Multiple Stellar Populations
Speculations on Cluster Migration and Gas Re-Accretion

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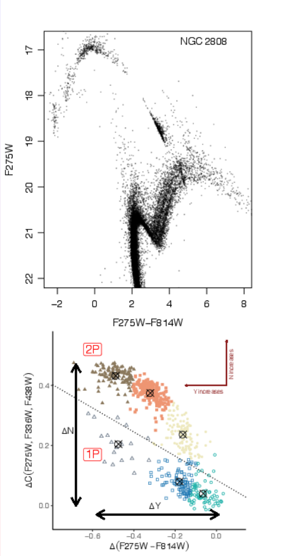
Brief Introduction - Observations



Bastian & Lardo 2018

- In massive clusters some stars have different abundances of light elements - C, O, Mg, Y, N, Na, Al
- Abundances are correlated or anti-correlated
- Very small Fe spreads allowed (0.1 dex)
- No age spread
- Enriched population centrally concentrated, with some exceptions
- MSP very obvious in massive and old clusters
- Richness of MSP increases with cluster mass, may increase with cluster age

Brief Introduction - Theoretical Ingredients and Scenarios

- 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
  seen in all old clusters with large enough masses
- Pollution occurs at time of cluster formation
  no observed age spread

- 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

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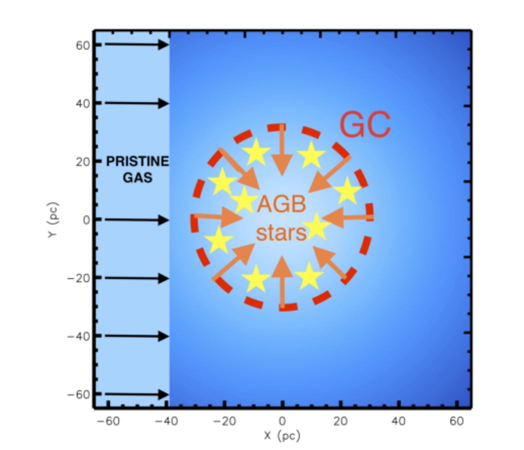
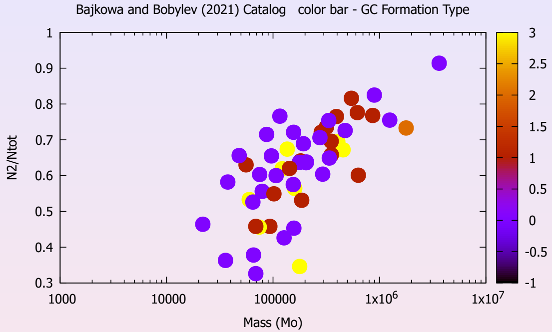
AGB - Calura Scenario

- Formation of the First Generation stars and removal of the remaining gas
- Re-accretion of the pristine gas at t_{start} time
- 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 at t_{delay} time
- Both populations separately in equilibrium



Credits: Calura et al. 2019

MW GC Population - Observations



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

Chen & Gnedin (2024) - 10 structural and kinematic observational parameters of MWGCs used to determine which GCs formed in-situ and which ex-situ. About 60% of the MWGCs were formed in-situ.

0 - in-situ formation, 1 - ex-situ Gaia-Sausage/Enceladus formation, 2 - ex-situ Sagittarius dwarf, 3 - ex-situ other mergers with dwarf galaxies, -1 - type not specified.

Cai et al. (2016) presented a formula to find the size of a circular orbit for which the GC mass loss is the same as for an eccentric orbit

$$Rc = a(1+e)(1-0.71e)^{(5/3)}$$

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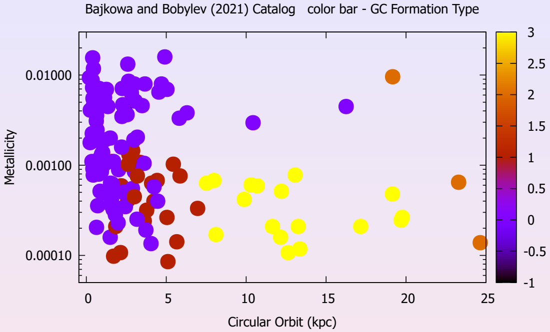
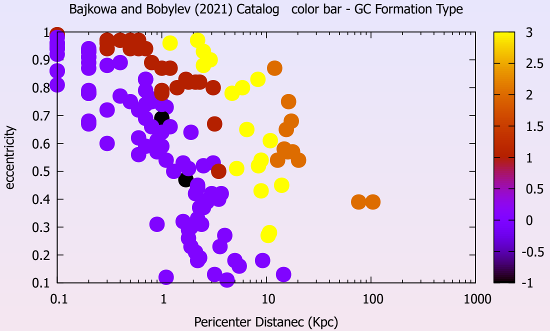
MW GC Population - Observations





- In-situ GCs have smaller "circular orbits" than ex-situ ones. They orbits are mostly confined in 10 kpc. Ex-situ have more extended orbits
- Ex-situ GCs have smaller metallicity than in-situ ones

- Clear correlation between the eccentricity and the pericenter distance
- Ex-situ GCs have larger pericenter distance than ex-situ ones

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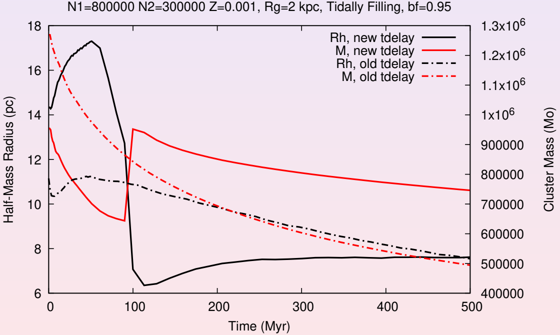
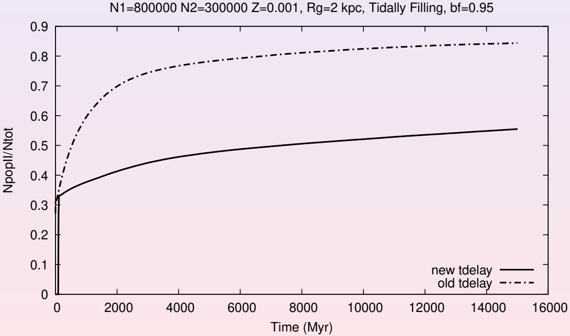
MOCCA Simulations with Time Delay for POP2 Formation

- Cluster collapse during the gas re-accretion
- Larger mass and half-mas radius for model with the gas re-accretion



- Much smaller ratio N_2/N_{tot} for model with gas re-accretion



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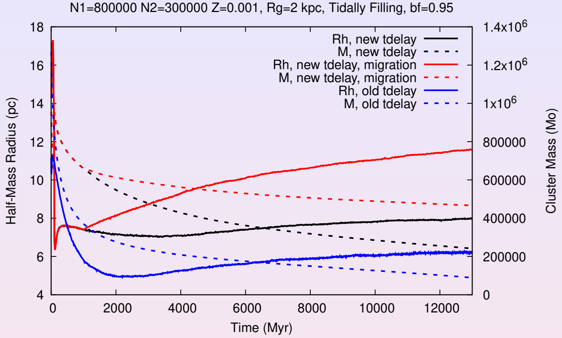

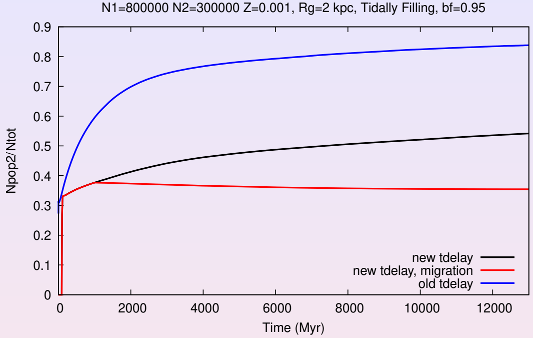

- Migration of GCs to greater galactocentric distances increases the R_t. GCs becomes a TuF from the TF.
- GC mass and R_h increases after migration compared to GC without migration
- Ratio N_2/N_{tot} strongly decreases after migration compared to GC without migration
- To maintain a large ratio, we need an additional physical process to help keep it high

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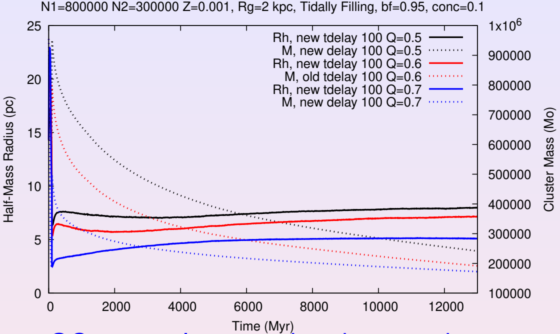

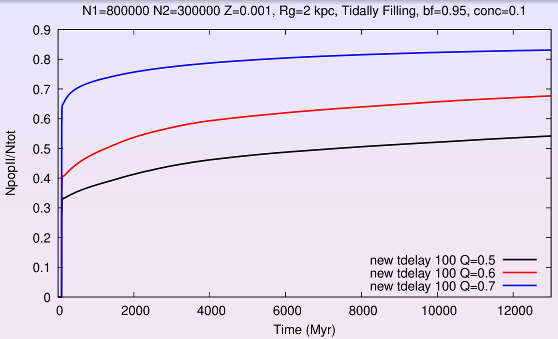

- GCs strongly expand and are not in virial equilibrium when the residual gas is removed after POP1 formation
- There is an excess of kinetic energy relative to potential energy
- The larger the virial ratio, the smaller the mass of the cluster and its R_h

- As expected, the larger the virial ratio, the larger ratio N_2/N_{tot}
- Larger virial ratio helps to get model with larger ratio and smaller R_h, but still the GC mas is too small

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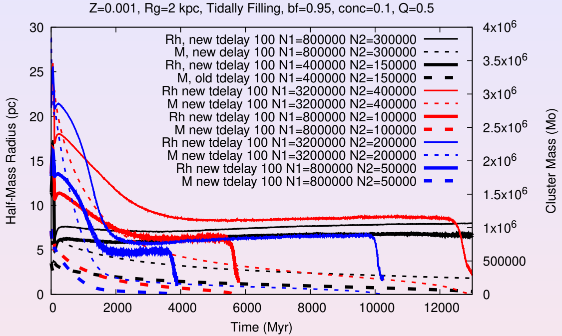

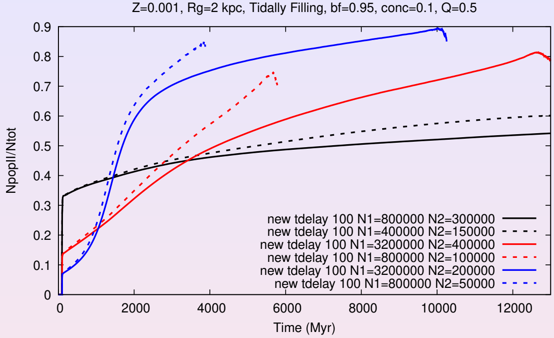

- The smaller the N_1, the faster the GC dissolution. The smaller the N_2, the higher the ratio N_2/N_{tot}
- For small N_2, the ratio for about 1 Gyr is close to the initial value

- The initial MSP parameters relevant to the GC observational parameters are: N_1, N_2, W_{o_1}, R_G, Q. Other parameters e.g. maximum IMF mass, t_{delay}, R_{h_2}/R_{h_1} do not have much impact

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Speculative Scenario for MSP Formation

- GCs just after the ejection of the residual gas should be TF or only slightly TuF. GCs should form close to the galactic center. Too large R_G means very large R_t. In large R_G it is difficult to form a cluster that is TF
- Only TF or slightly TuF models can achieve N_2/N_{tot} ratio within the observed limits
- The larger R_G for newly formed GCs with the same masses the larger R_h and the smaller N_2/N_{tot}
- The smaller W_{o_1} the larger N_2/N_{tot} ratio, the smaller cluster mass and R_h
- The larger Q the greater the N_2/N_{tot} ratio the smaller the mass and R_h
- Migration to larger R_G leads to an increase in cluster mass and R_h. The N_2/N_{tot} ratio remains virtually constant after migration

The joint action of cluster migration and initial models with $Q > 0.5$ seems to work in the desired direction (R_h of a few pc and significant values of N_2/N_{tot}), provided that the cluster is formed relatively close to the galactic center. We should start with a TF cluster close to the center of the galaxy with a mass of at least $10^6 M_o$ and a bit out of virial equilibrium.

Speculative Scenario for MSP Formation

REPRODUCING the GC mass N_2/N_{tot} CORRELATION

- The larger R_G the smaller availability of gas. So the GCs will have smaller POP1 mass and more importantly smaller N_2/N_{tot}
- The small N_2/N_{tot} causes its increase to be slow initially and only increase significantly after a period of 1 - 2 Gyr. Thus, if the cluster migrates during this time, its observed N_2/N_{tot} will be relatively low
- For massive clusters formed with small R_G the availability of gas is very high, so initially N_2/N_{tot} is relatively large and during the evolution quickly stabilizes in large values. Cluster migration can stop the N_2/N_{tot} ratio at relatively large values
- Dynamical Frictions for very massive GCs formed with small R_G or having after migration not very eccentric orbits will lead to quick "absorption" by NSC. GCs with larger eccentricities will survive
- Less massive GCs are likely to migrate to larger distances, so dynamic friction will not be effective
- The mutual interaction of dynamical friction, migration and availability of gas may lead to the generation of the observed correlation M - N_2/N_{tot}

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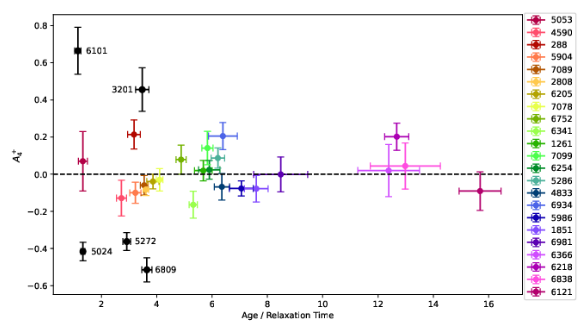
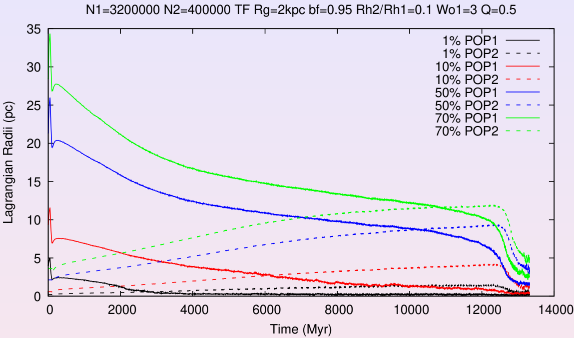
Reverse Concentration - POP1 more Concentrated than POP2

Credit: Leitinger + (2023)





- Some GCs have reversed A+. POP1 is more centraly concentrated than POP2
- Small mass, large R_h, relatively large N_2/N_{tot}, eccentric orbit

- MOCCA simulations with delayed POP2 formation can reproduce observations. Model parameters at 12 Gyr are very similar to the observed ones

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Thank you for your attention