Multi-scale simulations of merging galaxies with supermassive black holes

Lucio Mayer\textsuperscript{1}, Stelios Kazantzidis\textsuperscript{2}, Piero Madau\textsuperscript{3}, Monica Colpi\textsuperscript{4}, Thomas Quinn\textsuperscript{5} and James Wadsley\textsuperscript{6}

\textsuperscript{1} Institute f"ur Astronomie, ETH Z"urich at H"onggerberg, 8093 Z"urich, Switzerland lucio@phys.ethz.ch
\textsuperscript{2} Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA stelios@cfcp.uchicago.edu
\textsuperscript{3} Department of Astronomy and Astrophysics, University of California, 1156 High Street, Santa Cruz, CA 95064, USA pmadau@ucolick.org
\textsuperscript{4} Dipartimento di Fisica, Universita’ Milano-Bicocca, Piazza della Scienza 3, 20126 Milano, Italy Monica.Colpi@mib.infn.it
\textsuperscript{5} Astronomy Department, University of Washington, Stevens Way, Seattle, WA 98195, USA trq@astro.washington.edu
\textsuperscript{6} Department of Physics and Astronomy, McMaster University, 1280 Main Street West, Hamilton, ON L8S 4M1 Canada wadsley@mcmaster.ca

Summary. We present the results of the first multi-scale N-Body+SPH simulations of merging galaxies containing central supermassive black holes (SMBHs) and having a spatial resolution of only a few parsecs. Strong gas inflows associated with equal-mass mergers produce non-axisymmetric nuclear disks with masses of order $10^{9} M_{\odot}$, resolved by about $10^{6}$ SPH particles. Such disks have sizes of several hundred parsecs but most of their mass is concentrated within less than 50 pc. We find that a close SMBH pair forms after the merger. The separation of the two SMBHs then shrinks further owing to dynamical friction against the predominantly gaseous background. The orbits of the SMBHs decay down to the minimum resolvable scale in a few million years for an ambient gas temperature and density typical of a region undergoing a starburst. These results suggest the initial conditions necessary for the eventual coalescence of the two holes arise naturally from the merging of two equal-mass galaxies whose structure and orbits are consistent with the predictions of the $\Lambda$CDM model. Our findings have important implications for planned gravitational wave detection experiments such as LISA.

1 Introduction

Recent observations of molecular gas in the nuclear region of candidate merger remnants such as starbursting ultraluminous infrared galaxies (ULIRGs) reveal the presence of rotating gaseous disks which contain in excess of $10^{9} M_{\odot}$ of gas within a few hundred parsecs ([3],[5]). Some of these galaxies, such as Mrk 231, also host a powerful AGN. The high central concentration of gas is likely the result of gaseous inflows driven by the prodigious tidal torques and hydrodynamical shocks occurring during the merger ([1], [7]),
and possibly provides the reservoir that fuels the SMBHs. If both the progenitor galaxies host a SMBH the two holes may sink and eventually coalesce as a result of dynamical friction against the gaseous background. The sinking of two holes with an initial separation of 400 pc in a nuclear disk described by a Mestel model has been studied by [6] and [4]. Here we avoid any assumption on the structure of the nuclear gaseous disk and initial separation of the pair; rather, we follow the entire merging process starting from when the cores of the two galaxies are hundreds of kiloparsecs apart up to the point where they merge, produce a nuclear disk, and leave a pair of SMBHs separated by the adopted force resolution of 10 pc. Previous hydrodynamical simulations of merging galaxies with SMBHs have not followed the evolution of the central region below a scale of a few hundred parsecs due to their limited mass and force resolution ([11], [7]). In this study we are able for the to extend the dynamic range of previous works by orders of magnitude using the technique of particle splitting.

2 The Numerical Simulations

Our starting point are the high-resolution simulations presented in [7] which, as the new simulations presented here, were performed with the parallel tree+SPH code GASOLINE [13]. In particular we refer to those simulations that followed the merger between two equal-mass, Milky-Way sized early type spirals having 10% of the mass of their exponential disk in a gaseous component and the rest in stars. The structural parameters of the two disks and their NFW dark matter halos, as well as their initial orbits, are motivated by the results of cosmological simulations. We apply the static splitting of SPH particles [8] to increase the gas mass resolution in such calculations (the stars and dark matter resolution remain the same), and reduce the gravitational softening accordingly as we increase the mass resolution. We select an output about 50 Myr before the merger is completed, when the cores of the two galaxies are still \( \sim 6 \) kpc away, and split each SPH particle into 8 children, reaching a mass resolution of about 3000 \( M_\odot \) in the gas component (Figure 1). The gravitational softening of the gas particles is decreased from 200 pc to either 40 pc, 10 pc, or 2 pc (one run is performed for each of the three different softenings). With the new mass resolution even for the smallest among the gravitational softenings considered the number of SPH particles within a sphere of radius equal to the local Jeans length is much larger than twice the number of SPH neighbors (=32), thus avoiding spurious fragmentation ([2]). The two SMBHs are point masses with a softening length set equal to 10 pc and a mass of \( 3 \times 10^6 M_\odot \). The simulations presented here do not include star formation but gas masses are only a factor of 3 higher than those measured in the star formation simulations of [7] at the same evolutionary stage.

We have run a suite of simulations with different prescriptions for the gas thermodynamics, and show here the results of two runs in which radiative
Multi-scale simulations of merging galaxies with supermassive black holes

Fig. 1. Color coded density map of the nuclear region 50 Myr before the merger (top panels) and just after the merger (bottom panels). The top panels show a box 30 kpc on a side (left) and a zoom-in within the inner 6 kpc (right). The bottom panels show the inner 300 pc, with the disk seen face-on (left) and edge-on (right). An adiabatic equation of state with $\gamma = 7/5$ was used in this run.

cooling and heating processes are not included directly, rather an adiabatic equation of state with either $\gamma = 7/5$ or $\gamma = 5/3$ is adopted (irreversible shock heating, which is important during the merging phase, is included via an artificial viscosity term in the energy equation). According to the radiative transfer calculations of [10] the case $\gamma = 7/5$ approximates quite well the balance between radiative heating and cooling in a starburst galaxy (in [7] a central starburst indeed does occur in the final phase of the merger that we are considering here). A stiffer equation of state such as that with $\gamma = 5/3$ might instead be relevant when an additional strong heating source, for example
AGN feedback, comes into play ([11]). Although one should follow directly the various cooling and heating mechanisms, this simple scheme can provide us with a guide of how gas thermodynamics can affect the results.

3 Results

Our simulations allow to assess in a self-consistent way the evolution of the nuclear region of a gas-rich remnant of a major merger as well as the orbital evolution of SMBHs in the nuclei of the two merging galaxies.

3.1 Gas Inflows and the Structure of the Nuclear Disks

About 80% of the gas originally belonging to the two galaxies is funneled to the central kiloparsec during the last stage of the merger and settles into two rotationally supported disks. When the cores of the two galaxies finally merge, the two disks also merge into a single gaseous core which rapidly becomes rotationally supported as radial motions are largely dissipated in shocks. The disk however remains non-axisymmetric, with evident bar-like and spiral patterns (Figure 1). A coherent thick disk forms independent of the relative inclination of the initial galactic disks, albeit the orientation of its angular momentum vector relative to the global angular momentum will change depending on those initial parameters ([7]). In the run with $\gamma = 7/5$, that was designed to reproduce the thermodynamics of a starburst region, the disk has a vertical extent of about 20 pc and $v_{\text{rot}}/\sigma > 1$ out to about 600 pc. The thickness is about 5 times higher in the run with $\gamma = 5/3$. The scale height in the $\gamma = 7/5$ run is comparable to that of the disks in the multi-phase simulations of a 1 kpc-sized nuclear region performed by [12]. The simulations of [12] include radiative cooling and resolve the turbulence generated from supernovae explosions as well as gravitational instability, suggesting that our equation of state yields a characteristic pressure scale that accounts for the combined thermal and turbulent pressures.

Gravitational torques and the balance between gravity and the thermodynamical pressure at small scales depend ultimately on the adopted gravitational softening. We verified that the mass inflow seen in the simulations for a given value of $\gamma$ converges as the softening approaches 10 pc (see Figure 2). Convergence in the disk vertical extent is also observed at such a spatial resolution. Figure 2 shows that at high resolution more than 60% of the mass piles up within as little as 30 pc.

3.2 Pairing of SMBHs

The merger between the two galactic cores delivers a close but unbound pair of SMBHs. The pair is separated by about 100 pc and is embedded within
the newly formed nuclear gaseous disk. Up to this point the orbital decay of the two SMBHs had been equivalent to that of the cores in which they were embedded, and was driven by dynamical friction of the cores within the surrounding collisionless background of stars and dark matter. Once inside the massive gaseous disk the orbital decay of the two holes is dominated by dynamical friction in a gaseous background ([9]). The intensity of the drag is then higher or lower depending on whether the black holes move supersonically or subsonically with respect to the background, and increases also as the characteristic density of the background increases. The run with $\gamma = 7/5$ falls in the supersonic regime (the orbital velocity of the black holes is of order 300 km/s, which corresponds to a temperature of about $10^6$ K), while the black holes move slightly subsonically in the run with $\gamma = 5/3$. In the latter run the average background density is also a factor $\sim 2$ lower compared to the run with $\gamma = 7/5$. These differences in the thermal and density structure of the remnants explain why in the run with $\gamma = 7/5$ the two black holes reach a separation comparable to the force resolution limit.
(10 pc) in about 10 Myr whereas they remain separated by a distance larger than 100 pc in the other run (Figure 3). In neither case the SMBHs form a binary by the end of the simulation. However, with an even higher force resolution the formation of a bound pair is likely in the $\gamma = 7/5$ since the orbital energy of the binary is only marginally positive at $t = 5.128$ Gyr. Instead in the simulation with $\gamma = 5/3$ the binding of the two SMBHs will be aborted because their orbital decay time is longer than the Hubble time on the last few orbits.

As shown in Figure 3 the two black holes end up on moderately eccentric orbits ($e = 0.3 - 0.5$) in all the simulations. However the orbits might circularize as the evolution proceeds further ([4], and these proceedings).
4 Conclusions

We have performed multi-scale hydrodynamical simulations of merging galaxies with SMBHs and shown that dense, rotationally supported nuclear disks are the natural outcome of dissipative mergers starting from cosmologically motivated initial conditions. The nuclear disks reported here likely provide the reservoir of gas that fuels the central SMBHs. The orbital evolution of the close pair of SMBHs formed at the center of the merger remnant is dominated by dynamical friction against the surrounding gaseous medium. The details of this process are extremely sensitive to thermodynamics of the gas. Our results indicate that the formation of a bound SMBH pair requires an equation of state not stiffer than that expected during a major starburst. This suggests that either AGN feedback has a minor impact on the gas in the disk or that strong AGN feedback has to be delayed for several million years after the galaxy merger is completed. In the second case the coalescence of the two black holes will occur when the merger remnant is a powerful starburst, such as a ULRIG, rather than a powerful AGN.

Acknowledgements

SK is supported by the Swiss National Science Foundation and by The Kavli Institute for Cosmological Physics (KICP) at The University of Chicago. We thank David Merritt for helpful comments. The simulations were performed on Lemieux at the Pittsburgh Supercomputing Center and on the Zbox and Zbox2 supercomputers at the University of Zürich.

References

1. Barnes, J., & Hernquist, L.: ApJ 471, 115 (1996)
2. Bate, M., & Burkert, A.: MNRAS 288, 1060 (1997)
3. Davies, R.I., Tacconi, L.J., & Genzel, R.: ApJ 613, 781 (2004)
4. Dotti, M., Colpi M., & Haardt F.: to appear on MNRAS
5. Downes D., & Solomon, P.M.: ApJ 507, 615 (1998)
6. Escala A., Larson, R.B., Coppi, P.S., & Mardones, D.: ApJ 630, 152 (2005)
7. Kazantzidis, S., Mayer. L., Colpi, M., Madau, P., Debattista, V., Quinn, T.,
   Wadsley, J., & Moore, B.: ApJ 623, L67 (2005)
8. Kitsionas, S., & Whitworth, S.: MNRAS 330, 129 (2002)
9. Ostriker, E.: ApJ 513, 252 (1999)
10. Spaans, M., & Silk: MNRAS 538, 115 (2000)
11. Springel, V., Di Matteo, T., & Hernquist, L.: MNRAS 361, 776 (2005)
12. Wada, K., & Norman, C.: ApJ 566, L21 (2002)
13. Wadsley, J., Stadel, J., & Quinn, T: New Astronomy 9, 137 (2004)