The Relation of Young Massive Clusters to the Ancient Globular Clusters
Review of 2nd lecture

• YMC populations are dominated by size-of-sample effects, higher SFR galaxies *form more clusters*

• Need to be very careful of selection effects when studying cluster populations

• Clusters don’t live forever, they disrupt which can be seen in their age distributions

• The IMF within YMCs appears to be normal
9 starburst galaxies observed with the FOC on HST

10-50% of UV light from compact sources

Fraction increases with $\Sigma_{SFR}$

caveat: assumes clusters and the field have same extinction

also found in other starbursts e.g. Zepf et al. 1999

Meurer et al. 1995
QUANTIFYING CLUSTER POPULATIONS

• Specific luminosity for globular clusters (number of GCs per unit luminosity of the host galaxy)

• not very useful for YMCs, as their mass function is a power-law

• also the host galaxy luminosity depends on mean age

• Specific luminosity: \( T_L = 100 \times \frac{L_{\text{clusters}}}{L_{\text{galaxy}}} \) (Larsen & Ritchler 1999)

• Use a blue filter (U) to trace young populations
• Sample of 21 nearby spiral galaxies

• Specific luminosity:
  \[ T_L = 100 \times \frac{L_{\text{clusters}}}{L_{\text{galaxy}}} \]

• Interpretation: cluster formation efficiency varies with \( \Sigma_{\text{sfr}} \)

Larsen & Richtler 1999, 2000, Larsen 1999

Portegies Zwart et al. 2010

Larsen 2002

Adamo et al. 2011
POTENTIAL PROJECT

• relatively easy to model (building cluster populations)

• hasn’t been done yet - looking for how TL(U) or other bands depend on the input parameters (star-formation history, fraction of stars in clusters)
BRIGHTEST CLUSTER VS. STAR FORMATION RATE

• more star formation = more clusters
  = more luminous brightest cluster

• vertical offset corresponds to $\Gamma$

• overall $\Gamma \sim 0.08$ (the fraction of stars forming in clusters)
Cluster formation in galaxies

$\Gamma = \text{fraction of stars formed in bound clusters}$

Bastian 2008

- $\Gamma = \text{CFR/SFR}$
- Can be estimated in a number of ways
- Young samples (<10 Myr) suffer from contamination
- Old samples suffer from disruption effects

Fouesneau et al. 2014
Estimating $\Gamma$

- Take a mass limited sample
- Sum up the mass in clusters in a given age range
- Correct for the clusters that are not observed (due to the completeness limit)
- Divide by the age range used, to get the cluster formation rate
- Compare this to the star-formation rate (SFR)
Sample of nearby dwarf galaxies from the HST ANGST survey
Dependence on Galactic Properties

- Apparent increase of $\Gamma$ with star-formation rate surface density
- Decent agreement with model predictions
- Still early days with observations
- $\Gamma_{\text{max}} \sim 50\%$

Adamo et al. 2015
Dependence on Galactic Properties

- $\Gamma$ varies within the same galaxy
- Correlated with gas surface density
- In agreement with predictions

Adamo et al. 2015

**Gas surface density**

**Galactocentric distance**

- CLASS 1
  - $\Gamma$ [10–50] Myr; $>5000 M_\odot$
  - $\Gamma$ [1–10] Myr; $>1000 M_\odot$
  - $\Sigma(H_2)$ - observed
  - Kruijssen 12 - fiducial model

Ha emission
The fraction of stars that form in clusters in most galaxies is $\Gamma \sim 10\%$.

This is difficult to measure though so the errors can be quite large and systematic.

Correlation between $\Gamma$ and the SFR surface density ($\Sigma_{\text{SFR}}$)

More stars form in clusters at high $\Sigma_{\text{SFR}}$

If more clusters are formed, then more higher mass clusters are formed.

Did GCs form in high SFR environments (starbursts)?
Using YMCs to Constrain GC Formation

- Are GCs just the ancient analogues to YMCs?
- Many theories for GC formation invoke multiple epochs of star formation within them
- Is there any evidence for multiple (or continuous) star-formation within YMCs?

Carretta et al. 2009

Piotto et al. 2015
From YMCs to GCs

• The typical mass of GCs today is \( \sim 10^5 \) Msun
• Known YMCs have masses between \( 10^4 - 10^8 \) Msun
• YMCs have similar sizes and densities

While Globular Cluster formation (at high-z) may have been fundamentally different from massive clusters forming today, \textbf{all} main theories for the origin of multiple populations predict that it should be happening in young clusters today.

\textit{i.e. current theories do not invoke any special conditions/physics for GC formation.}
Example: AGB Scenario

- Form a 1st generation of stars in a massive cluster
- Ejecta of AGB stars collects in the centre of the cluster (30-200 Myr after 1st generation formation)
- Form a 2nd generation (enriched stars) from this material

Predicts that multiple epochs of star-formation should be in massive clusters

- Massive clusters should be gas rich
- Clusters were 10-100x more massive at birth
Constraints on Ongoing Star-Formation (i.e. 2nd generation)

Bastian et al. 2013a
Constraints on Ongoing Star-Formation (i.e. 2nd generation)

No clusters, older than 10 Myr, were found with signs of ongoing star formation

Constraints on Ongoing Star-Formation (i.e. 2nd generation)

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Bastian et al. 2013a
Constraints from the SFH of clusters (NGC 34-1)

Single population - 100 Myr
No evidence for an extended SFH
$2 \times 10^7$ Msun
Constraints on Gas within YMCs

Cabrera-Ziri et al. 2015

Whitmore et al. 2014

50-200 Myr
1-3 x 10^6 Msun
No gas detected
(<1-10% cluster mass)

see also Bastian & Strader 2014
Constraints on Gas within YMCs

Longmore 2015

Used the D’Ercole et al. (2008) simulation of the ‘AGB scenario’ which predicts a gas profile

This is a lower limit based on the assumptions adopted

Calculated expected extinction

$A_V > 8$ in inner pc
$A_V > 3$ in inner 3 pc

Extinction profile expected of a YMC

Inconsistent with YMC observations ($A_V < 0.2$)
Constraints on Gas within YMCs

YMCs are gas free (expelled any remaining gas left over from the formation of the cluster) within \(<3-4 \text{ Myr}\), independent of mass.

Before the first SNe

Whitmore et al. 2011
Bastian et al. 2014

Hollyhead et al. 2015

Westerlund 2
\(~2 \text{ Myr}\)
Summary of young massive clusters

- Appear to be gas free at young ages (<3 Myr) - a problem for the FRMS scenario - Hollyhead et al. 2015
- No evidence for ongoing star formation in *any* young massive cluster studied to date (older than 10 Myr) - Bastian et al. 2013
- Integrated spectroscopy of YMCs (>10^7 Msun) shows no evidence for multiple bursts or extended SFH - Cabrera-Ziri et al. 2014
- Models with multiple star formation events are disfavoured by CMDs of YMCs - Niederhofer et al. 2014
- No gas reservoirs found in YMCs - Cabrera-Ziri et al. 2015

Previous (popular) models all ruled out
Multiple Populations in Young in Intermediate Age Clusters?

NGC 1806
eMSTO LMC cluster
$2 \times 10^5$ Msun
$\sim 1.5$ Gyr

No abundance spreads!

Also true of NGC 1846, 1866, 1651, 1783, 1978, 2173

Mucciarelli et al. 2014
- Rup 106 - No MPs! Old, relatively high mass GC
- $10^5$ Msun LMC clusters (1-2 Gyr): No MPs!
- Not a simple mass limit
- Maybe an age limit?
Multiple Populations in YMCs

• So far none found - perhaps GC formation was different than YMCs?

• None found in resolved YMCs up to $\sim2 \times 10^5$ M$_{\odot}$

• Difficult to see in more massive YMCs, requires detailed spectral modelling - early days.

• Not a simple mass limit where MPs are found/not found
Constraints from the GC Population

The Remarkable Constancy of the enriched fraction of stars in GCs

\[ f_{\text{enriched}}(\text{initial}) \sim 0.05 \]
\[ f_{\text{enriched}}(\text{observed}) \sim 0.6 \]

Models that invoke nucleosynthesis in 1st generation stars to pollute 2nd generation stars, require that GCs were much more massive at birth (>10x) than presently

e.g. Caloi & D’Antona 2011

All GC mass loss mechanisms will leave an imprint on the GC properties \( (f_{\text{enriched}} \text{ will vary from cluster to cluster}) \)

e.g. Khalaj & Baumgardt 2015
Constraints from the GC Population
The Remarkable Constancy of the enriched fraction of stars in GCs

35 GCs (without Fe spreads)

No evidence of heavy mass loss in GCs
Observed $f_{\text{enriched}}$ likely represents initial value

Bastian & Lardo 2015
<table>
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<th>YMCs</th>
<th>Abundances</th>
<th>Variety/stochasticity</th>
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<th>Lack of trends with metallicity</th>
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GC Formation

- Are GCs just the ancient analogues to YMCs?
- Similar size distribution, high masses, similar densities
- Similar stellar mass functions within them (stellar content)
- Overlapping metallicity distributions
- Very different mass functions
- Currently unknown if YMCs host multiple populations
Can cluster disruption remove the low mass clusters in order to turn the power-law YMC MF into the log-normal seen in the GCs?
GCs as normal YMCs at High-Z

- proto-GCs form in discs
- most are disrupted within 10s of Myr due to interactions with the ISM
- galaxy interactions/mergers ‘liberate’ GCs into the halo where they are able to survive
- clusters that remain in disks are disrupted and do not become GCs
GCs as normal YMCs at High-Z

Evolution of the mass function

Most cluster mass loss/disruption takes place in the gas rich disk of the galaxy

Elmegreen & Hunter 2010
Elmegreen 2010
Kruijssen 2015
EAGLE: Evolution and Assembly of GaLaxies and their Environments

Gas associated with a typical spiral galaxy (colour encodes temperature)
Simulation by Rob Crain & the EAGLE collaboration

$z = 29.9$
$t = 0.1 \text{ Gyr}$
$L = 2.0 \text{ cMpc}$

Visualised with Typhoon (Geach & Crain)
## Implications of Gamma - $\Sigma_{SFR}$ Relation

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<thead>
<tr>
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<th>Galaxy 1</th>
<th>Galaxy 2</th>
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<tr>
<td>Stellar mass</td>
<td>$10^9$ Msun</td>
<td>$10^9$ Msun</td>
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<tr>
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<td>Field</td>
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<tr>
<td>SFH</td>
<td>High SFR burst</td>
<td>Continuous low SFR</td>
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<tr>
<td>GCs</td>
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<td>few</td>
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Mistani et al. 2015

![Histogram of Fraction vs. $M_{GC} [M_\odot]$ for Cluster and Field](image)

![Histogram of Fraction vs. $M_{GC} [M_\odot]$ for Cluster and Field](image)