Massive black hole binaries in gaseous nuclear discs

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Abstract. We study the evolution of a massive black hole pair in a rotationally supported nuclear disc. The distributions of stars and gas mimic the nuclear region of a gas–rich galaxy merger remnant. Using high–resolution SPH simulations, we follow the black hole dynamics and trace the evolution of the underlying background, until the black holes form a binary. We find that the gravitational perturbation of the pair creates a core in the disc density profile, hence decreasing the gas-dynamical drag. This leads the newly formed binary to stall at a separation of $\sim 5$ pc. In the early phases of the sinking, black holes lose memory of their initial orbital eccentricity if they co–rotate with the disc, as rotation of the gaseous background promotes circularization of the BH orbits. Circularization is efficient until the black holes bind in a binary, though in the latest stages of the simulations a residual eccentricity $\sim 0.1$ is still present. Black holes are treated as sink particles, allowing for gas accretion. We find that accretion strongly depends on the dynamical properties of the black holes, and occurs preferentially after circularization.

Key words. Black hole physics – Hydrodynamics – Galaxies: starburst – Galaxies: evolution – Galaxies: nuclei

1. Introduction

Collisions of gas rich spiral galaxies may trigger starbursts as those observed in luminous infrared galaxies (LIRGs). A large number of LIRGs hosts a central rotationally supported massive (up to $10^{10} M_\odot$) gaseous disc extending on scales of $\sim 100$ pc (Sanders & Mirabel 1996; Downes & Solomon 1998). These discs may be the end–product of gas–dynamical, gravitational torques excited during the merger, when large amounts of gas is driven into the core of the remnant (Kazantzidis et al. 2005; Mayer et al. 2007).

Inside a massive self–gravitating disc, a putative MBH pair can continue its dynamical evolution, and, possibly, can accrete gas, producing an observable double AGN (Kocsis et al. 2005, Dotti et al. 2006). Here we study the role of a nuclear gaseous disc in driving the or-
bital evolution of the MBH binary, and asses
the possibility of gas accretion into each pair
member.

2. Simulation setup

We follow the dynamics of MBH pairs in
nuclear discs using numerical simulations
run with the N–Body/SPH code GADGET
(Springel, Yoshida & White 2001).

In our models, two MBHs are placed in
the plane of a a gaseous disc, embedded in a
larger scale stellar spheroid. The gaseous disc
is modeled with 2 \times 10^6 particles, has a total
mass \( M_{\text{Disc}} = 10^9 \text{M}_\odot \), and follows a Mestel
surface density profile. The disc is rotation-
ally supported, and has a radial and vertical
scale of 100 and 10 pc, respectively. SPH par-
ticles evolve adiabatically (with a polytrophic
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The disc is modeled with 10^5 collisionless particles, initially
distributed as a Plummer sphere, with a core
radius of 50 pc, and a total mass \( M_{\text{Bulge}} = 6.98 M_{\text{Disc}} \).

The two MBHs are equal mass \( (M_{\text{BH}} = 4 \times 10^6 \text{M}_\odot) \). \( M_1 \) is placed at rest at the cen-
tre of the circumnuclear disc, while \( M_2 \) is ini-
tially orbiting in the plane of the disc on an
orbit whose eccentricity is \( \approx 0.7 \), at a separa-
tion of 50 pc from \( M_1 \). \( M_2 \) can either be co–or
counter–rotating with respect to the circumnu-
clear disc (runs A and B, respectively).

We allow the gas particles to be accreted
onto the MBHs if the following two criteria are
fulfilled:

- the total energy (kinetic + internal + gravi-
tational) of the gas particle is lower than 7/10
of its gravitational energy (all the energies are
computed with respect to each MBH)
- the total mass accreted onto a MBH every
timestep is lower than the \( M \) corresponding to
an Eddington luminosity \( (L_{\text{Edd}}) \) assuming a ra-
diative efficiency of 10%.

The spatial resolution of the hydrodynamical
force in the highest density regions is \( \approx 0.1 \)
pc. We set the gravitational softening for the
gaseous particles and the MBHs at the same
value to prevent numerical errors due to the
different resolution. With this spatial resolution
we can resolve the influence radius of \( M_1 \) \( (\approx 1 \)
pc), a condition necessary to asses gas accre-
tion \(^1\).

3. MBHs dynamical evolution

The upper panel of Fig. 1 shows the separa-
tion between the two MBHs as a function of
time for run A. The two MBHs reach a sepa-
ration of the order of few pc in less than 10
Myr. After an initial fast migration, the shrink-
ing process becomes inefficient and the binary
stalls at a separation of \( \approx 5 \) pc, larger than our
force resolution.

The eccentricity evolution of the MBH pair
is presented in the middle panel of Fig. 1. The
MBH pair loses memory of its initial eccen-
ctricity in the early phases of the orbital de-
cay, when the two MBH are at a separa-
tion of \( \sim 10 \) pc. Such circularization happens because of
the different effects that dynamical friction
exerts on \( M_2 \) at different orbital phases (see
Dotti, Colpi & Haardt 2006; Dotti et al. 2007
for a detailed review). Dynamical friction is ef-
cient in reducing the eccentricity down to val-
ues \( < 0.1 \), while, when the binary forms, ec-
centricity grows again, up to \( \approx 0.1 \).

The stalling of the MBH pair and the resid-
ual eccentricity are due to the formation of a
central core in the gaseous disc, as shown in
Fig. 2. The primary cause of the core forma-
tion is energy and angular momentum transfer
from the orbiting MBH to the disc due to the
dynamical friction. The inner core forms dur-
ing the early phases of the MBH orbital decay,
when \( M_2 \) orbit is still eccentric. We note that
the interaction between the MBHs and the cir-
cumnuclear disc in this phase was not fully re-
solved in Dotti et al. (2007). As a check of our
initial conditions, we evolved the disc without
\( M_2 \) for \( \sim 10^7 \) yr, and no core formation was ob-
served. We also ran the same simulation with
accretion switched off, and we found no differ-

\(^1\) The influence radius of \( M_2 \) depends on the
phase of its orbit.
Fig. 1. Run A. Upper panel: MBH separation as a function of time. Middle panel: MBH pair eccentricity evolution. The shaded area refers to the time before the first apocentre, when we can not evaluate the value of the eccentricity. Lower panel: Eddington accretion ratio as a function of time. Red and blue lines refer to M1 and M2, respectively.

ences in the dynamical evolution of the MBH pair, as expected due to the small amount of gas accreted by the MBHs with respect to the total mass of the circumnuclear disc (∼0.1%).

For the counter-rotating case (Run B) we find that the two MBHs also stall at a separation of ≈5 pc with a non zero eccentricity as illustrated in Fig. 3. The middle panel of Fig. 3 shows the evolution of the z–component of the orbital angular momentum \( L_z \) of \( M_2 \), normalized to its initial value. The angular momentum (initially negative) grows very efficiently during the first Myr, when \( M_2 \) is passing through the central, high density region of the disc. Angular momentum continues to grow monotonically for the next 3−4 Myrs, then becomes positive (\( L_z \approx 0.1 \)). That is, \( M_2 \) starts to move on a co–rotating orbit with respect to the disc. The dynamical friction process is the ultimate cause of this orbital “angular momentum flip”.

4. Accretion processes

Fig. 1 and 3 allow a direct comparison between the dynamical properties of the two MBHs and the accretion rates in runs A and B respectively. The upper panels show the MBHs separation, while the lower panels show the Eddington ratio \( f_{\text{Edd}} = \dot{M}/\dot{M}_{\text{Edd}} \) for the central (red lines) and orbiting (blue lines) MBHs. In both runs, \( M_1 \) accretes at \( f_{\text{Edd}} \approx 0.5 \), with a slight decrease with time. \( M_2 \), instead, behaves differently. In run A, during the first 7 Myrs, on average it owns \( f_{\text{Edd}} \approx 0.4 \). \( M_2 \) accretion history can be divided in two phases:

1a) for \( t \sim < 2.5 \) Myrs the circularization process is still efficient. During this phase \( f_{\text{Edd}} \approx 0.3 \) on average, showing strong variability;

2a) for \( t \sim > 2.5 \) Myrs, \( M_2 \) is moving on a quasi–circular orbit, and the relative velocity between \( M_2 \) and the gaseous disc is reduced. In this phase, \( f_{\text{Edd}} \approx 0.45 \) on average. Larger variability of \( f_{\text{Edd}} \) can be observed onto the counter–rotating \( M_2 \) in run B. We can still distinguish two phases: 1b) for \( t \sim < 3 \) Myr, \( M_2 \) is still counter–rotating (\( L_z < 0 \)), and \( f_{\text{Edd}} \approx 0.1 \), well below \( f_{\text{Edd}} \approx 0.25 \) obtained averaging over 5 Myr;

2b) for \( t \sim > 3 \) Myr, \( M_2 \) accretes at \( f_{\text{Edd}} \approx 0.45 \) (on average).
Fig. 3. Run B. Upper panel: MBHs separation as a function of time. Lower panel: Eddington accretion ratio as a function of time. Red and blue lines refer to $M_1$ and $M_2$, respectively.

5. Conclusions

Our two high resolution runs show that the gas–dynamical interaction between the massive circumnuclear disc and MBHs is unable to bring the two MBHs at separations of the order of the force resolution ($\approx 0.1$ pc) in $\approx 5$ Myr. Circularization of the initially eccentric orbit of $M_2$ is efficient until the MBHs form a binary. In the latest stages of our simulations the eccentricity grows again up to $\approx 0.1$. These results are strictly connected to the formation of a central core in the surface density profile of the circumnuclear disc, due to the energy and angular momentum exchange between the MBH pair and the gaseous particles. We stress that we could catch the formation of the central core (and the stalling of the binary) because of the high spatial resolution adopted from the beginning of the simulation, which was increased by a factor $\approx 10$ compared to our previous simulations. It must be pointed out that, as discussed in Mayer et al. 2007, the fate of the MBH binary could be strongly affected by cooling/heating processes, not implemented in our runs.

Thanks to the high spatial resolution of our simulations that allows the code to resolve the sphere of influence of the MBHs, we studied for the first time the mass accretion rate as a function of the dynamical properties of the MBHs: we found that variable double nuclear activity can be observable for few Myr, when the two MBHs orbit with relative separations $\approx 10$ pc. The accretion rate on counter–rotating orbits is more variable, and lower by a factor of 4-5 when compared to $M_2$ co–rotating with the disc.

References