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Pairing of supermassive black holes in unequal-mass mergers

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Abstract. Disk galaxies with a spheroidal component are known to host Supermassive Black Holes (SMBHs) in their center. Unequal-mass galaxy mergers have been rarely studied despite the fact that they are the large majority of merging events by number and they are associated with the typical targets of gravitational wave experiments such as LISA. We perform N-body/SPH simulations of disk galaxy mergers with mass ratios 1:4 and 1:10 at redshifts z=0 and z=3. They have the highest resolution achieved so far for merging galaxies, and include star formation and supernova feedback. Gas dissipation is found to be necessary for the pairing of SMBHs in these minor mergers. Still, 1:10 mergers with gas allow an efficient pairing only at high z when orbital times are short enough compared to the Hubble time.

Key words. black hole physics — cosmology: theory — galaxies: mergers — hydrodynamics — methods: numerical

1. Introduction

Observations of nearby galaxies show that Supermassive Black Holes (SMBHs) ranging between $\sim 10^6$ and $\sim 10^9 M_\odot$ inhabit the centers of virtually all massive galactic spheroids, from massive ellipticals to pseudo-bulges of late-type. Their masses, as inferred from dynamical measurements, appear to be correlated with various properties of their hosts, e.g. bulge luminosity and mass (e.g. Kormendy & Richstone (1995); Magorrian et al. (1998); Marconi & Hunt (2003)), velocity dispersion (Tremaine et al., 2002; Ferrarese & Merritt, 2000), concentration of the light profile (Graham et al., 2001). In the ΛCDM model, galaxies build up their masses hierarchically starting from initial, gravitationally amplified fluctuations (e.g. White & Rees (1978)); therefore, every time two galaxies merge, the remnant is expected to host two (or more) SMBHs. The formation of a binary SMBH sistem has been shown to proceed quickly once both the compact objects are embedded in a circumnuclear gaseous disk (see Mayer et al. (2007); see also Mayer, Kazantzidis & Escala in this volume), but whether the large scale merger can lead them to such a favorable configuration is still a mat-

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ter of debate: while mergers between galaxies of equal mass have been quite extensively explored in literature and seem to lead to the formation of a SMBH pair (Kazantzidis et al., 2005; Springel et al., 2005), little attention has been paid to the fate of SMBHs in events which are much more frequent in the typical history of a ΛCDM galaxy, i.e. minor mergers with mass ratios from 1:4 to 1:10 and less (Stewart et al., 2008).

2. Simulations and results

2.1. Initial conditions

We discuss here results from N-body/SPH simulations of mergers between disk galaxies with mass ratios $q = 0.25$ and 0.1 at an unprecedented resolution. The galaxy models were initialized as three-component systems comprising a Hernquist bulge, an exponential disk with a gaseous mass fraction f_g, and a dark matter halo with an adiabatically contracted NFW profile, plus a central collionless particle representing the SMBH, whose mass was chosen following the $M_{\rm BH} - M_{\rm bulge}$ relation (Magorrian et al., 1998). For more details on the setup of the initial conditions for the reference model see Kazantzidis et al. (2005). We also ran mergers with initial conditions rescaled to $z = 3$ according to the Mo et al. (1998) (MMW) and Bullock et al. (2001) models, and keeping $V_{\rm vir}$ fixed, as expected for the high-z progenitors of our present-day models (Wechsler et al., 2002; Li et al., 2007). A large fraction of the gravitational wave signal from coalescences of SMBH binaries is expected to come from this cosmic epoch (Sesana et al., 2005), if SMBH pairing is efficient. The satellite galaxies are initialized self-consistently with the same three-component structure of the primary, and a mass in each component scaled down by q. The baricenters of the two galaxies in each run were initally placed at a separation equal to the sum of their virial radii, on parabolic orbits with pericentric distances equal to 0.2 times the virial radius of the more massive halo (Khochfar & Burkert, 2006; Benson, 2005). We ran collisionless ("*dry*", with $f_g = 0$) and gasdynamical ("*wet*", $f_g = 0.1$ and 0.3) simulations using GASOLINE (Wadsley et al., 2004). We will define two SMBHs a "pair" if their relative orbit shrinks to a separation equal to our force softening ($\sim$ 20 pc); at these distances, Mayer et al. (2007) have shown that sinking proceeds very quickly and a SMBH binary can be formed in $\sim$ 1 Myr. Since our main purpose is to check which processes favour or inhibit this pairing, we do not employ any additional prescription in order to to keep them at the center of their galaxies' potential wells or to facilitate their orbital sinking.

2.2. Collisionless mergers

The galaxy merger and the sinking of the lighter SMBH towards the more massive one can be roughly divided in three stages: during the first, the orbit of the satellite decays because of dynamical friction on the halo of the primary; the second encompasses the most crucial phase of mass stripping in the denstest, baryon-dominated region where the fate of the SMBH pair is decided; in the final stage the remnant settles to its final dynamical state.

For $q = 0.25$, dynamical friction on the dark matter halo of the primary is efficient, and the satellite galaxy sinks down to a few $\sim$ 10 kpc from the center. However, a collisionless system is not able to dissipate the energy gained through tidal shocks at pericentric passages (Gnedin et al., 1999; Taffoni et al., 2003); thus, the satellite is disrupted before its SMBH can reach the center of the remnant. No pair is formed, and the smaller SMBH is left several kiloparsec away from the other; at these distances its dynamical friction timescale (Chandrasekhar, 1943) is longer than a Hubble time, but this is also where gas dynamics can affect the sinking (see 2.3).

On the other hand, even after 10 Gyr the 1:10, $z = 0$ dry merger is not able to enter the regime where the inclusion of gas could speed up the sinking, because dynamical friction in the halo is too slow. Mergers at $z = 3$, instead, allow for an efficient sinking on much shorter timescales. The MMW scalings predict, for a given $V_{\rm vir}$, masses and radii that are a factor of $H(z = 3)/H_0 \sim 1/5$ smaller; as a conse-

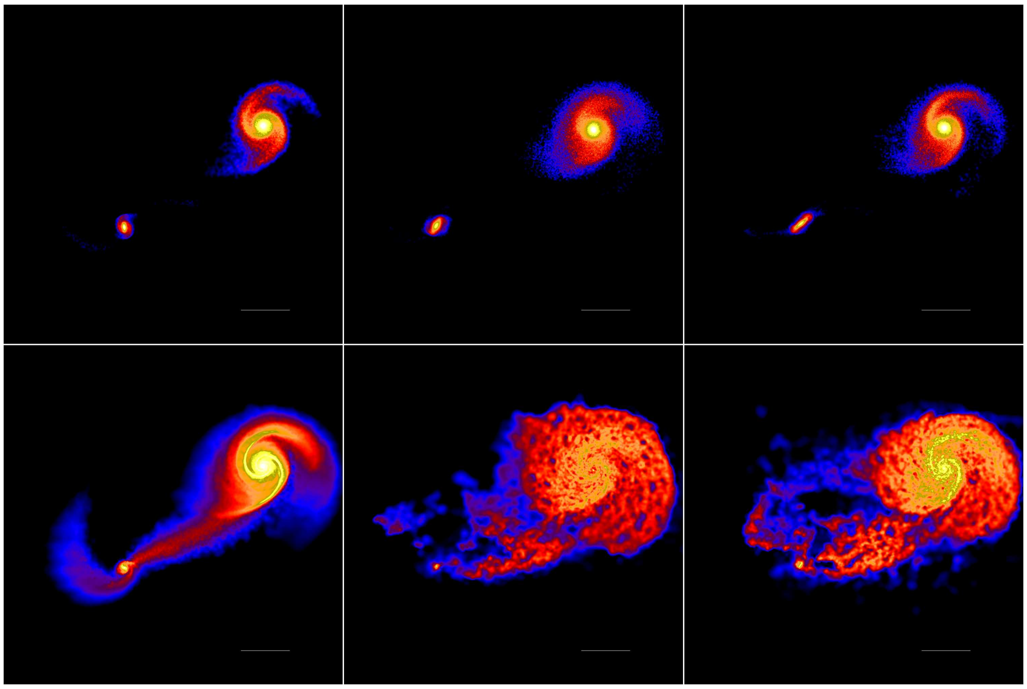

Fig. 1. Color-coded density maps for stars (upper row) and gas (lower row) at the second apocenter for three different $q = 0.1$ mergers at $z = 3$: from left to right, the case with gas gooling ($f_g = 10\%$), star formation ($f_g = 10\%$) and star formation ($f_g = 30\%$) are shown. Each frame is 30 kpc across. In the runs with star formation, supernova feedback creates a clumpy and diffuse ISM, resulting in strong ram pressure stripping when the orbit of the satellite passes through the gaseous disk of the primary galaxy.

quence, orbital periods associated with orbits of same energy and pericenter (in units of $R_{\rm vir}$) are reduced by the same factor. Therefore, the 1:10 collisionless merger at $z = 3$ is completed in ~ 2.5 Gyr. Like for $q = 0.25$, a wandering SMBH is left at ~ 10kpc from the center of the remnant.

2.3. Gas dynamics

Gas dynamics can change the orbital evolution only during the second stage of the merger, when the satellite is moving through the densest, baryon-dominated region of the parent galaxy; this is when tidal shocks and ram pressure become so strong that gaseous dissipation can significantly affect mass stripping around the smaller SMBH.

For this reason, the dry and wet, $q = 0.25$ mergers differ only after the first couple of orbits ($t \sim 6$ Gyr). As already pointed out in Kazantzidis et al. (2005), gaseous dissipation is a key element in the second stage of SMBH pairing in unequal-mass mergers: for 1:4 mergers, the presence of gas is a necessary and sufficient condition for the formation of a pair at the force resolution. The pair is embedded in a nuclear gaseous disk of radius ~ 500 pc, supported mainly by rotation (~ 200 km s^{-1}), and comprising a mass of $\sim 3 \cdot 10^9$ M$_\odot$.

In the 1:10, $z = 3$ merger with cooling, the gas in the outer disk of the satellite gets tidally stripped; however, most of it, after the first couple of pericentric passages, is funnelled by tidal torques to the center of the satellite, ending up in a $\sim 7 \cdot 10^7$ M$_\odot$ circumnuclear structure. This central overdensity steepens the mass profile of the satellite, allowing it to survive subsequent tidal shocks until it gets dragged down to the nucleus of the remnant, where a SMBH pair is formed. The gaseous nuclear structure in the remnant is disk-like, of thickness equal to our softening length and supported by rotation in the disk plane (with rotational velocity ~ 180 km s^{-1}).

2.4. Star formation

We discuss now preliminary results from the last set of simulations, which include star formation and feedback from supernovae according to the prescriptions and fiducial parameters detailed in Stinson et al. (2006). A comparative view of three $q = 0.1$, $z = 3$ mergers is shown in figure 1.

When star formation is included, the Interstellar Medium (ISM) in the disks shows a multiphase and irregular structure, with larger scalelengths both in the radial and vertical direction. For this reason, the first pericentric passage of the satellite is not able to excite strong, coherent inflows which can steepen the density profile. Thus, during the second orbit, ram pressure exerted by the ISM of the primary galaxy strips most of the gas away from the satellite. The fraction of gas remaining in its center can then either be consumed by star formation, or stripped when the orbit reaches the densest regions of the primary: in this case, the small SMBH might not be able to pair with the more massive one before tidal shocks disrupt the core of the satellite.

3. Conclusions

Understanding the formation of SMBH binaries is of fundamental importance for the search of gravitational waves as well as for all studies of black hole demography and host galaxy coevolution. SMBH pairing in unequal-mass mergers depends crucially on gasdynamical effect: satellites are disrupted too quickly, leaving wandering SMBHs in all the collisionless cases we studied. *The presence of gas seems to be necessary for the pairing of SMBHs*. While it also appears sufficient for $q = 0.25$, lower mass objects are more heavily affected by feedback from star formation, and their outcome could be very sensitive to the details of the physical processes involved.

References

Benson, A. J. 2005, MNRAS, 358, 551

Bullock, J. S., Kolatt, T. S., Sigad, Y., et al. 2001, MNRAS, 321, 559

Chandrasekhar, S. 1943, ApJ, 97, 255

Ferrarese, L. & Merritt, D. 2000, ApJ, 539, L9

Gnedin, O. Y., Hernquist, L., & Ostriker, J. P. 1999, ApJ, 514, 109

Graham, A. W., Erwin, P., Caon, N., & Trujillo, I. 2001, ApJ, 563, L11

Kazantzidis, S., Mayer, L., Colpi, M., et al. 2005, ApJ, 623, L67

Khochfar, S. & Burkert, A. 2006, A&A, 445, 403

Kormendy, J. & Richstone, D. 1995, ARA&A, 33, 581

Li, Y., Mo, H. J., van den Bosch, F. C., & Lin, W. P. 2007, MNRAS, 379, 689

Magorrian, J., Tremaine, S., Richstone, D., et al. 1998, AJ, 115, 2285

Marconi, A. & Hunt, L. K. 2003, ApJ, 589, L21

Mayer, L., Kazantzidis, S., Madau, P., et al. 2007, Science, 316, 1874

Mo, H. J., Mao, S., & White, S. D. M. 1998, MNRAS, 295, 319

Sesana, A., Haardt, F., Madau, P., & Volonteri, M. 2005, ApJ, 623, 23

Springel, V., Di Matteo, T., & Hernquist, L. 2005, MNRAS, 361, 776

Stewart, K. R., Bullock, J. S., Wechsler, R. H., Maller, A. H., & Zentner, A. R. 2008, Merger Histories of Galaxy Halos and Implications for Disk Survival

Stinson, G., Seth, A., Katz, N., et al. 2006, MNRAS, 373, 1074

Taffoni, G., Mayer, L., Colpi, M., & Governato, F. 2003, MNRAS, 341, 434

Tremaine, S., Gebhardt, K., Bender, R., et al. 2002, ApJ, 574, 740

Wadsley, J. W., Stadel, J., & Quinn, T. 2004, New Astronomy, 9, 137

Wechsler, R. H., Bullock, J. S., Primack, J. R., Kravtsov, A. V., & Dekel, A. 2002, ApJ, 568, 52

White, S. D. M. & Rees, M. J. 1978, MNRAS, 183, 341