GALAXY ROTATION AND RAPID SUPERMASSIVE BINARY COALESCENCE

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ABSTRACT

Galaxy mergers usher the supermassive black hole (SMBH) in each galaxy to the center of the potential, where they form an SMBH binary. The binary orbit shrinks by ejecting stars via three-body scattering, but ample work has shown that in spherical galaxy models, the binary separation stalls after ejecting all the stars in its loss cone—this is the well-known final parsec problem. However, it has been shown that SMBH binaries in non-spherical galactic nuclei harden at a nearly constant rate until reaching the gravitational wave regime. Here we use a suite of direct N-body simulations to follow SMBH binary evolution in both corotating and counterrotating flattened galaxy models. For \(N > 500\), we find that the evolution of the SMBH binary is convergent and is independent of the particle number. Rotation in general increases the hardening rate of SMBH binaries even more effectively than galaxy geometry alone. SMBH binary hardening rates are similar for co- and counterrotating galaxies. In the corotating case, the center of mass of the SMBH binary settles into an orbit that is in corotation resonance with the background rotating model, and the coalescence time is roughly a few 100 Myr faster than a non-rotating flattened model. We find that counterrotation drives SMBHs to coalesce on a nearly radial orbit promptly after forming a hard binary. We discuss the implications for gravitational wave astronomy, hypervelocity star production, and the effect on the structure of the host galaxy.

Key words: black hole physics – galaxies: kinematics and dynamics – Galaxy: center

1. INTRODUCTION

Supermassive black holes (SMBHs), with masses between \(10^6\) and \(10^{10}\) solar masses, lie at the heart of nearly every galaxy (e.g., Kormendy & Richstone 1995). With a few notable exceptions, these SMBHs dwell within stellar spheroids—spiral bulges, ellipticals, and S0s—and observationally the SMBH mass is highly correlated with properties of its host spheroid (e.g., Ferrarese & Merritt 2000; Gebhardt et al. 2000; Khan et al. 2013; Kormendy & Ho 2013; McConnell & Ma 2013; Graham & Scott 2015). This seems to show that the evolution of the SMBH and its host are deeply tied, and innumerable observational and theoretical studies bear this out (Di Matteo et al. 2005; Micic et al. 2007; Hopkins & Quataert 2010; Volonteri & Bellovary 2012; Sherman et al. 2014).

There is an emerging picture that SMBH hosts all rotate to some degree. In terms of spiral bulges, rotational support is common. The early-type stars in our own galactic center have a net corotation of 120 km s\(^{-1}\) (Gewol et al. 1996; Schödel et al. 2009). The prototypical pseudobulges are rapidly rotating, disk-y structures (Kormendy & Kennicutt 2004), and most classical bulges show some rotation as well (Gadotti 2012).

Low mass ellipticals and S0s are well-known to be disky and rotationally supported (e.g., Bender et al. 1994; Faber et al. 1997; Cappellari et al. 2007). However, rotation may be pervasive in all early-type galaxies; a volume-limited census of the nearest 250 early-type galaxies ATLAS3D found that an astonishing 86% are fast rotators (Emsellem et al. 2011), with less than 3% of the sample being described as non-rotating. One of these non-rotators was thought to be the giant cD galaxy M87 (Emsellem et al. 2004; Krajnović et al. 2011), and yet new IFU data reveal that even this canonical non-rotator has an unmistakable kinematically distinct core (Arnold et al. 2014; Emsellem et al. 2014). In fact, nearly half of the ATLAS3D sample contains kinematically decoupled cores (Krajnović et al. 2011; see also Bender 1988; Franx & Illingworth 1988; Davies et al. 2001; Emsellem et al. 2004), so it appears that SMBH hosts not only rotate, but that the rotational structure is quite complex.

It is easy, theoretically, to expect that rotation is practically ubiquitous in stellar spheroids. Gas-rich formation scenarios give rise to rotation, as do dry, non-radial, major mergers (Bender et al. 1992; Khochfar & Silk 2009; Bois et al. 2011; Tsatsi et al. 2015). Indeed, a non-rotating galaxy seems to be a special, and rare, class that may be created exclusively through a slew of gas-poor minor mergers (Naab et al. 2014). Since SMBH hosts clearly rotate, and since the link between the SMBH and its host is so well established, any study of the dynamics with an SMBH host should consider rotation. This paper explores the evolution of binary SMBHs in a rotating, flattened stellar system, and its effect on the structure of the stellar host.

Binary SMBHs are expected to form within the galaxy core after a merger, and if the two SMBHs coalesce, they are arguably the most powerful sources of gravitational radiation in the universe (Hughes 2003). One problem that plagues SMBHs is how they merge together. The binary can eject stars via three-body scattering, bringing the SMBHs ever closer. Once the ejected stars extract enough energy from the binary orbit to shrink the separation to roughly milliparsec scales, gravitational radiation dominates, and the SMBHs coalesce (Begelman et al. 1980). However, the problem is that analytical calculations and simulations of static, spherical galaxies show that the binary’s orbital separation stalls before the SMBHs can plunge toward merger (see Milosavljević & Merritt 2003 for a review). The root cause of this hang up is simply a lack of low-angular momentum stars capable of interacting with the binary via three-body scattering. This theoretical bottleneck has
become known as the infamous “final parsec problem.” Recent work by several teams has shown that SMBHs can readily coalesce in more realistically shaped galaxy models (Berczik et al. 2006; Khan et al. 2011, 2013; Preto et al. 2011; Gualandris & Merritt 2012), because the stellar orbits in triaxial and flattened galaxies can continually replenish the SMBH binary loss cone (e.g., Yu 2002; Merritt & Poon 2004; Holley-Bockelmann & Sigurdsson 2006; Li et al. 2014; Vasiliev et al. 2015).

SMBH binary dynamics has been studied in spherical rotating systems, but the resolution of the simulations (fewer than 100,000 particles) could not accurately track the evolution of the binary to the gravitational wave regime. Experiments suggest that we need of the order of 1 million particles to resolve the true evolution of the binary beyond the hard binary stage. These previous studies primarily looked at the evolution of binary eccentricity and inclination with respect to the host (Amaro-Seoane et al. 2010; Sesana et al. 2011; Gualandris et al. 2012; Wang et al. 2014), and discovered that the eccentricity of the binary increased dramatically in counter-rotating systems, while in corotating systems, the binary tends to circularize.

Here we study SMBH binary dynamics and evolution in a flat rotating galaxy model with $c/a = 0.8$, which is quite a bit less flattened than a realistic galactic nucleus. In the non-rotating version of this model, we found a $N$-independent SMBH binary evolution that coalesced in a few Gyr (Khan et al. 2013). Note that Vasiliev et al. (2014) used Monte Carlo simulations on a similarly shaped model and found, on the contrary, that mere axisymmetry is not sufficient to drive sustained binary black hole hardening. Delving into the differences between the results for these two non-rotating models will be the subject of a future study. The purpose of this work is to use a flattened non-rotating model as a baseline, and quantify the change in the hardening time that rotation induces.

We will explore the dependence of SMBH binary evolution on particle number for various amounts of rotation in the surrounding cusp. We also study the energy, angular momentum and eccentricity evolution of the SMBH binary and estimate the coalescence times by scaling our model to various observed nearby galaxies.

The paper is organized in the following way: in Section 2 we describe the initial conditions and numerical methods for our direct $N$-body simulations. The results for the evolution of the SMBH binary in rotating axisymmetric galaxy models are explained in Section 3. Finally, Section 4 concludes, discussing caveats and future work.

2. INITIAL CONDITIONS AND NUMERICAL METHODS

To isolate the effect of rotation, we used the Flat8 model in Khan et al. (2013; hereafter KH13) to generate our rotating models; this allows us to directly compare the SMBH binary orbital evolution results here to those in the identical non-rotating model. For this flattening ratio, we found that the SMBH binary evolved into the gravitational wave regime, and the evolution did not depend on particle number for $N > 500$ K.

We introduced rotation by flipping the $z$ component of the angular momentum, $L_z$, in the positive direction for a subset of particles which has negative $L_z$. Our fiducial model, the A series, flips every particle with negative $L_z$, while our B series only flips 50% of the negative $L_z$ particles, meaning that 75% of the particles have a positive $L_z$.

Our galaxy models have an inner density slope, $\gamma$, of 1.0 and minor to major axis ratio of 0.8, measured at the half-mass radius. In model units, the total galaxy mass is 1 and the SMBH at the center of each model has a mass of 0.005. Because we adiabatically squeeze the model to generate its shape (Holley-Bockelmann et al. 2001), the system can and does change its shape with radius as it adiabatically adjusts to a live and changing SMBH-embedded potential. In addition, the scale radius slowly shrinks from 1.0 to 0.5; we could resize our model such that the scale radius is 1.0 again, but we instead choose to adopt physical units to reflect this increased central density. Discussion on scaling of our model to observed galaxies is given in Section 4 and Table 2 scales the model to physical units.

To determine the stability of our rotating models, we ran them in isolation for 40 time units; this duration is about half the maximum evolution time of the SMBH binaries in this study. Figure 1 shows that both the density profile and half-mass axes ratio remain very stable for whole duration of the A0 run; this behavior is seen in the B and C model series as well. The kinematics are also fairly stable; inside the radius of influence, however, the system does become hotter, with $v/\sigma$ decreasing from 0.6 to 0.4 for the A0 model as the SMBH re-establishes its characteristic cusp in velocity dispersion. This decrease in rotational support affects only the innermost $\sim 5000$ particles, but since it is also in the region of the model that exhibits a less flattened but triaxial shape, it may well be that this region contains orbits that are less stable to rotation (Deibel et al. 2011). The orbit content of this model will be a subject for future study.

To explore the SMBH binary evolution in flat rotating galaxies, we introduce an equal-mass secondary SMBH at a distance of 0.5 with 70% of the galaxy’s circular velocity at that initial separation. We investigated SMBH binary orbits that are corotating and counterrotating with the sense of the galaxy rotation. Table 1 describes parameters of our SMBH binary study. Note that we also evolved the SMBH binary in non-rotating spherical and flattened galaxy models with the same density profile to facilitate the comparison.

The numerical methods and hardware used for this work is described in Section 2.2 of KH13.

3. SMBH BINARY EVOLUTION IN FLAT ROTATING GALAXY MODELS

Here we discuss the results of our numerical studies of SMBH binary evolution in flat rotating galaxy models. The top panel of Figure 2 shows the evolution of the inverse semimajor axis for the A models. We see that for $N$ greater than 500 K, the inverse semimajor axis evolution is independent of $N$; we approach $N$ as high as 1.5 million here, which has never used before in such a study. For reference, we also plot the $1/a$ evolution of a flat non-rotating model with 1 million particles from our previous study (KH13), as well as a 1.5 million particle run in spherical galaxy (SO) model with the same density profile as our rotating galaxy model. We can see that in rotating flat models, the SMBH binary evolves at a rate considerably faster than in mere flat galaxy models. We see $N$-independent evolution of the SMBH binary in flat rotating galaxy models for $N$ as large as 1.5 million. This may point to rotation as a possible stellar dynamical solution to the final parsec problem within flattened galaxy models.
We also studied SMBH binary evolution in a galaxy with less dramatic bulk rotation; in this case, only 75% particles corotate with the massive binary (models B in Table1). The middle panel of Figure 2 again shows that the model experiences $N$-independent evolution of $1/a$, for $N \geq 800$ K. However, the binary coalesces at a slower pace when compared to models A for the same particle number. For example, the convergent A models pass $1/a = 1500$ at 40 time units, while the convergent B models take nearly 50 time units to pass this same point.

The bottom panel of Figure 2 shows the evolution in the semi-major axis for the SMBH binary in a counterrotating orbital orientation (models C). Here, the binary orbit shrinks at rates slightly different from the previous models at various time intervals, although not with a clear trend. At around 50 time units, the slope of the $1/a$ line seems very similar for $N > 500$ K, and again we notice the rapid evolution of $1/a$ when compared to flat and spherical models. However, we have doubts that we are capturing the SMBH binary evolution accurately because there is a clear dependence on particle number at later stages. In Section 4 we discuss why we believe that SMBH binary coalescence is achieved in our counterrotating models, despite the lack of convergence in the model suite.

For consistency between runs, we calculate the hardening rates $s$ for all our runs by fitting a straight line to the inverse semimajor axis $s = \frac{d}{dt} \left( \frac{1}{a} \right)$ in the interval of 50–70 time units (Figure 3). Both corotating and counterrotating binaries (runs A and C) have hardening rates of about $s \sim 28$, which is about 30% higher than mere flat models. The B runs have slightly lower values of $s \sim 25$ when compared to (runs A and C). Overall, we find that $s$ in both co- and counterrotating models is approximately 4 times higher than in spherical models with exactly the same density profile, for our best resolved runs with 1.5 million particles.
For a spherical, homogeneous, isothermal background, the hardening parameter $H$ is related to the hardening rate $s$ through $H = s \sigma / G \rho$; for the full loss cone regime, $H \approx 15$ (Quinlan 1996; Sesana et al. 2006). We calculate $H$ by substituting values of $\rho$ and $\sigma$ at the influence radius, defined as a sphere around the SMBH binary containing twice the mass of the binary in stars. Figure 4 shows that for runs A2, A1, and A0 with $N \geq 800$ k, where the evolution is independent of $N$, the value of $H$ remains constant around 11. The value of $H$ from these $N$-body simulations is within 70% of scattering experiments. For models B, again we see a constant value of $H \approx 10$ for runs with $N \geq 800$ k. For the spherical run S0 with the greatest particle number $N$, $H \approx 1.9$, almost 8 times smaller than what is predicted for a full loss cone in scattering experiments. We would like to point out that in our models, the background profile is not at all isothermal and there is also some ambiguity for where one should measure $\sigma$ and $\rho$ to make a fair comparison with scattering experiments. With this in mind, it is very encouraging that the $H$ obtained from our study is well within a factor of 2 of idealized scattering experiments.

Figure 2. Evolution of the semimajor axis of the SMBH binary for the A (top) B (middle) and C (bottom) model suites (see Table 1). For comparison, the gray lines represent one million non-rotating flattened (uppermost gray) and non-rotating spherical (bottommost gray) particle models. The opacity of the purple lines scale with the particle number—the most transparent line has the fewest particles in the suite.

Figure 3. Hardening rates for all our numerical experiments. Gray points are for the spherical models (S); purple represents models A; green is for models B; and the red points are for models C.

Figure 4. Hardening parameter $H$ for all our numerical experiments. Colors are as in Figure 3.
counterrotating SMBH binaries, the eccentricity approaches \( e \sim 1 \) as soon as the binary forms. This is consistent with the findings of previous studies (Sesana et al. 2011).

The dichotomy in eccentricity behavior is borne out in the difference in the evolution of the angular momentum loss. Figure 6 shows the angular momentum evolution of SMBH binaries for our best resolved co- and counterrotating models.

It is clear that in the counterrotating case, the angular momentum loss is much more rapid. As we see from Figure 2, the inverse semimajor axis evolution (and hence energy loss) is very similar for both co- and counterrotating models. This faster loss of angular momentum translates into a rapid rise in eccentricity.

We also investigated the center of mass motion of the binary in models A and C. Figure 7 shows the position of the center of mass throughout the run.

The trajectory of the SMBH binary center of mass is strongly affected by rotation. For non-rotating flattened models, the binary center of mass exhibits a small random walk characteristic of Brownian motion (Chatterjee et al. 2002). On the other hand, the center of mass in the corotating system settles into a corotation resonance at the radius of influence, following a roughly circular orbit of radius \( R_{\text{infl}} \) nearly in the \( x-y \) plane.

The counterrotating case, on the other hand, shows no binary orbital coupling (Figure 8), and the SMBH binary center of mass undergoes a random walk very similar to the non-rotating case. The inclination of the SMBH binary orbital plane we find is consistent with Gualandris et al. (2012); in counterrotating models, the inclination suffers large changes, while corotating models feature a stable binary orbital plane inclination.

4. SMBH BINARY COALESCENCE

We also estimate the SMBH binary evolution for each case after the end of our simulation. We choose three Virgo cluster

![Figure 5. SMBH binaries eccentricity for models with \( N \geq 1 \) million. SMBH binaries in corotating, flat, and spherical models have very small values of eccentricity \( e \sim 0.1 \) whereas eccentricity approaches unity in counterrotating models. Here, the transparency represents the particle number; opaque lines are the \( N = 1.5 \) million runs, while the fainter lines show results for \( N = 1 \) million particles. Orange lines show the counterrotating model; green lines represent models B; purple lines show models A; and the gray lines are for the spherical and non-rotating axisymmetric models.

![Figure 6. Angular momentum evolution for corotating (top) and counterrotating (bottom) SMBH binaries. The green line is \( L_z \), while the pink and brown lines are \( L_x \) and \( L_y \), respectively.

![Figure 7. Motion of the center of mass of the SMBH binary in model A0 (purple) and the non-rotating flattened model (gray). Fainter colors indicate earlier epochs. Note that for model A0, the binary’s center of mass settles into a roughly circular orbit about the galactic center with a radius of \( \sim 0.05 \) in model units, roughly the SMBH radius of influence. In contrast, the center of mass of the SMBH binary in the non-rotating model undergoes simple Brownian motion about the galactic center.](image)
Figure 8. Motion of the SMBH binary center of mass in model C0 (purple) and the non-rotating flattened model (gray). The color transparency is as in Figure 7. In our counterrotating model, the binary center of mass executes a random walk, like the non-rotating model.

galaxies as references to physically scale our models: M87, NGC 4472, and NGC 4486A. In each case, the mass scale is set by the observed SMBH mass. For the length scale, we set the influence radius of the SMBH binary-embedded galaxy model to the size of the observed influence radius of reference galaxy model. NGC 4472 may best represent our model density profile with its moderate central cusp, while the central core in M87 and the steep cusp of NGC 4486A span the range of typical density cusps. Table 2 shows useful quantities for the physical scales in our models.

Our technique for extrapolating the evolution of the SMBH binary beyond the endpoint of the simulation is explained in detail in Section 4.3 of Khan et al. (2012b). We choose the runs with highest particle number in each model (A0, B0, C0) for this extrapolation technique, and the evolution is shown in Figure 9. The top panel shows the SMBH binary evolution scaled to M87.

In the non-rotating case, the SMBH binary coalesces in roughly 1.5 Gyr for this physical scaling. For corotating models A0 and B0, coalescence times are roughly 1.1 and 1.3 Gyr. For the counterrotating run C0, we evolve the SMBH binary from 1/α = 1000 (see Figure 2) at a system time T = 27, and we only consider hardening by gravitational waves; this is because we are not certain that the scattering results converge when the binary orbit is smaller than this. The SMBH binary coalesces in a mere 100 Myr—essentially immediately—due to its near radial eccentricity. The middle panel of Figure 9 shows the SMBH binary evolution for NGC 4472. Here, the SMBH binaries coalesce approximately two times faster than in M87; a case in point: in the corotating model A0, the SMBH binary coalesces in roughly 500 Myr. Finally, the bottom panel of Figure 9 scales to NGC 4486A, and in this case the SMBHs merge in model A0 in about 1.5 Gyr while the SMBH binaries coalesce in almost 2 Gyr within the non-rotating model. Neglecting stellar hardening, the SMBH binary in the counterrotating case coalesces in roughly 2 Gyr. However, if we assume that the SMBH binary reaches an asymptotic hardening rate in C0, coalescence happens immediately after a hard binary forms. Clearly, SMBH binaries coalesce faster in rotating flattened models, but the mechanism behind the coalescence is very different depending on the sense of rotation. In corotating models, the rapid coalescence is due to higher hardening rates, but for counterrotating models high eccentricity drives the merger. Out of three representative galaxies, the SMBH binary coalescence time is shortest for NGC 4472.

We show the coalescence time for different runs and physical scaling in Table 3. Technically, the clock starts here when two SMBHs form a pair with a separation ≈10 influence radii (presumably after a major galaxy merger), and ends with the coalescence of the binary from gravitational radiation.

### Table 2

| Galaxy   | $M_\star (M_{\odot})$ | $r_0$ (pc) | $T$ (Myr) | $L$ (kpc) | $M$ (M$_{\odot}$) |
|----------|-----------------------|------------|-----------|-----------|------------------|
| M87      | $3.6 \times 10^{10}$  | 460        | 3.92      | 3.68      | $7.2 \times 10^{11}$ |
| NGC 4472 | $5.94 \times 10^{10}$ | 130        | 1.45      | 1.04      | $1.2 \times 10^{11}$ |
| N4486A   | $1.3 \times 10^{10}$  | 31         | 1.14      | 0.25      | $2.6 \times 10^{9}$ |

**Note.** Columns from left to right: (1) reference galaxy, (2) observed SMBH mass, (3) observed SMBH radius of influence, (4) time unit, (5) length unit, (6) mass unit.

5. STRUCTURE OF THE MERGER REMNANT

In this section, we go over the imprint of the binary black hole merger on the galaxy remnant. As expected, Figure 10 shows that the density cusp is scoured out by three-body scattering as the black holes coalesce (Graham 2004). One puzzling result can be seen in Figure 11, where the final velocity dispersion spikes; this is in contradiction to the dip in velocity dispersion expected from the stellar hardening phase (Meiron & Laor 2013), and fully consistent with the velocity dispersion cusp expected in an equilibrium SMBH-embedded nucleus. Further study is needed, using simulations with shorter snapshot output cadence, to help pinpoint the occurrence and longevity of this potential kinematic signature of three-body scattering.

6. CONCLUSION

We investigated the effect of bulk rotation on SMBH binary coalescence in N-body-generated flattened galaxy models. Overall, we found that rotation drives the SMBH binary more efficiently through the three-body scattering phase, resulting in coalescence timescales that are between 3 and 30 times faster than the same non-rotating model for co- and counterrotating models, respectively. The three-body scattering phase removes roughly 1.3 times the binary SMBH mass, scouring the density cusp out to about 1.1 kpc if scaled to the M87 core.

We found that when the SMBH binary and the galaxy are corotating, the eccentricity remains low at approximately 0.1, while counterrotation acts to pump the SMBH binary eccentricity up to nearly 1 during the inspiral phase. Such a high eccentricity enhances the coalescence of the SMBH binary, as is seen in many previous studies (e.g., Sesana 2010; Khan et al. 2012a). Though we caution that the eccentricity behavior is not convergent even for 1.5 million particles, we suspect that the eccentricity will remain high in the convergent regime; when the SMBH is counterrotating, the abundance of retrograde orbits can extract angular momentum from the binary very efficiently, and secular dynamical anti-friction (Madigan & Levin 2012) torques the orbit so that it bleeds angular momentum. A systematic study is needed to
gauge the degree of counterrotation and binary orbital plane alignment needed to pump the eccentricity into the nearly radial regime; if the binary eccentricity is very sensitive to minor degrees of counterrotation, then few mergers will linger in the three-body scattering stage. In this case, we should expect fewer hypervelocity star ejections than for a corotating system. For such high eccentricities, we should expect residual eccentricity to persist into the last few orbits in the gravitational wave regime; this will have profound implications for gravitational wave detection using waveform template matching.

Figure 9. Complete orbital evolution of the SMBH binary from formation to coalescence for runs A0 (yellow), B0 (orange), C0 (blue), and Flat (gray) when our galaxy model is scaled to M87 (top panel), NGC 4472 (middle panel), and NGC 4486A (bottom panel). In the bottom panel, the very different counterrotating timescales either include (short timescale with fainter hue) or exclude (longer timescale with stronger hue) stellar hardening.

Figure 10. Initial (green) and final (orange) density profile of model A, showing the clear mass deficit out to $r \sim 0.3$ of 1.3 times the binary SMBH mass.

Figure 11. Initial (orange) and final (red) three-dimensional velocity dispersion profile of model A, showing a sharp spike in the velocity dispersion at the end of the run.

in the three-body scattering stage. In this case, we should expect fewer hypervelocity star ejections than for a corotating system. For such high eccentricities, we should expect residual eccentricity to persist into the last few orbits in the gravitational wave regime; this will have profound implications for gravitational wave detection using waveform template matching.

Table 3

| Run | $s$  | $H$  | $e$  | $T_{c,M87}$ | $T_{c,4472}$ | $T_{c,4486A}$ |
|-----|------|------|------|-------------|-------------|-------------|
| A0  | 27.7 | 10.87 | 0.17 | 1.17        | 0.57        | 1.52        |
| B0  | 23.90| 9.20 | 0.06 | 1.27        | 0.62        | 1.67        |
| C0  | 23.6 | 8.66 | 0.99 | 0.11        | 0.04        | 2.04(0.14)  |

Note. Columns from left to right: (1) SMBH binary evolution run, (2) SMBH binary hardening rate, (3) hardening parameter $H$, (4) SMBH binary eccentricity, (5) Coalescence time (in Gyr) when our model is scaled to M87, (6) NGC 4472 (7), and NGC 4486A.
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