Star Clusters: From the Milky Way to the Early Universe
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The connection between stellar and nuclear clusters: Can an IMBH be sitting at the heart of the Milky Way?

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Abstract. A vast number of observed galactic nuclei are known to harbour a central supermassive black hole (SMBH). In their early lifetime, these systems might have witnessed the strong interaction between the SMBH and massive star clusters formed in the inner galactic regions. Due to the strong tidal field exerted from the SMBH, clusters are likely to undergo tidal disruption, releasing their stars all around the SMBH, and possibly driving the formation of a nuclear cluster (NC). This mechanism can contribute to populate galactic nuclei with intermediate-mass black holes (IMBH). Interactions with the central SMBH can lead to the formation of tight massive BH binaries (MBBH) that undergo coalescence via gravitational waves (GW) emission. We discuss this mechanism in the context of the Milky Way centre, exploring the possibility that SgrA*, the Galactic SMBH, has an IMBH companion.

Keywords. Star clusters; galactic nuclei; black hole physics; gravitational waves

1. Introduction

A large number of observed galaxies shows the presence, in their innermost regions, dense and massive stellar systems called nuclear clusters (NC) Böker *et al.* 2002. Sometimes, these NCs harbor a supermassive black hole (SMBH) in their centre Neumayer & Walcher 2012, like in the case of the Milky Way (MW) Schödel *et al.* 2014). The formation of NCs is thought to be a combination of two main processes Antonini (2013): star clusters (GC†) inspiral driven by dynamical friction (or "*dry-merger*" scenario) (Tremaine *et al.* 1975; Capuzzo-Dolcetta 1993; Antonini *et al.* 2012), and in-situ star formation (Milosavljević 2004). The dry merger scenario nicely explain several features of observed NCs: NC-host galaxy scaling relation (Gnedin *et al.* 2014; Arca Sedda & Capuzzo- Dolcetta 2014; Antonini *et al.* 2015), rotation (Tsatsi *et al.* 2017), the seemingly absence of NCs in massive ellipticals and dwarf galaxies (Arca Sedda *et al.* 2016; Arca Sedda & Capuzzo-Dolcetta 2017a,b), or the copious X- (Perez *et al.* 2015) and Gamma- (Hooper & Goodenough 2011) ray excess observed at the Galactic Centre (Brandt & Kocsis 2015; Arca Sedda *et al.* 2018; Fragione *et al.* 2017; Abbate *et al.* 2018). Recent N-body models (Arca Sedda *et al.* 2015), tailored on observations of the Henize 2–10 dwarf starburst galaxy (Reines *et al.* 2011; Nguyen *et al.* 2014), showed that NCs likely form on short timescales ($<$ 1Gyr) long after SMBH build-up, and that the SMBH leads to NCs with larger cores. During the NC build-up, spiralling GCs can transport into galactic centre their compact remnants, like stellar mass BHs (Arca Sedda & Gualandris 2018; Arca Sedda & Capuzzo-Dolcetta 2019), and in some cases an intermediate-mass

† Throughout the text we refer to star clusters with GC, although this is not meant to indicate globular clusters only

Table 1. Main parameters of N-body simulations.

Model	$M_{\rm SMBH}$ 10^6 M$_\odot$	$M_{\rm IMBH}$ 10^4 M$_\odot$	$M_{\rm GC}$ 10^6 M$_\odot$	$e_{\rm GC}$	NC	N	m_* M$_\odot$	$t_{\rm GW}$ Gyr
Sa1	5	0.1	1	0	No	1048576	33	679
Sb1	5	0.1	1	0.5	No	1048576	33	77
Sc1	5	0.1	1	0.7	No	1048576	33	6.6
Sa2	5	1	1	0	No	1048576	33	26
Sb2	5	1	1	0.5	No	1048576	33	2.2
Sc2	5	1	1	0.7	No	1048576	33	1.3
Ma	5	1	1	0	Yes	1048576	45	3.3
Mb	5	1	1	0.5	Yes	1048576	45	2.0
Mc	5	1	1	0.7	Yes	1048576	45	0.3

Merger rates estimates

redshift	luminosity distance Gpc	galaxy number density 10^3 Mpc^{-3}	merger rate yr^{-1}
0.2	1	8	0.003
2.0	16	8	16

BH (IMBH) (Ebisuzaki *et al.* 2001; Portegies Zwart *et al.* 2006; Mastrobuono-Battisti *et al.* 2014; Arca Sedda & Gualandris 2018; Arca Sedda & Capuzzo-Dolcetta 2019). IMBH candidates have been observed recently in the Galactic NC (see for instance Oka *et al.* 2018). The inevitable interactions between the delivered IMBH(s) and the SMBH can lead to coalescence and emission of gravitational waves (GWs) potentially audible to low-frequency detectors, like the laser interferometer space antenna (LISA†). In this contribution, we discuss the implications of this mechanism on the formation, evolution, and merger of an IMBH-SMBH binary (MBBH) forming at the Galactic Centre.

2. Intermediate mass black holes in Milky Way - like galactic nuclei

Using a suite of 9 direct N-body simulations, we modelled the evolution of a GC harbouring an IMBH and orbiting an SMBH sitting in the nucleus of a MW-sized galaxy. We assume two different cases: a NC is already in the galactic centre (models set S), or a NC is absent (models set M). As summarized in Table 1, we vary the IMBH mass and the GC orbit in both class of models (see Arca Sedda & Gualandris 2018 for further details). The GC is placed on an initial orbit 50 pc away from the SMBH, either circular (models labelled with letter a), mildly radial (b), or highly eccentric (c). The galaxy nucleus is modelled self-consistently by particles up to 150 pc, using more than 1 million particles for each simulation.

In all the cases investigated, we find that the complex IMBH-GC-SMBH-NC evolution can be described in four phases: I) GC decay, II) GC dissolution and IMBH decay, III) IMBH-SMBH pairing and MBBH formation, IV) MBBH hardening and coalescence. Typical timescales for different phases depend on the GC eccentricity $e_{\rm GC}$, the IMBH mass $M_{\rm IMBH}$, and the presence or not of a central NC in the galactic centre. GCs moving on highly eccentric orbits reach the Galactic centre earlier, because of the increased dynamical friction efficiency, favouring the formation of SMBH-IMBH binaries with a larger initial eccentricity $e_{\rm BBH}$. Continuous interactions with passing by stars affect the MBBH evolution, leading to its circularization if $e_{\rm GC} < 0.5$. The high density connected with an NC, instead, allow the IMBH to penetrate deeper into the Galactic nucleus, leading to the formation of a much tighter MBBH. Stellar hardening pushes progressively the MBBH into the GW emission-dominated regime. Despite the high resolution, our simulations are unable to represent the MBBH last evolutionary phases since: they don't

† https://www.elisascience.org/

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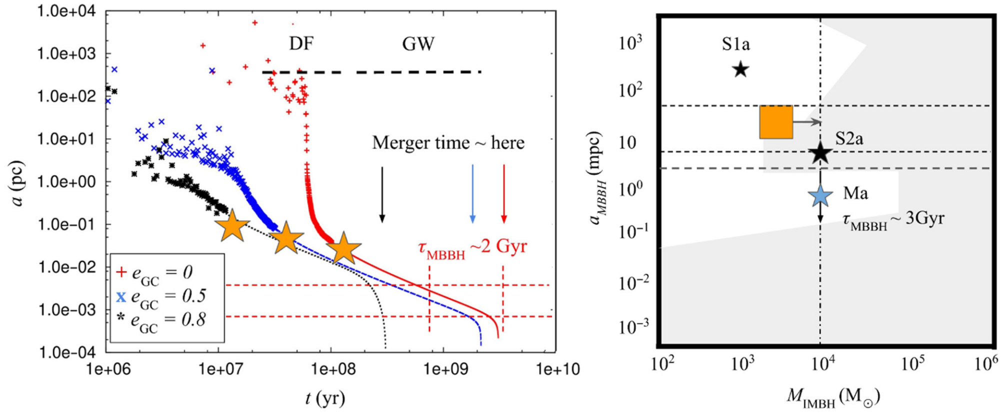

Figure 1. Left panel: time evolution of SMBH-IMBH semimajor axis in models Ma, Mb, and Mc. Yellow stars separate the direct N-body simulation and the semi-analytic integration of the MBBH orbit. We highlight the dynamical friction (DF) and GW-dominated phases for model Ma. Right panel: semi-major axis vs mass for SMBH-IMBH binaries at the Galactic Centre. Shaded areas delimit regions excluded by previous works, whereas the orange area marks a candidate region predicted by Gualandris & Merritt (2009). Stars identify the semimajor axis where a SMBH-IMBH binary spends most of its life in our models Sa1, Sa2 (black stars) and Ma (blue star). A smaller star corresponds to a smaller IMBH (plot adapted from Gualandris & Merritt 2009).

include general relativistic terms, and gravitational interactions are smoothed through a softening parameter. Therefore, to evolve our MBBHs down to the GW-dominated phase, we record semimajor axis and eccentricity at the last snapshot produced by the N-body models, and evolve them forward in time solving the coupled set of differential equations described in Gualandris & Merritt (2012). Using this approach, we find that the MBBH merges within a Hubble time in almost all the cases investigated, unless the IMBH mass falls below $M_{\rm IMBH} \leqslant 1000\ {\rm M}_\odot$ and the GC eccentricity is smaller than 0.5. Merger times for all our models are listed in Table 1. These systems, having mass ratios $M_{\rm IMBH}/M_{\rm SMBH} = 2\times10^{-4} - 2\times10^{-3}$, are potentially observable with the next generation of space based observatories, like LISA (Amaro-Seoane *et al.* 2007). In the local Universe, we predict a merger rate $\Gamma \simeq 3\times10^{-3}$ yr^{-1} Gpc^{-3} Arca Sedda & Gualandris (2018). Assuming that LISA will observe these mergers even at high redshift ($z \leqslant 2$), and that galaxies number density does not vary severely in the 0-2 redshift range, implies a potential number of detection rate of 16 per year with LISA. Left panel of Figure 1 shows the time evolution of the MBBH semimajor axis in Ma, Mb, and Mc models. The two phases — N-body and numerical solution of the orbit — are clearly distinguishable in the plot. Since the GW emission phase is much longer than the dynamical friction driven phase, one can define the "*MBBH observable lifetime*" ($\tau_{\rm MBBH}$) as the time over which the binary semimajor axis $a_{\rm MBBH}$ varies slowly, as evidenced in the left panel of Figure 1. In model Ma, for instance, we find that the MBBH has $a_{\rm MBBH} \sim 1-10$ mpc over a lifetime $\tau_{\rm MBBH} \sim 2$ Gyr. This quantity can be used to place constraints on the possible presence of an IMBH in the MW centre, or to obtain clues about a possible SMBH-IMBH collision in the MW past.

Right panel of Figure 1 shows the IMBH mass and the average $a_{\rm MBBH}$ value taken over $\tau_{\rm MBBH}$ for models Sa1, Sa2, and Ma. The latter, corresponding to the case in which the GC delivers its IMBH into an already fully grown NC, provides two crucial informations. On the one hand, the short MBBH lifetime (< 3 Gyr) can be indicative of a catastrophics collision between SgrA* and a massive IMBH occurred in the past few Gyr. On the

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other hand, it can also be that the IMBH is currently orbiting very close to SgrA* – $a_{\rm MBBH} < (0.1{-}1)$ mpc. In this case, the tight MBBH can affect the evolution of stars orbiting in the SMBH closest vicinity potentially ejecting some of them with velocities up to $10^3 - 10^4$ km s^{-1} (Rasskazov *et al.* 2019). The recently discovered hyper-velocity star S5 – HVS1, traveling away from the Galaxy at 1700 km s^{-1} (Koposov *et al.* 2019), can have formed through this mechanism.

3. Conclusion

We studied the evolution of massive GCs, harbouring a central IMBH, orbiting around a SMBH sitting in the centre of a MW-like galactic nucleus. We show that if an IMBH reaches the galactic centre, the unavoidable formation of a SMBH-IMBH binary culminates with a merger in almost all the cases, unless the IMBH has low mass ($M_{\rm IMBH} \leqslant 10^3$ M$_\odot$) and the GC eccentricity is small ($e_{\rm GC} < 0.5$). Our results suggest that LISA could potentially observe up to 16 SMBH-IMBH coalescence per year, under the most optimistic assumptions. Applying our models to the MW, we find that SgrA* can be currently orbited by a massive companion ($M_{\rm IMBH} > 10^4$ M$_\odot$) moving on a tight orbit ($a_{\rm MBBH} = 0.1{-}1$ mpc). However, given the short lifetime of MBBH at the Galactic Centre, such a massive binary can have merged in the past few Gyr.

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References

F. Abbate, A. Mastrobuono-Battisti, M. Colpi, *et al.* 2018, *MNRAS*, 473:927–936
P. Amaro-Seoane, J. R. Gair, M. Freitag, *et al.* 2007, *Class. Quan. Grav.*, 24(17), pp. R113–R169
F. Antonini, 2013, *ApJ*, 763:62
F. Antonini, E. Barausse, & J. Silk, 2015, *ApJ*, 812:72
F. Antonini, R. Capuzzo-Dolcetta, A. Mastrobuono-Battisti, & D. Merritt, 2012, *ApJ*, 750:111
M. Arca-Sedda & R. Capuzzo-Dolcetta, 2014, *MNRAS*, 444:3738–3755
M. Arca-Sedda & R. Capuzzo-Dolcetta, 2017a, *MNRAS*, 464:3060–3070
M. Arca-Sedda & R. Capuzzo-Dolcetta, 2017b, *MNRAS*, 471:478–490
M. Arca-Sedda & R. Capuzzo-Dolcetta, 2019, *MNRAS*, 483:152–171, Feb. 2019.
M. Arca-Sedda, R. Capuzzo-Dolcetta, F. Antonini, A. Seth, *et al.* 2015, *ApJ*, 806:220
M. Arca-Sedda, R. Capuzzo-Dolcetta, & M. Spera, 2016, *MNRAS*, 456:2457–2466
M. Arca-Sedda & A. Gualandris, 2018, *MNRAS*, 477:4423–4442
M. Arca-Sedda, B. Kocsis, & T. D. Brandt, 2018, *MNRAS*, 479:900–916
T. Böker, S. Laine, R. P. van der Marel, M. Sarzi, H.-W. Rix, L. C. Ho, & J. C. Shields, 2002, *AJ*, 123:1389
T. D. Brandt & B. Kocsis, 2015, *ApJ*, 812:15
R. Capuzzo-Dolcetta, 1993, *ApJ*, 415:616
T. Ebisuzaki, J. Makino, T. G. Tsuru, *et al.* 2001, *ApJL*, 562:L19–L22
Fermi-LAT Collaboration, 2017, *ArXiv e-prints*
G. Fragione, F. Antonini, & O. Y. Gnedin, 2017, *MNRAS*, 475:5313–5321
O. Y. Gnedin, J. P. Ostriker, & S. Tremaine, 2014, *ApJ*, 785:71
A. Gualandris & D. Merritt 2009, *ApJ*, 705, 361–371
A. Gualandris & D. Merritt, 2012, *ApJ*, 744, 74
D. Hooper & L. Goodenough, 2011, *Physics Letters B*, 697:412–428

Koposov, Sergey E. and Boubert, Douglas, Li, Ting S. *et al.* 2019, arXiv:1907.11725
A. Mastrobuono-Battisti, H. B. Perets, & A. Loeb, 2014, *ApJ*, 796:40
D. E. McLaughlin, A. R. King, & S. Nayakshin, 2006, *ApJL*, 650:L37–L40
M. Milosavljević, 2004, *ApJL*, 605:L13–L16
N. Neumayer & C. J. Walcher, 2012, *Advances in Astronomy*, 2012
D. D. Nguyen, A. C. Seth, A. E. Reines, *et al.* 2014, *ApJ*, 794:34
T. Oka, S. Tsujimoto, Y. Iwata, *et al.* 2018, *Nature Astronomy*, 1, 709-712
K. Perez, C. J. Hailey, F. E. Bauer, *et al.* 2015, *Nature*, 520:646–649
S. F. Portegies Zwart, H. Baumgardt, S. L. W. McMillan, *et al.* 2006, *ApJ*, 641:319–326
A. Rasskazov, G. Fragione, N. Leigh, *et al.* 2019, *ApJ*, 878, 17pp.
A. E. Reines, G. R. Sivakoff, K. E. Johnson, & C. L. Brogan, 2011, *Nature*, 470:66–68
R. Schödel, A. Feldmeier, D. Kunneriath, *et al.* 2014, *A&A*, 566:A47
S. D. Tremaine, J. P. Ostriker, & L. Spitzer, Jr., 1975, *ApJ*, 196:407–411
A. Tsatsi, A. Mastrobuono-Battisti, G. van de Ven, *et al.* 2017, *MNRAS*, 464:3720–3727