Multiple Stellar Populations and the Evolution of Star Clusters
Lecture VII

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Star Cluster Dynamics and Evolution

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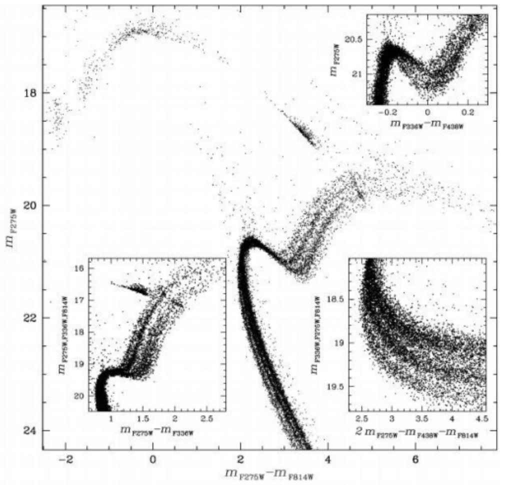
Brief Introduction - Observations



Milone et al. 2015, MNRAS, 450, 3750

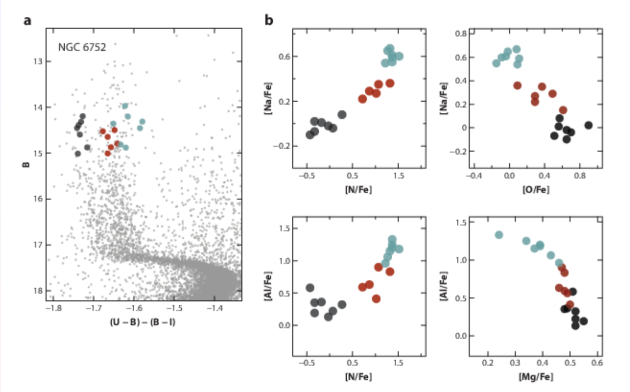
NGC 2808

Our view of Globular Clusters has fundamentally changed in the last decades. A large body of spectroscopic and photometric data have conclusively established that globulars are neither coeval nor monometallic, reopening the issue of the formation of such stellar systems

Already in seventies and eighties of the last century spectroscopic observations of RGs for the most massive GCs revealed chemical inhomogeneities. However they were attributed to peculiar behavior of some stars

HST and VLT telescopes era brought spectroscopic and photometric data that clearly showed that GCs are not chemically homogeneous

Brief Introduction - Observations



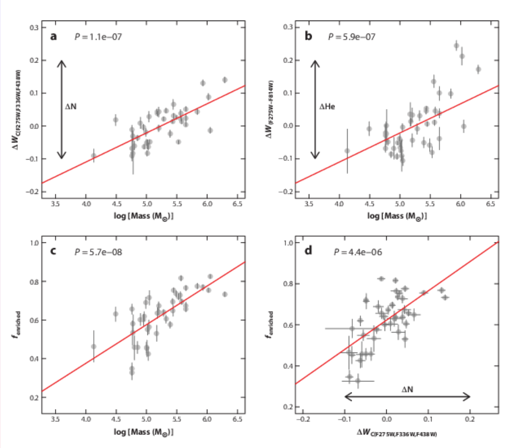
Credits:Bastian & Lardo 2018

GCs show a large variation in the abundances of light elements (Li,C, N, O, F, Na, Mg, and Al - Kraft 1994, Gratton + 2004, Carretta + 2010c, Martell & Smith 2009, Kayser + 2008, Pancino + 2010, Gratton + 2012a

Conversely, the abundances of heavier α (Si, Ca, Ti), ironpeak (Fe, Ni, Cu), and neutron-capture elements (Ba, La, Eu) do not show the same star-to-star variation

Clearly visible correlations and anti-correlations between the light elements

Brief Introduction - Observations



Credits:Bastian & Lardo 2018

MSP are very obvious in massive and old clusters

Richness of MSP increases with cluster mass, may increase with cluster age

MSPs are not observed in GCs younger than 2 Gyr

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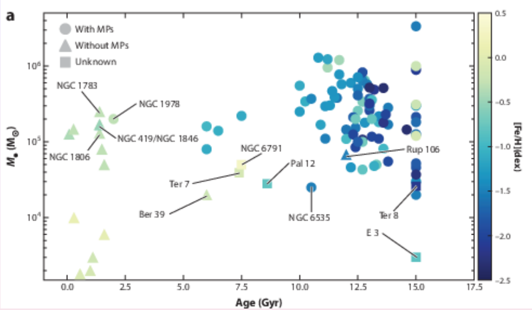
BH GROWTH
Growing Black Holes in Star Clusters

Brief Introduction - Observations



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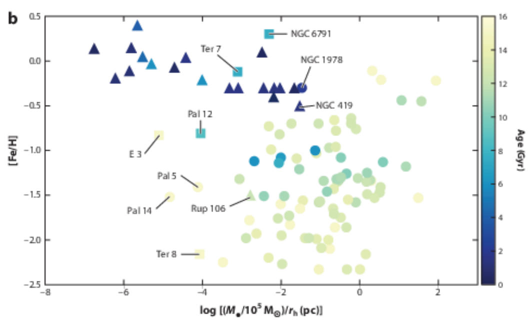

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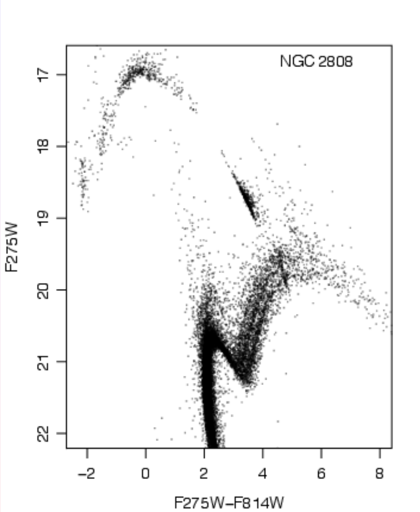

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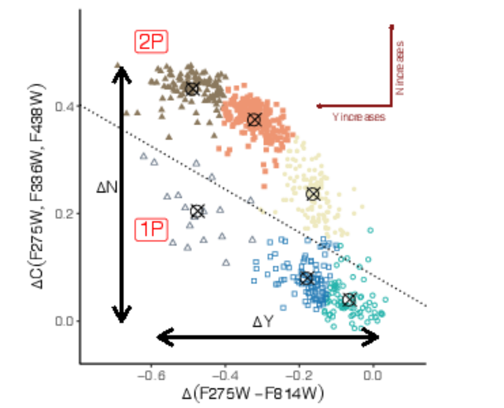

Credits:Bastian & Lardo 2018

Enriched population centrally concentrated

- A source of material that has been through hot hydrogen burning, (70MK) but not helium burning

  Consistent with abundance trends

- Dense cluster environment

  abundance trends essentially not seen in field population

- Ubiquitous process, no special conditions required

  seen in all clusters

- Pollution occurs at time of cluster formation

  no observed age spread

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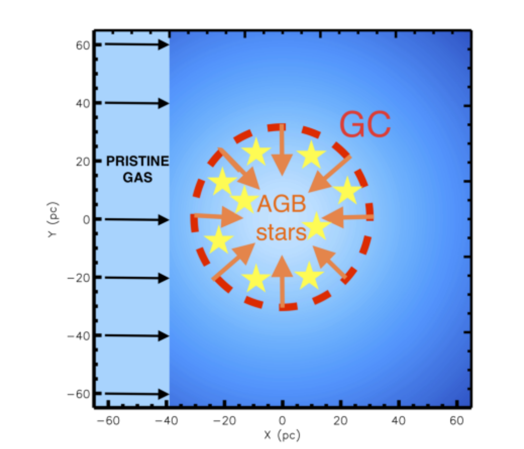
Brief Introduction - Scenarios

- The Asymptotic Giant Branch Scenario
- Fast-Rotating Massive Stars and Interacting Binaries
- The Early Disc Accretion Scenario
- Turbulent Separation of Elements During Globular Cluster Formation
- Reverse Population Order for Globular Cluster Formation Scenario
- Extended Cluster Formation Event
- Very Massive Stars Due to Runaway Collisions

AGB - Calura Scenario

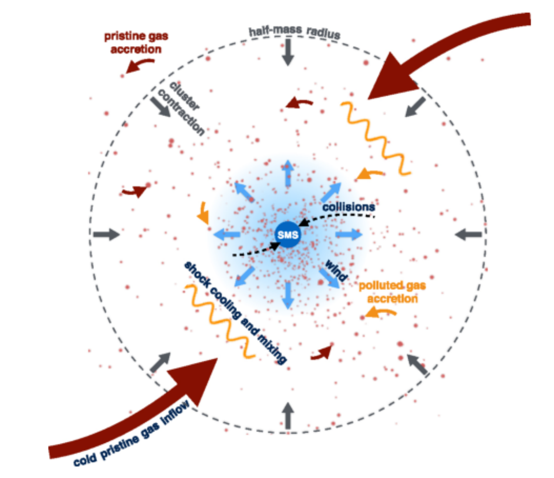
- Formation of the First Generation stars and removal of the remaining gas
- Re-accretion of the pristine gas
- Ejected chemically processed material by AGB stars is diluted with the pristine gas
- Gas is accumulated in the cluster center
- Second Generation stars are formed with lower IMF maximum mass
- Fixed GC potential



Credits: Calura et al. 2019

Very Massive Star Scenario

- Very dense system $> 10^8 M_\odot/pc^3$ leads to runaway merger of MS stars and formation of Very Massive Star (VMS)
- This process takes less than 2 Myr
- VMS accretes pristine gas and collide with surrounding stars
- VMS is convective and ejects processed elements in surroundings
- Second Generation stars are formed with lower IMF maximum mass
- Formation and Fate of VMS is very uncertain



Credits: Gieles et al. 2018

Problems with Scenarios

All scenarios cannot explain all/most of the observational evidences

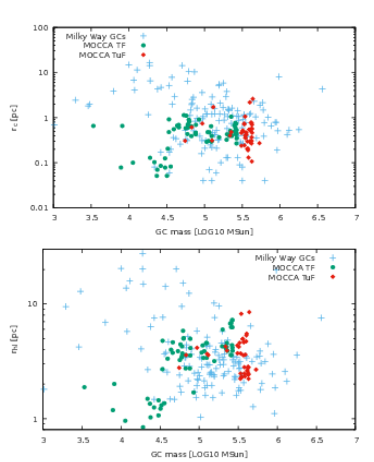
Adding environment effects can help

Observational facts

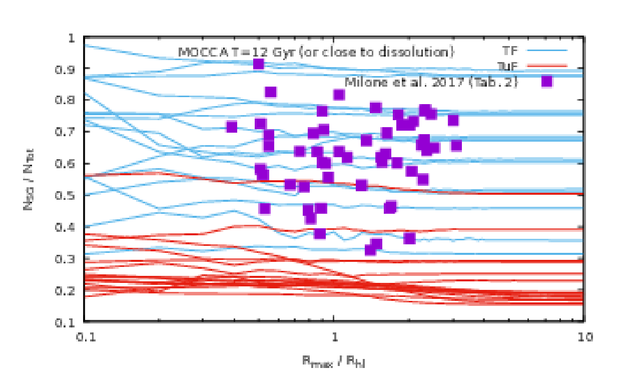
Kind of pollutor	(near) Ubiquity (§2)	Abundances (§5.1)	Li correlations (§5.1.2)	Variety/stochasticity (§5.1.3)	Mg-Al (§5.1.5)	Discreteness (§5.2)	Mass budget (§5.4)	$f_{enriched}$ correlation with GC mass (§5.5)	He spread correlation with GC mass (§5.5)	YMCs (§5.6)	Age Trend (§5.6.1)
AGB	✗	✗*	✗*	✗	✓*	✗*	✗*	✗	✗*	✗	✗
FRMS	✗	✗*	✗	✗	✗	✗	✗*	✗	✗	✗	✗
VMS	✗	✗*	✗	?	✗*	✗	✓*	✓*	✓*	✓	✗
EDA	✗	✗*	✗	✗	✗	✗	✗*	✗	✗	✓*	✗
Reverse Order	✗	✗*	✗	?	?	✗	✓*	✗	✗	✗	✗
eSF Period	✗	✗*	✗	✗	✗	✗	✗*	✗	✗	✓	✗

Bastian & Lardo 2018

AGB Scenarios



Credits: Hypki et al. 2024



Credits: Hypki et al. 2024

Very different initial models than used earlier - POP-1 tidally filling, POP-2 strongly concentrated, small galactocentric distance

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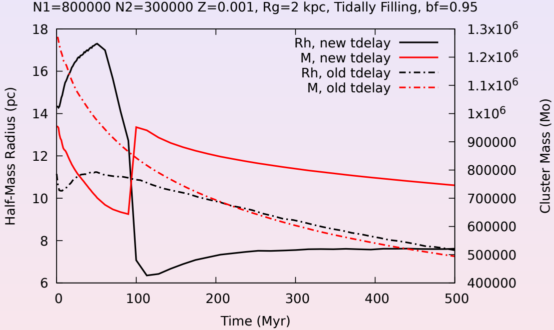
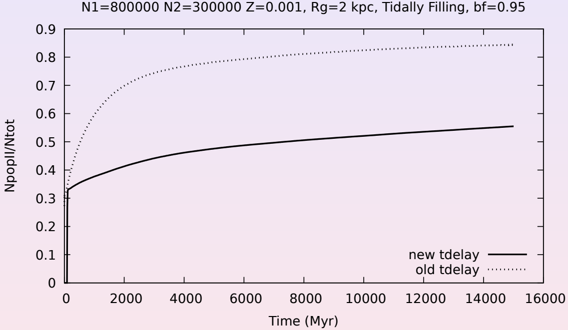
Adding Pristine Gas

Credits: Giersz et al. 2024

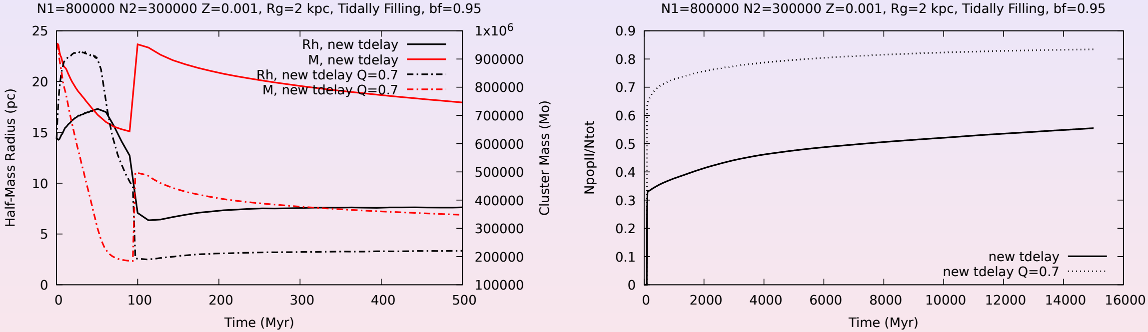




Adding gas to the first population the cluster decreases its size, increases its mass, and substantially reduces the ratio between the PoP2 and the total number of objects

Adding Pristine Gas, Lack of Virial Equilibrium

Credits: Giersz et al. 2024



A cluster that is initially not in virial equilibrium (HOT) expands stronger, loses more mass and has larger ratio between the Pop2 and the total number of objects

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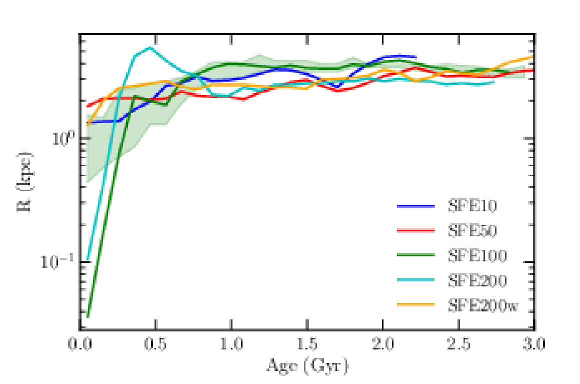
Cluster Migration

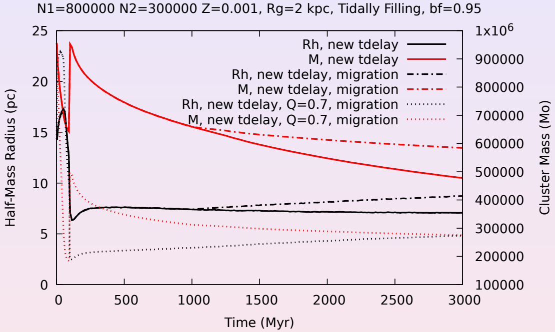
- Globular Clusters formed together with the MW
- At that time environment was very harsh and the tidal field was changing on a very short time scale
- Minor and Major mergers with incoming galaxies introduced additional stress on the tidal field
- All those factors acting together cause cluster migration to larger glactocentric distances - Kruijssen 2015; Forbes et al. 2018, El-Badry et al. 2016, Meng & Gnedin 2022

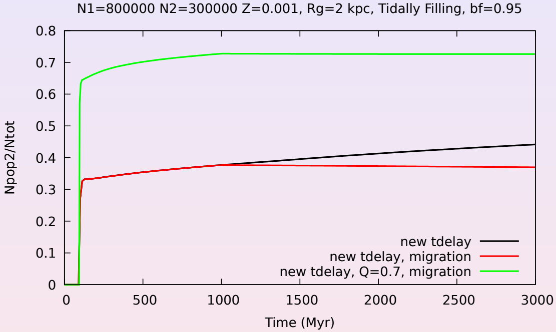


Credits: Meng & Gnedin 2022

Cluster Migration

Credits: Giersz et al. 2024





Cluster migration to the larger Galactocentric distances reduces cluster mass loss, increases a bit cluster half-light radius and decreases slightly the ratio between the Pop2 and the total number of objects

Short Summary

- GCs show a large variation in the abundances of light elements (Li,C, N, O, F, Na, Mg, and Al, and do not show variations in the heavy elements (Si, Ca, Ti, Fe, Ni, Cu,Ba, La, Eu)
- Clearly visible correlations and anti-correlations between the light elements
- Enriched population centrally concentrated
- Richness of MSP increases with cluster mass, may increase with cluster age
- MSPs are not observed in GCs younger than 2 Gyr
- Non of the proposed scenarios for MSP formation can explain all observational properties
- The most promising scenarios are: AGB and VMS

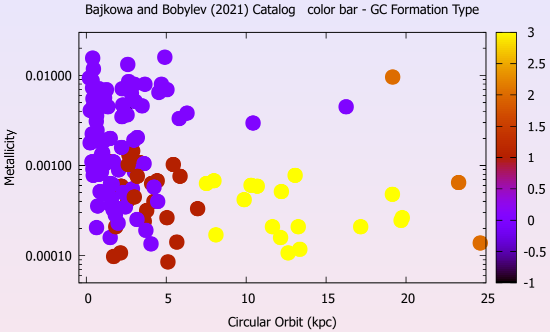
Putting All Facts Together - Summary

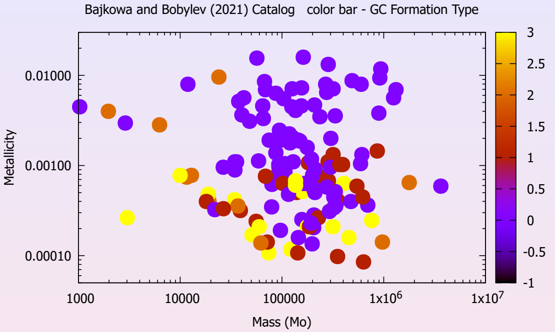
- Globular Clusters are formed togeder with host galaxies
- Globular Clusters are formed in dense, quickly changing and harsh environment. Tidal field acting on clusters is strongly and rapidly varying
- They are formed close to the galactic center as a massive tidally filling objects
- Globular Clusters formed at greater distances from the MW center (e.g. due to major/minor mergers with other galaxies) should have smaller masses and smaller ratios between N_2/N_{tot}
- Major/minor mergers with other galaxies also bring new globular clusters (previously associated with incoming galaxies) and induce clusters migration
- Globular Clusters formed too close or not migrating outward merge with the center of the MW and participate in the formation of Nuclear Star Cluster - M - N_2/N_{tot} correl.
- After a few Gyr of evolution MW environment becomes smoother and cluster orbits becomes more predictable
- Dynamical frictions only play role at the beginning of the MW evolution. Now they are important only for clusters with small pericenter distances

Putting All Facts Together - Predictions and Speculations

- Dwarf galaxies have lower metallicity than MW, so associated GCs should have lower metallicity than MW on average.
- GCs associated with merged galaxies should have larger galactocentric distances on average than MW GCs
- GCs are formed in dense, central parts of galaxies, where tidal forces are greatest and vary strongly over time. GCs that are not massive enough or do not migrate outward are dissolved or "eaten" by NSCs
- GCs formed a little farther from the galactic center have lower masses, larger tidal radii, and smaller N_2/N_{tot}
- GCs associated with merged galaxies should have a bit smaller masses - less gas availability
- The time-varying gravitational potential of the MW and interactions with galactic "large structures" cause GCs to scatter in phase space. This leads to a relatively large scatter of predicted/observed correlations between GC parameters, and also leads to blurred correlation of GC mass and distance

Observations



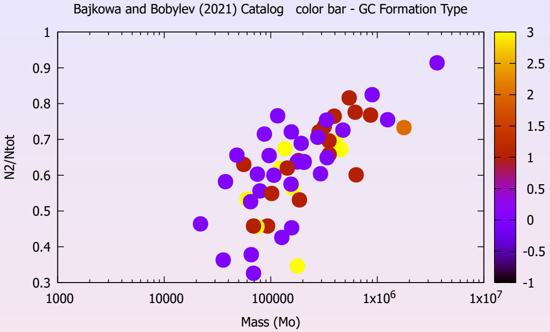


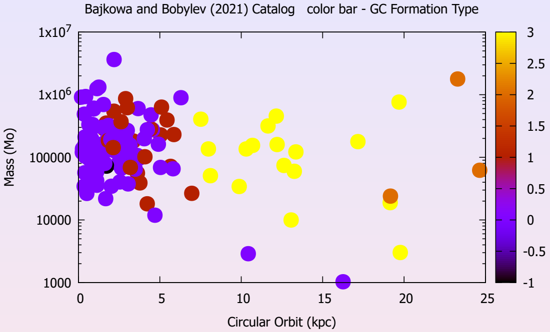
Relatively clear correlation between circular orbit size and GC metallicity. Ex-situ GCs have larger galactocentric distances and lower metallicity than in-situ GCs.

The mass range of in-situ and ex-situ GCs is similar, but only in-situ GCs occupy regions of high metallicity and mass

Relatively good agreement with predictions

Observations





- Clear correlation between the ratio N_2/N_{tot} and cluster mass
- No clear differences between in-situ and ex-situ GCs

- A small sign of correlation for ex-situ GCs - GC mass is smaller for larger distances
- Large concentration of in-situ GCs close to the galactic center

Relatively good agreement with predictions

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