FORMATION AND EVOLUTION OF DUSTY STARBURST GALAXIES. I. A NEW METHOD FOR DERIVING A SPECTRAL ENERGY DISTRIBUTION

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ABSTRACT

We present a new numerical code that is designed to derive a spectral energy distribution (SED) for an arbitrary spatial distribution of stellar and gaseous components in a dusty starburst galaxy. We apply a ray-tracing method to numerical simulations and thereby estimate extinction and reemission of stellar light by dusty gas in an explicitly self-consistent manner. By using this code, we can investigate simultaneously dynamical and photometric evolution of a dusty galaxy based on stellar and gaseous dynamical simulations. As an example, we demonstrate when and how a major galaxy merger with dusty starburst becomes an ultraluminous infrared galaxy owing to strong internal dust extinction. We furthermore discuss advantages and disadvantages of the present new code in clarifying the nature and the origin of low- and high-redshift dusty starburst galaxies.

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

1. INTRODUCTION

Recent observational studies have discovered possible dusty starburst candidates in various classes of galactic objects such as low-$z$ ultraluminous infrared galaxies (ULIRGs) (e.g., Sanders et al. 1988; Sanders & Mirabel 1996), intermediate-$z$ ones (e.g., Tran et al. 1999), faint sub-millimeter sources detected by the Submillimeter Common-User Bolometer Array (SCUBA) (Holland et al. 1999) on the James Clerk Maxwell Telescope (Smail, Ivison, & Blain 1997; Hughes et al. 1998; Burger et al. 1998; Smail et al. 1998; Ivison et al. 1999; Lilly et al. 1999), extremely red objects (EROs) (Elston, Rieke, & Rieke 1988; Graham & Dey 1996; Cimatti et al. 1998; Dey et al. 1999; Smail et al. 1999), optically faint radio sources detected by the Very Large Array (VLA) (e.g., Richards et al. 1999), Lyman-break galaxies (Steidel et al. 1996; Lowenthal et al. 1997), and near-infrared emission-line galaxies (e.g., Mannucci et al. 1998). These dusty starburst candidates are generally considered to provide valuable information on the formation and the evolution of galaxies; accordingly, the origin and the nature of these galaxies have been extensively discussed in variously different contexts. These discussions include, for example, the importance of dissipative dynamics in the formation of elliptical galaxies at low and high redshift (Kormendy & Sanders 1992; Barnes & Hernquist 1992), an evolutionary link between starburst and active galactic nuclei (Norman & Scoville 1988), fueling of dusty gas to the central $\sim 100$ pc for nuclear starburst in major galaxy mergers (e.g., Mihos & Hernquist 1996), physical correlations between morphological and photometric properties in ULIRGs (Bekki, Shioya, & Tanaka 1999; Bekki & Shioya 2000a), merging and clustering processes of high-$z$ dusty mergers within a hierarchical clustering scenario (e.g., Somerville & Primack 1998), and cosmic star formation history (e.g., Pei & Fall 1995; Meurer et al. 1997; Madau, Pozzetti, & Dickinson 1998; Pascalele, Lanzetta, & Fernandez-Soto 1998; Blain et al. 1999; Steidel et al. 1999). One of important problems in extragalactic astronomy is to settle the above discussions on high-redshift dusty starburst galaxies, though observational analysis still has some difficulties in determining precisely redshifts (Sanders 1999), identifying optical counterparts (Richards 1999), and estimating the degree of dust extinction (e.g., Meurer, Heckman, & Calzetti 1999) for high-$z$ dusty starburst galaxies.

Spectral energy distributions (SEDs) are generally considered to be one of essentially important factors that can determine the nature of dusty starburst galaxies. Accordingly, several theoretical attempts have been made to derive the SEDs of galaxies with dusty starburst regions. Rowan-Robinson & Crawford (1989) discussed how the far-infrared spectra of a sample of galaxies observed by Infrared Astronomical Satellite (IRAS) can be reproduced by a theoretical model with a given temperature of stars embedded by dust, the optical depth, and the density distribution (or geometry) of dust. Witt, Thronson, & Capuano (1991) investigated transfer processes of stellar light for models with variously different spherical geometries of dust with special emphasis on the effects of scattered light on photometric properties of galaxies and SEDs. Calzetti, Kinney, & Storchi-Bergmann (1994) analyzed ultraviolet (UV) and optical spectra of 39 starburst and blue compact galaxies and thereby provided an analytical formulation of the effects of dust extinction in galaxies and an effective extinction law for correcting the observed UV and optical spectral continua. Witt & Gordon (1996) investigated the radiative transfer processes of a central stellar source surrounded by a spherical, statistically homogeneous but clumpy two-phase scattering medium and found that the structure of a dusty medium can greatly affect the conversion of UV, optical, and near-infrared radiation into thermal far-IR dust radiation in a dusty system. By comparing the observed SEDs of 30 starburst galaxies with theoretical radiative transfer models of dusty systems, Gordon, Calzetti, & Witt (1997) discussed the importance of
geometry of stellar and gaseous components in determining the SED of a dusty starburst galaxy. Takagi, Arimoto, &
Vansevičius (1999) investigated radiative transfer models with variously different ages of secondary starburst components and optical depths for dusty starburst galaxies and proposed a new method for estimating precisely the effect of ages of young starburst populations and that of dust attenuation on the shape of SED in UV and near-infrared bands. Efstathiou, Rowan-Robinson, & Siebenmorgen (2000) treated starburst galaxies as an ensemble of optically thick giant molecular clouds (GMCs) centrally illuminated by recently formed stars and thereby constructed a new radiative transfer model for calculating SEDs from UV to millimeter band of dusty starburst galaxies. By using this model, they discussed how the age and the star formation history of a dusty starburst galaxy can control the SED, particularly for the prototypical starburst galaxy M82 and NGC 6090.

Although the above previous studies have succeeded in clarifying important dependences of SEDs on physical parameters such as spatial distribution of dust, geometries of stellar and gaseous components, and dust properties in dusty starburst galaxies, many of them did not discuss the time evolution of SEDs. Main reasons for some previous theoretical studies’ not discussing the time evolution of SEDs are the following three. First, previous models did not follow the time evolution of stellar and gaseous distribution and accordingly could not derive the time evolution of SEDs in dusty starburst galaxies. Second, hydrodynamical evolution of interstellar gas (e.g., time evolution of gaseous density) was not included in previous studies, and accordingly the time evolution of optical depth could not be derived. Third, some previous studies did not consider chemical evolution of dusty interstellar medium and that of stellar components, they could not follow time evolution of metallicity and that of dust properties. Considering that low-z infrared luminous galaxies with dusty starburst and high-z faint SCUBA sources with possible dusty starburst show very peculiar morphology (Sanders et al. 1988; Sanders & Mirabel 1996; Smail et al. 1998), spherical symmetric approximation or axisymmetric one adopted in previous theoretical and numerical studies for the stellar and gaseous distribution of a dusty galaxy should be also relaxed in order that the nature and the origin of low- and high-z dusty galaxies can be extensively investigated by theoretical studies.

The purpose of the present paper and our future papers is to investigate in detail the formation and the evolution of dusty starburst galaxies by using a new numerical code for deriving the time evolution of SEDs of these galaxies. We first perform numerical simulations that can follow dynamical evolution of stellar and gaseous components, star formation history, and chemical evolution for dusty starburst galaxies in an explicitly self-consistent manner. We then derive stellar and gaseous distribution and age and metallicity distribution of stellar populations and thereby calculate galactic SEDs. Furthermore, we describe how the present numerical code is useful and helpful for investigating variously different physical properties of low- and high-z dusty galaxies. As an example, we here present the results of a major merger with dusty interstellar gas. We particularly demonstrate how dynamical evolution of stellar and gaseous components controls the time evolution of SEDs in dusty galaxy mergers and thus their photometric evolution.

The layout of this paper is as follows. In § 2 we summarize numerical models used in the present study and describe in detail the methods for deriving the SEDs corrected by internal dust extinction. In this section we also point out the limitations of the present numerical code. In § 3 we present numerical results on the time evolution of morphology, SED, and photometric properties in a gas-rich major merger. In § 4 we discuss the origin of high-z dusty starburst galaxies such as faint SCUBA sources and EROs. The conclusions of the present study are given in § 5.

2. MODEL

The most remarkable difference in deriving SEDs of dusty galaxies between the present model and previous models (e.g., Mazzei, Xu, & De Zotti 1992; Franceschini et al. 1994; Witt & Gordon 1996; Gordon et al. 1997; Guidorzi et al. 1998) is that we derive SEDs of galaxies based on the result of numerical simulations that can follow both dynamical and chemical evolution of galaxies. The derivation of an SED for a galaxy with dusty starburst consists of the following three steps. In the first step we simultaneously derive age and metallicity distribution of stellar component in the galaxy, based on numerical simulations. Second, we use a stellar population synthesis code (e.g., Bruzal & Charlot 1993) and thereby calculate the SED of the galaxy, based on the derived age and metallicity distribution of stellar population in the galaxy. In this second step, the dust effects are not included. Third, we consider extinction and reemission of stellar light by dusty interstellar gas and modify the SED of the galaxy, by using our new code. The details of our new method for modifying galactic SEDs are given in § 2.3.

2.1. Merger Model

2.1.1. Initial Conditions

We construct models of galaxy mergers between gas-rich disk galaxies with equal mass by using Fall-Elstathiou model (1980). The total mass and the size of a progenitor disk are $M_d$ and $R_p$, respectively. From now on, all the mass and length are measured in units of $M_d$ and $R_p$, respectively, unless specified. Velocity and time are measured in units of $v = (GM_d/R_d)^{1/2}$ and $t_{\text{dyn}} = (R_d/GM_d)^{1/2}$, respectively, where $G$ is the gravitational constant and assumed to be 1.0 in the present study. If we adopt $M_d = 6.0 \times 10^{10} \ M_{\odot}$ and $R_p = 17.5 \ \text{kpc}$ as a fiducial value, then $v = 1.21 \times 10^2 \ \text{km \ s}^{-1}$ and $t_{\text{dyn}} = 1.41 \times 10^8 \ \text{yr}$, respectively. In the present model, the rotation curve becomes nearly flat at 0.35 radius with the maximum rotational velocity $v_m = 1.8$ in our units. The corresponding total mass $M_t$ and halo mass $M_h$ are 5.0 and 4.0 in our units, respectively, which means that the baryonic mass fraction of the initial disk galaxy is 0.2. The radial ($R$) and vertical ($Z$) density profile of a disk are assumed to be proportional to $\exp \left( -R/R_0 \right)$ with scale length $R_0 = 0.2$ and to $\text{sech}^2(Z/Z_0)$ with scale length $Z_0 = 0.04$ in our units, respectively. The velocity dispersion of halo component at a given point is set to be isotropic and given according to the virial theorem. In addition to the rotational velocity made by the gravitational field of 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) $Q = 1.2$. The vertical velocity dispersion at given radius is set to be 0.5 times as large as the radial velocity dispersion at that
point, as is consistent with the observed trend of the Milky Way (e.g., Wielen 1977). As is described above, the present initial disk model does not include any remarkable bulge components, and accordingly corresponds to "purely" late-type spiral without galactic bulge. Although it is highly possible that galactic bulges greatly affect the chemical evolution of galaxy mergers, we however investigate this issue in our future papers.

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, the 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. We assume that the fraction of gas mass ($f_g$) in a disk is set to be 0.5 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. For example, recent observational results on the total mass of molecular gas for faint SCUBA sources (e.g., Frayer et al. 1999a, 1999b) revealed that SMM J14011+0252 with some indications of major merging at $z = 2.565$ has $\sim 5.0 \times 10^{10} M_\odot$. If the progenitor of this gas-rich high-redshift merger has a mass of $6.0 \times 10^{10} M_\odot$ (i.e., the same as that of the Galaxy), the gas mass fraction is $\sim 0.42$ for this galaxy. The gas mass fraction is observationally suggested to be larger for higher redshift mergers (e.g., Evans, Surace, & Mazzarella 1999). Guided by these observational results, we adopt the above value (0.5) as the initial gas mass fraction in order to discuss higher redshift galaxy mergers. Although the difference of gas mass fraction probably could yield a great variety of chemical and dynamical structures in mergers, we do not intend to consider this important difference for simplicity in the present paper and will address in our future paper. The radial and tangential restitution coefficient for cloud-cloud collisions are set to be 1.0 and 0.0, respectively. The number of particles for an above isolated galaxy is 10,000 for dark halo, 10,000 for stellar disk components, and 10,000 for gaseous ones.

In all of the simulations of mergers, the orbit of the two disks is set to be initially in the $x$-$y$ plane and the distance between the center of mass of the two disks, represented by $r_{\text{int}}$, is assumed to be the free parameter that controls the epoch of galaxy merging. The pericenter distance, represented by $r_p$, is also assumed to be the free parameter that controls the initial total orbital angular momentum of galaxy mergers. The eccentricity is set to be 1.0 for all models of mergers, meaning that the encounter of galaxy merging is parabolic. The spin of each galaxy in a pair merger is specified by two angle $\theta_i$ and $\phi_i$, where suffix $i$ is used to identify each galaxy. $\theta_i$ is the angle between the $z$-axis and the vector of the angular momentum of a disk. $\phi_i$ is the azimuthal angle measured from $x$-axis to the projection of the angular momentum vector of a disk onto $x$-$y$ plane. In the present study, we show the results of only one model with $\theta_1 = 0.0, \theta_2 = -150.0, \phi_1 = 0.0, \phi_2 = 0.0, r_p = 17.5$ kpc, and $r_{\text{int}} = 140$ kpc: This model describes a nearly prograde-retrograde merger. The results of the models with variously different $\theta_i, \phi_i, r_p$ and $r_{\text{int}}$ will be described in our future papers. 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, $M_\star$, is given as

$$M_\star \propto C_{SF} \times (\rho_g / \rho_0)^{\gamma-1.0},$$

where $\rho_g$ and $\rho_0$ are the gas density around each gas particle and the mean gas density at 0.48 radius of an initial disk, respectively. This density-dependent star formation model is similar to that of Mihos, Richstone, & Bothun (1992), and the probability approach of the gas consumption rate is similar to that described by Katz (1992) and O’Neil et al. (1998). 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, $P_{\text{SF}}$, that the gas particle is converted into stellar one by setting the $P_{\text{SF}}$ to be proportional to the $M_\star$ 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 $C_{SF}$ in the equation (1) is the parameter that controls the rapidity of gas consumption by star formation. We determine the initial value of the $C_{SF}$ so that mean star formation rate of an isolated late-type disk galaxy model with the typical gas mass fraction of $\sim 0.2$ can become an order of $1 M_\odot \text{yr}^{-1}$ for the first 1 Gyr evolution. The positions and velocity of the new stellar particles are set to be the same as those of original gas particles.

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

2.2. Method for the SED of Stellar Populations

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 $R_{\text{chemi}}$ from the position of the new stellar particle and then count the number of the neighbor gas particles, $N_{\text{gas}}$. This $R_{\text{chemi}}$ 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 $R_{\text{chemi}}$ relative to the typical size of a galaxy is set to be 0.01. 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:

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

(2)

where the $\Delta M_Z$ represents the increase of metal for each gas particle, $Z_i$, $R_{\text{met}}$, $m_s$, and $y_{\text{met}}$ 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 $R_{\text{met}}$ and that of $y_{\text{met}}$ are set to be 0.2 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:

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

(3)

where $m_t$, $m_g$, 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 $R_{\text{met}}$ is 0.0. Thus, in testing the validity of the present code of chemical enrichment, we set the value of $R_{\text{met}}$ 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 $R_{\text{met}}$ is not 0.0, the difference in the value of total metallicity between the left- and right-hand sides in the above equation is negligibly small. Our numerical results do not depend so strongly on $R_{\text{chemi}}$, $R_{\text{met}}$, and $y_{\text{met}}$ within plausible and realistic ranges of these parameters.

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

$$F_\lambda(T) = \sum_{\text{star}} F_{\text{SSP},i}(Z_{i}, \tau_i) \times m_s,$$

(4)

where $F_{\text{SSP},i}(Z_{i}, \tau_i)$ and $m_s$ are a monochromatic flux of SSP of age $\tau_i$ and metallicity $Z_{i}$, where suffix $i$ identifies each stellar particle, and mass of each stellar particle, respectively. The age of SSP, $\tau_i$, is defined as $\tau_i = T - t_i$, where $t_i$ is the time when a gas particle is converted into 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

$$F_{\text{SSP},i}(Z_{i}, \tau_i) = \int_{M_{\text{cl}}}^{M_{\text{u}}} \phi(M) f_{\text{s}}(M, \tau_i, Z_{i}) dM,$$

(5)

where $M$ is mass of a star, $f_{\text{s}}(M, \tau_i, Z_{i})$ is a monochromatic flux of a star with mass $M$, metallicity $Z_{i}$ and age $\tau_i$, $\phi(M)$ is a initial mass function (IMF) of stars and $M_{\text{cl}}$, $M_{\text{u}}$ are upper and lower mass limit of IMF, respectively. We here adopt the Salpter IMF with $M_{\text{cl}} = 120 M_{\odot}$ and $M_{\text{u}} = 0.1 M_{\odot}$. In this paper, we use the $F_{\text{SSP},i}(Z_{i}, \tau_i)$ of GISSEL96, which is the latest version of Bruzual & Charlot (1993).

2.3. Model of Internal Dust Extinction

2.3.1. Derivation of an SED Modified by Dust Effects

Using the derived each stellar particle’s SED not corrected by dust ($F_{\text{SSP},i}(Z_{i}, \tau_i) \times m_s$ shown in equation (4)) and stellar and gaseous distribution, we can obtain the SED of a galaxy corrected by dust. From now on the SED of a stellar particle, $F_{\text{SSP},i}(Z_{i}, \tau_i) \times m_s$ is referred to as $F_{\text{sed},i}$ for convenience. We first calculate dust extinction of star light for each stellar particle and dust temperature for each gaseous particle, based on the three-dimensional spatial distribution of stellar and gaseous particles. We then sum each stellar particle’s SED corrected by dust extinction and the dust reemission of each gaseous particle. The method to derive the dust extinction and reemission for each particle consists of the following three steps. First we assume that each stellar particle with the SED $F_{\text{sed},i}$ emits rays with the SED for each of the rays equal with $F_{\text{sed},i}/N_{\text{ray},i}$, where $N_{\text{ray},i}$ is the total number of the rays. We generate random numbers for each ray and thereby determine the direction of each ray from the stellar particle. Figure 1 represents a schematic explanation of this first step. $N_{\text{ray},i}$ is set to be 10 for all stellar particles in the present study. Second, we investigate whether each of rays emitted from a stellar particle can penetrate a gas particle for all gas particles and thereby estimate dust extinction of stellar light for each of the rays. This investigation and estimation is done for all stellar particles. The second step is to regard a ray as penetrating a gas particle and thus being affected by internal dust extinction if the ray passes through the region within the gas cloud radius ($r_{cl}$). This second step is also schematically shown in Figure 1. Here gas clouds with the masses of $m_{cl}$ are assumed to be spherical and the cloud radius $r_{cl}$ is changed following the relation (Kwan & Valdes 1987),

$$r_{cl} = k_{cl} \times \left( \frac{m_{cl}}{4 \times 10^6 M_{\odot}} \right)^{1/3} \text{ pc},$$

(6)
Absorption of stellar light for each of rays from a stellar particle is modeled according to the following reddening formulation (Black 1987; Mazzei et al. 1992); 

$$E(B-V) = N(H)/4.77 \times 10^{21} \text{cm}^{-2} \times (Z_0/0.02),$$

where $N(H)$ and $Z_0$ are gaseous column density and gaseous metallicity, respectively. Since dust absorption is estimated for each of gas particles penetrated by a ray emitted from a stellar particle, the above $N(H)$ and $Z_0$ correspond to column density of each gas cloud particle [$N(H)_n$] and metallicity of the particle ($Z_0$), respectively. The $Z_0$ is derived from our numerical simulations and the $N(H)_n$ is derived from the relation between cloud mass and size shown in equation (6). Using the derived redding $E(B-V)$ and extinction law by Cardelli et al. (1989), we adopt the so-called screen model for rays from a stellar particle and calculate the dust absorption of the stellar particle. Third, by assuming the modified black body radiation with the emissivity ($\varepsilon$) law $\varepsilon \propto v^2$, we determine the dust temperature of a gas particle such that total energy flux of dust absorption is equal to that of dust re-emission. In the present study, we show the results of a model with $\alpha_{em} = 2$. We here do not include the albedo for dust grains, which means that only stars and new stars heat dust. Thus the SED of a galaxy consists of the stellar continuum modified by dust extinction and the re-emission of dusty gas.

The method adopted in the present numerical code calculating dust absorption and re-emission is essentially the same as the so-called ray-tracing method adopted in previous theoretical calculations on radiative transfer problems (e.g., Witt 1977; Efstathiou & Rowan-Robinson 1990). This paper is the first step toward a sophisticated combination of $N$-body simulations with the already existing ray-tracing method. Therefore there are still some problems of the present new code in calculating correctly the SED within feasible timescale for a simulation with the total particle number approximately equal to $10^5$. The most significant problem is on the time that we spent in calculating the SED. The time necessary for the SED calculation for each time step in a simulation can be roughly scaled to $n_g \times n_g \times n_g \times n_g \times n_g$, where $n_g$, $n_g$, and $n_g$ are total particle number of stars, that of gas, and that of rays emitted from each stellar particle. Therefore it is very time-consuming to derive an SED in each time step of a simulation, in particular, for large $N$-body simulations with both $n_g$ and $n_g$ larger than $10^5$: It is obviously our future work to develop a new method for calculating SEDs of such large $N$-body systems. Furthermore, our SED calculation becomes also time-consuming, unless we carefully choose the parameter value of $n_g$. Although we can more correctly estimate SEDs of galaxy mergers with dusty starburst for the models with larger $n_g$, we should adopt a feasible and reasonable value of $n_g$, considering that the time for our SED calculation is roughly proportional to $n_g \times n_g \times n_g$. In order to determine a plausible value of $n_g$, we investigated the dependence of an SED on $n_g$ ($1 \leq n_g \leq 50$) in a dusty starburst merger model and found that if $n_g \geq 10$, the differences in SEDs between models with different $n_g$ become negligibly small. We thus adopt $n_g = 10$ as a feasible and plausible value for our SED calculations in the present study. Although our new numerical method allows us to derive an SED for an arbitrary distribution of stellar and gaseous component for a dusty galaxy in numerical simulations, it still has some problems such as those described above. Both our method and previous ones (i.e., those by which numerical studies can precisely solve radiative transfer processes.

Although physical processes associated with the growth and the disruption of gas clouds have been investigated (e.g., Kwan 1979; Kwan & Valdes 1987; Olson & Kwan 1990a, 1990b), it is not so clear which the most probable and physically reasonable value of $k_{cl}$ is for evolving galaxies. A probable value of $k_{cl}$ is $~0.1$ for disk galaxies (Kwan & Valdes 1987), whereas the typical cloud mass and size depend strongly on time in merging galaxies owing to coalescence and disruption of gas clouds (Olson & Kwan 1990a, 1990b). Olson & Kwan (1990b) demonstrated that although most of the cloud-cloud collisions induced by galaxy merging is disruptive, several very large gas clouds with masses greater than $10^7 M_\odot$ can form after merging owing to successive coalescence of colliding clouds. Furthermore, the density of gas clouds in ULIRGs considered to be ongoing mergers is suggested to be very high from that in disk galaxies (Aalto et al. 1991a, 1991b), which implies that the size and the mass might be also different from those of isolated disk galaxies. Accordingly, it is reasonable for us to assume that $k_{cl}$ is a free parameter for the present study. In the present paper, however, we show only the results for the model with $k_{cl} = 4.68$. The $k_{cl}$ dependence in major mergers will be described in our future papers.
and estimate galactic SEDs within a certain spherical symmetric approximation or axisymmetric one) have advantages and disadvantages, and therefore we stress that the present numerical study is complementary to previous ones.

### 2.3.2. Limitations of the Present Code

Our numerical model can derive an SED for a galaxy with an arbitrary distribution of stellar and gaseous components and accordingly enable us to examine an SED of a galaxy with very peculiar mass distribution, such as galaxy mergers and forming galaxies. However, our model has the following four limitations in investigating the time evolution of SEDs in galaxies. First, we do not include physical processes related to dust production, grain destruction, and grain growth in interstellar medium in the present model and thus cannot follow the time evolution of dust composition. Dwek (1998) developed a new self-consistent model for the evolution of the compositions and abundances of elements and the dust in galaxies by including condensation, accretion, and destruction processes of grains in the model. By using this model, Dwek (1998) investigated the time evolution of dust composition (e.g., whether interstellar gas is silicate rich or not) and suggested that extinction law, which is an important factor for calculating a galactic SED, depends on the evolution. The method developed by Dwek (1998) is mainly for one-zone models of galactic chemical evolution; accordingly, it cannot be so simply applied to N-body numerical simulations. It is thus our future study to combine the method provided by Dwek (1998) with our numerical code and thereby to derive a galactic SED in a more self-consistent manner. Furthermore, Chang, Schiano, & Wolfe (1987) investigated how the radiation from QSOs affect the hydrodynamical evolution of dusty interstellar gas, considering ion-field emission, ion sputtering, coupling between gas ions and dust grains, photoionization, and photoelectrical processes. They found that owing to the high sputtering on the grain surface in dusty interstellar gas, most of the grains inside 7 kpc of a QSO host galaxy can be destroyed within $\sim 3 \times 10^7$ yr. Although their results are not directly related to the dust destruction processes in dusty starburst galaxies, we consider that the essence of their results can be applied to the case of starburst galaxies. The timescale for intense starburst in ULIRGs formed by major mergers is suggested to be $\sim 10^8$ yr and the total luminosity of ULIRGs is similar to QSOs (e.g., Sanders et al. 1988), and accordingly the radiation from nuclear strong starburst can also destroy the dust grains in ULIRGs. If the dust grains are efficiently destroyed by radiation of starburst, the total flux of far-infrared reemission from dusty starburst can be greatly decreased. Our present model does not include this effects of starburst radiation on dust grains, we stress that the total value of infrared and far-infrared luminosity can be overestimated in major mergers with dusty starburst.

Second, we do not consider the effects of small grains with the size between 1 and 10 nm, and consequently cannot precisely estimate an SED around $10^8$ Å in a dusty system. Devriendt, Guiderdoni, & Sadat (1999) included contributions from polycyclic aromatic hydrocarbons (PAHs), small grains, and big ones in their model and succeeded in reproducing reasonably well the SEDs of several ULIRGs. To construct multicomponent dust model is accordingly the next step of our studies toward the more precise estimation of SEDs of dusty galaxies. Third, the parameter $k_{el}$ is fixed at a possibly reasonable value during a simulation; accordingly, our model cannot follow the time evolution of cloud size and mass. Witt & Gordon (1996) demonstrated that the change of the structure of interstellar medium in a dusty system provides the change in effective optical depth and consequently controls the SED of the system. They furthermore suggested that a breakup of large interstellar cloud complexes into numerous smaller clouds and an intercloud medium of enhanced density in a galaxy merger can greatly affect the SED of the merger. Fourth, we do not include the effects of albedo at all in the present study, though several authors have already investigated in detail the effects of dust albedo (e.g., multiple scattering of stellar light) on SEDs in dusty systems (e.g., Witt & Gordon 1996; Gordon et al. 1997). Although the total number of parameters increase if we include the effects of dust albedo in our numerical simulations, it is our future work to investigate the importance of dust albedo in determining galactic SEDs. Thus our numerical results should be carefully interpreted owing to the above four limitations of the code used in the present study.

### 2.4. Main Points of Analysis

The main important advantages of the present study are the following two. First, we can investigate simultaneously morphological, structural, kinematical, and photometric properties at a given time step in a galaxy merger with dusty starburst based on the derived SED of the merger. Second, by using the SED derived for a merger at a given redshift and considering the effects of k-correction, we can investigate how the morphological and photometric properties of the merger change with redshift. Accordingly, we mainly investigate the time evolution of morphology, star formation, global colors, luminosity, and $A_V$ in a dusty starburst galaxy merger. Furthermore, we investigate two-dimensional distributions of colors, luminosity, and $A_V$, which have not been investigated at all in previous theoretical studies of dusty galaxies. In order to discuss apparent morphology of intermediate- and high-z dusty galaxies, we also investigate how dust-enshrouded starburst galaxy mergers at $z = 0.4, 1.0,$ and 1.5 can be seen in the Hubble Space Telescope (HST). The method to construct the synthesized $HST$ images of galactic morphology in the present study is basically the same as that described by Miyoshi (1995) and Bekki, Shioya, & Tanaka (1999). We adopt Madau's model (Madau 1995) for intervening absorption of neutral hydrogen and consider k-correction of galactic SEDs in order to derive the synthesized images. For comparison, we also show how dust-enshrouded starburst galaxy mergers at $z = 0.4, 1.0,$ and 1.5 can be seen in the SUBARU, which is a Japanese large (8.2 m) ground-based telescope. The results on the synthesized $HST$ and SUBARU images are presented in § 3.3 and for discussing the origin of high-z faint SCUBA sources and EROs. In order to calculate the SEDs of the merger model at each redshift, we assume that mean ages of old stellar components initially in a merger progenitor disk at the redshift $z = 0.4, 1.0,$ and 1.5 are 7.14, 3.80, and 2.46 Gyr, respectively.

We here describe mainly the results of only one merger model with $k_{el} = 4.68$ (i.e., $r_{el}$ is 0.011 in our units corresponding to 200 pc) because the main purpose of the present study is not to give dependences of SEDs on physical parameters of galaxy mergers but to demonstrate useful-
Formulations of the present code in studying theoretically dusty starburst galaxies. From now on this mode is referred to as the standard model. We do not intend to change the values of important free parameters such as $M_d$, $M_t$, $r$, $r_p$, $\phi$, $\theta$, and $f_p$ in the present study. Dependences of the evolution of dusty starburst mergers on parameters will be described in our future papers (Bekki & Shioya 2000b). Although each of the results described in the following sections have many implications for the nature of ULIRGs and can be compared with up-to-date observational results such as near-infrared colors (e.g., Scoville et al. 1999), surface brightness distribution (e.g., Sanders et al. 1999; Scoville et al. 1999), and high-resolution optical/near-infrared images of ULIRGs (e.g., Surace, Sanders, & Evans 1999), we do not intend to discuss so extensively the origin and the nature of ULIRGs in the present study: this is simply because the most important purpose of the paper is to demonstrate the importance and the usefulness of the present code in investigating dusty starburst galaxies. We will discuss the origin of ULIRGs in our future papers. In the following the cosmological parameters and are set to be 50 km s$^{-1}$ and 0.5, respectively.

3. RESULT

3.1. Evolution of Morphological Properties and SEDs

Figures 2 and 3 describe time evolution of morphology of the standard model for each of four components, dark halo, stars initially located within two disks, gas, and new stars formed during galaxy merging. From now on, for convenience, the time $T_m$ represents the time that has elapsed since the two disks began to merge. As galaxy merging proceeds, the two disks are strongly disturbed to form a long tidal tail in the disk orbiting in a prograde sense at 0.6 < $T_m$ < 1.1 Gyr. A remarkable tidal tail is not developed in the disk orbiting in a retrograde sense. This one long tidal arm is characteristics of prograde-retrograde mergers. The two disks finally sink into the center of massive dark halos owing to dynamical friction during merging and consequently are completely destroyed by violent relaxation of galaxy merging ($1.1 < T_m < 1.7$ Gyr). As a result of this, the two disks form an elliptical galaxy with the structure and kinematics similar to the observed ones ($T_m = 1.7$ Gyr).

During violent major merging, interstellar gas is very efficiently transferred to the central region of the two disks owing to gaseous dissipation of colliding gas clouds and gravitational torque. Gas accumulated in the central region of the merger is then consumed by massive starburst and consequently converted into new stars. As is shown in Figure 4, the star formation rate becomes maximum ($\sim 378 M_\odot$ yr$^{-1}$) at $T_m = 1.3$ Gyr when two disks of the merger become very close to suffering from violent relaxation. The maximum star formation rate is roughly 2 orders of magnitude larger than the mean star formation rate of an isolated disk in the present study and comparable to that required for explaining the strong infrared luminosity observed in ULIRGs. After the strong starburst, star formation rate rapidly declines ($\sim 1 M_\odot$ yr$^{-1}$) within less than 1 Gyr after $T_m = 1.3$, essentially because most of the gas is consumed up by the starburst. These results are qualitatively consistent with those in Mihos & Hernquist (1996).

We here stress that the above one-time starburst in the late phase of major merging is applied only to the present prograde-retrograde merger with the adopted inclination of two disks and internal structure of the disks. Mihos & Bothun (1998) demonstrated that physical details such as internal structure of merger progenitor disks and their

![Fig. 2.—Time evolution of mass distribution projected onto x-y plane (orbital plane) for dark halo (top row), stars (second row from the top), gas (second row from the bottom), and new stars (bottom row) in the standard merger model at each time $T_m$. The $T_m$ indicated in the upper right-hand corner represents the time that has elapsed since the two disks begin to merge. Here the scale is given in our units (17.5 kpc) and each of the 24 frames measures 200 kpc on a side.](image)
Fig. 3.—Same as Fig. 2, but for mass distribution projected onto $x$-$z$ plane.

Fig. 4.—Time evolution of star formation rate of the standard model. The star formation rate of the merger becomes maximum ($\sim 378 M_\odot$ yr$^{-1}$) at $T_m = 1.3$ Gyr.

Fig. 5.—Mass distribution of stars (left panels), gas (middle panels), and new star (right panels) at $T_m = 1.13$ Gyr projected for $x$-$y$ plane (upper row) and $x$-$z$ one (lower row) in the standard model. Here the scale is given in our units (17.5 kpc) and each of the six frames measures 47 kpc on a side. This figure describes the mass distribution of the merger at the prestarburst epoch.

initial gas mass fraction are important for the star formation history and the luminosity evolution in ULIRGs, by using imaging observations on four ULIRGs. They furthermore found that the spatial distribution of Hα emission from starburst regions is very diverse in the four ULIRGs (i.e., some ULIRGs show the strong Hα emission only in the central region and Hα emission is quite extended in some ULIRGs) and accordingly suggested that several different factors play a role in triggering starburst in ULIRGs. Considering these important observational results, we suggest that the results on the star formation history and the resultant luminosity evolution described in the present study are only true for some ULIRGs.

Figures 5 and 6 give mass distribution projected onto $x$-$y$ plane (orbital plane) and $x$-$z$ plane at $T_m = 1.1$ (prestarburst phase) and 1.7 Gyr (poststarburst phase) for stars, gas, and new stars. New stars formed mainly by secondary massive starburst are more compactly distributed in the merger than old stars initially located within disks at the prestarburst (weak starburst) epoch when the two cores in the merger have not yet merged with each other to form an elliptical galaxy. This is essentially because new stars experience much more gaseous dissipation when they were previously gaseous components. Consequently, new stars with younger ages are more heavily obscured by dusty gas than old stars during galaxy merging. This result, that young stellar components can be preferentially obscured by dust during evolution of galaxy mergers, is suggested to be very important for understanding the nature of poststarburst galaxies detected by Smail et al. (1999) in SCUBA surveys of...
intermediate-redshift clusters of galaxies (Shioya & Bekki 2000). Three very small compact stellar clusters composed mainly of new stars (and gas) can be seen above the two cores at $T_m = 1.1$. This result suggests that efficient star formation during galaxy merging can occur not only in the central part of a merger but also in stellar clusters located in the outer part of the merger. As is shown in Figure 6, the morphology of the merger only $\sim 0.4$ Gyr after the maximum starburst looks like an elliptical galaxy, which implies that the timescale within which a merger can be seen as an ULIRG with the very peculiar morphology is very short (less than 0.5 Gyr).

Figure 7 describes the SEDs of the merger that we derive based on the mass distribution of stellar and gaseous component shown in Figures 2 and 3 and the age and metallicity distribution of stellar populations of the merger at $T_m = 0.6, 1.1, 1.3$ (the epoch of maximum starburst), 1.7, 2.3, and 2.8 Gyr. We can clearly observe how the dust extinction of interstellar gas can change the shape of the SED of the merger at each time by comparing the results of the model with dust extinction with those without dust extinction. The UV flux with the wavelength less than 3000 Å rapidly increases during $1.1 < T_m < 1.3$ Gyr owing to a large number of young massive stars formed by the strong starburst whereas it decreases during $1.3 < T_m < 2.8$ Gyr because of very small star formation rate after the starburst in the model without dust extinction. The infrared and submillimeter fluxes become larger during $1.1 < T_m < 1.3$ Gyr in the model with dust extinction. This is first because star formation rate, which is closely associated with the total mount of stellar light absorbed by interstellar dust, becomes considerably higher owing to the efficient gas transfer to the central region of the merger and second because the density of dusty gas becomes also very high in the later phase of the merging ($1.1 < T_m < 1.3$ Gyr) so that the gas can heavily obscure the strong starburst. After the maximum starburst at $T_m = 1.3$ Gyr, both infrared and submillimeter fluxes rapidly decline ($1.3 < T_m < 1.7$ Gyr). This is principally because most of interstellar gas indispensable for strong starburst and dust obscuration is rapidly consumed by star formation in the merger till $T_m \sim 1.7$ Gyr. Thus the time evolution of SED of a merger depends strongly on that of the star formation rate, which is basically controlled by dynamical evolution of the merger.

Figures 8 and 9 describe the mass distribution and the SED at the epoch of maximum starburst in the standard model, respectively. Figure 8 clearly shows that both new stars and gas are more centrally concentrated than old stellar components, which means that star light from new stars formed by the massive starburst are more heavily obscured by dusty interstellar medium than that of old stellar components. The SED at $T_m = 1.3$ Gyr in Figure 9 is rather similar to the observed SED of typical ULIRGs, which implies that the present dusty starburst merger model can be observed as an ULIRG in the late of galaxy merging. These results in Figure 8 and 9 clearly demonstrate that starburst population in the merger is so heavily obscured by dusty interstellar medium (the mean $A_V \sim 2.46$ mag) that the dust reemission in far-infrared ranges ($L_{IR}$) becomes very strong at the maximum starburst ($L_{IR} = 1.59 \times 10^{12} L_\odot$). The reasons for this heavy dust extinction are first that column density of dusty interstellar medium becomes extremely high owing to the strong central accumulation of gas and second that the central gaseous metallicity, which is a measure of total amount of dust, also becomes rather large ($\sim 0.04$) because of efficient and rapid chemical evolution in galaxy merging with secondary starburst.

Based on the derived mass distribution and SEDs at the maximum starburst (at ULIRG phase), we can examine two-dimensional distribution of $K$-band surface brightness (Fig. 10), rest frame $R - K$ color (11), and $A_V$ (12), all of
which have been observationally investigated in a very extensive manner for the better understanding of the nature of ULIRGs. As is shown in Figure 10, near-infrared surface brightness is the highest (the smallest in number) in the central region within which most of young bright massive stars are located. This is essentially because most of young stars are formed in the central region at $T_{\rm m} = 1.3$ Gyr. The $R-K$ color is also the largest in the central part of the merger (Fig. 11), because the central starburst components

![Figure 8](image1.png)

**Fig. 8.** Mass distribution of the standard model projected onto $x$-$y$ plane (upper four frames) and $x$-$z$ one (lower four frames) at $T_{\rm m} = 1.3$ Gyr corresponding to the epoch of maximum starburst of the merger for total components (upper left), old stellar components initially located in two disks (upper right), gaseous ones (lower left), and new stellar ones formed by secondary starburst (lower right). Each of the eight frames measures 64 kpc on a side.

![Figure 9](image2.png)

**Fig. 9.** The rest-frame SED of the galaxy merger at $T_{\rm m} = 1.3$ Gyr (black solid line) for all stellar components. For comparison, the SED of the merger without dust extinction and reemission is also given by a red dotted line. Furthermore, the SED for stellar component located within the central 3.5 kpc is given by a green long-dashed line. We can clearly see the effects of dust extinction and reemission on the SED shape in the merger at $T_{\rm m} = 1.3$ Gyr by comparing the black solid line and the red dotted one. For comparison, the observed SED of Arp 220 by Rigopoulou, Lawrence, & Rowan-Robinson (1996) is also given by a blue short-dashed line with blue open squares. The reason for our failure to reproduce the observed SED around $10^5$ Å is essentially that we do not include the effects of small grains in the present study. The SED within the central 3.5 kpc of the present merger mode is more similar to the observed one.

![Figure 10](image3.png)

**Fig. 10.** Two-dimensional distribution of $K$-band surface brightness projected onto $x$-$y$ plane at $T_{\rm m} = 1.3$ Gyr in the standard model. Each frame measures 64 kpc on a side and includes 400 bins ($20 \times 20$). The size of the frame is the same as that shown in Fig. 8 and the scale is given in our units (17.5 kpc). We here estimate the mean values of surface brightness for each bin based on SEDs of stellar particles located within each bin. For the bin within which no stellar particles are found to be located, any color contours are not given for clarity. As is shown in the color legend of this figure, the magnitude of the surface brightness ranges from 16.1 in the central part to 26.6 mag arcsec$^{-2}$ in the outer one. Note that the inner region of the merger is brighter in $K$ band owing to the central dusty starburst.
are most heavily obscured by dust owing to the very high gaseous density there. Accordingly, this result implies that an ULIRG formed by major merging can show negative color gradients. As is shown in Figure 12, $A_V$ is larger in the central region of the merger than in the outer part, which indicates that dust absorption and its reemission is larger in the central region. This result is consistent with those described in Figure 11.

### 3.2. Photometric and Color Evolution

Figure 13 describes the time evolution of absolute magnitude from optical to near-infrared wavelength ($M_V$, $M_R$, and $M_K$) for the standard model with and without dust extinction. As galaxy merging proceeds, $M_V$, $M_R$, and $M_K$ gradually rise up owing to the increase of star formation rate ($1.1 < T_m < 1.3$ Gyr). These $M_V$, $M_R$, and $M_K$ then become $-21.0$, $-21.5$, and $-24.2$ mag, respectively, at the epoch of maximum star formation rate ($T_m = 1.3$ Gyr) in the model with dust extinction. The difference in magnitude between the models with and without dust extinction at the epoch of maximum starburst is the largest for $V$ band ($2.5$ for $V$, $2.1$ for $R$ and $1.3$ for $K$ band), which reflects the fact that stellar light with shorter wavelength can be more greatly absorbed by dust. The mean value of $M_K$ in ULIRGs ($-25.2$ mag; Sanders & Mirabel 1996) is about 1 mag brighter (smaller in number) than the $M_K$ of the present merger at $T_m = 1.3$ Gyr, which probably means that initial total mass of the host disk of a typical ULIRG is about 2 times larger than that of the Galaxy adopted as a merger progenitor disk in the present study. Furthermore, irrespectively of wavelength, the difference in absolute magnitude between the two models in the present study is the largest at the epoch of maximum starburst. This is essentially because young and very luminous stellar components formed by starburst are the most heavily obscured by dust at the maximum starburst epoch when a larger amount of dusty gas is transferred to form very high density region around the compact starburst. As the star formation rate rapidly declines, $M_V$, $M_R$, and $M_K$ also rapidly decline ($1.3 < T_m < 2.8$ Gyr) because of the death of young and luminous stellar components (OB stars formed in starburst) and the aging of
stellar populations. The present results thus suggest that
time variation of absolute magnitude during galaxy
merging becomes moderate owing to dust extinction.

Figure 14 shows the time evolution of $V-I$, $I-K$, and
$R-K$ colors in the standard model with and without dust
extinction. Although the colors in the model without extinction
become very blue at the epoch of maximum starburst, these colors are changed into redder ones for a starburst
galaxy because of the heavy dust extinction in the merger.
The color difference between the models with and without
dust extinction is the most remarkable at the epoch of
maximum starburst. Figure 15 describes the time evolution
of infrared flux at 60 and 100 $\mu$m and submillimeter one at
450 and 850 $\mu$m for the model with dust extinction. Clearly
these fluxes resulting mainly from dust reemission become
maximum when the magnitude of starburst is the largest
and the density of dusty gas in the central region of the
merger is also considerably high. Furthermore, these fluxes
become an order of magnitude smaller than the maximum
values within $\sim 1$ Gyr after the maximum starburst. This
result implies that the timescale during which a dusty star-
burst merger can be identified as a submillimeter source
detected recently by the SCUBA is very short (an order of
$10^8$ year). As is shown in Figure 16, the dust temperature of
the model becomes maximum ($\sim 32$ K) when the star forma-
tion rate becomes maximum and total amount of radiation from young massive stars formed by starburst
becomes the largest. We here note that the dust temperature
is the mean value for all gas particle for each of which the
dust temperature is calculated. Figure 16 implies that the
dust temperature in mergers with dusty starburst depends
strongly on the strength of starburst.

3.3. Evolution with Redshift

Figures 17, 18, and 19 describe how the difference in the
epoch of galaxy merging affects the global colors ($V-I$, $I-K$, and $R-K$, respectively) in observed frame for the
standard model. For clarity, we give the dependence of
colors on the merging epoch $z$ only for the three different
phases of the merger, the prestarburst epoch ($T_m = 1.1$ Gyr),
the maximum starburst one (1.3), and the poststarburst one
(1.7). As is shown in Figure 17, optical color $V-I$ in
observed frame is the reddest at the epoch of poststarburst
($T_m = 1.7$ Gyr) at each redshift (i.e., at the epoch of galaxy
merging). Furthermore, the $V-I$ color difference between
different redshifts is about 0.7 mag for the epoch of
maximum starburst when infrared flux becomes the largest.
As has been shown in Bekki et al. (1999), the submillimeter
flux at 850 $\mu$m at $z > 1.0$ for the maximum starburst phase

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{fig14.png}
\caption{Same as Fig. 13, but for rest-frame colors, $V-I$, $I-K$, and $R-K$.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{fig16.png}
\caption{Time evolution of dust temperature for the model with dust extinction.}
\end{figure}
Fig. 17.—Redshift dependence of $V-I$ in the standard model for $T_m = 1.1$ Gyr (prestarburst phase), $T_m = 1.3$ Gyr (maximum starburst), and $T_m = 1.7$ Gyr (poststarburst phase). Here $V-I$ is the color in observed frame (not in rest frame) and $z$ represents the redshift at which the two disks cause their maximum starburst. This figure describes how the $V-I$ color for each phase of galaxy merging in observed frame depends on the epoch of galaxy merging.

$T_m = 1.3$ Gyr is a few mJy that is well above the current detection limit of the SCUBA ($\sim 2$ mJy). These results thus imply that the observed color difference in $V-I$ for the faint SCUBA sources (Smail et al. 1998) is due partly to the difference in redshifts between dusty starburst galaxies detected by the SCUBA. Irrespectively of redshifts, near-infrared colors $I-K$ and $R-K$ are the reddest for the poststarburst phase (Figs. 18 and 19). Furthermore, these colors are redder in higher $z$ for the poststarburst phase ($T_m = 1.7$ Gyr) because of the $k$-correction of stellar populations in this phase. It should be noted here that the $R-K$ color for the poststarburst phase becomes larger than $\sim 6.0$ around $z = 1.5$. These results imply that an ERO with the $R-K$ color larger than 6.0 is more likely to be formed in the poststarburst phase of a gas-rich major merger with the strong dusty starburst and at higher redshifts ($z > 1 \sim 2$). These results on the redshift evolution of global colors are only for one merger model. Therefore, we stress that although the above results are useful and helpful for understanding the nature of the SCUBA sources and EROs, the results can be true only for some high-$z$ dusty mergers. It is our future work to investigate a much larger number of dusty merger models and thereby clarify the nature and the origin of high-$z$ dusty starburst galaxies such as the faint SCUBA sources and EROs.

4. DISCUSSION

One of advantages of the present new numerical code is that we can investigate both dynamical and photometric evolution of dusty starburst galaxies in an explicitly self-consistent manner. Therefore we can address some important questions that classical one-zone models on galaxy evolution have not yet answered so clearly for the origin of dusty starburst galaxies. Here, we particularly enumerate three problems that the newly developed code is rather helpful and useful for clarifying and thus will be discussed in our future papers.

4.1. Origin of Faint SCUBA Sources

Recent observational studies with the SCUBA have revealed possible candidates of heavily dust-enshrouded starburst galaxies at intermediate and high redshift, which could be counterparts of low-redshift ULIRGs (Smail, Ivison, & Blain 1997; Barger et al. 1998; Hughes et al. 1998; Smail et al. 1998; Ivison et al. 1999; Lilly et al. 1999). Although optical morphology of these submillimeter extragalactic sources should be treated with caution owing to the absence of high-resolution submillimeter imaging capability (Richards 1999), more than 50% of those are suggested to show the indication of galactic interaction and merging (Smail et al. 1998). Furthermore, observational studies of an extremely red object ERO J 164502 $- 4626.4$ (HR 10) with the redshift of 1.44 by the Hubble Space Telescope and the SCUBA have found that this high-redshift galaxy is also a dust-enshrouded starburst galaxy with clear indication of galaxy merging/interaction (Graham & Dey 1996; Cimatti et al. 1998; Dey et al. 1999). Although low-redshift ULIRGs are generally considered to be ongoing galaxy mergers with the triggered prominent nuclear activities (starburst or active galactic nuclei) heavily obscured by dust (Sanders et al. 1988; Sanders & Mirabel 1996), the origin of the faint
SCUBA sources is not so clearly understood. In particular, it is not clear whether the observed very large submillimeter luminosity, which could result either from active galactic nuclei obscured by dust or from dusty starburst, is due essentially to physical processes associated closely with major galaxy merging.

Concerning this problem, one of tests to assess the validity of merger scenario of the faint SCUBA source formation is to compare the observed morphological, structural, and kinematical properties of the sources with those of a certain theoretical merger model at the considerably strong starburst epoch, when submillimeter flux of the merger can exceed the detection limit of the SCUBA. Therefore, theoretical studies should investigate simultaneously the time evolution of submillimeter flux at 850 $\mu$m, morphology, structure, and kinematics of a dusty major galaxy merger in order to compare the results with the corresponding observational ones. Although classical one-zone models can investigate photometric evolution of dusty starburst galaxies at each wavelength and thus have contributed greatly to the understanding of dusty galaxies (e.g., Mazzei et al. 1992), they cannot predict dynamical evolution of galaxies simultaneously. The present model, on the other hand, can predict not only photometric evolution from UV to submillimeter wavelength but also dynamical evolution in a dusty galaxy. For example, as is shown in the present study, we can predict optical and near-infrared morphology of a merger with the 850 $\mu$m flux larger than 2 mJy (the current detection limit of the SCUBA) at a given redshift. Thus we expect that future theoretical studies with our new code will provide valuable clues to the origin of the faint SCUBA sources.

### 4.2. Origin of EROs

Recent observational studies have discovered a significant number of high-$z$ EROs with $R - K \geq 5 - 6$ (Elston et al. 1988; Cimatti et al. 1998; Dey et al. 1999; Benitez et al. 1998; Cimatti et al. 1998; Smail et al. 1999; Soifer et al. 1999), and accordingly the nature and the origin of EROs have now been discussed very extensively both in observational studies and in theoretical ones. Thompson et al. (1999) argued that EROs are most likely to lie in the redshift range $1 < z < 2$ and they represent an important population in high-redshift universe. Beckwith et al. (1998) argued that the surface density of EROs with $R - K \geq 6$ mag and $K \leq 19.75$ mag is 0.14 arcmin$^{-2}$ for EROs with $R - K \geq 6$ and $K \leq 19.75$. Furthermore, Thompson et al. (1999) derived a surface density of EROs with $R - K^\prime \geq 6$ mag and $K^\prime \leq 19.0$ of $0.039 \pm 0.016$ arcmin$^{-2}$ and estimated that the volume density of bright EROs to be as high as that of nearby Seyfert galaxies. There are mainly two possible interpretations for EROs (We here do not intend to discuss whether some EROs are actually low-mass Galactic stars such as main-sequence M stars brown dwarfs). One is that EROs are passively evolving red elliptical galaxies at high $z$ (e.g., those recently discovered by the VLT; Benitez et al. 1998), and the other is that EROs are dusty starburst galaxies with starburst components obscured heavily by dust (e.g., HR 10; Dey et al. 1999). It still remains unclear which interpretation among the two is more plausible, essentially because not enough spectroscopic studies of EROs have yet been accumulated to reveal unambiguously the redshift of EROs and thus discriminate the effects of aging of stellar populations and those of dust extinction.

Recent observational results on EROs have begun to (or will soon begin to) provide valuable information concerning this problem. For example, Smail et al. (1999) discovered two EROs with $I - K \geq 6.0$ and 6.8 among their SCUBA sources samples, which implies that the submillimeter telescopes with the improved detectability (the detection limit of the order of 10$^2$ mJy) can detect submillimeter flux indicative of the obscured dusty starburst in a significant number of EROs. Furthermore, statistical spectroscopic studies of EROs by the already existing large ground-based telescopes (e.g., SUBARU with IRS and FMOS) will reveal the strength of H$\alpha$ emission that is not affected so strongly by dust extinction and thereby clarify star formation rate and history of EROs. It is also possible that the future improved HST ACS and the 8 m class ground-based telescopes provide the detailed morphology of an ERO. Accordingly, one of important works for clarifying the origin of EROs is to compare emission-line strengths, submillimeter flux, and morphological properties observed (or those that will be observed in near future) in EROs with those predicted by a certain theoretical dusty starburst model. In order to make this comparison possible, theoretical models of dusty starburst galaxies should investigate the time evolution of $R - K$ color, $K$-band magnitude, emission lines, submillimeter flux, and morphology for a dusty starburst galaxy in a self-consistent manner. Although the present code still cannot predict emission- and absorption-line strengths of a dusty starburst galaxy, our new code enables us to investigate most of the above important properties simultaneously in numerical simulations. Thus it is one of important issues for future numerical and theoretical studies with the present new code to clarify the origin of EROs.

### 5. Conclusion

We present a new code that is designed to derive an SED for an arbitrary spatial distribution of stellar and gaseous components for a dusty starburst galaxy. By using this code, we can calculate SEDs based on numerical simulations that can analyze simultaneously dynamical and chemical evolution, structural and kinematical properties, morphology, star formation history, and transfer of metals and dust in interstellar medium for a starburst galaxy. Accordingly, we can investigate variously different properties of starburst galaxies, such as effects of dynamical evolution on galactic SEDs, physical correlations between morphology and SEDs, photometric evolution from UV to submillimeter wavelength, two dimensional distribution of $A_v$, and dependence of SEDs on line of site of an observer. Thanks to this code, we can furthermore try to clarify the origin of possible candidates of starburst galaxies, such as low-$z$ ULIRGs (e.g., Sanders et al. 1988; Sanders & Mirabel 1996), intermediate-$z$ ones (e.g., Tran et al. 1999), faint SCUBA sources (Smail, et al. 1997; Barger et al. 1998; Hughes et al. 1998; Smail et al. 1998; Ivison et al. 1999; Lilly et al. 1999), EROs (Elston, et al. 1988; Dey et al. 1999; Smail et al. 1999), optically faint radii sources detected by VLA (e.g., Richards et al. 1999), Lyman-break galaxies (Steidel et al. 1996; Lowenthal et al. 1997), and emission-line galaxies (e.g., Mannucci et al. 1998). By using a new code developed in the present study, we try to answer the following seven questions in our forthcoming papers: (1) When and how does a gas-rich major galaxy merger become an ULIRG during the dynamical evolution of the merger? (2) How do high-$z$
faint SCUBA sources with dusty starburst form and evolve? (3) What are physical conditions for high-z dusty galaxies to become EROs? (4) Are there any evolutionary links between high-z possible dusty starburst galaxies, such as faint SCUBA sources, EROs, optically faint radio sources recently detected by VLA, emission-line galaxies, and Lyman-break ones? (5) When does a forming disk galaxy show the strongest submillimeter flux? (6) What physical processes can determine the shapes of SEDs observed in Lyman-break galaxies? (7) How does dusty interstellar gas affect the apparent morphology of intermediate- and high-z dusty galaxies? Although this code has some disadvantages in deriving very precise SEDs of dusty starburst galaxies, we believe that this code enables us to grasp some essential ingredients of physical processes related to galaxy formation with starburst at low- and high-z universe.

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