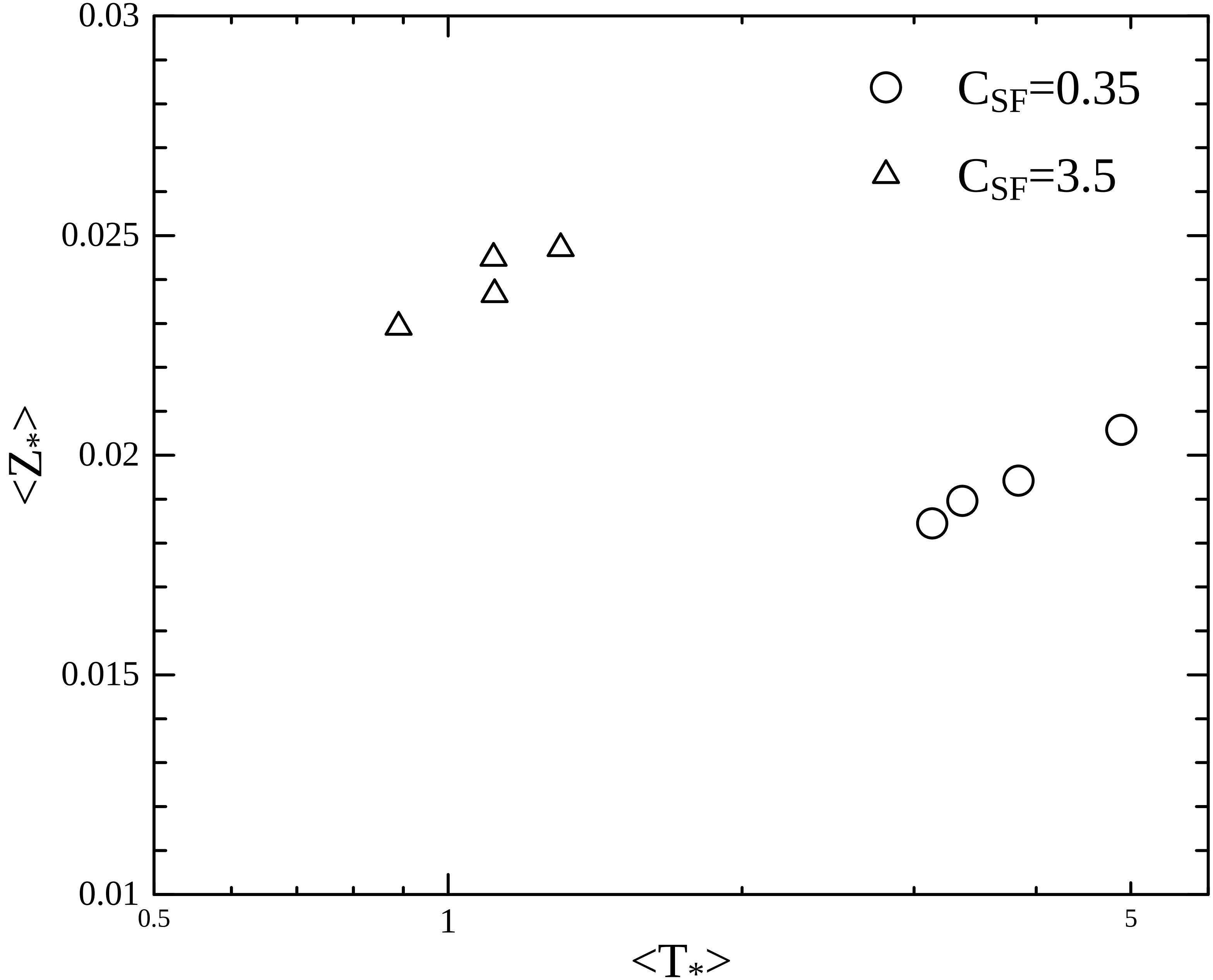

0.03
0.025
0.02
0.015
0.01
$\langle Z_* \rangle$
10^{-1}
10^{0}
10^{1}
C_{SF}


6
4
2
0
$\langle T_* \rangle$
10^{-1}
10^{0}
10^{1}
C_{SF}

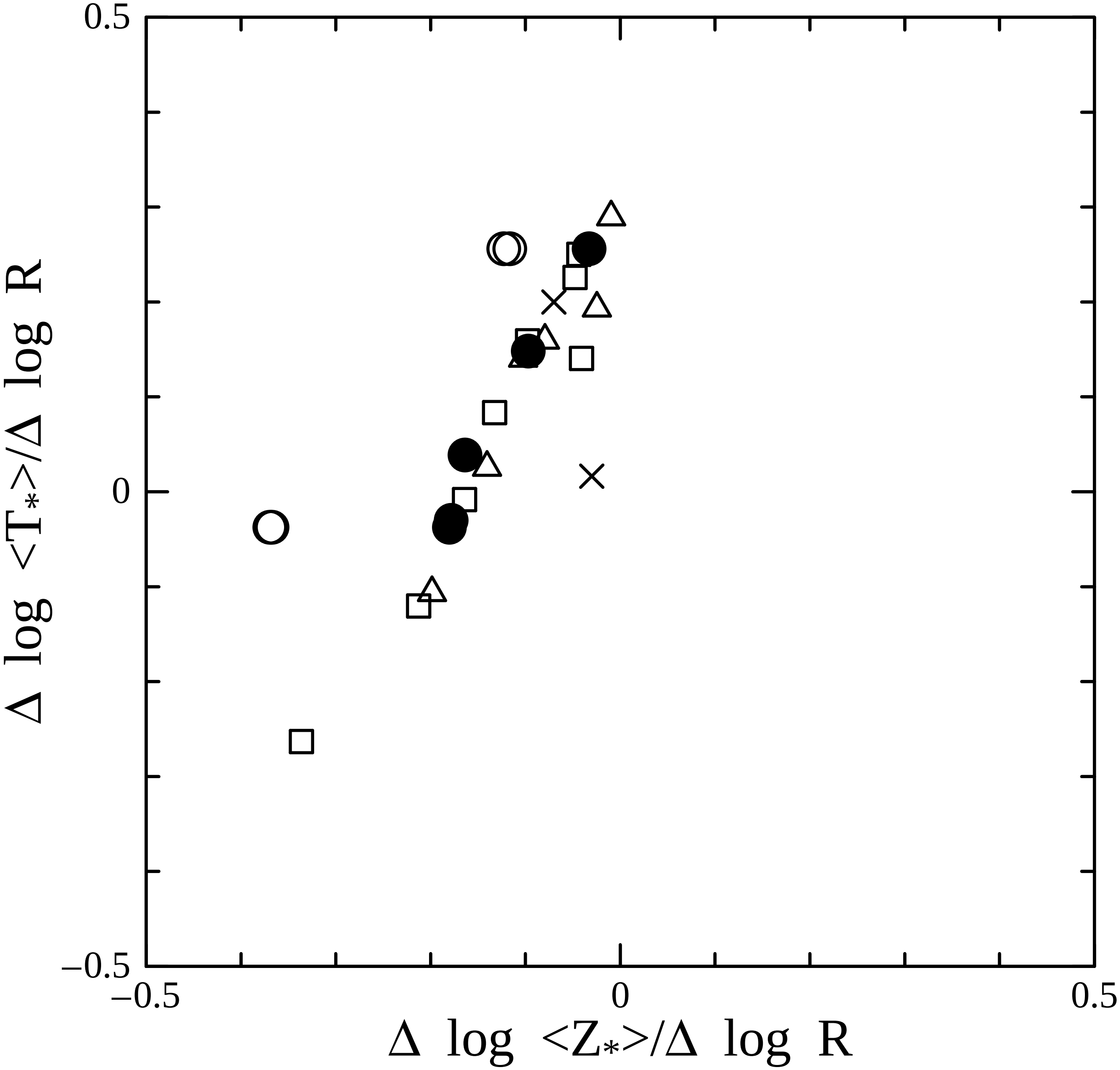


0.5
0
−0.5
−1
10^{-1}
10^{0}
10^{1}
C_{SF}
$\Delta \log \langle Z_* \rangle / \Delta \log R$

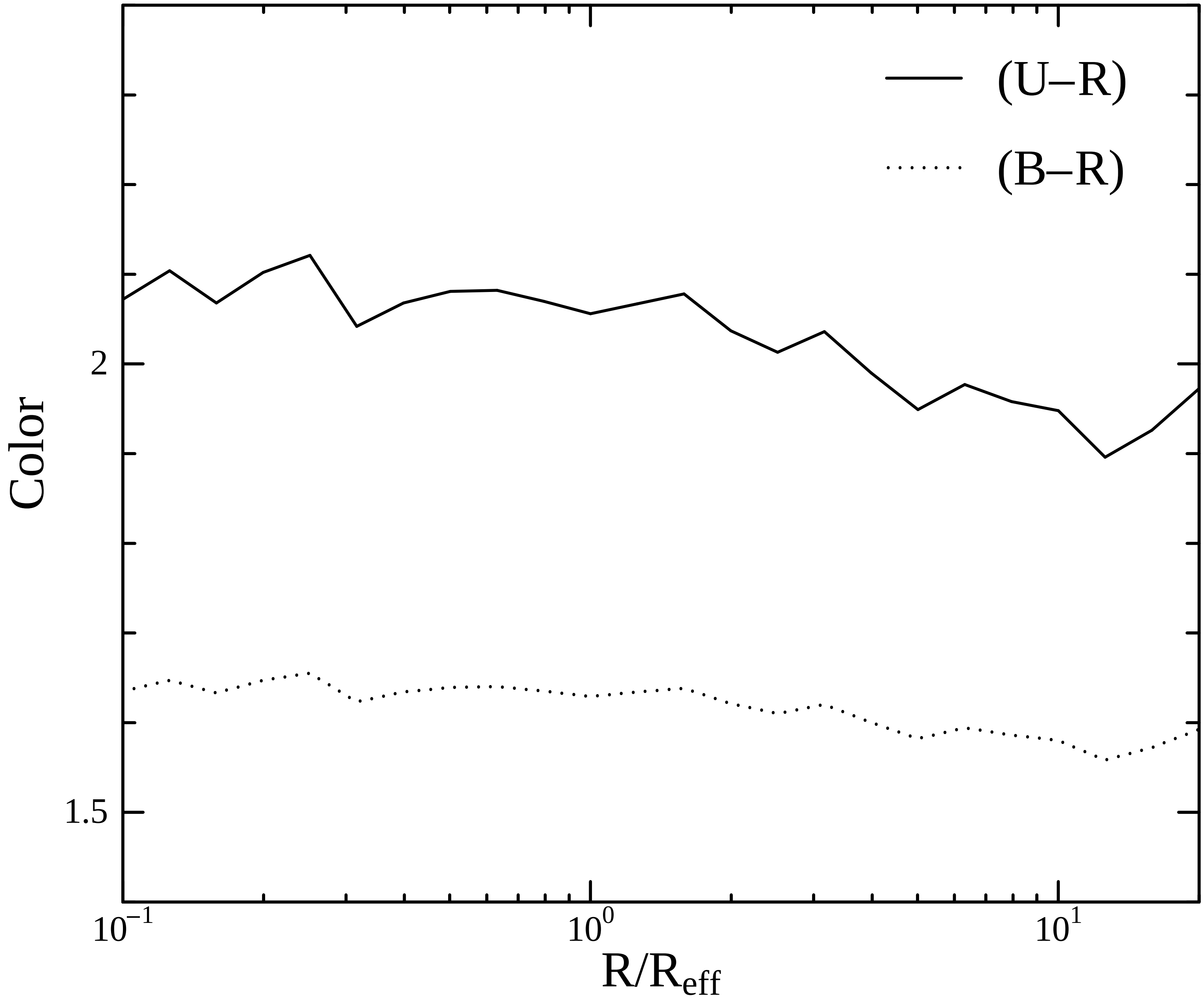

0.5
0
−0.5
−1
10^{-1}
10^{0}
10^{1}
C_{SF}
Δ log $<T_*>/\Delta$ log R



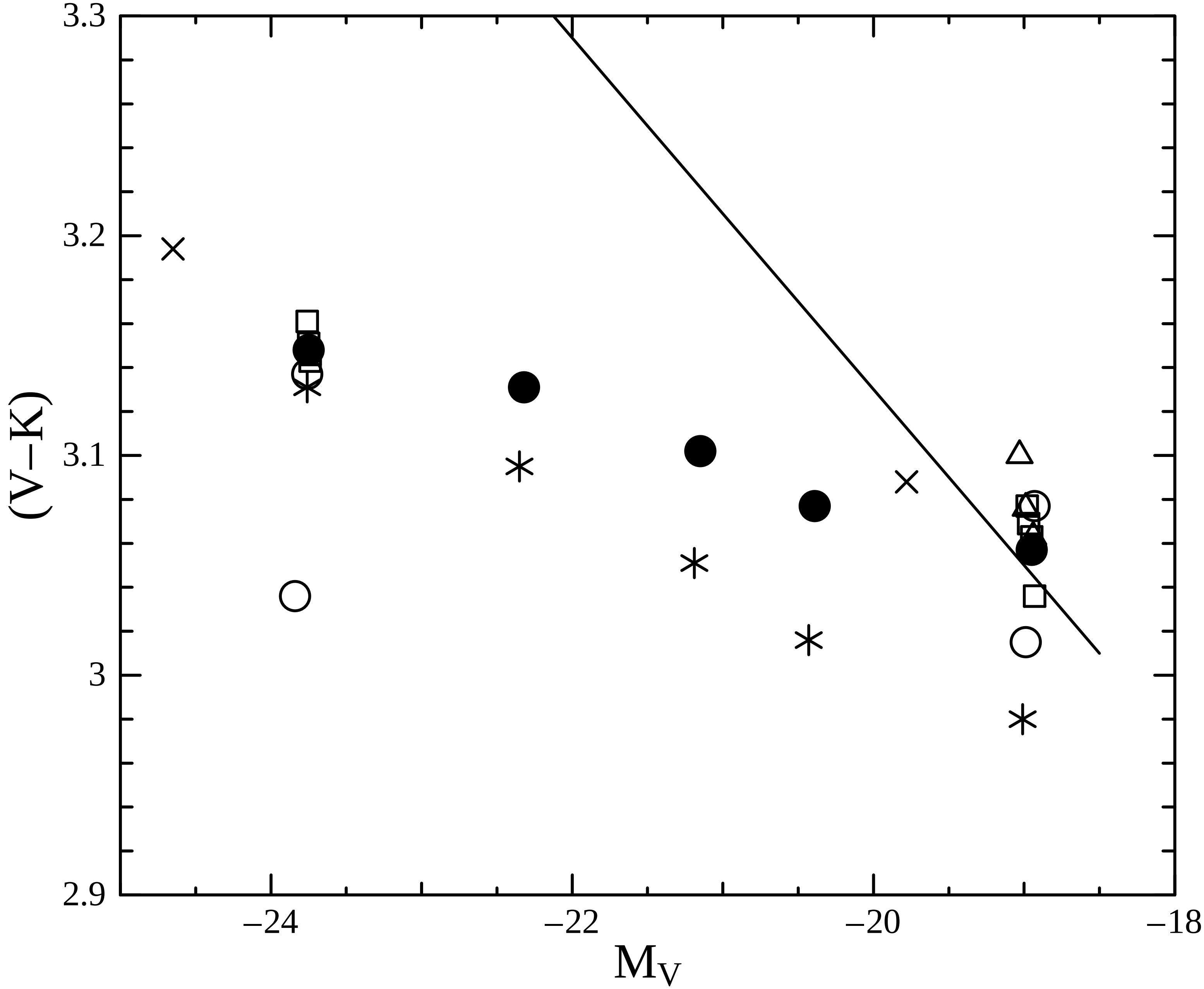
C_SF=0.35
C_SF=3.5
0.03
0.025
0.02
0.015
0.01
0.5
1
5
<Z*>
<T*>

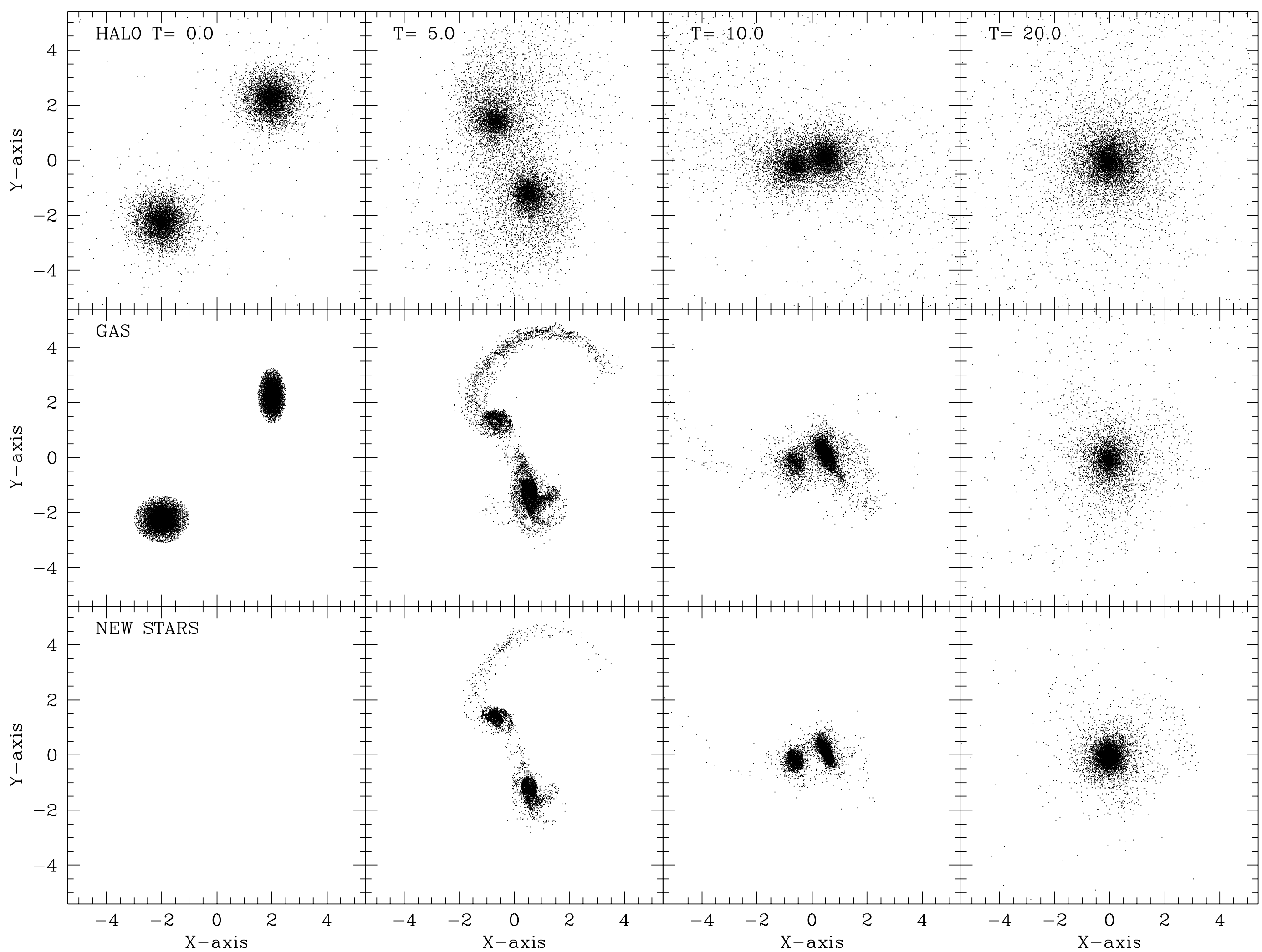


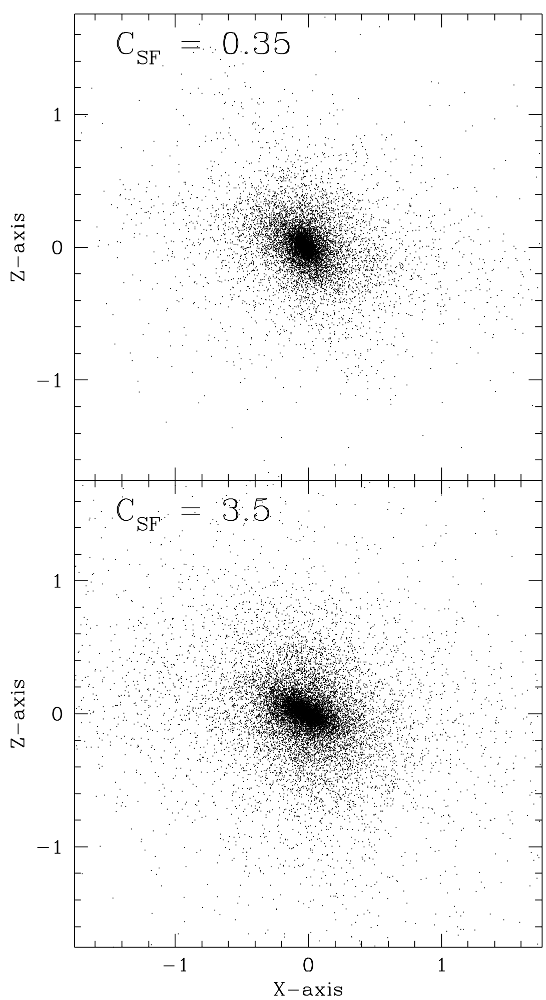
0.5
0
−0.5
−0.5
0
0.5
Δ log <T*>/Δ log R
Δ log <Z*>/Δ log R



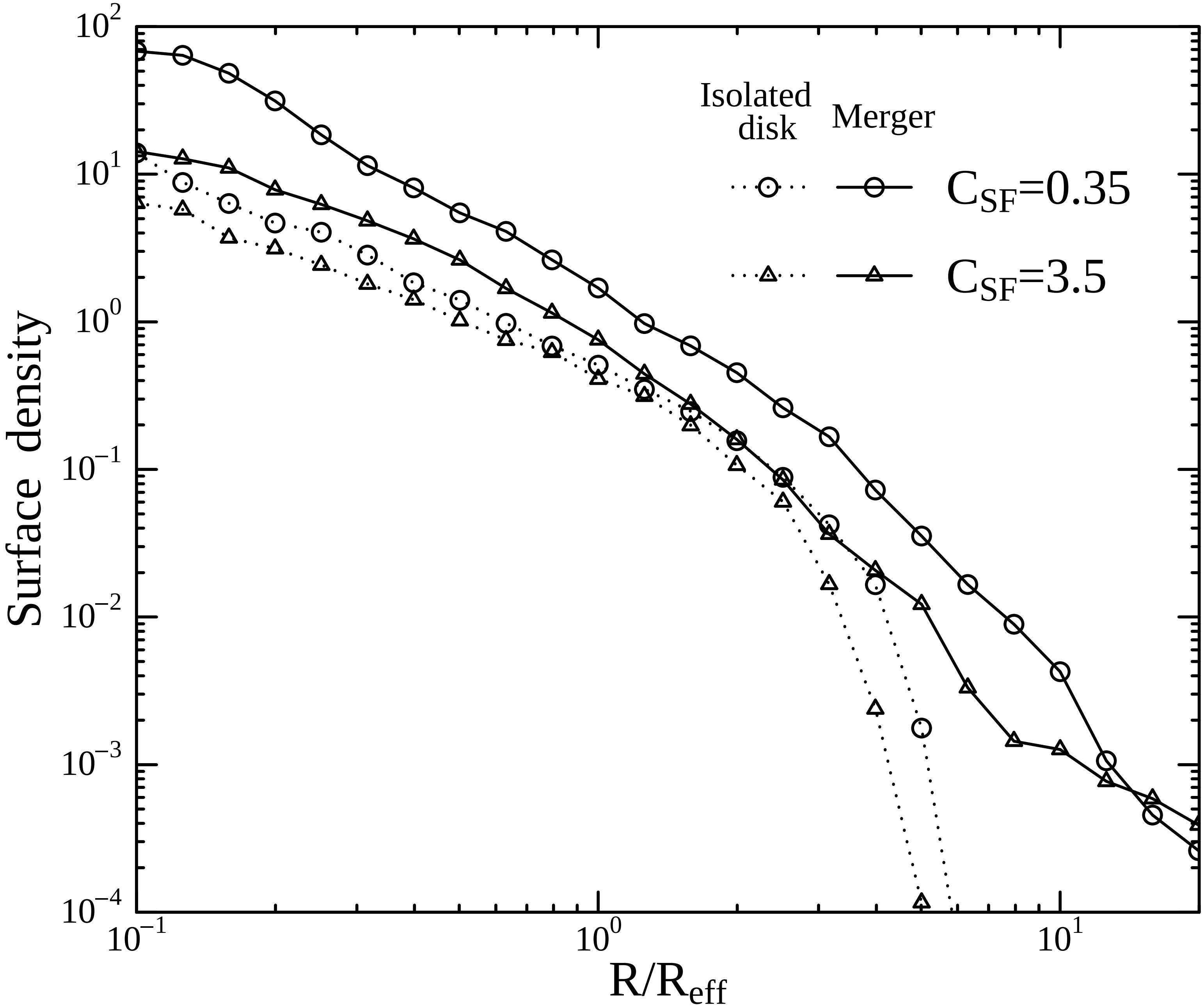
(U–R)
(B–R)
Color
2
1.5
10^{-1}
10^{0}
10^{1}
R/R_{eff}


3.3
3.2
3.1
3
2.9
(V–K)
−24
−22
−20
−18
M_V


HALO T= 0.0
T= 5.0
T= 10.0
T= 20.0
GAS
NEW STARS
Y−axis
X−axis



C_{SF} = 0.35
C_{SF} = 3.5
Z−axis
Z−axis
X−axis
1
0
−1
1
0
−1
−1
0
1



Surface density
R/R_eff
Isolated disk
Merger
C_SF=0.35
C_SF=3.5
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-1
10^0
10^1

TABLE 1

Model parameters and summary of the results

model No.	$C_{\rm SF}$	$R_{\rm che}$	$r_{\rm in}$	$r_{\rm p}$	$< Z >$	$< Z_* >$	f_g	$< Z_{\rm Sim} >$	$< Z_{*,\rm Sim} >$	$< T_* >$	$T_{M*/M=0.6}$	$\left.\frac{\Delta \log < Z_* >}{\Delta \log R}\right\|_{xy}$
A1	0.35	0.4	—	—	0.0321	0.0191	0.250	0.0416	0.0162	3.479	6.4	-0.465
A2	3.5	0.4	—	—	0.0581	0.0243	0.086	0.0735	0.0231	0.920	0.9	-0.279
A3	0.35	0.4	—	—	0.0213	0.0130	0.440	0.0246	0.0106	4.154	> 25	-0.948
A4	3.5	0.4	—	—	0.0234	0.0144	0.396	0.0278	0.0118	3.624	1.8	-0.938
B1	0.35	0.4	6.0	1.0	0.0250	0.0185	0.313	0.0349	0.0141	3.115	6.8	-0.180
B2	0.7	0.4	6.0	1.0	0.0287	0.0198	0.260	0.0405	0.0158	2.189	3.7	-0.178
B3	1.0	0.4	6.0	1.0	0.0332	0.0211	0.208	0.0471	0.0174	1.952	2.7	-0.164
B4	1.75	0.4	6.0	1.0	0.0412	0.0226	0.149	0.0571	0.0200	1.533	1.8	-0.097
B5	3.5	0.4	6.0	1.0	0.0514	0.0237	0.106	0.0673	0.0220	0.948	1.0	-0.033
B6	0.35	0.1	6.0	1.0	0.0182	0.0215	0.313	0.0349	0.0141	3.115	6.8	-0.367
B7	3.5	0.1	6.0	1.0	0.0478	0.0241	0.106	0.0673	0.0220	0.948	1.0	-0.117
B8	0.35	0.02	6.0	1.0	0.0164	0.0221	0.313	0.0349	0.0141	3.115	6.8	-0.370
B9	3.5	0.02	6.0	1.0	0.0457	0.0241	0.106	0.0673	0.0220	0.948	1.0	-0.123
B10	0.35	0.4	3.0	1.0	0.0237	0.0190	0.310	0.0350	0.0142	3.345	8.7	-0.199
B11	0.35	0.4	12.0	1.0	0.0267	0.0194	0.276	0.0386	0.0153	3.823	7.6	-0.141
B12	0.35	0.4	18.0	1.0	0.0295	0.0206	0.234	0.0436	0.0167	4.876	7.3	-0.102
B13	3.5	0.4	3.0	1.0	0.0452	0.0229	0.128	0.0617	0.0210	0.890	0.9	-0.079
B14	3.5	0.4	12.0	1.0	0.0589	0.0245	0.079	0.0763	0.0235	1.113	1.0	-0.010
B15	3.5	0.4	18.0	1.0	0.0594	0.0247	0.075	0.0779	0.0237	1.150	0.9	-0.025
C1	0.35	0.4	6.0	1.0	0.0266	0.0190	0.288	0.0373	0.0149	3.278	6.4	-0.164
C2	3.5	0.4	6.0	1.0	0.0528	0.0238	0.102	0.0686	0.0222	0.954	1.0	-0.048
D1	0.35	0.4	6.0	1.0	0.0247	0.0188	0.305	0.0356	0.0144	2.994	5.7	-0.336
D2	3.5	0.4	6.0	1.0	0.0502	0.0234	0.108	0.0667	0.0219	0.953	1.0	-0.041
E1	0.35	0.4	6.0	1.0	0.0251	0.0171	0.333	0.0330	0.0135	3.069	8.2	-0.133
E2	3.5	0.4	6.0	1.0	0.0558	0.0242	0.0867	0.0734	0.0230	1.045	0.9	-0.044
F1	0.35	0.4	6.0	0.5	0.0259	0.0196	0.283	0.0379	0.0151	3.391	7.1	-0.213
F2	3.5	0.4	6.0	0.5	0.0496	0.0233	0.115	0.0648	0.0216	0.902	1.0	-0.098
G1	0.35	0.4	—	—	0.0169	0.0186	0.396	0.0278	0.0118	4.271	19.0	-0.030
G2	3.5	0.4	—	—	0.0237	0.0216	0.253	0.0413	0.0161	3.153	5.7	-0.070