The effect of AGN feedback on the migration timescale of supermassive black holes binaries

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ABSTRACT

The gravitational interaction at parsec to sub-parsec scales between a circumbinary gas disc and a super massive black hole binary (SMBHB) is a promising mechanism to drive the migration of SMBHBs toward coalescence. The typical dynamical evolution can be separated in two main regimes: I) Slow migration ($T_{\text{mig}} \sim 10^{3-4} \times T_{\text{orb}}$), where viscous torques are not efficient enough to redistribute the extracted angular momentum from the binary, leading to the formation of a low density cavity around the binary. II) Fast migration ($T_{\text{mig}} \sim 10^{1-2} \times T_{\text{orb}}$), in which the redistribution of angular momentum is efficient and no low density cavity is formed in the circumbinary disc. Using N-Body/SPH simulations we study the effect of AGN feedback in this phase of a SMBHB evolution. We implement an AGN feedback model in the SPH code Gadget-3 that includes momentum feedback from winds, X-ray heating/radial-momentum and Eddington force. Using this implementation we run a set of simulations of SMBHB+disc in the two main shrinking regimes. From these simulations we conclude that the effect of the AGN mechanical feedback is negligible for SMBHBs in the slowly shrinking regime. However, in the fast shrinking regime the AGN wind excavate a “feedback cavity” leaving the SMBHB almost naked, thus stalling the orbital decay of the binary.

Key words: black hole binary – AGN – gravitational waves

1 INTRODUCTION

Central SMBHs are found in practically every galaxy with a significant bulge (Richstone et al. 1998; Magorrian et al. 1998; Gültekin et al. 2009). Within the currently accepted evolutionary model of the Universe the merger between galaxies is a common event (White & Frenk 1991).

In mergers of galaxies with similar mass, if each galaxy involved in the merger hosts a SMBH, both SMBHs will sink by dynamical friction to the innermost region of the core of the merger remnant (e.g. Colpi 2014; Volonteri et al. 2016, and references therein). When the mass enclosed by the orbit of these two SMBHs is smaller than the sum of their masses, they will form a SMBH binary (Pfister et al. 2017, and reference therein). Understanding the further evolution of these SMBH binaries (SMBHBs) is crucial because if two SMBHs are able to reach separations of $a_{\text{GW}} \sim 10^{-3} (M_{\text{SMBBH}}/10^{6} M_{\odot})$ pc, then the binary becomes a strong emitter of gravitational waves, which leads to its coalescence (Peters & Mathews 1963; Peters 1964). Gravitational waves from SMBHs are a prime source in the frequency range of the future Laser Interferometer Space Antenna (LISA, Amaro-Seoane et al. 2017).

If the binary is formed in a gas-rich environment it is typically assumed that its evolution leads to the formation of a circumbinary disc around the SMBHB. These discs have been produced in the final stage of simulations of SMBHB formation inside massive nuclear discs (del Valle et al. 2015). Recently, in the context of the accretion of clumpy cold gas on to SMBH binaries, it has been shown that a continuous supply of incoherent clouds produces an intermittent formation and disruption of circumbinary structures (Maureira-Fredes et al. 2018; Goicovic et al. 2018).

The dynamical evolution of a SMBHB embedded in a circumbinary disc is driven by gravitational torques produced by the disc on to the binary. A variety of studies on the interaction between binaries and discs in a broad range of contexts show that the angular momentum extracted from the binary is redistributed in the disc by means of viscous diffusion (e.g. Goldreich & Tremaine 1980; Armitage & Rice 2005; Shi et al. 2012). If this redistribution is inefficient then the binary will excavate a tidal gap/cavity of low density in the disc, resulting in a drop of the intensity of the gravitational torque exerted on to the binary and therefore the
binary evolves slowly \((\text{d}a_{\text{bin}}/\text{d}t)(1/a_{\text{bin}}) \sim 1/(10^2 t_{\text{orb}}))\). Instead, if the viscous diffusion in the disc redistributes the extracted angular momentum rapidly enough, then no tidal gap/cavity formation occurs and the binary evolves on a shorter timescale \((\text{d}a_{\text{bin}}/\text{d}t)(1/a_{\text{bin}}) \sim 1/t_{\text{orb}})\) (Lin & Papaloizou 1986; Escala et al. 2005; Cuadra et al. 2009). Motivated by this relation between the formation of a tidal gap/cavity in the disc and the shrinking rate of the binary, del Valle & Escala (2012, 2014) derived a gap/cavity opening criterion for comparable mass binaries \((q \sim 1)\) comparing the timescales for opening the tidal gap/cavity, driven by the gravitational torque of the binary, with the timescale for closing the tidal gap/cavity, driven by the viscous diffusion on the disc.

In this work we use del Valle & Escala (2012, 2014) criterion to select binary-disc systems in the two migration regimes and we study the effect of SMBH accretion/feedback in both regimes. The effect of AGN feedback on the dynamical evolution of SMBHs has been studied in the context of the inspiral of SMBH pairs in a star forming massive nuclear disc (Souza Lima et al. 2017) and in the context of gravitationally recoiled SMBHs (Sijacki et al. 2011). Both studies have found that AGN thermal feedback can disturb the wake produced by the SMBHs on the background gas, decreasing significantly the effect of dynamical friction on to the SMBHs. These works are consistent with the work of Park & Bogdanović (2017) in which they studied the effect of AGN radiation on the dynamical friction experienced by an accreting SMBH that travels, with constant velocity, in a homogeneous distribution of gas. They found that if the HII region around the SMBH is larger than the wake produced by the black hole (that is comparable to the gravitational influence sphere of the black hole) then dynamical friction is totally suppressed. All of these studies suggest that AGN feedback can be a crucial aspect of the dynamical evolution of SMBHs. We explore further this idea by studying the effect of AGN feedback on the evolution of SMBHs binaries at small separation, in the regime where dynamical friction is not the dominant process driving the dynamics.

The structure of this paper is as follows: in section 2 we discuss how we constrain and select the initial conditions, in section 3 we present the numerical method and parameters that we use in the simulations, in section 4 we present the results and finally in section 5 we outline the main results and conclusions of this study.

2 CONSTRAINTS ON CIRCUMBINARY DISCS PARAMETERS

We use the tidal gap/cavity opening criterion of del Valle & Escala (2014) to select the initial conditions for the simulations of this study. This criterion can be expressed as

\[
\frac{\Delta_{\text{open}}}{\Delta_{\text{close}}} = \frac{1}{0.33} \left( \frac{v}{v_{\text{bin}}} \right)^2 \left( \frac{c_s}{v} \right) \left( \frac{h}{h_{\text{bin}}} \right) \leq 1, \quad (1)
\]

where \(c_s\) is the sound speed of the gas, \(v\) the rotational velocity of the binary-disc system, \(v_{\text{bin}}\) the keplerian velocity, \(h_{\text{bin}}\) the separation of the binary and \(h\) the scale height of the disc. We represent the tidal gap/cavity opening criterion in the space of parameter \(\left( (v_{\text{bin}}/v)^2, (c_s/v)(h/h_{\text{bin}}) \right)\) as a solid blue line in Fig. 1.

The interpretation of Fig. 1 is simple; in the absence of AGN feedback any combination of parameters above the solid blue line represents binary-disc systems where no tidal gap/cavity formation will occur (fast shrinking binaries) and any combination of parameters below the solid blue line represents binary-disc systems where a tidal gap/cavity will form (slowly shrinking binaries). Therefore, if we want to study the effect of AGN feedback on the migration of a system where a slow/fast migration is expected we have to select a point below/above the solid blue line and this point will have the information of the combination of parameters of that binary-disc system.

In addition to this, we set another constraint to the parameters of the binary-disc systems. We limit our study to systems that are stable against self-gravity to avoid the presence of clumps that can perturb the orbit of the binary through close encounters, because their effect on the dynamics of the SMBHB could be difficult to disentangle from the effect of AGN feedback.

To make this selection clear, we write the Toomre parameter \(\mathcal{Q}\) (Toomre 1964) as a function of the parameters of Fig. 1. For this we take the usual form of the Toomre parameter:

\[
\mathcal{Q} = \frac{c_s k}{\pi G \Sigma}, \quad (2)
\]

where \(k\) is the epicyclic frequency and \(\Sigma\) the surface density of the disc. We express \(k\) as a function of the orbital frequency \(\Omega = v/(\pi a_{\text{bin}})\) as \(k = 4 \Omega^2 + \Omega a_{\text{bin}} (d\Omega/dr)\) which leads to

\[
k^2 = \frac{v^2}{a_{\text{bin}}^2} \frac{1}{f^2} (8\pi + [5f - 3] - 6) \quad (3)
\]

with \(f = 1 + (M_{\text{bulge}}/M_{\text{bin}})\), where \(M_{\text{bin}}\) is the mass of the
binary and $M_{\text{bulge}}$ the enclosed mass of a bulge of stars, following a Plummer profile, that surrounds our binary-disc system. The radius at which we compute this enclosed mass is the orbital radius of the binary, therefore $f$ depends on the initial separation of the binary. The values of $f$, for the four binary separations that we use, range from $f = 1.001$ to $f = 1.5$. Henceforth we use its mean value $f \approx 1.1$.

We express the surface density of the disc as $\Sigma = 4 M_{\text{gas}} / (\pi R_{\text{bin}}^2)$ with $M_{\text{gas}}$ the mass of gas enclosed by the binary. We express this mass as a function of the velocities of the system as $M_{\text{gas}} = (2 G / \sigma_{\text{bin}}^4) \left( v^2 - f v_{\text{bin}}^2 \right)$.

With these expressions for $k$ and $\Sigma$ we rewrite the Toomre stability parameter as:

$$Q = \frac{(x f)^{-1} \sqrt{A v_\beta}}{2 \pi^2}.$$  \hspace{1cm} (4)

where $\beta = (c_5 / v) (\sigma_{\text{bin}} / h)$ is a parameter of order unity for rotational supported systems, $x = (v_{\text{bin}} / v_{\text{gas}})^2$, $y = (c_5 / v_{\text{gas}})^2$ and $A = A_0 + x A_1$ with $A_0 = 4 \pi - 3$ and $A_1 = (5 f - 3)/2$.

Therefore, the curve that defines $Q = 1$ in the parameter space $\left( (v_{\text{bin}} / v_{\text{gas}})^2, (c_5 / v_{\text{gas}}) (h / \sigma_{\text{bin}}) \right)$ is

$$y = \frac{2 \pi^2}{\beta} \left( 1 - x f \right)^2 \left( A_0 + x A_1 \right).$$  \hspace{1cm} (5)

This curve is shown as a red dashed line in Fig. 1. The parameter space that we use for the initial conditions of the simulations of this paper is at the right of the red dashed line that corresponds to systems with $Q > 1$.

3 SIMULATIONS

3.1 Implementation of AGN Feedback

To study the effect of AGN feedback on the dynamical evolution of a SMBHB embedded in a circumbinary disc we use a modified version of the code Gadget-3 (Springel 2005) in which we implement flux accretion on to the SMBHs and the subsequent AGN radiative/mechanical feedback following Choi et al. (2012).

We choose flux accretion instead of Bondi-Hoyle accretion because the Bondi radius is typically larger than the size of the binary-disc system in our setup. In our implementation of accretion we define a spherical region around the SMBH of radius $R_{\text{acc}}$ in which all the gas that enters is eligible to be accreted by the SMBH. In addition the gas has to fulfill an angular momentum condition; the gas will be accreted by the SMBH only if its angular momentum is smaller than the angular momentum of a circular orbit of radius $R_{\text{acc-disc}}$. We define $R_{\text{acc-disc}}$ as the maximum radius of a Shakura and Sunyaev disc that is stable against self gravity (Kolykhakov & Sunyaev 1980). The effect of this condition on the accretion rate is presented in appendix A1.

To model radiative feedback we compute the total radiative luminosity emitted by the SMBH accreting at a rate $M_{\text{BH}}$ as $L_r = \varepsilon_r M_{\text{BH}} c^2$ where $c$ is the speed of light and $\varepsilon_r$ is the radiative efficiency that, following Choi et al. (2012), we set as $\varepsilon_r = 0.1$. This total luminosity is used to compute an X-ray feedback (coming from Compton cooling/heating, photo-ionization and electron scattering) and an Eddington force (coming from electron scattering). For the X-ray feedback we convert the total radiated luminosity to a luminosity flux $F_r = L_r / 4 \pi r^2$, where $r$ denotes the distance of the gas particles to the SMBH. Then we convert this flux in a net volume heating rate term $\dot{E}$ using the description of Sazonov et al. (2005) of the net heating rate per unit volume of a cosmic plasma in photoionization equilibrium embedded in a radiation field that corresponds to the average spectral energy distribution of quasars (e.g. Novak et al. 2011). We use $\dot{E}$ to heat every gas particle and we include the effect of X-ray pressure by adding a total momentum per unit time $\dot{p} = \dot{E} / c$ (DeBuhr et al. 2011, 2012) which does not take into account the effect of dust. For the Eddington force we use the luminosity flux $F_r$ to compute the total momentum per unit time on to each gas particle due to electron scattering as $\dot{p} = F_r N_e \sigma_T c / N_e$ the number of free electrons and $\sigma_T$ the Thomson cross-section for electrons.

The mechanical part of the AGN feedback models line-driven winds launched in accretion discs (Proga et al. 2001). To model this wind, as in Choi et al. (2012), we assume a single-velocity wind with $v_w = 10^4$ km s$^{-1}$ and we define the wind mass rate as $M_w$. Defining $M_{\text{inf}}$ as the rate of gas mass that fulfills the conditions of flux accretion then, by simple mass conservation, we have that $M_{\text{BH}} = M_{\text{inf}} - M_w$.

Therefore, defining $\phi = M_{\text{BH}} / M_{\text{inf}}$ we can write the SMBH accretion rate, the wind mass rate and the momentum and kinetic energy of the wind as

$$M_{\text{BH}} = M_{\text{inf}} \frac{1}{1 + \phi}$$  \hspace{1cm} (6)
$$M_w = M_{\text{inf}} \frac{\phi}{1 + \phi}$$  \hspace{1cm} (7)
$$\dot{E}_w = \varepsilon_w c^2 M_{\text{inf}} \frac{1}{1 + \phi}$$  \hspace{1cm} (8)
$$\dot{p}_w = M_{\text{inf}} v_w \frac{\phi}{1 + \phi}.$$  \hspace{1cm} (9)

where $\varepsilon_w = 5 \times 10^{-4}$ denotes the wind efficiency in the momentum feedback model. Using these equations we can write $\phi = 2 \varepsilon_w c^2 / v_w^2 \approx 0.9$ which give us $M_w \approx 0.5 M_{\text{inf}}$. Therefore, to model this wind we select half of the particles that are eligible to be accreted by the SMBH and we eject them with a velocity $v_w$ radially from the SMBH in the direction of the original angular momentum of the particles. In this way we mimic a wind that is launched perpendicular to the accretion disc.

Finally, we include cooling to model the radiative losses of the gas. The cooling function that we use is computed for an optically thin gas with solar metallicity. For temperatures between $10^4$ and $10^6$ we compute the cooling function essentially as described by Katz et al. (1996) (bremsstrahlung and lines cooling) and for temperatures below $10^4$ we use the parameterization of Gerritsen & Ike (1997). For this cooling function, and the mean density of the gas on the initial conditions, the cooling time is of the order of $t_{\text{cool}} \approx 1$ yr, which is much shorter than the orbital time of the binary ($>100$ kyr). For this efficient cooling the energy injected thermally to the gas is radiated away in a time $\sim t_{\text{cool}}$. Therefore, thermal AGN feedback is completely ineffective for the scales and densities that we explore in this study. For this reason we implement a radiative and momentum based AGN feedback instead of a purely thermal AGN feedback.
3.2 Initial Conditions and Simulations

We select the parameters of the binary-disc systems using the constraints presented in section 2. We select four binary-disc systems as initial conditions and they are represented as colored squares in Fig. 1. Of these four initial conditions, two correspond to systems with an initial tidal gap/cavity (label with “GAP” in table 3.2).

In the four binary-disc systems that we generate the gas disc follows a Mestel surface density profile with a maximum radius of \( R_{\text{disc}} = 45 \) pc, an initial thickness of \( H_{\text{disc}} = 5 \) pc and a uniform gas temperature of \( 2 \times 10^4 \) K. In three of these initial conditions the total mass of the disc is \( 10^6 M_\odot \) and in one of them is \( 10^4 M_\odot \). We model these discs using \( 2 \times 10^6 \) SPH particles and for one case we use \( 2 \times 10^5 \) SPH particles (labeled as “lowr” in table 3.2), each with a gravitational softening of 0.005 pc.

In addition to the disc we include an external potential to mimic the presence of a spherical bulge of stars, formed at the core of a galaxy merger remnant, around the binary-disc system. We include this external potential because such bulge can have an impact on the dynamics of the gas launched as a wind from the SMBHs. We model this bulge as a Plummer potential of core radius 65 pc and to maximal mass \( 2 \times 10^6 M_\odot \). We relax the gaseous disc, for 30 orbits, under the presence of the Plummer potential and a spherical external potential that mimics the presence of the binary. This external potential is a homogeneous sphere of mass \( M_{\text{bin}} \) and radius equal to the binary separation \( a_{\text{bin}} \).

After the disc is relaxed we select all the gas particles that are in a ring of radius \( a_{\text{bin}}/2.0 \), and width \( 0.02 a_{\text{bin}} \), and compute their mean rotational velocity. Then we add an equal mass SMBHB in a circular orbit with this velocity, mass \( M_{\text{bin}} \) and separation \( a_{\text{bin}} \). The total mass of the binary and its initial separation in the four initial conditions are \((a_{\text{bin}}, M_{\text{bin}}) = (1 \text{ pc}, 10^6 M_\odot), (2 \text{ pc}, 10^5 M_\odot), (2 \text{ pc}, 10^5 M_\odot), (3 \text{ pc}, 10^4 M_\odot)\) For all these cases we model the binary with two collision-less particles of gravitational softening 0.005 pc.

In table 3.2 we list the simulations. For each of the four initial conditions we run two simulations: one without AGN feedback and one with AGN feedback (label “AGN” in table 3.2).

4 RESULTS

4.1 Evolution of SMBH binaries without AGN feedback

In Fig. 2 we show the temporal evolution of the binary separation \( a_{\text{bin}} \) normalized to the initial binary separation \( a_0 \) for simulations without AGN feedback.

In the simulations GAP-a3 and GAP-a2 the binary separation is constant over a timescale of roughly \( \sim 10^2 t_{\text{orb}} \), which is consistent with the expectations of the migration timescale of a system with tidal cavity (decrease on a timescale of \( (d a_{\text{bin}}/d t)(1/a_{\text{bin}}) \sim 10^{-3} - 10^{-4} t_{\text{orb}} \).

Also consistent with the analytic expectations, in the simulations a1 and a1-lowr the binary shrinks in \( \sim 1 - 2 t_{\text{orb}} \) which is consistent with a system in which the redistribution of angular momentum on the disc is rapid enough to maintain gas close to the binary and therefore where no tidal cavity is formed.

4.2 Evolution of SMBH binaries with AGN feedback

In the presence of a tidal cavity the inflow of gas towards the SMBHs is smaller than in simulations without tidal cavity and therefore the maximum wind luminosity is lower (see Fig. 3). Furthermore, the outflows do not interact with the disc. They escape freely through the cavity and their velocity does not change, leaving the disc almost unperturbed (see Fig. 5).

This means that when a tidal gap opens, the binary separation for simulations with AGN feedback (GAP-a3-
AGN feedback and SMBHB shrinking

Figure 3. Luminosity of the wind launched from the SMBHB as a function of time. The time is in units of the initial orbital time \( t_{\text{orb}} \). Even though in simulations without tidal cavity (a1-lowr-AGN, a1-AGN and a2-AGN) the mass of the black holes are smaller, the luminosity of the wind reaches higher values than in simulations with tidal cavity (GAP-a3-AGN and GAP-a2-AGN) where the mass of the black holes is \( \sim 10^{-100} \) times larger.

Figure 4. Separation of the binary as a function of time for simulations where accretion and AGN feedback of the SMBHs is active. The binary separation \( a_0 \) is normalised by the initial binary separation \( a_0 \) and the time is in units of the initial orbital time \( t_{\text{orb}} \). The evolution of systems with tidal cavity is not affected by AGN feedback (GAP-a3-AGN and GAP-a2-AGN). However, in simulations without tidal cavity (a1-lowr-AGN, a1-AGN and a2-AGN) AGN feedback does not allow the binary to shrink further.

AGN and GAP-a2-AGN in Fig. 4) has the same behaviour that their counterpart in simulations without AGN feedback (GAP-a3 and GAP-a2, in Fig. 2).

In these two simulations with AGN feedback the amount of matter in the outflows is very small compared with the mass of the disc enclosed by the orbit of the binary (Fig. 7). After \( \sim 10^2 t_{\text{orb}} \) the enclosed mass is about the same for simulations GAP-a3-AGN and GAP-a3 and for simulations GAP-a2 and GAP-a2-AGN. This implies that the effect of AGN feedback on the orbit of a binary in a disc with tidal cavity is negligible. Moreover, the discs in both pairs of simulations are basically indistinguishable. Because the discs are basically indistinguishable, simulations GAP-a3-AGN and GAP-a2-AGN remain in the slow migration regime (see figure 6).

In simulations that are not expected to form a tidal cavity without AGN feedback, the presence of this feedback has a strong effect on the dynamical evolution of the binary and the structure of the disc. When a cavity does not open, SMBHs are surrounded by dense gas and large inflows can reach the BHs triggering strong winds, as shown in Fig. 3.

In the simulations a1-lowr-AGN, a1-AGN and a2-AGN the SMBHBs do not evolve as rapidly as they do in the absence of AGN feedback (Fig. 2), instead they stall at parsec scale separations (Fig. 4). This stalling is caused by the de-
Figure 6. Time evolution of $\Delta t_{\text{open}} / \Delta t_{\text{close}}$ after the onset of AGN feedback for simulations with a tidal cavity. The dashed grey line corresponds to $\Delta t_{\text{open}} / \Delta t_{\text{close}} = 1$ and represents the threshold between fast migration and slow migration regime. The blue line corresponds to simulation GAP-a3-AGN and the green line to simulation GAP-a2-AGN. The squares represent the initial value of $\Delta t_{\text{open}} / \Delta t_{\text{close}}$ for both simulations. The value of $\Delta t_{\text{open}} / \Delta t_{\text{close}}$ for both simulations does not change in time because the BHs accretion is low and the winds generated by the AGN feedback escape from the circumbinary disc without altering it.

Figure 7. Ratio between the mass of gas inside $r = a_{\text{bin}}$ for simulations with and without AGN feedback as a function of time. The blue line corresponds to the ratio of the enclosed mass of simulations GAP-a3-AGN and GAP-a3. The green line corresponds to the ratio of the enclosed mass of simulations GAP-a2-AGN and GAP-a2. Time is in units of the initial orbital time $t_{\text{orb}}$. The enclosed mass in both binary-disc systems with cavity changes by 1-2% by the effect of AGN feedback. This results in a negligible effect of AGN feedback on the torques produced by the disc on to the SMBHBs.

Figure 8. Edge-on density slices of the disc in simulation a1-AGN. From top to bottom each panel corresponds to a different time. AGN winds collide against the disc, opening a feedback cavity which leaves both SMBHs almost naked. This results in the subsequent stalling of the SMBHB migration.
however, in simulations without a tidal cavity there is no effect on the sound speed of the disc (top panels Fig. 10). Noticeable for simulations without an initial tidal cavity. As it was the case for the binary separation, the effect is more pronounced in systems without initial cavity, up to one order of magnitude (upper panels in Fig. 13). This means that AGN feedback does not push the disc toward instability. Therefore, in our setup we do not expect star formation to occur within the circumbinary disc.

4.3 Effect of AGN feedback on the circumbinary disc

AGN feedback also has an impact on the circumbinary disc. As it was the case for the binary separation, the effect is more noticeable for simulations without an initial tidal cavity.

For systems with tidal cavity, AGN feedback has almost no effect on the sound speed of the disc (top panels Fig. 10). However, in simulations without a tidal cavity there is an increase in \( c_s \) from \( \sim 8.5 \text{ km s}^{-1} \) to \( \sim 9 \text{ km s}^{-1} \) (which corresponds to a variation on temperature of \( \sim 10^3 \text{ K} \)) at radii close to the edge of the “feedback cavity” (bottom panels Fig. 10).

The thickness of the disc remains almost unchanged by AGN feedback for simulations with and without a tidal cavity (Fig. 11). However, the rotational velocity of the disc can vary by a factor three in systems without tidal cavity due to AGN feedback (bottom panels Fig. 12). When this feedback is active the velocity of the gas close to the binary is not determined solely by the gravitational potential in that region but also by the winds generated by the feedback. In contrast, in simulations with tidal cavity (where AGN feedback does not generate strong winds that collide against the disc) the rotational velocity of the gas is about the same, regardless of the presence of AGN feedback (upper panels Fig. 12).

Regarding the stability of the disc, we find that AGN feedback can increase the value of \( Q \). This increment is larger in systems without initial cavity, up to one order of magnitude (upper panels in Fig. 13). This means that AGN feedback does not push the disc toward instability. Therefore, in our setup we do not expect star formation to occur within the circumbinary disc.

4.4 Outflows and Inflows

The interaction between the AGN wind and the circumbinary disc is different for systems with and without tidal cavity. This results in different kinematics of the outflows/inflows produced by AGN feedback.

In Fig. 14 we show the absolute value of the radial velocity of particles outside the circumbinary disc against their distance from the center of mass of the binary. In the same figure we plot the escape velocity of the gas \( v_{\text{esc}} = (2GM(R)/R)^{1/2} \) with \( M(R) \) the total mass (Bulge + Disc + Binary) enclosed by a sphere of radius \( R \). The AGN wind in simulation GAP-a3-AGN can freely escape from the disc maintaining its initial velocity \( v_w = 10^4 \text{ km s}^{-1} \). In contrast, in simulation a1-AGN the interaction of the AGN wind with the circumbinary disc results in a more complex kinematics of the outflow/inflow. Also, in simulation a1-AGN, a fraction of the outflow does not reach a velocity greater than the escape velocity of the system \( v_{\text{esc}} \) meaning that this gas is trapped by the gravitational potential of the stellar bulge and will inevitably return to the circumbinary disc.

Even though the environment around the circumbinary disc is not realistically modelled (because there is no extra gas and the presence of stars is modelled by a static spherical potential) the difference in the kinematics of the outflows/inflows for the two binary-disc regimes suggests that observations of the broad and narrow absorption lines of AGN could contain information on how the winds ejected from the accretion discs of a SMBH interact with the circumbinary disc. However, any relevant conclusion about this link will need more numerical studies that take into account the effects of gas and stars around the circumbinary.

5 CONCLUSIONS

In this work we have studied, using numerical simulations, the effect of AGN feedback on the shrinking rate of SMBHBs embedded in gaseous circumbinary discs. For this we have implemented in the SPH code Gadget-3 a model for AGN feedback, following Choi et al. (2012), which includes:

\[ M(\Delta t) \frac{\Delta t}{M_{\text{bin}}} \]

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**Figure 9.** Mass of gas inside \( r = a_{\text{inh}} \) as a function of time for three simulations: a1 (thin crossed line), a1-AGN (dashed thick line) and a1-lowr-AGN (solid thick line). The enclosed mass is in units of \( M_\odot \) and time is in units of the initial orbital time \( t_{\text{orb}} \). AGN feedback excavates a “feedback cavity”, decreasing the enclosed mass, on different timescales for simulation a1-AGN and a1-lowr-AGN. The binary therefore stalls at different separations in both simulations.
Figure 10. Sound speed of the gas $c_s$ as a function of radius. Each panel corresponds to simulations with the same initial conditions. The top panels correspond to simulations with tidal cavity and the bottom panels to simulations without tidal cavity. In each panel $c_s$ is shown at the beginning of the simulation (dashed line), at the end of the simulation without AGN feedback (solid line) and at the end of the simulation with AGN feedback (dotted line). In simulations with an initial tidal cavity/gap (top panels) the sound speed is not strongly affected by AGN feedback, however, in simulations without an initial tidal cavity/gap (bottom panels) AGN feedback opens a “feedback cavity” and increases the sound speed of the gas in this inner region.

Figure 11. Thickness of the disc as a function of radius. Each panel corresponds to simulations with the same initial conditions. The top panels correspond to simulations with tidal cavity and the bottom panels to simulations without tidal cavity. In each panel $H/R$ is shown at the beginning of the simulation (dashed line), at the end of the simulation without AGN feedback (solid line) and at the end of the simulation with AGN feedback (dotted line). For systems with and without tidal cavity AGN feedback does not have a strong effect on the thickness of the disc.
Figure 12. Rotational velocity of the disc as a function of radius. Each panel corresponds to simulations with the same initial conditions. The top panels correspond to simulations with tidal cavity and the bottom panels to simulations without tidal cavity. In each panel $v$ is shown at the beginning of the simulation (dashed line), at the end of the simulation without AGN feedback (solid line) and at the end of the simulation with AGN feedback (dotted line). In systems with tidal cavity (top panels) AGN feedback does not change significantly the rotational velocity of the gas, however, in systems without tidal cavity (bottom panels) AGN feedback generates strong winds that collide with the disc and modify the rotational velocity.

Figure 13. Stability parameter of Toomre $Q$ as a function of radius. Each panel corresponds to simulations with the same initial conditions. The top panels correspond to simulations with tidal cavity and the bottom panels to simulations without tidal cavity. In each panel $Q$ is shown at the beginning of the simulation (dashed line), at the end of the simulation without AGN feedback (solid line) and at the end of the simulation with AGN feedback (dotted line). For simulations with an initial tidal cavity (top panels) AGN feedback does not change significantly the stability of the disc. For simulations without an initial tidal cavity (bottom panels) AGN feedback increases the value of $Q$ in the inner region of the disc by a factor of $\sim 10$. 

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When AGN feedback is active in a binary-disc system, the binary shrinks from parsec to milli-parsec scale in 1-10 orbits. As expected, for simulations without AGN feedback, when a tidal cavity forms the binary separation remains the same after $2 \times 10^5$ orbits and for binary-disc systems where no tidal cavity is formed the binary shrinks from parsec to milli-parsec scale in 1-10 orbits.

- When AGN feedback is active in a binary-disc system with a tidal cavity, the evolution of the binary separation and the structure of the disc are not affected by the presence of the AGN feedback because the wind launched from the SMBHB can escape perpendicularly to the circumbinary disc through the tidal cavity without crashing against the disc.
- When AGN feedback is active in a system without tidal cavity the SMBHs accrete at high rates. The winds are strong and collide against the disc, pushing the gas away from the binary. This opens a “feedback cavity” which results in the stalling of the binary migration.
- The radial velocity of the outflows produced by the winds in the regime with tidal cavity is the wind initial velocity $v_w$. In the regime without tidal cavity, as the winds interact with the circumbinary disc, the radial velocity of the outflows cover a wider range and, in the presence of an external potential, a fraction of the displaced material returns to the disc, creating inflows as well as outflows.

From these results we conclude that if a SMBHB is embedded in an environment where its dynamical evolution is dominated by gas rather than stars, and if the SMBHB is not expected to open a tidal cavity in the gaseous environment, then AGN feedback is the most important factor determining the orbital evolution of a SMBHB. This is because it pushes gas away from the binary opening a “feedback cavity”, thus forcing the binary to migrate slower. AGN feedback can therefore stop the migration of the SMBHB. However, if the SMBHB opens a tidal cavity, then AGN feedback does not play a crucial role on the orbital evolution of the SMBHB.

In this context, we may expect SMBHBs to be part of a population of double peaked lines AGNs, double compact cores (e.g. Rodriguez et al. 2006) or quasi periodic quasars (e.g. Graham et al. 2015) that will not enter on the regime of gravitational wave emission until they become part of a new galaxy merger, where the binary can become part of a triplet (Bonetti et al. 2017), or until some inflow of gas reaches the binary, driving the further shrinking of the binary (Dotti et al. 2015; Maureira-Fredes et al. 2018; Goicovic et al. 2018).

However, further research has to be done to assess the relevance of AGN feedback in the full cosmological landscape of the evolution of SMBHs. For example, we need to understand in more detail the typical environment of parsec scale SMBHBs and how the characteristic of this environment depends on the previous history of the galaxy merger.

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**Figure 14.** Radial velocity of the outflows/inflows at different radii after ~2 Myr. Yellow (orange) points correspond to the absolute value of the radial velocity of the outflows (inflows) in simulation a1-AGN. Blue points correspond to the radial velocity of the outflows in simulation Gap-a3-AGN. The velocity of the AGN wind $v_w$ is represented by a grey dashed line and the escape velocity $v_{esc}$ by a cyan curve. The outflows generated by AGN feedback in the simulation with tidal cavity (Gap-a3-AGN) can freely escape without interacting with the circumbinary disc, therefore the outflows remain with their initial velocity $v_w = 10^4$ km s$^{-1}$. Instead, in the simulation without tidal cavity (a1-AGN) AGN wind crashes against the circumbinary disc, generating outflows/inflows with a wider distribution of velocities. Also, a portion of the outflows generated in simulation a1-AGN have velocities smaller than $v_{esc}$ meaning that this gas will return as inflows toward the circumbinary disc.

![Image of radial velocity of outflows/inflows](https://example.com/image.png)

**Table 1.** Radial velocity of the outflows/inflows at different radii after ~2 Myr. Yellow (orange) points correspond to the ab-...
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APPENDIX A: MBH ACCRETION/FEEDBACK IMPLEMENTATION TEST

To test the accretion and feedback implementation, we follow the evolution of a $Q$-stable gas disc rotating around a single SMBH of $10^{6} M_{\odot}$.

Initially the disc follows a Mestel surface density profile with a radius of 6 pc, a scale height of 0.5 pc and a total mass comparable with the mass of the SMBH. We use this SMBH + disc simulation to determine if feedback can regulate taccretion and to test the results against physical expectations.

The parameters that we vary in the test simulations are: accretion radius $R_{\text{acc}}$, total number of gas particles sampling the disc $N_{\text{gas}}$ and the number of neighbours of the SPH scheme $n_{\text{bg}}$.

In order to minimize the difference on the accretion rate due to difference in the size of the accretion radius, we include another condition on accretion: we only allow the SMBH to accrete gas that has an angular momentum $J_{\text{acc}}$ smaller than the angular momentum of a circular orbit of radius 0.01 pc around the SMBH. This condition corresponds to the maximum radius of an $\alpha$-disc stable against self gravity (Kolytkhalov & Sunyaev 1980). Different accretion radii result in different accretion rates. This difference can be easily understood: when the MBH has a larger region to eat from (larger $R_{\text{acc}}$) it eats more.

When AGN feedback is active (Fig. A2) the mean fractional difference between simulations “SR” and “MR” is of $\sim$ 89% which is slightly smaller than the mean fractional difference without AGN feedback $\sim$ 96%. For the simulation with the largest accretion radius (“LR”) the initial AGN feedback is so intense that the gas is blown away and the SMBH accretion stalls. This is even clearer in Fig. A3, where the strong AGN feedback in simulation “LR” destroys the disc.

In order to minimize the difference on the accretion rate due to difference in the size of the accretion radius, we only allow the SMBH to accrete gas that has an angular momentum $J_{\text{acc}}$ smaller than the angular momentum of a circular orbit of radius 0.01 pc around the SMBH. This radius corresponds to the maximum radius of an $\alpha$-disc stable against self gravity (Kolytkhalov & Sunyaev 1980). The extra condition allows the SMBH with larger accretion radius (“LR”) to continue its accretion without blowing away all the gas (Fig. A4). In fact, its accretion results in a total accreted mass compara-
A2 Mass Resolution and the Effect of Neighbour Number in Viscosity

We study how the number of particles that are sampling the gas disc can affect the accretion rate. For this purpose, we run 5 simulations with a different number of particles and a different number of neighbours used by the SPH scheme.

In Fig. A6 we show the accretion rate of the SMBH (normalized to the Eddington rate) in three different simulations, all of them with the same accretion radius. The solid line corresponds to a simulation with $2 \times 10^5$ particles sampling the gas disc and where the SPH kernel used 64 neighbours, the dashed line corresponds to a simulation where the disc is sampled with $10^6$ particles also with 64 neighbours and the dotted line corresponds to a simulation with $10^7$ particles but with 320 neighbours. The higher resolution simulations ($N_{\text{gas}} = 10^7$) have a smoother accretion rate curve. If we increase the number of particles without changing the number of neighbours (solid line compared to dashed line) the accretion rate decreases by a factor of $\sim 2$. This happens because accretion on to the SMBH is controlled by the viscosity in the disc, which can be estimated as $\nu_{\text{SPH}} = 0.1 \alpha_{\text{visc}} (h_{\text{SPH}}) c_s$ where $\alpha_{\text{visc}}$ is a constant value that is an input parameter of Gadget-3 to model the viscosity.

Figure A2. Accretion rate normalized by Eddington accretion rate against time in 3 simulations with different accretion radii. $R_{\text{acc}} = 0.4$ pc (red line or “LR”), $R_{\text{acc}} = 0.1$ pc (blue line or “MR”) and $R_{\text{acc}} = 0.04$ pc (green line or “SR”). All these simulations include the AGN feedback implementation. In simulations with small accretion radius (“SM”) and medium accretion radius (“MR”) the accretion rate of the black hole are comparable thanks to the AGN feedback. Instead, for the large accretion radius (“LR”), the initial spike in accretion generates strong feedback that totally stops any further accretion on to the black hole.

Figure A3. Density projection of simulation “LR” at three different times. The intense feedback in simulation “LR” pushes away all the gas around the black hole stopping any further accretion.

Figure A4. Ratio between accretion rate in simulations with a small accretion radius “SR” ($R_{\text{acc}} = 0.01$) and simulations with a large accretion radius “LR” ($R_{\text{acc}} = 0.4$). The dashed dark-red curve corresponds to simulations with accretion but without AGN feedback and the solid dark-green curve corresponds to simulations with accretion and AGN feedback. An angular momentum restriction on to the black holes results in a more similar accretion rate between simulations with a small accretion radius (“SR”) and a large accretion radius (“LR”).

Figure A5. Ratio between the total accreted mass in simulations with a small accretion radius “SR” ($R_{\text{acc}} = 0.01$) and simulations with a large accretion radius “LR” ($R_{\text{acc}} = 0.4$). The dashed dark-red curve corresponds to simulations with accretion but without AGN feedback and the solid dark-green curve corresponds to simulations with accretion and AGN feedback. The total mass accreted by the black hole is comparable between simulations with different a accretion radius when the AGN feedback is active and an angular momentum restriction is used for the accretion.

Figure A6. Ratio between accretion rate in simulations with accretion and AGN feedback. An angular momentum restriction is used for the accretion. The intense feedback in simulation “LR” pushes away all the gas around the black hole stopping any further accretion.

Figure A7. Density projection of simulation “LR” at three different times. The intense feedback in simulation “LR” pushes away all the gas around the black hole stopping any further accretion.

Figure A8. Ratio between the total accreted mass in simulations with accretion and AGN feedback. An angular momentum restriction is used for the accretion. The intense feedback in simulation “LR” pushes away all the gas around the black hole stopping any further accretion.

Figure A9. Ratio between the total accreted mass in simulations with accretion and AGN feedback. An angular momentum restriction is used for the accretion. The intense feedback in simulation “LR” pushes away all the gas around the black hole stopping any further accretion.
Figure A6. Accretion rate normalized by Eddington accretion rate against time. The solid line corresponds to a simulation with $2 \times 10^5$ gas particles, the dashed line to a simulation with $10^6$ gas particles and dotted-dashed line to a simulation with $10^6$ particles but where the number of neighbour of the SPH scheme has been increased in order to maintain the average smoothing length roughly constant. An increase in the number of particles, which decreases the average smoothing length and subsequently the viscosity, results in a decrease in the accretion rate (dashed line) while if we also increase the number of neighbours, to maintain the average smoothing length constant, the accretion rate does not change (dotted-dashed line).

The viscosity, $\langle h_{\text{SPH}} \rangle$ is the mean smoothing length and $c_s$ is the sound speed of the disc (Lodato & Price 2010). Therefore, for a higher number of particles, and constant number of neighbours, the smoothing length will decrease resulting in a decrease of the viscosity and, as a consequence, of the accretion rate. Accordingly, in a simulation with a larger number of particles sampling the disc ($N_{\text{gas}} = 10^6$) imposing a larger number of neighbours in the SPH scheme allows to recover an accretion rate similar to the one obtained with fewer gas particles ($N_{\text{gas}} = 2 \times 10^5$).

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