*Star Clusters: From the Milky Way to the Early Universe*
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# The ecology of the galactic centre: Nuclear stellar clusters and supermassive black holes

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**Abstract.** Supermassive black holes are found in most galactic nuclei. A large fraction of these nuclei also contain a nuclear stellar cluster surrounding the black hole. Here we consider the idea that the nuclear stellar cluster formed *first* and that the supermassive black hole grew *later*. In particular we consider the merger of three stellar clusters to form a nuclear stellar cluster, where some of these clusters contain a single intermediate-mass black hole (IMBH). In the cases where multiple clusters contain IMBHs, we discuss whether the black holes are likely to merge and whether such mergers are likely to result in the ejection of the merged black hole from the nuclear stellar cluster. In some cases, no supermassive black hole will form as any merger product is not retained. This is a natural pathway to explain those galactic nuclei that contain a nuclear stellar cluster but apparently lack a supermassive black hole; M33 being a nearby example. Alternatively, if an IMBH merger product is retained within the nuclear stellar cluster, it may subsequently grow, e.g. via the tidal disruption of stars, to form a supermassive black hole.

**Keywords.** Stellar clusters, galactic nuclei, black holes.

## 1. Introduction

Supermassive black holes are found in most, but crucially not all, galactic nuclei. Perhaps all, and certainly most, nuclei also host a nuclear stellar cluster at the very centre (Neumayer & Walcher 2012; Voggel *et al.* 2018, 2019; Nguyen *et al.* 2019). Intriguingly, some galactic nuclei are found to contain a nuclear stellar cluster but show no evidence for a supermassive black hole. M33 is a local example. This galaxy is bulge-free, which suggests a relatively quiet history without any major mergers. We therefore conclude that M33 likely has *never* possessed a supermassive black hole. Could it be therefore that nuclear clusters form first, and supermassive black holes then grow in a subset of these clusters?

Nuclear stellar clusters may form via the inspiral and merger of smaller stellar clusters (Antonini *et al.* 2012; Mastrobuono-Battisti *et al.* 2014). If a stellar cluster is sufficiently dense, an intermediate-mass black hole (IMBHs, having a mass between 100 and 1000 $M_\odot$) may form via either runaway collisions or via the growth of a stellar-mass black hole through the tidal disruption of stars (Portegies Zwart *et al.* 2004; Freitag *et al.* 2006; Stone *et al.* 2017). The outcome of Monte-Carlo $N$-body simulations of clusters initially containing $1.2 \times 10^6$ objects are shown in Fig. 1. In considering a broad range of initial cluster properties, about 25 per cent produce IMBHs (Askar *et al.* 2017; Arca Sedda *et al.* 2019).

To investigate how often supermassive black holes are likely to form and grow within nuclear stellar clusters, we have performed a series of numerical simulations of the merger



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**Table 1.** Table showing the simulated merging stellar cluster models. Each simulated model had three merging star clusters, a central cluster (C) comprising 50000 stars, an infalling cluster (IF1) comprising 30000 stars and a second infalling cluster (IF2) comprising 15000 stars. Each of these star clusters were Plummer models with a half-mass radius of about 2.4 pc. The table lists the simulated models, number and mass of the IMBHs they contain, the initial position of the IMBH(s) and the time up to which the models were simulated.

| Models | IMBH Number and Mass | Total Mass of Merging Clusters [$M_{\odot}$] | Initial Location of IMBH(s) | Evolution Time [Myr] |
|---|---|---|---|---|
| 0.1 | No IMBH | $8.4 \times 10^4$ | None | 375 |
| 1.1 | 1 - 1000 $M_{\odot}$ | $8.5 \times 10^4$ | C | 101 |
| 2.1 | 2 - 1000 $M_{\odot}$ and 500 $M_{\odot}$ | $8.55 \times 10^4$ | C and IF1 | 135.3 |
| 2.2 | 2 - 1000 $M_{\odot}$ and 100 $M_{\odot}$ | $8.5 \times 10^4$ | C and IF1 | 75 |
| 2.3 | 2 - 1000 $M_{\odot}$ and 200 $M_{\odot}$ | $8.52 \times 10^4$ | C and IF1 | 114.3 |
| 2.4 | 2 - 500 $M_{\odot}$ and 200 $M_{\odot}$ | $8.47 \times 10^4$ | IF1 and IF2 | 173.5 |
| 3.1 | 3 - 1000 $M_{\odot}$, 500 $M_{\odot}$, 200 $M_{\odot}$ | $8.57 \times 10^4$ | C, IF1 and IF2 | 195 |
| 3.2 | 3 - 500 $M_{\odot}$, 1000 $M_{\odot}$, 200 $M_{\odot}$ | $8.57 \times 10^4$ | C, IF1 and IF2 | 66.3 |

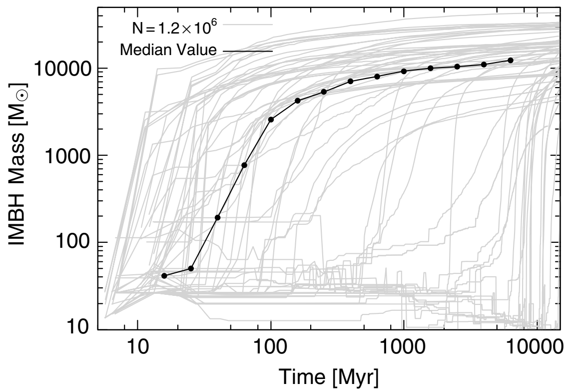


**Figure 1.** Mass of intermediate mass black holes as a function of time produced in clusters initially containing $1.2 \times 10^6$ stars as determined using the Monte-Carlo N-body code *MOCCA*.

of three stellar clusters. We consider a range of cases where various combinations of the three clusters contain IMBHs. As shown below, the outcomes will depend on the number of IMBHs contained within all three clusters.

## 2. Possible Outcomes of Cluster Mergers

Our runs are listed in Table 1. In all simulations we modelled the merger of three stellar clusters to form a nuclear stellar cluster. We considered simulations containing zero, one, two and three intermediate-mass black holes (IMBHs). Possible outcomes are described below as a function of the number of intermediate-mass black holes (IMBHs) contained within all three clusters.

*Zero IMBHs*. In Fig. 2, we show particle plots of model 0.1 where we model the merger of three clusters where no clusters contain an IMBH. The clusters merge quickly (in only a few orbits) producing a cylindrically symmetric nuclear stellar cluster containing roughly 85 per cent of the original stars.

*One IMBH*. In model 1.1, we consider the case where the central cluster contains a 1000 $M_{\odot}$ black hole. The merger follows in a very similar way to that seen in model 0.1.

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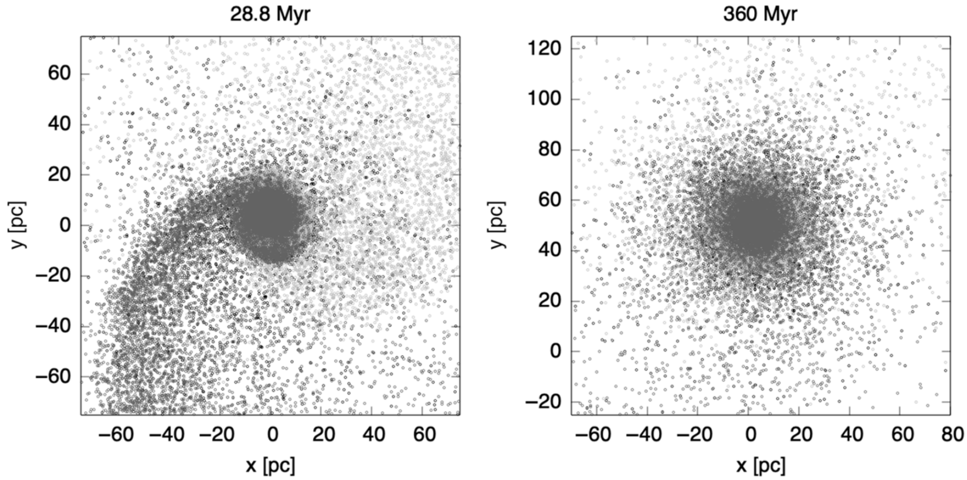


**Figure 2.** Particle plot showing the evolution of thee stellar clusters spiralling together to form a single nuclear stellar cluster (model 0.1 – containing zero intermediate-mass black holes).

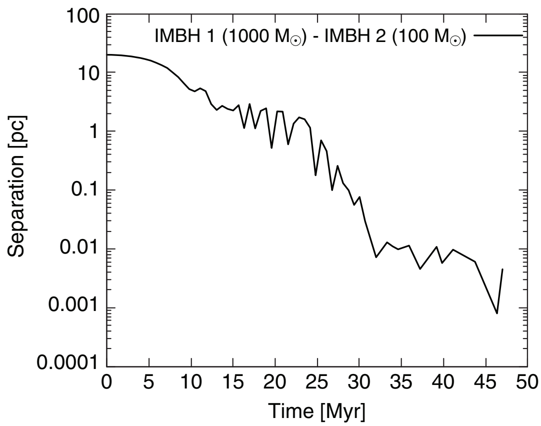


**Figure 3.** The instantaneous separation of the two IMBHs as a function of time for Model 2.2. After 30 Myr, the two black holes form a tight binary with essentially no stars between them. The non-smooth structure is due to the orbital eccentricity.

In other words, the IMBH is not found to have an immediate impact on the cluster. In at least some cases, the IMBH will later grow via stellar tidal disruptions.

*Two IMBHs*. We consider four combinations of IMBH masses and initial locations. In all cases, we find that the separation of the two IMBHs decreases significantly over time as they make their way into the central regions of the nuclear stellar cluster. They form a distinct binary after about 30 Myr. An example is shown in Fig. 3. Such binaries will likely merge via the emission of gravitational radiation and the scattering of stars. A recoil kick is likely to eject the merged black hole from the nuclear stellar cluster, unless the secondary mass is less than about 10 per cent of the primary (Baker *et al.* 2008; Morawski *et al.* 2018).

*Three IMBHs*. The results for these runs are closely related to what is seen above for two IMBHs. Two IMBHs typically form a binary first whilst the third black hole is left on a wider orbit. If the outer binary is ground down, the system may form a distinct triple (i.e. an object devoid of stars in the space between the IMBHs). The

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Kozai mechanism may then accelerate the merger process as the inner binary is driven to high eccentricities (Miller & Hamilton 2002). Alternatively, binary-single encounters involving all three IMBHs may lead to the ejection of one or all three IMBHs (Sigurdsson & Phinney 1993; Sigurdsson & Hernquist 1993; Kulkarni *et al.* 1993; Davies *et al.* 1994).

## 3. Summary

*SMBHs may form after NSCs*. We have shown how a nuclear stellar cluster (NSC) may form first via the merger of stellar clusters which then go on to form and grow a supermassive black hole (SMBH).

*IMBHs may form and grow in stellar clusters*. Intermediate-mass black holes may form and grow within stellar clusters before the clusters themselves merge to form a nuclear stellar cluster.

*1 + 1 = 0* . Merging black-hole binaries may be ejected from nuclear stellar clusters as they receive a recoil kick due to the asymmetric emission of gravitational radiation.

*2 + 1 = 2 or 0*. Encounters between an IMBH binary and a single IMBH may result in the ejection of one, or all three, IMBHs.

*1 + small = larger*. When two IMBHs merge, if the secondary mass is less than about 10 per cent of the primary, the recoil kick will be sufficiently small, that the merger product will be retained by the NSC. It may then grow into a supermassive black hole.

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