Globular clusters
Corinne Charbonnel – University of Geneva

Part I – GC general properties

Part II – Chemical dissection and multiple stellar populations in GCs
Towards a new paradigm

Part III – The evolution of the multiple stellar populations in GCs

Corinne Charbonnel
Dept of Astronomy, Univ. of Geneva & IRAP CNRS, Univ. of Toulouse
Globular clusters

In honor of Jean-Paul Zahn

C.Charbonnel - GCs - EES 2015
Part I – GC general properties

✓ GCs - Tools for Astrophysics and Cosmology
✓ The GC system of the Milky Way
  - Census
  - Luminosity and mass
  - Global metallicity
  - Ages

✓ GCs in the Local Group
GCs – « Historical » definition

✓ Globular clusters are compact, nearly spherical, bound systems of hundreds of thousands (sometimes millions) of stars
  Brightness \( M_V \sim -5 \) to \(-10 \)
  Masses \( \sim 10^4 – 10^6 \, M_\odot \) (M/L \( \sim 2 \))
  Size \( \sim \) a few to \( \sim 100 \) pc

✓ Most GCs orbit in the Galactic halo, in highly eccentric elliptical orbits (far from the thin disk of the Galaxy that contains most stars and younger open clusters) with orbital periods \( \geq 10^8 \) yr

✓ GCs in the Milky Way are old (ages greater than \( \sim 10^{10} \) years)

✓ In each individual GC, stars are coeval and were born with homogeneous chemical composition

✓ Their brightness and distinctive appearance makes them easy to detect at large distance

✓ They are seen in and around other galaxies
**GCs – Dynamical processes**

- Globular clusters are **compact, nearly spherical, bound systems of hundreds of thousands (sometimes millions) of stars**

  Holger

  - Fundamental **dynamical processes** (relaxation, mass segregation, core collapse) on timescales shorter than the Hubble time

  Baumgardt

- Along their orbit GCs are subject to a variety of perturbations

  - **Interactions** with the environment
  - Contribution to the **Galactic stellar populations**
  - Perhaps the survivors of a much wider **population partially disrupted**

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**Palomar 5 torn apart by the Milky Way**

**Koch et al. (04)**

**Odenkirchen et al. (09)**
Roughly ~20 GC streams are now known in the Milky Way halo. Some of these have known progenitors (e.g. Pal 5), others don’t…

Stream has [Fe/H]~2 and extends in distance from 7.5-9 kpc from us. Modelled by Sesar et al. 2015 as a ~$2 \times 10^4 \, M_\odot$ 12 Gyr old GC that disrupted a mere 240 Myr ago.
GCs – Galaxies

✓ Their brightness and distinctive appearance makes them easy to detect at large distance. (Hubble, ~ 100 GCs in M31)

# GCs are seen in and around galaxies of all Hubble types

# Very similar GCs properties, independently on the properties of the parent galaxy (but age)

→ Common path in the *early phases of galaxy evolution*

→ Clues to *galaxy formation, structure, and evolution*

MW : ~ 180 ± 20 GCs

Barmby *et al.* (00) Huxor *et al.* (14)

Harris (99)

M31 : ~ 500 GCs

M87 : ~ 15’000 GCs

C.Charbonnel - GCs - EES 2015
GCs – **Specific frequency in galaxies**

# Number of GCs in a galaxy divided by the galaxy’s luminosity \( (Harris \& van\ den\ Bergh 81) \)

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

# Measures the **formation efficiency** of GCs relative to field stars

# with \( \geq \) galaxy luminosity from 

\( M_V \) -11 to -20 mag

# \( \geq \) for \( M_V \) above -20

# Depends on galaxy morphology:

Over the full mass range, 2 x higher in **ellipticals** than in **spirals**

# Large dispersion @ all \( M_V \)

Evolution effects, disruption, etc

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**GC specific frequency versus absolute galaxy magnitude for the entire range of galaxy luminosity, masses, morphologies, and environments.**

**Georgiev et al. (2010)**
GCs – Specific mass and luminosity of GC systems

# Total mass of the GC system $M_{GCS}$
relative to the total mass of baryons of the host galaxy (stellar mass $M_*$ + HI gas mass $M_{HI}$)

$$S_M = 100 \frac{M_{GCS}}{(M_* + M_{HI})}$$

# Luminosity ratio of a GC system $L_{GCS}$ to $L_V$ of its host galaxy (Harris 1991)

$$S_L = 100 \frac{L_{GCS}}{L_V}$$

Georgiev et al. (2010)
GCs – Universe and galaxies

- GCs in the Milky Way are old (ages greater than ~ $10^{10}$ years)
- MW GCs range among the oldest objects of the Universe
  → Stringent lower limit to the age of the Universe before precision cosmology

# GC formation in a cosmological context
# GCs sample the very early phases of the formation and evolution of their galactic host
  → Chronology for the assembly of the halo, bulge, and disk of the Milky Way
# GCs probe star formation at large redshift
GCs – Galaxies

✓ GCs are not all uniformly old

LMC, SMC, M31 and M33 contain intermediate-age and young GCs

“Populous young clusters” in LMC: 10 Myr - 2 Gyr
R136 in 30 Doradus: 3 - 4 Myr

Young (~ 500 Myr) proto-GC candidates at the core of the giant elliptical NGC 1275 at the center of Perseus cluster

Nascent GC R136 in 30 Doradus (LMC)
WFPC2 Image HST
Credit NASA John Trauger & James Westphall
GCs – Galaxies

✓ GCs are not all uniformly old

There is much evidence for continued formation of massive star clusters in Local Group galaxies

Some are currently forming in ongoing mergers and starburst galaxies from large molecular-gas complexes

# Clues on mergers or collisions in the history of galaxies
# Clues on star formation in various environments

✓ Are the young, massive star clusters the modern counterparts of old GCs?

Nate Bastian
Patrick Hennebelle

Antennae Galaxy
~ 700 candidate GCs
GCs – Stellar physics and evolution

✓ Globular clusters host hundreds of thousands (sometimes millions) old, coeval stars born with homogeneous chemical composition

# Host a wide variety of interesting and unusual objects (millisecond pulsars, blue stragglers, low-mass X-ray binaries, …)

# GC CMDs : benchmarks for the theory of stellar evolution

Rood et al. (98 ESAP 413, 515)
GC studies bring insight on cosmology, galaxy formation and evolution, stellar dynamics, stellar evolution.

However, their formation and evolution are still poorly understood.

# Classical paradigm:
“Globular clusters are fairly simple large bound systems of coeval stars born with homogeneous chemical composition”

# However, GGCs probably did evolve chemically and dynamically and certainly consist of multiple stellar generations
# Globular Clusters

## Table 1. Importance of GCs.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Reasons for importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Witnesses of the early</td>
<td>• First to form</td>
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<tr>
<td>Galactic evolution</td>
<td>• Chemically uncontaminated</td>
</tr>
<tr>
<td>Stellar Evolution Laboratories</td>
<td>• Simple stellar populations</td>
</tr>
<tr>
<td></td>
<td>• Test of the ‘stellar clock’</td>
</tr>
<tr>
<td>Distance indicators</td>
<td>• Standard candles: the RR Lyrae stars</td>
</tr>
<tr>
<td></td>
<td>• GC system integrated luminosity function</td>
</tr>
<tr>
<td>Age indicators</td>
<td>• The turn-off luminosity = ‘the clock’</td>
</tr>
<tr>
<td></td>
<td>absolute ages: lower limit to the age of the universe</td>
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<tr>
<td></td>
<td>relative ages: ‘second parameter’ and Galaxy formation and evolution</td>
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<tr>
<td>Dynamics probes</td>
<td>• Dense environment</td>
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<td>core collapse</td>
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<td>collisions</td>
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<td></td>
<td>merging–surviving</td>
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<tr>
<td></td>
<td>segregation</td>
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<td>Containers of peculiar objects</td>
<td>• Test particle of the galactic gravitational field</td>
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<td></td>
<td>• X sources (strong–weak–diffuse)</td>
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<td></td>
<td>• Blue stragglers</td>
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<td></td>
<td>• Binaries</td>
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<td></td>
<td>• Planetary nebulae</td>
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<td>• White dwarfs</td>
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<td>• Cataclysmic variables</td>
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<tr>
<td></td>
<td>• Millisecond pulsars</td>
</tr>
<tr>
<td></td>
<td>• Neutron stars</td>
</tr>
</tbody>
</table>

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**David Barado**

**Holger Baumgardt**
Globular clusters

Part I – GC general properties

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  - Census
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  - Ages

✓ GCs in the Local Group
**MW GCs – Spatial distribution within ~ 20kpc of Gal center**

# Space distribution is approximately **spherical** except in the central bulge

# MW GCs are found **everywhere from deep within the Galactic bulge out to twice the distance of the Magellanic clouds**

**Harris (1996)**

137 GCs

« Distance scale » assume $M_V(HB) = 0.15 \ [Fe/H] + 0.80$

(X, Y, Z) : usual distance coordinates of clusters relative to the Sun

$X = R \ cos \ b \ cos \ \mathcal{U}$ (from the Sun in the direction of the Galactic center)

$Y = R \ cos \ b \ sin \ \mathcal{U}$ (in the direction of Galactic rotation)

$Z = R \ sin \ b$ (perpendicular to the Galactic plane northward)

($\mathcal{U}, \ b$) : Gal latitude and longitude, R dist of the cluster to the Sun

Sun : (0,0,0) kpc – Galactic center : (8,0,0) kpc
Milky Way GCs – Census

The 119 globular clusters within 50,000 LY of the galactic centre

Galactic centric (galactic longitude and latitude)

~ 15 kpc

Data from William E. Harris, McMaster University
http://www.physics.mcmaster.ca/Oblobular.html

3D Diagram by Larry McNish

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**MW GCs – Spatial distribution beyond 20kpc of Gal center**

# Space distribution of the MW GCs **more distant than** 20kpc from the Galactic center (points) and dwarf satellite galaxies (crosses)

→ **Much larger-scale asymmetric planar distribution**

→ **Distinct origin and history outside the MW proper**

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**X, Y measured relative to the Galactic center**

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GCs, satellite galaxies, and tidal streams of the MW halo

Importance of the Sloan Digital Sky Survey and of several IR surveys

→ GCs, dwarf spheroidal galaxies, ultra-faint dwarf galaxies, stellar tidal streams (or “overdensities”)

~ 180 ± 20 GCs
+ ~ 35 dwarf galaxies
+ Tidal streams

4 GCs (e.g. M54) are likely members of the Sagittarius dwarf galaxy (discovered in 1994) currently merging with the MW
**Milky Way GCs – Recent discoveries**

# New members found thanks to
- near IR/IR surveys of the low-latitude regions (e.g. 2MASS, Spizer, …)
- wide-field sky surveys of the high-latitude sky

![GLIMPSE-01](image.png)

Kobulnicky et al. (05 AJ 129, 239)

*Spitzer Space Telescope* imaging from the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE)
Angular diameter $\sim 1 – 2$ pc
Mass $\geq 10^5$ Msun
# New members found thanks to
- near IR/IR surveys of the low-latitude regions (e.g. 2MASS, Spizer, …)
- wide-field sky surveys of the high-latitude sky

→ The structural parameter space of GCs in the MW halo is not yet fully explored

→ Most new halo GCs are low luminosity ($M_V > -4$) and diffuse: classification?

→ Short remaining survival times, evidence for a once much larger population of GCs

3′ × 3′ SDSS cutout image of Koposov 1

Koposov et al. (07 ApJ 669, 337)

*SLOAN Digital Sky data release 5*

Size vs absolute magnitude (data from Harris 96 in diamonds)

**Extremely low luminosity** GC ($M_V \sim -1$ mag)

Observed size $\sim 3$pc

Halo at $\sim 40 – 50$ kpc

KOPOSOV1

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**Milky Way GCs – Recent discoveries**

**Crater: The Milky Way’s Most Remote GC?**

Simultaneously discovered in VST/ATLAS (Belokurov et al 2014) and PS1/3Pi Surveys (Laevens et al 2014)

\[ D \sim 145-170 \text{ kpc}, \quad R_h \sim 20-30 \text{ pc}, \quad M_V \sim -4.5 \text{ to } -5.5 \]

Bonifacio *et al.* (15) → Crater is a dwarf galaxy

Kirby *et al.* (15) → Crater is a GC

\[ [\text{Fe} / \text{H}] = -1.7 \] (both studies, X-shooter and Keck spectro of bright giant stars)
Globular clusters

Part I – GC general properties

- GCs - Tools for Astrophysics and Cosmology
- The GC system of the Milky Way
  - Census
  - Luminosity and mass
  - Global metallicity
  - Ages
  - Correlations between the properties

- GCs in the Local Group
**Milky Way GCs – Luminosity function**

# Integrated luminosity = cumulative light of all stars

→ Direct **indicator of the total cluster mass**, as long as we know the total mass-to-light ratio (Mass/Light ~ 2)

# Total cluster magnitude $M_v^T = V^T - (m-M)_V$

= apparent total magnitude – apparent distance modulus

# GCLF: relative number of GCs per unit magnitude

Unimodal, ~ symmetric, close to a Gaussian – Very luminous and very faint GCs are rare

→ **Relic of both**

  the initial mass spectrum at cluster formation
  and 11 – 13 Gyr of dynamical evolution

Fig. 1.33. Number of globular clusters per 0.2-magnitude bin, for the Milky Way. A Gaussian curve with mean $M_v = -7.4$ and standard deviation $\sigma = 1.15$ mag is superimposed to indicate the degree of symmetry of the distribution.

Harris (1996)
Globular clusters

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✓ GCs in the Local Group
No ultra-poor GGC
\[ -2.4 \leq [\text{Fe/H}] \leq 0 \]

- Pre-galactic enrichment Harris & Pudritz (94) - James et al. (04)
- Disruption of very metal-poor GCs?

Gratton et al. (04 ARAA)
**Milky Way GCs – Iron-peak elements**

- Most GGCs are mono-metallic → No self-enrichment

Observed intrinsic dispersion in Fe from GIRAFFE spectra vs visual total magnitude of 19 GGCs

Carretta et al. (09)

- Rare exceptions: The most massive GGCs ΩCen, M54, M22, NGC 3201, NGC 1851

Omega Centauri

Remnant of a dwarf galaxy?

Da Costa et al. (09)

Marino et al. (11)
**Milky Way GCs – [Fe/H]**

# [Fe/H] distribution: 2 major subpopulations

(Suspected by Kinman 1959 confirmed by Zinn 1985)

Metal-poor component : ~ ¾ of all clusters; spread throughout the halo

Metal-rich component : ¼ , almost entirely concentrated within the solar circle, \( R_G \sim 8 \text{kpc} \)

# 2 Gaussians, clear 1dex separation \( \rightarrow \) Suggests distinct formation/evolution histories

![Histogram of [Fe/H] values for Milky Way GCs](image)

- [Fe/H] = -1.6 ± 0.3
- [Fe/H] = -0.6 ± 0.2

Harris (1996)

137 GCs

[Fe/H] from Zinn-West (84) scale (photometric integrated light index)
**Milky Way GCs – [Fe/H] spatial distribution**

# Metal-rich clusters form a sub-system with a much smaller scale size and (better) associated to the Galactic bulge

# Nb ratio of the 2 types of clusters, $N(MRC) / N(MPC)$ steadily rises inward to the Galactic center

*Harris (96)*

137 GCs

[Fe/H] from Zinn-West (84) scale

![Graph](image)

« Distance scale » assume $M_V(HB) = 0.15 \, [Fe/H] + 0.80$

$(X, Y, Z)$ : usual distance coordinates of clusters relative to the Sun

$X = R \cos b \cos \ell$ (from the Sun in the direction of the Galactic center)

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$(\ell, b)$ : Gal latitude and longitude; R dist of the cluster to the Sun

Sun : (0,0,0) kpc – Galactic center : (8,0,0) kpc
Milky Way GCs – [Fe/H] versus Galactocentric distance

# Large scatter in metallicity at any $R_G$
# Small net metallicity gradient for the inner regions at $R_G < 10$ kpc
# No detectable mean gradient at $R_G > 10$ kpc

Fig. 1.8. [Fe/H] plotted against Galactocentric distance $R_g$. Upper panel: Individual clusters are plotted, with MRC objects as solid symbols and MPC as open symbols. Lower panel: Mean [Fe/H] values for radial bins. Both MRC and MPC subsystems exhibit a slight gradient $\Delta$[Fe/H] $\Delta$log$R_g = -0.30$ for $R_g \leq 10$ kpc, as shown by the solid lines. For the more distant parts of the halo, no detectable mean gradient exists.

Harris (1996)
137 GCs
[Fe/H] from Zinn-West (84) scale
Milky Way GCs – [Fe/H]

# [Fe/H] from Carretta et al. (09 A&A 508, 695)
UVES/ Flames spectroscopy
→ New homogeneous metallicity scale (recalibration of the photometric indices)

Data from Harris (2010)
157 GCs
with [Fe/H] from Carretta et al. (09) scale
MWGCs – Absolute visual magnitude versus [Fe/H]

# No correlation between GC luminosity (e.g. mass) and [Fe/H]
→ Mass of GC is independent of the metallicity of the proto-GC molecular cloud?
→ Self-enrichment negligible

Data from Harris (2010)
157 GCs
with [Fe/H] from Carretta et al. (09) scale

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Globular clusters

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Ages

# Different “clocks” of the ages of GCs

David Barrado

See also
Cassisi & Salaris (2013)
Cassisi (EES2013 The ages of star)
and references therein
**Milky Way GCs – Absolute ages**

# Milky Way GCs:
- **Metal-poor** ([Fe/H] < -2.2, left): Mean age 12.5 Gyr
- **Metal-rich** (-1.0 ≤ [Fe/H]): Mean age 11.1 Gyr

Fig.11 and 16 from VandenBerg *et al.* (13 ApJ 775, 134)
[Fe/H] from Carretta *et al.* (09 A&A 508, 695) – UVES/ Flames spectroscopy
→ New homogeneous metallicity scale (recalibration of the photometric indices)
- Assumed distances based on (very good) fits of theoretical ZAHB to lower bound of the observed distribution of HB stars
- Age from (very good) main-sequence turnoff isochrone fitting
**Milky Way GCs – Age-[Fe/H] relationship**

- **Most metal-poor** \(([\text{Fe/H}] < -1.7)\): Mean age 12.5 Gyr, dispersion \(\sim \pm 0.5\) Gyr
- **At higher metallicity, the AMR is bifurcated:**
  - **Intermediate metallicity**: larger age spread
  - **Highest metallicity**: Mean age \(\sim 11\) Gyr

**Important implications for the formation/assembly of MW GC system**

Fig.33 from VandenBerg *et al.* (13 ApJ 775, 134)
**Milky Way GCs – Relative ages**

- The younger metal-rich GCs: systematically younger, ~ 11 Gyr (ok with Vandenberg)
- The oldest metal-rich GCs are ~ coeval with the most metal-poor ones
  - Not seen in AMR of VandenBerg et al. (13)
  - Different age – metallicity relation
  - Associated to accretion events

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*Figure 10. Globular cluster normalized ages as a function of [M/H] in the CG-metallicity scale (upper panel), and as a function of galactocentric distance (r_{GC} kpc, lower panel). These results have been derived using the D07 stellar evolution library. Open circles, filled triangles, and filled circles represent GCs within the low-, intermediate-, and high-metallicity groups, respectively. For each of the three metallicity groups, mean age and rms are indicated. See text for details.*

Marín-Franch *et al.* (09 ApJ 694, 1498)
**Milky Way GCs – Age-\(R_G\) relationship**

- Considering the whole data set: Virtually no dependence of the mean age and of age dispersion with galactocentric distance.
- Old, very metal-poor GCs found at all \(R_G\).
- Majority of metal-rich GCs are younger and located at lower \(R_G\).

Fig. 34 from VandenBerg et al. (13 ApJ 775, 134)

Filled triangles, open triangles, and composite correspond to \([\text{Fe/H}] < -1.7\), \([\text{Fe/H}] \geq -1.0\), and \(-1.7 \leq [\text{Fe/H}] < -1.0\), respectively.

Suggests an outside-in scenario for the formation of the Galaxy.

But compatible with mergers of dwarf galaxies.
Globular clusters

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  - Ages
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The census of Local Group GCs

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>N_{GC}</th>
<th>M_V</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW</td>
<td>~160 ?</td>
<td>-21.3</td>
<td>Sbc</td>
</tr>
<tr>
<td>M31</td>
<td>~500 ?</td>
<td>-21.8</td>
<td>Sb</td>
</tr>
<tr>
<td>M33</td>
<td>~50</td>
<td>-19</td>
<td>Scd</td>
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<td>-13.9</td>
<td>dSph</td>
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<tr>
<td>Fornax</td>
<td>5</td>
<td>-13.0</td>
<td>dSph</td>
</tr>
</tbody>
</table>

Veljanoski et al. 2013, Hwang et al. 2011, Cockcroft et al. 2011
de Tullio Zinn & Zinn 2013, 2014, Harris et al. 2013

# Roughly 130 new Local Group GCs have been discovered in the last 5 – 10 years since Brodie & Strader (2006 ARAA)
# [Fe/H] distribution:
- 2 major subpopulations
  - Metal-poor component: Mean $[\text{Fe/H}] \sim -1.4$
  - Metal-rich component: Mean $[\text{Fe/H}] \sim -0.6$

# Very similar to the MW GC metallicity distribution
→ Analogous to the Galactic “halo” and “disk/bulge” cluster systems
M31 GCs - Metallicity

# Small overall metallicity gradient
→ Enrichment timescale for the proto-galactic gas was shorter than the collapse timescale

# No evidence for a relationship between L (and presumably M) and metallicity
→ Neither self-enrichment nor cooling from metals are important for GC formation

# Very similar to the MW GC metallicity distribution
Barmby et al. (2000)
**M31 halo seen by PAnDas**

# Pan-Andromeda Archaeological Survey (LP CFHT 220 hr 2008 – 2011 PI McConnachie)

- MegaCam imagery @ CFHT
- ~380 deg^2 mapped with MegaCam to within ~ R_{proj}~150 kpc around Local Group neighbours M31 and M3
- g and i bands to g_{AB}~26.0 and i_{AB}~24.8 (5σ)
- mean seeing ~0.6-0.7"
- 96 million sources, 10 million M31 red giant branch stars, 3 mag below RGB tip

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Ibata et al. (14), McConnachie et al. (13)
Martin et al. (13)

Annette Ferguson - IAUS316 Formation, Evolution and Survival of Massive Star Clusters

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**M31 stellar halo resolved by PAnDas**

# M31 outer (> 50 kpc) stellar halo is dominated by various tidal stellar streams, mostly metal-poor ([Fe/H] ~ -1.3 thought to be the remnants of accreted galaxies

→ Rich accretion history

# GCs project on top of stellar streams and other outer halo debris and offer an exciting (but puzzling?!) way forward

# Radial velocities of GC “subgroups” show compelling velocity correlations. Combined with local density measurements, infer that **60% of halo GCs consistent with accretion**
Uniform census of GCs in M31 halo

# Pan-Andromeda Archaeological Survey (PAndAS)
MegaCam imagery @ CFHT within ~ 150 kpc of M31
→ Discovery of ~ 60 new GCs
→ Survey complete down to Mv = - 6.0
  50 % completeness at Mv ~ - 4.1
→ PAndAS imaging to measure luminosities, colours and size for all known
  M31 GCs outside 25 kpc

Huxor et al (2014, Fig.2)
PAndAS
MegaCam g-band images (1 arcmin x 1arcmin)
GCs in M31 halo

Huxor et al (2014, Fig.17)
PAndAS

For MW GCs: $R_{proj} = R_{gc} \times (\pi / 4)$

# M31: Substantial population of luminous GCs at $R_{proj} > 30$ kpc (not seen in the MW)
ACCRETION ORIGIN FOR THE HALO GCS?

About 80% of the halo GCs are found to project onto stellar over-densities. The probability of such a configuration occurring by chance is <1% (Mackey et al. 2010, ApJL 717, 11). The luminosity distribution also provides a tentative support.

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GCLF in M31 halo

- Full sample of M31 halo clusters: Median value of $M_V \sim -7.6$
  (-7.3 for the MW)
- Only outer halo clusters ($R_{\text{proj}} > 30$ kpc): Bimodal GCLF with peaks at $\sim -7.5$ and $-5.5$ (accreted into M31 halo with their parent galaxy? Mackey et al. 10)

Huxor et al (2014, Fig.15)  
PAndAS
GCs sizes in M31 halo

M31: # Many clusters with \( r_h \) between 5 and 20 pc at all \( R_{\text{proj}} \)
# Different \( r_h \) distribution @ \( R > 30 \text{kpc} \)
→ Lower tidal field in the outer regions of M31?
→ Or likely origin of many of these GCs in accreted dwarf galaxies (Da Costa et al. 09, Hwang et al. 11)

Huxor et al (2014, Fig.20, 21)
PAndAS
For MW GCs: \( R_{\text{proj}} = R_{\text{gc}} \times \left(\frac{\pi}{4}\right) \)

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PA-7 & PA-8 in the South-West cloud in M31 halo

# Photometric CMDs:
- ~ 1mag below HB
- $[\text{Fe/H}] = -1.35 \pm 0.15$ from adjustment to GGCs fiducial sequences at $\neq Z$
- Red HB
- Age between 6 and 12 Gyr from isochrone fitting and relation between age, HB morphology, and $[\text{Fe/H}]$
  (from Dotter et al. 11)

Mackey et al (2014)
The census of Local Group GCs

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>N_{GC}</th>
<th>M_{V}</th>
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</tr>
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<tbody>
<tr>
<td>MW</td>
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<td>-18.4</td>
<td>Irr</td>
</tr>
<tr>
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<tr>
<td>Fornax</td>
<td>5</td>
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Veljanoski et al. 2013, Hwang et al. 2011, Cockcroft et al. 2011,
de Tullio Zinn & Zinn 2013, 2014, Harris et al. 2013
Dwarf galaxies can reach GC specific frequencies $S_N > 100$ (Milky Way: $S_N \sim 1/2$)

Important implications for GC mass loss / disruption.

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

Georgiev et al. (2010)
GCs in the Fornax dSph

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

Total stellar mass \textit{formed}

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

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

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Slide courtesy: Søren Larsen - IAUS316
Formation, Evolution and Survival of Massive Star Clusters

C.Charbonnel - GCs - EES 2015
Metallicities from high-dispersion spectroscopy

<table>
<thead>
<tr>
<th>Fornax</th>
<th>[Fe/H]</th>
<th>[Ca/Fe]</th>
<th>$v_\text{e}$ (km s$^{-1}$)</th>
<th>Source</th>
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<tbody>
<tr>
<td>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>
</tr>
<tr>
<td>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>
</tr>
<tr>
<td>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>
</tr>
<tr>
<td>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>
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<tr>
<td>5</td>
<td>$-2.1 \pm 0.1$</td>
<td>$+0.27 \pm 0.09$</td>
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- Fornax 1, 2, 3, 5 all have [Fe/H] < -2 [Larsen et al. (12)]
- Field star metallicities peak near [Fe/H] = -1 [Battaglia et al. 2006; Kirby et al. 2011].

GCs in the Fornax dSph

GCs much more metal-poor than most field stars.

Few field stars at [Fe/H]<-2

Field stars: Battaglia et al. (2006), Ca II triplet spectroscopy.
GCs: Letarte et al. (2006); Larsen et al. (2012)
GCs and field stars in the Fornax dSph – Z distribution

For [Fe/H] < -2: Mass in
- Field stars: \( \sim 3 \times 10^6 \, M_\odot \)
- GCs \( \sim 1 \times 10^6 \, M_\odot \)

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

(Milky Way halo: about 2-3%)

Fornax dSph unlikely to have lost any field stars (Peñarrubia et al. 2009; Battaglia, IAUS317).

Difficult to accommodate large amount of cluster mass loss/dissolution in Fornax dSph.
### The census of Local Group GCs

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Figure 1. The Age-Abundance relation for LMC clusters with ages determined from main sequence turnoff photometry. The "old" clusters however, have been assigned an age of $15 \pm 2$ Gyr.

Da Costa (1991)
**Globular clusters**

Part I – GC general properties

- GCs - Tools for Astrophysics and Cosmology
- The GC system of the Milky Way
  - Census
  - Luminosity and mass
  - Global metallicity
  - Ages
- GCs in the Local Group

**GCs vs Young Massive Clusters?**

Nate Bastian

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