Compact Objects and Binaries in Dense Star Clusters
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Dynamical evolution of lower mass binary stars in the Milky Way Nuclear Stellar Cluster

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Abstract. Most intermediate-mass galaxies, including the Milky Way, host both a supermassive black hole (SMBH) and a nuclear stellar cluster (NSC). We simulate the 10 Gyr evolution of lower-mass binaries near the hard-soft boundary, including three-body encounters and von Zeipel-Lidov-Kozai oscillations. Encounter-driven kicks cause both inward and outward migration for hard binaries on timescales shorter than classical binary mass segregation, determining whether the systems survive, merge, or evaporate. The process is, however, too slow to bring binaries into the inner arcsecond within the ages of the S-stars or G-objects, but suggests that *i)* the S-cluster is contaminated by merger remnants from earlier star formation events and more generally that *ii)* a primordial population of blue stragglers ($\lesssim 2M_\odot$) should be scattered towards the outer parts of the inner parsec – providing new constraints on NSC stellar populations and dynamical histories.

Keywords. Nuclear Stellar Clusters, Numerical modelling, Simulations, Binaries, Blue Stragglers

1. Introduction

The Milky Way (MW) Nuclear Stellar Cluster (NSC) is home to many special objects; a supermassive black hole (SMBH, see Neumayer et al. 2020, and references therein), the S-stars (Schödel et al. 2020, and references therein), G-objects (Ghez et al. 2005; Ciurlo et al. 2020), Blue Straggler stars (BSSs, Thorsbro et al. 2023) and more. The origin of these objects remains somewhat debatable, but they are typically believed to originate from binaries (see also e.g. Trani et al. 2019). Binaries make up most of the systems in the Galactic field (Raghavan et al. 2010; Moe and Di Stefano 2017), yet in the NSC, only a handful of stellar binaries have been observed (Martins et al. 2006; Pfuhl et al. 2014; Peißker et al. 2024). This lack of binaries can be partially explained by the extreme dynamical environment of the NSC. High number densities lead to frequent encounters that can destroy binaries (see e.g. Marklund et al. 2025), and other

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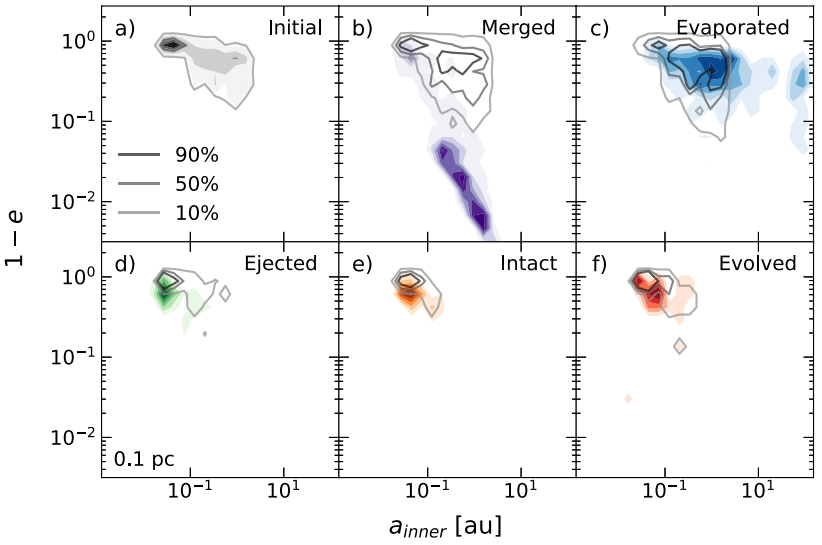


Figure 1. Initial (solid line contours) and final distributions (coloured contours) of binaries in the semi-major axis and $1-$ eccentricity originating at 0.1 pc from the SMBH: *a)* initial distribution, *b)* merged binaries *c)* evaporated binaries, *d)* ejected binaries, e.g. unbound to the SMBH, *e)* intact binaries and *f)* binaries where primary has evolved owing to stellar evolution. Figure adapted from Marklund et al. (2025).

secular processes such as von Zeipel-Lidov-Kozai (ZLK, von Zeipel 1910; Lidov 1962; Kozai 1962) oscillations can drive binaries to near-parabolic orbits where they merge (e.g. Prodan et al. 2015; Stephan et al. 2019). The outcome and evolution of these binaries depend on many different initial parameters, such as, for example, the initial distribution of the binaries' orbital elements and the region in which they originate in the NSC. It therefore becomes useful to define the hard/soft boundary (H/SB); where the ratio between a binary's binding energy and the average kinetic energy of the surrounding stars is unity ($h \sim 1$). Very soft binaries ($h \ll 1$) inevitably evaporate, and very hard binaries ($h \gg 1$) eventually merge (Rose et al. 2020), while for binaries $h \sim 1$, binary evolution is not reliably predictable and requires numerical simulations (Marklund et al. 2025).

2. Numerical set-up

We perform numerical simulations of three-body encounters using `tsunami` (Trani and Spera 2023), where in addition we also incorporate the quadrupole approximation for ZLK following the implementation described in Naoz et al. (2013) and tidal dissipation as implemented in Mardling and Aarseth (2001). In total, we evolve 5736 binaries originating at a distance of either 0.1 or 0.3 pc from the SMBH, for 10 Gyr or until they are either destroyed (merge or evaporate), unbound from the SMBH (ejected) or the primary evolves due to stellar evolution (this process can dominate the binary's evolution, and therefore diminishing the role the dynamical processes). The initial population is chosen to be low-mass ($\leq 1\,M_\odot$ stars) short-period binaries ($\lesssim 1000$ days) that are found in the Galactic field (Moe and Di Stefano 2017), and are sampled with `COSMIC` (Breivik et al. 2020). A significant fraction of the binaries ($\gtrsim 1/3$) lie very near the H/SB.

3. Results

Figures 1 & 2 show the distributions of binaries in the (inner) separation-eccentricity plane at 0.1 and 0.3 pc, respectively. The line contours show the initial distribution, while

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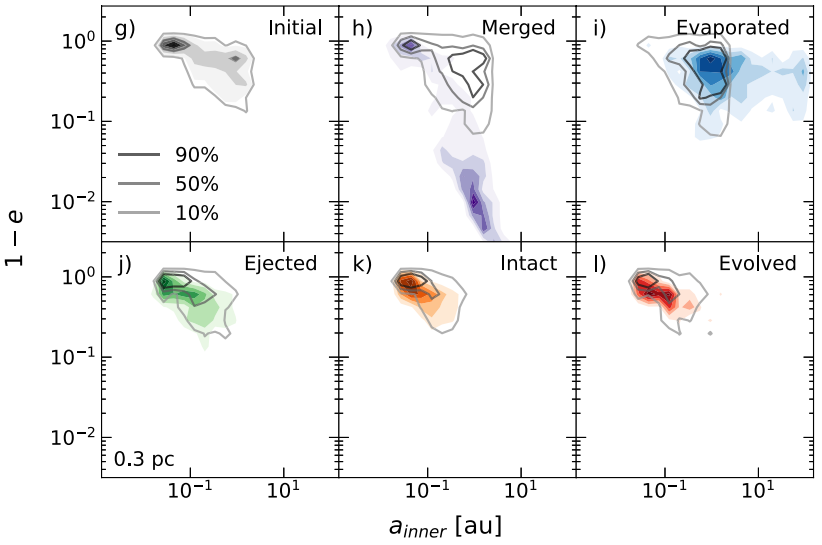


Figure 2. Same as figure 1 but for binaries originating at 0.3 pc from the SMBH. Figure adapted from Marklund et al. (2025).

the coloured contours show the final distribution for each respective panel: *a)* Initial total sample, *b)* Merged binaries, *c)* Evaporated binaries, *d)* Ejected binaries, *e)* Intact binaries (10 Gyr), and finally *f)* Evolved binaries. There are two distinct groups; initially softer binaries are exclusively destroyed via mergers and evaporation, while the initially harder binaries are subject to all different outcomes. We find that the kick received in three-body encounters is the deciding factor; an inward migration typically leads to the binaries being destroyed whereas outward migration does the opposite – binaries typically remain intact, with a few unbinding from the SMBH and a few evolving before 10 Gyr. The binaries that evolve either have a primary with an initial mass $M_* \geq 0.97\ \mathrm{M}_\odot$, or due to stellar collisions with surrounding stars, gain mass and acquire an accelerated stellar evolution.

Figure 3 shows the average distance of intact binaries as a function of time (red solid lines) for binaries originating at 0.1 and 0.3 pc in panels *a)* and *b)*, respectively. Each panel also show the corresponding position and time of all mergers, and are colour-coded by their total expected lifetime (both pre-merger and post-merger). Notably, a group of binaries originating at 0.1 pc have migrated to the inner arcsec (~ 0.04 pc) where they then merge, within a few 10^8 years. Furthermore, and interestingly enough, there are a lot of binaries that migrate outwards where the timescales for most dynamical processes are longer, allowing them to remain intact for $\gtrsim 10$ Gyr. A significant fraction of these binaries merge close to present day, and would therefore be observable as either main-sequence or recently evolved BSSs (see also for example Thorsbro et al. 2023).

4. Conclusions

The main conclusion from this study is that binaries may migrate both inward and outward as a consequence of strong kicks from binary-single encounters. This in turn leads to (i) mergers in the inner arcsec of the NSC that occur after $\gtrsim 10^8$ years, which is too slow to explain the S-stars and G-objects that have estimated ages of $\lesssim 10^7$ years (e.g. Schödel et al. 2020; Peißker et al. 2024) and (ii) both intact and recently merged binaries (which should appear as BSSs) throughout the NSC. A more detailed discussion of the consequences for these points is included in Marklund et al. (2025).

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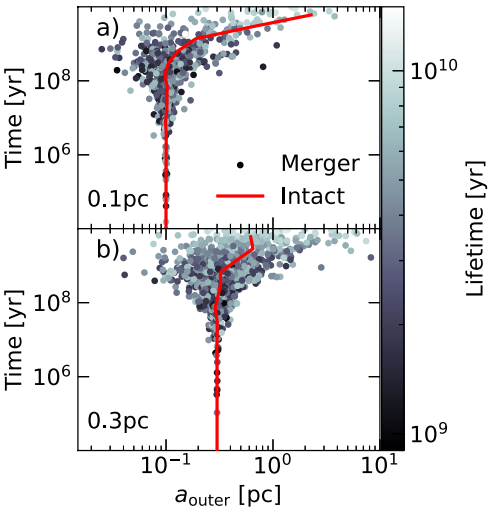


Figure 3. Time (y-axis) and outer semi-major axis (x-axis) of mergers colour-coded by total expected lifetime (pre-merger and post-merger). The red solid line(s) show the mean outer semi-major axis of all intact binaries as a function of time; *a)* binaries originating at 0.1 pc from the SMBH and *b)* binaries originating 0.3 pc from the SMBH.

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