Young Massive Clusters

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Research interests: YMCs, cluster populations, globular cluster formation and multiple populations, galaxy evolution
It’s a school, so....

• Ask lots of questions (to teachers and other students)

• Let us know your interests, we can spend more/less time on any subject

• No set material to cover, so no need to rush

• Let us know if you have a hard time understanding (language or subject)
OB associations

- 20-500 pc
- $\rho \sim 0.1$ stars/pc$^3$
- gravitationally unbound
- 12 within 650 pc

Embedded clusters

- few - 10 pc
- $\rho \sim 100 - 1000$ stars/pc$^3$
- age $< 3-5$ Myr
- may or may not be bound
- still gas in/around the cluster

Open clusters

- core radii $\sim 2$ pc
- mass $= \sim 100 - 5000$ M$_\odot$
- $\sim 3$ Myr $< $ age $< $ few Gyr - no gas leftover
- characteristic lifetime $\sim$ few hundred Myr
- gravitationally bound

Globular clusters

- few to couple 10s of pc
- mass $= \sim 10^4 - 10^6$ M$_\odot$
- age $\sim 10-12$ Gyr
- gravitationally bound
nuclear clusters

- few to couple 10s of pc
- mass = $\sim 10^5 - 10^8 \, M_\odot$
- age $\sim$ multiple epochs of star formation
- centers of some galaxies

Seth et al. 2006
Young Populous Clusters

- ~100 Myr old
- ~$10^5$ Msun
- in the LMC
Young/intermediate age clusters in the LMC

<table>
<thead>
<tr>
<th>Name</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>R136</td>
<td>2 Myr</td>
</tr>
<tr>
<td>NGC 1850</td>
<td>90 Myr</td>
</tr>
<tr>
<td>NGC 1866</td>
<td>180 Myr</td>
</tr>
<tr>
<td>NGC 1856</td>
<td>280 Myr</td>
</tr>
<tr>
<td>NGC 1806</td>
<td>1.5 Gyr</td>
</tr>
<tr>
<td>NGC 1846</td>
<td>1.6 Gyr</td>
</tr>
<tr>
<td>NGC 1783</td>
<td>1.7 Gyr</td>
</tr>
<tr>
<td>NGC 419</td>
<td>1.5 Gyr (SMC)</td>
</tr>
</tbody>
</table>

All $\sim 10^5\text{ Msun}$
Where are they in the Galaxy?

Galactic Clusters
+ : open clusters
O : globular clusters
Young Massive Clusters in the Galaxy

<table>
<thead>
<tr>
<th>Name</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 3603</td>
<td>2 Myr</td>
</tr>
<tr>
<td>Arches</td>
<td>2-4 Myr</td>
</tr>
<tr>
<td>Trumpler 14</td>
<td>2 Myr</td>
</tr>
<tr>
<td>Westerlund 1</td>
<td>5-7 Myr</td>
</tr>
<tr>
<td>RSGC 1</td>
<td>12 Myr</td>
</tr>
<tr>
<td>RSGC 1</td>
<td>17 Myr</td>
</tr>
<tr>
<td>Glimpse C01</td>
<td>0.5-2 Gyr</td>
</tr>
</tbody>
</table>

All between $10^4$-$10^5$ Msun
Young massive clusters (YMCs) in the Galaxy

Davies et al. 2011
also see Portegies Zwart, McMillan, & Gieles 2010
Reviews of YMCs and their properties

- Portegies Zwart et al. (2010, ARAA) - PZMG10
- Longmore et al. (2014, PPVI review of YMCs)
- Larsen 2010 (arXiv:0911.0796)
- Whitmore 2001 - (astro-ph/0012546)
Historical development

- Have been known in the LMC for a long time (e.g. R136 in 30dor)

- Schweizer (1987) - GCs may form in galaxy mergers, bright blue sources in ongoing mergers - young globular clusters

- Holtzman et al. (1992) - HST WFPC imaging of NGC 1275

  - hundreds of “bright blue clusters”, sizes < 15pc, bluer than any globular clusters, and brighter than the “blue” LMC clusters
Historical development

* Ashman & Zepf (1992) - “The formation of globular clusters in merging and interacting galaxies”

* Zepf & Ashman (1993) - “Globular Cluster Systems Formed in Galaxy Mergers”

Abstract

We show that current observations support the hypothesis that globular clusters form in galaxy mergers. In a previous paper, we presented a model in which globular cluster formation is a result of interactions and mergers of galaxies. Here, this model is compared with new observations of the globular cluster systems of recent galaxy mergers and normal elliptical galaxies. We find that our model is consistent with the number and luminosity of young globular clusters in currently merging galaxies. If elliptical galaxies form through mergers of spiral galaxies, the model also predicts that the globular cluster systems of normal elliptical galaxies should have at least two peaks in the metallicity distribution. We show that observations of the globular cluster systems of nearby elliptical galaxies support this prediction. More generally, the presence of more than one peak in the globular cluster metallicity distribution strongly argues against a single formation epoch for globular clusters in elliptical galaxies. Instead, these observations favour formation models in which globular clusters form in two or more bursts, as is the case in our merging model.
J. Hibbard

Miller et al. 1997; Schweizer & Seitzer 1998; Maraston et al. 2004; Bastian et al. 2006

NGC 7252
A GALAXY IN TRANSITION
NGC 4038/39
The Antennae

Whitmore et al. 1999; 2010
NGC 3256

Zepf et al. 1999; Trancho et al. 2007
NGC 1316

“Young” elliptical galaxy
Major merger ~3 Gyr ago

Goudfrooij et al. 2001
Young GCs Forming Today

• Young cluster populations forming today
• Some have similar properties to the ancient GCs
• Globular cluster populations forming (at least partially) in galaxy mergers
• It was the spatial resolution of HST that opened this field
We also see Young Massive Clusters forming in nearby spirals

Larsen & Richtler 1999; 2000; Bastian et al. 2005
And also in ‘starbursting’ dwarf galaxies

Anders et al. 2004
Young GCs Forming Today

- Not just in galaxy mergers though
- Also in normal spirals and star bursting dwarfs
- Wherever the star-formation rate is high, young GCs are forming
Their properties: Luminosity function

- The number of clusters as a function of luminosity
- Basic property, directly from the observations, no ‘fitting’ is necessary.
Their properties: Luminosity Function

The Antennae

\[ N dL \sim L^{-\alpha} dL \]

Whitmore et al. 1999

Whitmore et al. 2010
Their properties: Luminosity Function

$$NdL \sim L^{-\alpha}dL$$

4 spiral galaxies

Larsen 2002
Their properties: Luminosity Function

\[ NdL \sim L^{-\alpha} dL \]

M51 (spiral galaxy)

\[ M_B \quad M_V \]

Gieles et al. 2006
Their properties: Luminosity Function

Globular cluster LF

Jordan et al. 2007
Their properties: Luminosity Function

- Power-law, $N \sim L^{-\alpha} dL$, with index $\alpha = 2$
- Some evidence for steeping at bright luminosity (Schechter type distribution)
- Very different from the ancient GCs, which have a Gaussian luminosity function
Their properties: Size distribution

Luminosity profiles

Old GCs show truncations (King profiles), young GCs show power-law profiles (with index $\eta$)

Schweizer 2004
Their properties: Size distribution

$R_{\text{eff}}$ is the radius containing half the light of the cluster
Surprisingly Universal: mean $R_{\text{eff}} = \sim 2.5$ pc (similar to GCs)
Their properties: Size distribution

M83 (spiral galaxy) cluster population

Ryon et al. 2015
Their properties: Cluster sizes

- Gaussian or ‘log-normal’ with a peak at \( \sim 2.5 \) pc
- GCs and YMCs show the same basic size distribution
- However, YMCs show extended luminosity profiles (Elson, Fall and Freeman - EFF) while GCs generally show a truncation (King profile)
Deriving cluster ages, extinctions and masses
Deriving cluster ages, extinctions and masses

Colour Magnitude Diagram (CMD)

From Galactic YMCs (<10 Myr) age spreads < 1-2 Myr

Kudryavtseva et al. 2012
Deriving cluster ages, extinctions and masses

Colour Magnitude Diagram (CMD)

NGC 2157
Niederhofer et al. 2015

From LMC YMCs (<300 Myr) age spreads < 50 Myr
Deriving cluster ages, extinctions and masses

Colour Magnitude Diagram (CMD)

Larsen et al. 2011
CMD summary

• in young massive clusters that can be resolved, their CMDs show small (or non-existant age spreads)

• the constraints that can be put depend on the age of the cluster, best constraints for youngest clusters

• consistent with no age spreads, but there are CMD features that are not fully explained yet
population synthesis

• for each mass/age a star has a given colour/Teff, magnitude and spectra

• for “simple stellar population models”, all stars have the same age and metallicity

• ‘make’ a bunch of stars populating an IMF

• assign each star a weight (based on the luminosity) at each wavelength

• sum everything up
ignore the problems...

• binaries
• uncertain aspects of stellar evolution
• cluster effects on evolution (stellar exotica)
• assume a fully sampled initial mass function of stars
continuum shape

absorption line strengths

can get age, metallicity simultaneously (<1 Gyr)

above ~2 Gyr strong degeneracy between age and metallicity

González-Delgado et al. 2005
• locate a cluster in colour space
• move it along extinction vector until you hit the SSP model
• sometimes multiple solutions exist
• once you have the age and extinction, you get the mass by comparing the observed luminosity to that of the models
Colour-colour plots of cluster populations in 2 parts of M83 (spiral galaxy)

What can we see about the relative average age in each region?
• locate a cluster in colour space
• move it along extinction vector until you hit the SSP model
• sometimes multiple solutions exist
• once you have the age and extinction, you get the mass by comparing the observed luminosity to that of the models
Their properties: Ages and Extinction

• In a limited number of cases can get all the basic info from resolved star CMDs

• But for most extragalactic YMCs we need to compare their integrated light (spectroscopy or photometry) with simple stellar population models (SSPs)

• Allows us to get the age, extinction and mass, but there are some important caveats (degeneracies) to keep in mind.

• Spectroscopy and line diagnostics can break the degeneracies in most cases - but expensive
Bastian et al. 2008
Their properties: Mass functions

• Similar to Luminosity functions

• Need to convert observables (luminosity) to physical properties

• Extinction and age effects have been taken into account

\[ N dM \sim M^{-\beta} dM \]
Mass functions

Larsen 2009
Bastian et al. 2012
Their properties: Mass functions

- $N \, dM \sim M^{-\beta} \, dM$, with $\beta = 2$ for most of the observable mass range
- Evidence for a turn-down at high masses, similar to a Schechter function, $M_c$
- $M_c$ appears to vary with environment, $\sim 2 \times 10^5$ Msun in spirals and dwarfs and $> 10^6$ Msun in mergers/starbursts
- $M_c$ also varies within the same galaxy
- The turn-down is a small effect, but it has important implications in the luminosity and age distributions
GLIMPSE CLUSTER-01

* located within 0.1 degrees of the Galactic plane

* can rule out very young ages (< 20 Myr)

* assumed then to be an old globular crossing the plane

Davies et al. 2011
GLIMPSE CLUSTER-01

σ = 9.7 km/s

M_{\text{present}} = 5-10 \times 10^4 \text{Msun}

rotating with Galactic disk

few $10^7 < \text{age/yr} < \text{few} \times 10^9$

Davies et al. submitted
Age spreads from CMDs?

Niederhofer et al. 2015b