

Formation of discs around super-massive black hole binaries

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Abstract. We model numerically the evolution of $10^4 M_{\odot}$ turbulent molecular clouds in near-radial infall onto $10^6 M_{\odot}$, equal-mass supermassive black hole binaries, using a modified version of the SPH code GADGET-3. We investigate the different gas structures formed depending on the relative inclination between the binary and the cloud orbits. Our first results indicate that an aligned orbit produces mini-discs around each black hole, almost aligned with the binary; a perpendicular orbit produces misaligned mini-discs; and a counter-aligned orbit produces a circumbinary, counter-rotating ring.

Keywords. black hole physics, accretion discs, hydrodynamics

1. Introduction

Supermassive black holes (SMBHs) are ubiquitous in galactic nuclei (Richstone *et al.* 1998), and binaries of these massive objects are a likely product of the hierarchical evolution of structures in the universe. After a galaxy merger, where both progenitors host a SMBH, different mechanisms are responsible for the evolution of the binary orbit depending on its separation (see review by Colpi 2014). Dynamical interaction with stars appears to be efficient to bring the SMBHs down to parsec scales only, what is known as the “last parsec problem” (Begelman *et al.* 1980, Yu 2002). A possible way to overcome this barrier and merge the SMBHs within a Hubble time is interaction with gas. Many theoretical and numerical studies have focused on the orbital evolution of a sub-parsec binary surrounded by a circumbinary disc (e.g. Armitage & Natarajan 2005, Cuadra *et al.* 2009, Amaro-Seoane *et al.* 2013, Nixon *et al.* 2013, Roedig & Sesana 2014). However, the exact mechanism that would produce such discs is still unclear; it is necessary an efficient transport of gas from thousands or hundreds of parsecs to the central parsec.

Turbulence and gravitational instabilities in the interstellar medium, through the formation of clumps, allow portions of gas to travel almost unaffected by its surrounding, enhancing the probability of reaching the galactic nuclei (Hobbs *et al.* 2011). A possible manifestation of these events is the putative molecular cloud that resulted in the unusual distribution of young stars orbiting our Galaxy’s SMBH. In particular, the simulation of Bonnell & Rice (2008) shows a spherical, turbulent cloud falling with a very low impact parameter (~ 0.1 pc) onto a one million solar masses SMBH.

Assuming that these accretion events are common in galactic nuclei, the goal of our work is to model such an event onto a binary instead of a single SMBH. In particular, we are interested on the properties of the discs that will form given different relative orientations between the orbital angular momenta of the cloud and the binary. Notice that this study is complementary to that shown in Dunhill *et al.* (2014), as we are modeling clouds with very low orbital angular momentum.

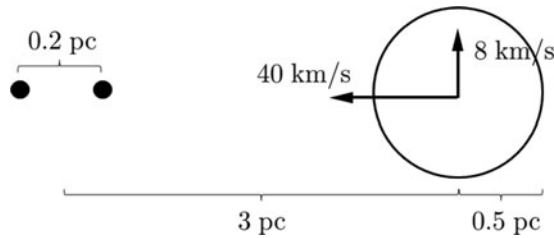


Figure 1. Initial setup of the simulations. The circle on the right represents the cloud, while the black, solid circles are the SMBHs.

2. The numerical model

We model the interaction between the binaries and clouds using a modified version of the SPH code GADGET-3 (Springel 2005). The cloud is represented using over 4×10^6 gas particles with a total mass of $10^4 M_\odot$, an initial turbulent velocity field and uniform density. The SMBHs are modeled as two equally-massive sink particles that interact only through gravity and can accrete SPH particles. The total mass of the binary is $10^6 M_\odot$, and its initial orbit is Keplerian and circular.

The physical setup of the simulation is shown in Figure 1. The initial velocity of the cloud yields a highly eccentric ($e \approx 0.98$), bound orbit where the pericenter distance is $r_{\text{peri}} \approx 0.07$ pc, which is less than the binary radius, making the interaction between the gas and SMBHs very strong. As we expect clouds approaching the binary from different directions, we model systems with three different inclinations between the cloud and binary orbits: aligned, perpendicular and counter-aligned.

3. Results: formation and properties of the gaseous discs

In this section we present the main results of the simulations with the different inclinations, in particular the discs that form around the binary and each SMBHs.

Aligned orbits. On the left panel of Figure 2 we show the column density map of the simulation at different times, where we can see how the interaction develops. As the gas falls almost radially onto the binary, around 80% of the cloud is accreted by the SMBHs. Most of the remaining gas is pushed away due to an efficient slingshot. The bound material forms a tail that get stretched and diluted over time, feeding “mini-discs” that form around each SMBH.

To measure the alignment between the binary orbit and the mini-discs, we compute its angular momentum on the corresponding black hole reference frame. We show the time evolution of the direction of both discs on the Hammer projection of Figure 2. Here we observe that they tend to align with the orbit of the binary, as expected, although one disc is slightly tilted with respect to the aligned position and also precesses around that position. This behavior could have distinctive electromagnetic signatures. For example, the misalignment could affect the variability of spectral lines, or each disc have different polarization. The precession could be observed if jets are launched from the SMBHs and align with the mini-discs.

Perpendicular orbits. With this inclination, as in the previous case, around 80% of the cloud mass is added to the SMBHs. However, the interaction between the gas and the binary, that we can see in Figure 3, is completely different respect to the aligned case. Due to a less efficient slingshot, most of the remaining material stays bound to the system and it retains its original angular momentum, forming an unstable structure

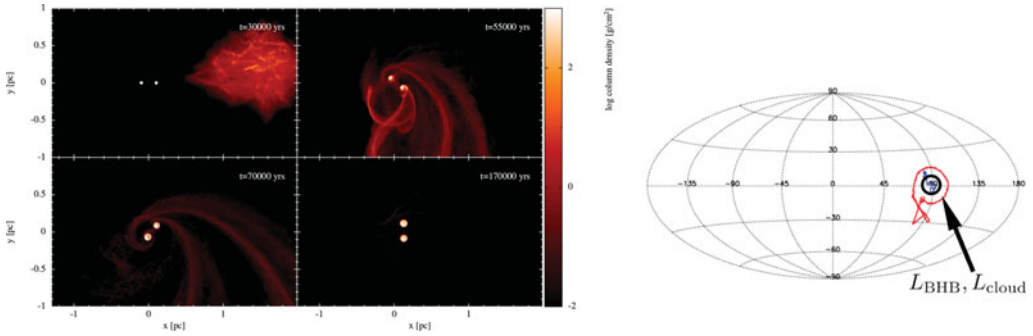


Figure 2. Left: Column density map of the aligned simulation at different times. For reference, the cloud and the binary move on the x-y plane. (For animations check <http://www.astro.puc.cl/~fgarrido/animations>) Right: Time evolution of the angular momentum direction of the mini-discs formed around each black hole (red and blue lines), in a Hammer projection. The triangle shows the formation of the disc and the square the end of the simulation.

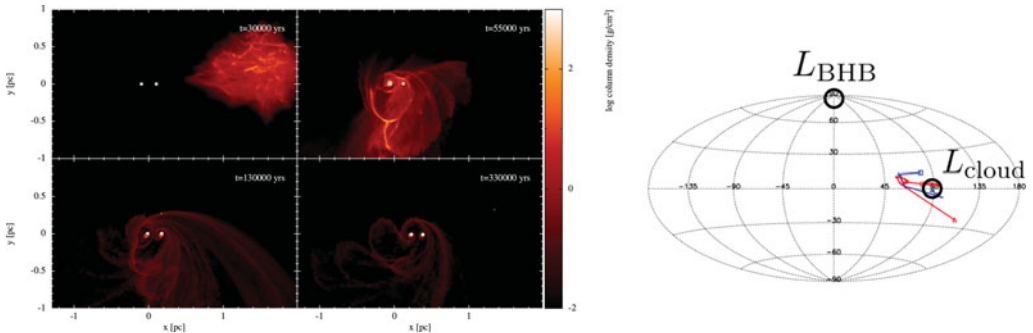


Figure 3. As Fig. 2, but for the model with perpendicular orbits. In this case the cloud moves on the x-y plane while the binary is on the x-z plane.

around the binary. The gas that reaches the SMBHs also produce mini-discs, but they are less massive and more intermittent than in the aligned case.

The direction of the mini-discs, shown on the right panel of Figure 3, shows that they tend to follow the original direction of the cloud, which makes them completely misaligned respect to the binary orbit. As well as the previous case, this could have distinctive signatures on the variability of lines or the direction of possible jets.

Counter-aligned orbits. In this case we have that the interaction of the binary with the gas produces shocks that cancel angular momentum, allowing the SMBHs to accrete even more material than in the previous cases; around 90% of the cloud is swallowed. The remaining material forms a tail that, due to the gravitational torques, produces a circumbinary ring. In this case we do not observe mini-discs during the entire length of the simulation.

Finally, we compute the eccentricity distribution of the gas on three different stages, as shown on the right panel of Figure 4. It is interesting that, if there is star formation in the ring, the stars would have very different orbits around the binary depending on the formation time-scale. For a very rapid star formation we could have highly eccentric orbits (solid line), while for a slow process the stars could be distributed on a narrow ring with nearly circular orbits (dashed line).

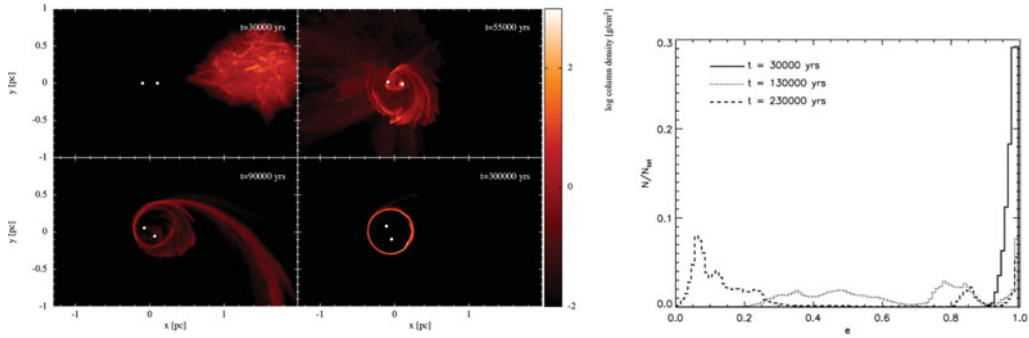


Figure 4. Left: As Fig. 2, but for the model with the counter-aligned orbits. In this case, the cloud and the binary move on the x-y plane, but the latter is rotating clockwise. Right: Eccentricity distribution of the gas for three different times in the simulation.

4. Conclusions and outlook

The preliminary results presented here show that accretion events onto binaries result in very different disc morphologies, depending on the relative inclination between the cloud and the binary orbits. Our work in progress is extending this study to larger impact parameters, showing lower accretion rates, and exploring the effect of the interaction on the black holes orbit and spin evolution. These results are likely to have important implications on the multi-messenger future studies of SMBH binaries and on the long-term evolution of these systems.

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