Coevolution of Supermassive Black Holes and their Host Galaxies with Galaxy Mergers

CHI-HONG LIN 1, KE-JUNG CHEN 1, AND CHORNG-YUAN HWANG 2

1 Institute of Astronomy and Astrophysics, Academia Sinica, Taipei 10617, Taiwan R.O.C.
2 Institute of Astronomy, National Central University, Taoyuan 32001, Taiwan R.O.C.

ABSTRACT

Understanding the formation of the supermassive black holes (SMBHs) present in the centers of galaxies is a key topic in modern astrophysics. Observations have detected the SMBHs with mass $M$ of $10^9 M_\odot$ in the high redshifts galaxies with $z \sim 7$. However, how SMBHs grew to such huge masses within the first billion years after the big bang remains elusive. One possible explanation is that SMBHs grew in a short period through the frequent mergers of galaxies, which provides sustainable gas to maintain the rapid growth. In this study, we present the hydrodynamics simulations of the SMBHs’ growth with their host galaxies using the GIZMO code. In contrast to previous simulations, we developed a molecular cloud model by separating molecular-gas particles from the atomic-gas particles and then evolving them independently. During major mergers, we showed that the effect of the mass segregation of the atomic and molecular gas particles can enhance the dynamical friction of molecular particles. Consequently, molecular gas is substantially accreted onto the galactic centers that grows SMBHs from $10^6 M_\odot$ to $10^9 M_\odot$ within 300 Myr, explaining the rapid growth of SMBHs, and this accretion also triggers a violent starburst at the galactic center. Furthermore, We examined the impact of minor mergers on the bulge of a Milky-Way-like galaxy and found that the size and mass of the bulge can increase from $0.92 \text{ kpc}$ to $1.9 \text{ kpc}$ and from $4.7 \times 10^{10} M_\odot$ to $7 \times 10^{10} M_\odot$.

Keywords: Supermassive Black Hole, Galaxy Evolution, Galactic Bulge, Starburst, Galaxy Merger, Computational Astrophysics.

1. INTRODUCTION

Supermassive black holes (SMBHs) have been discovered in most galaxies (e.g., Lynden-Bell 1969; Kormendy & Richstone 1995; Magorrian et al. 1998), suggesting that the existence of SMBHs may be associated with their host galaxies. Growing evidence shows that the mass of an SMBH is correlated to its galactic bulge, including luminosity (e.g., Kormendy & Richstone 1995; Wu & Han 2001; Graham & Driver 2007; Marconi & Hunt 2003), stellar mass (e.g., McLure & Dunlop 2002; Häring & Rix 2004; Graham et al. 2001, size (Ferrarese 2002; Lauer et al. 2007), and dynamics and velocity dispersion $\sigma$ (e.g., Ferrarese & Merritt 2000; Tremaine et al. 2002; Aller & Richstone 2007; Soker & Meiron 2011; King & Pounds 2015). These observational results exhibit strong connections between the SMBHs and their host galaxies (e.g., Wandel 2002; Feoli et al. 2011; Kormendy & Ho 2013).

The SMBH of the Milky Way (MW), known as "Sagittarius A*," has a mass of $(4.1 \pm 0.6) \times 10^6 M_\odot$ (Ghez et al. 2008). The maximum accretion rate of the Sagittarius A* is $8 \times 10^{-5} M_\odot \text{ yr}^{-1}$, which has been determined from X-ray and infrared research (Quataert et al. 1999). However, Mortlock et al. (2011) and Venemans et al. (2015) discovered SMBHs of $10^9 M_\odot$ in the early universe at $z > 6.5$. To grow an SMBH with mass of one thousand times larger than that of Sagittarius A*, high accretion rates are required in a very short period (The universe’s age is only $\simeq 0.83 \text{ Gyr}$ at $z = 6.5$). How an SMBH grows in a short time and how the host galaxy provides a suitable environment for the growth remain unknown.

One possible explanation is that an SMBH grows through galaxy mergers (Volonteri & Rees 2005), which supply the SMBH with a new gas reservoir. An SMBH can rapidly grow during wet merger (Hopkins et al. 2006), with robust gas accretion flows onto the SMBH (Takeo et al. 2019). Simultaneously, the feedback of SMBHs also self-regulates its accretion and star formation rates inside the galactic bulge (Springel et al. 2005a). Simulations of galaxy merger by Di Matteo et al. (2005) showed that an SMBH can grow from $4 \times 10^5 M_\odot$
to $10^8 \, M_\odot$ in 1.5 Gyr, but growing an SMBH to $10^9 \, M_\odot$ within 1 Gyr is still challenging.

The accretion of dense molecular gas is promising for growing an SMBH in a short time because of the mass segregation of the atomic and molecular gas particles. The principle of mass segregation causes the atomic and molecular gases to exhibit different dynamics behaviors. During galaxy mergers, molecular gas can be efficiently transferred to the center of galaxies, feeding the black holes and forming stars. The burst of star formation likely occurs in the nucleus regions, known as the nucleus starburst. Joseph & Wright (1985) and Schweizer (2005) showed that the star formation rates (SFRs) in the starburst are higher by a factor of several thousand above the typical values in normal galaxies. However, recent studies have determined that not all major mergers can trigger starbursts; for example, Knapen et al. (2015) and Barrera-Ballesteros et al. (2015) have found that the enhancement of SFRs in some merging galaxies increases only by a few factors.

Due to the strong impact of a galaxy-galaxy collision, the original spiral structures of galaxies can be disrupted during major mergers. On the other hand, minor mergers are more promising for growing a galaxy's size (Bédorf & Portegies Zwart 2013) and contributing to a bulge's mass (Hopkins et al. 2010), producing irregular galaxies (Bournaud et al. 2005). Furthermore, a minor merger may account for the inner components (inner discs and rings) in unbarred spiral galaxies (Eliche-Moral et al. 2011). Our study aims to examine the impact of minor mergers on bulge growth.

Herein, the growth of SMBHs and bulges in galaxies (Mihos & Hernquist 1995; Kaufman et al. 2002; Anglés-Alcázar et al. 2017) is studied by simulating major and minor mergers with a novel molecular gas model. The structure of this paper is as follows. Sections 2 describes the simulation setup and the relevant physics required to model galaxy mergers. Then, the simulation results of the SMBH's coevolution and its host galaxies are presented and discussed in 3 and 4, respectively. Finally, in 5, our results are compared with those of previous studies and the conclusions are presented.

2. NUMERICAL METHODS

2.1. The GIZMO code

We performed our galaxy simulations using the mesh-free hydrodynamic code: GIZMO (Hopkins 2015). It is an open-source code that is based on the widely used cosmological code, GADGET-2 (Springel 2005), for the domain decomposition and N-body algorithms.

We employ the Meshless Finite-Mass (MFM) and Meshless Finite-Volume (MFV) methods in our GIZMO simulations. In the MFM and MFV methods, each particle is treated as a mesh-generating point that defines the volume. The physical quantities of each particle determine the fluid properties. The code solves the hydrodynamics equations by integrating the domain of each particle. Compared to other public codes in astrophysical simulations, GIZMO (Hopkins 2015) exhibits superior performance in conserving angular momentum, which is critical for modeling the dynamics of galaxy mergers.

2.2. Simulation setup

We build up the pre-merging galaxies based on the MW, and they are divided into two types: gas-poor and gas-rich galaxies. The gas-poor galaxies are identical to the MW with a mass of $1.46 \times 10^{12} \, M_\odot$ and have parameters obtained from the Gaia observation (Brown et al. 2016; Li 2016; Posti & Helmi 2019) and the N-body study of Fujii et al. (2019). The gas-rich galaxies also adopt the MW parameters, but their gas mass is artificially increased to $1.42 \times 10^{11} \, M_\odot$. Such gas-rich galaxies are typical among high redshift galaxies ($z > 2$) (Solomon & Vanden Bout 2005). Herein, both the gas-poor and gas-rich galaxies here are called MW-like galaxies. In addition to the MW-like galaxies, we fabricate dwarf galaxies with mass $\sim 1 \times 10^{11} \, M_\odot$ for minor mergers. The detailed parameters of these three types of galaxies are listed in Table: 1. Then, we use the DICE code (Perret et al. 2014) with input parameters from Table: 1 and create the initial galaxies for evolution in the GIZMO code. Our simulations consider the following scenarios:

1. Model $M_{\text{poor}}$ denotes a major merger of two gas-poor galaxies.
2. Model $M_{\text{rich}}$ denotes a major merger of two gas-rich galaxies.
3. Model $M_{\text{dwarf}}$ denotes two minor mergers of one gas-poor galaxy with two dwarf galaxies.

For the major mergers, we place two galaxies in a $(100 \, \text{kpc})^3$ cubic simulation box, and their separation is $30 \, \text{kpc}$ with an approaching velocity of $180 \, \text{km/s}$. The two galaxies will collide 0.1 billion years after the commencement of the simulation.

For the minor merger case, we place a gas-poor galaxy and two dwarf galaxies in the simulation box. The gas-poor galaxy is located at the center of the box, while two dwarf galaxies are separately placed 37 kpc and 55 kpc away from it. The two dwarf galaxies approach the gas-poor galaxy with a velocity of $120 \, \text{km s}^{-1}$. The
initial conditions for these three scenarios are illustrated in Table 2.

We evolved the three models for five billion years (5 Gyr). The simulation results are analyzed with python packages SciPy (Virtanen et al. 2020), pylab (Hunter 2007), and h5py (Collette 2013) with data visualization using Matplotlib (Hunter 2007) and the SPLASH code (Price 2007).

2.3. ISM Physics in GIZMO

The cooling and heating of the interstellar medium (ISM) gas in GIZMO includes the hydrogen and helium ionization+recombination, photo-electric, collisional, free-free, molecular, fine-structure, and the Compton effects from Hopkins et al. (2018). Moreover, multi-species-dependent metal-line cooling models (Wiersma et al. 2009; Hopkins et al. 2018) are also considered. A single-phase polytropic gas describes the equation of state for the ISM. (Springel & Hernquist 2003). The gas model of Hopkins et al. (2018) comprises the atomic and molecular gas particles; the number of molecular gas particles is estimated from the equilib-
rium molecular fraction in the gas particles. We employ the same algorithm in our simulation but differentiate between the dynamics of molecular gas particles and atomic gas particles by modifying their particle masses. The mass of molecular-gas particles differs from that of atomic-gas particles of $\sim 10^3 M_\odot$, and it is set to be similar to that of a giant molecular cloud (GMC) of $\sim 10^6 M_\odot$ based on the GMC observations. Therefore, the mass of a molecular-gas particle is 1000 times heavier than that of an atomic-gas particle. The physical motivation behind this modification is as follows. When a particle orbits within the galaxy, it experiences a drag force due to the gravitational pull from the gas, stars, and dark matter behind it. This force is known as dynamical friction, $f$ (Chandrasekhar 1943; Carroll & Ostlie 2017; Di Matteo et al. 2019), which can be expressed as

$$ f \propto C \frac{M^2 \rho}{v_M^3}, \quad (1) $$

where $M$: the object’s mass, $v_M$: the object’s velocity, $\rho$: the density of the surrounding medium, and $C$ is a function that depends on how $v_M$ compares with the velocity dispersion of the surrounding medium. In our gas model, the massive molecular-gas particles experience stronger dynamical friction (see Eq. 1) that causes them more efficiently to accrete onto the SMBHs. The galactic star formation in our simulations follows the star formation model of Springel & Hernquist (2003), which only allows stars to form from molecular gas. Additionally, we adopt the stellar feedback recipe from the star formation model of Springel & Hernquist (2003), which only allows stars to form from molecular gas. Abundant molecular gas falls into the SMBHs can grow quickly due to the adequate accretion of molecular gas. Abundant molecular gas falls into the galaxy’s center when a major merger happens, which feeds the SMBH via the mass segregation mechanism mentioned in Section 2. Since molecular gas particles are 1000 times more massive than atomic gas particles and more effective in removing angular momentum, they can grow an SMBH at an unprecedented rate. This result exhibits a promising explanation for the so-called rapid growth of SMBHs in a major merger.

3. RESULTS

3.1. Rapid Growth of SMBH during the Major Mergers

First, we show the mass evolutionary tracks of SMBHs for the major merger of galaxies in Fig. 1. Overall, the average mass accretion rate is $\sim 5 M_\odot$ yr$^{-1}$ and $\sim 7 M_\odot$ yr$^{-1}$ for the $M_{\text{poor}}$ and $M_{\text{rich}}$ models, respectively. The mass accretion increased the mass of the SMBHs from $10^6 M_\odot$ to $10^9 M_\odot$ within 300 Myr. The SMBHs can grow quickly due to the adequate accretion of molecular gas. Abundant molecular gas falls into the galaxy’s center when a major merger happens, which feeds the SMBH via the mass segregation mechanism mentioned in Section 2. Since molecular gas particles are 1000 times more massive than atomic gas particles and more effective in removing angular momentum, they can grow an SMBH at an unprecedented rate. This result exhibits a promising explanation for the so-called rapid growth of SMBHs in a major merger.

The mass of an SMBH has environmental effects. Furthermore, the SMBHs in gas-rich galaxy mergers can grow larger than those in gas-poor galaxy mergers. The increase of gas inside the galaxy provides sufficient accretion materials for SMBH to increase its mass. We stop plotting the black hole mass at $t = 800$ Myr, when the distance between two SMBHs approaches 1 kpc and their merger occurs. Since our spacial resolution cannot satisfactorily resolve the SMBH merger process, we
Figure 1. The SMBH mass growth over the simulation time. The blue and red lines denote the average masses of two SMBHs in the $M_{\text{poor}}$ and $M_{\text{rich}}$ models, respectively. The average accretion rate (dash-dot line) is $5 \ M_\odot \ yr^{-1}$ and $7 \ M_\odot \ yr^{-1}$ for the $M_{\text{poor}}$ and $M_{\text{rich}}$ models, respectively. SMBHs can grow extremely fast with a high accretion rate ($>1 \ M_\odot \ yr^{-1}$), which indicates that a considerable amount of molecular gas falls into the central region, feeding the SMBH. The oscillation of the dash-dot line can be explained by the interaction between the SMBH’s accretion and feedback. The accretion rate increases until the SMBH grows to around $3 \times 10^7 \ M_\odot$; then, the feedback becomes strong enough to suppress the accretion. The interplay between feedback and accretion results in an oscillatory pattern in the accretion rate.

only discuss the SMBH growth in the pre-SMBH merger stage.

### 3.2. Starbursts

At the beginning of our galaxy simulation, star formation mainly occurs in the spiral arms and the bulge that hosts GMCs until the two galaxies start to collide. The SFR distribution of the major merger cases is shown in Figure. 2. Many molecular-gas particles form and flow into the centers of two galaxies, triggering rapid star formation. In Figure. 3, a high star formation rate is observed at the central region of $r \lesssim 1 \ kpc$, contributing to over 50% of the star formation in the galaxy, and this active SFR area lasts 150 Myr. In our simulation, we only allow star formation from a molecular-gas particle; thus, the SFR distribution can reflect the importance of the dynamics of molecular gases. Star formation stems from molecular gas; therefore, the gas abundance affects the SFRs. In our result, the starburst only occurs in the merger of gas-rich galaxies.

### 3.3. The Bulge Growth with Minor Merger

Since the bulge size for a detached galaxy is independent of the gas abundance, gas-poor and gas-rich galaxies have the same bulge size of 0.92 kpc. Moreover, the bulge sizes remain approximately constant during their evolution. A major merger cannot increase the bulge of a spiral galaxy because the merger usually disrupts the original disk and bulge of galaxies and yields a giant elliptical galaxy.

To investigate the growth of the bulge of a spiral galaxy, we consider minor mergers to avoid destroying the original structure of the primary galaxies. We consider the minor merger of a gas-poor galaxy with two dwarf galaxies (parameters from Table: 1) and run this model for 5 Gyr; then, we check how the bulge evolves during the minor mergers (Fig. 4). In Figure. 5, shows that the bulge of the gas-poor galaxy grows from 0.9 to $\sim 1.9 \ kpc$; additionally, the mass of the bulge increases from $4.7 \times 10^{10} \ M_\odot$ to $7 \times 10^{10} \ M_\odot$ after the minor mergers with the dwarf galaxies. The average growth rate of the bulge is $\sim 30 \ M_\odot \ yr^{-1}$. The bulge of a disk galaxy grows during a minor merger because when the minor merger occurs, the primary galaxy intakes the components from the secondary galaxy, consequently increasing the dark matter inside the primary galaxy. Furthermore, the dark matter will re-distribute and yield a heavier dark matter halo. The bulge mass is related to the properties of the dark matter halo (Ferrarese 2002); hence, the increase of the dark matter mass during a minor merger can result in the growth of the bulge of a galaxy. Our results indicate that minor mergers are a promising channel for growing the mass and radius of the bulge of a disk galaxy.
4. DISCUSSIONS

Our results display that the SMBH in the MW-like galaxy ($\sim 10^{12} \, M_\odot$) can accrete molecular gas to increase its mass via a major merger. This process allows the SMBHs' mass to rapidly increase from $10^6 \, M_\odot$ rapidly to $10^9 \, M_\odot$ within 300 Myr. The SMBH rapidly grows when a major merger happens because the mass segregation mechanism causes the atomic and molecular gases to have different dynamics. Therefore, GMCs can remove their kinetic energy and fall into the galaxy’s center to feed the SMBH. Our simulation of the major merger confirms the above phenomenon, which is consistent with the massive SMBHs in observation. Furthermore, the SMBHs in a gas-rich galaxy merger can attain larger masses than those in a gas-poor galaxy merger (Fig. 1.); this result well matches the results of Di Matteo et al. (2005), but our SMBHs’ growth time is considerably shorter than that of Di Matteo et al. (2005).

In our simulations, we observed two kinds of active star formation. During the merger of gas-poor galaxies, their SFR increases by a factor of 2 to 3, which well agrees with the observational results of Pearson et al. (2019) for low redshift galaxies. However, during the merger of the gas-rich galaxies, their SFR significantly increases and exhibits a nucleus burst (Fig. 3). The timescale for the starburst is 150 Myr, which is close to the observational merger samples of $10^7 \, \text{yr}$ to a few $10^8 \, \text{yr}$ in Cortijo-Ferrero et al. (2017). The large SFR stems from the merger-driven central star formation (Barnes & Hernquist 1991; Mihos & Hernquist 1995; Saitoh et al. 2009; Sparre & Springel 2016) when the fresh molecular gas flows into the galactic center and forms numerous stars.

In the original molecular model of GIZMO, no starburst is observed during both gas-poor and gas-rich mergers. Their SFRs are enhanced by a few factors. However, in our new molecular model, the starburst phenomenon (a galaxy with an SFR up to 100 times greater than that of a typical galaxy) can occur in the gas-rich merger environment (Fig. 3). Additionally, our minor merger simulations show that a possible way for growing the bulge in a spiral galaxy is through several minor mergers (Bédorf & Portegies Zwart 2013). The results show that the bulge can grow from 0.9 kpc to 1.9 kpc for a gas-poor galaxy, and that the mass of the bulge can increase from $4.7 \times 10^{10} \, M_\odot$ to $7.0 \times 10^{10} \, M_\odot$ after two minor mergers with dwarf galaxies. Based on the above results, the current black hole mass of our Sagittarius A* is too small ($\sim 10^6 \, M_\odot$) to explain a major merger event. Thus, we suggest that Sagittarius A* may not have undergone any major mergers in its life span.

Although our gas model can realize the rapid growth of SMBHs, it still has several drawbacks to be improved. Our simulation results cannot explain the formation of molecular gas in observation and cannot explain how the molecular gas is decomposed to atomic gas. Recently,
good progress has been made to improve the gas chemistry for galaxy simulations; for example, Popping et al. (2014) developed the $H_2$ formation recipes, and Hopkins et al. (2018) estimated the molecular fraction $f_{H_2}$ in gas particles. However, the critical issue is the modeling of the chemistry of molecular hydrogen and atomic/ionized hydrogen and simultaneously separating their dynamics. This requires a comprehensive method for modeling the multi-phase ISM in the galaxy simulations, which has not yet been established. Therefore, herein, we set the molecular and atomic/ionized gas ratios as a constant in our simulations.

Our results are summarized in Fig. 6. A gas-poor galaxy experiencing a major merger can grow its SMBH and enhance star formation. Furthermore, a gas-rich galaxy undergoing a major merger triggers a nucleus starburst when growing its SMBH.

---

**Figure 3.** The total and the nucleus SFRs during major mergers. Blueline: The total SFR of the $M_{\text{poor}}$ model; a major merger can enhance the total SFR by at least a factor of 2; Red line: The total SFR of the $M_{\text{rich}}$ model. Before the merger occurs, the SFR increases, and then, the strongest SFR (hundreds of times higher than the isolated counterpart) is observed at around $t = 800$ Myr. This spike in the SFR history is known as the starburst. The starburst phenomenon appears to last for about 150 Myr. The blue and red dashed lines are the SFR in the central 1kpc region of the $M_{\text{poor}}$ and $M_{\text{rich}}$ models, respectively. The trend of the nucleus star formation is highly related to the starburst, signifying that a large amount of molecular gas is moving to the galaxy’s center in this period.
5. CONCLUSION

In this study, we have presented the simulations of merging galaxies with GIZMO. Our simulations contain the major mergers of gas-poor and gas-rich galaxies as well as minor mergers. We find that the dynamics of molecular clouds play an essential role in galaxy mergers. Massive molecular-gas particles can more efficiently lose their kinetic energy than atomic-gas particles due to stronger dynamical friction, which causes them to fall into the center of the galaxy. Consequently, SMBHs can grow from $10^6 M_\odot$ to $10^9 M_\odot$ within 300 Myr, providing a possible explanation for the creation of massive SMBH ($10^9 M_\odot$) in the universe.

The SFRs in the galaxies mergers also become higher than those in the isolated case, and around 50% of the star formation occurs in the central region; the SFRs
Figure 5. The evolution of bulge in the $M_{\text{poor}}$ model. The green line represents the bulge size. The initial size of the bulge in the $M_{\text{poor}}$ model is 0.92 kpc, and it grows to 1.9 kpc after two minor mergers. The orange line denotes the total mass of the bulge. The initial mass of bulge in the $M_{\text{poor}}$ model is $\sim 4.7 \times 10^{10} M_\odot$, and it increases to $\sim 7.0 \times 10^{10} M_\odot$ after minor mergers. The solid line sections from the bulge fitting refer to the SMBH as the bulge center. However, during minor mergers, the intensity profile cannot well fit with the sersic function referring to the SMBH. Therefore, we select the brightest region as the bulge center for fitting, and it yields the dashed line sections.

We will be able to unravel the physics behind the growth of SMBHs and their impact on galaxy evolution in the early universe.

Acknowledgement

We thank Yen-Chen Pan and You-Hua Chu for their valuable comments. Sanctity Lin acknowledges his colleague Ching-Yao Tang. The Ministry of Science and Technology supported K.C., Taiwan, under grant no. MOST 110-2112-M-001-068-MY3 and the Academia Sinica, Taiwan, under a career development award under grant no. AS-CDA-111-M04. S.L. was supported by the Academia Sinica Institute of Astronomy and Astrophysics (ASIAA). Numerical simulations were performed at the National Energy Research Scientific Computing Center (NERSC), a U.S. Department of Energy Office of Science User Facility operated under Contract No. DE-AC02-05CH11231, and at the TIARA Cluster at the ASIAA.

REFERENCES

Aller, M., & Richstone, D. 2007, The Astrophysical Journal, 665, 120
Anglés-Alcázar, D., Dáv, R., Faucher-Giguère, C.-A., Özel, F., & Hopkins, P. F. 2017, Monthly Notices of the Royal Astronomical Society, 464, 2840
Barnes, J. E., & Hernquist, L. E. 1991, The Astrophysical Journal, 370, L65
Barrera-Ballesteros, J., Sánchez, S., García-Lorenzo, B., et al. 2015, Astronomy & Astrophysics, 579, A45
Bédorf, J., & Portegies Zwart, S. 2013, Monthly Notices of the Royal Astronomical Society, 431, 767
Figure 6. Schematic of the galaxy mergers and their consequence. Red line: major merger of a gas-rich disk galaxy, blue line: major merger of a gas-poor galaxy, and yellow line: minor merger of a gas-poor galaxy. The solid lines represent the results of our simulations, and the dashed lines represent the possible evolution tracks. After the rapid growth of the SMBH, the SMBH mass becomes large enough and provides strong feedback that ejects the gas from the host galaxy. Under extreme cases, the SMBH can trigger an active galactic nucleus feedback and cause the galaxy to evolve into a giant elliptical galaxy.
SMBHs and their host galaxies

Hopkins, P. F., & Quataert, E. 2011, Monthly Notices of the Royal Astronomical Society, 415, 1027
Hopkins, P. F., Torrey, P., Faucher-Giguère, C.-A., Quataert, E., & Murray, N. 2016, Monthly Notices of the Royal Astronomical Society, 458, 816
Hopkins, P. F., Bundy, K., Croton, D., et al. 2010, The Astrophysical Journal, 715, 202
Hopkins, P. F., Wetzel, A., Kereš, D., et al. 2018, Monthly Notices of the Royal Astronomical Society, 480, 800
Hunter, J. D. 2007, IEEE Annals of the History of Computing, 9, 90
Joseph, R., & Wright, G. 1985, Monthly Notices of the Royal Astronomical Society, 214, 87
Kaufman, M., Sheth, K., Struck, C., et al. 2002, The Astronomical Journal, 123, 702
Kim, J.-h., Agertz, O., Teyssier, R., et al. 2016, The Astrophysical Journal, 833, 202
King, A., & Pounds, K. 2015, Annual Review of Astronomy and Astrophysics, 53, 115
Knapen, J. H., Cisternas, M., & Querejeta, M. 2015, Monthly Notices of the Royal Astronomical Society, 454, 1742
Kormendy, J., & Ho, L. C. 2013, Annual Review of Astronomy and Astrophysics, 51, 511
Kormendy, J., & Richstone, D. 1995, Annual Review of Astronomy and Astrophysics, 33, 581
Lamberts, A., Garrison-Kimmel, S., Clausen, D., & Hopkins, P. 2016, Monthly Notices of the Royal Astronomical Society: Letters, 463, L31
Lauer, T. R., Faber, S., Richstone, D., et al. 2007, The Astrophysical Journal, 662, 808
Li, E. 2016, arXiv preprint arXiv:1612.07781
Lynden-Bell, D. 1969, Nature, 223, 690
Magorrian, J., Tremaine, S., Richstone, D., et al. 1998, The Astronomical Journal, 115, 2285
Marconi, A., & Hunt, L. K. 2003, The Astrophysical Journal Letters, 589, L21
McLure, R., & Dunlop, J. 2002, Monthly Notices of the Royal Astronomical Society, 331, 795
Mihos, C., & Hernquist, L. 1995, arXiv preprint astro-ph/9512099
Mortlock, D. J., Warren, S. J., Venemans, B. P., et al. 2011, Nature, 474, 616
Pearson, W., Wang, L., Alpaslan, M., et al. 2019, Astronomy & Astrophysics, 631, A51
Perret, V., Renaud, F., Epinat, B., et al. 2014, Astronomy & Astrophysics, 562, A1
Popping, G., Somerville, R. S., & Trager, S. C. 2014, Monthly Notices of the Royal Astronomical Society, 442, 2398
Posti, L., & Helmi, A. 2019, Astronomy & Astrophysics, 621, A56
Price, D. J. 2007, Publications of the Astronomical Society of Australia, 24, 159
Quataert, E., Narayan, R., & Reid, M. J. 1999, The Astrophysical Journal Letters, 517, L101
Saitoh, T. R., Daisaka, H., Kokubo, E., et al. 2009, Publications of the Astronomical Society of Japan, 61, 481
Schweizer, F. 2005, in Starbursts (Springer), 143–152
Sersic, J. L. 1968, Cordoba
Sokere, N., & Meiron, Y. 2011, Monthly Notices of the Royal Astronomical Society, 411, 1803
Solomon, P., & Vanden Bout, P. 2005, Annu. Rev. Astron. Astrophys., 43, 677
Sparre, M., & Springel, V. 2016, Monthly Notices of the Royal Astronomical Society, 462, 2418
Springel, V. 2005, Monthly notices of the royal astronomical society, 364, 1105
Springel, V., Di Matteo, T., & Hernquist, L. 2005a, The Astrophysical Journal, 620, L79
—. 2005b, Monthly Notices of the Royal Astronomical Society, 361, 776
Springel, V., & Hernquist, L. 2003, Monthly Notices of the Royal Astronomical Society, 339, 289
Takoe, E., Inayoshi, K., Ohsuga, K., Takahashi, H. R., & Mineshige, S. 2019, Monthly Notices of the Royal Astronomical Society, 488, 2689
Tremaine, S., Gebhardt, K., Bender, R., et al. 2002, The Astrophysical Journal, 574, 740
Venemans, B., Bañados, E., Decarli, R., et al. 2015, The Astrophysical Journal Letters, 801, L11
Virtanen, P., Gommers, R., Oliphant, T. E., et al. 2020, Nature methods, 17, 261
Volonteri, M., & Rees, M. J. 2005, The Astrophysical Journal, 633, 624
Wandel, A. 2002, The Astrophysical Journal, 565, 762
Wiersma, R. P., Schaye, J., & Smith, B. D. 2009, Monthly Notices of the Royal Astronomical Society, 393, 99
Woods, T. E., Agarwal, B., Bromm, V., et al. 2019, Publications of the Astronomical Society of Australia, 36
Wu, X.-B., & Han, J. 2001, Astronomy & Astrophysics, 380, 31