Evolution of Helium-enhanced Stellar Populations (in Globular Clusters & the Milky Way Bulge)

Young-Wook Lee
Yonsei University, Seoul, South Korea

D. Lim, S. Hong, C. Chung, S. Jang, J. Kim, D. Han (Yonsei) & S.-J. Joo (KASI)
Spectroscopy of RR Lyrae stars in Baade's Window and in ω Centauri

R.G. Gratton1, A. Tornambé2,3, and S. Ortolani4

1 Osservatorio Astronomico di Roma, Via del Parco Mellini 84, I-00136 Roma, Italy
2 European Southern Observatory, Karl-Schwarzschild-Str. 2, D-8046 Garching bei München, Federal Republic of Germany
3 Istituto di Astrofisica Spaziale, C.N.R., c.p. 67, I-00044 Frascati (Roma), Italy
4 Osservatorio Astrofisico di Asiago, I-36012 Asiago (VI), Italy

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Summary. New ΔS values (for the definition of S, see Preston, 1959) have been derived for 35 RR Lyrae stars in ω Centauri and Baade's Window. Intensities of a blend of lines near 4300 Å have also been estimated for the ω Centauri variables. Intensities of this blend are correlated with K line intensities in ω Centauri. Our results confirm that ΔS does not correlate with the period shift within ω Centauri, while it does in the galactic centre.

The results have been interpreted with a view to understanding the “Sandage effect” on Population II variables. Our conclusions for ω Centauri, for other globular clusters, and for Baade's window variables may be summarized as follows:

- Constraints are found that the less metal rich (ΔS > 5) RR Lyrae variables in ω Centauri are not Zero Age Horizontal Branch (ZAHB) stars but are the evolutionary descendants of blue ZAHB stars. This can account for the observed behaviour of the luminosity of RR Lyrae variables versus metallicity and rules out the idea of metallicity fluctuations. The existence of...
Discovery of Multiple Populations in GCs

letters to nature

Multiple stellar populations in the globular cluster ω Centauri as tracers of a merger event


* Center for Space Astrophysics, Yonsei University, Seoul 120-749, Korea
† National Optical Astronomy Observatories/Cerro Tololo Interamerican Observatory (NOAO/CTIO), Casilla 603, La Serena, Chile

The discovery of tidally disrupted globular clusters by the accretion of satellite clusters contains several distinct stellar populations, with the most notable being the ω Centauri population. The accretion of ω Centauri by the Milky Way Galaxy and Sagittarius d probably enriched the Milky Way with massive stars. The discovery of these populations has led to over 500 papers since 1999.

Lee+99; Pancino+00; Rey+04; Bedin+04; Norris 04; D’Antona+04; D’Antona+Caloi 04, 08; Lee+05; Piotto+05; Bekki+06; Decressin+08; D’Ercole+08; Renzini 08; Carretta+09; Ferraro+09; Johnson+Pilachowski+09, 15; Ventura+09; Han+09; JWLee+09; Vesperini+10, 13; Dalessandro+11; Gratton+11, 12, 13; Mucciarelli+12; Joo+Lee 13; Lee+13; Kunder+13; Jang+14; Marino+14; Da Costa+14; Yong+14; Piotto+15; Milone+15; Lim+15; Jang+Lee 15; Han+15...

500+ papers!

G1: Normal He
G2+G3: He, Na, N.. (Fe, Ca..) enriched by IMAGB, WMS, (SNe)
Milestones in the discovery of He-enhanced population

Sandage+1981; Sweigart, Renzini, Tornambe 1987: RRL’s in metal-poor OoII GCs might be He-rich

Lee+1999; Pancino, Ferraro+2000: discovered MSP from RGB stars in Omega Cen

D’Antona+2002, 2004: suggested He-enhanced pop. from AGB ejecta & HB morphology

Bedin+2004: discovered a MS split from Omega Cen

Norris 2004: suggested He-enhanced pop. from a MS split of Omega Cen

Lee+2005: He-enhanced pop. can explain MS split & EHB simultaneously

Piotto+2005: indirect evidence for He-enhanced pop. from spectroscopy of MS stars → Blue MS stars are more metal-rich & thus should be He-rich

Carretta+2009; Gratton+2012: established Na-O anti-correlation among GCs → He-enhanced stars are also enhanced in Na & N

Villanova+2012; Marino, Milone+2014: direct spectroscopic confirmation of He-enhanced stars on bluer HB
Effects of Helium Abundance on HR diagram

He-rich stars (higher $T_c$ & less envelope opacity):

1. brighter & bluer at a given mass
2. evolve faster and thus have smaller masses at a given age
   $\Rightarrow$ fainter & bluer on the MS
3. bluer color on HB at a given age (for metal-poor GCs)
Effects of He on MS: ω Centauri

Observation: Bedin+2004

Model: Lee+2005; Joo & Lee 2013

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>-1.81</td>
<td>0.231</td>
<td>0.0</td>
<td>13.1 ±0.3</td>
<td>0.42</td>
</tr>
<tr>
<td>G2</td>
<td>-1.55</td>
<td>0.232</td>
<td>0.0</td>
<td>13.0</td>
<td>0.27</td>
</tr>
<tr>
<td>G3</td>
<td>-1.31</td>
<td>0.41</td>
<td>0.14</td>
<td>12.0</td>
<td>0.17</td>
</tr>
<tr>
<td>G4</td>
<td>-1.01</td>
<td>0.38</td>
<td>0.47</td>
<td>11.4</td>
<td>0.08</td>
</tr>
<tr>
<td>G5</td>
<td>-0.62</td>
<td>0.39</td>
<td>0.47</td>
<td>11.4</td>
<td>0.05</td>
</tr>
</tbody>
</table>
Effects of He on HB morphology

Omega Cen:
Lee+2005; Joo & Lee 2013

NGC 2808:
Lee+2005; D’Antona+2005
The Oosterhoff (1939) Period Groups

According to mean period of type ab RR Lyrae variables in GCs and halo field

Oo group I:
$\langle P_{ab} \rangle \sim 0.55$ day, metal-rich

Oo group II:
$\langle P_{ab} \rangle \sim 0.65$ day, metal-poor

Oo group III:
$\langle P_{ab} \rangle \sim 0.70$ day, very metal-rich

One of the long-standing problems in modern astronomy!

Most RRL’s in M15 (Oo II) are from G2, mildly enhanced in He & N

$$\Delta Y (G2-G1) = 0.015$$
$$\Delta Z_{CNO} = 0.0003$$
$$\Delta t = \sim 1 \text{ Gyr}$$

Jang, Lee+2014

(cf. Sandage+81; SRT 87)

Table 1. Parameters from our best-fit simulation of M15.

<table>
<thead>
<tr>
<th>Population</th>
<th>[Fe/H]$^a$</th>
<th>$\Delta Z_{CNO}$</th>
<th>$Y$</th>
<th>Age (Gyr)</th>
<th>Mass Loss$^b$</th>
<th>$\langle M_{HB}\rangle^c$</th>
<th>Fraction</th>
<th>$\Delta \log P^d$</th>
<th>$\Delta (P_{ab})^c$</th>
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</thead>
<tbody>
<tr>
<td>G1</td>
<td>-2.2</td>
<td>0</td>
<td>0.230</td>
<td>12.5</td>
<td>0.140</td>
<td>0.686</td>
<td>0.36</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>G2</td>
<td>-2.2</td>
<td>0.00026</td>
<td>0.245</td>
<td>11.4 ± 0.2</td>
<td>0.142</td>
<td>0.684</td>
<td>0.22</td>
<td>0.040</td>
<td>0.087</td>
</tr>
<tr>
<td>G3</td>
<td>-2.2</td>
<td>0.00026</td>
<td>0.327</td>
<td>11.3 ± 0.2</td>
<td>0.129</td>
<td>0.589</td>
<td>0.42</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Period-Shift between Oo groups → “Population-Shift” within the instability strip (Jang, Lee+2014)

RR Lyraes produced mostly by
- G1 for Oo I,
- G2 for Oo II,
- G3 for Oo III

(G1/G2 overlap if metal-rich or Δt < 0.5 Gyr)
When our models are extended to all metallicity regimes...

The Oosterhoff dichotomy reproduced!

Outer Halo (R > 8kpc):
\[ \Delta t (G1-G2) = \sim 1 \text{ Gyr} \]

Inner Halo (R < 8kpc):
\[ \Delta t (G1-G2) = 0.5 \text{ Gyr} \]
\[ \Delta t (\text{Inner-Outer}) = \sim 1 \text{ Gyr} \]
\[ \Delta Y (G2-G1) = 0.012 \]

Consistent with the dual origin of halo (Zinn 1993; Lee+2007; Carollo+2007)

Jang & Lee 2015
Double Red Clump (RC) in the MW Bulge

Discovery of Two RCs ($|l| > 5.5$): McWilliam & Zocalli 2010; Nataf et al. 2010
The X-Shaped Bulge in the Milky Way

X-Shaped Bulge from bar instability:
bright RC (foreground) + faint RC (background)
McWilliam & Zocalli 2010; Nataf+2010, 2015; Saito+2012; Ness, Freeman+2012, 2013; Li & Shen 2012; Uttenthaler+2012; Wegg & Gerhard 2013; Vasquez+2013; Rojas-Arriagada+2014; Gonzalez+2015... **120+ papers**

→ Even high latitude field of the bulge has “pseudo bulge” characteristic

*But, an alternative interpretation is possible!* (Lee+2015)
Hint from Terzan 5: A metal-rich bulge GC with double RC!

The cluster Terzan 5 as a remnant of a primordial building block of the Galactic bulge

F. R. Ferraro¹, E. Dalessandro¹, A. Mucciarelli¹, G. Beccari², R. M. Rich³, L. Origlia⁴, B. Lanzoni⁵, R. T. Rood⁵, E. Valenti⁶-⁷, M. Bellazzini⁴, S. M. Ransom⁸ & G. Cocozza⁴

Metal-rich counterpart of ω Cen (Ferraro et al. 2009)

→ Brighter RC is younger (Ferraro+2009; 2016) and super-He-rich (D’Antona+2010; Lee+2015)

→ Very analogous to the double RC in bulge!

Figure 2 | The two horizontal branch clumps of Terzan 5. Main panel, MAD
In the metal-rich regime...

Super-He-rich HB stars are on the brighter RC!

\[ \Delta Y = 0.13 \]
When the observed $\Delta t$, $\Delta[\text{Fe/H}]$ & $\Delta[\alpha/\text{Fe}]$ (Ferraro+2016; Origlia+2011) are taken into account, we still need a large $\Delta Y \sim 0.07$ (Joo, Lee, & Chung 2017)
Multiple Population Models for the Double RC in Bulge

G1: normal-He
$\Delta Y/\Delta Z = 2$

G2: enhanced-He
$Y = 0.39$ ($\Delta Y/\Delta Z = 6$) at $[\text{Fe/H}] = -0.1$

Lee, Joo & Chung 2015
Joo, Lee & Chung 2017
In the metal-poor regime, our models can also reproduce:

Two populations of RR Lyrae variables in the bulge (Pietrukowicz et al. 2015)

\[
\langle [\text{Fe/H}] \rangle = -1.1
\]

Our model (Lee & Jang 2016)

\[
\Delta Y (G2-G1) = 0.012
\]
Double RC, two bulge RRL populations, & Oosterhoff dichotomy are different manifestations of the same phenomenon!!

Double RC at solar metallicity is a natural extension of this trend!

Strong metallicity dependence of $\Delta Y(G2-G1)$ is predicted from our chemical evolution models for proto-GCs

Lee & Jang 2016
Chemical Evolution Models (Kim & Lee 2017)

Major assumptions/ingredients:

1. SN blast waves undergo blowout without expelling the leftover gas (Tenorio-Tagle+2015; Silich & Tenorio-Tagle 2017)
   → Chemical evolution is dictated by AGB & WMS (winds of massive stars)!

2. Star formation beyond G2 is allowed to continue, G3, G4...

3. IMF slope $s \sim 2$, SFE $\sim 60\%$

4. Specific star formation history is required ($\Delta t \sim 10^8$ yrs between G1, G2, G3...)

5. Stellar yields from:
   Ventura+2013, 2014; Di Criscienzo+2016 (AGB)
   Portinari+1998; Hirschi+2005 (WMS)
NGC 2808

Observation: Carretta et al. 2015

\[ [\text{Fe/H}] = -1.14 \]

<table>
<thead>
<tr>
<th>Population</th>
<th>Y</th>
<th>( \Delta [\text{Na/Fe}] )</th>
<th>( \Delta [\text{O/Fe}] )</th>
<th>( \Delta [\text{N/Fe}] )</th>
<th>( \Delta Z_{CNO} )</th>
<th>fraction Original</th>
<th>fraction Remaining</th>
<th>t(Gyr)</th>
</tr>
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<tbody>
<tr>
<td>G1</td>
<td>0.235</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.47</td>
<td>0.39</td>
<td>0.0</td>
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<tr>
<td>G2</td>
<td>0.269</td>
<td>0.30</td>
<td>-0.16</td>
<td>0.79</td>
<td>0.00010</td>
<td>0.26</td>
<td>0.26</td>
<td>0.23</td>
</tr>
<tr>
<td>G3</td>
<td>0.303</td>
<td>0.42</td>
<td>-0.37</td>
<td>1.00</td>
<td>0.00012</td>
<td>0.14</td>
<td>0.16</td>
<td>0.31</td>
</tr>
<tr>
<td>G4</td>
<td>0.335</td>
<td>0.50</td>
<td>-0.77</td>
<td>1.13</td>
<td>0.00014</td>
<td>0.08</td>
<td>0.12</td>
<td>0.36</td>
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<tr>
<td>G5</td>
<td>0.369</td>
<td>0.65</td>
<td>-1.11</td>
<td>1.30</td>
<td>0.00093</td>
<td>0.05</td>
<td>0.08</td>
<td>0.91</td>
</tr>
</tbody>
</table>
Observation: Carretta et al. 2009

\[ \text{s} = 2.1, \text{SFE}= 60\%, \quad [\text{Fe/H}] = -1.3 \]

\( \Delta t \sim 10^8 \text{ yrs expected from orbital period, MS lifetime of AGB, Lyman & Werner cooling timescale} \) (see, e.g., Conroy & Spergel 2011)

Table 2. Results of our chemical evolution model for the inner halo globular cluster M5.

<table>
<thead>
<tr>
<th>Population</th>
<th>Y</th>
<th>( \Delta [\text{Na/Fe}] )</th>
<th>( \Delta [\text{O/Fe}] )</th>
<th>( \Delta [\text{N/Fe}] )</th>
<th>( \Delta Z_{\text{CNO}} )</th>
<th>fraction Original</th>
<th>fraction Remaining</th>
<th>t(Gyr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>0.233</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.49</td>
<td>0.31</td>
<td>0.0</td>
</tr>
<tr>
<td>G2</td>
<td>0.256</td>
<td>0.34</td>
<td>-0.07</td>
<td>0.90</td>
<td>0.00035</td>
<td>0.27</td>
<td>0.23</td>
<td>0.45</td>
</tr>
<tr>
<td>G3</td>
<td>0.280</td>
<td>0.47</td>
<td>-0.23</td>
<td>1.09</td>
<td>0.00042</td>
<td>0.13</td>
<td>0.26</td>
<td>0.6</td>
</tr>
<tr>
<td>G4</td>
<td>0.303</td>
<td>0.54</td>
<td>-0.48</td>
<td>1.21</td>
<td>0.00044</td>
<td>0.07</td>
<td>0.13</td>
<td>0.7</td>
</tr>
<tr>
<td>G5</td>
<td>0.326</td>
<td>0.61</td>
<td>-1.12</td>
<td>1.3</td>
<td>0.00048</td>
<td>0.04</td>
<td>0.07</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Our models predict super-He-rich G2 stars in the bulge!

Strong metallicity dependence of $\Delta Y(G2-G1)$ is mostly due to the winds of metal-rich massive stars (Maeder 1992; Meynet+2008)

Unlike He, main contributor of Na & N is AGBs, without strong Z dependence, and our models are consistent with observed spreads in [Na/Fe] & [N/Fe] in MW bulge! (Johnson+2012; Schiavon+2017)
Bright RC stars are enhanced in CN (& He)!

du Pont 2.5m low-resolution spectroscopy for 462 RC & RGB stars in the bulge (b = -8.5):

Direct evidence that (1) double RC is due to multiple population phenomenon, & (2) bulge stars have GC origin!!

See poster by Hong, Lim & Lee
The double red clump of the Milky Way bulge has nothing to do with an X-shaped structure!

1. It is another manifestation of helium-enhanced multiple population phenomenon (Lee+2015).
2. In the metal-poor regime of the bulge, the same phenomenon is observed as two sequences of RR Lyrae stars on the period-amplitude diagram (Lee & Jang 2016).
3. The required helium enhancement ($\Delta Y/\Delta Z = 6$) for the second generation stars is naturally predicted by our chemical evolution models (Kim & Lee 2017).
4. The bright RC stars are enhanced in CN, which traces N, Na, & He! The $\Delta$CN(bRC-fRC) is consistent with $\Delta$CN(G2-G1) observed in GCs! (see poster by Hong, Lim, & Lee)
5. The observed spread in [Na/Fe] among bulge RGB stars is 2-3 times larger than that of the disk (bar) population, and is consistent with our chemical evolution models.
6. Our models can reproduce key observations: double RC = $f ([Fe/H], b, l)$ (Lee+2015; Joo+2017)
7. Our models are not inconsistent with observed kinematics (see Lee+2015).
8. The claimed X-shaped structure from WISE residual map (Ness & Lang 2016) is most likely an artifact or exaggeration. Even if it is real, the stellar density in the faint X-shaped structure is way too low to be observed as the double RC (Han & Lee 2017).
9. The observed difference in I magnitude between the RR Lyrae stars and the RC (~0.55 mag) is consistent with our multiple population models.
10. There is also no evidence for the X-shaped structure from main sequence stars & Mira variables (Lopez-Corredoira 2016, 2017).
Summary & Implications

1. He-enhanced G2 can naturally explain the Oosterhoff dichotomy in the halo & the two populations of RR Lyraes in the bulge (Jang & Lee 2015; Lee & Jang 2016).

2. Double RC in MW bulge is another manifestation of He-enhanced multiple populations in metal-rich regime, and has nothing to do with an X-shaped structure (Lee+2015; Joo, Lee, Chung 2017).

3. This is supported by our chemical evolution models and CN observations.

4. MW has a composite bulge (bar + classical bulge).

5. Proto-GCs were the major building blocks in the classical bulge formation!

6. Early-type galaxies would be similarly prevailed by super-helium-rich population! → Na-enhanced gE’s (van Dokkum & Conroy 2010) are explained w/o bottom heavy IMF (see Lee+2015): They are also CN-enhanced!! (e.g., Worthey 1998)

7. Gaia distances can provide a further test!

In order to understand galaxies and their formation, you need to first understand the amazing life of He-enhanced stars in GCs!