Globular Clusters in Massive Galaxies

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Globular Cluster Systems

$GCs = \text{most luminous (} \sim 10^4-10^6 L_\odot \text{) discrete tracers of galaxy halos}$

present in all galaxies ($M > 10^8 M_\odot$) in all environments

- compact ($r_h \sim 2-4 \text{pc}$)
- pointlike for $>20 \text{ Mpc (ground)}$
  $>80 \text{ Mpc (HST)}$

<table>
<thead>
<tr>
<th>Graph</th>
<th>Harris, Harris &amp; Alessi 2013</th>
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<td>observed to $&gt;200 \text{ Mpc}$</td>
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<td>spectroscopically to $\sim20 \text{ Mpc}$</td>
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not-quite-so-simple

simple stellar populations

- Complement to resolved halo star studies, PNe, diffuse light studies
  (eg. Rejkuba, Arnaboldi, Mihos, Peacock talks)

- Old (10.5-13 Gyr) ages and high masses
  product of earliest intense bursts of SF
  'fossil record' of earliest stages of hierarchical galaxy formation

+ later mergers and accretion of GCs
bimodal color distributions common in most luminous galaxies
(Larsen+2001, Kundu+Whitmore 2001…)

= bimodal metallicity distribution
eg. MW, NGC 3115

• comparison with stellar halo MDF?
  (see also Rejkuba talk)

NGC 5128  Woodley+2010

Blue/Red = MP/MR subpopulations
• often kinematically distinct (Brodie talk)
• relative ages constrain formation timescales
  blue GC (z~4-8)  red GC (z~2-4)

before most SF and feedback
GC systems in massive galaxies extend to $>10-30 \, R_e$ 
$\sim 100 \, \text{kpc}$+ (Rhode+Zepf 2004, Bassino+2006, Peng+2011, G.Harris+2012)

- outer halo - presence of intracluster GCs? (IGCs; eg. Lee+2010, Peng+2011) probe the cluster potential; accretion history of massive galaxies
- relationship with UCDs = luminous GCs? nuclei of stripped galaxies? (Voggel talk)

GCs important *kinematic* tracers of galaxy/cluster DM halo
- to $8-10 \, R_e$ (Lee+2010; Brodie talk)
• GC Luminosity Function (GCLF)
  • remarkably similar shape in all galaxies
  • result of cluster $N(m) \propto m^{-2}$ or log-normal initial GC mass function + low-mass GC destruction

$M_{GCLF,TO} \sim 1-2 \times 10^5 M_\odot$

GCs useful probes over wide range of R in all galaxy types, environments
GC Numbers

- most ‘accessible’ observable in GCS studies
- 0,1 GC in faintest dE/dI galaxies to $N_{GC} = 15000-30000+$
  in most luminous cD/BCG galaxies
  (eg. Alamo-Martinez+2013, Harris+2014…)

$N_{GC} \propto L$

Significant deviations (at highest and lowest L) from simple $N_{GC}$ vs. L scaling
**Specific Frequency $S_N$**
(Harris + van den Bergh 1981)

- comparison of global GC formation efficiency to that of field stars
- some variation due to M/L differences b/w morphological types

\[ S_N = N_{GC} 10^{0.4(M_V+15)} = 9.6 \times 10^7 \frac{N_{GC}}{L_V / L_\odot} \]

$S_N$ variations in dwarf galaxies.
SN feedback suppressing field SF?
(eg. Peng+2008, Georgiev+2010)

wide variations of $S_N$ in most luminous galaxies (largely ETGs)

$S_N$ a measure of GC formation efficiency or field star SF efficiency?
Something more fundamental? \textbf{MASS}

$S_N$ variations in massive galaxies reduced if inclusion of X-ray gas mass

GC fraction of total \textit{baryonic} mass? \hspace{1cm} (McLaughlin 1999)

$S_N$ increases \textit{w/} $\sigma$ for BCG/cD galaxies

$N_{GCS} \Rightarrow M_{GCS}$ scales with \textbf{total} mass

(Blakeslee+1997, Blakeslee 1999)

\[
\eta_h = \frac{M_{GCS}}{M_{\text{halo}}} = \frac{M_{GCS}}{M_{(DM+\text{stars}+\text{gas})}}
\]

$\eta_h$ remarkably similar regardless of galaxy morphology, luminosity and environment

(Spitler+Forbes 2009, Georgiev+2010, Harris+2013

Harris talk)
Important connection between (surviving) GCS mass and mass of DM halo at time of (early) formation ($z > \text{few}$) — over almost 5 orders of magnitude in mass!

suggested by hierarchical $\Lambda$CDM models of blue/metal-poor GC formation (eg. Moore et al 2006, Kravtsov+Gnedin 2005)
With $M_{\text{GCS}} \propto M_{\text{halo}}$

$S_N$ variations largely due to field star formation efficiency (and related feedback) (eg. Blakeslee 1997, Harris+2013)

Prediction if $N_{\text{GC}}$ scales as galaxy halo (DM+*) mass

BUT…. ‘biased’ GC formation in dwarfs near M87 (Peng+2008)
Radial Distribution of GCs

- relationship b/w GCS and spheroid, halo, DM halo

- clear differences between profiles of MP and MR GCs

Blue/metal-poor GCs have more extended radial distribution than main spheroid

similar profile to MP stellar halo?
relation to galactic/cluster DM halo?

Red/metal-rich GCs more centrally concentrated matching spheroid light

coeval dissipational formation?
(eg. Forbes+1997, Forte+2005…)
Radial Distribution of blue GCs

Blue/metal-poor GCs have more extended radial distribution (similar to PNe at larger $r$; Longobardi 2013, talk)

expectation that MP halo stars and blue GCs should have similar profiles (eg. Moore+2006) NGC 3115

red GCs $\rightarrow$ 0 by 200 kpc

blue GCs useful probes of (proxy for?) the metal-poor stellar halos of galaxies
Blue GCs as tracers of outer metal-poor halos of massive galaxies

NGC3379: MP stellar halo at ~33 kpc (10-12R_e) (Harris+2007)

NGC 5128 - MP halo stars out to 140 kpc (~25R_e) (Rejkuba+2014, Rejkuba, Bird talks)

For more distant galaxies:

Virgo (d=16.5Mpc) \(\Sigma_{GC} \sim 0.20\) arcmin^{-2}
\(\Sigma_{GC} \sim 0.05\) arcmin^{-2}

\(\mu_V \sim 28.7\) mag/arcsec^2
\(\mu_V \sim 30.0\) mag/arcsec^2
(S_N=6; Williams+2007)

With improved GC selection, can trace fainter SB’s of metal-poor halo

GC/star ratio higher in metal-poor clusters compared to metal-rich
NGVS: ~900,000 point sources

Sgr dwarf galaxy stars

MW halo stars

MW disk + halo MS stars

Virgo GCs from Durrell+2014
NGVS: extensive distribution of GCs throughout main subclusters (M87, M49, M60…)

Virgo cluster: $N_{GC} = 67300 \pm 14400$ (35% in M87+M49 alone)

GCs extend to few x 100 kpc from major galaxies

Virgo cluster-wide GCS: $\eta_h \sim 2.9 \times 10^{-5}$

M87/M49 (to $r=200$ kpc) have very similar $\eta_h$
M87 more massive, less L than M49
blue GCs extended (+irregular) 2D distribution surrounding massive galaxies

metal-poor intracluster GCs = later/ongoing accretion?
Cluster GCS Comparison

A1689: Alamo-Martinez+2013
Coma: Peng+2011
Virgo: Durrell+ 2014

IGCs in outermost regions (r>200-300+ kpc) = trace cluster DM halo increase with dynamical state of cluster?

Virgo/Fornax = lower density of IGCs
Coma/A1689 = higher density of IGCs = increased tidal stripping/accretion?
GCs in the outer halos of galaxies: kinematics

trace DM halo of galaxy or galaxy+cluster potential? \( \Rightarrow \) intracluster GCs

effects of early formation or later accretion?

M87 - intracluster PNe w/ large \( \sigma \)  
(eg. Doherty+2009, Longobardi+2013, talk)

low \( \Sigma_{GC} \) (\(~\text{few} \times 0.01 \text{ kpc}^{-2}\) = issues with small N, \( \theta \) coverage

Need improved photometric selection, spectroscopic follow-up at large R
GCs in the outer halos of galaxies: kinematics
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Photometric selection of extragalactic GCs
reduce bkg. contamination for (necessary)
spectroscopic follow-up

**BVR, gri** v. good

improved bkg. galaxy removal with *u*-band
(eg. Kim+2014; see also Hilker talk)

*ugi/ugz* shows improvement (factor few)
Virgo Cluster GCs - NGVS-IR (Muñoz+2014)

Photometric selection of extragalactic GCs
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\textit{uiK} for blue GCs
(which dominate outermost regions)

also, improved ground-based seeing
(eg. G.Harris+2012, NGVS:Ferrarese+2012)
Summary

• GCs effective discrete tracers of galactic halos (and galaxy clusters)
  • visible in many galaxies to large distances, + chemical history
• GCs formed/survived in numbers $N_{GC}$ related to the total mass (DM+gas+stars) of the galaxy/cluster
  • $S_N$ variations largely a reflection of field star formation efficiency
• metal-poor GCs probe stellar halos in large galaxies
  • accretion history? related to presence of IGCs
• future: studies of more GCSs to $R>100-200$+ kpc
  • importance of complete SED coverage UV$\rightarrow$IR for GC selection
  • wide field photometry + (yet) more WF spectroscopy (!) eg. NGVS, MATLAS, SLUGGS, FDS, Rhode+ work