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Evolution of supermassive black hole binaries in gaseous environments

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Abstract. In this contribution, I discuss some aspects of the dynamical evolution of supermassive black hole binaries and their accretion discs. Firstly, I discuss the issue of alignment of the spins of the two binary component, which has important implications for the shape of the gravitational wave emitted at merger and for the possibility of a strong recoil of the remnant black hole. Even under the favourable assumption that mass flow through the gap is not inhibited by tidal torque, we demonstrate that differential accretion onto the two components of the systems results in a very different spin evolution of the two black holes. Secondly, I revisit the issue of how much mass can flow within the cavity carved in the disc by an equal mass binary. Recent simulations have shown that the tidal torque of the binary is generally not sufficient to prevent accretion onto the binary component. Here, I demonstrate that such results are heavily dependent on the disc thickness. While for $H/R \sim 0.1$ (the value adopted in most simulations to date), we reproduce the previous results, we show that as H/R is decreased to ~ 0.01, mass flow through the gap is essentially shut off almost completely. Thirdly, I show numerical simulations of the process of gas squeezing during the merger proper, demonstrating that most of the disc mass is accreted producing a super-Eddington flare.

Keywords. black hole physics, hydrodynamics, gravitational waves

1. Introduction

The dynamics of a binary of supermassive black holes in a gaseous environment is extremely important in several respects. On the one hand, it determines to a large extent the gravitational wave signal emitted when the binary shrinks down and eventually merges, because it affects the binary orbital parameters, including the likelihood of spin alignment at merger. On the other hand, regardless of the gravitational wave signal, this dynamics has profound implication for the cosmic evolution of black holes: if the black hole spins are strongly misaligned at merger, the remnant black hole can in principle receive a recoil with velocities as large as $\approx$ 4000 km s^{-1}, in principle able to displace it significantly from the galaxy nucleus. Finally, such systems may display peculiar time-dependent electromagnetic emission, that might be used as an "electromagnetic counterpart" to gravitational wave emission.

2. Three new results for SMBH binaries

2.1. *Differential accretion and spin alignment*

In a recent paper (Gerosa *et al.* 2015), we have demonstrated that differential accretion onto the two components of an unequal mass binary can strongly affect the process of spin alignment due to the Bardeen-Petterson effect. In particular, assuming that most of the circumbinary disc mass is funnelled into the cavity carved by the binary and feeds the two individual 'mini-discs' around each black hole (but see below for more details on this issue), still it is mostly the secondary that acquires most of the mass, while the

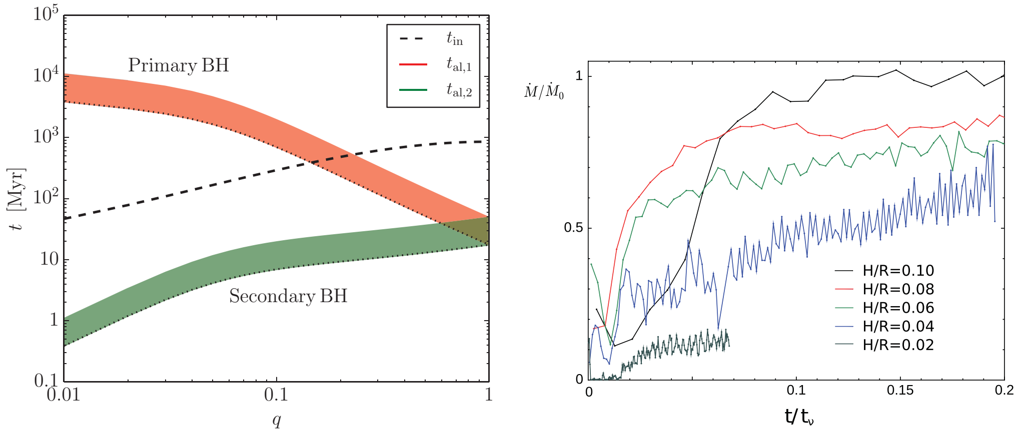

Figure 1. Left: a comparison of inspiral time (dashed line) and alignment times of the primary (red band) and secondary (green band) as a function of mass ratio q. Right: ratio of the mass accretion rate into the cavity over the unperturbed rate as a function of time for various values of the disc aspect ratio H/R. .

primary black hole remains starved, so that its alignment time becomes very large. In Figure 1 (left panel) I show a comparison of the inspiral time (dashed line) and the spin alignment time of the primary (red band) and secondary (green band), respectively, as a function of the mass ratio q, for maximally spinning black holes. It can be easily seen that for $q \lesssim 0.2$ the primary black hole does not have enough time to align its spin to that of the secondary. However, even if some misalignment can be retained in these cases, we still expect to have kicks no larger than ≈ 200 km s^{-1}, due to the low mass ratio of the system.

2.2. *Mass flow through the cavity*

Many recent investigations (Farris *et al.* 2014; D'Orazio *et al.* 2013) have shown that the tidal potential of the binary is in generally not effective at holding the circumbinary disc mass away from the binary and that substantial inflow still occurs through non-axisymmetric streams, at a rate comparable to the accretion rate through the circumbinary disc. However, all such investigations have assumed that the disc is thick, with $H/R \approx 0.1$, whereas typical AGN models predict that at scales of a fraction of a pc the disc should be much thinner, with $H/R \approx 0.001$. We have run 3D SPH simulations at high resolution (typically using 2M particles) of the process (for a circular, equal mass binary) with the aim to understand how much mass flows into the cavity when more realistic values of H/R are assumed (Ragusa *et al.* 2015, in prep.). The results are summarized in Figure 1 (right panel). For $H/R = 0.1$ we recover in great detail previous results (and in particular we reproduce accurately the results by Farris *et al.* 2014), and we confirm that indeed $\dot{M}/\dot{M}_0 \sim 1$ (the ratio between the accretion rate into the cavity and the corresponding rate for a single black hole). However, as H/R is decreased, the mass flow through the cavity decreases, with respect to the single object case, almost in direct proportionality with H/R. We thus predict that for realistic values of H/R, only $\approx 1\%$ of the unperturbed accretion rate would feed the two binary components. This would have on the one hand the effect of making such a system very much underluminous with respect to a standard AGN, and on the other hand it would significantly increase the alignment times discussed above.

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2.3. *Super-Eddington flares at merger*

Finally, I consider the fate of a remnant circumprimary disc during the merger proper, as the binary merges due to the gravitational wave emission. Early investigations (Armitage & Natarajan 2002) predicted that a super-Eddington flare should arise as the disc is squeezed by the decaying binary. Such an effect has been challenged recently due to two effects: (a) Chang *et al.* (2010) have estimated the fossil disc mass at decoupling to be very small (of order of a few Jupiter masses), so that even its complete accretion would hardly provide a luminous flare; (b) Baruteau *et al.* (2012) have run numerical simulations of the squeezing process, finding that most of the circumprimary disc mass escapes accretion by flowing past the secondary orbit as it decays to merger. We have revisited both aspects and have found that the results by Chang *et al.* (2010) actually suffer from an incorrect implementation of the binary torque: once this error is corrected, the estimated circumprimary disc masses at decoupling are of the order of $1M_{\odot}$ and would thus be able, if accreted, to produce a super-Eddington flare (Tazzari & Lodato 2015). Secondly, we have run, using again a 3D SPH code, simulations of the merger process and found again that the mass flow through the secondary orbit is a strong function of H/R (Cerioli *et al.* 2015): while Baruteau *et al.* (2012) have used a relatively large value of $H/R \approx 0.1$, when we use more realistic values (note that Lodato *et al.* 2009 predict $H/R \approx 0.001$ in the circumprimary disc at decoupling), we find that almost 80% of the mass is accreted, producing a flare lasting for several weeks with peak luminosities of the order of $1\text{–}20 \times L_{\rm Edd}$.

3. Conclusions

In this contribution I have revisited several issues concerning the dynamics of a supermassive black hole binary in a gaseous environment. My main results can be summarized as follows: (1) Spin alignment between the two components of the binary should not be taken for granted, especially for unequal mass binaries, where differential accretion is expected to starve the primary black hole and thus to lengthen significantly its alignment process; (2) I do not confirm the results of previous simulations that apparently show a significant mass inflow from the circumbinary disc into the cavity produced by the binary. This only occurs for large H/R which are not expected in these systems. When realistic values of H/R are assumed, accretion into the cavity is effectively shut off; (3) I also do not confirm previous claims that the squeezing of a fossil circumprimary disc during the black hole merger proper does not provide a super-Eddington flare. Contrary to previous results, I find that the fossil disc mass is large and is effectively accreted during the merger.

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