Globular Cluster Systems in Rich Galaxy Environments: New Issues in Formation and Evolution

Bill Harris, McMaster University
ESO June 29, 2011
Clusters are laboratories for galaxy evolution
Globular Cluster Systems in Rich Galaxy Environments: New Issues in Formation and Evolution

Globular Clusters are laboratories for stellar evolution.
Globular Cluster Systems in Rich Galaxy Environments: New Issues in Formation and Evolution

Globular Clusters are laboratories for galaxy evolution

Globular Clusters are tracers of galaxy evolution
Studying the ensembles of globular clusters in galaxies is a hybrid field mixing stellar populations with galaxy structure and evolution.
NGC 3311/3309  \( d = 50 \) Mpc
Hydra I cluster

GCs are mostly starlike for
\( D > 15 \) Mpc (ground-based)
\( D > 80 \) Mpc (HST)
Visible as a statistical excess
of point sources spatially
concentrated around the host
galaxy

Present day: \(< 1\% \) of total
stellar mass

Initially: \( > 10\% \) ?

Gemini-S + GMOS (E.H.Weher & W.E.Harris)
Bimodality: standard, near-universal “blue” and “red” sequences
mean \([Fe/H]\) \(\sim\) -1.5 -0.5

Weak metallicity gradients \(<Fe/H>\ \sim\ R^{-0.1}


Formation redshifts \(z = 10-5\) (blue) ages 12-13 Gyr
\(5-2\) (red) ages 10-12 Gyr

Two distinct formation epochs? Doubtful ...
Host environments should be $\gtrsim 10^9 M_\odot$ gas disks; all GCs assumed to form in mergers from beginning to end.

External reionization unimportant; massive host dwarfs self-shielded.

$$N_{GC}(t) \sim \text{Merger rate} \times \text{cloud mass}$$

Semi-realistic bimodality emerges naturally though not every time.

Realistic mass distributions and spatial distributions.

Too many young, metal-rich GCs?

Later accretion may add to the low-[Fe/H] population of halo clusters.
Heavy-element retention scales as

\[ f_Z \sim \exp \left\{ - \frac{k f r_C^\text{eff}}{M_C} \right\} \]

\( \sim 1/e \) at \( 4 \times 10^7 M_\odot \) (protocluster)

\( 4 \times 10^6 M_\odot \) (today's GC)

---


Internal self-enrichment possible, if initial SN ejecta can be retained in the protocluster during the first \( \sim 10 \) Myr (note that the dense cloud is mostly gaseous if SFE \( \sim 0.3 \))

Enriched gas will be retained if it lies inside an “escape radius” where total energy < potential energy at edge of cloud.
Pre-enrichment = initial cloud metallicity
Self-enrichment = additional metallicity generated during formation

Nonlinear mass-metallicity relation expected along both sequences, but easily visible only on blue sequence

UCD and dE,N regime?
Massive-GC regime

M104 data and simulation (Harris & 2010, MNRAS 401, 1965)

6 BCGs (Harris 2009)

7 more cD’s coming!
Links with UCD/dE regime

NGC 4874 (Coma)

NGC 3311 (Hydra)
Misgeld && 2011, AA 531, A4

\( r_h > 10 \text{ pc} \)

\( M_V \)

\( \sigma \)
What determines the total population of GCs in a galaxy?

\[ S_N = \alpha_1 \frac{N_{GC}}{L^*} \]


30th anniversary! (Harris & van den Bergh 1981)
Specific frequency and specific mass

"The obvious generalization of these results is that most galaxies may have been subject to a single, common cluster formation efficiency." (McLaughlin 1999)

-- but efficiency relative to what?
$N(GC) \sim M(\text{total}) = \text{dark+baryonic?}$

$S_M = \frac{M(GC)}{M(\text{stellar})}$

Peng & & 2008
Georgiev & & 2010

Curve assumes $M(\text{halo})/M(\text{stellar})$ model
from vandenBosch & & 2007
Maximally efficient conversion of infalling gas to stars near $10^{10} L_0$. 

$$\frac{M(\text{halo})}{M(\star)} = f(M(\text{halo}))$$
Assume GC formation is proportional to $M(\text{halo})$ instead of stellar mass

$$\frac{M(\text{halo})}{M(\ast)} = f(M(\text{halo}))$$

$N_{GC} = \alpha_2 M(\text{halo})$

$$S_N = \alpha_1 \frac{N_{GC}}{L_\ast} = \alpha_1 \alpha_2 \left(\frac{M}{L}\right)_\ast \frac{M(\text{halo})}{M(\ast)}$$

$NB$: Transition from nuclear star cluster to central supermassive black hole occurs near $2 \times 10^9 L_\odot (M_V \sim -18.5)$
\[ M(\text{halo}) \approx 2.5 \times 10^9 \, N_{GC} \approx 1.7 \times 10^4 \, M_{GC}(\text{now}) \]

Are the most massive protoglobular clusters (densities \( \rightarrow 10^6 \, M_\odot/\text{pc}^3 \), scale sizes \( \approx 1 \, \text{pc} \)) self-shielded from either extreme?

Dekel & Birnboim 2006, MNRAS 368, 2

Shock heating + AGN feedback

SNe + starburst winds + photoionization feedback
Protocluster formation peaks earlier than lower-density field-star formation.

Earliest epochs less subject to external disruption.
Links with other Galaxy Features

Spitler & Forbes
2009, MN 392, L1

Burkert & Tremaine

G. Harris & W. Harris 2011,
MNRAS 410, 2347

Low-SMBH outliers = pseudobulges?
(e.g. Milky Way; Kormendy & 2006)
45 galaxies with all of $N(GC)$, $R_e$, $\sigma_e$, $M(SMBH)$

$M(SMBH)$ vs. $N(GC)$, with errorbars from literature:
Slope = 0.82 +- 0.06

MCMC formalism: additional cosmic scatter required (or quoted uncertainties too small)

G.Harris, W.Harris, G.Poole 2011

GCs and early SMBH’s have similar ages. How far out into the protogalactic halo can the AGN influence cluster formation?

Relativistic AGN jet + fractal-like ISM
$N(GC)$ vs. $M(dyn)$: Slope $= 1.02 \pm 0.08$

$$M_{dyn} = 3 \, R_e \, \sigma_e^2 / G$$
$M$(SMBH) vs. velocity dispersion $\sigma_e$:
Slope = 4.79 $\pm$ 0.33
**GC Scale Sizes and Tidal Limits: an impending confrontation with tidal-limit theory?**

\[ r_h \sim R_{gc}^{-0.2} \text{ out to } 5 R_e \]

\[ \langle r_h \rangle \sim 2.5 \text{ pc with large-}r \text{ “} \text{tail”;} \]
somewhat larger in dwarfs

+ Puzia et al. N1399 data
M87 GC size measurements from extremely deep M87 HST/ACS images in (V,I) \( ightarrow \) \( r_h \) measurable to \( \pm 0.5 \) pc

\[
\begin{align*}
  r_t & \propto \left( \frac{m_{GC}}{M_{gal}} \right)^{1/3} r_{gal} \quad \text{and} \quad M_{gal} \propto r_{gal} \\
  \Rightarrow r_t & \propto m_{GC}^{1/3} r_{gal}^{2/3}
\end{align*}
\]

Projection to 2D \( \rightarrow \)

\[
 r_t, r_h \sim m_{GC}^{1/3} R_{gc}^{0.5}
\]

Observations: \( r \sim R_{gc}^{0.2} \)
M87 system model assuming:

- Observed GC spatial dist'n (spherical symmetry)
- Standard GC mass distribution function
- King-model cluster profiles, standard c-distribution
- Isotropic (or anisotropic) velocity distribution with measured $\sigma(R)$ profile
- Tidal radius is set at or near perigalacticon
- Assume King $r_t$ same as tidal-theory $r_t$

In progress:
- HST Cycle 19 imaging of outer halo clusters
- N-body integrations
What we need from theory:
- Full SPH models of GC formation for $10^5$-$10^7 M_\odot$ protoclusters sufficient to resolve star formation
- ... and coupled to galaxy-scale hierarchical merging including AGN feedback.
- N-body integrations of tidally limited GCs covering range of halo locations

Questions
- Does bimodality in color / metallicity result naturally from a single formation sequence during hierarchical merging?
- Does self-enrichment really work in dense, massive protoclusters? (does star formation last for 10 Myr or more in such systems?)
- How much (and how far out into the halo) can SMBH/AGN feedback influence GC formation?
- Is the GC population size a good tracer of total galaxy mass (including DM)?