Observational constraints on GC formation scenarios

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Multiple populations in GCs - key points:

- **Ubiquitous**: Na/O anti-correlation is present in all *old* GCs observed to date (though Mg/Al and large He spreads only in some).
- Most GCs show no, or only very small (≤0.05 dex), spreads in Ca, Fe
- Fraction of “anomalous” stars is *large*: 50% or more.

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**Na/O anti-correlation**

- 19 GCs (Carretta et al. 2009)

**Mg/Al anti-correlation**

- NGC 2808 (Carretta 2014)

**Complex CMDs**

- NGC 2808 (Piotto et al. 2007)
The Mass Budget Problem

• Enriched wind material (whether from AGB or MS stars) is insufficient to form a 2nd generation that is as massive as the 1st gen.

• Initial masses of GCs predicted to have been 10-20 x higher than currently observed (Decressin et al. 2007; D’Ercole et al. 2008; Vesperini et al. 2010; Bekki 2011; Valcarce & Catelan 2011; Conroy 2012)
  - More than 50% of the Galactic halo might consist of “lost” GC stars (e.g. Martell et al. 2011; Gratton et al. 2012).

• “Early disc accretion” scenario:
  - polluted material is swept up by discs around “1st gen” low-mass stars.
  - Massive interacting binaries provide enough ejecta to avoid mass-budget problem (Bastian et al. 2013).
The Na/O anticorrelation

Only found in old GCs so far. But YMCs with comparable masses are rare and far away.
ESO 338-IG04 - Cluster 23

$t = 6^{+4.2}_{-2}$ Myr
$A_v = 0$
$M \approx 1 \times 10^7$ Msun
$R_{\text{bubble}} \approx 120-200$ pc
$Z = 0.2 Z_{\text{sun}}$

• Bubble began expanding 1-3 Myr after formation
• Efficiently removed any pristine material out to hundreds of parsecs (still expanding at 40 km/s)
• Metallicity below that of Galactic globular clusters that show anomalies

Courtesy N. Bastian

Östlin et al. 2007
GCs in dwarf galaxies

Some dwarf galaxies have extremely rich GC systems for their sizes

\[ S_N = N_{GC} \times 10^{0.4(M_V+15)} \]

![Graph showing the relationship between the specific frequency of GCs \( S_N \) and absolute magnitude \( M_V \) for various types of galaxies. The graph includes data points for dEs, dSphs, Sm galaxies, dIrrs, and others, with lines connecting certain points to indicate trends. The graph also includes labels for specific galaxies such as IKN, Fornax, and WLM, with their corresponding \( S_N \) values.](image-url)
The Fornax dSph

5 GCs, $M_V \sim -13.1$
(Hodge 1961; Mateo 1998)

Total stellar mass
$M^* \sim 6 \times 10^7 M_\odot$
(Coleman & de Jong 2008).

Mass of GCs $\sim 10^6 M_\odot$
($\sim 1.7\%$ of $M^*$)

4.2.1. Fornax

The Fornax dwarf provides probably the clearest case of a dwarf whose stellar component has not been disturbed by Galactic tides. Not only is the tidal radius clearly well outside the luminous radius, but also there is no evidence for distortions in the outer profile that may be ascribed to the past effect of tides. A $c_k = 4$ King model fits the surface density profile of Fornax extremely well, down to the last measured point.

Peñarrubia et al. 2009
The Fornax GCs

HST WFPC2+WFC3
F343N/F555W/F814W

~24 pc

Fornax 1
(R=1.6 kpc)

Fornax 2
(R=1.1 kpc)

Fornax 3
(R=0.4 kpc)

Fornax 4
(R=0.2 kpc)

Fornax 5
(R=1.4 kpc)
### Metallicities from high-dispersion spectroscopy

<table>
<thead>
<tr>
<th></th>
<th>[Fe/H]</th>
<th>[Ca/Fe]</th>
<th>$v_r$ (km s$^{-1}$)</th>
<th>Source</th>
<th>Source Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fornax 1</td>
<td>$-2.5 \pm 0.1$</td>
<td>$+0.15 \pm 0.04$</td>
<td>$59 \pm 1$</td>
<td>Letarte et al. 2006</td>
<td>Indiv. stars</td>
</tr>
<tr>
<td>Fornax 2</td>
<td>$-2.1 \pm 0.1$</td>
<td>$+0.20 \pm 0.03$</td>
<td>$64 \pm 1$</td>
<td>Letarte et al. 2006</td>
<td>Indiv. stars</td>
</tr>
<tr>
<td>Fornax 3</td>
<td>$-2.3 \pm 0.1$</td>
<td>$+0.25 \pm 0.08$</td>
<td>$60.4 \pm 0.2$</td>
<td>This work</td>
<td>Integr. light</td>
</tr>
<tr>
<td>Fornax 4</td>
<td>$-1.4 \pm 0.1$</td>
<td>$+0.13 \pm 0.07$</td>
<td>$47.2 \pm 0.1$</td>
<td>This work</td>
<td>Integr. light</td>
</tr>
<tr>
<td>Fornax 5</td>
<td>$-2.1 \pm 0.1$</td>
<td>$+0.27 \pm 0.09$</td>
<td>$60.6 \pm 0.2$</td>
<td>This work</td>
<td>Integr. light</td>
</tr>
</tbody>
</table>

- Fornax 1, 2, 3, 5 all have [Fe/H] < -2
- Field star metallicities peak near [Fe/H] = -1
  (Battaglia et al. 2006; Kirby et al. 2011).

Larsen et al. (2012)
GCs and field stars in Fornax

Field stars: Battaglia et al. (2006), Ca II triplet spectroscopy.
GCs: Letarte et al. (2006); Larsen et al. (2012)

Few field stars at $[\text{Fe/H}]<-2$

GCs much more metal-poor than most field stars.
Field stars and GCs in Fornax: Metallicity distributions

For \([\text{Fe/H}] < -2\):

- Mass in field stars \(\sim 3 \times 10^6 \, M_\odot\)
- Mass in GCs \(\sim 1 \times 10^6 \, M_\odot\)

About 1/5-1/4 of all metal-poor stars in Fornax dSph belong to F1+F2+F3+F5.

Clusters could at most have been \(\sim 4-5\) times more massive initially!

This assumes no other clusters or field stars formed with similar metallicity, no “infant mortality”.

Larsen et al. (2012, A&A 544, L14)
Field stars: Battaglia et al. (2006), corrected for spatial coverage.
GCs: Letarte et al. (2006), Larsen et al. (2012)
The WLM dIrr

D(WLM-Milky Way) ~ 925 kpc
D(WLM-M31) ~ 950 kpc
Near edge of Local Group
M_v ~ -14.5

1 old GC: M_v = -9.0, M ~ 6 \times 10^5 M_\odot

(Humason et al. 1956; Ables & Ables 1977; Sandage & Carlson 1985; Larsen et al. 2014a)
WLM: field stars vs GC

Field stars:

Stellar mass $M^* \sim 1.6 \times 10^7 \, M_\odot$

$\langle [\text{Fe/H}] \rangle = -1.28$

(Leaman et al. 2013, Ca II IR triplet spectroscopy of RGB stars)

Globular cluster:

$M \sim 6 \times 10^5 \, M_\odot$

Metal-poor ($[\text{Fe/H}] \sim -2.0$)

GC accounts for 17%-31% of metal-poor stars

(Larsen et al. 2014a)
The IKN dSph
Karachentsev et al. (2002)
Fig. 1. The distribution of galaxies in the NGC 2403/M 81/NGC 4236 complex in supergalactic coordinates. Top: overview of the entire region, bottom: the central part of the M 81 group.

Since 1998 many more distance measurements in the M 81 group have become available thanks to observations with the Hubble Space Telescope (HST) and the use of the tip of the red giant branch (TRGB) method. Based on the brightness of the tip of the RGB, Caldwell et al. (1998), Lynds et al. (1998), and Sakai & Madore (1999) determined distances to four dwarf galaxies in the M 81 group: BK5N, F8D1, UGC 6456, and M 82. Many more probable members of the M 81 group were included in the snapshot survey of nearby galaxies (programs SNAP 8192 and 8601, PI: Seitzer) with the Wide Field and Planetary Camera 2 (WFPC2) aboard HST. As a result, we measured the TRGB distances to nine dSph galaxies (Karachentsev et al. 1999, 2000, 2001) and to one dIrr (Dolphin et al. 2001). In this paper we present new distance estimates for 13 late type galaxies observed with the HST. The new availability of accurate distances to most galaxies of the NGC 2403/M 81/NGC 4236 complex allows us to consider the 3D- structure, kinematics, and dynamics of the complex, a map of which is shown in Fig. 1. The stellar populations and star formation history of the observed galaxies will be discussed by us in the next paper.

2. HST WFPC2 photometry and color-magnitude diagrams
WFPC2 images of 15 objects in the M 81 group were obtained during 2000 July 11 to 2001 June 27 as part of our snapshot survey of probable nearby galaxies (SNAP 8601; Seitzer et al. 1999). Usually our target galaxies were centered on the WF3 chip, but for some bright targets the WFPC2 position was shifted towards the galaxy periphery to decrease a stellar crowding effect. The 600 s exposures were taken in F606W and F814W for each object. Digital sky survey (DSS) images (POSS-I,E) of the fifteen galaxies are shown in Fig. 2, on which the HST WFPC2 footprints are superimposed. The field size of the DSS images is 10' by 10'.

The photometric reduction was made using the HSTphot stellar photometry package described in detail by Dolphin (2000a). After removing cosmic rays with the HSTphot cleansep routine, simultaneous photometry was performed on the F606W and F814W frames using multiphot, with aperture corrections for an aperture with 0.5 radius. Charge transfer efficiency corrections and calibrations were then applied based on the Dolphin (2000b) formulae, producing VI photometry for all stars detected in both images. Because of the relatively small field of the Planetary Camera (PC) chip, very few bright stars were available for the computation of an aperture correction. Thus the PC photometry was omitted from further analysis. Additionally, stars with a signal-to-noise ratio < 5, |χ| > 2.0, or |sharpness| > 0.4 in each exposure were eliminated from the final photometry list. We estimate the uncertainty of the photometric zeropoint to be within 0.05 (Dolphin 2000b).

Figure 3 shows mosaic images of the galaxies, where both filters were combined. The compass in each field indicates the North and East directions.

DSS image: brightest GC marked (IKN dSph itself practically invisible)
GCs in the IKN dSph
IKN: Field stars vs GCs

\[ \frac{L_{GC}}{L_{tot}} \approx 13\% \]

Field star metallicities from photometry of RGB (Lianou et al. 2010)

1 GC (IKN-5) has \([\text{Fe/H}] \sim -2.0\)

Field:GC ratio about 1:1 at \([\text{Fe/H}] = -2\)

(Larsen et al. 2014a)
Light elements in Fornax GCs: Individual stars

Tentative hints at the Na/O anti-correlation

(Also integrated light; Larsen et al. 2012; 2014a).

Letarte et al. 2006

Fig. 2. The finding charts for our observations of the Fornax GCs, from 1 (left) to 3 (right). North is up and East is left, as indicated. Note that star CI3-B59 is outside of the cluster 3 HST field, to the west.
Constraining abundances with photometry

WFC3/F343N band sensitive to N abundance

\[ \Delta(m_{F343N} - m_{F555W}) \sim 0.2 \text{ mag for } \Delta[N/Fe] \sim 2; \]

typical range seen in GCs (e.g. Yong et al. 2008)
N spreads in Fornax GCs

F555W-F814W: Insensitive to [N/Fe], spread consistent with errors
F343N-F555W: Spread larger than errors, Δ[N/Fe]~2 dex, similar to M15

Isochrones from Dotter et al. 2007
Synthetic colours based on ATLAS12/SYNTHE model spectra.

Larsen et al. (2014b)
Bottom line:

The GCs in the Fornax dSph (and probably other dwarfs) are similar to their Milky Way counterparts in terms of multiple stellar populations.

GC formation models must account for both "internal" (large number of polluted stars) and "external" (high ratio of GC/field stars in dwarf galaxies) mass budget problems.
Radial distributions

- All scenarios: enriched population should be more centrally concentrated
  - AGB: Formation from cooling flow
  - Massive stars: enriched population forms near mass-segregated massive stars
  - Early disc accretion: Accretion most effective in central regions, where density is high.
Radial distributions of sub-populations

SDSS data, $r > 0.5 r_h$:

*Enriched* stars generally the most centrally concentrated.

Expected in all scenarios
- AGB scenario (cooling flow)
- Massive stars (mass segr.)
- Disc accretion (most efficient near centre)

Lardo et al. (2011)
Radial distributions in M15

Group A ("pristine") stars most centrally concentrated.

K-S test for radial distr. of A vs (B,C): $P = 3 \times 10^{-5}$. 
Combining HST and SDSS data

“U”-shaped trend of normal vs. “enriched” stars.

Enriched stars are preferentially located near the half-mass radius.

Not expected in any of the current scenarios.

Mass segregation?

- If enriched stars are strongly He-enriched ($Y \sim 0.40$), then $M_{\text{TO}} \sim 0.6 \, M_\odot$ instead of $0.8 \, M_\odot$ at 13 Gyr

- Mass segregation might then “push” enriched RGB stars outwards from the centre

- In outer regions, primordial trends would be preserved because of long relaxation time.

- Does this work?
N-body simulations

NBODY6 simulations for stars of
- different masses
- same initial distrib.

Evolved to 11.5 Gyr

(Lützgendorf et al. 2013; McNamara et al. 2012)

It might just work!
But…

Effect of $Y$ on isochrones

Dartmouth isochrones

$(\text{Dotter et al. 2007})$

$\Delta_{F606W-F814W} \approx 0.03 \text{ mag}$

for $Y=0.25$ vs $Y=0.40$

*Measurable.*

Dartmouth isochrones

$(\text{Dotter et al. 2007})$
No colour difference!

Mean colours of all (normal, interm., extreme) stars identical to within 0.001 mag in F606W-F814W.

$\Delta Y < 0.005$ and $\Delta M < 0.01 M_\odot$.

Mass segregation will not work!
Summary

• Young massive clusters are very gas-poor very early on.

• High ratio of metal-poor GCs to field stars in dwarf galaxies is a challenge to AGB and FRMS scenarios.

• Radial distribution of subpopulations in M15 is a challenge to all scenarios.