Multiple populations in GCs: constraints on formation scenarios from kinematics & dynamics

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IAU 316: Formation, evolution, and survival of massive star clusters
What is the source of pollution?

How to get this polluting material into a large fraction of GC stars?

- Multiple generations of star formation?  e.g. D'Ercole+ 2008
- Accretion onto low-mass PMS stars?  Bastian+ 2013
- Something completely different??

ICs  long-term dynamical evolution

\[ \text{[O/Fe]} \]

- 70% “anomalous” (enriched)
- 30% “normal” (primordial)
GCs are collisional systems

Mixing

Mass segregation

low-mass stars

high-mass stars

BHs

e.g. Hénault-Brunet+ 2015; Vesperini+ 2013
Decressin+ 2008

Aarseth 2012
Spatial distribution & kinematics of subpopulations

**Nature vs Nurture**

- longer relaxation time
- less mixing
- imprints of formation?

- shorter relaxation time
- more mixing
- mass segregation?

\[ t_{r1} \propto \frac{\langle v^2 \rangle^{3/2}}{\langle m \rangle \rho} \]
Spatial and kinematic mixing of subpopulations

Complete spatial mixing when 60-70% of mass lost due to two-body relaxation

Vesperini+ 2013

Hénault-Brunet+ 2015
Spatial and kinematic mixing of subpopulations

Complete spatial mixing when **60-70%** of mass lost *due to two-body relaxation*

Same applies to kinematic differences between populations…

Hénault-Brunet+ 2015; see also Decressin+ 2008
Spatial and kinematic mixing of subpopulations

Some memory of ICs should be preserved in outer parts of many GCs

see Gieles, Heggie, Zhao 2011

data from Harris catalogue
Observations: spatial distribution and kinematics

Enriched population -> more centrally concentrated
e.g. Lardo+ 2011

Enriched population -> lower velocity dispersion
(when kinematic differences are found)
e.g. Bellazzini+ 2012, Kucinskas+ 2014
Observations: spatial distribution and kinematics

47 Tuc - HST proper motions near $R \sim 2 r_h$

Enriched stars -> more **radially anisotropic** velocity distribution

![Graph showing PM dispersion vs color group](image)

- **Radial Dispersion**
- **Tangential Dispersion**

**Richer+ 2013**

VINCENT HÉNAULT-BRUNET (SURREY)
Observations: spatial distribution and kinematics

NGC 2808 - HST proper motions  Bellini+ 2015

Enriched stars -> more **radially anisotropic** velocity distribution beyond $R \sim r_h$
On the uniqueness of the observed signatures…

N-body simulations scaled to 47 Tuc

Hénault-Brunet+ 2015; see also Mastrobuono-Battisti & Perets 2013
Clues from differential rotation of subpopulations?

Formation of 2nd generation
- flattened and rotating enriched pop. (Bekki 2010, 2011)

Removing >90% of 1st generation removes large fraction of its angular momentum

Enriched stars on preferentially radial orbits -> less rotation

Marginal evidence in clusters from Bellazzini+ 2012

Rotation curve

![Diagram showing rotation curves](image)
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Rotation curve

\[ \langle v_\phi \rangle \text{ [km/s]} \]

\[ r \text{ [pc]} \]

\[ t = 1 \text{ Gyr} \]

Hénault-Brunet+ 2015
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Rotation curve

$\langle v_\phi \rangle$ [km/s]

$\frac{r}{\text{pc}}$

$t = 11 \text{ Gyr}$

Hénault-Brunet+ 2015
Spatial distribution of subpopulations: central regions of M15

Primordial population more centrally concentrated than enriched population!

Larsen+ 2015
Spatial distribution of subpopulations: central regions of M15

Mass segregation?
-> need $\Delta m \sim 0.25 \, M_\odot$
-> If due to helium spread -> $\Delta Y = 0.15$ (inconsistent with CMD)

Larsen+ 2015
Spatial distribution in central regions: additional considerations

- What about *binaries*?
  
larger binary fraction for primordial stars (12% vs 1%; D’Orazi+ 2010)
larger core binary fraction?

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**Spatial Distribution**

**a)** $N_{s,0} = 95000$

$N_{b,0} = 5000$

**Time Evolution**

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- core binary fraction
- "global" binary fraction
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**Binary Fraction vs Time**

- *Hurley+ 2007*

**Graphical Data**

- **Larsen+ 2015**
Spatial distribution in central regions: additional considerations

- What about **binaries**?
  - larger binary fraction for primordial stars (12% vs 1%; D’Orazi+ 2010)
  - larger core binary fraction?

- **Other clusters**?
  - NGC 2808: no significant difference in spatial distribution of evolved stars
    D’Alessandro+ 2011; Iannicola+ 2009
  
  - NGC 2419: giants with blue $u-V$ colors more centrally concentrated
    Beccari+ 2013; see also Larsen+ 2015

* effect of mass segregation sensitive to cluster concentration
Multi-mass model using limepy (Gieles & Zocchi 2015)

Vincent Hénault-Brunet (Surrey)

Dynamics of multiple populations in GCs

NGC 2808

surface brightness

l.o.s. velocity dispersion

M 15

NGC 2808
Multi-mass model using limepy (Gieles & Zocchi 2015)

Effect of mass segregation maximal in densest clusters like M15.
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- **Initial conditions** matter
Conclusions

- Spatial/kinematic imprints of the formation of multiple populations can survive to the present day

- All observations consistent with an enriched population forming more centrally concentrated

- *None of the observed signatures unique* to a given formation scenario. Differential rotation may provide useful constraints.

- Explaining the more centrally concentrated primordial population in the inner regions of M15 in terms of mass segregation remains challenging

- Could binaries play a role??