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Globular Cluster Bimodality

- Milky Way GC’s demonstrate a trend of bimodality both in color and metallicity. This is a feature now known to exist in many external galaxies.

- Models of galaxy formation - both simulations and semi-analytical - have thus far been unable to reproduce this feature.

Harris (2001)
Our Recipe For Cluster Formation

• Massive clusters are formed according to the observed CIMF

\[
\frac{dN_{cl}}{dM} = N_0 M^{-2}
\]

The formation efficiency of GC’s relative to gas mass is taken from hydro simulations. (Kravtsov & Gnedin 2005)

\[
M_{GC} = 3 \times 10^6 M_\odot \left( \frac{M_h f_{gas}}{10^{11} M_\odot} \right)
\]

• Mass assembly histories taken from DM-only cosmological N-body simulations. (Kravtsov et al. 2003)

• We use scaling observed relations to get gas fraction and metallicity for each DM halo.

• Major merger criterion: GC formation is triggered by merging gas-rich progenitor galaxies. The nature of this criterion is a parameter in the model
Progenitor Galaxy + Gas Distribution at High Redshift

Kravtsov & Gnedin (2005)

300 kpc (physical)

14 kpc

20 pc

dark matter

gas

Kravtsov & Gnedin (2005)
Parameterizing The Cold Gas Fraction And Metallicity

- We use scaling relation of Milky Way dwarf galaxies to get $M_{\text{star}}-M_h$ and $[\text{Fe/H}]-M_{\text{star}}$ (Woo et al. 2008). Another study gives us $M_{\text{gas}}-M_{\text{star}}$. (McGaugh 2005)
- We consider their evolution with cosmic time (Conroy & Wechsler 2008)

Conroy & Wechsler (2008)  
Woo et al. (2008)
Main Result: Bimodal Metallicity Distribution

KS Test: 80%
Dip Test 99%

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The Origin of Bimodality In Our Model

- In hierarchical galaxy formation, it is expected that the galaxy will undergo several phases of mergers.
- Early phase: frequent mergers of low-mass, gas-rich, metal-poor halos.
- Late phase: sparse mergers of high-mass halos with enriched gas.

\[ [\text{Fe/H}] > -1 \]
\[ [\text{Fe/H}] < -1 \]
Mass Function of GC’s

• Initially, each halo has a power law distribution of clusters $dN/dM \sim M^{-2}$. But, globular clusters are prone to mass loss and disruption over time.

• We include effects of two-body relaxation and stellar evolution. The results look OK.

• KS test: 7.4%

• Comparable means and dispersions

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Is The Distribution Unique?

- 6-dimensional parameter space leads to ‘slices’ of solutions within the parameters that all give viable results.
- How do we choose the best one for our Galaxy?
  - KS probability for both mass and metallicity
  - Constrain that $N = 150$ (as observed)

\[
M_{h,i} > p_3 M_{h,i-1}
\]

\[
M_{GC} = 3 \times 10^6 M_\odot (1 + p_2) \frac{M_g/f_b}{10^{11} M_\odot}.
\]
Bimodality Is Not Unique – It’s Natural

- Many realizations of our model are shown to be non-unimodal by the Dip Test.
Summary

• We present a prescriptive model for globular cluster formation that successfully reproduces a bimodal metallicity distribution.
• We have included a model for mass disruption. Our mass function is consistent with observations (more or less).
• Bimodality occurs for a wide range of model parameters. It is therefore a natural result for hierarchical galaxy formation.
Luminosity and Color Distributions

- Model with uniform age 12.1 GYr
- Model with varying age
- Observed

Obtained with the GALAXEV population synthesis code of Bruzual & Charlot (2003)

GALAXEV stole our bimodal distribution
The Radial Distribution of Clusters

- Inherent problem with hierarchical formation model: DM is too far out. That means GCs in our model are also too far out
Globular Clusters vs Field Stars

![Graphs showing the comparison between Globular Clusters and Field Stars.](image)