Massive black hole and gas dynamics in mergers of galaxy nuclei. II. Black hole sinking in star–forming nuclear discs.

Alessandro Lupi¹, Francesco Haardt¹,², Massimo Dotti²,³ & Monica Colpi²,³.

¹DiSAT, Università degli Studi dell’Insubria, Via Valleggio 11, I-22100 Como, Italy
²INFN, Sezione di Milano-Bicocca, Piazza della Scienza 3, I-20126 Milano, Italy
³Dipartimento di Fisica, Università degli Studi di Milano-Bicocca, Piazza della Scienza 3, Milano I-20126, Italy

ABSTRACT

Mergers of gas–rich galaxies are key events in the hierarchical built–up of cosmic structures, and can lead to the formation of massive black hole binaries. By means of high–resolution hydrodynamical simulations we consider the late stages of a gas–rich major merger, detailing the dynamics of two circumnuclear discs, and of the hosted massive black holes during their pairing phase. During the merger gas clumps with masses of a fraction of the black hole mass form because of fragmentation. Such high–density gas is very effective in forming stars, and the most massive clumps can substantially perturb the black hole orbits. After \( \sim 10 \) Myr from the start of the merger a gravitationally bound black hole binary forms at a separation of a few parsecs, and soon after, the separation falls below our resolution limit of 0.39 pc. At the time of binary formation the original discs are almost completely disrupted because of SNe feedback, while on pc scales the residual gas settles in a circumbinary disc with mass \( \sim 10^5 M_\odot \). We also test that binary dynamics is robust against the details of the SNe feedback employed in the simulations, while gas dynamics is not. We finally highlight the importance of the SNe time–scale on our results.

Key words: black hole physics - hydrodynamics - galaxies: formation - galaxies: evolution - galaxies: nuclei

1 INTRODUCTION

Understanding the black hole binary formation path in galaxy’s mergers is a key step towards understanding the mode of assembly of massive black holes (MBHs) across cosmic history (Di Matteo, Springel & Hernquist 2005; Sesana et al. 2014; Dubois, Volonteri & Silk 2014). The masses and spins of MBHs are sculpted by complex processes that involve episodes of accretion and mergers, during the hierarchical growth of structures. The coalescence in a single, more massive BH (induced by gravitational wave emission) is expected to occur whenever the two MBHs present in each of the interacting galaxies reach sub–parsec separation under the action of stellar and gas torques (Amaro-Seoane et al. 2013).

The dynamics of MBHs is complex as it occurs in the time–varying environment of a galaxy merger where stars, and cool gas, turning into new stars, evolve on comparable time–scales (see Colpi 2014 for a review), and is customarily described as a three–step process: (I) pairing during the merger of the galaxies embedded in their dark matter haloes, resulting in the formation of a Keplerian binary, (II) migration by gas or/and hardening by stars, and lastly (III) gravitational wave driven inspiral.

The seminal paper by Begelman, Blandford & Rees (1980) showed that in an already established spherical galaxy remnant devoid of gas, the fastest of these three phases is that of pairing under the action of dynamical friction against stars. The MBHs are driven down to parsec separations and form a Keplerian binary, when the stellar mass enclosed in their orbit drops below their mass. Begelman, Blandford & Rees (1980) further noticed that hardening of the binary by encounters with individual stars in phase (II) is the most critical and long–lived phase, representing a bottleneck to the path to coalescence, at least for MBHs with masses larger than \( \sim 2 \times 10^6 M_\odot \) (see e.g. Merritt & Milosavljevic 2005; Merritt, Mikkola & Szell 2007). The so–called last parsec problem for the most massive MBHs has been recently alleviated after considering more realistic galaxy’s background (Begelman, Blandford & Rees 1980) mention

¹ We will not consider here MBH pairing in pure stellar environments and refer to Pretor et al. (2011), Khan et al. (2013), Vasiliev, Antonini & Merritt (2014, 2015) and Sesana & Khan (2015) for recent findings.
on the possibility that gas can accelerate the orbital decay. In this case, torques from gas distributed around the binary in the form of a circumbinary disc are central for driving the binary down to coalescence but they depend on how massive and long-lived are these discs and little is known about their formation, structure and lifetime in the relic galaxy (Cuadra et al. 2009; Roedig et al. 2011, 2012; del Valle & Escala 2012).

Thanks to major advances in numerical computing, a number of studies have begun tracing phase (I) of MBH pairing in the very early stages of a merger when the two dark matter haloes first touch, and later when the galactic discs (stellar and gaseous) and bulges interact to drive and terminate the morphological transformation of the galaxies (Mayer et al. 2007; Roskar et al. 2015). A leap in understanding the role of gas during the pairing phase was taken when studying minor mergers, i.e. mergers with nominal 1:4 mass ratios and less. It was demonstrated that thanks to its dissipative action, gas deepens the gravitational potential of the less massive galaxy reducing the action of tides by the primary (Kazantzidis et al. 2003). This prevents the wandering to the lighter MBH in the periphery of the primary when sufficient gas is present in the host galaxy, raising the question as to whether minor mergers lead in general to binary formation (Callegari et al. 2009, 2011). Follow-up studies have indicated that the dividing line from success and failure in forming an MBH binary (MBHB hereon) is around 1:10 mass ratios (Bellovary et al. 2010; Van Wassenhove et al. 2012), but still depends on details such as the encounter geometry and gas content.

Major mergers among gas-rich galaxies represent a natural path for MBH pairing and binary formation. The orbital braking is in these cases driven by gas-dynamical friction which is faster than dynamical friction from stars (Escala et al. 2005; Dotti, Colpi & Haardt 2006; Mayer et al. 2007; Chapon, Mayer & Teyssier 2013). Massive inflows of gas during the merger lead to the formation of a circumnuclear disc comprising most of the gas initially hosted in the individual discs. It is in this new disc that the two MBH sink forming a Keplerian system down to pc scale on a time.

2 Noticeably, the pairing of the MBHB in this last study has been followed using a high accuracy direct N-body code to evolve the distribution of stars previously obtained from an SPH run.
background of a merger itself, but also on how fragmentation of gas clouds, star formation and supernova (SNa) feedback shape and change the thermodynamical state of the gas, considered to play a key role in guiding the orbital decay of the MBH. The mass distribution of the star–forming clumps appears to be a relevant parameter which affects the degree of stochastic forcing of the MBH orbit and the distribution of the sinking times from ~ 100 pc scale down to 0.1 pc.

In this paper we simulate the evolution of two gaseous discs [type (b)] and of their embedded black holes in the aim at studying the MBH dynamics within a multiphase gas shaped by cooling, star formation and SNa feedback, using the adaptive mesh refinement code (AMR) RAMSES (Teyssier 2002) modified to accurately track the MBH dynamics as presented in Lupi, Haardt & Dotti (2015). AMR codes like RAMSES are known to better resolve gas shocks with respect to SPH codes (Agertz et al. 2007), thus allowing a more accurate description of the gas dynamics when the two gaseous discs collide. A key question to pose is: in a star–forming medium what is the role of SNa feedback in shaping the gas mass distribution around the MBHs? The transit from the binary phase II to phase III of gravitational wave inspiral depends on the strength of gas–driven migration in a circumbinary disc surrounding the MBH binary (Cuadra et al. 2009; Shi et al. 2012; Roedig et al. 2011, 2012; del Valle & Escala 2012). Here we first attempt to explore under which conditions a circumbinary disc forms around the two MBHs and how this depends on the recipes adopted to model the physics of star–forming regions.

The paper is organised as follows. In Section 2 we describe the numerical setup used to simulate the massive gas discs embedded in a stellar bulge and the recipes introduced to model star formation and SNa feedback. In Section 3 we present the results focusing on both the MBH dynamics and the properties of the multiphase gas surrounding the MBH binary. Section 4 contains our conclusions.

2 NUMERICAL SETUP AND INITIAL CONDITIONS

We consider the late stages of a galaxy gas rich merger, in which both galaxies host an MBH surrounded by a circumnuclear disc. Full details of the initial conditions can be found in Paper I. Here we simply summarise the basic features.

We initially set each of the two merging nuclei in dynamical equilibrium, assuming they are constituted by three different components:

- a stellar spherical structure (termed ‘nucleus’ hereafter) described by an Hernquist profile (Hernquist 1990), defined in spherical coordinates as

\[
\rho_b(r) = \frac{M_b}{2\pi} \frac{a}{(r + a)^2},
\]

where \(\rho_b(r)\) is the density as a function of radius \(r\), \(M_b = 2 \times 10^8 M_\odot\) the total nucleus mass, and \(a = 100\) pc the nucleus scale radius containing 1/4 of \(M_b\);

- an exponential gaseous disc with surface density profile defined (in cylindrical coordinates) as

\[
\Sigma_d(R) = \frac{M_d}{2\pi R_d^2} \exp(-R/R_d),
\]

where \(R\) is the disc radius, \(R_d = 50\) pc the disc scale radius containing 0.26 of the total disc mass \(M_d = 10^4 M_\odot\);

- an MBH with mass \(M_{\text{BH}} = 10^7 M_\odot\), at rest in the centre of the disc.

We build the two equal mass corotating gaseous discs, each described by \(10^6\) particles, by means of the publicly available code GD_Basic (see Lupi, Haardt & Dotti 2015 for the algorithm description) and we relaxed them for about 10 Myr to ensure stability. The discs are initially set at 300 pc on an elliptical orbit with eccentricity \(e = 0.3\), and with orbital angular momentum antiparallel to the angular momentum of the discs. We stress that each galaxy disc plane is in principle uncorrelated to the orbital plane of the merger, and, to the first order, the same is valid for the CNDs.\(^3\) We arbitrarily chose the geometry that maximises the impact of the two discs along their orbit and that ensures the highest cancellation of angular momentum, enhancing the inflows towards the centremost regions. Such a geometry has not been explored in the literature yet. The initial conditions for the AMR runs are obtained by mapping the gas particle distribution on the grid using the publicly available code TipGrid.\(^4\)

We perform a total of six simulations using the AMR code RAMSES (Teyssier 2002), where we change the prescriptions regarding gas cooling, stellar mass formation (SF) and SNa feedback to survey how the implementation of sub-grid physics affects the evolution of the system. The gas has primordial composition, it is optically thin and cools down under lines and continuum emission. The maximum spatial resolution (at the highest refinement level) for all our simulations is \(\sim 0.39\) pc and the mass resolution for particles forming the stabilising stellar nucleus is \(2 \times 10^3 M_\odot\). The Jeans length is always resolved with at least 4 cells (14 in the highest refinement level) and we also add a pressure support term, modelled as a polytrope with \(\gamma = 5/3\) and temperature \(2 \times 10^4 K\) at the star formation threshold, in order to avoid the formation of spurious clumps due to resolution limits.

In order to achieve the best possible treatment of MBH dynamics, we adopt the additional refinement criterion described in Lupi, Haardt & Dotti (2015). We allow stellar particle creation when gas matches two criteria: (i) the gas temperature drops below \(2 \times 10^4\) K, and (ii), the gas density in a cell exceeds a pre-defined value. We assume two different fiducial values for the SF density threshold, i.e., \(n_{\text{H}_2} = 2 \times 10^5\) and \(n_{\text{H}} = 2 \times 10^6\) cm\(^{-3}\), where \(n_{\text{H}_2}\) is the local hydrogen number density, and a typical SF time–scale of 1.0 Myr. The resulting average mass of stellar particles is of \(\sim 300 M_\odot\). Such value is significantly more massive than, e.g., what employed in Amaro-Seoane, Brem & Cuadra (2013), who however simulated a lighter and more compact system. We checked that our prescription results in a gas–to–stellar mass conversion rate not lower than the local Kennicutt–Schmidt law.

\(^3\) Here we are neglecting the possible tidal effect exerted by one disc on to the other. This effect would tend to align (or antialign) the two discs, enhancing the chances of having an orientation between the two CNDs similar to the one we assumed as initial conditions.

\(^4\) The code is available at http://www.astrosim.net/code/doku.php?id=home:code:analysistools:misctools
In order to model SNe explosions, we consider each stellar particle as a stellar population following a Salpeter IMF, and a SNe yield of 15%. We further employ two different recipes for the SNe thermal feedback. In both SNe feedback recipes the energy budget associated ($10^{50}$ erg/$\text{M}_\odot$) is completely released in the parent cell as purely thermal energy. The first criterion (termed ‘ThFB’ after thermal feedback) assumes that the heated gas starts cooling right after the SNe event; the second criterion (termed ‘BWFB’ after blast wave feedback) assumes instead that the energy released by SNe is decoupled from the gas radiative cooling, i.e., it is not radiated away for $\sim\! 20$ Myr (Teyssier et al. 2013) and this triggers the formation of a momentum–driven blast wave. This latter scheme is aimed at modelling non–thermal processes energising the blast wave, which are characterised by time–scales longer than thermal processes (see e.g. Enßlin et al. 2007). We usually assume that no star formation occurs within the two discs before the merger, and that SNe explode after a time $\Delta t_{\text{SN}} = 10$ Myr. Stellar mass particles forming the stabilising bulge are not allowed to release energy as SNe.

We run two further simulations at the highest density threshold for star formation (termed ‘ThFBh’ and ‘BWFBh’) assuming no time–lag between star formation and SNe explosion. The aim of these runs is to test the effects on the global (gas and BHs) dynamics of a maximally fast SN feedback, comparing the results to the standard $\Delta t_{\text{SN}} = 10$ Myr case. While simulations with standard delay are meant to model star formation as triggered by the merger of the two circumnuclear discs, the 0–lag case may represent a situation where sustained star formation is already in progress at the time of the merger.

Finally, in order to avoid inaccurate integration of the orbits, all runs are stopped when the MBH separation is approximatively three to four times the cell length. Table 1 summarises our six simulations with the parameter used.

| Run            | $\nu_H$ $(\text{cm}^{-3})$ | $\Delta t_{\text{SN}}$ (Myr) | Feedback     |
|----------------|-----------------------------|------------------------------|--------------|
| ThFBl          | $2 \times 10^5$             | 10.0                         | Thermal      |
| ThFBh          | $2 \times 10^6$             | 10.0                         | Thermal      |
| BWFBh          | $2 \times 10^5$             | 10.0                         | Blast wave   |
| BWFBh'         | $2 \times 10^6$             | 10.0                         | Blast wave   |
| ThFBh'prompt   | $2 \times 10^6$             | 0.0                          | Thermal      |
| BWFBh'prompt   | $2 \times 10^6$             | 0.0                          | Blast wave   |

Table 1. The complete suite of runs. The second column shows the density threshold for SF, the third column the lifetime of massive stars and the fourth column the type of feedback employed.

3 RESULTS

3.1 Black hole dynamics

We start by describing the MBH dynamics for the two simulations characterised by standard thermal SNa feedback and a typical time for SNe explosions of 10 Myr (runs ‘ThFBl’ and ‘ThFBh’). These two runs are meant to represent a case where star formation is indeed triggered by the merger event, while gas thermodynamics is governed by standard thermal processes. The two different density thresholds for SF are used to assess the effects that the efficiency of gas conversion into stars has on the MBH dynamical evolution.

In Fig. 1 we show the MBH projected orbits (left–hand panel), and MBH separation versus time (right–hand panel). The two MBHs exhibit a peculiar orbital motion, which can be explained when considering the gravitational interactions between the MBHs and massive gas/star clumps forming in the merging discs. Such interactions typically accelerate the orbital decay of the MBHs, and a gravitationally bound MBHB forms after $\sim\! 10$ Myr (the binary formation time is indicated as a blue dot in the right–hand panel). In the case of ThFBl run (dashed red lines), the MBH orbits appear more perturbed, and the orbital decay is somewhat faster.

Fragmentation of gas, occurring just after the simulation starts, tends to form massive gas clumps, especially in the high–density regions surrounding the two MBHs. In high–density clumps star formation is very effective, and overall, a large fraction of the initial disc gas is converted into stellar mass within 10 Myr. This is apparent from Fig. 2 (left–hand panel), where the stellar mass and the residual gas mass are shown as a function of time. The right–hand panel of Fig. 2 instead, shows the star formation rate versus time. A fast increase of star formation occurs initially since gas shocked during the disc collision fragments into small clumps which immediately convert into stellar particles. After $\sim\! 2$ Myr, only low–density gas survives. Hence, star formation is no longer efficient and almost steadily decreases in time. In Fig. 3 we plot the mass–weighted gas density map at time $t = 2.1$ Myr, defined as the time of the peak in star formation rate (see Fig. 2 right–hand panel).

In order to quantify the impact of gas clumps on MBH dynamics, we estimate the total mass in gas/star clumps, along with the lump mass distribution. We define ‘clumps’ those gravitationally bound regions that feature a single peak in the 3D density field. Fig. 4 shows the total mass in clumps as a function of time for run ‘ThFBl’. Two distinct phases can be observed, with a peak in the total mass of clumps occurring after a time $t_{\text{peak}} \sim\! 2.5$ Myr. The initial fast growth of the gas locked in clumps is the result of the collision between the two unperturbed gaseous discs. Indeed, gas fragmentation is promoted along the shock surface (resulting also in the peak of star formation rate, see Fig. 2 right–hand panel).

Fig. 5 shows, for the same ‘ThFBl’ run, the mass distribution of clumps at different selected times marked as red dots in Fig. 4. We selected two times corresponding to a relatively low total clump mass ($\sim\! 1.8 \times 10^5$ $\text{M}_\odot$, left–hand panel) and two times corresponding to a larger mass value ($\sim\! 5 \times 10^7$ $\text{M}_\odot$, right–hand panel), respectively, one before and one after $t_{\text{peak}}$. The mass distribution lies in the range $10^{5–7}$ $\text{M}_\odot$, with few clumps as massive as the MBHs. These very massive clumps typically form after $t_{\text{peak}}$, most probably due to gas accretion from low–density regions and to mergers between less massive clumps, and eventually will merge with the gas overdensity surrounding each MBHs. When one of these more massive clumps manages to approach an MBH at close range, then a transient MBH–clump binary system forms, strong gravitational perturbations develop, and the MBH orbit greatly deviates from its original path. This is the reason behind the ‘wiggling orbits’ seen in Fig. 1 right–hand panel. The typical BH–
3.2 Gas dynamics

We discuss here the dynamics of the gas during the merger event. We focus on the case with the low–density threshold for SF (run ‘ThFBl’), keeping in mind that the higher density case produces a qualitatively and quantitatively similar outcome.

Fig. 6 shows the gas distribution around the MBHB after $t = 11$ Myr. On large scale (left–hand panel), the relic disc resulting from the collision of the progenitor discs is almost totally disrupted because of SNe feedback. This residual structure is counter–rotating relative to the MBHB orbit. On scales of the order of few pc (right–hand panel), the gas which has not been converted into stellar particles settles in a circumbinary disc, with a total mass of few $10^5 M_\odot$. The small disc corotates with the MBHB thanks to the drag–ing of gas by the MBHs during their inspiral towards the centre. Note that this implies that the angular momentum of the residual gas changed sign during the evolution of the system.

We report in Fig. 7 the evolution of the modulus of MBH orbital angular momentum and compared it to the modulus of the total angular momentum of the gas which is the closest to the MBHs in the simulation, defined as the gas within a sphere of radius equal to 0.5 times the MBH separation. We observe that at the beginning of the simulation the angular momentum of the gas is larger than that of the MBHs, and we remind that the gas is counter–rotating. After $\gtrsim 4$ Myr, the angular momentum associated with the MBH orbit exceeds that of the gas and in principle there are the conditions for a change in the sign of the gas angular momentum, being dragged by the MBHs. The gas angular momentum actually changes sign after $\sim 9$ Myr, when the MBH separation is $\sim 45$ pc. At this evolutionary stage, a large fraction ($\gtrsim 90\%$) of the initial gas mass is already converted in stellar particles. After $\sim 10$ Myr, when SNe start to explode, the released energy is radiated away by the small amount of residual gas, which is however unable to form further stellar mass at a comparable rate. In other words, star formation is not halted by SNe feedback, rather by gas consumption.

Concerning the impact of blast wave feedback (BWFB–type runs), as expected it does not alter the gas dynamics for a time $\sim \Delta_{\text{SN}}$ (at that point the two MBHs have already reached the centre of the system). After that time, the almost simultaneous SNe events release a fairly large amount of energy which heats the gas up but is not radiated away. The net result is that the remaining gas is pushed at very large distances from the MBHB (up to $\sim 500$ pc) by the increased pressure. The MBHB lives then in a very low–density environment, and no circumbinary disc is formed on any scale.

3.3 Prompt SNe explosions

Both the MBH and gas dynamics are unaffected by feedback for the first 10 Myr as this is the assumed lifetime of massive stars (and hence for the onset of SNe feedback). To test
Figure 1. MBH dynamical evolution for runs ‘ThFBl’ (solid black lines) and ‘ThFBh’ (dashed red lines). Left–hand panel: projected orbital evolution. Right–hand panel: MBH separation versus time. The blue dots correspond to the time of binary formation.

Figure 2. Star formation in run ‘ThFBl’. Left–hand panel: total stellar mass (solid red line) in units of the initial disc mass $M_d$, and the residual gas mass in units of $M_d$ (dashed blue line) as a function of time. Right–hand panel: star formation rate versus time.

how our results depend upon such choice, we consider the extreme case of $\Delta t_{SN} = 0$ Myr, i.e., massive stars explode as soon as they form.

We find that, as long as the SN feedback is governed by thermal processes, only small differences in the MBH dynamics exist compared to the standard delay case previously discussed. This similarity occurs because the SNa energy is mostly released in high–density clumps, where gas cools down very rapidly, and the clumps can survive the explosion. As a consequence, star formation can proceed until almost all clump gas is consumed.

Large differences occur instead if, along the $\Delta t_{SN} = 0$ assumption, we employ the blast wave recipe for SNa feedback. In Fig. 9 we compare the projected MBH orbits (left–hand panel) and the MBH separation versus time (right–hand panel) for runs BWFBh_{prompt} and ThFBh_{prompt}. In the case of blast wave like feedback, the orbital decay is slower, with a typical binary formation time–scale of $\gtrsim 13$ Myr. The difference is due to the early SNa explosions that, coupled with the blast wave–like feedback, tend to disrupt the gas clumps and to deplete the gas reservoir progressively forming around the MBHs. As a consequence, the two MBHs evolve in a lower density, smoother environment, where low–mass clumps are typically unable to induce strong orbital perturbations. The net result is a less disturbed orbital decay (Fig. 9 left–hand panel).

We therefore conclude that in the case of prompt SNa explosions, contrary to the standard delay case, the dynamical evolution of the MBHs is strongly affected by the feedback mechanism employed. The SF density threshold instead does not result in relevant differences anyway.

While MBH dynamics is basically unaffected by the value of $\Delta t_{SN}$ in the case of thermal SNa feedback, substantial differences occur in the dynamics of the gas component. Along with a small–scale corotating circumbinary disc, we do observe a further, much larger disc/ring–like structure on $\sim 100$ pc scale (see Fig. 10). Indeed, feedback from SNe does not occur suddenly after 10 Myr but it is instead diluted in time, so that the (rapidly cooling) gas has time to readjust in a disc–like structure. Though several other possi-
MBH dynamics: binary formation

Figure 5. Mass distribution of clumps in run ‘ThFBl’. Left–hand panel: mass distribution at two selected times when the number of clumps is relatively small. Right–hand panel: same as left–hand panel, but at two times when the number of clumps is larger. The four selected times are marked as red dots in Fig. 4.

Figure 6. Face–on gas density maps for run ‘ThFBl’ around the MBHB at the end of the simulation (t ~ 11 Myr). Left–hand panel: on large scales the disc is almost totally disrupted because of SNa explosions. Right–hand panel: zoom in of the nuclear region where an inner corotating gas disc forms.

ble explanations exist (e.g., secular evolution of the Galactic disc), it is tempting to associate such structure to the central molecular zone of the Milky Way (Jones et al. 2011). It is interesting to note that the larger scale disc keeps memory of the initial angular momentum, and it is then counter–rotating with respect to the small inner circumbinary disc which is, as discussed above, dragged by the MBHB.

The case of blast wave–like feedback is still different. We do not observe a disc–like structure, rather we find a massive triaxial gas distribution surrounding the MBHB with density of few $10^5$ cm$^{-3}$ (see Fig. 11). This difference is produced by the different nature of the SNa feedback, which is in this case able to heat the gas and provide a pressure support large enough to prevent gas contraction.

Because of the large fraction of gas available (due to the SNa feedback which reduces the net star formation by destroying gas clumps, as discussed above) the gas will continue to cool down, resulting in alternated phases of star formation (due to gas cooling and contraction) and re–heating (due to SNa feedback). We observe a large number of dense gas streams flowing from low–density regions towards the centre where the MBHB resides. This large inflow will result in a burst of star formation in the nucleus and in a following phase of SN explosions. The energy provided by SNe will then reheat the gas, stopping the contraction and eventually expand the entire gas structure into a less dense state. These alternated phases, if occurring for enough time, could convert a large fraction of gas into new stellar mass,
which could eventually form a massive nuclear stellar cluster surrounding the MBHB.

4 DISCUSSION AND CONCLUSIONS

By means of high-resolution, AMR hydrodynamical simulations, we explored the evolution of two massive gas discs hosting at their centre an MBH. The two discs are on an elliptic orbit and merge, to mimic the encounter between two very gas–rich disc galaxies. To maximise the strength of the interaction, the orbital angular momentum is chosen to be antiparallel to the disc’s angular momenta.

Strong shocks that develop during the merger of the two discs become sites of intense star formation, and stellar feedback alters significantly the thermal and dynamical state of the gas which undergoes a major transformation. Most of the gas is turned into new stellar particles through the formation of clumps of mass $\lesssim 10^6 M_\odot$. Only few clumps form as massive as the MBHs, weighing $10^7 M_\odot$.

We explored different SNa feedback recipes: the thermal and blast wave feedback, assuming a lifetime of $\sim 10^6$ Myr for the massive stars. Furthermore, we considered a case in which prompt SNa explosion is coupled with both thermal and blast wave feedback. We find that the orbits of the two MBHs are perturbed due to their interaction with single clumps during the paring phase I, resulting in impulsive kicks that imprint sudden changes in the direction and velocity of the orbit. Sinking times of $\sim 10 - 20$ Myr are found, considering the set of parameters used. The paring phase terminates with the formation of a Keplerian binary.

The MBH orbit is stochastic due to the presence of the gas clumps. However, we do not see a sizeable delay or spreading in the sinking time due to gas clumpiness, contrary to what found in [Fiacconi et al. (2013)], where the level of stochasticity of the orbit was higher. We interpret this difference as due to the geometry of the collision that mainly
Figure 10. Same as Fig. 6 but for run ‘ThFBh_prompt’ at time $t \sim 10$ Myr. Left–hand panel: gas settles in a disc/ring like structure which is counter–rotating relative to the MBHs. Right–hand panel: zoom in of the region where an inner corotating gas disc forms around the MBHB visible on the east side of the left–hand panel.

Figure 11. Gas density maps for run ‘BWFBh_prompt’ around the MBHB at the end of the simulation ($t \sim 20$ Myr). The gas settles in a triaxial structure with a denser central core. The core mass is $\sim 10^7 M_\odot$ within a radius $\sim 25$ pc. The upper panel shows the face–on view, while the two bottom panels show the edge–on views of the triaxial gas configuration.

confines star formation along the oblique shock forming at the time of impact of the two discs, and to the fact that in our case the mass distribution of the clumps evolves as gas is turned into stellar mass which spread due to dynamical relaxation. Our simulated MBHs do not leave the orbital plane due to clump–induced kick, contrary to what seen in [Roskar et al. 2015], as our simulation is strictly coplanar. We expect that an inclined encounter would lead to a change in the orbital plane also in our case, and this will be explored in future. During the pairing phase, the MBH dynamics is mostly affected by the presence of clumps and not by the recipe used to model the feedback processes.

We note that, on the contrary, the gas distribution around the MBHs is significantly affected by feedback. Thermal feedback leaves no large–scale disc around the MBHB. Yet a residual corotating circumbinary disc of mass much smaller than the MBH mass forms around the two black holes which we expect will control the further spiral-in via migration–like mechanisms.

Blast wave feedback is a way to model the expansion of SNe–driven bubbles. With the code it is then possible to
mimic the ballistic phase of the shock triggered by the SNe explosion. As cooling is shut off in this phase, a multiphase gas forms and the sweeping of the gas induced by the blast wave leads to the almost complete evacuation of gas. The MBHB thus inhabits a region completely devoid of gas. Blast wave feedback in the prompt scenario leads instead to a configuration in which the MBHB is surrounded by a gas cloud with little angular momentum and triaxial in shape.

The lesson to learn is that star formation in merging gaseous discs is a key process which affects the physical state of the gas in the surroundings of the MBHs. Under these circumstances it is difficult to predict the actual distribution of gas when the most active phase of the merger has subsided, as the outcome depends upon the modelling and on sub-grid physics, and firm conclusions should be taken with caution. Still, the presence of cool gas has deep implications for the evolution and observability of close MBHBs. First, the evolution of a binary on sub-pc scales towards the coalescence is strongly dependent on the gaseous and stellar distribution in its immediate surroundings (Colpi & Dotti 2011 for a review). The time-scale of the MBHs shrinking on sub-pc scales is of fundamental importance as it affects the expected rate of binaries possibly observable as gravitational wave sources. This is particularly true in mergers between gas-rich galaxies, a fraction of which can host binaries detectable by future space-based gravitational wave detectors such as eLISA (Amaro-Seoane et al. 2013). Secondly, the presence of gas is a necessary condition for the possible detection of the binary during the hardening phase (Dotti, Sesana & Decarli 2012) as well as for pinpointing an electromagnetic counterpart of the MBHB coalescence (see e.g. Schnittman 2013, Bogdanović 2015). The lack of a clear consensus on the processes shaping the environment of MBHBs, whose evolution actually depends on the physical modelling, and the lack of observations available on the small scales we considered in our work witness the need of investigating a wider range of parameters.

5 ACKNOWLEDGEMENTS

We thank R. Teyssier and L. Paredi for many fruitful discussions. We acknowledge financial support from italian MIUR, through PRIN 2010-2011. Simulations were run on the EU-ROA cluster at CINECA and on the Lucia cluster at DiSAT, University of Insubria.

REFERENCES

Amaro-Seoane O. et al., 2007, MNRAS, 380, 963
Amaro-Seoane P. et al., 2013, GW Notes, Vol. 6, p. 4-110, 6, 4
Amaro-Seoane P., Brem P., Cuadra J., 2013, ApJ, 764, 14
Begelman M. C., Blandford R. D., Rees M. J., 1980, Nature, 287, 307
Bellovary J. M., Governato F., Quinn T. R., Wadsley J., Shen S., Volonteri M., 2010, ApJ, 721, L148
Bogdanović T., 2015, Astrophysics and Space Science Proceedings, 40, 103
Callegari S., Kazantzidis S., Mayer L., Colpi M., Bellovary J. M., Quinn T., Wadsley J., 2011, ApJ, 729, 85
Callegari S., Mayer L., Kazantzidis S., Colpi M., Governato F., Quinn T., Wadsley J., 2009, ApJ, 696, L89
Capelo P. R., Volonteri M., Dotti M., Bellovary J. M., Mayer L., Governato F., 2015, MNRAS, 447, 2123
Chapon D., Mayer L., Teyssier R., 2013, MNRAS, 429, 3114
Colpi M., 2014, Space Sci. Rev., 183, 189
Colpi M., Dotti M., 2011, Advanced Science Letters, 4, 181
Cuadra J., Armitage P. J., Alexander R. D., Begelman M. C., 2009, MNRAS, 393, 1423
del Valle L., Escala A., 2012, ApJ, 761, 31
del Valle L., Escala A., Maureira-Fredes C., Molina J., Cuadra J., Amaro-Seoane P., 2015, ArXiv e-prints
Di Matteo T., Springel V., Hernquist L., 2005, Nature, 433, 604
Dotti M., Colpi M., Haardt F., 2006, MNRAS, 367, 103
Dotti M., Sesana A., Decarli R., 2012, Advances in Astronomy, 2012
Dubois Y., Volonteri M., Silk J., 2014, MNRAS, 440, 1590
Enßlin T. A., Pfriemmer C., Springel V., Jubelgas M., 2007, A&A, 473, 41
Escala A., Larson R. B., Coppi P. S., Mardones D., 2005, ApJ, 630, 152
Fiacco D., Mayer L., Roškar R., Colpi M., 2013, ApJ, 777, L14
Hernquist L., 1990, ApJ, 356, 359
Jones D. I., Burton M., Jones P., Walsh A., Rowell G., Aharonian F., 2011, ArXiv e-prints
Kazantzidis S. et al., 2005, ApJ, 623, L67
Khan F. M., Holley-Bockelmann K., Berczik P., Just A., 2013, ApJ, 773, 100
Lupi A., Haardt F., Dotti M., 2015, MNRAS, 446, 1765
Mayer L., Kazantzidis S., Madau P., Colpi M., Quinn T., Wadsley J., 2007, Science, 316, 1874
Merritt D., Mikkelson S., Szell A., 2007, ApJ, 671, 53
Merritt D., Milosavljević M., 2005, Living Reviews in Relativity, 8, 8
Preto M., Berentzen I., Berczik P., Spurzem R., 2011, ApJ, 732, L26
Roedig C., Dotti M., Sesana A., Cuadra J., Colpi M., 2011, MNRAS, 415, 3033
Roedig C., Sesana A., Dotti M., Cuadra J., Amaro-Seoane P., Haardt F., 2012, A&A, 545, A127
Roskar R., Fiacconi D., Mayer L., Kazantzidis S., Quinn T. R., Wadsley J., 2015, MNRAS, 449, 494
Schnittman J. D., 2013, Classical and Quantum Gravity, 30, 244007
Sesana A., Barausse E., Dotti M., Rossi E. M., 2014, ArXiv e-prints
Sesana A., Khan F. M., 2015, ArXiv e-prints
Shi J.-M., Krolik J. H., Lubow S. H., Hawley J. F., 2012, ApJ, 749, 118
Teyssier R., 2002, A&A, 385, 337
Teyssier R., Pontzen A., Dubois Y., Read J. I., 2013, MNRAS, 429, 3068
Van Wassenhove S., Volonteri M., Mayer L., Dotti M., Bellovary J., Callegari S., 2012, ApJ, 748, L7
Vasiliev E., Antonini F., Merritt D., 2014, ApJ, 785, 163
Vasiliev E., Antonini F., Merritt D., 2015, ArXiv e-prints