A NEW ZEAL FOR GLOBULAR CLUSTERS

DUNCAN FORBES, SWINBURN
JEAN BRODIE, UC SANTA CRUZ
Globular Clusters and Galaxy Formation

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The Fellowship

- Robert Proctor
- Jay Strader
- Soeren Larsen
- Lee Spitler
- Mike Beasley
- Trevor Mendel
  (next talk)
Collaborators

Half of this conference, plus back home at Swinburne…

• Robert Proctor
• Trevor Mendel
• Michael Pierce
TWO TOWERS

Most (perhaps all) large galaxies reveal two distinct sub-populations of globular clusters.

\[ [\text{Fe/H}] = 0.155 \pm 0.15 \]
Bimodal or not Bimodal?

Yoon et al. 2006

Unimodal

Bimodal or not Bimodal?

Unimodal

Bimodal

Yoon et al. 2006
NGC 5128 Bimodal!

Spitler et al. 2007
NGC 4472 Bimodal!

Fig. 3.— Histogram of $[m/H]$ for NGC 4472 GCs. Density estimates with an Epanechnikov kernel (bin width 0.2 dex) for NGC 4472 (solid line) and the Milky Way (dashed line) are overplotted. The differences in peak locations is a direct result of the mean GC metallicity–
glomer luminosity relationships for both subpopulations.

Strader et al. 2007
The return of the King (Profile)

HST/ACS imaging of GCs in M31

Barmby et al. 2007
Globular Cluster Formation

When?  How?

Ongoing accretion
Recent mergers
Early formation
Forbes et al. 2003
Ongoing GC Accretion

Sgr Dwarf Galaxy
M54 (dwarf nucleus)
+ 5 GCs + Whiting 1
Well fit by a closed box model
Pal12, Ter7 $[\alpha/Fe] \sim 0$
M54 $[\alpha/Fe] \sim +0.3$
(Pritzl et al. 2005)

Forbes et al. 2004
Fellhauer NZ conf.
Canis Major

4-6 GCs
+ 2 old open clusters (not BH176, Pal1)

Different age-metallicity relation for the in situ GCs?
Half-light radius vs Magnitude

Huxor et al. 2005

Peng NZ conf.

UCDs Willman1 dwarfs

FFs M31

Huxor et al. 2005

Peng NZ conf.
Milky Way GCs


⇒ ~50 MW GCs with S/N ~ 100

Test SSP models using a multi-line fitting technique to Lick indices

Compare results to `known’ values
Alpha elements

SN II vs SNIa chemical enrichment history from high resolution spectra

Pritzl et al 2005
Metal-poor halo stars

Arnone et al. 2005
Hierarchical Merging vs Early Collapse

“This [early collapse] view has been tenaciously resistant to challenges.”

De Lucia, Springel, White et al. (2005)
Galaxy Formation

Merging of dark matter halos is well understood but details of baryon physics less understood
Dissipative Collapse

Forbes et al. 2005
To form an Elliptical galaxy GC system, new metal-rich GCs (red after ~2Gyrs) are required to form. The number of metal-poor (blue) GCs is unchanged.

Ashman & Zepf 1992
Blue GCs vs galaxy mass

Spitler NZ conf
Blue GCs vs environment
Virgo NGC 4365 AMR

Brodie et al. 2005

Redshift 0

Galaxy age

$[\frac{Z}{\text{H}}]$ vs. Age (Gyrs)

Brodie et al. 2005
NGC 4365 spectrum
Leo Group NGC 3379 AMR

Pierce, Beasley, Forbes et al 2005
NGC 4649 colours

Forbes et al. 2005
Canis Major

Half-light radius of Canis Major GCs are smaller than typical Milky Way GCs

Forbes et al. 2004
Spiral+dwarf with Keck

- March 2003
- 1 hr long-slit spectrum
- Spiral velocity = 43,433 +/- 99 km/s
- Dwarf velocity = 43,445 +/- 225 km/s
- Redshift = 0.15
- Distance = 2 billion light years
- Spiral galaxy mass = $10^{12}$ solar masses
- Dwarf galaxy mass = $10^{10}$ solar masses
Dwarf properties

$R_{\text{eff}} = 1$ kpc

$\mu_{\text{eff}} = 23$ V mag/sq arcsec

$\mu_o = 21$ V mag/sq arcsec

$M_v = -16.0$

Recent starburst

Twisted isophotes

$\Rightarrow$ dwarf elliptical with $\sim 10$ GCs

Forbes et al. 2003
diirr ->
dE ->
dSph?
NGC 1052 vs NGC 1316

Both are recent wet mergers:
Gas and dust
Fine structure
2-3 Gyr old stars

● = N1052, ▲ = N1316

Forbes et al. 2001
Multi-GC systems

Both red and blue sub-pops are coeval at ~12 Gyr old.

Strader et al. 2005

Old age isochrones

Blue

Red

Most GC formation in massive ellipticals happened at $z > 2$, not in recent mergers.
Young Elliptical NGC 1052 AMR

Pierce, Brodie, Forbes et al. 2005
Wet...or Damp Mergers?

V-I

Red

Cluster (V-I)_1

0.8

0.6

1.4

1.6

Galaxy age [Gyr]

Forbes et al. 2007

g-z

Red

Cluster (g-z)_1
Early-type Galaxies
ACS/Virgo Galaxies

![Graph showing the relationship between GC g-z (mag) and Galaxy age (Gyr). The graph includes data points and trend lines for different percentages of galaxy age.](graph.png)
Dry Merger

Galaxy Cluster MS1054-03
STScI OPO • P. van Dokkum (University of Groningen), ESA and NASA
Galaxy Bimodality

$M_V \sim -19.5, \ M_\star \sim 3 \times 10^{10} \ M_\odot, \ M_{\text{halo}} \sim 6 \times 10^{11} \ M_\odot$

Luminosity function, Colour-magnitude, Star formation rates, bulge/disk ratio, X-ray emission, stellar age, AGN emission, $M/L$ ratio

Globular Cluster Specific Frequency

Transition from hot accretion flows to cold accretion and SN winds (Dekel)
Virgo galaxies

For low mass galaxies
$M/L \sim M^{-0.67}$

For high mass galaxies
$M/L \sim M^{+0.5}$

Forbes 2005
Bekki NZ conf
Virgo galaxies

Bekki, Yahagi & Forbes 2006
$S_N$ in 1996

Durrell et al. 1996
Tag Team Handover
Similar slope to star-galaxy relation.

Provides constraints on hierarchical merging.

MP GCs forming at very high z "knew" the galaxy to which they would ultimately belong

Brodie & Strader 2006
See also Peng et al 2006
Hierarchical GC Formation

Need blue GC truncation at $z \sim 5$ to give bimodal colours.

Reionization?

Beasley, Baugh, Forbes et al. 2002
Blue Tilt
A mass-metallicity relation for blue GCs.
Due to self-enrichment in dark matter mini-halos?
BCGs: Harris et al 2006
Summed dEs: Mieske et al 2006
Sombrero: Spilter et al 2006
Spirals: Forde et al 2007
Strader et al. 2006
Jordan NZ conf
Early GC Formation


Need blue GC truncation at z > 5 to give bimodal colors.

Reionization?
$\Lambda$CDM...

N-body simulations suggest dark matter halos “sitting” on top of large overdensities collapse first (z>10)

The majority of these halos combine to form massive galaxies at z=0
The Biasing Scenario

- "Biasing" - halos on top of large over densities collapse before those on periphery
- Reionization truncates metal-poor GC formation
- Halos that collapse first produce metal-poor GCs of higher metallicity
- First-collapsing halos produce the metal-poor subpopulation of the most luminous galaxies
- More distant halos survive independently to become dwarf galaxies
Biased Hierarchical Merging

Must simultaneously accommodate:
1) MP GC metallicity - galaxy L relation
2) Some merging since $z \sim 2$

MP GC relation was different at high $z$
- Merging was biased - direct result of, and strong end constraint on, hierarchical structure formation
- MP relation rules out mergers and accretion but only in the local universe for structure forming at present day

Brodie & Strader 2006
Blue GCs vs galaxy mass

![Graph showing the relationship between T_{blue} and log(M_*).]
Reionization

- If blue GC formation is truncated by reionization GC surface density distributions probe epoch & (in)homogeneity of reionization
- Blue GC surface density distributions for galaxies of different masses and environments

Conclusions

• Although ongoing accretions and recent mergers contribute, most GC formation is early \((z > 2, \text{ age } > 10 \text{ Gyrs})\), i.e. massive galaxies formed early

• GC \(S_N\) bimodality mirrors galaxy bimodality

• GCs provide the best observable link between baryons and dark matter

• GC scaling relations constrain hierarchical growth: red GCs trace bulge formation, blues trace DM halos at earliest times + reionization
Cloud collision rate in LMC, and hence GC formation, is dramatically enhanced 3.6 Gyrs ago when LMC/SMC reach close pericentre.

Bekki et al. 2004