PAIRING OF SUPERMASSIVE BLACK HOLES IN UNEQUAL-MASS GALAXY MERGERS

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Abstract

We examine the pairing process of supermassive black holes (SMBHs) down to scales of 20-100 pc using a set of N-body/SPH simulations of binary mergers of disk galaxies with mass ratios of 1:4 and 1:10. Our numerical experiments are designed to represent merger events occurring at various cosmic epochs. The initial conditions of the encounters are consistent with the $\Lambda$CDM paradigm of structure formation, and the simulations include the effects of radiative cooling, star formation, and supernovae feedback. We find that the pairing of SMBHs depends sensitively on the amount of baryonic mass preserved in the center of the companion galaxies during the last phases of the merger. In particular, due to the combination of gasdynamics and star formation, we find that a pair of SMBHs can form in 1:10 minor mergers provided that galaxies are relatively gas-rich (gas fractions of 30% of the disk mass) and that the mergers occur at relatively high redshift ($z \sim 3$), when dynamical friction timescales are shorter. Since 1:10 mergers are most common events during the assembly of galaxies, and mergers are more frequent at high redshift when galaxies are also more gas-rich, our results have positive implications for future gravitational wave experiments such as the Laser Interferometer Space Antenna.

Subject headings: black hole physics — cosmology: theory — galaxies: mergers — hydrodynamics — methods: numerical

1. Introduction

Compelling dynamical evidence indicates that supermassive black holes (SMBHs) with masses ranging from $10^6$ to above $10^{10} M_\odot$ reside at the centers of most galaxy spheroids (e.g., Ferrarese & Ford 2005). The masses of SMBHs appear to be correlated with various properties of their hosts, including luminosity or mass (Magorrian & al. 1998) and velocity dispersion (Ferrarese & Merritt 2000, Gebhardt & al. 2000). In the currently favored model for structure formation, $\Lambda$CDM, galaxies grow hierarchically through mergers and accretion of smaller systems (e.g., White & Rees 1978). Thus, if more than one of the merging galaxies contained a SMBH, the presence of two or more SMBHs in their remnant will be almost inevitable during galaxy assembly (Begelman et al. 1980). However, it is unclear if the dynamical processes at play are efficient in forming a close SMBH pair with separations $\sim 10-100$ pc, which may subsequently shrink to a bound binary, and eventually merge via gravitational wave radiation. Such black hole coalescence events are expected to give rise to gravitational wave bursts that should be detectable by the Laser Interferometer Space Antenna (LISA) (Vecchio 2004).

SMBH pairing has been shown to proceed quickly when both compact objects are hosted by steep stellar cusps approaching each other from close distances (Milosavljević & Merritt 2001), or when embedded in a circumnuclear gaseous disk under appropriate thermodynamic conditions (Mayer et al. 2007), but whether the large-scale merger can lead the black holes to such a favorable configuration is still a matter of debate. Previous studies have found that following a galaxy merger, the relative distance of the SMBHs in the remnant is very sensitive to the structure of the merging galaxies, and to their initial orbit (Governato et al. 1994). Kazantzidis & al. (2005) showed that the pairing is very efficient in equal-mass disk galaxy mergers with cosmologically relevant orbits, while the presence of a dissipative component is a necessary ingredient for the pairing of SMBHs in 1:4 mergers. Other recent studies (e.g., Springel et al. 2005, Johansson et al. 2008) focused on the effect of energetic feedback from black hole accretion onto the surrounding galaxy, but were not designed to follow the orbital evolution of SMBHs. Substantially less effort has been devoted to examining the fate of SMBHs in minor mergers (but see Boylan-Kolchin & Ma 2007), which are much more frequent in $\Lambda$CDM cosmologies (Lacey & Cole 1993, Fakhouri & Ma 2008). Investigating the necessary conditions for SMBH pair formation in this regime is of primary importance for the search of gravitational waves, as well as for all studies of SMBH demographics and activity.

In this Letter, we report on the efficiency of the SMBH pairing process using a set of N-body/SPH simulations of disk galaxy mergers, with mass ratios $q = 0.25$ and 0.1, constructed to represent mergers occurring at various cosmic epochs. The choice of the initial conditions, in particular the masses of the SMBHs, is such that eventual coalescence events between the SMBHs following the galaxy merger would be detectable with LISA (Sesana et al. 2005). Our simulations comprise collisionless encounters and mergers including gas dynamics as well as star formation (SF) and blastwave feedback from supernovae.
2. Simulation Set-Up

The galaxy models were initialized as three-component systems following the methodology outlined in Hernquist (1993). They comprise a Hernquist spherical stellar bulge (Hernquist 1990), an exponential disk with a gas mass fraction $f_g$, and an adiabatically contracted dark matter halo (Blumenthal et al. 1986) with an initial NFW profile (Navarro et al. 1996). In addition, a collisionless particle representing the SMBH, whose mass was chosen according to the $M_{\text{BH}} - M_{\text{bulge}}$ relation (Magorrian & al. 1998), was added at the center of the model galaxies.

Our reference model is a Milky-Way type galaxy, with a virial velocity $V_{\text{vir}} = 145$ km/s which corresponds to $M_{\text{vir}} = 10^{12}M_\odot$, a disk mass fraction $M_d = 0.04M_{\text{vir}}$, and a bulge mass fraction $M_b = 0.008M_{\text{vir}}$. The disk scale height and the bulge scale radius are $z_0 = 0.1R_d$ and $a = 0.2R_d$ respectively, $R_d$ being the exponential disk scale length. $R_s$ is determined according to the prescriptions of Mo, Mao, & White (1998) (MMW in the following), which yield disk galaxies consistent with the Tully-Fisher relation. A summary of our set of simulations is presented in Table 1. Models at redshift $z = 0$ were initialized with a halo concentration parameter $c = 12$, appropriate for present-day galaxies in this range of masses (Bullock et al. 2001). We also ran mergers with initial conditions rescaled to $z = 3$ according to MMW, keeping $V_{\text{vir}}$ fixed, as expected for the progenitors of our $z = 0$ models (Wechsler et al. 2002; Li et al. 2007). Considering high-redshift mergers is crucial because the merger rate increases with look-back time, and a large fraction of the gravitational wave signal from coalescences of SMBH binaries is predicted to originate from this cosmic epoch at the corresponding mass scale (Sesana et al. 2005; Volonteri et al. 2003). Following MMW, all masses, positions and softening lengths were rescaled by a factor $H(z = 3)/H_0$, i.e. the ratio between the Hubble constant at $z = 3$ and its present-day value for a ΛCDM “concordance” cosmology ($H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$). The halo concentration was chosen according to Bullock et al. (2001), $c = 3$. Satellite galaxies were initialized with the same structure, with the mass in each component being scaled down by $q$. Our choice for the galaxy masses and the assumption that the SMBHs follow the $M_{\text{BH}} - M_{\text{bulge}}$ relation result in black hole masses between a few times $10^6$ and $10^9M_\odot$. These masses fall in the typical mass range of coalescing black holes that will be detectable with LISA (Sesana et al. 2005).

We choose orbital parameters for the merging galaxies that are typical of merging halos in cosmological simulations (Khochfar & Burkerti 2006; Benson 2005): the two galaxies were placed at a distance equal to twice their virial radii and set on parabolic orbits with pericentric distances of 20% of the virial radius of the most massive halo. All mergers were considered to be coplanar and prograde, i.e., the angular momentum of each galaxy was parallel to the orbital angular momentum vector.

All simulations were performed with GASOLINE, a TreeSPH N-body code (Wadsley et al. 2004). We ran collisionless (“dry”), with $f_g = 0$ and gasdynamical (“wet”) mergers with the same gas fraction in the primary and secondary galaxies, either $f_g = 0.1$ or 0.3. In wet runs, atomic gas cooling was allowed; SF was treated using the blast-wave model described in Stinson et al. (2006). Gas particles are eligible to form stars if their density exceeds 0.1 cm$^{-3}$ and their temperature drops below $1.5 \times 10^4$ K, and the energy deposited by a Type-II supernova in the surrounding gas is $4 \times 10^{50}$ erg. With this choice of parameters our blastwave feedback model was shown to produce realistic galaxies in cosmological simulations (Governato et al. 2007).

In each galaxy (with the exception of a very high-resolution test, see below), we employed $10^9$ particles for the dark matter halo, and, initially, $2 \times 10^8$ star particles and $10^5$ gas particles, when included. The force softening was 100 pc in our reference model, scaled down by $q^{1/3}$ in the satellites, and by $H(z)/H_0$ in the high-$z$ runs, yielding a force resolution of $\sim 20$ pc in the satellite galaxy in the $q = 0.1$ merger at $z = 3$. By employing such a high particle number, the particle mass in the bulge and disk of the satellite is an order of magnitude lower than $M_{\text{BH}}$, ensuring that the black hole dynamics are not affected by spurious two-body collisions. In what follows, we define two SMBHs as a “pair” if their relative orbit shrinks down to a separation equal to twice the softening. At these distances, sinking may proceed very quickly and a SMBH binary may form in $\sim 1$ Myr (Mayer et al. 2007).

3. Results

The galaxy merger and the sinking of the lighter SMBH towards the more massive one can be divided into three stages: first, the orbit of the satellite decays because of dynamical friction on the halo of the primary while tidal torques can affect crucially the structure of the satellite; the second stage encompasses the phase dominated by mass stripping of the central region of the satellite as it crosses the densest, baryon-dominated part of the primary galaxy – this is when the fate of the two SMBHs is decided; in the last phase, the remnant settles to its final dynamical state and the final configuration of the two black holes is achieved. Table 1 presents a summary of the final separations of the SMBHs for the simulations discussed here.

3.1. Collisionless Mergers

In collisionless runs, the satellite is not able to dissipate energy gained through tidal shocks at pericentric passages (Gnedin et al. 1999; Taffoni et al. 2003). For $q = 0.25$, dynamical friction on the dark matter halo of the more massive galaxy is efficient, and the satellite sinks down to a few $\sim 10$ kpc from the center after 3 orbits. However, at that point the central density of the satellite has already decreased because of tidal heating (Kazantzidis et al. 2004). As a result, even its inner region is disrupted before its SMBH can reach the center of the remnant. In this case, no pair is formed, and the smaller SMBH is left wandering a few kiloparsecs from the center of the remnant. At such distances, dark matter is dynamically important. Even at high resolution, the mass of the dark matter particles of the primary galaxy is comparable with that of the SMBH, hence dynamical friction cannot be
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3.2. Gas Dynamics and Star Formation

The presence of a star-forming gaseous component crucially affects the orbital decay of the SMBH, starting from the early phases of the merger, via its dynamical response to tidal forces and torques experienced at the first pericentric passages.

The orbits of dry and wet, $q = 0.25$ mergers start to differ only after the first couple of orbits ($\sim 6$ Gyr). Tidal forces acting on the satellite excite a strong bar instability during the second orbit. Dissipation in the gas and the torques exerted by the stellar bar onto the gas drive a gaseous inflow toward the center of the satellite (Figure 1). Thus, its potential well deepens, ensuring resilience of the baryonic core of the satellite to tidal stripping and shocks all the way down to the center of the primary. The core thus continues to sink via dynamical friction, delivering the smaller SMBH to the center of the primary. As a consequence, the two SMBHs form a pair at our force resolution, confirming previous results (Kazantzidis et al. 2005). The central kiloparsec of the remnant still comprises a gaseous mass of $5 \times 10^6\, M_\odot$, which could facilitate the formation of a bound Keplerian SMBH binary under appropriate thermodynamic conditions (Mayer et al. 2007).

In $q = 0.1, z = 3$ wet mergers, both $f_g = 0.1$ and $0.3$ were employed; the latter should be a more realistic case, since disk galaxies at $z = 3$ are expected to have a high gas mass fraction. Star formation and supernovae feedback affect the structure of the interstellar medium (ISM) in the disks quite dramatically in this mass range (see also Governato et al. 2007). The disks develop a clumpy and irregular multiphase structure, and turbulent velocities of the gas become a significant fraction ($30\%$) of the circular velocity in this mass range ($V_{\text{vir}} = 64\, \text{km s}^{-1}$). The distribution of stars and gas in the satellites becomes non-axisymmetric under the effect of tides, but gas inflows and associated SF inhibit the growth of the $m = 2$ mode and the formation of a strong stellar bar (Debattista et al. 2006), as shown in Fig. 1. Therefore, in the absence of bar-driven torques, the strong gaseous inflow seen for higher-mass ($q = 0.25$) objects does not happen for $q = 0.1$. Still, the presence of gas allows the satellite to dissipate some of the energy injected by tidal shocks. Star formation is not globally enhanced with respect to the average SF rate measured for the same model in isolation, but under the effect of tides it becomes more concentrated in the innermost region (Fig. 2). During the first three orbits, the $f_g = 0.1$ case preserves its initial central density, while in the $f_g = 0.3$ satellite a steeper stellar cusp develops. Once the satellite goes through the second pericentric passage, its ISM is prone to ram pressure stripping by the gas disk of the primary galaxy. The ram pressure stripping radius $R_{\text{ram}}$, outside which the satellite is not able to retain gas, can be expressed as $R_{\text{ram}} = 2\pi P_{\text{ram}} \left( \rho_{g,\text{vir}}(R_{\text{ram}}) v(R_{\text{ram}}) \right)^{-1}$ (Marcolini et al. 2003), where $\rho_{g,\text{vir}}$ is the gas density and $g$ the gravitational acceleration due to the satellite's self-gravity. The ram pressure $P_{\text{ram}} \approx \rho_{\text{ext}} v^2$ depends on the gas density $\rho_{\text{ext}}$ in the primary, and on the relative velocity $v$ between the two galaxies. Contrary to test runs we conducted without SF in which a large amount of gas was funnelled by torques toward the region inside $R_{\text{ram}}$, the turbulent and clumpy ISM offers a large effective area to ram pressure, particularly in these lower-mass satellites. Nearly $90\%$ of it is swept away when first entering the disk of the primary (Fig. 1), while what remains is stripped during the next orbit: at $t = 2$ Gyr, the satellite has lost all its gas content, even in its central region. From this point onward, the satellite behaves like a cuspy, gas-poor object, subject to dynamical friction in the stellar and gaseous background. Its sinking is relatively fast: in fact, its steeper stellar density profile increases the mass inside its tidal radius, enhancing dynamical friction and preserving it from tidal disruption because its response to tidal shocks is nearly adiabatic (Gnedin et al. 1999). On the contrary, the satellite of the
that of the primary galaxy. Torques in the early stages of the merger are not acting to concentrate gas to the center, due to the absence of a stellar bar and the stabilizing effect of turbulence. As a result ram pressure strips all of the ISM of the satellite. Still, gas-rich satellites \((f_g = 0.3)\) undergo a central burst of star formation during the first orbits which increases their central stellar density, thus allowing their survival and ensuring the pairing of the two SMBHs via dynamical friction in a few \(10^8\) yr after the disruption of the satellite. On the other hand, in a satellite with lower gas content \((f_g = 0.1)\) star formation is not as effective in enhancing its concentration; as a consequence, even its central region is disrupted at a few hundred parsecs from the center of the primary, and the pairing between the two SMBHs is delayed by a few billion years. Therefore, while with a gas-rich satellite the pairing is inefficient, in the sense that it occurs on a timescale smaller than the merging time of the two galaxies, if the satellite has a low gas content the pairing is less efficient, since it occurs on a longer timescale.

If the \(M_{\text{BH}} - M_{\text{bulge}}\) relation approximately holds at \(z = 3\) as in the local Universe, the galaxies here considered should be typical objects leading to the formation of representative SMBH pairs at this cosmic epoch, as predicted by hierarchical models of SMBH-galaxy coevolution \cite{Volonteri+2003}. These pairs are also expected to contribute significantly to the high-\(z\) gravitational wave signal in the LISA band \cite{Sesana+2005}. Our findings show that gas-dynamical processes can efficiently drive the pairing of SMBHs, strengthening expectations for the observability of black hole coalescence events. On the other hand, even assuming that the two black holes will eventually merge if they can pair at the center of the primary, the discovered sensitivity of this process on the gaseous content of the merging galaxies implies that SMBH coalescences cannot be trivially considered as tracers of galaxy mergers in general. This has important implications on the interpretation of the LISA gravitational wave signal.

We note that dynamical friction timescales of wandering, “naked” SMBHs can be shortened, if a massive dense component such as a nuclear star cluster (NSC), either originally present in the satellite, or formed during the merger as a consequence of the nuclear starburst, is preserved from tidal stripping. Since the typical sizes of NSCs are smaller than our force resolution, we cannot exclude this possibility. If these NSCs follow scaling relations similar to those observed in the local Universe \cite{WehnerHarris2006,Ferrarese+2006}, their masses should be roughly 10 times higher than those of the SMBHs, for a given velocity dispersion of the host, but still an order of magnitude lower than those given by the stellar cusps at our force resolution (Fig. 2). In this way, the formation of a SMBH pair via dynamical friction could happen in a few \(10^8\) yr once the merger has delivered the two SMBHs within a separation of \(\sim 1\) kpc, as we find for the 1:10, \(f_g = 0.1\) merger. However, even in this case, sinking timescales would still be longer than a Hubble time for the SMBHs in the dry mergers here considered, because the smaller SMBH is left wandering at a distance significantly exceeding a kiloparsec.

Lastly, a general limitation of our simulations is that they lack a treatment of gas accretion onto the SMBHs and associated energy feedback. Additional heating from the active SMBH should reduce the binding energy of the gas, making it more susceptible to stripping processes and perhaps inhibiting the formation of a steep stellar cusp. This would go in the direction of reducing the efficiency of the pairing process,
but the overall effect will strongly depend on when the black hole becomes active during the merger. As for accretion, even an order of magnitude increase of the mass of the smaller SMBH, which is a rather extreme assumption (Colpi et al. 2007), would at most lead to a dynamical evolution similar to what discussed for the presence of a NSC. Although it is unlikely that these effects will change the overall picture presented in this Letter, they will have to be explored in a forthcoming paper.

The authors are grateful to B. Devecchi, M. Dotti, A. Maller, D. Merritt, D. Weinberg, and S. White for fruitful discussions, and to D. Potter for technical support. The simulations were performed on the zBox2 and zBox3 supercomputers at the ITP, University of Zürich. SK is supported by the Center for Cosmology and Astro-Particle Physics (CCAPP) at The Ohio State University. MC thanks the Aspen Center for Physics for its hospitality while this work was in progress. FG is supported by the NSF grant AST-0607818. TQ and FG are supported by NASA grant NNX07AH03G.

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