LMSA and High-Redshift Dusty Starburst Mergers

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Abstract

By using a new numerical code for deriving the spectral energy distributions of galaxies, we have investigated the time evolution of morphological properties, the star formation rate, and the submillimeter flux at 850 μm in high-redshift (z) dusty starburst mergers with mass ratio ($m_2$) of two disks ranging from 0.1 (minor merger) to 1.0 (major one). We found that the maximum star-formation rate, the degree of dust extinction, and the 850 μm flux are larger for mergers with larger $m_2$. The 850 μm flux from mergers at $1.5 \leq z \leq 3.0$ in the observer frame is found to be a few mJy for major merger cases, and at most $\sim 100 \mu$Jy for minor ones. This result suggests that only high-redshift major mergers are now detected by SCUBA with the current 850 μm detection limit of a few mJy. These results imply that LMSA with the expected detection limit of the order of 10 μJy at 850 μm can be used to study high-redshift mergers with variously different $m_2$, and thus provide an important clue to the formation of galaxies in a high-redshift universe.

Key words: galaxies: formation — galaxies: interactions — infrared: galaxies
1. Introduction

One of fruitful and remarkable achievements of recent optical, infrared, and radio observations of distant galaxies is that interstellar dust has been found to affect the photometric and spectroscopic evolution of galaxies at high redshift (e.g., Meurer et al. 1997; Steidel et al. 1999). For example, deep surveys in the submillimeter regime with the Sub-millimeter Common-User Bolometer Array (SCUBA) (Holland et al. 1999) on the James Clerk Maxwell Telescope (Smail et al. 1997; Hughes et al. 1998; Barger et al. 1998; Smail et al. 1998; Lilly et al. 1999), in the Mid/Far-Infrared with the Infrared Space Observatory (ISO) (e.g., Flores et al. 1999), and in the radio with the Very Large Array (VLA) (e.g., Richards 1999) have revealed the nature of starburst galaxies whose star formation is heavily obscured by dust at intermediate and high redshifts. These observations have simultaneously demonstrated that optical data alone can provide a partial view of the galactic evolutionary history, which is possibly qualitatively incorrect.

A major remaining challenge is thus to reveal how heavily distant starburst galaxies are obscured by dust and what physical process determines the degree of dust extinction in these galaxies. Galaxy merging has been observed to be closely associated not only with low-z dust starburst galaxies, such as ultra-luminous infrared galaxies (Sanders, Mirabel 1996), but also with intermediate/high-z ones, such as faint SCUBA sources (Smail et al. 1998). Accordingly, it is primarily important to investigate how intermediate/high-z galaxy merging can determine the nature of dusty starburst galaxies. Bekki, Shioya, and Tanaka (1999) first investigated both the morphological and photometric evolution of high-z dusty starburst major mergers, and found that major mergers can successfully reproduce the morphological and photometric properties of faint SCUBA sources observed by Smail et al. (1998). However, they only described the evolution of dusty starburst major mergers and did not consider at all how dusty gas is important for the evolution of minor mergers with the mass ratio of two merging disks less than 0.1 \((m_2 < 0.1)\) and that of unequal-mass ones with \(m_2 \sim 0.3\). Minor merging is considered to be occurring more frequently than major merging, and is important for the growth of bulges (e.g., Mihos, Hernquist 1994), whereas an unequal-mass one has been demonstrated to be related to the formation of S0s (Bekki 1998). Thus, investigating different types of dusty mergers (with different \(m_2\)) not only leads to a better
understanding of the nature of dusty starburst galaxies, but also provides a new clue to the origin of the Hubble sequence.

This paper considers how the mass ratio, \( m_2 \), controls the time evolution of the morphological properties, the degree of dust extinction, and the submillimeter flux at 850 \( \mu m \) in dusty starburst mergers. We furthermore demonstrate how the 850 \( \mu m \) flux in the observer-frame depends on \( m_2 \) if mergers are located at \( z = 1.5 \) and 3.0. Based on our present numerical results, we discuss whether the Large Millimeter and Submillimeter Array (LMSA) can detect reemission of dusty gas at 850 \( \mu m \), and suggest that LMSA can particularly play a vital role in revealing morphological transformation processes of galaxies in a high-redshift universe.

2. Model

We here consider both the time evolution of the galactic morphology and that of the spectral energy distributions (SEDs), based on the results of numerical simulations that could follow both the dynamical and chemical evolution of galaxies. The numerical techniques for solving galactic chemodynamical and photometric evolution and the methods for deriving SEDs in numerical simulations of galaxy mergers with dusty starburst are given in Bekki and Shioya (2000). The advantages and disadvantages of the model in reproducing the observed SED of ULIRGs are summarized in detail by Bekki and Shioya (2000). For example, our model does not include physical processes related to dust production, grain destruction, and grain growth in the interstellar medium, and thus can not follow the time evolution of dusty starbursts from the optically thick dusty cocoon stage to the optical thin one in detail. Mazarellar et al. (1991) compared the far-IR properties of 187 Markarian galaxies with those of the IRAS Bright Galaxy Sample and extensively discussed the nature of these in terms of the grain-size distribution. Although our model can not include this important effect of the grain-size distribution (and dust compositions) on the photometric properties of dusty starburst galaxies, owing to the adopted simple model assumption in the present paper, we should investigate this in the future.

We constructed models of galaxy mergers between two bulgeless gas-rich disks embedded in massive dark-matter halos by using the Fall-Efstathiou model (Fall and Efstathiou 1980). The initial mass-ratio
of dark matter halo to disk was 4:1 for the two disks. The mass ratio of the smaller disk (referred to as the ‘secondary’) to the larger one (the ‘primary’) in a merger, which is represented by $m_2$, was considered to be a critical determinant for the evolution of dusty starburst mergers in the present study. We mainly describe the results of the model with $m_2 = 0.1$ (minor merging), 0.3 (unequal-mass), 0.5, and 1.0 (major). The disk mass ($M_d$) was $6.0 \times 10^{10} M_\odot$ for the primary in all merger models of the present study. The exponential disk scale length and the maximum rotational velocity for disks were $3.5(M_d/6.0 \times 10^{10} M_\odot)^{1/2}$ kpc and $220(M_d/6.0 \times 10^{10} M_\odot)^{1/4}$ km s$^{-1}$, respectively. These scaling relations were adopted so that both the Freeman law and the Tully Fisher relation with a constant mass-to-light ratio could be satisfied for the structure and kinematics of the two disks. For example, parameter values for disk structure and kinematics for the model with $m_2 = 0.3$ were as follows. The size and mass of a disk are set to be 17.5 (9.6) kpc and 6.0 (1.8) $\times 10^{10} M_\odot$, respectively, for the primary (the secondary). The scale length and the scale height of an initial exponential disk is 3.5 (1.9) kpc and 0.7 (0.38) kpc, respectively, for the primary (the secondary). The rotational curve of the primary (the secondary) becomes flat at 6.1 (3.4) kpc with the maximum velocity of 220 (163) km/s. The Toomre stability parameter (Binney, Tremaine 1987) for initial disks was set to be 1.2.

The collisional and dissipative nature of disk interstellar gas was represented by discrete gas (Schwarz 1981) and the initial gas mass fraction was set to be 0.5 (corresponding to a very gas-rich disk). The mass and the size for each of the clouds were $3.0 \times 10^6 M_\odot$ and 130 pc, respectively. Star formation in gas clouds during galaxy merging is modeled by converting gas particles to stellar ones according to the Schmidt law with an exponent of 2.0 (Schmidt 1959; Kennicutt 1989). Although the effects of supernovae feedback on dynamical evolution of the mergers are not included, the effects probably would not change significantly the present numerical results, mainly because the adopted mass of a merger progenitor disk was fairly large. Stellar components that are originally gaseous ones are referred to as new stars. Chemical enrichment through star formation during galaxy merging was assumed to proceed both locally and instantaneously in the present study. The fraction of gas returned to interstellar medium in each stellar particle and the chemical yield were 0.3 and 0.02, respectively. The initial metallicity $Z_*$ for each stellar and gaseous particle in a given galactic radius $R$ (kpc) from the center of a disk
was given according to the observed relation \( Z_* = 0.0610^{-0.197\times(R/3.5)} \) of typical late-type disk galaxies (e.g., Zaritsky et al. 1994). All of the simulations were carried out on the GRAPE board (Sugimoto et al. 1990) with a gravitational softening length of 0.53 kpc. For calculating the SED of a merger, we use the spectral library GISSEL96, which is the latest version of Bruzual and Charlot (1993). The SEDs of dusty mergers and the way to calculate the 850 \( \mu \)m flux from high redshift mergers both for observer-frame and for rest-frame are described in detail by Bekki et al. (1999) and Bekki and Shioya (2000). In the following, the cosmological parameters \( H_0 \) and \( q_0 \) are assumed to be 50 km s\(^{-1}\) Mpc\(^{-1}\) and 0.5, respectively.

3. Results

Figure 1 gives the \( m_2 \) dependence of the morphological properties of mergers at the epoch of maximum starburst. For the minor merger model with \( m_2 = 0.1 \), the secondary sinks into the deep gravitational potential well of the primary owing to the strong dynamical friction, and is finally completely destroyed in the central part of the primary. The primary in the merger, on the other hand, leaves its disk morphology even after merging, though the primary suffers from dynamical heating due to the accretion of the secondary, and consequently forms a thick disk. Furthermore, mergers with larger \( m_2 \) become more similar to early-type galaxies (E/S0), principally because the disk destruction due to tidal gravitational force and dynamical relaxation more drastically proceeds for mergers with larger \( m_2 \). These results suggest that \( m_2 \) is an important factor for controlling the morphological properties of dusty starburst galaxies formed by merging. These results also imply that \( m_2 \) is one of important factors for the origin of the Hubble sequence.

Figure 2 shows how the star-formation rate and the degree of dust extinction at the epoch of maximum starburst in mergers depend on \( m_2 \). Here, we estimate \( A_V \) for a given \( m_2 \) by comparing the \( B - V \) color in the model with dust extinction and that in the model without dust extinction. The maximum star-formation rate is larger for mergers with larger \( m_2 \), essentially because a larger amount of interstellar gas can be transferred to the central region, and consequently converted into new stars in mergers with larger \( m_2 \). Furthermore, \( A_V \) is larger for mergers with larger \( m_2 \), which means that young luminous populations formed by starburst are more heavily obscured by dusty gas for larger \( m_2 \).
For mergers with larger $m_2$, the stronger tidal disturbance triggers efficient cloud–cloud collisions, and consequently induces a larger amount of gaseous dissipation. As a natural result, the dusty interstellar gas is more efficiently transferred to the central regions to form higher density gaseous regions surrounding the nuclear starburst populations in mergers with larger $m_2$. This is the main reason for the above $m_2$ dependence of $A_V$.

Figure 3 shows the following three new and important results on the dependence of the observed 850 µm flux from high-redshift mergers on the redshift and $m_2$. Firstly, the observed 850 µm flux is not so significantly different between dusty starburst mergers at $z = 1.5$ and 2.0 owing to a large negative $K$-correction in the submillimeter range, though the flux is smaller in higher redshift mergers for a given $m_2$. Secondly, the observed 850 µm flux is larger for mergers with a larger $m_2$. This is firstly because total amount of stellar light from young massive stars, which can be reemitted in dusty gas, is larger for mergers with the larger $m_2$, and secondly because a larger amount of dusty gas can be transferred to the central region, and consequently obscure more heavily starburst populations in mergers with larger $m_2$. Thirdly, the observed 850 µm flux greatly exceeds the current SCUBA detection limit of $\sim$ a few mJy for larger $m_2$ (= 0.5, 1.0). Considering the results shown in figure 1, it is strongly suggested that high-redshift dusty early-type galaxies which are being formed by mergers with larger $m_2$ are preferentially detected by SCUBA. Furthermore, this result implies that dusty starburst triggered by minor merging, which is considered to be more frequently occurred than major merging with $m_2 = 1.0$ and an important determinant for the dynamical evolution of early-type disk galaxies (e.g., Mihos, Hernquist 1994), should not be studied by SCUBA, but by a future submillimeter array with a detection limit of $10^{-100}$ µJy.

4. Discussion and Conclusion

Considering the present numerical results, LMSA has the following three advantages in studying the origin and the nature of high redshift dusty starburst galaxies. Firstly, LMSA is expected to detect a submillimeter flux of $10^{-100}$ µJy at 850 µm and therefore can investigate not only high-redshift dusty starburst galaxies formed by major mergers, but also those by minor and unequal-mass ones. Since minor and unequal-mass mergers are suggested to be important for the formation of Sa and for that of
S0 (Mihos, Hernquist 1994; Bekki 1998), respectively, extensive studies of dusty galaxies with 850 µm flux of the order of 10 – 100 µJy by LMSA will provide a new clue to the origin of the Hubble sequence. Secondly, LMSA can investigate the nature of dusty starburst galaxies at variously different dynamical stages of merging. Bekki and Shioya (2000) have demonstrated that the 850 µm flux from dusty starburst populations depends strongly on the degree of the dynamical relaxation of merging galaxies. Accordingly, LMSA will find a physical relationship between the dynamical evolution and the photometric one at the submillimeter band in high-redshift dusty starburst galaxies, if future deep optical and near-infrared morphological, structural, and kinematical studies will have revealed the dynamical conditions of these galaxies.

Thirdly, and most importantly, LMSA can provide valuable information concerning forming disk galaxies at high redshift. Recent numerical simulations based on the hierarchical assembly of cold dark-matter (CDM) halos have demonstrated that the star formation rate is estimated to be on the order of ∼10 $M_\odot$ yr$^{-1}$ when successive minor merging of subgalactic clumps becomes important for the formation of galactic disks at $z = 1 – 2$ (e.g., Steinmetz, Müller 1995; Bekki, Chiba 2000). The present study has demonstrated that the 850 µm flux in minor mergers at the redshift of 1 – 3 is at most on the order of ∼100 µJy and, accordingly, high redshift forming disk galaxies can be investigated by LMSA rather than by SCUBA. We suggest that a detailed comparison between LMSA submillimeter studies and future optical and infrared spectrophotometric ones would reveal the degree of dust extinction ($A_V$) and the physical parameters for $A_V$ in forming disk galaxies.

By using a new and original code for calculating the SEDs of dusty starburst galaxies, we have demonstrated that the mass ratio, $m_2$, controlling the strength of tidal disturbance (or the degree of disk destruction) in galaxy merging is an important determinant for the maximum star-formation rate and the degree of dust extinction ($A_V$). The derived dependence on $m_2$ does not depend very strongly on other parameters, such as the orbital configurations, internal structure, and gas mass fraction of galaxy mergers (Shioya, Bekki, in preparation). Based on these essentially new results, we emphasize the importance of LMSA in investigating and revealing the nature of high-redshift dusty starburst galaxies. We lastly expect that future observational studies of high-redshift galaxy mergers with different $m_2$ will provide
new clues to the formation and evolution of galaxies.

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Figure Captions

Fig. 1. Dependence of the morphological properties of mergers at the epoch of the maximum star-formation rate projected onto the \(xz\) plane on the mass ratio of two merging disks \(m_2\). Stars, gas, and new stars are plotted in the same panel. We here do not display dark halo components in order to show more clearly the morphological properties of the disk components. Each frame measures 77 kpc, and the mass ratio of \(m_2\) is indicated in the upper-left corner of each panel. The epoch of maximum star-formation rate is \(T = 3.06\) Gyr for \(m_2 = 0.1\), 1.63 Gyr for \(m_2 = 0.3\), 1.50 Gyr for \(m_2 = 0.5\) and 1.29 for \(m_2 = 1.0\), where \(T\) represents the time that has elapsed since the two disks begin to merge for each of the four models. Note that the primary disk of the merger with larger \(m_2\) is more greatly destroyed by the accretion of the secondary. The final morphology of each of merger remnant in nearly virial equilibrium (\(\sim 1\) Gyr after maximum starburst) is basically similar to that at the epoch of maximum starburst. The final morphology also depends on \(m_2\), such that the merger remnant with larger \(m_2\) is more similar to early-type galaxies (E/S0). We stress that the merger remnant with \(m_2 = 0.3\) is more similar to S0s with no remarkable thin stellar disk such as NGC 3245 and 4684 than those with thin extended stellar disks such as NGC 4111 and 4710 [see the Hubble Atlas of Galaxies of Sandage (1961)].

Fig. 2. The \(m_2\) dependence of maximum star formation rate in units of \(M_\odot\) yr\(^{-1}\) (upper panel) and that of the degree of dust extinction \((A_V)\) in units of mag (lower one). Note that both the maximum star-formation rate and the degree of dust extinction is larger for dusty starburst mergers with a larger \(m_2\). Also note that the maximum star-formation rate in the major merger with \(m_2 = 1.0\) is \(\sim 378\) \(M_\odot\) yr\(^{-1}\), which corresponds roughly to (or is larger than) that required for explaining infrared luminosity in ultra-luminous infrared galaxies (Sanders, Mirabel 1996).

Fig. 3. The \(m_2\) dependences of 850 \(\mu\)m flux of high redshift mergers at \(z = 1.5\) (solid line) and 3.0 (dotted one) in the observer-frame. The current detection limit in SCUBA (2 mJy) and the expected one in LMSA (40 \(\mu\)Jy) are also given by the thick solid lines. Note that in comparison with SCUBA, LMSA can detect not only dust reemission from major mergers at
high $z$ but also that from minor ones.