A Photometric Study of the Evolved Stars in the Globular Cluster M 55 (NGC 6809)

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Wednesday April 18, 2007
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Introduction: Globular Clusters

- ~150 GC in the Milky Way Galaxy
- \(10^4\) to \(10^6\) stars gravitational bound stars

General properties:
- Core radius: \(r_c \sim 1.5\) pc
- Median radius: \(r_h \sim 10\) pc
- Tidal radius: \(r_t \sim 50\) pc
- Mass: \(M \sim 6 \times 10^5\) \(M\)
- Lifetimes: \(\sim 10^{10}\) yrs

Properties that varies from cluster to cluster:
- Metallicity
  - \(-2.29 < [\text{Fe/H}] < 0.22\)
- Luminosity
  - \(-10.4 < M_V < -3.0\)
- Concentration
  - \(c = \log(r_t/r_c)\)
  - \(0.5 < c < 2.5\)
M 13: The Great Globular Cluster in Hercules
Image: Eddie Guscott
Introduction: Globular Clusters

- ~150 GC in the Milky Way Galaxy
- $10^4$ to $10^6$ stars gravitational bound stars

General properties:
- Core radius: $r_c \sim 1.5$ pc
- Median radius: $r_h \sim 10$ pc
- Tidal radius: $r_t \sim 50$ pc
- Mass: $M \sim 6 \times 10^5 M$
- Lifetimes: $\sim 10^{10}$ yrs

Properties that varies from cluster to cluster:
- Metallicity
  - $-2.29 < [Fe/H] < 0.22$
- Luminosity
  - $-10.4 < M_v < -3.0$
- Concentration
  - $c = \log(r_t/r_c)$
  - $0.5 < c < 2.5$
AM 4:
- $c = 0.4$
- $M_V = -1.6$

NGC 6752:
- $c = 2.5$
- $M_V = -7.73$

Images: The STScI Digitized Sky Survey (http://archive.stsci.edu/cgi-bin/dss_form)
Introduction: Color-Magnitude Diagram

- Useful for stars’ classification
- Theoretical Version – Hertzsprung-Russell Diagram (HRD):
  - Effective Temperature (or Spectral Class) vs. Luminosity
HR Diagram

- 22,000 stars from the Hipparcos Catalog
- 1,000 from the Gliese Catalog of Nearby stars

Image: R. Powell
Introduction: Color-Magnitude Diagram

- Useful for stars’ classification
- Theoretical Version – Hertzsprung-Russell Diagram (HRD):
  - Effective Temperature (or Spectral Class) vs. Luminosity
- Observer Version – Color-Magnitude Diagram (CMD):
  - Color (i.e. $B - V$, $V - I$, etc.) vs. Magnitude ($M_V$, $V$, etc.)
M 3’s CMD

- Very different from the HRD
M 3’s CMD

- CMD features:
  - Different stages of stellar evolution

- Ideal test site for stellar evolution theory
  - Use star count
M 55 Image: B. J. Mochejska, & J. Kaluzny
Introduction: M 55

- Original discovery:
  - June 16, 1752
  - Nicolas Louis de Lacaille
  - Lac I.14

- “Second” discovery:
  - July 24, 1778
  - Charles Messier
  - Renamed: M 55

- New General Catalogue of Nebulae and Clusters of Stars
  - 1880s
  - John Louis Emil Dreyer
  - Renamed: NGC 6809

- Properties:
  - Apparent size: 19’.0
  - $d = 5.3 \text{kpc}$
  - $M_v = -7.75$
  - $c = 0.76$
  - $[\text{Fe/H}]_{ZW84} = -1.82 \pm 0.15$
  - $[\text{Fe/H}]_{CG97} = -1.58 \pm 0.15$
Why M 55?

- Other GCs with similar $[\text{Fe/H}]$ and HB morphology are expected to have a small AGB population.
- May provide an *observational* constraint on the HB evolutionary tracks.
HB tracks for $[\text{Fe/H}] = -1.78$, $[\text{O/Fe}] = 0.66$ (Dorman 1992)
# Data Reduction

## Table 2.1. Summary of the studies used in this compilation

<table>
<thead>
<tr>
<th>Study</th>
<th>Photometry Type</th>
<th>FOV</th>
<th>Resolution (arcsec/pixel)</th>
<th>Filters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lee (1977)$^a$</td>
<td>Photographic</td>
<td>7′5</td>
<td></td>
<td>$BV$</td>
</tr>
<tr>
<td>Mandushev et al. (1997)</td>
<td>CCD</td>
<td>4′ × 4′</td>
<td>0.235</td>
<td>$UBVIC$</td>
</tr>
<tr>
<td>Pych et al. (2001)</td>
<td>CCD</td>
<td>14′5 × 23′</td>
<td>0.435</td>
<td>$BV$</td>
</tr>
<tr>
<td>Richter et al. (1999)</td>
<td>CCD</td>
<td>6′3 × 6′3</td>
<td>0.377</td>
<td>$vby$</td>
</tr>
</tbody>
</table>

$^a$In this study we only used the stars that occupy the region between 3′ – 7′5 in the outer part of the cluster.
Data Reduction: Coordinate Match

- Unify the different datasets into a single system of coordinates
  - Pych et al. (2001) – larger FOV
- DAOMATCH and DAOMASTER
  - Create position transformation equations to convert the coordinate system of a field to the coordinate system of another field
    \[ x_{\text{new}} = a + cx_{\text{old}} + ey_{\text{old}} \]
    \[ y_{\text{new}} = b + dx_{\text{old}} + fy_{\text{old}} \]
- Assign sky coordinates
Lee (1977) finding chart
Mandushev

Pych

Lee

Richter

Mandushev
Data Reduction: Photometry Merge

- Combine the datasets in a single and reliable photometric system
  - Mandushev et al. (1997)
  - Residual calculation vs. color
  - Least square fitting
\[ V_{M97} - V_{P01} = 0.112 + 0.0002(B-V)_{M97} \]

\[ B_{M97} - B_{P01} = 0.072 - 0.015(B-V)_{M97} \]
\[ b_{R99} - B_{M97} = -0.402 - 0.399 \left( B - V \right)_{M97} + 0.076 \left( B - V \right)_{M97}^2 \]

\[ y_{R99} - V_{M97} = -0.372 - 0.070 \left( B - V \right)_{M97} + 0.087 \left( B - V \right)_{M97}^2 \]
\[ V_{P01} - V_{L77} = -0.058 + 0.048(B - V)_{P01} \]

\[ B_{P01} - B_{L77} = -0.042 + 0.047(B - V)_{P01} \]
- 341 RGB
- 268 HB
- 13 RR Lyr
- 44 AGB
Results: Helium Abundance ($Y$)

- **Why?**
  - Estimate of the primordial helium abundance ($Y_p$)

- **The $R$-parameter**
  - $R = \frac{N_{HB}}{N_{RGB}} = \frac{t_{HB}}{t_{RGB}}$
  - Helium sensitive parameter
    - Depends only on star count
    - On average: $\delta R/\delta Y \sim 10$
  - $N_{RGB}$ is the number of RGB stars brighter than $V_{ZAHB}$
    - $V_{ZAHB}$ is magnitude of the lower envelope of the HB stars
    - $V_{ZAHB} = \langle V_{RR} \rangle + 0.04[M/H] + 0.15$
Determining $V_{ZAHB}$

- **Finding $\langle V_{RR} \rangle$:**
  - Use a GC with similar metallicity and know $\langle V_{RR} \rangle$
    - M 68 if $-1.7 < [\text{Fe/H}] < -1.5$
  - Shift the two CG until HB tail and RGB overlie each other.
- $\Delta V = 1.16 \pm 0.10$
- $\Delta (B - V) = -0.07 \pm 0.01$
Determining $V_{ZAHB}$

- Finding $\langle V_{RR} \rangle$:
  - Use a GC with similar metallicity and know $\langle V_{RR} \rangle$
    - M 68 if $-1.7 < [\text{Fe/H}] < -1.5$
  - Shift the two CG until HB tail and RGB overlie each other
    - $\langle V_{RR} \rangle_{M\,55} = \langle V_{RR} \rangle_{M\,68} - \Delta V$
    - $\Delta(B - V) \approx E(B - V)_{M\,55}$

\[
\langle V_{RR} \rangle_{M\,55} = 14.48 \pm 0.10 \text{ mag}
\]
\[
V_{ZAHB} = 14.57 \pm 0.10 \text{ mag}
\]
\[
N_{RGB} = 162 \pm 12.73
\]
Finding $R$ and the Helium Abundance ($Y$)

$N_{RGB} = 162 \pm 12.73$

$N_{HB} = 271 \pm 16.46$

$R = 1.67 \pm 0.16$
$R$ vs. $[\text{Fe/H}]$ with theoretical calibration for $Y = 0.245$ and age of 13 Gyr (Salaris et al. 2004)
Finding $R$ and the Helium Abundance ($Y$)

$$N_{RGB} = 162 \pm 12.73$$

$$N_{HB} = 271 \pm 16.46$$

$$\Delta Y = \frac{\Delta R}{\delta R/\delta Y} = \frac{R_{theo} - R_{M55}}{10}$$

$$Y_{GC} = Y_{theo} + \Delta Y \approx 0.245 + \Delta Y$$

$$R_{theo} = \begin{cases} 
1.39 \pm 0.02; & \text{ZW84} \\
1.37 \pm 0.02; & \text{CG97}
\end{cases}$$

$$Y = \begin{cases} 
0.273 \pm 0.016; & \text{ZW84} \\
0.274 \pm 0.016; & \text{CG97}
\end{cases}$$
How much He does M 55 have?

- Average value for GC:
  - \( Y = 0.243 \pm 0.006 \)

- Primordial helium abundance:
  - \( Y_p = 0.248 \pm 0.001 \)

- M 55’s value is \(~1.6\sigma\)
  - But still consistent

- So, does M 55 have an He-enriched subpopulation?
He-enriched Subpopulation?

- First generation of stars:
  - Short lived, $\sim 10^8$ yrs, intermediate mass stars
  - Chemical pollution due to ejecta
  - Material is not lost

- Second generation of stars:
  - Helium rich stars
Results: HB Modeling

- To better understand the AGB production.
  - How many will become traditional or “almost” AGB stars?
- Cassisi et al. (2004) synthetic HB
  - $Z = 0.0006$ and $Z = 0.0003$
  - Mass dispersion of $0.02 \, M$
- Easier to compare models and data in $I$ band
  - Monotonic relationship between HB’s mass and its magnitude
HB Fiducial line
Parametric Function $S$

\[ S = -V + 3(B-V) + 16.23 \]
M 55’s HB population using the synthetic $I$-band

Histogram

- **Solid line**
  - (all HB stars)
  - $\langle I \rangle = 14.68$
  - $\sigma = 0.57$

- **Dash line**
  - ($13.8 < I < 15.9$)
  - $\langle I \rangle = 14.74$
  - $\sigma = 0.44$
HB’s $I$-band Distribution

Table 3.1. Properties of HB populations displayed in Figure 3.6.

<table>
<thead>
<tr>
<th>Z</th>
<th>$\langle M \rangle$ ($M_\odot$)</th>
<th>$\langle I \rangle$ (mag)</th>
<th>$\sigma_I$ (mag)</th>
<th>$R_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0003</td>
<td>0.64</td>
<td>15.00</td>
<td>0.54</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>0.66</td>
<td>14.69</td>
<td>0.47</td>
<td>0.12</td>
</tr>
<tr>
<td>0.0006</td>
<td>0.64</td>
<td>14.72</td>
<td>0.51</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>0.66</td>
<td>14.45</td>
<td>0.43</td>
<td>0.11</td>
</tr>
</tbody>
</table>
Results: The $R_2$ parameter

- Establish relative duration between AGB and HB phases
  
  \[ R_2 = \frac{N_{AGB}}{N_{HB}} = \frac{t_{AGB}}{t_{HB}} \]

  \[ R_2 = 0.156 \pm 0.023 \]

- According to synthetic models:
  
  \[ \langle R_2 \rangle = 0.12 \pm 0.02 \implies M\,55'\text{s }R_2\text{ is }\sim1.6\sigma \]

- Sandquist & Bolte (2004) also find disagreement
  
  - Attributed to its blue morphology
  
  - Argues that the $R$, and $R_1 = \frac{N_{AGB}}{N_{RGB}}$ are “normal”
HB tracks for $[\text{Fe/H}] = -1.78$, $[\text{O/Fe}] = 0.66$ (Dorman 1992)
Results: HB Radial Variations
Top Panel:
- Total HB
- bright RGB
- AGB

Bottom Panel:
- ER HB
- EB HB
- Red-half of BHB
- Blue-half of BHB
## Results of the Kolmogorov-Smirnov test

<table>
<thead>
<tr>
<th>Relation between population</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>ER BHB and BHB</td>
<td>$4.8 \times 10^{-6}$</td>
</tr>
<tr>
<td>EB HB and BHB</td>
<td>0.12</td>
</tr>
<tr>
<td>All HB and bright RGB</td>
<td>0.27</td>
</tr>
<tr>
<td>RR Lyr and BHB</td>
<td>0.91</td>
</tr>
<tr>
<td>Red and blue half of BHB</td>
<td>0.82</td>
</tr>
</tbody>
</table>
Explanation: Could the ER HB stars be evolved BSS?

On M 55:
- BSS are dynamically segregated
  - ER HB should be on the core
  - No apparent connection with the ER HB
- HB tracks suggest ER HB are evolved BHB
  - Then why the position distribution?

¿Qué está pasando aquí???????
Conclusions

- $Y = 0.273 \pm 0.016$
  - $\Rightarrow ~1.6\sigma$ away from $Y_p$
  - $\Rightarrow$ Possible He-enriched subpopulation?

- $R_2 = 0.156 \pm 0.023$
  - $\Rightarrow ~1.6\sigma$ from theoretical predictions
  - $\Rightarrow$ **Bluest HB morphology that still produces normal AGB stars**

- HB position distribution:
  - $\Rightarrow$ Red HB concentrated in the outskirts of the GC
  - $\Rightarrow$ **Dynamical evolved GC in spite of its low concentration**