Multiple stellar populations and their evolution in globular clusters

Part II – Multiple Populations
Towards a new paradigm

✓ Heavy elements in GCs
✓ Light elements and the presence of multiple populations
✓ Photometric signatures
✓ Potential polluters
  Details on AGB physics
  Details on massive star physics
✓ GC initial masses
✓ Early dynamical and chemical evolution
  Towards a global scenario (?)

Corinne Charbonnel
Dept of Astronomy, Univ. of Geneva & IRAP CNRS, Univ. of Toulouse
C-N, O-Na, Mg-Al, F-Na, Li-Na anticorrelations 

\[(C+N+O)] \sim \text{constant} \quad \text{within experimental errors}

[Fe/H] \text{ constant}

H-burning through CNO, NeNa, MgAl

H-burning ashes mixed with pristine gas \implies 2d generation

No recycling of He-burning products

No recycling of supernovae ejecta, except in some rare (most massive) cases (e.g., Ω Cen or M22)
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C.Charbonnel - GCs - EES 2015
Proposed polluters (H-burning at T ~ 72 to 78 MK)

Fast Rotating Massive Stars (FRMS) 
\( \geq 25 \, M_{\odot} \)

Massive AGB 
\( \sim 5 - 6 \, M_{\odot} \)

Prantzos & Charbonnel (06)  
Decressin et al. (07a,b), Krause et al. (12,13)

Massive binaries 
\( \sim 10 - 20 \, M_{\odot} \)

De Mink et al. (10)

Supermassive stars 
\( \sim 10^4 \, M_{\odot} \)

Denissenkov & Hartwick (14)
Who is the culprit?
When and how did it happen?

Supermassive star
Massive binaries

AGB
FRMS
Who is the culprit?
When and how did it happen?
Thermally-pulsing AGB stars

- Unique nucleosynthesis
- 3d dredge-up
- Strong mass loss

From ~0.9 to 8M

Thermally Pulsing AGB

1st dredge-up

ZAMS

Early AGB

M=5

M=1

2d dredge-up

To PN and WD...
3d dredge-up of the ashes of the thermal pulse into the convective envelope

\[ ^{16}\text{O}, ^{22}\text{Ne} \]
\[ \text{C+N+O} \]

**He burning**

\[ 3\alpha \rightarrow ^{12}\text{C} \rightarrow ^{12}\text{C}(\alpha,\gamma)^{16}\text{O} \]

\[ ^{14}\text{N} \text{ (CNO)} \rightarrow ^{14}\text{N}(\alpha,\gamma)^{18}\text{F}(\beta^+)^{18}\text{O}(\alpha,\gamma)^{22}\text{Ne} \]

\[ \text{C+N+O} \]

**HBB** (M > 4\( \odot \)) CNO, NeNa, MgAl

At high T, \[ ^{23}\text{Na}(p,\gamma)^{24}\text{Mg} \]

\[ ^{26}\text{Al} \text{ produced from } ^{25}\text{Mg} \]

At very high T: \[ ^{24}\text{Mg} \]

**TP-AGB**

He burning shell (HeBS)

Convective envelope

Intershell mass

Degenerate CO core
Subtle competition between

- **Third dredge-up** (M ≥ 1.5M☉ at Z☉)
  - products of He-burning in the TP →
    - $^4$He, $^{12}$C, $^{16}$O, $^{22}$Ne, $^{25,26}$Mg (s-process elements)

- **Hot-bottom burning** (M ≥ 4 – 4.5M☉)
  - CN-cycle: $^{12}$C → $^{14}$N
  - ON-cycle: $^{16}$O → $^{14}$N
  - NeNa: → Na↑ and ↓ at higher T
  - MgAl: Al↑ at the expense of $^{25,26}$Mg and eventually of $^{24}$Mg

Difficult to get the O-Na anticorrelation (rather a correlation)
Impact of mass loss, convection treatment, metallicity, etc …

*Ventura & D’Antona (02, 05a,b,c, 06, 07, 08a,b, 09, 10)*
Evolution of the surface abundances of O and Na

# Delicate interplay of 3d dredge-up and hot bottom burning

(a) No 3DUP, only HBB
→ Large $^{16}$O depletion
→ $^{23}$Na depletion
(due to the lack of primary $^{22}$Ne dredged-up)

(b) Strong 3DUP, HBB, no mass loss
→ 3DUP of the $^{16}$O-rich layers below the TP
→ $^{23}$Na increase (from dredged-up $^{22}$Ne)

→ O-Na CORRELATION

See also the models by
Ventura, D’Antona et al.,
Lattanzio, Karakas, Fenner et al.,
Decressin, Charbonnel et al.

Denissenkov & Herwig (03) Full evolution models

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**Treatment of convection**

Ventura & D’Antona (05a)
See also Renzini & Voli (81), Sackmann & Boothroyd (91)
Blöcker & Schönberner (91), D’Antona & Mazzitelli (96)

Full Spectrum of Turbulence (Canuto & Mazzitelli 91)
→ **much more efficient HBB** than with MLT
(on the AGB: higher L, stronger mass loss, less 3DUPs)

---

**MLT17:**
Little O depletion (factor of ~2)
Increase of Na and N
C+N+O increase by ~ 0.8 dex

**FST:**
Larger O depletion
Slight decrease of Na
C+N+O ~ conserved

C.Charbonnel - GCs - EES 2015
Evolution of the surface abundances of O and Na

# Delicate interplay of 3d dredge-up and hot bottom burning

→ O-Na CORRELATION

« While Na and O appear to be anticorrelated in the cluster stars, from the stellar models they turn out to be correlated into the AGB ejecta… Thus the 2d generation stars should exhibit an O-Na correlation, in glaring conflict with the observations.»

D’Ercole, D’Antona, Vesperini (11)
Almost 1 order of magnitude rise of \([C+N+O / Fe]\) within 1Gyr of formation (due to the DUP of the products of He-burning)

C+N+O is found to be \(~\) constant in many GCs (Pilachowski et al. 88, Dickens et al. 91, Smith et al. 96, Ivans et al. 99)
Meridional circulation and shear turbulence
Transport of angular momentum and of chemicals
Zahn (92), Chaboyer & Zahn (95)
Talon & Zahn (97), Maeder & Zahn (98)

Same physics successfully applied to
Massive stars: HeBCN anomalies (Maeder & Meynet 00)
Low-mass stars: Hot side of the Li dip, Li in subgiants (Charbonnel & Talon 99,
Palacios et al.03, Pasquini et al.04)
Intermediate-mass stars: Primary N production at low Z (Chiappini et al. 06)
$5 \text{M}_\odot$, $[\text{Fe/H}] = -2$ Abundance profiles at the end of central He-burning

Decressin, Charbonnel, Siess, Palacios, Meynet & Georgy (09)
Decressin, Charbonnel, Siess, Palacios, Meynet & Georgy (09)
AGB scenario – Anticorrelation possible only by dilution

→ Need to re-accrete original gas to turn the O-Na correlation into an anticorrelation (D’Ercole + 11)

AGB yields → O-Na correlation in glaring conflict with observations

Slide courtesy D’Antona (Sexten 2014)
Survey of 130 Galactic and extra-galactic YMCs ($10^4 < M/M_\odot < 10^8$; $10 < \text{age}/\text{Myr} < 1000$): No evidence for extended or multiple SF episodes within $30 - 100$ Myr

Bastian et al. (13); Cabrera-Ziri et al. (14)

**AGB scenario**

Massive AGB scenario

$1^{\text{st}}-2^{\text{nd}}$ generations: $\Delta t \sim 50 - 100$ Myr
**AGB scenario**

Distinct stellar generations but no recycling of the SNe ejecta

- Need to **re-accrete gas** to form the 2G and to turn the correlation into an anticorrelation (D’Ercole + 11)

How do all the GCs manage to re-accrete gas with exactly the same [Fe/H] than the one of the proto-GC, after having travelled around for ~ 50 – 100 Myrs?

**Massive AGB scenario**

1st-2nd generations: Δt ~ 50 - 100 Myr

---

**Supernovae feedback?**
Baumgardt et al. (08), D’Ercole et al. (08), Decressin et al. (10)

**Dark remnant activation?**
Krause, Charbonnel et al. (12)

---

**Energetic event**
- Ejection of gas and SNe yields

**AGB evolution**

- SFR (M$_S$/Myr)
- CCSN (per Myr)
- SNIIa (per Myr)

**How do all the GCs manage to re-accrete gas with exactly the same [Fe/H] than the one of the proto-GC, after having travelled around for ~ 50 – 100 Myrs?**

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**C. Charbonnel - GCs - EES 2015**
Who is the culprit?
When and how did it happen?
Fast Rotating Massive Stars scenario

Prantzos & Charbonnel (06), Decressin et al. (07a,b,09,10)
Schaeerer & Charbonnel (10), Krause et al. (12,13)

Transport of angular momentum and chemicals by meridional circulation and shear turbulence
Zahn (92), Maeder & Zahn (98), Meynet & Maeder (00)

Same physics successfully applied to
Massive stars: HeBCN anomalies (Maeder & Meynet 00)
Intermediate-mass stars: Primary N production at low Z (Chiappini et al. 06)
Low-mass stars: Hot side of the Li dip, Li in subgiants (Charbonnel & Talon 99, Palacios et al. 03, Pasquini et al. 04)

Higher rotational velocities in young massive clusters than in the field
(Huang & Gies 06; Strom et al. 05; Dufton et al. 06)
Be-type stars
FRMS – Main sequence

# Meridional circulation and turbulence extract angular momentum from the fast rotating stellar core
→ The star reaches critical rotation velocity (centrifug acceleration compensates gravity)
→ Equatorial matter released in a keplerian orbit

Formation of a slow outflowing disk (Be stars)

Decressin et al. (07)
Main sequence and LBV phase at break-up:
Transport of H-burning-products from the core to the surface and disk

Decressin et al. (07)

Star formation in the “decretion disc”

\[ [\text{O/Na}] = -2 \text{ to } 0.6 \text{ (disk)} \]

\[ [\text{O/Na}] = -2 \text{ (surface)} \]

Green: pristine \([\text{O/Na}]=0.6\]
Blue: H-burning products \([\text{O/Na}]=-2\]
Red: He-burning products \([\text{O/Na}]=3\]
After the LBV phase, the star moves away from break-up

The disk is disconnected from the star, and the classical radiatively-driven fast winds ($\geq 1000$ km.sec$^{-1}$) take over

\[ \text{No recycling of the stellar ejecta of more advanced phases (He-burning products and metals)} \]

Decressin et al. (07)
FRMS – Evolution of the central Abundances during the main sequence

60 $\text{M}_\odot$

$[\text{Fe/H}] = -1.5$

$T_c \in [48 ; 75] \times 10^6 \text{ K}$

NACRE (full black)

Illiadis et al. (01), Hale et al. (02, 04) nominal (long dashed blue)

Id experimental limits (short dashed green)

Id & 24Mg(p,$\gamma$) (Illiadis et al. 01)

$x 10^5 @ \sim 50 \text{ MK} \text{ and } x 10^{1.5} @ \sim 60 \text{ MK}$ (dotted red)

Decressin et al. (07a)
FRMS – Evolution of the surface abundances

$60 \, M_\odot, \, Z = 5 \times 10^{-4}$
$\Omega / \Omega_c = 0.95$
Meridional circulation and shear turbulence

NACRE (full black)
Illiadis et al. (01), Hale et al. (02, 04)
nominal (long dahed blue)
Id experimental limits (short dashed green)
Id &
$^{24}\text{Mg}(p,\gamma)$ (Iliadis et al. 01) $\times 10^3$ (dotted red)

Magnitude of abundance variations in NGC 6752 stars

Decressin et al. (07)
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**Mass budget issue**

<table>
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<tr>
<th>1st population</th>
<th>~ 30 ± 7 %</th>
</tr>
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<tr>
<td>2nd population</td>
<td>~ 70 ± 7 %</td>
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</tbody>
</table>

If 1G polluters follow a standard IMF (Salpeter X=1.35 or Kroupa), today’s ratio 1G:2G should be ~ 90:10

Decressin et al. (07), D’Ercole et al. (08)

---

**Flat polluter IMF**

| X ~ 0.6 - 0.8 (≥ 20 M☉) |
| X < -0.65 (5 - 6.5 M☉) |

Compare with Salpeter X = 1.35
Prantzos & Charbonnel (06)
Smith & Norris (82, C-N data) D’Antona & Caloi (04)
Downing & Sills (07) Marks & Kroupa (10) Marks et al. (12)

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**Delayed (~ 2 – 4 Myr) star formation**

Original gas: only 1P massive stars
Polluted gas: only 2P low-mass stars
Initial GC mass ~ 2 – 4 x present-day mass

Charbonnel et al. (14)
**Mass budget issue**

1\textsuperscript{st} population  \( \sim 30 \pm 7\% \)

2\textsuperscript{d} population  \( \sim 70 \pm 7\% \)

If 1G polluters follow a standard IMF (Salpeter X=1.35 or Kroupa)
today’s ratio 1G:2G should be \( \sim 90:10 \)
Decressin et al. (07), D’Ercole et al. (08)

Standard IMF  \( \rightarrow \)
Loss of \( \sim 95\% \) of 1G low-mass stars

Prantzos & Charbonnel (06), Decressin et al. (07)
D’Ercole et al. (08, 10), Carretta (10) Vesperini et al. (10)
Schaerer & Charbonnel (11), Conroy (12)

8 – 25 \times \) present-day mass  \( \rightarrow 6 – 20\% \) of the stellar mass of
the Galactic halo

Carretta et al. (10, VII)
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  Towards a global scenario (?)
  Or at least possible effects to take into account
A typical proto-GC in the framework of the self-enrichment with standard IMF

NGC 6752 (today’s $M \sim 3 \times 10^5 \, M_\odot$, no Fe spread)
Proto-GC cloud of $M_{\text{tot}} = 9 \times 10^6 \, M_\odot$
Half-mass radius $r_{1/2} = 3\, \text{pc}$
SFE = 1/3

Salpeter IMF for 1G stars with $M_i > 0.8 M_\odot$
~ 5700 massive stars between 25 and 120 $M_\odot$
log-normal IMF for 1&2G stars with $M_i \leq 0.8 M_\odot$

Mass-segregated cluster (Hillenbrand 97; de Grijs+02; Klessen 01; Bonnel+01)

Plummer profile for mass distribution
(Baumgardt+08; Decressin et al. 10; Baumgardt & Khalaj 14)

Gas mass proportional to $M_{\text{tot}}$, SFE, core radius

Stellar properties (energy, winds, radiation, lifetimes) and feedback to ISM

1P low-mass stars
1P massive stars and 2P low-mass stars

Plummer profile: Gravity peaks at core radius, and declines outside
Cluster is impacted by the stellar winds.
Stellar winds unable to lift any noteworthy amount of gas out of the GC on a relevant timescale.
Formation of hot, overlapping bubbles around massive stars, that quickly (~ 0.1 Myr) fill the entire volume within the half mass radius.
Lyman-Werner photons
\[ Q_{\text{LW}}(M) = 7 \times 10^{43} \left( \frac{M}{M_\odot} \right)^{2.9} \text{ s}^{-1} \]

\[ \rightarrow \text{Photodissociation of molecular H} \]
\[ T_{\text{gaz}} \sim 100 \text{K} \]

\[ \rightarrow \text{No « classical » star formation} \]
Conroy & Spergel (11)
Schaerer & Charbonnel (11)
Krause et al. (13)
Stellar evolution

Spongy structure for ISM

First generation star formation
Wind bubble phase
Slow equatorial winds and accretion
Second generation star formation

Stellar lifetime
120 $M_\odot$
25 $M_\odot$
9 $M_\odot$

Time
0
0.7 Myr
3.5 Myr
8.8 Myr
35 Myr
40 Myr

0.05 pc
1 pc
Slow equatorial mass ejection at critical rotation velocity

\[ \Delta M \sim 1M_\odot \]

Shadowing of the disc frees the equatorial region from radiation pressure

→ Establishment of an accretion flow of surrounding dense original gas
→ Time- and orbit-averaged Bondi accretion rate \( \sim 10^4 M_\odot /\text{Myr} \)
Viscous processes transport material within the disc.

Equatorial mass ejection vs accretion

Disc fed both by stellar processed matter and original material

Mixture of gas within the disk:
\[ \sim \frac{1}{2} \text{ pristine} - \frac{1}{2} \text{ ejecta (on average)} \]
Self-gravitating discs
(mass similar to the central star) (eg Armitage 11)
Toomre criterion (Shu 92)
  → The disc reach the critical mass for
  gravitational instability on timescale
  of ≤ 10^6 yrs
  → Formation of 2G low-mass stars
Studied in the context of planet
  (eg review by Kley & Nelson 12)
Very complex problem, lots of physics:
Transport/exchange of matter and angular momentum, role and influence of disk self-gravity and
magnetohydrodynamic turbulence, …
2P stars formation around individual massive stars:
H-burning ashes ejected by slow equatorial winds at critical rotation velocity
mixed with
Accretion flow of surrounding dense pristine gas

Fast Rotating Massive Star scenario
Stars with masses > 25 M☉
1st-2nd populations: Δt ~ 3.5 - 10 Myr

Prantzos & Charbonnel (06)
Decressin et al. (07a,b), Krause et al. (12,13)
Are there any 1\textsuperscript{st} generation stars in GCs today?

# Disc fed both by stellar processed matter and original material

Mixture of gas within the disk:

\[ \sim \frac{1}{2} \text{ pristine} - \frac{1}{2} \text{ ejecta (on average)} \]

(actual dilution is time-dependent)

Theoretical distribution of Na abundance for low-mass “2\textsuperscript{d} generation” stars at birth

Assuming

- Salpeter IMF for massive stars
- Log normal distribution Paresce & De Marchi 00

Are there any 1\textsuperscript{st} generation stars in GCs today?

“Fake” 1\textsuperscript{st} generation stars

1\textsuperscript{st} generation : [Na/Fe]_{min} + 0.3 dex

Charbonnel et al. (14)

C.Charbonnel - GCs - EES 2015
Are there any 1st generation stars in GCs today?

# Disc fed both by stellar processed matter and original material

Mixture of gas within the disk:
\~ \frac{1}{2} \text{pristine} – \frac{1}{2} \text{ejecta (on average)}
(actual dilution is time-dependent)

Theoretical distribution of Na abundance for low-mass \(2^{\text{d}}\) generation stars at birth
Assuming
- Salpeter IMF for massive stars
- Log normal distribution Paresce & De Marchi 00

\begin{align*}
\text{"Real" 1st generation stars} \\
\text{"Fake" 1st generation stars} \\
\text{2d gen stars}
\end{align*}

Delayed (~ 2 – 4 Myr) star formation
Original gas: only massive stars
Polluted gas: only low-mass stars
Initial GC mass \~ 2 – 4 \times \text{present-day mass}

Charbonnel et al. (14)
Mass limit for stars to explode as SNe?
$M \geq 25 \, M_{\odot}$ may turn silently into black holes
(Portegies Zwart et al. 97; Ergma & van der Heuvel 98; Kobulnicky & Skillman 97; Fryer 99; Belczynski et al. 12)

Loss of 1G stars during the supernovae phase?

Energetic arguments: SNe: agents of gas expulsion
$\rightarrow$ Fast ejection of gas and SNe yields
$\rightarrow$ Sudden change of gravitational potential and loss of 1G stars
Baumgardt et al. (08), D’Ercole et al. (08), Decressin et al. (10)
Rayleigh-Taylor instability develops whenever shell acceleration overcomes gravitational acceleration \((a-g > 0)\) and disrupts the shell when \(\lambda > \text{shell radius}\) → This favours fall back towards the cluster centre, and in this case gas expulsion fails.

Shell momentum given by the applied forces:

\[
\frac{\partial}{\partial t}(Mv) = pA - Mg
\]

Rayleigh-Taylor scale

\[
\lambda = (a - g)\tau^2
\]

Rayleigh-Taylor instability grows via spherically symmetric thin shell approximation

\[\text{Brown, Burkert & Truran (91,95)}\]

\[\text{Growth of the superbubble via spherically symmetric thin shell approximation}\]

\[\text{Brown, Burkert & Truran (91,95)}\]

Rayleigh-Taylor scale

\[
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\]

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Shell momentum given by the applied forces:

\[
\frac{\partial}{\partial t}(Mv) = pA - Mg
\]

Rayleigh-Taylor scale

\[
\lambda = (a - g)\tau^2
\]
**Energy sources: Stellar winds and SNe explosions**

Winds of massive stars
SNe explosions (10^{51} erg per explosion, with an efficiency parameter for the transfer of energy to the gas of 20%)

Energy injection and shell dynamics

Krause, Charbonnel et al. (12)
Energy sources: Stellar winds and SNe explosions

While the energy injected by the SNe in total is sufficient, it is not delivered fast enough to overcome the RT instability.

Rayleigh-Taylor instability length scale $\lambda = (a-g) \tau^2$

$\Rightarrow$ Shell is burst and disrupted before it reaches the escape speed

$\Rightarrow$ Shell fragments fall back

Slow and oscillatory shell expansion (<4Myr)

(gravitational pull)

Gravity declines sharply around $r_{1/2}$

$\Rightarrow$ shell acceleration
Energy source: Sudden activation of dark remnants

> 25\,M_\odot \rightarrow 3\,M_\odot \text{BH}, accretion of local gas adds energy to the gas at a rate of 20% of Eddington L
10-25\,M_\odot \rightarrow 1.5\,M_\odot \text{neutron stars, contribute 20% of Eddington L}

Shell expands immediately due to sudden power increase

Shell soon (0.03-0.06\,Myr) reaches escape velocity

Rayleigh-Taylor instability not able to affect the entire shell

\[ \rightarrow \text{Gas is expelled from the cluster} \]

Krause, Charbonnel et al. (12)
Energy source: Sudden activation of dark remnants

Only coherent onset of accretion of local ISM onto the stellar remnants succeeds in expelling cold gas and unbinds 1st generation stars.

Shell expands immediately due to sudden power increase.

Shell soon (0.03-0.06 Myr) reaches escape velocity.

Rayleigh-Taylor Ity not able to affect the entire shell.

Gas is expelled from the cluster.

Krause, Charbonnel et al. (12)
**FRMS scenario**
Stars with masses > 25 $M_\odot$
1st-2nd populations: $\Delta t \sim 3.5 - 10$ Myr

**Massive AGB scenario**
Stars with masses ~ 6.5$M_\odot$
Gas re-accretion and 2G * formed in a cooling flow

SNe energy not released quickly enough

Accretion onto and activation of dark remnants at the end of the SNe phase (turbulence decreases in the ISM)

**Challenge:**
Gas-free young massive star clusters

When and how did gas and 1G * ejection happen?
**Challenge: Gas-free young massive star clusters**

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Cluster</th>
<th>Age$^a$ (Myr)</th>
<th>$M_\ast$ $b$ (10$^5$M$_\odot$)</th>
<th>$r_h$$^c$ (pc)</th>
<th>$C_5$$^d$</th>
<th>$Z^e$ (Z$_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 6946</td>
<td>1447</td>
<td>12 ± 2.5</td>
<td>8</td>
<td>17.4</td>
<td>0.46</td>
<td>0.5</td>
</tr>
<tr>
<td>NGC 1569</td>
<td>A</td>
<td>6 ± 1</td>
<td>7.6</td>
<td>1.5</td>
<td>5.1</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>15 ± 5</td>
<td>14</td>
<td>2.4</td>
<td>5.9</td>
<td>0.4</td>
</tr>
<tr>
<td>NGC 1705</td>
<td>1</td>
<td>12.5 ± 2.5</td>
<td>11</td>
<td>1.5</td>
<td>7.3</td>
<td>0.33</td>
</tr>
<tr>
<td>NGC 1140</td>
<td>1</td>
<td>5 ± 1</td>
<td>11</td>
<td>14</td>
<td>0.79</td>
<td>0.5</td>
</tr>
<tr>
<td>The Antennae</td>
<td>T352/W38220</td>
<td>4 ± 2</td>
<td>9.2</td>
<td>4.1</td>
<td>2.2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Knot S</td>
<td>5 ± 1</td>
<td>16</td>
<td>14</td>
<td>1.1</td>
<td>1</td>
</tr>
<tr>
<td>ESO 338-IG04</td>
<td>Cluster 23</td>
<td>6$^{+4}_-2$</td>
<td>50</td>
<td>8.9</td>
<td>5.6</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Bastian *et al.* (14)

YMCs in starburst and merging galaxies with no gas and no star formation

Ages < ~ 15 Myr (although largely uncertain)
Masses and radii comparable to the values postulated for GCs from self-enrichment considerations

Very compact
Compactness index : $C_5 = (M_\ast/10^5 M_\odot) / (r_h / \text{pc})^{-1}$

Higher metallicity than old GCs

**T352 in the Antennae**
Gas-free YMCs – Individual gas expulsion modelling

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<th>$r_h^c$ (pc)</th>
<th>$C_5^d$</th>
<th>$Z^e$ ($Z_\odot$)</th>
<th>Ex/W</th>
<th>Ex/SN</th>
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(Y) Success of gas expulsion by
- Stellar winds (W)
- SNe $10^{51}$ erg
with 20% feedback efficiency
and assuming SFE = 0.3

Gas expulsion efficient
only for the less compact objects
Compactness index: $C_5 = (M_*/10^5 M_\odot) / (r_h/pc)^{-1}$

Krause, Charbonnel, Bastian, Diehl (15)
Gas-free YMCs – Individual gas expulsion modelling

<table>
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<tr>
<th>Galaxy</th>
<th>Cluster</th>
<th>Age(^a) (Myr)</th>
<th>(M_*)(^b) (10^5 M_\odot)</th>
<th>(r_h)(^c) (pc)</th>
<th>(C_5)(^d)</th>
<th>(Z_\odot)(^e)</th>
<th>Ex/ W(^f)</th>
<th>Ex/ SN(^f)</th>
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(Y) Success of gas expulsion by
- Stellar winds (W)
- SNe 10\(^{51}\) erg
when assuming SFE = 0.3
and 20% feedback efficiency

For the more compact YMCs, need hypernovae (10\(^{52}\) and 10\(^{53}\) erg) if SFE = 0.3

Or for a much higher SFE ≥ 0.8 for the most compact clusters
(less gas to be expelled)

→ However in this case, no loss of 1G stars, as the potential well does not change significantly

Krause, Charbonnel, Bastian, Diehl (15)

Gas expulsion efficient
only for the less compact objects
Compactness index: \(C_5 = (M_* / 10^5 M_\odot) / (r_h / \text{pc})^{-1}\)

C.Charbonnel - GCs - EES 2015
**Abundance properties – The key role of initial cluster mass**

- MW and LMC GCs with anticorrelation
- Sagittarius dSph GC without anticorrelation
- Old open clusters
- No or too few data

**Minimum present-day mass for a star cluster to exhibit [Fe/H] dispersion**

**Minimum present-day mass for a star cluster to exhibit the O-Na anticorrelation (but no [Fe/H] dispersion)**

C.Charbonnel - GCs - EES 2015
Abundances and gas ejection – The key role of compactness

Lines indicate the critical SFE for a given compactness index and energy scheme
Compactness index : $C_5 = (M_*/10^5 M_\odot) / (r_h / \text{pc})^{-1}$

Single stellar population:
No problem to expulse the gas but no O-Na anticorrelation

Multiple stellar populations with O-Na anticorrelation:
Gas expulsion under very special conditions
Or
High SFE

Krause, Charbonnel, Bastian, Diehl (15)
Multiple stellar populations with O-Na anticorrelation: Gas expulsion under very special conditions
Or
High SFE

GC constraints: Require runaway gas accretion onto BH and NS @ ~ 40Myrs
If YMCs ~ GC progenitors, i.e., early gas loss or consumption:
Require hypernovae,
or SFE > 50 – 80 %, thus no loss of 1G stars

Krause, Charbonnel, Bastian, Diehl (15)
Are YMSCs comparable to GC progenitors?

- **Yes** – Universal process for the formation and evolution of MSCs
- **No** – Importance of metallicity (ISM physics)?
  Importance of environment?
  Very unique conditions in the early Universe?

Krause, Charbonnel, Bastian, Diehl (15)

C.Charbonnel - GCs - EES 2015
Formation, evolution, and survival of massive star clusters

Universal processes in the early and present-day universe?
→ Importance of comparative studies!
→ Key role of multiple stellar populations!

(Some of the) Theoretical challenges of the next decade

→ Tailor-made models for MSC member stars

→ Models of MSCs (N-body and chemodynamical)
coupling stellar evolution, ISM physics, and feedback

→ Advanced population synthesis models
accounting for the chemical and photometric peculiarities of
multiple stellar populations