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Star Cluster Disruption by a Supermassive Black Hole Binary

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Binary supermassive black holes (BBHs) are expected to be one of the most powerful sources of low-frequency gravitational waves (GWs) for future space-borne detectors. Prior to the GW emission stage, BBHs evolving in gas-poor nuclei shrink primarily through the slingshot ejection of stars approaching the BBH from sufficiently close distances. Here we address the possibility that the BBH shrinking rate is enhanced through the infall of a star cluster (SC) onto the BBH. We present the results of direct summation N-body simulations exploring different orbits for the SC infall, and we show that SCs reaching the BBH on non-zero angular momentum orbits (with eccentricity 0.75) fail to enhance the BBH hardening, while SCs approaching the BBH on radial orbits reduce the BBH separation by $\sim 10\%$ in less than 10 Myr, effectively shortening the BBH path towards GWs.

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1. Introduction

Binary supermassive black holes (BBHs) are a natural by-product of galaxy mergers; as such, they are expected to form in large numbers along cosmic time [1]. The study of BBHs has received considerable attention in the last decades: when the BBH members reach separations of the order of a few mpc, they coalesce into a single supermassive black hole (SMBH) via a burst of low-frequency gravitational waves (GWs) [2]. Such GW sources will shine in the band of the future space-borne LISA observatory, making BBH mergers among the main targets for the LISA mission [3].

In the early stages of a galaxy merger, dynamical friction drives the SMBHs toward the centre of their common potential well. When the BBH separation drops below parsec scales, the BBH shrinking in gas-poor nuclei is primarily driven by three body scatterings ('slingshot ejections') of stars on sufficiently low angular momentum orbits [1]. At the beginning of the slingshot phase, the BBH promptly expels from the galaxy almost all stars able to reach its neighbourhood. After that, the BBH shrinking can slow down considerably and even stop at roughly parsec scale, unless any physical processes can guarantee a steady repopulation of the binary loss cone (i.e. the region of phase-space containing stars with sufficiently low angular momentum) [4]. For this reason, a number of studies in the last decades have investigated whether BBHs can efficiently merge in gas-poor environments [1, 5]. Currently, a general solution to the 'final parsec problem' is believed to reside in the non-sphericity of the host galaxy [6, 7, and references therein]. If the host galaxy is triaxial, gravitational torques ensure a steady scattering of stars into the BBH loss cone [8]; given that galaxy mergers are expected to naturally induce non-sphericity in the merger relic [9], most BBHs are believed to find their way to coalescence within a few Gyr [6].

Here we propose a novel possible way to shorten the BBH path to coalescence, via the infall of a massive stellar cluster (SC) onto a parsec-scale BBH. In fact, young SCs are common in galactic nuclei, and may form in a burst of star formation following the galaxy merger [10]; then, SCs may sink towards the centre of the system via dynamical friction, interacting with the BBH, and possibly significantly contributing to its hardening. The work presented here is a summary of [11]; a further study addressing the effect of SC infalls onto BBHs can be found at [12].

2. Methods and initial conditions

We simulate the infall of a SC onto a BBH adopting the highly accurate, direct summation N-body code HiGPUs [13]. We place two $10^6 \mathrm{M}_\odot$ SMBHs on a circular orbit with semimajor axis $a = 1$ pc; the BBH centre of mass coincides with the bottom of the galactic potential well, modelled as a rigid Dehnen profile [14] with total mass $5 \times 10^{10} \mathrm{M}_\odot$, scale radius 250 pc, and inner density slope $\gamma = 0.5$. A $\approx 8 \times 10^4 \mathrm{M}_\odot$ SC is set at 20 pc from the BBH centre of mass; the SC follows an isotropic King density profile [15] with core radius $r_k = 0.4$ pc, and the SC mass spectrum is modelled with a Kroupa mass function [16]. We explore three different configurations for the cluster infall: in run 1p (2p), the SC is initially at rest, and its orbital plane is perpendicular (coplanar) with respect to the BBH orbital plane; in run 3p, the SC is placed at the apoapsis of an eccentric orbit with eccentricity 0.75, coplanar with the BBH, with counter-aligned angular momentum. Each simulation is integrated for 10 Myr.

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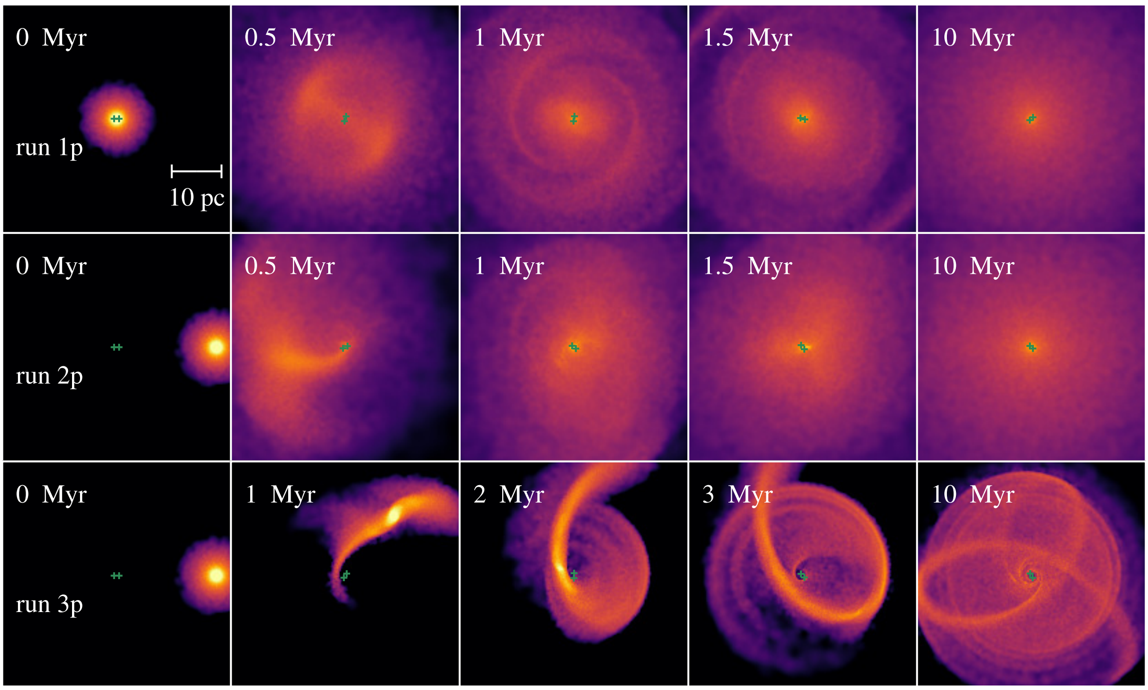

Figure 1: Time evolution of the stellar surface density projected on the BBH orbital plane for runs 1p (top row), 2p (central row), 3p (bottom row). The green central crosses mark the position of the two SMBHs. The colour coding is logarithmic, and it refers to the smoothed projected mass density of stars, ranging from 10^{-1} (black) to 10^4 $M_\odot$ pc^{-2} (white).

3. Results

Fig. 1 shows different snapshots of the simulations projected on the BBH orbital plane. The BBH response to the SC infall significantly depends on the SC orbital angular momentum.

3.1 Radially infalling SCs

If the SC is in free fall (i.e. it has zero initial angular momentum, as in runs 1p and 2p), its interaction with the BBH is rather violent: the cluster gets completely destroyed within the first $1-2$ Myr. After roughly 10 Myr, the SC stars are isotropically distributed around the BBH, and the density profile of the cluster remnant, centred on the BBH centre of mass, falls off as $\rho(r) \propto r^{-2}$ between ≈ 1 and 20 pc.

The time evolution of the BBH separation and semimajor axis is shown in the left-hand panel of Fig. 2: after 10 Myr, the BBH has shrunk by ≈ 10 (13) per cent in run 1p (2p)[1]; the BBH hardening is more efficient when the SC infall is coplanar, as in this configuration the relative velocity between the SC and the BBH members is lower. In the radial runs, the SC induced BBH hardening rate $s = d(a^{-1})/dt$ after 3.5 Myr is $\sim 10^{-2}$ pc^{-1} Myr^{-1}. The BBH eccentricity e is not significantly influenced by the interaction: in fact, $e < 0.1$ at all times.

[1]The BBH semimajor axis, as shown in the left-hand panel of Fig. 2, initially does not shrink monotonically: this results from the fact that the BBH is marginally soft with respect to the initial infalling SC.

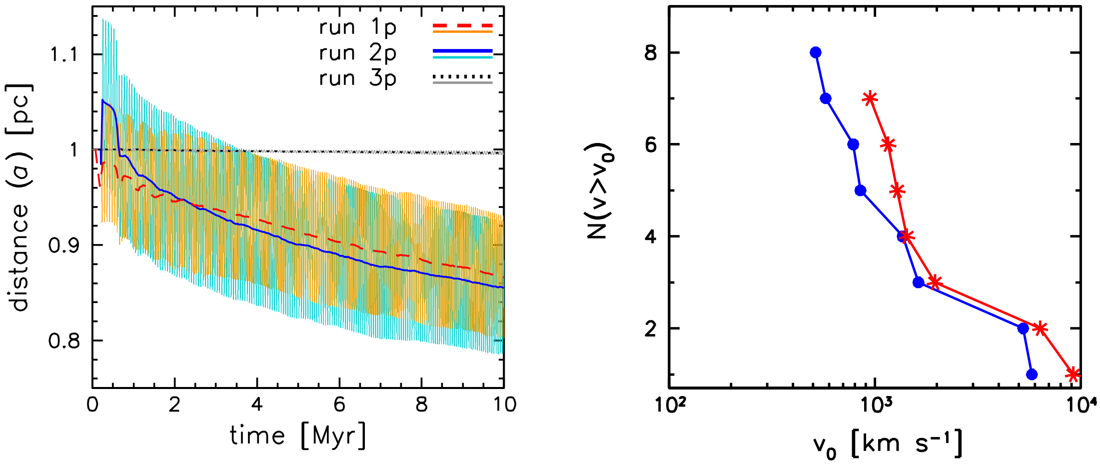

Figure 2: Left-hand panel: time evolution of the BBH separation and semi-major. Red dashed, blue solid and black dotted thick lines show the evolution of the BBH semimajor axis in runs 1p, 2p, 3p, respectively. The solid thin orange, light blue and grey lines show the time evolution of the BBH separation in the same runs. Right-hand panel: number of unbound stars N whose velocity v is greater than a threshold velocity v_0, as a function of v_0 for run 1p (red line, asterisks) ad run 2p (blue line, circles). Note that the velocities shown here are computed from a snapshot at $t = 10$ Myr.

3.2 SCs on non-zero angular momentum orbit

When some angular momentum is added to the infalling SC (i.e. in run 3p, with eccentricity 0.75), the BBH response to the SC infall is significantly weaker. In particular, the BBH semimajor axis shrinks by less than 0.5 per cent in 10 Myr (Fig. 2, left-hand panel), and its hardening rate is always of the order of $s \sim 10^{-4}$ pc^{-1} Myr $^{-1}$. Consistently, the BBH eccentricity stays nearly equal to zero throughout the simulation. The difference between run 3p and the other two simulations has to be ascribed to the amount of stars inside the loss cone region: in run 3p, a negligible fraction of stars (less than 0.3 per cent) is found to inhabit the loss cone at all times; in comparison, the fraction of stars on loss cone orbits in runs 1p and 2p is always above 25 per cent, and higher than 50 per cent at the first SC periapsis passage.

As a result of the weak interaction, the SC stars settle on a three-lobed discy structure around the BBH (Fig. 1, bottom right-hand panel), whose external radius is $R \lesssim 20$ pc and whose thickness is $\sim 0.1R$.

3.3 Hyper-velocity stars

During the interaction, most stars remain bound to the combined potential of the BBH and the galaxy throughout the 10 Myr of evolution. This happens because the BBH is still marginally soft, thus each star is expected to undergo multiple scatterings before being finally ejected from the galaxy. However, a handful of stars manages to escape the combined potential of the SMBHs and the galaxy (7 and 8 stars, respectively) in runs 1p and 2p. The number of unbound stars whose velocity is greater than a given velocity v_0 as a function of v_0 is shown in Fig. 2 (right-hand panel). The escape velocities at the moment of the ejection are always above 1,000 km s^{-1}, and can even reach 10,000 km s^{-1}; such escaping stars can be classified as genuine hyper-velocity stars.

4. Discussion and conclusion

In the present study, we studied the interaction between a 2×10^6 $M_\odot$ BBH and an SC weighting roughly 1/20 of the BBH mass. We found that the interaction is rather weak if the SC initial orbit is non-radial, as no significant BBH hardening results from the SC infall. On the other hand, if the SC radially approaches the BBH, the binary semimajor axis shrinks by ~ 10 per cent in less than 10 Myr. This result suggests that the interaction of a BBH with a ~ 10 times more massive SC (or equivalently, the radial infall of ~ 10 SCs as massive as the ones simulated in this study) might bring the BBH close to the GW emission phase.

One may wonder how often we expect a radial SC infall to happen. Several recent studies [17, 18] show that at least part of the star formation observed in the centre of our Galaxy is consistent with being triggered by the collision between molecular clouds. A SC formed as a result of such collision may have a very low angular momentum [19], thus it is expected to infall towards the centre of its host system.

Finally, our work shows that the radial infall of an SC onto a pc scale BBH may produce a number of hyper-velocity stars, whose velocities might attain values of the order of $10,000$ km s^{-1}.

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