Star Formation of Merging Disk Galaxies with AGN Feedback Effects

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Abstract

Using a numerical hydrodynamics code, we perform various idealized galaxy merger simulations to study the star formation (SF) of two merging disk galaxies. Our simulations include gas accretion onto supermassive black holes and active galactic nucleus (AGN) feedback. By comparing AGN simulations with those without AGNs, we attempt to understand when the AGN feedback effect is significant. Using \textasciitilde 70 simulations, we investigate SF with the AGN effect in mergers with a variety of mass ratios, inclinations, orbits, galaxy structures, and morphologies. Using these merger simulations with AGN feedback, we measure merger-driven SF using the burst efficiency parameter introduced by Cox et al. We confirm previous studies which demonstrated that, in galaxy mergers, AGN suppresses SF more efficiently than in isolated galaxies. However, we also find that the effect of AGNs on SF is larger in major than in minor mergers. In minor merger simulations with different primary bulge-to-total ratios, the effect of bulge fraction on the merger-driven SF decreases due to AGN feedback. We create models of Sa-, Sb-, and Sc-type galaxies and compare their SF properties while undergoing mergers. With the current AGN prescriptions, the difference in merger-driven SF is not as pronounced as in the recent observational study of Kaviraj. We discuss the implications of this discrepancy.

Key words: galaxies: active – galaxies: evolution – galaxies: interactions – galaxies: spiral – galaxies: starburst

1. Introduction

According to the \textit{Λ}CDM cosmology, galaxy mergers play an essential role in the formation and evolution of galaxies. These events not only change the morphologies of the galaxies involved (Toomre & Toomre 1972; Naab et al. 2006), but also give rise to impressive features such as tidal tails (Toomre & Toomre 1972) or shells (Quinn 1984) that are long-lived (Ji et al. 2014), or spawn dwarf objects along their tidal features (Barnes & Hernquist 1992; Bournaud & Duc 2006; Bournaud et al. 2007).

Another important aspect of galaxy mergers is the strong star formation (SF) that occurs during the interactions. Larson & Tinsely (1978) first suggested that galaxy interactions could trigger strong SF in galaxies (Lonsdale et al. 1984; Bushouse 1987; Kennicutt et al. 1987). Observational studies (e.g., Bushouse 1987) found that a burst of SF occurs in the central regions of interacting galaxies, and Hernquist (1989), with his merger simulation, claimed that the tidal effect of a companion galaxy triggers a concentration of the gas in the center of the disk, and subsequent merger-driven central SF.

Since then, the understanding of merger-driven SF has continued to develop with the use of numerical simulations. Mihos & Hernquist (1994) demonstrated that the existence of a bulge in disk galaxies influences the SF driven by minor-mergers, and Cox et al. (2008, hereafter C08) quantified the amount of merger-driven SF in merging galaxies under various initial conditions. However, they did not include the effects of active galactic nucleus (AGN) feedback in their models.

AGNs represent a powerful source of feedback energy. Their location means they can have significant effects on gas that is driven to a galaxy’s center during the merging process. The effects of AGNs on the SF of merging galaxies was found to be very significant in equal-mass galaxy merger simulations where large quantities of gas are funneled to the galaxy’s centers (Di Matteo et al. 2005; Springel et al. 2005a, 2005b). However, Newton & Kay (2013) found that in isolated galaxies, AGN feedback was less important. Hayward et al. (2014) performed several merger simulations with AGN feedback, focusing on the comparison between two different types of code, but once again considering only equal-mass mergers.

However, according to Capelo et al. (2015), the mass ratio between the two merging galaxies is an important factor that affects the growth of supermassive black holes (SMBHs) and AGN activity. So far, a detailed study of the impact of AGNs on SF in non-equal mass mergers has not been conducted, and this forms the central motivation for our study.

The observational study of Kaviraj (2014, hereafter K14) demonstrated that the enhancement in the specific star formation rate (SSFR) of disk galaxies experiencing minor mergers is stronger when the galaxy is of type Sc or Sd. They argued that this is because the bulge component, which contributes to the stabilization of the disk and suppresses gas inflow and subsequent SF, is small in late-type spiral galaxies. This interpretation was based on the results of minor merger simulations by Mihos & Hernquist (1994), but they focused mainly on the role of the bulge fraction for regulating SF, and did not consider AGN feedback. However, a bulge may suppress gas inflow, which could affect the central SF, but gas inflow can also affect AGN feedback. This AGN feedback, in turn, may affect central SF. Thus the behavior of SF in the presence of a bulge and an AGN is highly complex and nonlinear, and requires dedicated modeling.

Therefore, in this work, we study the SF of two merging disk galaxies using idealized galaxy merger simulations with AGN feedback, and we consider a range of mass ratios for both major and minor mergers. Furthermore, we explore the SF caused by minor mergers and its connection with the bulge fraction of primary galaxies with AGN. We quantify merger-driven SF using the burst efficiency defined by C08, for mergers with various initial conditions including type of orbit,
inclination, gas fraction and black hole (BH) mass, and galaxy morphology.

This paper is organized as follows. In Section 2, we describe the simulations we performed; the results of the isolated and merging galaxies are presented in Sections 3 and 4, respectively, and we discuss the results in Section 5.

2. Simulations

We utilized the adaptive mesh refinement (AMR) hydrodynamics code RAMSES (Teyssier 2002). This code treats systems of stars or dark matter as collisionless particles and solves the Poisson equation in order to describe their dynamics. Gas follows the Euler equation, and RAMSES determines fluid motions and properties by solving it with the second-order Godunov method.

We choose a simulation box size of 300 kpc, which is sufficient to contain the galaxies during the merger process. The entire domain is divided using a level 7 coarse grid and the cells can be refined up to a maximum of level 13 depending on the refinement criteria. That is, if a given cell contains a gas mass greater than \(5 \times 10^4 M_\odot\), or the cell size is greater than a quarter of the local Jeans length (Truelove et al. 1997), it is further refined. The size of the cell with the maximum level of refinement is 300 kpc/2^13 \(\approx 37\) pc.

The SF is modeled based on the Schmidt law, \(\dot{\rho}_s = \epsilon_d \rho_{\rm gas}/t_{\rm ff}\) (Schmidt 1959), where \(\epsilon_d = 0.02\) is the SF efficiency. \(\rho_{\rm gas}\) is the gas density of a cell and \(t_{\rm ff} = \sqrt{3\pi/32G\rho_{\rm gas}}\) is the free-fall time. We choose an SF density threshold of 10.0 H cm\(^{-3}\) and the corresponding masses of new-born star particles are 1.58 \(\times 10^4 M_\odot\). The number of new star particles is determined by the Poisson distribution \(P(N) = \lambda^N/N! \exp(-\lambda)\), where \(\lambda = \epsilon_d (\rho_{\rm gas} \Delta x^3/m_\odot) (\Delta t/t_{\rm ff})\) is the mean and \(\Delta x\) is the size of the star-forming cell. We adopted the kinetic supernova feedback of Dubois & Teyssier (2008). We assume that the fraction of mass that evolves to the supernova in each star particle \(\eta_{\rm sn}\) is 0.1, the mass loading factor \(\eta_{\rm fl}\) is 1.0, and the fraction of supernova energy released in the kinetic form is 0.5. The supernova bubble radius is 75 pc.

We adopt the equation of state of Bournaud et al. (2010). In this approach, the interstellar medium is modeled assuming equilibrium between cooling (atomic and molecular) and heating by ultraviolet radiation. This helps to save time in the calculation of those processes during the simulation. The equation of state is the following: for a density of \(10^{-3} < n < 0.3\) H cm\(^{-3}\), \(T = 10^4\) K. Below \(10^{-3}\) H cm\(^{-3}\), \(T = 4 \times 10^6 (n/10^{-3})^{2/3}\) and \(T = 10^4 (n/0.3)^{-1/2}\) K above 0.3 H cm\(^{-3}\). We force the grid refinement to ensure that the thermal Jeans length of the gas is always resolved by at least four cells (Truelove et al. 1997). However, in the densest gas, this may surpass our maximum refinement level. Thus, we also use a temperature floor for the highest-density gas, which can be considered as a subgrid model for the unresolved turbulent motions of the gas at scales smaller than our maximum grid resolution (Bournaud et al. 2010; Teyssier et al. 2010).

In RAMSES, both gas accretion to SMBHs and AGN feedback are implemented. This has been accomplished in a variety of ways in the past (e.g., Dubois et al. 2009, 2012; Teyssier et al. 2011). However, we follow the AGN prescription of Gabor & Bournaud (2013) who simulated SMBHs in disk galaxies. SMBHs accrete gas around them at the Bondi–Hoyle accretion rate (Bondi & Hoyle 1944; Bondi 1952)

\[
\dot{M}_{\rm BH} = \frac{4\pi G^2 M^2_{\rm BH}\rho}{(c_s^2 + u^2)^{3/2}}
\]

where \(M_{\rm BH}\) is the BH mass, \(G\) is the gravitational constant, \(\rho\) is the gas density, \(c_s\) is the sound speed, \(u\) is the gas velocity relative to the SMBH, and \(\alpha\) is the boost factor. For the computation of the gas accretion rate, gas cells within a radius of \(4\Delta x\) are considered. Here, \(\Delta x\) is the size of the cell with the maximum refinement level. The average gas properties are calculated using the properties of the individual cells within this radius, weighted by the distance from the BH (Krumholz et al. 2004). Larger weights are given to the cells close to the BH. In cosmological simulations, it is assumed that the boost factor is greater than unity (Teyssier et al. 2011; Dubois et al. 2012), because the limitation of spatial resolution and the difficulty of modeling of cold interstellar medium causes an underestimation of accretion rate (Booth & Schaye 2009).

In this work, we set \(\alpha = 1\) since the resolution of our simulations is higher than those of such cosmological simulations and we can model the cold interstellar medium thanks to the equation of state model of Bournaud et al. (2010). We perform an additional equal-mass merger simulation with density-dependent \(\alpha\) following Booth & Schaye (2009) and find that our choice of boost factor does not affect the integrated SF significantly. The gas accretion rate is limited by the Eddington limit

\[
\dot{M}_{\rm Edd} = \frac{4\pi G M_{\rm BH} m_p}{\epsilon_r \sigma_T c^2}.
\]

Here, \(m_p\) is the proton mass, \(\sigma_T\) is the Thomson cross-section, \(c\) is the speed of light, and \(\epsilon_r\) is the efficiency with which accreted gas mass is converted into luminous energy. At each coarse time step, thermal energy is injected into the ambient gas (quasar mode). The amount of energy is

\[
\Delta E_{\rm acc} = \epsilon_r \epsilon_c \dot{M}_{\rm acc} c^2 dx dt
\]

The value of the coupling efficiency \(\epsilon_c\) is 0.15 (Booth & Schaye 2009; Teyssier et al. 2011). This energy injection occurs when the thermal energy can increase the weighted averaged temperature of the cells to a minimum temperature \(T_{\min} = 10^7\) K. In Gabor & Bournaud (2013), there is a maximum temperature \(T_{\max} = 5 \times 10^9\) K which prevents excess heating, but we confirm it rarely occurs in our merger simulations.

3. Isolated Galaxies

3.1. Initial Conditions

Our disk galaxy models consist of a dark matter halo, stellar disk, gas disk, and stellar bulge. The density profile of the dark matter halo is described by a Navarro–Frenk–White profile (Navarro et al. 1996). We choose values for the halo concentration that are consistent with ΛCDM cosmological simulations (Neto et al. 2007; Prada et al. 2012; Correa et al. 2015; Klypin et al. 2016), and follow the usual \(z = 0\) trend of increasing concentration with decreasing mass. The ratio of stellar mass to dark matter halo mass depends on the halo mass.
Table 1

| Stellar mass ($M_*$) | G1          | G2          | G3          | G4          |
|----------------------|-------------|-------------|-------------|-------------|
|                       | $2.00 \times 10^{10}$ | $6.65 \times 10^9$ | $3.33 \times 10^9$ | $2.00 \times 10^9$ |
| Stellar disk mass ($M_{*disk}$) | $1.60 \times 10^{10}$ | $6.00 \times 10^9$ | $3.16 \times 10^9$ | $2.00 \times 10^9$ |
| Bulge mass ($M_{bulg}$) | $4.00 \times 10^9$ | $2.00 \times 10^9$ | $1.33 \times 10^9$ | $1.00 \times 10^9$ |
| Gas disk mass ($M_{galk}$) | $4.00 \times 10^9$ | $6.65 \times 10^9$ | $1.66 \times 10^9$ | $0.00$ |
| Halo mass ($M_{halo}$) | $6.65 \times 10^{11}$ | $2.22 \times 10^{11}$ | $1.11 \times 10^{11}$ | $6.65 \times 10^{10}$ |
| Concentration | $8.40$ | $9.47$ | $10.22$ | $10.81$ |
| $M_*/M_{halo}$ | $0.03$ | $0.03$ | $0.03$ | $0.03$ |
| $M_{BH}$ ($M_*$) | $4.00 \times 10^6$ | $6.65 \times 10^5$ | $1.66 \times 10^5$ | $5.00 \times 10^4$ |
| $M_{BH}/M_{halo}$ | $0.001$ | $0.001$ | $0.001$ | N/A |
| $N_{total}$ | $3,500,000$ | $1,166,667$ | $583,333$ | $350,000$ |
| $N_{disk}$ | $300,000$ | $112,500$ | $59,375$ | $37,500$ |
| $N_{bulge}$ | $75,000$ | $12,500$ | $3125$ | $0$ |
| $N_{halo}$ | $3,125,000$ | $1,041,667$ | $520,833$ | $312,500$ |
| $m_{disk}$ ($M_*$) | $5.32 \times 10^4$ | $5.32 \times 10^4$ | $5.32 \times 10^4$ | $5.32 \times 10^4$ |
| $m_{bulge}$ ($M_*$) | $5.32 \times 10^4$ | $5.32 \times 10^4$ | $5.32 \times 10^4$ | $5.32 \times 10^4$ |
| $m_{halo}$ ($M_*$) | $2.13 \times 10^5$ | $2.13 \times 10^5$ | $2.13 \times 10^5$ | $2.13 \times 10^5$ |
| Mass ratio with G1 | 1:1 | 3:1 | 6:1 | 10:1 |

(Moster et al. 2010) and it may differ even if two dark matter haloes have the same mass (Ferrero et al. 2012; Miller et al. 2014). However, we decide to fix this ratio to 0.03, because changing stellar mass leads to a change in other related parameters such as gas fraction or bulge size, and makes our experiments more complex to interpret. The stellar disk follows an exponential profile radially and sech$^2$ profile vertically. We determine the radial scale lengths of stellar disks based on the r-band scale length–stellar mass relation seen in observed galaxies (Fathi et al. 2010). The truncation radius of the stellar disks is four times the scale radius. For example, G1 has a scale radius of 2.5 kpc and a truncation radius of 10 kpc. The vertical scale height and truncation height are initially 10% of the radial scale lengths (e.g., 0.25 and 1.0 kpc for G1). The gas disk follows an exponential profile both radially and vertically, and its radii (both scale and truncation) are 1.6 times those of the stellar disk (Cayatte et al. 1994). The vertical scale heights of the gas disks are given in Table 1. The amount of gas in a component follows the profile of Hernquist (1990).

Our galaxies are modeled to mimic local spiral galaxies from type Sb to Sd. The bulge-to-total ratio (B/T, bulge mass divided by the sum of bulge and stellar disk mass) decreases from large to small galaxies. We determine the values following the B/T light ratios of galaxies with different morphologies (Graham & Worley 2008). We model our largest galaxy, G1, after an Sb-like galaxy because they are abundant in the local universe and mergers including Sb primary galaxies are more common (Khim et al. 2015). We also produce Sa- or Sc-like primary galaxies and their merger-driven SF properties are discussed in Section 4.8. The smaller galaxies become increasingly late-type as we move from G2, to G3, and to G4.

We fixed the $M_{BH}/M_{bulge}$ for all galaxies except G4, which is bulgeless. We confirm that this choice is allowed within the uncertainties in the relation between the BH mass and bulge mass of observed galaxies (Marconi & Hunt 2003; Bennett et al. 2011).

Face-on images of the simulated disk galaxies, evolved in isolation for 1.0 Gyr, are presented in Figure 1, and details of the disk galaxy models are provided in Table 1.

### 3.2. Evolution of Isolated Galaxies

We performed simulations with low-resolution (level 11) for the first 0.3 Gyr, which is roughly similar to the dynamical timescale of G1. This is because all the components of a disk galaxy are not in equilibrium, which causes density perturbations. We allowed SF to occur with a density threshold of $0.1 \text{ H cm}^{-3}$, but we did not allow gas accretion and AGN feedback to occur. During this period, a ring-like structure appears in the disk, moves outwards from the center to the outskirts, and then disappears. After 0.3 Gyr, we ran the simulations with a level 13 resolution and an SF density threshold of $10.0 \text{ H cm}^{-3}$. Gas accretion and AGN feedback were switched on after this time. Numerical effects resulting from the change in resolution are very short-lived because cooling timescales are significantly shorter than dynamical timescales. Figure 2 presents the star formation histories.
of galaxies evolving in an isolated environment. The largest galaxy, G1, exhibits the greatest SFR (blue lines) and the SFRs of the other three galaxies (G2, G3 and G4) are similar to each other (green, orange, and red lines). As AGN feedback is not allowed to occur during the first 0.3 Gyr, the AGN feedback affects the SFR only after 0.3 Gyr (blue solid and dashed line).

We confirm the results of Newton & Kay (2013) that, for isolated galaxies, an AGN does not strongly influence the SF. For example, in our G1 model the SF over 6 Gyr is only reduced by 13.2% due to the presence of an AGN.

4. Mergers

In this section, we discuss the SF properties of various merging galaxies. For clarity, we define terms that will be frequently used throughout this paper. In non-equal merger cases, we call the larger and smaller galaxy the primary and secondary galaxy, respectively. We define the merger mass ratio as the ratio of the stellar mass of the primary galaxy to that of the secondary galaxy, that is, $M_{\text{primary}} / M_{\text{secondary}}$. We deal with galaxy mergers with mass ratios of 1:1, 3:1 (major), and 6:1 and 10:1 (minor).

Each merger simulation starts with two galaxies separated by an initial distance of $0.8 R_{\text{vir}}$, where $R_{\text{vir}}$ is the virial radius of the primary galaxy. The initial positions and velocities of the galaxies are determined by the orbits we want to simulate (elliptical, parabolic, or hyperbolic) with the center of mass of the two galaxies located at the simulation box center. However, in 10:1 mergers with hyperbolic orbits, we shift the center of mass from the box center to prevent secondary galaxies with large initial velocities from escaping from the box after the first encounter of the two galaxies.

When the separation between the two galaxies becomes a minimum for the first time, we call this the first passage (FP). The second minimum separation is defined as the second passage (SP). We define the final coalescence (FC) as the moment when the centers of the two galaxies are closer than 1 kpc (Lotz et al. 2008). We use the center of mass of the bulge component as the galaxy center, as it is small and concentrated, except in the 10:1 mergers where the lower-mass galaxy lacks a bulge. Then we use the center of mass of the stellar disk instead.

As with the isolated galaxy simulations discussed in Section 3.2, the merger simulations are initially performed with a lower resolution for the first 0.3 Gyr, to ensure stability (similar to Gabor et al. 2016), before switching to the high-resolution phase. During this period, gas accretion and AGN feedback are switched off. We confirm that first passage and
the corresponding burst of SF always occur during the high-resolution phase.

In any merger, there are a vast number of parameters that can be varied. In order to conduct our parameter study, we adopt the following procedure: we fix all other parameters while varying only a single parameter, so as to clearly see the dependence of the SF on that parameter (Sections 4.3 and 4.4).

### 4.1. Burst Efficiency

In order to quantify the merger-driven SF, we use the burst efficiency $\epsilon$ that was used by C08. This parameter is defined as the difference between the fraction of gas consumed by SF in the interacting system and that in isolation. If the burst efficiency of a galaxy merger is zero, it means that the merger does not trigger the starburst at all and the SFHs of isolated and merging galaxies are identical. If this value is 0.5, it means that 50% of the initial gas mass has been converted to merger-driven SF. When measuring the burst efficiency, we consider the SF that occurs between first passage and twice second passage. This is partly because the absence of the stellar bulge in G4 makes it difficult to determine the final coalescence time in 10:1 mergers. However, in practice we find that the two timescales ($FC + 1\ Gyr$) match well and, in any case, the burst efficiencies are very similar to each other. For instance, in a 1:1 merger simulation without AGN feedback, the second passage timescale is $1.22\ Gyr$ and the final coalescence timescale is $1.37\ Gyr$. The burst efficiency measured with the second passage time and with the final coalescence time is 0.486 and 0.485, respectively. The reason why they are so similar is because there is very little SF toward the end of the simulations and so, although we choose a factor of 2 arbitrarily, our results are not sensitive to this choice.

### 4.2. AGN Feedback and Mass Ratios

In previous studies of the effect of AGN feedback on SF in galaxy mergers (Di Matteo et al. 2005; Newton & Kay 2013; Hayward et al. 2014), only equal-mass mergers had been targeted and simulated. However, a suite of merger simulations by Capelo et al. (2015) demonstrated that the mass ratio of two galaxies is the most important factor that determines the growth...
of SMBHs and AGN activity. In order to see the effect of AGNs on SF in mergers with different mass ratios, we compare merger simulations (with and without AGN feedback) for four mass ratios (1:1, 3:1, 6:1 and 10:1). These are created with the combination of G1 and one of the four galaxies from G1 to G4.

Figure 3 presents the SFHs of these simulations. A decrease in SFR by AGN feedback is observed in the mergers of all mass ratios. Independent of mass ratio, the SF shortly after first passage is not affected significantly by the AGN feedback but the decrease in SF after second passage is more pronounced. This is because the concentration of gas in the galaxy center after first passage is not as intense as that at second passage or final coalescence. Immediately after first passage, SF still occurs throughout the disks, so the AGN effect is small. However, at a late evolutionary stage such as final coalescence, bursts of SF are severely affected by AGN activity because the gas is concentrated in the galaxy center, surrounding the AGN. Not only the instantaneous SFR but also the integrated SF is significantly affected. We measure the total mass of new stars that form during the first 6 Gyr for our simulations. In isolation, our G1 model produces 13.2% less mass in stars when an AGN is included. But in an equal-mass merger of two G1 galaxies, 40.4% less stellar mass is produced by including the effects of AGN feedback. This is consistent with the findings of Newton & Kay (2013) which indicate that AGNs have a small impact in isolated galaxies while the suppression of SF by AGNs is more dominant in galaxy mergers, which tend to drive gas to the galaxy centers, feeding the AGN. We find that in 3:1, 6:1, and 10:1 mergers, the total stellar mass produced in 6 Gyr is reduced by 39.5%, 37.8%, and 30.5%, respectively, indicating that the more major mergers are better able to drive gas onto the AGN.

For equal-mass-ratio mergers, the burst efficiency is 0.486 without AGNs, and 0.233 with AGN feedback, corresponding to 52% of its original value. The 3:1 merger shows a similar proportion of decrease in the value of burst efficiency (from 0.282 to 0.135, a 52% reduction). The minor mergers exhibit an even greater decrease in burst efficiencies (65% and 60%, respectively for 6:1 and 10:1 mergers).

The difference in the mass growth of SMBHs accounts for the variations in the extent of SF suppression by AGN feedback in mergers with different mass ratios. In Figure 4, we present the SMBH activities of merging galaxies. In the equal-mass merger, the mass growth of the BH is modest at first passage and second passage. But at final coalescence, both the BH merger and intense gas accretion contribute to a large growth of the BH. For increasingly minor mergers, the mass growth of the SMBH becomes less pronounced and the amount of gas accretion decreases. For our most minor merger (10:1 mass ratio) the SMBH does not show any enhancement in BH activity. This result is in agreement with that of Capelo et al. (2015), who claimed that major mergers have a significant impact on the growth of the primary galaxy’s SMBH due to the strong tidal torques from large companion galaxies. The moment when the highest accretion rate occurs also changes depending on merger mass ratio. For example, the highest accretion rate appears before final coalescence in the 1:1 merger while it is highest before second passage in the 3:1 and 6:1 mergers. The duration over which accretion rates are maintained also depends on mass ratio. In equal-mass mergers, the accretion rate becomes almost zero after 2 Gyr, while the SMBHs in the other mergers maintain their gas accretion.

4.3. Inclination

We measured the burst efficiencies of mergers between G1 and G3 (mass ratio 6:1) with AGN feedback by changing the angle between the spin plane of the primary galaxy (G1) and

![Figure 4. BH growths in AGN simulations with mass ratios 1:1, 3:1, 6:1, and 10:1. The top panels present the evolution of the SFRs which are the same as those in the lower panel of Figure 3. Panels in the middle row display the mass of the SMBH of the primary galaxy. For comparison, the BH mass of the isolated G1 model is indicated by a dashed line. The bottom panels show the accretion rates of primary BHs with Eddington limits. FP, SP, and FC times are given as vertical dotted lines. Note that the AGN starts at 0.3 Gyr (Section 3.2).](image-url)
orbital plane of the secondary galaxy (G3). We fixed the galactic disk of the secondary galaxy to be in its orbital plane.

As mentioned in Section 4.1, the inclination of a galaxy can lead to an artificially lowered rate of SF due to numerical effects. This can be seen in the difference in the SF rates between the isolated and merger models during the low-resolution phase (before 0.3 Gyr) in Figure 5. We minimize the impact of this effect by neglecting the contribution of SF during the lower-resolution phase, when numerical effects will be strongest. We find that inclination angles of coplaner mergers (0° and 180° inclination) have larger increases in SFR. This effect must be partly physical, as the merger simulations of C08 were conducted with a smoothed particle hydrodynamics code and found similar results with regard to the fact that coplaner mergers result in the highest SF enhancement.

In C08, the total SF over the whole simulation period was reported to be higher in prograde mergers, in contrast to Di Matteo et al. (2007) who reported more efficient SF in retrograde mergers. Our results show a larger value of the burst efficiency in the retrograde merger, driven primarily by the strength of the starburst that occurs immediately after first passage.

4.4. Orbits

Orbits are determined by the initial positions and velocities of secondary galaxies. In Figure 6, we present the SFHs of minor mergers (mass ratio 6:1 and 10:1) with three different types of orbits. For a given mass ratio, the secondary galaxy with an elliptical orbit (eccentricity e = 0.97) possesses the lowest kinetic energy of all the orbits. The initial kinetic energy increases with the eccentricity of the orbit. The parabolic orbit has e = 1.00, and the hyperbolic orbit has e = 1.03. Our choice of a maximum eccentricity of 1.03 is because, if it is larger, then in the 10:1 hyperbolic merger the secondary galaxy comes too close to the simulation box boundaries.

For a given mass ratio, SF peaks after the first passage is highest in a hyperbolic orbit. In this orbit, the secondary galaxy moves faster and encounters the primary galaxy earlier than that in the other orbits. There is more gas available at this early moment, leading to a higher SFR. On the other hand, it takes longer for the secondary galaxy to finally merge with the primary galaxy on such an energetic orbit. Since less gas remains at this late epoch, SFR after the second passage is lower in such an orbit. The opposite is true in an elliptical orbit: the SF peak is lowest after first passage and highest after second passage, compared to its counterparts on other orbits. Because of this, there is no simple correlation between the shape of the orbit and the burst efficiency observed.

4.5. Bulge Fractions

Using observational data, K14 demonstrated that the enhancement in the SSFR of spiral galaxies possessing disturbed features (which are thought to be caused by minor mergers) is more prominent in later-type spiral galaxies such as Sc and Sd. He interpreted this as being due to those galaxies

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Figure 5. SFHs of 6:1 mergers with various inclinations. The format is the same as in Figure 3. The inclination angle and burst efficiency are given in each panel. The orbit is parabolic and AGN feedback is considered in all merger simulations.

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In this work e denotes eccentricity since e is used for burst efficiency.
Figure 6. SFHs of minor mergers with three different orbits. In each panel, mass ratios, orbits and burst efficiencies are given. AGN feedback is considered.

Figure 7. SF and SMBH activities of merging galaxies with various B/T ratios. The top panels show the SFRs of simulations without AGN feedback and the middle panels show those of the simulations with the AGN. The accretion rate of the primary SMBH of the AGN simulations is given in the bottom three panels with the same format as in Figure 4.
having low bulge-to-total ratio \((M_{\text{bulge}}/(M_{\text{bulge}} + M_{\text{stellar disk}}))\) and high gas fraction \((M_{\text{gas disk}}/(M_{\text{gas disk}} + M_{\text{stellar disk}}))\). In this section, we consider the effect of the bulge on merger-driven SF, and fix the gas fraction. The effect of the gas fraction will be treated in Section 4.6.

The interpretation of K14 of bulge fraction and SF enhancement is based on the minor merger simulations of Mihos & Hernquist (1994). In their study, a bulgeless disk galaxy shows larger SFR enhancement compared to one with a bulge component. They suggested that gas inflow and the subsequent starburst are regulated when there is a central bulge. The simulations of C08 also varied the bulge-to-total ratio in the case of minor mergers, and found higher values of burst efficiency for lower bulge-to-total ratio. However, neither of these studies included a treatment of AGN feedback.

Similar to Mihos & Hernquist (1994), we fix the stellar disk mass while varying the B/T ratio with values of 0.0, 0.2, and 0.4. This is conducted on the primary galaxy, which has the properties of G1 (except of course the bulge). The secondary galaxy is always G3.

Figure 7 shows the resulting SFHs and accretion rates of these simulations. When the AGN feedback effect is ignored (top three panels), the bulgeless galaxy exhibits a larger instantaneous SFR at final coalescence and burst efficiency than those of the others. However, these differences are less prominent when AGN feedback is considered (middle panels). This is because the central concentration of the gas, which is less suppressed in low B/T galaxies, triggers not only the starburst but also the intense gas accretion and subsequent AGN activity. In the bottom panels, it is shown that the gas accretion rate in a bulgeless galaxy (right panel) is maintained at a higher value than in the other galaxies between first passage and second passage. BH activity becomes weaker after second passage but increases again after final coalescence.

With AGN feedback, the burst efficiency still increases with decreasing B/T ratio. However, the peak instantaneous SFR, especially around final coalescence, does not show such a clear trend with B/T ratio. This suggests that the dependence of merger-driven SF on the bulge fraction seen in previous studies is weakened when AGN feedback is included.

4.6. Gas Fraction

Another factor suggested by K14 that causes a stronger enhancement in SSFR in late-spirals is gas fraction. We present the SFHs of 6:1 mergers (merger between primary galaxy and G3) with different primary galaxy gas fractions in Figure 8. The primary galaxy with \(f_{\text{gas}} = 0.200\) is G1, but we vary the gas fraction while fixing the stellar mass.

In this suite of simulations, mergers with high gas fractions show higher burst efficiencies. This is opposite to the result of C08. They claimed that galaxies with a high gas fraction consume a large amount of gas regardless of a merger; therefore, those galaxies show smaller values of burst efficiency. In our simulations, it is true that higher gas fractions do lead to higher SFRs in isolated galaxies. However, regardless of this, our mergers with higher gas fractions show increased SFRs, suggesting that our galaxies still have sufficient gas for a starburst when the mergers occur. The reason for this difference may be two fold. Perhaps their mergers occur later, when more of the gas has been used up, or their sub-grid physics treatment of SF differs from our own.

The increase in SF with gas fraction that we see is most prominent after second passage. This could be because at second passage the central gas concentration may not be so strong, and so there is no intense AGN activity. However, SF after the third passage or final coalescence is not significantly affected by gas fraction, perhaps because the AGN plays a stronger role, or maybe because more gas was consumed earlier.

4.7. Black Hole Mass

Regarding the relation between SF and galactic morphology, earlier studies such as those of Mihos & Hernquist (1994) and C08 focused on the role of the bulge that prohibits gas inflow and starburst. However, the effect of SMBHs at the center of the bulge requires a thorough understanding, given that the BH mass is coupled with the bulge mass or velocity dispersion (Magorrian et al. 1998; Marconi & Hunt 2003; Gültekin et al. 2009; Bennert et al. 2011).

To investigate the role of the BH mass, we use G1 as our primary galaxy, and vary the BH mass while fixing every other parameter. Figure 9 illustrates the results. We see no strong dependence on BH mass, except regarding the peak instantaneous SFR occurring at third passage or final coalescence, where a more massive BH can slightly suppress the SF. But overall we find no clear trend between BH mass and burst efficiency.
dependence of the SFR on these parameters. The presence of AGN feedback has significantly weakened the relation between SF and bulge fraction. Therefore, we now use our simulations to understand the AGN feedback effect.

In our simulations, we derive different values of $\gamma$ for different B/T ratios. When the B/T ratios of the primary galaxies are 0.4, 0.2, and 0.0, the simulation results give values of $\gamma = 0.30$, 0.38, and 0.42, respectively. The variation in $\gamma$ with B/T ratio is less than in the C08 simulations without AGN feedback ($\gamma = 0.61, 0.74$, and $1.02$ for B/T = 0.33, 0.17, and 0.00). However, readers should note that burst efficiency might be sensitive to the recipes of SF and feedback in different kinds of simulations. Therefore, further investigations to understand the effect of AGNs on $\gamma$ under the same conditions and the application to galaxy formation models are required in the future. The implication of the result of the semi-analytic galaxy formation model is discussed in Section 5.

### 4.8. Morphology

Combining bulge fraction, gas fraction, and BH mass, we produce model Sa- and Sc-like primary galaxies. Table 2 summarizes these models. The Sb-like primary galaxy is G1, as mentioned in Section 3.2. Generally, galaxy mass decreases from early to late spirals (Khim et al. 2015), but we fix the stellar mass of the three primary galaxies for simplicity. We calculate the burst efficiencies of minor mergers of the combinations of three primary galaxies (Sa, Sb, and Sc), secondary galaxies (G3 and G4) and orbits (elliptical, parabolic, and hyperbolic).

Figure 10 presents these results. We do not see any clear trends with galaxy morphology, despite the fact that more late-type galaxies have smaller B/T and higher gas fraction. We believe this is because, as demonstrated in Sections 4.5 and 4.6, the presence of AGN feedback has significantly weakened the dependence of the SFR on these parameters.

### 4.9. Parameterization in Semi-analytic Models

The burst efficiency is parameterized as follows in certain semi-analytic galaxy formation models:

$$ e = e_{1:1} \left( \frac{M_{\text{secondary}}}{M_{\text{primary}}} \right)^{\gamma}. $$

Here, $e_{1:1}$ is the burst efficiency of an equal-mass merger. In the semi-analytical models of Somerville et al. (2008) and Lee & Yi (2013), this value is determined by the AGN simulations of Robertson et al. (2006). However, $\gamma$, which describes the relation between the galaxy mass ratio and merger-driven SF, is determined by the non-AGN simulations of C08. The latter yielded a value of $\gamma$ which depends on the bulge-to-total ratio of primary galaxies and Somerville et al. (2008) adopted this value in their model. However, as discussed in Section 4.5, the presence of an AGN changes the relation between SF and bulge fraction. Therefore, we now use our simulations to obtain $\gamma$ considering the AGN feedback effect.

In our simulations, we derive different values of $\gamma$ for different B/T ratios. When the B/T ratios of the primary galaxies are 0.4, 0.2, and 0.0, the simulation results give values of $\gamma = 0.30$, 0.38, and 0.42, respectively. The variation in $\gamma$ with B/T ratio is less than in the C08 simulations without AGN feedback ($\gamma = 0.61, 0.74$, and $1.02$ for B/T = 0.33, 0.17, and 0.00). However, readers should note that burst efficiency might be sensitive to the recipes of SF and feedback in different kinds of simulations. Therefore, further investigations to understand the effect of AGNs on $\gamma$ under the same conditions and the application to galaxy formation models are required in the future. The implication of the result of the semi-analytic galaxy formation model is discussed in Section 5.

### 5. Summary and Conclusions

Using the AMR hydrodynamics code RAMSES, we have performed galaxy merger simulations to study the SF of merging disk galaxies. We have run idealized merger simulations, changing different parameters such as the mass ratios of the two galaxies, the angle between the galactic spin plane and orbital plane of the secondary galaxy, type of orbit, primary galaxy’s bulge fraction, gas fraction, and BH mass. With the burst efficiency previously introduced by C08, we quantify the merger-driven SF of all merger simulations.

We performed approximately 70 individual numerical simulations of isolated and merging galaxies and obtained the following results.

1. We find that in isolated galaxies, the presence of an AGN is not very significant for the suppression of SF. However, in merging galaxies the effect of the AGN is more prominent, as much more gas is funneled into the centers of the galaxies, feeding AGN activity. This result is consistent with that of Newton & Kay (2013). We additionally find that the timing is important. After first passage the AGN does not play a strong role, but after final coalescence it becomes highly significant in suppressing SF.

2. In our models, gas is efficiently funneled to the galaxy centers at the stage of the final coalescence. As a result, at this time AGN activity peaks and SF is more efficiently
suppressed. This is consistent with Di Matteo et al. (2005); however, we consider a wide range of galaxy mass ratios, and by 10:1 we find that AGN activity enhancement is negligible. This is because minor mergers only weakly perturb the gas disk, as shown by Capelo et al. (2015). We test the impact of having an AGN on the amount of stars produced during the simulations, and find the impact is stronger in major mergers.

3. Coplanar mergers produce more new stars compared to mergers with other inclination angles. In our simulations, the retrograde merger shows a larger value of burst efficiency than that of the prograde merger because strong starburst occurs after first passage in the retrograde merger.

4. No correlation between orbital eccentricity and SF has been found. However the dependence on orbital parameters is
complicated by the fact that more eccentric orbits tend to coalesce at later times, when there is less gas available for a starburst. Thus we find that the timing of the merger, and its relation to gas fraction, can play a dominant role in controlling the burst efficiency.

5. Previously the bulge-to-total ratio was found to strongly affect the amount of stars produced in mergers. However, we find that with AGN feedback, merger-driven SF becomes significantly less dependent on the bulge fraction of the primary galaxy. This is because the stronger concentration of gas in the galaxy centers that occurs in a bulgeless galaxy also triggers strong AGN activity, which in turn can suppress SF.

6. The gas fraction affects the SFR at first passage and second passage, but not as the galaxies approach final coalescence. This is because, at first passage and second passage, most of the SF occurs away from the BH. This result is in contrast to the simulations of CO8, which could be the result of a differing sub-grid treatment of SF, or due to differing times when the merger occurs.

7. We find that SFRs are fairly independent of BH mass, except during final coalescence when the gas is most funneled to the galaxy center.

8. Sc-type disk galaxies in our simulations do not always show large SF and burst efficiency. This is because the AGN activity tends to suppress the additional SF that would come from late-type galaxies being more gas rich, and less bulge dominated.

9. We obtained a burst efficiency fit in our simulations with AGN feedback. Compared to the non-AGN simulations of CO8, our results suggest smaller dependence of γ on bulge fraction.

The inclusion of AGN feedback in merger simulations leads to a lower value of burst efficiency (Section 4.9); hence, a decrease in the amount of merger-driven SF is expected if the AGN effect is accurately considered in galaxy formation models. In our simulations, the total mass of stars formed by mergers could decrease by as much as a factor of two or three in the presence of AGN feedback. However, we do not expect that this has a significant impact on the stellar masses of the global population of galaxies. Indeed, some semi-analytical models have demonstrated that merger-driven SF only contributes a few percent of the total stellar mass in massive galaxies (Lee & Yi 2013).

Our Sc-type disk galaxies exhibit lower SFRs and burst efficiencies in some cases while those in observations (K14) show larger SF enhancement by minor mergers. This is because SF is suppressed efficiently by AGN feedback in our Sc models. However, as pointed out by Newton & Kay (2013), different AGN models yield different results for SF in merging galaxies. Many studies on AGNs focused on the calibration of model-related parameters using global properties such as the $M-\sigma$ relation in cosmological simulations (Booth & Schaye 2009) and small-scale processes around SMBHs were ignored. We expect that this leads to an exaggeration of the strength of AGN activity, and adopting AGN prescriptions designed for cosmological simulations in galactic-scale simulations causes the results to be inconsistent with observations. Some attempts at understanding AGN-related physics at smaller scales (Park & Ricotti 2011, 2012) and making connections with the properties of host galaxies (Park et al. 2016) have been made, but there are still many gaps between AGN simulations at different physical scales. In this regard, further studies on small-scale AGN physics and the development of AGN models applicable to galactic-scale simulations are required.

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