Massive black hole binary evolution in gas-rich mergers

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Received 26 November 2008, in final form 18 March 2009
Published 20 April 2009
Online at stacks.iop.org/CQG/26/094029

Abstract

We report on key studies on the dynamics of black holes (BHs) in gas-rich galaxy mergers that underscore the vital role played by gas dissipation in promoting BH inspirals down to the smallest scales ever probed with the use of high-resolution numerical simulations. In major mergers, the BHs sink rapidly under the action of gas-dynamical friction while orbiting inside the massive nuclear disc resulting from the merger. The BHs then bind and form a Keplerian binary on a scale of $\lesssim 5$ pc. In minor mergers, BH pairing proceeds down to the minimum scale explored of 10–100 pc only when the gas fraction in the less massive galaxy is comparatively large to avoid its tidal and/or ram pressure disruption and the wandering of the light BH in the periphery of the main halo. Binary BHs enter the gravitational wave dominated inspiral only when their relative distance is typically of $\sim 10^{-3}$ pc. If the gas preserves the degree of dissipation expected in a star-burst environment, binary decay continues down to 0.1 pc, the smallest length scale ever attained. Stalling versus hardening below $\lesssim 0.1$ pc is still matter of deep investigations, and there is no unique answer depending on the yet unexplored dynamics of gas in the vicinity of the binary.

PACS numbers: 04.70.−s, 04.30.−Db

1. Introduction

Dormant black holes (BHs) with masses in excess of $\gtrsim 10^6 M_\odot$ are found to be ubiquitous in bright spheroids, today [1, 2]. This local population comprises the dead remnants of a bright past, when the same BHs were powering the most luminous quasars. The recent discovery of scale relations between the BH mass and the properties of the stellar bulge [3], likely
set via AGN feedback, has prompted the study of BH growth and evolution in the general framework of galaxy evolution. According to the current $\Lambda$CDM paradigm for structure formation, galaxies interact and merge as their dark matter halos assemble in a hierarchical fashion [4], and BHs incorporated through mergers into larger and more massive systems evolve concordantly: major central gas inflows are triggered during the violence of a merger that feed the BH and power AGN activity [5]. In this context, close BH pairs form as inescapable outcome of galaxy evolution [6]. In our local universe, NGC 6240 and Mrk 463 provide compelling evidence of ongoing gas-rich mergers where two active nuclei are present, still at large separations of $\sim$ kpc. Whether these BHs will spiral inward, form a BH binary and coalesce under the emission of gravitational waves is a matter of our concern. The Laser Interferometer Space Antenna (LISA) is expected to record these extraordinary events out to redshift $z \sim 20$ providing not only a firm test of general relativity, but also a view, albeit indirect, of galaxy clustering together with an extremely accurate measure of the BH mass and spin [7–9].

Galaxy mergers cover cosmological volumes (of hundred kpc aside) whereas BH coalescences probe volumes from a few parsecs (when they bind in nuclear discs) down to an astronomical unit and less. Thus, following a merger, how can BHs reach the gravitational wave inspiral regime? Our aim is at studying the BH dynamics in gas-rich environments, and in particular, the transit from the state P of pairing when each BH moves individually inside the time-varying potential of the colliding galaxies, to state B when the two BHs dynamically couple their motion to form a binary. After all transient inflows have subsided and the new galaxy has formed, the BH binary, surrounded by a massive circum-nuclear disc, enters phase H where it hardens to smaller separations under the action of gas-dynamical and gravitational torques, ideally down to $\sim 10^{-3}$ pc (for typical BH mass of $10^6 M_\odot$) where the gravitational wave domain G starts. There is a number of key questions to address: (i) how does transition from state P $\rightarrow$ B depend on the gas thermodynamics and level of dissipation? (ii) In the grand nuclear disc inside the remnant galaxy, how do orbits evolve? (iii) Do the BHs reach the gravitational wave driven domain? (iv) During the hardening through phase B $\rightarrow$ H, do the BHs collect substantial amounts of gas to form cold individual discs?

2. Pairing of massive black holes in gas-rich mergers

There are two types of mergers: major mergers between galaxies of comparable mass ratios (1:1 mass ratio) and minor mergers between galaxies with smaller mass ratios (1:10 typically).

Major mergers have been studied with N-body/SPH simulations with unprecedented force resolution (down to $\sim 1$ pc using splitting techniques and GASOLINE as integrator; see [10]) to describe the collision of two galaxies similar to the Milky Way. Each galaxy comprises a central BH of $2.6 \times 10^6 M_\odot$, a stellar bulge, a disc of stars and gas (with mass fraction of 10% relative to the total disc mass) and an extended spherical dark matter halo (of $10^{12} M_\odot$) with NFW density profile (see [10] for details).

The galaxies first experience two close fly-bys: in this early phase, the cuspy potentials of both galaxies are deep enough to allow for the survival of their baryonic cores that sink under the action of dynamical friction against the dark matter background, dragging together the two BHs. Strong spiral patterns appear in both the stellar and gaseous discs, and as the merger continues, non-axisymmetric torques redistribute angular momentum: as much as 60% of the gas originally present in each disc of the parent galaxies is funneled inside the inner few hundred parsecs of the individual cores. This is illustrated in the upper right panel of figure 1, where the enlarged color coded density map of the gas is shown, after 5.1 Gyr from the onset of the collision. Each BH is surrounded by a rotating stellar and gaseous disc of
The different stages of the merger between two identical disc galaxies seen face-on. The color-coded density maps of the gas component are shown using a logarithmic scale, with brighter colors for higher densities. The four panels to the left show the large-scale evolution at different times (obtained with a force resolution of 100 pc). The boxes are 120 kpc on a side (top) and 60 kpc on a side (bottom) and the density ranges between $10^{-2}$ atoms cm$^{-3}$ and $10^2$ atoms cm$^{-3}$. During the interaction, tidal forces tear the galactic discs apart, generating spectacular tidal tails and plumes. The upper panel to the right shows a zoom in view of the two discs before they merge into a single rotating nuclear gaseous disc embedded in a series of large-scale ring-like structures (middle panel). The boxes are now 8 kpc on a side and the density ranges between $10^{-2}$ atoms cm$^{-3}$ and $10^5$ atoms cm$^{-3}$. The two bottom panels, with a gray color scale, show the detail of the inner 160 pc of the middle panel (here the force resolution is 2 pc); the nuclear disc is shown edge-on (left) and face-on (right), and the two BHs are also shown in the face-on image.

mass $\sim 4 \times 10^8$ $M_\odot$ and size of a few hundred parsecs. The two discs and BHs are just 6 kpc far apart, and at the same time a star burst of $\sim 30$ $M_\odot$ yr$^{-1}$ has invested the central region of the ongoing merger.

At this stage, the simulation is stopped and restarts with increased resolution (of $\sim 2$ pc). In order to simulate the environment of a star burst where cool gas coexists with the warm phase heated by stellar feedback, the pressure is set equal to $P = (\gamma - 1)\rho u$ with $\gamma = 7/5$ (according to fits by [11]). The internal energy per particle $u$ evolves with time as a result of $PdV$ work and shock heating modeled via the standard Monaghan artificial viscosity term.

With time, the two baryonic discs get closer and closer and eventually merge into a single massive self-gravitating, rotationally supported nuclear disc, now weighing $3 \times 10^9$ $M_\odot$. This is illustrated again in figure 1 (mid and bottom right panels). The gaseous disc, dominant in mass, is surrounded by a background of dark matter and stars distributed in a spheroid.
Figure 2. Orbital separation of the two BHs as a function of time during the last stage of the galaxy merger. The orbit of the pair is eccentric until the end of the simulation. The two peaks at scales of tens of parsecs at around $t = 5.1213$ Gyr mark the end of the phase during which the two holes are still embedded in two distinct gaseous cores. Until this point the orbit is the result of the relative motion of the cores combined with the relative motion of each BH relative to the surrounding core, explaining the presence of more than one orbital frequency. The inset shows the details of the last part of the orbital evolution, which takes place in the nuclear disc arising from the merger of the two cores. The binary stops shrinking when the separation approaches the force resolution limit (2 pc).

The BHs have been dragged together toward the dynamical center of the merging galaxies, and move inside the grand disc spiraling inward under the action of gas-dynamical friction. In less than a million years after the merger, they eventually bind gravitationally to each other, as the mass of the gas enclosed within their separation is less than the mass of the binary. It is the gas that controls the orbital decay, not the stars. The transition between state P to B is now completed as illustrated in figure 2. Dynamical friction against the stellar background would bring the two BHs this close only on a longer timescale, $\sim 10^8$ yr [10]. This short sinking timescale comes from the combination of the fact that gas densities are much higher than stellar densities in the center, and that in the mildly supersonic regime the drag against a gaseous background is stronger than that in a stellar background with the same density [12]. It is worth noticing that the transition $P \rightarrow B$ is sensitive to the gas thermodynamics: BH coupling is delayed if gas were to follow thermal evolution with a $\gamma = 5/3$ [10].

Does BH pairing proceed similarly, in minor mergers predicted to be common events in the high redshift universe [8] and of primary importance for LISA [9]? To answer this question we extended our numerical investigation to 1:4 mergers at $z = 0$, and 1:10 mergers at $z = 3$, assuming a roughly constant $M_{\text{BH}} - M_{\text{bulge}}$ relation in between these cosmic epochs, and initial galaxy models replica of a Milky Way suitably rescaled in mass and size (see for details [13]). The masses of the two BHs in the $z = 3$ runs are thus $6 \times 10^5$ and $6 \times 10^4 M_\odot$, and their expected inspiral and coalescence signal falls nicely in the LISA sensitivity window [9].

It is found that minor mergers differ profoundly from major mergers as early noticed by [14]. The encounter is closer to an accretion process whereby the less massive galaxy is
Figure 3. BH separation as a function of time in four of our simulations. Upper row: BH distance in 1:4 mergers (for galaxy models at $z = 0$); the thin and thick lines refer to simulations with no-gas and with gas ($f_{\text{gas}} = 0.1\%$), respectively. Lower row: BH distance for the 1:10 mergers (for galaxy models at $z = 3$); the thin and thick lines refer to simulations with no-gas and with gas ($f_{\text{gas}} = 0.3\%$), respectively. The insets show the color-coded density maps of stars (left) and gas (right), 4 kpc on a side. The large dot on the BH curve indicates the time at which the two snapshots are recorded. Colors code the range $10^{-2} - 1 M_{\odot} \text{pc}^{-3}$ for stars, and $10^{-3} - 0.1 M_{\odot} \text{pc}^{-3}$ for the gas. These snapshots are representative of the average behavior of the satellites during the first two orbits. Note the formation of a strong bar for the 1:4 minor merger, which is absent for the 1:10 case, and the truncation of the gaseous disc in the 1:10 satellite caused by ram pressure stripping.

dramatically damaged during its sinking into the primary. In our recent study [13], pairing is found to be very sensitive to the details of the physical processes involved. In all cases with no-gas (i.e., in ‘dry’ runs) the formation of a close BH pair is aborted: tidal shocks progressively lower the density in the satellite until it dissolves, leaving a wandering black hole in the remnant. This is illustrated in figure 3 (thin lines) where the BH relative distance remains as large as 1–10 kpc. Only with the inclusion of a cold gaseous disc component and star formation the outcome of the merger changes significantly.

Figure 3 depicts the stellar and gaseous components of the satellite to show their profound structural damage (the primary is not shown). For mass ratios 1:4 at $z = 0$, bar instabilities excited at pericentric passages funnel gas (present in a fraction $f_{\text{gas}}$ of the total disc mass) to the center of the satellite, steepening its potential well and allowing its survival against tidal disruption down to the center of the merger remnant. As shown in figure 3 (thick lines), the BHs pair down to $\sim 100$ pc scales (the force resolution limit), creating conditions favorable to the formation of a BH binary. The smaller satellites (with 1:10 mass ratio at $z = 3$) are more strongly affected by both internal star formation and the gas–dynamical interaction between their interstellar medium and 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 interstellar medium of the satellite. Only the gas-rich satellites (those with $f_{\text{gas}} = 0.3$) undergo a central burst of star formation during the first orbits which increases their central stellar density allowing for their survival. In these models, pairing of the two BHs via dynamical friction occurs down to $\sim 100$ pc, a few Gyr after the disruption of the satellite (see figure 3).

3. Black hole binaries in massive nuclear discs

As shown in section 2, massive circum-nuclear discs form in the aftermath of a major gas-rich merger. It is in these discs that the BHs complete their transition from $P \rightarrow B$, and continue to spiral inward under the action of gas–dynamical torques from $B \rightarrow H$ [16–18]. A still open issue is whether the BHs will reach the domain of gravitational waves inspiral within a Hubble time: for a $10^6 M_\odot$ BH binary on a circular orbit, the transition $H \rightarrow G$ occurs when the separation is around $10^{-3}$ pc. Can material and gravitational torques be effective in driving the BHs down to this tiny scale?

Here we describe our attempts to explore the transition from $P \rightarrow B \rightarrow H$, for BHs orbiting inside a circum-nuclear disc using GADGET as N-Body/SPH code with a force resolution of only $\approx 0.1$ pc, and no splitting during the entire course of the evolution [15]. In our selected model, a BH (called primary) is set at the center of a massive differentially rotating gaseous disc in equilibrium with a stellar bulge (see [17, 18] for details). A second BH (called secondary) with similar/equal mass is delivered at a large distance ($\sim 50$ pc) from the center, along a coplanar eccentric ($e = 0.7$) orbit that can either be co- or counter-rotating relative to the background disc. The $10^6$ SPH particles, making the disc, evolve as in [10]: accordingly,
the gas thermodynamics is described by the index $\gamma = 7/5$ that accounts for the presence of net cooling in a star-forming region. Shocks here are less important as the equilibrium disc is only mildly perturbed by the BHs. Figure 4 shows the BH separation as a function of time for the co-rotating and counter-rotating cases. No stalling is observed in both cases, as the relative BH distance decays rapidly (in $\lesssim 20$ Myr) down to the force resolution length scale. In the final stages, the more rapid orbital decay is due to the torque exerted by the ellipsoidal deformation that forms in the gas when the heads of the density wakes overlap and whose axis is misaligned relative to the BH binary axis [16].

In the counter-rotating case, the angular momentum of the secondary BH (initially negative) grows very efficiently during the first Myr, when the BH is passing through the central, high density region of the disc. Angular momentum continues to grow monotonically for the next 3–4 Myr, then becomes positive, i.e. the BH starts to move on a co-rotating orbit with respect to the disc. This is illustrated in figure 5. It is dynamical friction that causes this orbital ‘angular momentum flip’. In both cases the eccentricity of the orbit decreases to very small values (also in the counter-rotating case, after the orbit becomes co-rotating) due to the different response of the fluid to the gravitational pull of the BH at the different orbital phases. When at pericenter the BH moves faster than the gas and it is decelerated by the density wake excited behind its trail; when at apocenter the BH is moving more slowly than the gas and the wake is trailing in front causing a tangential acceleration. The composite effect is a decrease of $e$.

In a suite of runs, the BHs have been modeled as ‘sink particles’, i.e. they are allowed to accrete gas particles during their dynamical evolution [15]. We introduced an ‘on flight’ algorithm for accretion and determined the amount of gas that binds to the BHs. It is only when the BH binary circularizes that gas is accreted to such an extent that both BHs are surrounded by their own accretion disc, and these discs are expected to play a role in guiding the subsequent hardening phase down to the gravitational domain.
4. Open issues

Numerical simulations, carried on with unprecedented accuracy, have revealed that the transit of dual BHs from \( P \rightarrow B \rightarrow H \), and finally from \( H \rightarrow G \) is a sensitive function of the merger type and of amount of cold gas present in the interacting galaxies. While the transition from \( P \) (pairing) \( \rightarrow B \) (binary formation) appears to be likely in gas-rich major mergers as well as in gas-rich minor mergers at high redshift, hardening down to the gravitational wave domain remains still uncertain on scales below \( \sim 0.1 \) pc and not fully explored. It has been suggested that a circum-binary viscous disc inevitably forms around the BH binary on sub-parsec scales that absorbs the angular momentum of the binary [19]. This circum-binary disc would represent the last cold environment for BH hardening from \( H \rightarrow G \). Braking of the BH rapid motion requires energy loss and angular momentum transport through a mechanism that is reminiscent of planet migration in proto-stellar discs [19, 20]: while tidal torques from the BH binary carry away orbital angular momentum, viscous torques inside the disc sustain the radial motion of the gas toward the BHs, maintaining the binary in near contact with the disc. Equilibrium between these two torques would cause the slow drift of the BHs toward smaller and smaller separations, until gravitational waves guide the final inspiral. No calculation has reproduced yet the formation of a circum-binary disc from the earlier phase, in a self-consistent manner, nor it is clear how fast will be the inspiral, and how large the growth of the eccentricity [21]. The BH binary likely enters phase \( G \) with a residual eccentricity still imprinted in the gravitational wave signal, despite the circularizing action of the gravitational wave back reaction. \textit{LISA} is expected to be launched by 2020. By that time, our theoretical understanding of binary hardening in a gas-rich environment will hopefully improve thanks to the progress expected in numerical simulations, and in our ability to model fragmentation, star formation and feedback, inside galactic nuclei.

Acknowledgments

We thank all collaborators that made this research possible: F Governato, S Kazantzidis, F Haardt, P Madau, B Moore, L Paredi, J Wadsley, M Ruszkowski, J Stadel, T Quinn and M Volonteri.

References

[1] Kormendy J and Richstone D 1995 \textit{Annu. Rev. Astron. Astrophys.} \textbf{33} 581

[2] Richstone D \textit{et al} 1998 \textit{Nature} \textbf{395} A14

[3] Ferrarese L and Ford H 2005 \textit{Space Sci. Rev.} \textbf{116} 523–624 (arXiv:astro-ph/0411247)

[4] Springel V, Frenk C S and White S D M 2006 \textit{Nature} \textbf{440} 1137–44

[5] Hopkins P F, Hernquist L, Cox T J and Kereš D 2008 \textit{Astrophys. J. Suppl. Ser.} \textbf{175} 356–89 (arXiv:0706.1243)

[6] Kazantzidis S, Mayer L, Colpi M, Madau P, Debattista V P, Wadsley J, Stadel J, Quinn T and Moore B 2005 \textit{Astrophys. J. Lett.} \textbf{623} L67–L70

[7] Vecchio A 2004 \textit{Phys. Rev. D} \textbf{70} 042001

[8] Volonteri M, Haardt F and Madau P 2003 \textit{Astrophys. J.} \textbf{582} 559–73

[9] Sesana A, Haardt F, Madau P and Volonteri M 2005 \textit{Astrophys. J.} \textbf{623} 23–30

[10] Mayer L, Kazantzidis S, Madau P, Colpi M, Quinn T and Wadsley J 2007 \textit{Science} \textbf{316} 1874

[11] Spaans M and Silk J 2000 \textit{Astrophys. J.} \textbf{538} 115–20 (arXiv:astro-ph/0002483)

[12] Ostriker E C 1999 \textit{Astrophys. J.} \textbf{513} 252–8 (arXiv:astro-ph/9810324)

[13] Callegari S, Mayer L, Kazantzidis S, Colpi M, Governato F, Quinn T and Wadsley J 2008 \textit{arXiv}:0811.0615

[14] Governato F, Colpi M and Maraschi L 1994 \textit{Mon. Not. R. Astron. Soc.} \textbf{271} 317

[15] Dotti M, Ruszkowski M, Paredi L, Colpi M, Volonteri M and Haardt F 2009 \textit{arXiv}:0902.1525

[16] Escala A, Larson R B, Coppi P S and Mardones D 2005 \textit{Astrophys. J.} \textbf{630} 152–66

[17] Dotti M, Colpi M and Haardt F 2006 \textit{Mon. Not. R. Astron. Soc.} \textbf{367} 103–12
[18] Dotti M, Colpi M, Haardt F and Mayer L 2007 Mon. Not. R. Astron. Soc. 379 956–62
[19] Cuadra J, Armitage P J, Alexander R D and Begelman M C 2008 arXiv:0809.0311
[20] Gould A and Rix H W 2000 Astrophys. J. Lett. 532 L29–L32
[21] Armitage P J and Natarajan P 2002 Astrophys. J. Lett. 567 L9–L12 (arXiv:astro-ph/0201318)
[22] Dotti M et al in preparation