Globular Cluster Sub-populations and Galaxy Assembly

Jean P. Brodie
UCO/Lick Observatory
University of California Santa Cruz

Study of Astrophysics of Globular clusters in Extragalactic Systems

P. Barmby (Harvard), M. Beasley, D. Forbes (Australia), J. Huchra (Harvard), M. Kissler-Patig (Germany), S. Larsen (UCSC), T. Puzia (Germany), J. Strader (UCSC)

Associated with galaxies of all morphological types
~150 in MW
~400 in M31
> 10,000 in some ellipticals
Good tracers of star formation histories of galaxies

- Massive star clusters form during all major star formation events
  (Schweizer 2001)
- # of young clusters scales with amount of gas involved in interaction
  (Kissler-Patig, Forbes & Minniti 1998)
- Cluster formation efficiency depends on SFR in spirals
  (Larsen & Richtler 2000)

Advantages over galaxy starlight

- GCs are **simple stellar populations** — single age and metallicity
- GCs can be studied out to several $R_{eff}$ — probe DM halos/galaxy cluster potential
- Galaxy starlight usually only sampled in center $\leq 1 R_{eff}$ — difficult to disentangle different stellar populations
  — recent but unimportant (in mass) star formation episode can dominate
Ages and Metallicities of Extragalactic GC Systems

Bimodal Color Distributions

NGC 4472 (M49)  Puzia et al. (1999) AJ

Bimodality: Implications

Bimodal color distributions \( \nu \) globular cluster sub-populations

Color differences are due to age differences and/or metallicity differences

\( \nu \) Multiple epochs and/or mechanisms of formation

\([\text{Fe/M}]\) = -0.95 -0.65

Jean Brodie, UC Santa Cruz (KITP Globular Clusters 1/30/03)
Ages and Metallicies of Extragalactic GC Systems

**GC/Galaxy Formation Models**

1. Formation of ellipticals/GCs in mergers (Schweizer 1987, Ashman & Zepf 1992)
2. In situ/multi-phase collapse (Forbes, Brodie & Grillmair 1997)
3. Accretion/stripping (Cote et al. 1998)
4. Hierarchical merging (Beasley et al. 2002)

2 & 4 require (temporary) truncation of GC formation at high redshift.

---

**Model Predictions**

Key properties:
- Ages, metallicities, abundance ratios, kinematics, luminosity functions of *red* and *blue* sub-pops

- **Merger model**
  - \( \tau \) old population
    - (age of universe less \( \sim 1 \) Gyr) + young population with age of merger

- **Multi-phase collapse**
  - \( \tau \) 2 old populations one slightly (\( \sim 2-4 \) Gyr) younger than other

- **Accretion**
  - \( \tau \) *blue* and *red* clusters about the same age

- **Hierarchical merging**
  - \( \tau \) age substructure in *red* sub-pop + *red* globulars in low-luminosity field/group ellipticals \( \sim 2 \) Gyr younger than in bright cluster ellipticals
How well can we estimate ages?

At distance of Virgo 6 hrs with Keck

- H_0 errors: +/- 0.15 – 0.3 Å
- 2 – 4 Gyr at 12 Gyr

Model-dependent absolute ages
Relative ages ~OK

- Models are highly degenerate at low metallicities and old ages
- Cannot distinguish relative ages
  > 10 Gyr in low metallicity
  ([Fe/H] ~ -1) systems
- Caveats BHBs, AGB luminosity function

Examples of Recent Work

- 17 relatively nearby “early-type”
  (ellipticals, lenticulars) galaxies
  observed with HST
- Homogeneous deep data set
- Data reach well below GCLF turnover
  (Is GCLF really universal?)

Larsen, Brodie, Huchra,
Forbes & Grillmair (AJ 2001)
Ages and Metallicities of Extragalactic GC Systems

**Color Histograms**

Nearby early-type galaxies
Kundu & Whitmore (2001)
- Average blue peak color \((V-I)\_o = 0.95 \pm 0.02\)
- Average red peak color \((V-I)\_o = 1.18 \pm 0.04\)

\([\text{Fe/H}] = -1.4, -0.6\)
(Kissler-Patig, Brodie, Schroder et al. 1998 AJ)

**Milky Way**

Peaks at
\([\text{Fe/H}] \sim -1.5 \text{ and } -0.6\)
(Zinn 1985)
Ages and Metallicities of Extragalactic GC Systems

**Sombrero**

Peaks at \((V-I)_0 = 0.96\) and 1.21

Larsen, Forbes & Brodie (MNRAS 2001)

Follow-up spectroscopy at Keck indicates vast majority of GCs (both red and blue) are old (~13 Gyr)

Larsen, Brodie, Forbes (2002)

**Correlations with Host Galaxy Properties**

- Colors of *both* reds and blues correlate with galaxy mass (\(M_B\) and \(\rho_0\)) at the 2–3 \(\rho\) level
- 4 \(\rho\) correlation between red GC colors and galaxy colors (2 \(\rho\) for blues)
- Slope steeper for reds

Larsen et al AJ 2001
Ages and Metallicities of Extragalactic GC Systems

Bulge GCs

Number of metal-rich GCs scales with the bulge

- Metal-rich GCs in spirals are associated with the bulge not the disk
- The number of bulge GCs scales with bulge luminosity (bulge $S_N \sim 1$)
- The total $S_N$ for field ellipticals is 1-3 (Harris 1991)
- The fraction of red GCs in ellipticals is about 0.5
- The bulge $S_N$ for field ellipticals is $\sim 1$
- Spirals and field ellipticals have a similar number of metal-rich GCs per unit starlight


Numbers/Specific Frequency
Metal-rich GCs in spirals and ellipticals have the same origin — they formed along with the bulge stars.

Brodie & Huchra 1991; Forbes, Brodie & Grillmair 1997; Forbes, Larsen & Brodie 2001

GC Ages

- Increasing evidence that both red and blue globular clusters are very old (> 10 Gyr)
- Small percentage of red globular clusters may be young
- Ellipticals/Lenticulars
  
  NGC 1399  (Kissler-Patig, Brodie, Schröder et al. 1998; Forbes et al. 2001)
  M87  (Cohen, Blakeslee & Ryzhov 1998)
  NGC 4472  (Puzia et al. 1998; Beasley et al. 2000)
  NGC 1023  (Larsen & Brodie 2002)
  NGC 524  (Beasley et al. 2002)
  NGC 3610  (Strader, Brodie et al. 2003)
  NGC 4365  (Larsen, Brodie et al. 2003)

- Spirals
  
  M 31  (Barmby, Huchra, Brodie et al. 2000)
  M 81  (Schröder, Brodie, Huchra et al. 2001)
  M 104  (Larsen, Brodie, Beasley et al. 2002)
NGC 3610

- Intermediate age (4 Gyr) merger remnant
- Keck spectra of 6 candidate young clusters (+ 2 with bluer colors)
- $3 < R_g < 13$ kpc
- $R_{eff3610} = 2.3$ kpc


Candidate Selection

Candidate young clusters are brighter and redder than majority of blue objects
Ages and Metallicities of Extragalactic GC Systems

**NGC 3610**

Spectra + Models

3 distinct sub-groups:
- old and **metal-poor**
- old and **metal-rich**
- **single** metal-rich young (~ 2 – 4 Gyr) cluster!

Within errors, all 7 old clusters are coeval

---

**Unimodal color distributions**

**NGC 4365**

Larsen et al (2001)

Ages and metallicities of extragalactic GC systems

**NGC 4365 Spectra**

- 14 clusters
- 6.5 hrs with Keck

**Spectroscopic Ages**

- Some, but not all, IR selected clusters are young (2–5 Gyr) and metal-rich (−0.4 [Z/H] 0) rather than old (∼10–15 Gyr) and metal-poor
- Ages and metallicities conspire to produce a single broad distribution in the optical
Where are the field stars?

- No signatures of recent mergers
- Luminosity-weighted age of \( \sim 14 \) Gyr for stellar population (Davies et al 2001)
- **At most** 1–5\% of mass could be hidden in a 2–5 Gyr field star population
- Estimate (from IR) \( \sim 25\% \) GCs in inner regions are of intermediate age
- **Where is the intermediate age stellar component?**

Summary I

Color, luminosity distributions of globular clusters in “nearby” galaxies

- Two Gaussians almost always preferred over a single Gaussian – peaks always consistent

Multiple epochs/mechanisms of formation universal
Summary II

Correlations with parent galaxy properties

- Correlation between globular cluster colors and host galaxy luminosity (mass) and color for both reds and blues
  - Both populations "knew" about the size of the final galaxy to which they would belong
  - Fragments in which GCs formed at early times were already embedded in dark halos of final galaxy
  - One of few observational constraints on properties of pre-galactic clouds that combined to build galaxies we see today
- Similarities between peak colors in spirals and ellipticals
  - Hints at universal GC formation processes

Summary III

- Slope of red GC color vs. galaxy mass relation same as galaxy color vs. galaxy mass relation
  - Common chemical enrichment history for metal-rich GCs (in spirals and ellipticals) and the host
- Old ages of both sub-populations
  - Inconsistent with late merger picture
  - Galaxy assembly happened at high z – rest is just "frosting"
- GCs can form with little associated field star formation (Blue GCs, NGC 4365?)
  - Biasing of cluster mass function, connection to SFR?
Conclusions

Our data are best explained by a formation scenario in which the bulk of both globular cluster sub-populations formed at early epochs within the potential well of the protogalaxy in multiple episodes of star formation.