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THE FATE OF MASSIVE BLACK HOLES IN GAS-RICH GALAXY MERGERS

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RESUMEN

Utilizando simulaciones numéricas SPH, investigamos los efectos de gas sobre la inspiral y la fusión de una binaria de agujeros negros masivos. Este estudio fue motivado por los discos de gas nucleares muy masivos que se observan en las regiones centrales de galaxias en fusión. Aquí presentamos los resultados que amplían el tratamiento de trabajos previos (Escala et al. 2004, 2005) mediante el estudio de la evolución de una binaria con diferentes masas de agujeros negros en un disco de gas masivo.

ABSTRACT

Using SPH numerical simulations, we investigate the effects of gas on the inspiral and merger of a massive black hole binary. This study is motivated by the very massive nuclear gas disks observed in the central regions of merging galaxies. Here we present results that expand on the treatment in previous works (Escala et al. 2004, 2005), by studying the evolution of a binary with different black holes masses in a massive gas disk.

Key Words: **BLACK HOLE PHYSICS — COSMOLOGY: THEORY — GALAXIES: EVOLUTION — HYDRODYNAMICS — QUASARS: GENERAL**

1. INTRODUCTION

A long-standing problem in astrophysics, that is whether galaxy mergers necessarily lead to massive black hole mergers in their centers. This problem has been widely studied in the context of the long-term evolution of a black hole binary at the center of a dense stellar system (Begelman et al. 1980). However, the fate of a binary in the stellar system is unclear and the coalescence stalls unless additional mechanisms are able to extract angular momentum from the binary (Makino & Funato 2004; Berczik et al 2005).

The situation is different if the MBH binary is inmersed in a gaseous medium, the best candidate mechanism for extracting angular momentum. Both observational and theoretical work indicate that large amounts of gas are likely to be present in the central regions of merging galaxies. In previous works, we investigated the effects of gas on the inspiral and merger of a MBH binary using SPH numerical simulations (Escala et. al 2004, 2005; see also Dotti et al. 2006). We ran a variety of models of MBH binaries inmersed in gas, ranging from smooth nearly spherical gas cloud to cases in which the gas is in a clumpy disk. We also varied the angle between the plane of the binary and the plane of the disk, and the mass ratio between the MBHs and the gaseous disk. In the variety of simulations that we performed, we found that gravitational drag is able to reduce the separation to distances where gravitational radiation is efficient in a timescale that varies between 5×10^6yr and 2.5×10^7yr

2. RESULTS

Here we extend our work by varying the mass ratio between the primary and secondary BHs. We perform simulations with four different binary mass ratios (M^1_{BH}/M^2_{BH}): 1, 2/3, 1/3 and 1/10 (Figure 1a). We choose the first 3 mass ratios in order to represent what happen with the MBHs in a 'major' galaxy merger, for MBHs with masses propotional to the host galaxy mass, and the last one to represent a 'minor' galaxy merger. We consider a MBH binary in which the primary black hole (M^1_{BH}) has a mass equal to 1% of the total gas mass, and the binary is initially in the plane of the disk. Figure 1a shows the evolution of the binary separation in these four cases over several orbits. In the early evolution of the system, approximately up to t=18 (being $2.5\,10^5$yr the time unit), there is not a clear difference between the four runs. This is because the binary separation diminishes mainly due to the migration of the primary MBH, that is the same in the four runs, to the center of mass of the system. After the arrival of the primary MBH to the center, the binary separation has a strong dependence on the mass ratio; this is

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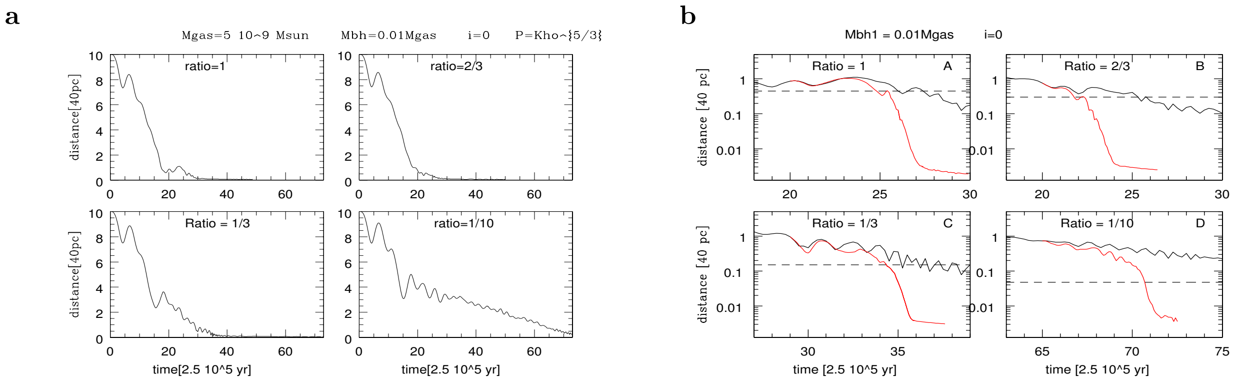

Fig. 1. (*a*) This plot shows the evolution of the binary separation for runs which assume 4 different ratios between the mass of each MBH and the mass of the gas disk: 0.01, 0.03, 0.05, 0.1. For these runs we adopt an equation of state with K=0.933, and the orbit of the binary is in the plane of the disk. (*b*) This plot shows the final evolution of the binary separation for runs with four different binary mass ratios. In all cases the mass of the primary MBH is 1% of the mass of the gas and the orbit of the binary is in the plane of the disk. The black curves are the same calculations shown in Fig. 3 but on a logarithmic scale. The red curves show the results for the simulations with smaller softening length.

because the binary separation diminishes now due to the migration of the secondary MBH to the center. As expected, the binary coalescence timescale increases as we decreases the mass of the secondary black hole, because the dynamical friction exerted by the background gas is weaker as we decrease the mass of the secondary.

The runs described above were continued until the MBH separation approaches the assumed gravitational softening length of 4 pc, at which point the evolution of the system artificially stalls. To continue the evolution of the binary it is necessary to reduce the gravitational softening length, something that is extremely expensive computationally. We choose to reduce it from $\epsilon_{\rm soft}$=4 to 0.01pc in order to follow the evolution of the binary separation by one more order of magnitude.

Figure 1b shows the evolution of the binary separation in these four cases over several orbits. The black curves are the same calculations shown in Fig. 1a but on a logarithmic scale, and the red curves show the results for the simulations with smaller softening length. In the early evolution of the system, the black and red curves show almost the same behavior in each case. The situation changes drastically when the binary separation becomes less than about 0.3 (being 40pc the length unit), that is, when the binary arrives at separations comparable to the 'gravitational influence' radius of the black holes: $\mathrm{R}^{(\mathrm{i})}_{\mathrm{inf}} = 2\mathrm{GM}^{(\mathrm{i})}_{\mathrm{BH}}/(\mathrm{v}^2_{\mathrm{BH}} + \mathrm{c}^2_{\mathrm{S}})$. At these distances the binary completely dominates the gravitational potential in its vicinity, and for the case of binaries with different black holes masses, the response of the medium is the formation of a 'pear-shaped' envelope. The axis of the 'pear-shaped' envelope is not coincident with the binary axis but lags behind it, and this offset produces a gravitational torque on the binary that is now responsible for the angular momentum loss.

The formation of the 'pear-shaped' envelope typically occurs when the binary separation is about $1.5\,\mathrm{R}^{(2)}_{\mathrm{inf}}$, denoted by the horizontal dashed line in Fig. 1b and that value ranges from 0.5 to 0.05 in these four cases. May be the most surprising result found in this work, is that almost no trend among the diferent runs is found during the ellipsoidal/'pear-shaped' regime. If we compare the red curves in Fig. 1b after they cross the horizontal dashed lines, they have almost the same slope for different mass ratios despite we vary the mass ratio within a factor of 10. This result has a simple explanation by studing the properties of the so called 'Pear-Shaped' configurations in equilibrium (Jeans 1929). These results will soon be published.

In all of the cases considered, the coalescence timescale varies between 2.5 and 10 initial orbital periods, or between 5×10^6yr and 2×10^7yr for typical ULIRGs.

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