# Hydrodynamical simulations of the triggering of nuclear activities by minor mergers of galaxies

Chao Yang<sup>1,2,3</sup>, Jun-Qiang Ge<sup>1,3</sup> and You-Jun Lu<sup>1,2,3</sup>

- <sup>1</sup> National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China; *chyang@nao.cas.cn*, *luyj@nao.cas.cn*
- <sup>2</sup> School of Astronomy and Space Sciences, University of Chinese Academy of Sciences, Beijing 100049, China
- <sup>3</sup> CAS Key Laboratory for Computational Astrophysics, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China

Received 2019 April 17; accepted 2019 May 20

Abstract Major mergers of galaxies are considered to be an efficient way to trigger Active Galactic Nuclei and are thought to be responsible for the phenomenon of quasars. This has however recently been challenged by observations of a large number of low luminosity Active Galactic Nuclei at low redshift ( $z \leq 1$ ) without obvious major merger signatures. Minor mergers are frequently proposed to explain the existence of these Active Galactic Nuclei. In this paper, we perform nine high resolution hydrodynamical simulations of minor galaxy mergers, and investigate whether nuclear activities can be efficiently triggered by minor mergers, by setting various properties for the progenitor galaxies of those mergers. We find that minor galaxy mergers can activate the massive black hole in the primary galaxy with an Eddington ratio of  $f_{\rm Edd} > 0.01$  and > 0.05 (or a bolometric luminosity  $> 10^{43}$  and  $> 10^{44} \, {\rm erg \, s^{-1}}$ ) with a duration of 2.71 and 0.49 Gyr (or 2.69 and 0.19 Gyr), respectively. The nuclear activity of the primary galaxy strongly depends on the nucleus separation, such that the nucleus is more active as the two nuclei approach each other. Dual Active Galactic Nuclei is only  $\sim 0.011 \, {\rm Gyr}$  and  $\sim 0.017 \, {\rm Gyr}$  with Eddington ratio of  $f_{\rm Edd} > 0.05$  and bolometric luminosity  $> 10^{44} \, {\rm erg \, s^{-1}}$ . This time period is typically shorter than that of dual Active Galactic Nuclei induced by major galaxy mergers.

Key words: galaxies: binary — quasars: general — methods: n-body simulations

## **1 INTRODUCTION**

Galaxy merging is a key process for the formation and evolution of galaxies in the  $\Lambda$ CDM hierarchical structure formation paradigm. It is widely accepted that the existence of supermassive black holes (SMBHs) at the centers of nearby galaxies is ubiquitous (Kormendy & Ho 2013; Kormendy & Richstone 1995). During the merging of two galaxies, a massive binary black hole (BBH) system may form naturally as the two central SMBHs approach each other due to dynamical friction and viscous drag (Begelman et al. 1980; Yu 2002). In the meantime, the angular momentum of gases may also be transferred out due to tidal interactions during the merging process, leading to gas sinking into the vicinity of one SMBH or both SMBHs and triggering nuclear activity or activities (e.g., Hernquist 1989). If only one of the SMBHs is activated, then the system may appear as an offset Active Galactic Nucleus (offset AGN, or oAGN), and if both of the SMBHs are activated, the system may appear as a dual AGN (dAGN) (e.g., Van Wassenhove et al. 2012; Comerford et al. 2012; Comerford & Greene 2014; Comerford et al. 2015; Barrows et al. 2016; Müller-Sánchez et al. 2016; Barrows et al. 2017; Capelo et al. 2017; Comerford et al. 2017; Blecha et al. 2018).

Galaxy mergers may provide an efficient way to transfer gas angular momentum outward and lead to the sinking of gas into the vicinity of SMBHs, thus triggering nuclear activity. However, the connection between galaxy merger and AGN triggering is still observationally inconclusive. Some observations clearly show the disk-like structure of low redshift, low luminosity AGN host galaxies, which suggests that minor galaxy mergers or secular processes trigger AGN activity (Cisternas et al. 2011; Kocevski et al. 2012; Hewlett et al. 2017; Lofthouse et al. 2017; Villforth et al. 2019). However, some other observations find that AGN host galaxies are highly perturbed in their morphology, which leads to a claim that major galaxy mergers dominate the triggering of AGNs (Ellison et al. 2011; Treister et al. 2012; Menci et al. 2014; Satyapal et al. 2014; Hong et al. 2015; Donley et al. 2018; Goulding et al. 2018). These two lines of observational results apparently contradict each other and hinder understanding of the triggering of nuclear activity.

Both dAGNs and oAGNs can be used as tracers of galaxy mergers. According to hydrodynamical simulations, if both progenitor galaxies are gas rich and comparable in mass (mass ratio > 1/3, i.e., a major merger), both SMBHs may be activated with relatively large Eddington ratios and high bolometric luminosities, and they emerge as a dAGN system with the two nuclei separated on a scale of ~ 1 - 10 kpc (e.g., Van Wassenhove et al. 2012; Blecha et al. 2013; Capelo et al. 2015; Steinborn et al. 2016; Capelo et al. 2017).

Observations do find such dAGN systems by employing various techniques (e.g., Komossa et al. 2003; Zhou et al. 2004; Wang et al. 2009; Xu & Komossa 2009; Comerford et al. 2009; Liu et al. 2010a,b; Comerford et al. 2011; Fu et al. 2011a,b; Koss et al. 2011; Frey et al. 2012; Fu et al. 2012; Ge et al. 2012; Koss et al. 2012; Blecha et al. 2013; Müller-Sánchez et al. 2015; Zhang & Feng 2016; Comerford et al. 2018; Wang et al. 2019).

The conditions for the formation of oAGNs may be different from those for dAGNs as the activation of only one SMBH is required. Both major and minor mergers may be responsible for the formation of dAGNs, but it is still not clear which one dominates the contribution to oAGNs (e.g., Comerford et al. 2015; Barrows et al. 2018)<sup>1</sup>.

In this paper, we use high resolution hydrodynamical simulations to study whether significant nuclear activities can be triggered by minor galaxy mergers and investigate whether dAGNs and oAGNs can emerge from the merging processes of minor galaxy mergers. The paper is organized as follows. In Section 2, we briefly introduce the numerical simulations we performed and their initial setups. Then we summarize the main results in Section 3. Finally, some discussion and conclusions are given in Section 4.

## 2 NUMERICAL SIMULATIONS

#### 2.1 Initial Setup

We implement the smoothed particle hydrodynamics (SPH) code GADGET-2 (Springel 2005) for simulation, in which we take into account physical processes including the star formation, supernova feedback, black hole (BH) accretion and AGN feedback.

To simulate the star formation and supernova feedback processes, the gas density ( $\rho_{\rm gas}$ ) is divided into a hot component  $\rho_{\rm h}$  and a cold component  $\rho_{\rm c}$  based on the hybrid model proposed in Springel & Hernquist (2003), from which we have  $\rho_{\rm gas} = \rho_{\rm h} + \rho_{\rm c}$ . The star formation rate (SFR) at a characteristic timescale  $t_*$  is defined as

$$\frac{d\rho_*}{dt} = (1-\beta)\frac{\rho_c}{t_*},\qquad(1)$$

where  $\beta$  denotes the mass fraction of the newly formed stars which explode as supernovae instantly. A gas particle will spawn a star particle when the gas density exceeds a given threshold  $\rho_{\rm th} = 0.35 \ h^2 \ {\rm cm}^{-3}$  to match the observational law (Springel & Hernquist 2003; Nagamine et al. 2004; Thompson et al. 2014).

With the defined gas density, the SMBH accretion rate is calculated by adopting the Bondi-Hoyle-Lyttleton parametrization (Hoyle & Lyttleton 1939; Bondi & Hoyle 1944; Bondi 1952) formalism

$$\dot{M} = \frac{4\pi\alpha G^2 M_{\rm BH}^2 \rho_{\rm gas}}{(c_{\rm s}^2 + v^2)^{3/2}},$$
(2)

where  $\alpha$  is a dimensionless parameter and is set as  $\alpha = 8$ for z = 3 cases, the same as that adopted in the literature, e.g., Booth & Schaye (2009), Johansson et al. (2009), Yang (2019), and set as  $\alpha = 100$  for z = 1 cases to account for the mass resolution of z = 1 cases being 10 times lower than that of the z = 3 cases (for discussions on the settings of  $\alpha$ , see Springel et al. 2005; Hayward et al. 2014; Rosas-Guevara et al. 2015; Negri & Volonteri 2017)<sup>2</sup>,  $c_{\rm s}$ corresponds to the speed of sound in the gas and v is the velocity of the BH relative to the gas. These settings of  $\alpha$ ensure a reasonable BH accretion rate. Here we limit  $\dot{M}$  to be not larger than the Eddington accretion rate  $\dot{M}_{\rm Edd}$ , in order to avoid super-Eddington accretion.

<sup>&</sup>lt;sup>1</sup> We also note here that in the final stage of a galaxy merger, the merged SMBH may gain a recoiling speed up to several thousand km s<sup>-1</sup> due to asymmetric gravitational wave emission (Campanelli et al. 2007). The recoiling BH can carry almost everything bounded to it (within  $\sim 10^5$  gravitational influence radii), and, as a consequence, the broad line region (BLR) will also move away bounded to the central SMBH, but the narrow line region (NLR) will be left behind (Madau & Quataert 2004; Blecha et al. 2011; Barrows et al. 2016; Skipper & Browne 2018). This may also contribute significantly to the census of oAGNs.

<sup>&</sup>lt;sup>2</sup> We choose a higher booster factor  $\alpha = 100$  to calculate the Bondi accretion rate for those three z = 1 cases. However, we find that the accretion rate is still relatively low compared to the z = 3 cases. An adaptive mesh refinement (AMR) method or a 10 times higher mass resolution may be required to better understand the gas feeding to the very central region of the galaxy. We defer this to a future study.

As to the AGN feedback, the energy injected into the surrounding gas is a fraction ( $\epsilon_f$ ) of the AGN bolometric luminosity

$$\dot{E}_{\rm feed} = \epsilon_{\rm f} L_{\rm bol} = \epsilon_{\rm f} \epsilon_{\rm r} \dot{M} c^2 \,, \tag{3}$$

where c is the speed of light in a vacuum and  $\epsilon_r$  is the mass to energy conversion efficiency. Here we take the typical values  $\epsilon_r = 0.1$  and  $\epsilon_f = 0.05$  to study AGN feedback (Di Matteo et al. 2005), which can regulate the evolution of the established galaxy following the observed  $M_{\rm BH} - \sigma$ relation (e.g., Magorrian et al. 1998; Tremaine et al. 2002; Kormendy & Ho 2013). In the simulation, the BH accretion process and AGN feedback are numerically implemented by following the procedure described in Springel et al. (2005).

#### 2.2 Construction of Galaxy Merger Systems

To study whether and how the central SMBH can be triggered by minor mergers, we design nine sets of these systems with different mass ratios and galaxy types as listed in Table 1. We denote those simulations according to their parameter settings for (q, f, z) in the following way (see Table 1). Here q represents the mass ratio of the two progenitor galaxies, with q5 and q10 representing 1:5 and 1:10 minor mergers, respectively; f signifies the gas fraction of each galaxy in units of 0.1, with the two consequent numbers after f representing the gas fraction of the primary galaxy and the secondary galaxy, respectively, e.g., f13 denotes that the gas fractions of the primary galaxy and the secondary galaxy are 0.1 and 0.3, respectively; ss and es represent the type of the primary and secondary galaxies, with s and e corresponding to a spiral galaxy and an elliptical galaxy, respectively; z1 and z3 represent the initial redshift of the simulation, i.e., z = 1 and z = 3, respectively. One of these nine cases has an extra symbol p10, which means that we specify a pericenter  $r_{\rm p} = 10$  kpc; for other cases we adopt the pericenter as 20% of the virial radius of the primary galaxy (9.3 kpc for z = 3 and 35.7 kpc for z = 1).

At redshift z = 3, galaxies tend to be gas rich and possibly have varying gas fractions. Hence, we start the simulation from q5f13ssz3, q5f31ssz3 and q5f33ssz3, which are 1:5 mergers starting from z = 3 but with different gas fractions included in the primary and secondary galaxies, with which we can quantify the effect of gas content on the AGN triggering. These three mergers are set to be co-planar (with inclination angle  $i = 0^{\circ}$ ) and prograde. Considering the different inclination angles, which indicate different angular momenta of these merging systems and which can affect the morphology of the merged galaxy (e.g., Springel & Hernquist 2005; Sparre & Springel 2017; Yang 2019), we then set the q5f33ssz3i system with inclination angle  $i = 45^{\circ}$  but keep the other parameters the same as q5f33ssz3 to investigate the effect of inclination angle. We also set the galaxy mergers with mass ratio 1:10 as  $i = 0^{\circ}$  (q10f33ssz3) and  $i = 45^{\circ}$  (q10f33ssz3i) to analyze how the triggering of AGN activity is affected by different mass ratios. The above six galaxy mergers are put into a parabolic Keplerian orbit (eccentricity e = 1), with the initial separation set as the sum of the virial radii of the primary and secondary galaxies. The pericenter is set to 20% of the virial radius of the primary galaxy.

At redshift z = 1, the fraction of elliptical galaxies increases compared to that at z = 3 (e.g., Hopkins et al. 2008; Ilbert et al. 2010; Conselice 2014). We then simulate one spiral-spiral (q5f33ssz1) and one ellipticalspiral (q5f03esz1) merging system starting at z = 1 to study how these differ from the z = 3 case. These two systems have the same orbital setup as that starting at z = 3. In addition, we set an elliptical-spiral minor merger (q5f03esz1p10) with lower pericenter  $r_p = 10 \text{ kpc}$  to make a closer encounter at the first pericentric passage and identify whether the gas transfer can be significantly changed in the merging process.

In our simulation, a spiral galaxy consists of a dark matter halo, a stellar bulge, a disk component with both stars and gas included, and a central SMBH. An elliptical galaxy includes a dark matter halo, a stellar bulge and a central SMBH.

For the spiral galaxy, we use a Hernquist profile (Hernquist 1990) to describe its dark matter halo with virial mass  $M_{\rm vir}$  given in Table 2. The disk mass is set as 0.04 of the virial mass, i.e.,  $m_{\rm d} = 0.04 M_{\rm vir}$ . Inside the disk, the gas fraction  $f_{\rm gas}$  varies from 0.1 to 0.3 for spiral galaxies. The galaxy bulge, which is also assumed to be distributed as a Hernquist profile, is set as 0.008 of the virial mass, which indicates an initial bulge-to-total ratio B/T=0.2. According to the  $M_{\rm BH}-M_{\rm Bulge}$  relation (e.g., Marconi & Hunt 2003), we set the central SMBH to have a mass fraction  $m_{\rm BH} = 1.0875 \times 10^{-5}$  of the virial mass, to guarantee the establishment of a typical and reasonable spiral galaxy. The SMBH particle settles down in the galactic center as a sink particle, which accretes the surrounding gas particles including both the mass and momentum.

For the elliptical galaxy, the disk and gas components are excluded. Both the bulge and dark matter halo are described by the Hernquist profile. The bulge mass fraction is  $m_{\rm b} = 0.05$ , and the BH mass fraction is  $m_{\rm BH} =$  $8.0 \times 10^{-5}$ , which is also set based on the  $M_{\rm BH}$ - $M_{\rm Bulge}$ relation.

Setups of all the other parameters for the elliptical and spiral galaxies are listed in Table 2, and the corresponding

Simulation	Galaxy Type	$M_{\rm vir1}(M_{\odot})$	$M_{\rm vir2}(M_{\odot})$	q	$f_{\rm gas1}$	$f_{\rm gas2}$	z	Notes
q5f13ssz3	spiral + spiral	$2.27\times 10^{11}$	$4.54\times10^{10}$	1:5	0.1	0.3	3	
q5f31ssz3	spiral + spiral	$2.27 \times 10^{11}$	$4.54 \times 10^{10}$	1:5	0.3	0.1	3	
q5f33ssz3	spiral + spiral	$2.27  imes 10^{11}$	$4.54  imes 10^{10}$	1:5	0.3	0.3	3	
q5f33ssz3i	spiral + spiral	$2.27\times10^{11}$	$4.54\times10^{10}$	1:5	0.3	0.3	3	Inclined by $45^{\circ}$
q10f33ssz3	spiral + spiral	$2.27\times 10^{11}$	$2.27\times 10^{10}$	1:10	0.3	0.3	3	
q10f33ssz3i	spiral + spiral	$2.27\times10^{11}$	$2.27\times10^{10}$	1:10	0.3	0.3	3	Inclined by $45^{\circ}$
q5f33ssz1	spiral + spiral	$2.0\times 10^{12}$	$4.0  imes 10^{11}$	1:5	0.3	0.3	1	
q5f03esz1	elliptical + spiral	$2.0 \times 10^{12}$	$4.0 \times 10^{11}$	1:5	0	0.3	1	
q5f03esz1p10	elliptical + spiral	$2.0\times10^{12}$	$4.0\times10^{11}$	1:5	0	0.3	1	$r_p = 10   \mathrm{kpc}$

 Table 1 Physical Parameters for Constructed Galaxy Mergers

Table 2 Physical Parameters of Individual Galaxies in Our Simulation

	z = 1			z = 3				
Symbol	Primary (E)	Primary (S)	Secondary (S)	Primary	Secondary (1:5)	Secondary (1:10)		
(1)	(2)	(3)	(4)	(5)	(6)	(7)		
$M_{\rm vir} (M_{\odot})$	$2.0\times 10^{12}$	$2.0\times10^{12}$	$4.0\times10^{11}$	$2.3  imes 10^{11}$	$4.5\times10^{10}$	$2.3\times 10^{10}$		
$m_{\rm d} \left( M_{\rm vir} \right)$	0	0.04	0.04	0.04	0.04	0.04		
$m_{\rm b} \left( M_{\rm vir} \right)$	0.05	0.008	0.008	0.008	0.008	0.008		
$M_{\rm BH} (M_{\odot})$	$1.6  imes 10^8$	$2.2 \times 10^7$	$4.4  imes 10^6$	$3.0 \times 10^6$	$6.0  imes 10^5$	$3.0 \times 10^5$		
$j_{\rm d} \left( j_{\rm halo} \right)$	0	0.04	0.04	0.04	0.04	0.04		
$R_{200}  (\rm kpc)$	178.50	178.50	104.42	46.53	27.08	21.59		
$R_{\rm H} \ ({\rm kpc})$	67.12	67.12	39.26	8.66	5.04	4.02		
$R_{\rm S}$ (kpc)	59.50	59.50	34.80	5.17	3.01	2.40		
H (kpc)	0	5.73	3.35	0.94	0.55	0.44		
$Z_0$ (kpc)	0	0.57	0.34	0.10	0.05	0.04		
A (kpc)	2.78	1.15	0.67	0.19	0.11	0.09		

The left column explains the symbols used for describing a galaxy, which, from top to bottom, represent the virial mass, disk mass fraction, bulge mass fraction, BH mass, disk spin, halo virial radius, scale radius of Hernquist profile, halo scale radius, disk scale length, disk thickness and bulge scale radius, respectively. Columns (2)–(7) list the corresponding values, (E) stands for an elliptical galaxy, (S) means a spiral galaxy, and (1:5) and (1:10) represent the secondary spiral galaxies in 1:5 and 1:10 minor mergers, respectively.

**Table 3** Mass and Spatial Resolutions for Different Particles at z = 1 and z = 3

	Mass Resol	ution $(M_{\odot})$	Softening Length (pc)			
Particle Type	z = 1	z = 3	z = 1	z = 3		
Dark Matter	$1.1\times 10^6$	$1.1\times 10^5$	30	30		
Bulge	$3.7 \times 10^4$	$3.7  imes 10^3$	10	10		
Disk	$3.7 \times 10^4$	$3.7 \times 10^3$	10	10		
Gas	$4.6 \times 10^4$	$4.6 \times 10^3$	20	20		

mass resolution and softening lengths of the four particles: dark matter, bulge, disk and gas are listed in Table 3.

## 2.3 Identification of AGN Activities

In the galaxy merging process, gas can be concentrated at the galaxy center and trigger the nuclear activity, but the corresponding detection depends on the detection capability of current telescopes. Therefore, in this paper, we set two thresholds for the bolometric luminosity  $(L_{\rm bol} = 10^{43} \, {\rm erg \, s^{-1}}, L_{\rm bol} = 10^{44} \, {\rm erg \, s^{-1}})$  and two for the Eddington ratio  $(f_{\rm Edd} = 0.01, f_{\rm Edd} = 0.05)$  to match the varying detection capabilities of different telescopes.

#### **3 RESULTS**

Figures 1, 2 and 3 demonstrate the evolution processes of the nuclear bolometric luminosity, Eddington ratio, BH mass, SFR and BH separation of all the nine minor mergers that are listed in Table 1. The nine evolution sets manifest the roles the primary and secondary galaxies play in the minor mergers.

Based on our constructed galaxy mergers, we can have a clear understanding of how the orbital decay depends on different initial conditions. The orbital decays of the first three simulations in Figure 1 and the first two simulations in Figure 3 are quite similar before the first three pericentric passages, which indicate that the dynamical friction at the early stages of minor mergers is determined by the mass ratio, instead of by gas content (Yu 2002). Those



**Fig. 1** Evolution of the nuclear bolometric luminosities (*first row*), Eddington ratios (*second row*), SMBH masses (*third row*), total SFRs (*fourth row*), and the separations between the primary and secondary SMBHs (*fifth row*). Columns, from left to right, show the results obtained from the four simulations starting from z = 3 with a mass ratio of 1:5. The *red* and *blue solid lines* in the first to third rows represent the corresponding evolution curves for the primary and secondary SMBHs, respectively. In each column, the *vertical dotted lines*, from left to right, mark cosmic time at the first, second, third and fourth pericentric passages, respectively. The three *horizontal dotted lines* in the bottom row indicate separations of the two SMBHs at the first to third pericentric passages, respectively.



Fig. 2 Parameter evolution of the minor mergers starting at z = 3 with mass ratio 1:10 (q10f33ssz3, left, and q10f33ssz3i, right). Lines and colors are the same as in Fig. 1.

minor mergers with an inclination angle (last column of Fig. 1 and second column of Fig. 2) or a smaller  $r_{\rm P}$  (last two columns of Fig. 3) can accelerate the merging process. When the mass ratio decreases from 1:5 (Fig. 1) to 1:10 (Fig. 2), the merging time increases by a factor of  $\sim 2$ , which can be easily understood in that the dynamical friction timescale is inversely proportional to the mass of the secondary galaxy.

At the beginning of the minor merger, the bolometric luminosities and Eddington ratios of the primary and secondary SMBHs are determined by their initial gas fraction. For the q5f13ssz3, q5f03esz1 and q5f03esz1p10 simulations, the gas fraction of the primary galaxy is lower than that of the secondary one, which causes correspondingly lower  $L_{\rm bol}$  and  $f_{\rm Edd}$ . For the other six cases, the primary SMBHs still have lower  $f_{\rm Edd}$  but their  $L_{\rm bol}$  are higher than that of the secondary galaxy during most of the evolution time.

Once the two merging galaxies go through the first pericentric passage, the primary galaxy begins to rob gas



Fig. 3 Parameter evolution of the minor mergers starting at z = 1 with mass ratio 1:5. Columns, from left to right, display the evolution curves of q5f33ssz1, q5f03esz1 and q5f03esz1p10 simulations, respectively. Lines and colors are the same as those shown in Fig. 1.

from the secondary galaxy, and the bolometric luminosity of the primary SMBH is systematically larger than that of the secondary galaxy for those gas-rich mergers. For the two elliptical-spiral minor galaxy mergers (right two columns of Fig. 3), the evidence of gas capture is clearer: both the  $L_{\rm bol}$  and  $f_{\rm Edd}$  of the primary SMBH increase dramatically after the first pericenter, and their  $f_{\rm Edd}$  are comparable with that of the secondary SMBH after the fourth pericentric passage, which means their  $L_{\rm bol}$  is  $\sim 5$  times higher than that of the secondary SMBH. This gas capturing process can actually decrease the nuclear activity of the secondary SMBH. On the other hand, the tidal torques can also enhance the gas concentration for the secondary SMBH. In all nine cases, we can see that both the  $L_{\rm bol}$  and  $f_{\rm Edd}$  increase after the first to fourth pericentric passages as signified by the four vertical dotted lines in each panel. The gas capture and tidal torque finally produce the oscillating  $L_{\rm bol}$  and  $f_{\rm Edd}$  evolution curves.

Due to the similar evolution processes, the SMBH masses of the two galaxies increase following similar trends as those in the minor mergers starting at z = 3 (Figs. 1 and 2). The primary SMBH mass increases about  $\sim 0.6$  dex, while the secondary SMBH has a maximum increase of only  $\sim 0.2$  dex. For those galaxy mergers starting at z = 1 (Fig. 3), since their galaxy and SMBH masses are 10 times larger than those at z = 3, the minor merger cannot supply enough gas accretion and the SMBH masses increase less than 0.1 dex.

The amplitudes of the SFR evolution for the nine galaxy mergers are different, and are determined by the total amount of gas included in the two galaxies. The total gas mass included in the q5f13ssz3 merger (left col-

umn of Fig. 1) is weaker than in the others because it has the smallest amount of gas fraction included in the two galaxies. In contrast, the q5f33ssz1 (left column of Fig. 3) contains the largest amount of gas, which then has the strongest SFR.

Figures 4 and 5 depict the morphology of the merging galaxies in four different snapshots for each simulation: (1) the first pericentric passage, (2) the first apocentric passage after the first pericentric passage, (3) the time when one of the two nuclei is active and (4) the last output of the simulation. In the two figures, each two rows show the four snapshots viewed from face-on (first row) and edge-on (second row) angles. After the first pericentric passage a tidal bridge appears, which is the channel for the material transportation between the two galaxies. In the cases where the secondary galaxy is colliding with inclination angle  $i = 45^{\circ}$  (q5f33ssz3i and q10f33ssz3i), a tidal tail outside the galactic plane can be clearly seen. The tidal tails and bridges are believed to be evidence of galaxy merger (Mihos 1995; Barnes & Hernquist 1996; Knierman et al. 2003; Di Matteo et al. 2007; Smith et al. 2007)

For galaxy merging processes in different galaxy types and gas fractions, the SMBH activities in the primary and secondary galaxies are triggered at different times, which depend on the gas contained in each galaxy. Figure 6 shows the duration time at different separations, bolometric luminosities and Eddington ratios for paired galaxies. Here the duration time means the observed timescale of an active nucleus at a given separation, bolometric luminosity and Eddington ratio for each simulation run. From this figure, we can glean the following interpretation: 1) for the spiral-spiral minor mergers, the black hole activities have



**Fig. 4** Snapshots of the four minor mergers starting at z = 3 with mass ratio 1:5. Every two rows from top to bottom correspond to the simulations q5f13ssz3, q5f31ssz3, q5f33ssz3 and q5f33ssz3i. In each two rows, the first row depicts the four snapshots viewed face-on (perpendicular to the galactic plane of the primary galaxy), and the second row those those viewed edge-on (parallel to the galactic plane of the primary galaxy). Numbers 1–4 at the top left of each panel represent the four snapshots during the merger: (1) the first pericentric passage, (2) the first apocentric passage after the first pericentric passage, (3) when one of the two nuclei is active and (4) the last output of the simulation. The separation between the two SMBHs is written at the bottom left of each panel. The *black circles* in each panel indicate the position of the two SMBHs; those SMBHs with  $L_{bol} > 10^{43} \text{ erg s}^{-1}$  are marked with *filled black circles*. The radii of the *circles* are not scaled to the real size of SMBHs.

dichotomous distributions: one peaks at larger separations ( $\gtrsim 50 \text{ kpc}$ ), and the other peaks at sub-kpc scale. 2) for the primary galaxies in the spiral-spiral minor mergers, following the mass increase of the central SMBH,  $L_{\text{bol}}$  increases at the sub-kpc activity peak, but the corresponding  $f_{\text{Edd}}$  are similar. 3) for the secondary galaxies in the spiral-spiral minor mergers, their  $L_{\text{bol}}$  at different separations have small oscillations, but their  $f_{\text{Edd}}$  decrease with smaller separations. 4) for the two elliptical-spiral mergers, if the two galaxies collide in a close encounter at the first pericentric passage (q5f03esz1p10, bottom row), the pri-

mary elliptical galaxy can capture gas from the secondary spiral galaxy more easily and its central SMBH can accrete more gas and become more active than in the case of the larger encounter (q5f03esz1, 8th row).

With the detected time duration of the two merging galaxies, we find that dAGN may emerge in several merging cases if using the lowest thresholds of  $L_{\rm bol} = 10^{43} \, {\rm erg \, s^{-1}}$  or  $f_{\rm Edd}$ , as set in Section 2. For the duration time of each SMBH, Table 4 lists the results based on the two  $L_{\rm bol}$  and two  $f_{\rm Edd}$  thresholds, respectively. In all the minor merger cases, the secondary SMBHs never



Fig. 5 Snapshots of the simulations. Legends are the same as in Fig. 4, except that the simulations shown here are q10f33ssz3, q10f33ssz3i, q5f33ssz1, q5f03esz1, and q5f03esz1p10, from top to bottom respectively.

have  $L_{\rm bol} \geq 10^{44} \,{\rm erg \, s^{-1}}$ . For each simulation, we count the time duration when both SMBHs are active and above the given  $L_{\rm bol}$  or  $f_{\rm Edd}$  thresholds, and list them in the row labeled 'dAGN'. We find that not all the minor mergers can trigger observable dAGNs with significant time duration. Comparing q5f13ssz3 with the other z = 3 cases, a system in which the primary galaxy has lower gas fraction than the secondary galaxy can significantly decrease the detection rate of dAGNs. The last row 'Offset' of each

simulation listed in Table 4 tells the time duration when the two nuclei reach the  $L_{\rm bol}$  or  $f_{\rm Edd}$  thresholds, and the secondary nucleus has larger luminosity or higher Eddington ratio than the primary galaxy, i.e., an oAGN system. From the 'Offset' fraction detected under the  $f_{\rm Edd} = 0.01$  threshold, the current nine merging systems only provide weak clues that oAGNs appear more frequently for those gas-rich mergers in which the two galaxies have different gas fractions (e.g., q5f13ssz3 and q5f31ssz3) than those



**Fig. 6** Duration time of the SMBH activities at different separations  $(\log(d/\text{kpc}))$  between the primary and secondary SMBHs, bolometric luminosities (*left two columns*), and Eddington ratios (*right two columns*) for the primary (*the first and third columns*) and secondary (*the second and fourth columns*) galaxies. Simulations, from top to bottom rows, correspond to those shown in Table 1 from top to bottom rows, respectively. The right color bar represents the exact duration time in different colors.

for gas-rich mergers with similar gas fractions (e.g., other spiral-spiral mergers) or elliptical-spiral mergers.

Figure 7 summarizes the AGN fraction of the primary (top row) and secondary (bottom row) galaxies detected at different luminosity and Eddington ratio thresholds. The dichotomous distributions shown in Figure 6 appear more clearly in Figure 7. The peaks located at larger separation are caused by the strong interaction after the first pericentric passage (see details in Figs. 1, 2 and 3). It is not surprising that the time fraction reaches its maximum at small separation since the galaxy interaction induces nuclear activity. The AGN fractions in the three z = 1 simulations are hard to identify because the two nuclei never reach ~100 pc in our simulation. None of the secondary nuclei can be more luminous than  $L_{\rm bol} = 10^{44} \, {\rm erg \, s^{-1}}$ .

#### **4** CONCLUSIONS

We perform nine hydrodynamical simulations with different settings for the progenitor galaxies (mass ratio, gas fraction, starting redshift and projected separation) to investigate how nuclear activity can be triggered in minor galaxy mergers. We find that, similarly to major galaxy mergers, minor galaxy mergers can trigger dAGNs but with a substantially smaller time duration (typically  $\leq$ 0.01 Gyr), more than an order of magnitude smaller than those by major mergers (typically  $\leq$  0.24 Gyr) (e.g., Yang 2019). Minor mergers can also result in oAGNs with a time duration of  $\leq$  0.22 Gyr.

The Eddington ratios of the nuclear activities induced by minor mergers barely exceed 0.1. As a comparison, those nuclear activities induced by major mergers can last



**Fig.7** The AGN fractions at different separations detected for the two luminosity thresholds ( $L_{bol} = 10^{43} \text{ erg s}^{-1}$  in the left column,  $L_{bol} = 10^{44} \text{ erg s}^{-1}$  in the middle-left column) and two Eddington ratio thresholds ( $f_{Edd} = 0.01$  in the middle-right column,  $f_{Edd} = 0.05$  in the right column) for the primary (*top row*) and secondary (*bottom row*) SMBHs. Line colors drawn from blue to red indicate the results of the nine simulations listed from top to bottom in Table 1.

Run		$L_{\rm bol} = 10^{43}  {\rm erg  s^{-1}}$		$L_{\rm bol} = 10^{44}  {\rm erg  s^{-1}}$		$f_{\rm Edd} = 0.01$		$f_{\rm Edd} = 0.05$	
		$t_{\rm AGN}$	$t_{\rm AGN}/t_{\rm tot}$	$t_{\rm AGN}$	$t_{\rm AGN}/t_{\rm tot}$	$t_{\rm AGN}$	$t_{\rm AGN}/t_{\rm tot}$	$t_{\rm AGN}$	$t_{\rm AGN}/t_{\rm tot}$
aEf120072	$BH_1$	1.31	0.52	0.06	0.03	1.92	0.77	0.42	0.17
Q01103320	$BH_2$	0.01	0.004	0	0	1.03	0.41	0.22	0.09
	dAGN	0	0	0	0	0.36	0.14	0	0
	Offset	0.002	0.0008	0	0	0.37	0.15	0.03	0.01
q5f31ssz3	$BH_1$	1.87	0.71	0.17	0.07	2.15	0.82	0.49	0.19
	$BH_2$	0.03	0.01	0	0	1.79	0.68	0.11	0.04
	dAGN	0	0	0	0	1.20	0.45	0.01	0.004
	Offset	0	0	0	0	0.43	0.17	0.09	0.03
	$BH_1$	1.87	0.73	0.05	0.02	2.05	0.79	0.23	0.09
451555525	$BH_2$	0.03	0.01	0	0	1.31	0.51	0.27	0.11
	dAGN	0.01	0.004	0	0	1.13	0.44	0.007	0.003
	Offset	0	0	0	0	0.15	0.06	0.05	0.02
aff33ccz3i	$BH_1$	2.00	0.80	0.05	0.02	2.03	0.80	0.12	0.05
4010033201	$BH_2$	0.003	0.001	0	0	1.02	0.41	0.28	0.11
	dAGN	0.002	0.001	0	0	0.92	0.37	0	0
	Offset	0	0	0	0	0.11	0.04	0.02	0.008
a10f220072	$BH_1$	2.69	0.62	0.19	0.44	2.71	0.62	0.18	0.04
q101335523	$BH_2$	0.05	0.001	0	0	1.49	0.34	0.33	0.08
	dAGN	0.02	0.005	0	0	1.33	0.31	0.004	0.001
	Offset	0	0	0	0	0.28	0.06	0.22	0.05
q10f33ssz3i	$BH_1$	2.45	0.57	0.11	0.03	2.39	0.56	0.28	0.07
	$BH_2$	0	0	0	0	1.16	0.27	0.26	0.06
	dAGN	0	0	0	0	0.98	0.23	0	0
	Offset	0	0	0	0	0.15	0.04	0.005	0.001
q5f33ssz1	$BH_1$	0.03	0.006	0	0	0	0	0	0
	$BH_2$	0.07	0.01	0	0	0.088	0.02	0	0
	dAGN	0	0	0	0	0	0	0	0
	Offset	0.05	0.01	0	0	0	0	0	0
q5f03esz1	$BH_1$	0	0	0	0	0	0	0	0
	$BH_2$	0.005	0.001	0	0	0.07	0.01	0	0
	dAGN	0	0	0	0	0	0	0	0
	Offset	0.006	0.001	0	0	0.06	0.01	0	0
q5f03esz1p10	$BH_1$	0.01	0.003	0	0	0	0	0	0
	$BH_2$	0.10	0.03	0	0	0.15	0.04	0	0
	dAGN	0	0	0	0	0	0	0	0
	Offset	0.05	0.01	0	0	0.14	0.04	0	0

Table 4 AGN Fractions for Different Thresholds of  $L_{\rm bol}$  or  $f_{\rm Edd}$ 

for more than a hundred million years with Eddington ratio larger than 0.1.

For all the simulations, the Eddington ratio of the primary galaxy increases after the first pericentric passage, no matter if the primary galaxy is initially gas poor  $(f_{\rm gas} = 0.1 \text{ in } q5f13ssz3 \text{ and } f_{\rm gas} = 0 \text{ in } q5f03esz1$ and q5f03esz1p10) or gas rich (the other six simulations), since the primary galaxy can always rob gas from its companion. After the fourth pericentric passage, the Eddington ratio of the secondary galaxy decreases gradually after the gas is either consumed by star formation or captured by the primary galaxy during the interaction. In the dry-wet mergers at z = 1 (q5f03esz1 and q5f03esz1p10), as the two galaxies approach each other, the primary galaxy gradually robs more and more gas from the secondary galaxy to feed the central engine. However, the amount of gas is still inadequate to trigger nuclear activity to a higher Eddington ratio.

The co-planar gas-rich mergers generally trigger a relatively longer-lived AGN (including dAGN and oAGN) than that merging with an inclination angle (e.g.,  $45^{\circ}$  in our simulation), because the galaxy interaction tends to be strongest in the co-planar case, in which more gas can be transferred to the vicinity of the central SMBH. From all the nine runs we find that minor galaxy mergers can trigger dAGN and oAGN systems but the time duration is relatively short compared to that of gas-rich major mergers (Van Wassenhove et al. 2012; Capelo et al. 2017; Yang 2019). Minor galaxy mergers can be responsible for triggering nuclear activity as luminous as  $L_{bol} = 10^{44} \text{ erg s}^{-1}$ if both of the two progenitors are not too dry ( $f_{gas}$  should not be much smaller than 0.1), especially at small BH separations.

Acknowledgements This work is supported by the National Key Program for Science and Technology Research and Development (No. 2016YFA0400704), the National Natural Science Foundation of China (Nos. 11690024 and 11873056) and the Strategic Priority Program of the Chinese Academy of Sciences (No. XDB 23040100).

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