Formation of the Nuclear Star Cluster

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Implications of globular cluster infall
Properties of the Nuclear Star Cluster

- stellar mass = $2 \times 10^7 \, M_\odot$
- half-light radius = 4 pc
- axis ratio $c/a = 0.7$
- density profile $\rho(r) \propto r^{-1.4}$

- centered on Sgr A*

\[ \text{Spitzer/IRAC 4.5 \, \mu m} \]
\[ \text{(Schodel et al. 2014)} \]
Nuclear Star Clusters in our and external galaxies have the highest surface density of any known stellar system

Feldmeier et al. 2014

Many stars at the Galactic Center form in-situ. Is there another way of building the Nuclear Star Cluster?

Misgeld & Hilker 2011
In addition to in-situ star formation, a nuclear star cluster can be assembled from globular clusters inspiraling towards the galaxy center by dynamical friction.

Why? There is a deficit of GCs relative to field stars near the center.

(Capuzzo-Dolcetta & Mastrobuono-Battisti 2009)
Dynamical friction

Calculated by Chandrasekhar in 1940s

\[ t_{df} = 0.45 \text{ Gyr} \left( \frac{r}{\text{kpc}} \right)^2 \left( \frac{V_c(r)}{\text{km s}^{-1}} \right) \left( \frac{M(t)}{10^5 M_\odot} \right)^{-1} f_\epsilon \]

quicker for massive objects
How many globular clusters could merger into a NSC?

Simple model: assume globular clusters in the Galaxy initially follow stellar density, migrate inward by dynamical friction, and tidally disrupt along the way.

Choose normalization such that surviving clusters match the observed density profile of Galactic clusters

...and reproduce the observed cluster mass function

(OG, J. Ostriker & S. Tremaine 2014)
**Do all clusters form at the same time?**

Galactic globular clusters show a systematic Age - Metallicity relation: metal-rich clusters are younger by a few Gyr.

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**Data:** resolved CMD with HST
- [red circles: within 8 kpc of MW center]
- [blue circles: outside 8 kpc]

Marín-Franch et al. (2009)
Dotter et al. (2011)
Vandenberg et al. (2013)
Leaman et al. (2013)

**Model that explains the age and metallicity distributions:**
- Muratov & OG 2010
- Li & OG 2014
- GCs form in gas-rich galaxy mergers
Now we can check how many clusters accumulate at the Galactic center.

Stellar mass of disrupted clusters at the Galactic center is more than enough to form the NSC ($\sim 10^7 M_\odot$).

*Predicted mass depends most sensitively on maximum globular cluster mass.*

(OG, Ostriker & Tremaine 2014)
What sets the maximum mass of star clusters?

Cosmological simulation of a Milky Way sized-galaxy (Hui Li, OG et al. 2016):

- MF is a power law with cutoff as observed for young star clusters

\[
dN/dM \propto M^{-\alpha} \exp(-M/M_{\text{cut}})
\]

slope \( \alpha \approx 2 \)

it’s a number, not a free cluster
Massive clusters form within galaxy disks, but the disks are perturbed by frequent mergers and accretion of satellites.
Maximum cluster mass scales with SFR

- Maximum cluster mass is consistent with that expected for a Schechter function

\[ M_{\text{max}} \propto SFR^{1.6} \]

\[ M_{\text{cut}} \propto SFR^{1.6} \]

\[ \alpha = 2.1 \]
Part of Nuclear Star Cluster built by GCs is higher in lower-mass galaxies \((< 10^{11} \, M_\odot)\) than giant E, while the in-situ formed part is likely to be higher in more massive galaxies.

\[ M_* = 8 \times 10^{11} \, M_\odot \]
\[ M_* = 2 \times 10^{11} \, M_\odot \]
\[ M_* = 5 \times 10^{10} \, M_\odot \]

+ additional mass from in-situ star formation

Remaining globular cluster system is similar to SMBH mass – coincidence?
Additional in-situ star formation: 
*adds 40% of total mass*

Scattering by SMBH: 
*removes almost the same amount*

Antonini et al. 2015, using semi-analytical model of galaxy formation
Relation to central black hole

Stone et al. 2016
Two-body relaxation may drive the inner 1-10 pc of NSC to collapse into an intermediate-mass black hole

In regular globular clusters, core collapse is reversed by the formation of binary stars that absorb potential energy, until they merge or get ejected. Very dense clusters with $\sigma > 40$ km/s cannot absorb enough energy to halt catastrophic core collapse (Miller & Davies 2012).

Core collapse time is shorter than the Hubble time within radius $r_{cc}$.
How massive can IMBH grow?

Stone et al. 2016
Summary

• A significant part of the old Nuclear Star Cluster can be built from infalling globular clusters
• Catastrophic core collapse could lead to the formation of a central black hole of $\sim 10^5 M_\odot$
• Remaining mass of globular cluster system is similar to the mass of SMBH: coincidence or not?
• Implications:
  - Globular clusters may bring millisecond pulsars to the Galactic center
  - Flattening of NSC may lead to more orbits of stars plunging close to SMBH, compared to spherical potential