Intermediate Mass Black Holes in Globular Clusters

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**GC Simulations with Central IMBHs - Monte-Carlo Method**

- Can be thought of as randomized N-body method
  - Star-by-star description of GC
  - Therefore easy to add additional physical processes
  - Resolves orbital evolution on relaxation time scale
    
    \[
    t_{\text{relax}} = \frac{N}{\log \gamma N} t_{cr} \gg t_{cr}
    \]

- Makes it much faster than direct N-body

- Can simulate cluster with realistic number of stars

- Includes tidal disruption of stars by IMBH (loss-cone)
  (analogous to Freitag et al. 2002)

- Stellar evolution: BSE code (Hurley et al.. 2002)

- Strong binary interactions: Fewbody (Fregeau 2004)
Imprints of IMBHs on the Structure of GCs

- cusp in surface density and velocity dispersion
  - Observed projected density cusp shallow
  - GC center dominated by dark remnants
  - only a few bright stars within the influence radius of IMBH to determine velocity dispersion cusp
- density cusp of bright stars follows a power-law slopes of 0.1-0.3
- based on cusp slopes Baumgardt et al. (2005) identified 9 candidate clusters with IMBH

To what extent does the absence of cusps constrain IMBH mass?
Modelling M10

- Nearby cluster: 4.4 kpc
- Galactic distance: 4.1 kpc
- Tidal radius (profile): 26 pc
- Concentration: 1.4 (W0=6.5)
- Mass: $10^5$ Msun

**surface brightness profile:**
- $R < 1.7$ pc: Noyola & Gebhardt (2006) (HST/WFPC2)
- $R > 1.7$ pc: Trager (1995) (various ground based data)

**star count data for stars <19mag:**
- Lanzoni (priv comm.) ACS/HRC
- cover the whole radial range
Results w/o IMBH

- Model: $W_0=5.5$, initial $M_c=360,000\text{ Msun}$; circular orbit at 0.9kpc
- fits observed SDP reasonably well
- find also good agreement for galactic distances up to 1.1kpc
- cluster still in core contraction, not in binary burning stage
Surface Densities with IMBHs

Models with $M < 0.75\% M_c$ fit observed SDP reasonably well.

Models with $M > 0.75\% M_c$ do not.
Kinematic Signature

- Velocity dispersion cusp within 2-3 arcsec
- Could be easily resolved
- BUT: only about 10-20 MS stars have significantly larger velocities
- might be difficult to reliably infer the presence of an IMBH
Mass Segregation Signature

\[ \Delta m(R) \]

\[ R / R_h \]

- no IMBH
- Beccari et al. (2010)
• noticable mass segregation quenching with IMBH
• cluster with IMBH agrees with mean mass profile
• also, no significant quenching through binaries alone
  – since cluster is still in core contraction
  – IMBH only explanation?
Mass Segregation Signature

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Escaped Stars

- due to presence of IMBH
  → increase in velocity dispersion
  → $v_{esc}/\sigma$ lower
  → stars escape more easily as they strive towards Maxwellian vel. distribution

- $v_{esc}/\sigma$ also lower in outer core region
Escaped Stars

- two distinct escape zones
  - outer core region 
    \((r > 0.1)\)
  - cusp region
    \((r < 0.01)\)
  - “zone of avoidance”
    \((0.01 < r < 0.1)\)
- reflects low vesc/sigma regions
Conclusions

- We created Monte Carlo models of the globular cluster M10
  - results suggest that M10 is still in its core contraction phase
  - although it shows no clear sign of an IMBH in its center (cuspy SBP), could still harbor one with M≤580 Msun
  - Velocity dispersion cusp easily resolvable
  - But: only 10-20 MS stars available that have significantly larger velocities
  - IMBH might turn out to be only explanation for mass segregation quenching
    - could mean M10 strong GC candidate with IMBH
- Mass segregation quenching not only due to strong binary encounters:
  - low vesc/σ in cusp region and outer core
  - stars escape through tail of Maxwell velocity distribution
Mass Segregation with IMBH

- noticable quenching of mass-segregation
- despite binary interactions with IMBH not included

M(BH) = 500 Msun; Rvir = 4.8 pc; W0 = 7;
N = 128k; Mcl = 68300 Msun
Imprints of IMBHs on the GC Structure

- massive IMBH → large core
- stellar disruption/escape → energy creation in core → core expansion
- for $\frac{M_{BH}}{M_{clus}} \sim 1\%$
    \[
    \frac{r_c}{r_h} \sim 0.3
    \]
- relation between cluster concentration, IMBH mass, and inner surface brightness slope (Miocchi 2007):
    \[
    11.6s - 4.85 \lesssim \log \left( \frac{M_{BH}}{M_{clus}} \right) \lesssim -1.14c - 0.694
    \]

Trenti et al. (2007)
Mass-Segregation in Clusters with IMBHs

- Mass-Segregation:
  - Massive stars sink to the center
  - Lighter stars pushed further out

- No IMBH:
  - average stellar core mass that of most massive stars/remnants
    - larger than average cluster mass

- With IMBH:
  - Average stellar core mass remains nearly constant
  - massive stars/remnants ejected through strong IMBH-binary interactions

Baumgardt et al. (2004)
Average Mass Profile and IMBHs

Gill et al. (2008)  
Pasquato et al. (2009)

\[ \Delta \langle m \rangle = \langle m \rangle (r = 0) - \langle m \rangle (r = r_h) \]

\[ \Delta \langle m \rangle = \langle m \rangle (r) - \langle m \rangle (r = r_h) \]
Model Parameters

- Initial Mass: 270,000 - 450,000 Msun
- King model with $W_0= 5, 5.5-6.5, 7$ (12 values)
- Galactic distances: 0.9 - 1.7 kpc
- IMF:
  - Kroupa et al. (2001)
  - 0.1 – 100 Msun
  - $N = 400,000 - 700,000$
- IMBH masses: 300 – 2000 Msun
- $Z=0.001$
- Binary fraction: 0 and 20%
- So far approx. 600 runs (each 2 days average runtime)
Choice of Tidal Cut-Off Radius

- Assume that cluster fills its Roche lobe initially
- Since orbit of M10 eccentric → SBP most strongly influenced near perigalacticon
- Axis-symmetric Galaxy model (Dinescu et al. 1999; left): $r_p = 3.4$ kpc
- Galaxy model with bar (Allen et al. 2006; right): $r_p = 0.7 - 3$ kpc
- Effective galactic distance of about 0.9-1.1 kpc leads to best fit
- Results in initial cluster virial radius of about 5 pc ($r_h = 4$ pc)
Comparison with Star Count data

- All final models:
  - in core contraction
  - mass: $7-8\times10^4$ Msun
  - $Trh = 4-4.5$ Gyr !! (800 Myr in Harris catalog)
  - expected BH mass: 600 Msun to sustain core.
Escaped Stars

M(BH)= 500 Msun; Rvir= 4.8 pc; W0= 7; N=128k; Mcl= 68300 Msun

• more massive stars escape inside IMBH cusp