Black Hole Subsystems in Galactic Globular Clusters: Unravelling BH Populations in GCs using MOCCA Star Cluster Simulations

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Artist impression of a stellar mass BH detected in NGC 3201 (Giesers et al. 2018)
Credit: ESO
Massive stars in GCs should evolve to BHs within few to several Myr

- ~ 2 BHs for every 1000 stars (typical initial mass function)

Retention of BHs in GCs: 2 Important Factors

1) Final Evolution of BH Progenitors & Natal Kicks – Highly Uncertain
   - Natal kicks as high as neutron stars? (Repetto, Davies & Sigurdsson 2012; Janka 2013, 2017) → 200 – 500 km/s up to 1000 km/s
     - asymmetric mass ejection and/or neutrino emission (during supernova explosion)
   - Lower kicks due to mass fallback; direct collapse? (Fryer 1999; Belczynski, Kalogera & Bulik 2002; Belczynski et al. 2010, Fryer et al. 2012)
     - Metallicity and initial progenitor mass is crucial in determining final BH mass and natal kick (see Spera & Mapelli 2017)

2) Cluster initial conditions – Poorly constrained
   - Determines cluster escape velocity when BHs form
Do GCs Contain Stellar Mass BHs? – Long-term Survival

- Long-term survival of BHs in GCs (Old Theoretical Picture):
  - BHs segregate to the center → Form a subsystem that behaves like an isolated cluster → Isolated (decoupled) subcluster of BHs has a small relaxation time → BHs strongly interact with each other and escape very quickly (~100 Myrs) → 1 or 2 BHs may survive up to a Hubble time (Kulkarni, Hut, McMillan 1993; Sigurdsson & Hernquist 1993).

Credit: Douglas Heggie’s Talk: “12 things they don't tell you about the dynamics of star clusters” (Lund 2015)

Thing 1: BHs in Star Clusters
Observations: BH Candidates in GCs

- ULX (could be a BH or a NS) observed in a GC in the elliptical galaxy NGC 4472 (Maccarone el. 2007)
- 2 X-ray/radio detected accreting BH candidates in M22 (Strader et al. 2012)
- Accreting BH candidate detection in M62 (Chomiuk et al. 2013)
- 47 Tuc X9 - Ultracompact BH-WD X-ray binary (Bahramian et al. 2017) - Maveric Survey
- Detached binary with a BH in NGC 3201 (Giesers et al. 2018)
Results from $N$-body and Monte Carlo simulations of GCs show that few tens to up to a 1000 BHs could be present in particular GCs at 12 Gyr:


Theoretical developments:

- Segregating BHs form a subsystem → subsystem provides energy (conduction) to support the rest of the cluster → evolution is governed by the overall relaxation time of the cluster → BHs do not escape quickly if a cluster has a long half-mass relaxation time (Breen & Heggie 2013a,b).

**What they don't say**

**Thing 1: BHs don’t all escape in all GCs**

1. Isolated clusters also expand on the relaxation time scale
2. Expansion counteracts tendency to segregate further
3. Black holes sit inside a much deeper potential well than an isolated cluster.
4. Would-be escapers cannot escape so easily
5. The would-be escapers donate their escape energy to the other stars
6. The black holes drive the expansion of the whole star cluster
7. They escape on the long relaxation time scale of the whole cluster

*See Breen & H (2013)*

Credit: Douglas Heggie

Talk: “12 things they don't tell you about the dynamics of star clusters” (Lund 2015)
Results presented here are based on 2 Papers:


• Collaborators: Manuel Arca Sedda (Heidelberg) & Mirek Giersz (Copernicus Center)

MOCCA SURVEY DATABASE I. Unravelling black hole subsystems in globular clusters

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ABSTRACT
In this paper, we discuss how the structural and observational properties of globular clusters (GCs) can be used to infer the presence of a black hole system (BHS) in their central regions. We present results from a detailed analysis of the MOCCA survey database, focusing on GCs with masses ranging from 10⁶ to 10⁹ solar masses. Our findings indicate that a significant fraction of these GCs host BHSs, suggesting a common origin for the formation of these systems in the early Universe. The implications of these discoveries for our understanding of the evolution of GCs and the distribution of black holes in the Milky Way are discussed in detail.

MOCCA-SURVEY Database I: Galactic globular clusters harbouring a black hole subsystem

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ABSTRACT
There have been increasing theoretical speculations and observational indications that certain globular clusters (GCs) could contain a sizeable population of stellar mass black holes (BHs). In this work, we present a comprehensive analysis of the MOCCA survey database, focusing on GCs with masses ranging from 10⁶ to 10⁹ solar masses. Our findings suggest that a significant fraction of these GCs host BHSs, providing new insights into the nature of these systems and their role in the formation and evolution of the Milky Way.

Goal:

- Investigate properties of about 165 GCs from MOCCA-Survey Database I that contain between 15 to 800 stellar mass BHs at 12 Gyr.
- Compare properties of these GC models with Galactic GCs and identify potential GCs that could contain a subsystem of stellar mass BHs.
All models had mass fallback enabled based on Belczynski, Kalogera & Bulik 2002 prescription → higher BH masses → lower natal kicks

Retention fraction of BHs (after all BH progenitors have evolved) is between 15 to 55% – depends on initial cluster mass, density and tidal radius.
BH Subsystems in Galactic GCs

Abbas Askar

BHs are mixed with other stars

- We define BHS size ($R_{BHS}$) as the radius of the sphere within which 50% of the cumulative mass is in BHs and 50% of mass is in other stars.

Definition of BHS size allows us to define various parameters:

- Mass of BHs inside the BHS ($M_{BHS}$)
- Mass density of BHs inside the BHS ($\rho_{BHS} = \frac{M_{BHS}}{R_{BHS}^3}$)
- Number of BHs inside the BHS ($N_{BHS}$)
- Average mass of BHs and others stars inside BHS ($\bar{m}_{BHS} & \bar{m}_{oth}$)

We found various correlations between these properties when combining results from the 165 GC models as well as observable properties of the entire cluster (AAG 2018a)

Properties of BHS also allow us to probe the dynamical state of the GC.
Correlation between BH Subsystem Properties at 12 Gyr

Presented in Arca Sedda, Askar & Giersz 2018
BH Populations and Dynamical State of the GC

- Models with more massive BHS are dynamically younger:
  - Larger average mass of BHs
  - More radially extended and low density BH subsystem
  - Higher average mass of BHs – Lower average mass of other stars
  - Fewer BHs in binary systems

- Models with less massive BHS are dynamically older:
  - Lower average mass of BHs
  - Compact and denser BH subsystem
  - Higher average mass of other stars
  - Higher fraction of BHs in binary systems
  - BH Subsystem is near depletion – few number of BHs in the GC

- Current dynamical state of GCs determined by initial conditions:
  - BHS models have typically large initial half-mass relaxation times
BH Subsytem in GCs: DRAGON Simulations

- Different populations of objects at 12 Gyrs – Wang et al. 2016 (NBODY6++GPU)
  Initial half-mass radius 7 pc → long half-mass relaxation time → Mass Fallback
  (Belczynski et al. 2002) - Lower BH Natal Kicks

Mock Observations of luminous stars simulated with COCOA
(Askar et al. 2018)
Correlating BHS Density with Observable Properties of the GC

- Correlation between BHS density and the total luminosity of the GC and its half-light radius:
  - BHS density increases with average surface luminosity (total GC luminosity divided by the square of the half-light radius)
  - BHS density can be estimated knowing the GC luminosity and half-light radius
  - From the estimated BHS density, we can get an approximate size of the BHS.
  - Correlations presented in AAG 2018a can be used to estimate properties of BHS: Mass of BHS, number of BHs, average mass of BHs, average mass of other stars, fraction of all BHs in binary systems, all BHs in GCs

- Goal of AAG 2018b was to use observed properties of Galactic GCs to identify which could be harbouring a BH subsystem
  - Not so straightforward: Need to compare other observed properties of GC models with Galactic GCs before applying correlations
  - Observed properties taken from Harris Catalogue (http://physwww.physics.mcmaster.ca/~harris/mwgc.dat)

Fig 1 in AAG 2018b
- Only Galactic GCs with Galactocentric radius values smaller than 17 kpc
- Nearly all GC models with more than 15 BHs had $R_{GC}$ values less than 17 kpc
- GC models with many BHs had central surface brightness values that were $\lesssim 1 \times 10^4 \, L_{\odot} \, pc^{-2}$
- Limited our comparison to Galactic GCs with low CSB values ($\lesssim 1 \times 10^4 \, L_{\odot} \, pc^{-2}$)
- Limited our comparison to observed GCs brighter than $M_v \sim -6.5$
- Sufficiently bright and comparable in magnitude to most model GCs with more than 15 BH at 12 Gyr
- Considered only GCs with observed half-mass relaxation time larger than 0.9 Gyr
- $t_{rh}$ of nearly all GC models with more than 15 BH at 12 Gyr is larger than a Gyr
- Identify 29 Galactic GCs that could possibly contain a sizeable number of BHs
Results: Galactic GCs with sizeable number of BHs

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<th>$D_{\text{GC}}$ (kpc)</th>
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Table 1 in AAG2018b
Results: Galactic GCs with sizeable number of BHs

Table 2 in AAG 2018b
Compared observed/estimated central velocity dispersion values for shortlisted models with central velocity dispersions from simulated GCs.

Models with mass fallback enabled and more than 15 BHs are in better agreement with $\sigma_0$ values for the shortlisted Galactic GCs.
Main Summary of Results

- Mean core radius of the shortlisted 29 GCs is 2.35 pc (relatively high)
  - Average core radius for all GC within 17 kpc (~115 in Harris catalogue) is 1.16 pc
  - Presence of many BHs in GCs leads to core expansion (Mackey et al. 2008)
- Total Number of BHs expected in these clusters ranges between 50 to 250 (considering errors in correlations, some GCs could contain up to 400 BHs)
- About 60% of the total number of BHs are within the BH Subsystem on average
- Average mass of BHs within the BH Subsystem is between \(~9.7 - 13.8\) M\(_\odot\)

Credit: Breen & Heggie 2013
Estimated number of BHs of binaries with at least 1 BH is between 7 to 11 (could be as high as ~20 or as low as 2 to 3).

- 1-3 mass transferring binary systems with a BH (Kremer et al. 2018)
- Higher fraction of BHs in binaries in GCs with low mass BHS
- BHS is denser but fewer number of total BHs
- Detection of 1 or 2 accreting BHs in GCs could indicate the presence of a sizeable number of single BHs

Prospects for detecting single BHs or BHs in detached binaries:

- Gravitational microlensing?
  - Minniti et al. 2015 identified a stellar mass BH lens in Galactic GC NGC 6553
  - Astrometric microlensing in the field
- Radial velocity measurements (Giesers et al. 2018)
- Proper motion measurements
Certain observable properties of shortlisted GCs can be reproduced by GC models without significant number of BHs (no mass fallback for BHs → high kicks)
- High binary fraction at 12 Gyrs (11% to 37%)
- Smaller core radius values compared to models with many BHs

Other physical processes could influence observed properties of GCs
- Strong influence of the Galactic tidal field could drive mass loss during pericenter passage
- Orbits of Galactic GCs from GAIA DR2 can help identify GCs with high eccentricities and low pericenter distance values – NGC 288, NGC 4833, NGC 5897, NGC5986, NGC 6171

Errors in observed GC Parameters
- Need better estimates of GC parameters and errors in observed values
  - Distance, characteristic radii, binary fractions, central velocity dispersions

Metallicity and age spread in observed GCs
- For a detailed discussion on limitations see Askar, Arca Sedda & Giersz 2018
Evolution of BHs inside the Cluster, N=700k, IBF=10%, Z=0.001

- Tidal Radius = 120 pc, Half-Mass Radius = 4.8 pc
- Tidal Radius = 120 pc, Half-Mass Radius = 2.4 pc
- Tidal Radius = 60 pc, Half-Mass Radius = 2.4 pc
- Tidal Radius = 60 pc, Half-Mass Radius = 1.2 pc

Number of Single BHs

Mass [M\(_{\odot}\)]

Core Radius [pc]

Half-light Radius [pc]
Evolution of BHs inside the Cluster, N=700k, IBF=10%, Z=0.001

Number of Escaping: BBH (12 Gyr):
53, 82, 87, 97

Number of Escaping BH-non-BH binary (12 Gyr):
58, 91, 91, 101

Number of Binary Single Interactions involving Binary BHs (12 Gyr): 8892, 13113, 12186, 12274

Number of Binary-Binary Interactions involving a BH (12 Gyr): 1989, 2378, 2481, 3101
Evolution of BHs inside the Cluster, N=700k, IBF=95%, Z=0.001

[Graphs showing the evolution of BHs with time, mass, and core radius.]
Certain GC models can sustain a sizeable population of BHs up to a Hubble time:

- Mass fallback is essential in keeping BHs in GCs
- Models should not be too dense → initial half-mass relaxation times larger than 500 Myrs
- BHs form a subsystem that is mixed with other stars → Useful definition of the BHS Size: Radius of the sphere within which half of the mass is in BHs and the other half is in other stars
- More massive BH Subsystems have larger size, lower density of BHs, larger average mass for BHs and lower fraction of BHs in binaries → dynamically younger

Density of the BHS correlates with the total luminosity and the half-light radius

- Can be used to infer properties of the BH population in a given GC
- Other properties such as central surface brightness, central velocity dispersion, core radius need to also be checked before applying correlations

We identify 29 Galactic GCs that could contain a sizeable population of single stellar-mass BHs.

- Not a high number of BHs in binary systems → Even fewer BHs in binary systems that are mass transferring → Presence of even few semi-detached or detached BHs in binary systems could indicate the presence of a large population of single BHs
MOCCA-Survey Database I: Initial Conditions

Number of Objects

- $4 \times 10^4$ (486 Models)
- $1 \times 10^5$ (513 Models)
- $4 \times 10^5$ (166 Models)
- $7 \times 10^5$ (637 Models)
- $1.2 \times 10^6$ (171 Models)

Metallicity ($Z$)

- 2 x 10^{-4}
- 0.001
- 0.005
- 0.006
- 0.02

Primordial Binary Fraction

- 5%
- 10%
- 30%
- 95% (Kroupa IBD)

Tidal Radius ($R_t$) (pc)

- 3
- 6
- 9

Tidal Radius/Half-Mass Radius

- 30
- 60
- 120

BH Natal Kicks

- No Fallback $\sigma = 265$ km/s
- Mass Fallback

BH and NS Natal Kicks $\sigma = 265$ km/s (Hobbs et al. 2005) or Mass Fallback

Prescription for BHs (Belczynski, Kalogera & Bulik 2002)

2 segment IMF (Kroupa 2001)

- $0.08 \leq M_\odot \leq 100.0$

Galactocentric Radii $\sim$ 1 to 50 kpc

27/June/2018
BH Subsystems in Galactic GCs – Abbas Askar
MODEST 18 - Santorini, Greece
Evolution of BHs inside the Cluster, N=700k, IBF=95%, Z=0.001

Mass of Most Massive BH in a Binary [M_{S\odot}]

Time [Gyr]

50% Lagrangian Radii of BHs [pc]

Time [Gyr]
Differentiating GC Models with a BHS or an IMBH

Figure 14 from Arca Sedda, Askar & Giersz 2018