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The Dynamics of Supermassive Black Holes in a Gaseous Medium

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Abstract
We present a numerical study of the dynamics of supermassive black holes (SMBH) in a gaseous medium. The importance of the study relies on its implications for the fate of SMBH in mergers of protogalaxies with large amounts of gas and in the accretion history of SMBH. We investigate the evolution of a binary SMBH in a gaseous sphere for different M_{gas}/M_{binary} ratios and for different equations of state (adiabatic, isothermal), in particular focusing on the merging timescales of the SMBH's leaving the role of accretion for future work.

1.1 Problem Setup

In order to model the self-gravitating gas we use the Smooth Particle Hydrodynamics (Lucy 1977) code called GADGET (Springel, Yoshida & White 2000). The code has been successfully tested in a broad range of problems such as galaxy formation, star formation & large scale structure.

We performed several tests of the code such as Evrard collapse, collapse of a rotating cloud and politropic oscillations. In this particular problem we also check that the results converge as we increase the number of particles.

The model consists of a self-gravitating gas sphere that is in hydrostatic equilibrium. Since we run models with two different equations of state the density profile is different in each case in order to satisfy such equilibrium. For an isothermal equation of state, the density profile follows the nonsingular isothermal sphere (Bonnor-Ebert stable). In the adiabatic case the density profile is obtained from the Lane-Emden equation for n=1.5.

We introduce a SMBH (collisionless particle) in a circular orbit within the equilibrium gas sphere and follow its evolution over several orbits.

1.2 Comparison to the Stellar Case

We focus on the importance of the hydrodynamical friction relative to the stellar dynamical friction. For that we compare the evolution of a single SMBH(the SMBH has 1% of the total mass of the gas) on a circular orbit in our gas configurations with the evolution of its stellar analog that is in a dynamical equilibrium and has the exact same density profile (chapter 4.4 of Binney & Tremaine).

The comparison between the gaseous and stellar isothermal sphere (Fig 1) shows that the drag timescale is approximately a factor of 2 shorter for the gas configu-

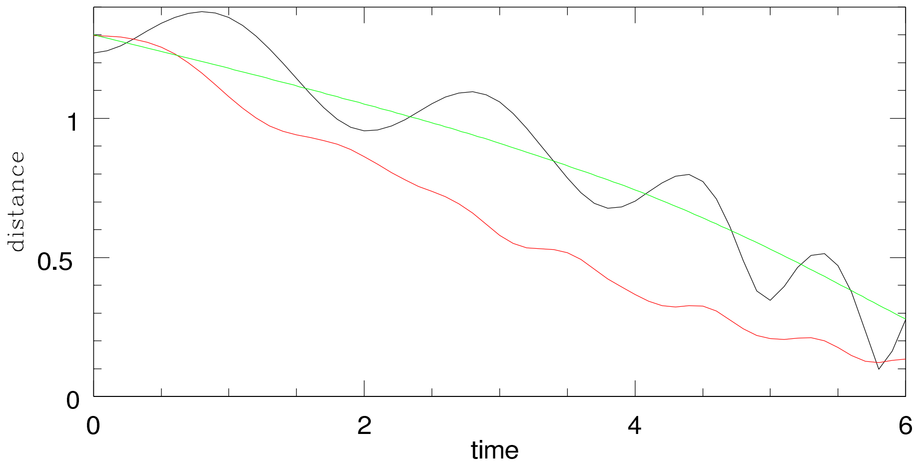

Fig. 1.1. The plot shows the evolution of the distance (in code units) of the SMBH measured from the center of mass of the isothermal sphere. The lines are the results for: gaseous sphere (red), stellar sphere (black) and Chandrasekhar's dynamical friction formula (green).

ration. The velocity of the SMBH is initially supersonic ($\sim 1.4\,C_S$) and remains barely supersonic throughout the simulation. Thus previous analytical work done by Ostriker(1999) overestimates the hydrodynamical friction in the transonic regime.

In the adiabatic case Fig 2 we obtain similar results (a higher drag effect in the gaseous configuration) as long as the velocity is supersonic (initially $\sim 1.4\,C_S$). Comparing Figs 1 & 2 we found that the drag effect compared with its stellar analog is only slightly higher in the isothermal case concluding that the role of the equation of state is relatively smaller than other effects that we will analyze later (mach number profile and the bh mass). When the SMBH velocity become subsonic (t=10 for the gas and t=16 for stars in Fig 2) the drag effect produced by stars became comparable to that produced by gas, as found by Ostriker(1999).

1.3 Evolution of a binary SMBH

We are interested in studying the importance of the drag on the evolution of a binary SMBH to determine the timescales for a considerable hardening of the binary and possible merging. Thus we follow the evolution of two equal mass massive bodies initially on a circular supersonic orbit.

Fig 3(top) shows the evolution of the binary for several orbits in the isothermal case. The different curves represent the binary separation for different (M_{binary}/M_{gas}) ratios: 0.02, 0.06 and 0.1. As expected the more massive black hole binary suffer a larger drag deceleration. The binary evolution has an strong dependence on the SMBH's masses, although such dependence is less than that expected from the Chandrasekhar formula.

The interaction of the massive bodies with the gas also produces an effect on the gas as shown in Fig 4(top) where the colors represent the density enhancement in

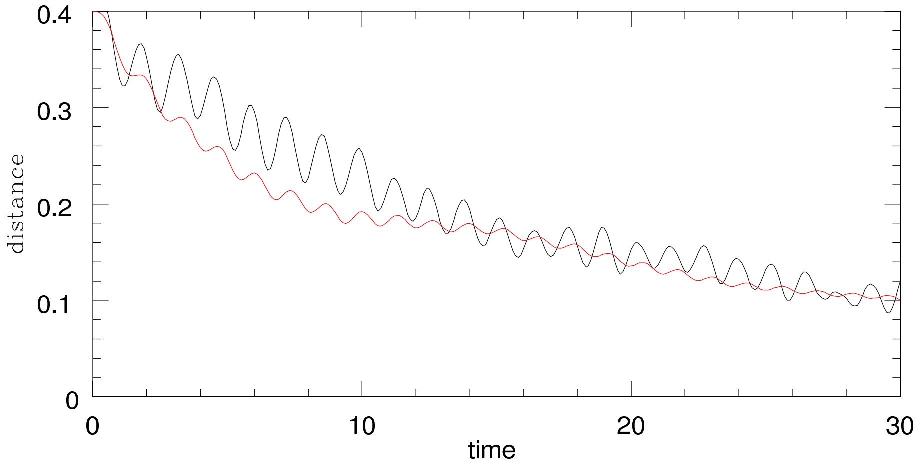

Fig. 1.2. The plot shows the evolution of the distance (in code units) of the SMBH measured from the center of mass of the adiabatic sphere. The lines are the predictions for: gaseous sphere (red), stellar sphere (black). The velocity of the SMBH became subsonic at t=9 for gas & t=15 for the stellar case.

the plane of the orbit. Each SMBH moves at a supersonic velocity producing a spiral shock that propagates outwards with a barely supersonic speed ($1.1\,C_S$).

We repeat the same procedure for the adiabatic sphere following the evolution of the binary for different mass ratios (Fig 3 bottom). The coalescence timescale is approximately a factor of 3 longer than in the isothermal sphere. This is mainly due to the fact that in the isothermal sphere the binary SMBH stays longer in the transonic regime where the drag force is more efficient (Ostriker 1999) than in the adiabatic sphere (steeper mach number profile). We also found a similar dependence of the evolution on the SMBH masses.

The spiral feature (Fig 4 bottom) that produces the interaction of the massive objects with the adiabatic gas is qualitatively the same as found for the adiabatic case. The only difference is that the density contrast ($\rho(r,t)/\rho(r,0)$) is now smaller due to the higher pressure exerted by the adiabatic gas.

1.4 Conclusions

We found that the hydrodynamical friction plays an important role in the evolution of a binary SMBH, reducing by almost 2 orders of magnitude the SMBH's separation in only few initial orbits. If we scale the adiabatic sphere to the center of an Ultra Luminous Infrared Galaxy, i.e. $M_{gas} = 10^{10} M_\odot$ & $r = 100pc$, the sound speed of the system is $t_{sound} = 3\,10^5 yr$. Thus a binary of $5\,10^8 M_\odot$ SMBH's will reduce it's separation from 160pc to 3pc in $3\,10^6 yr$.

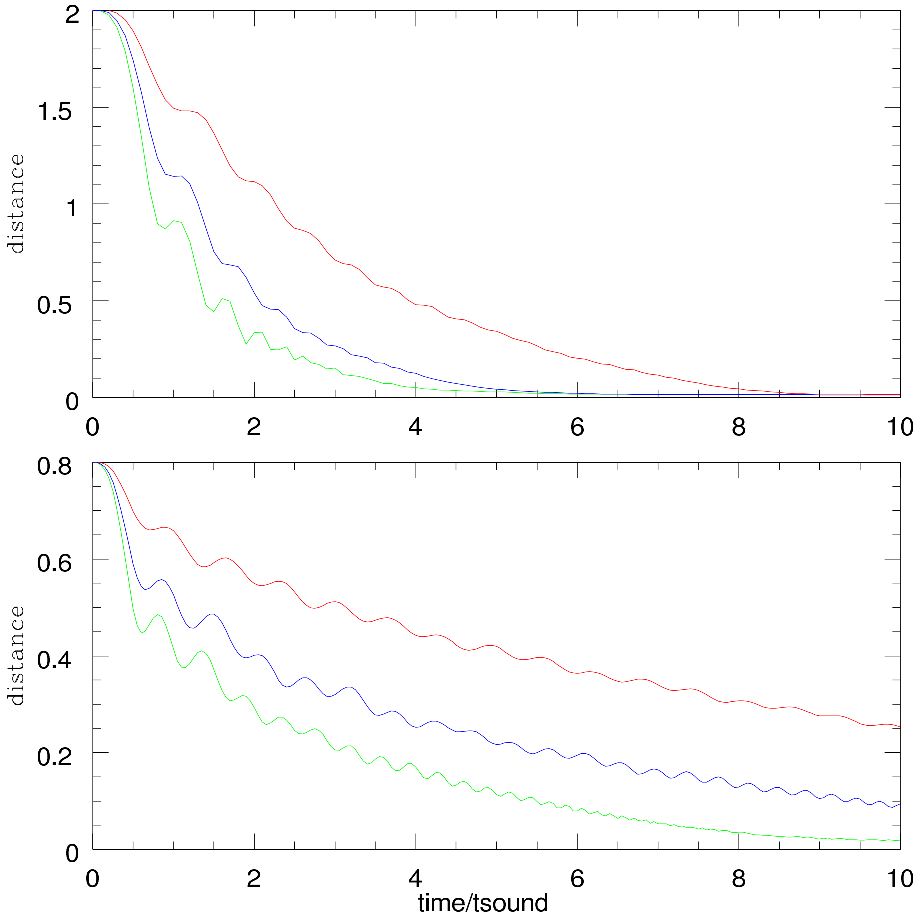

Fig. 1.3. The plot (top) shows the evolution of the binary in the isothermal sphere, the different curves represents the separation between the black holes for different mass ratios: $M_{binary} = 0.02 M_{gas}$ (red), $M_{binary} = 0.06 M_{gas}$ (blue), $M_{binary} = 0.1 M_{gas}$ (green). The bottom figure presents the same evolution but in an adiabatic sphere.

References

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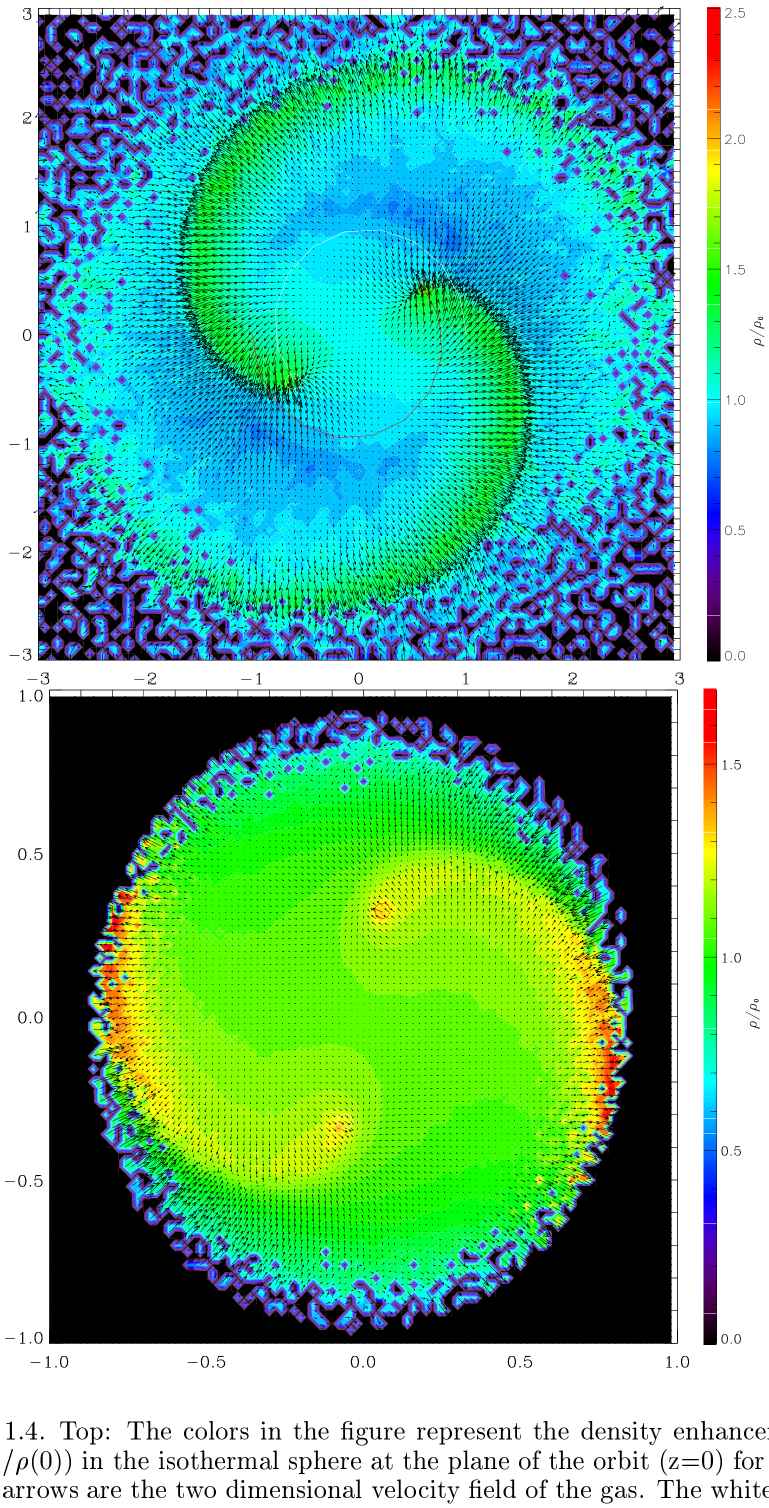

Fig. 1.4. Top: The colors in the figure represent the density enhancement $(\rho(t)/\rho(0))$ in the isothermal sphere at the plane of the orbit (z=0) for t=1. The arrows are the two dimensional velocity field of the gas. The white and red curves are the individual orbits of the SMBH's between t=0 and t=1. In this simulation the mass of the binary is 2% of the mass of the gas. bottom: Same as above in the adiabatic sphere.