The Origin of the Oosterhoff Dichotomy & the Double Red Clump in the Halo & Bulge of the Milky Way

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The Oosterhoff (1939) Period Groups
According to mean period of type ab RR Lyrae variables in GCs

Oo group I:
\(<P_{ab}> \sim 0.55\) day, metal-rich

Oo group II:
\(<P_{ab}> \sim 0.65\) day, metal-poor

Oo group III:
\(<P_{ab}> \sim 0.70\) day, very metal-rich

One of the long-standing problems in modern astronomy!

(~370 papers, including Sandage 2010)
**Pulsation theory** (e.g., van Albada & Baker 1971):

P – Mean density relation, $P_{RR} = f(L, M, T_{\text{eff}})$

$$\log P_f = 0.84 \log L - 0.68 \log M - 3.48 \log T_{\text{eff}} + 11.497,$$

where $P$ is in days and $L$ and $M$ are in solar units

**Suggested origin for the Oosterhoff dichotomy** (among $\sim$370 papers)

van Albada & Baker 1973: “Hysteresis effect” $\rightarrow$ $T_{\text{eff}}$ difference

Sandage 1981: “P-shift” at fixed $T_{\text{eff}}$ $\rightarrow$ $L$ difference

Lee, Demarque, & Zinn 1990: $L$ difference $\rightarrow$ Post-ZAHB evolution from blue HB

Yoon & Lee 2002: Metal-poor Oo II GCs were accreted from a satellite galaxy
Discovery of Multiple Stellar Populations in GCs

Lee+99; Pancino+00; Bedin+04; Norris 04; D’Antona+04; Lee+05; Piotto+05; Bekki+06; Decressin+08; D’Ercole+08; Renzini 08; Carretta+09; Ferraro+09; Ventura+09; Han+09; JWLee+09; Dalessandro+11; Gratton+12; Mucciarelli+12; Lee+13; Marino+14; Da Costa+14; Yong+14; Piotto+15; Nardiello+15; Milone+15; Lim+15; Han+15… 300+ papers!

G1: Normal He
G2+G3: He, Na, N.. (Fe, Ca..) enriched by IMAGB, FRMS, (SNe)
**Synthetic HB models with multiple populations**

(Jang, Lee+2014; Jang & Lee 2015; Lee+2015)

- **Stellar Libraries & Synthetic HB**
  - Lee, Demarque, & Zinn 1990, 94; Joo & Lee 2013
  - Yonsei-Yale (Y2) isochrones & HB evolutionary tracks with He & CNO enhancements

<table>
<thead>
<tr>
<th>[Fe/H]</th>
<th>-3.51, -2.51, -1.90, -1.51, -0.90, -0.65, -0.49, -0.17, 0.17, 0.39, 0.56</th>
</tr>
</thead>
<tbody>
<tr>
<td>[α/Fe]</td>
<td>0.0, 0.3, 0.6</td>
</tr>
<tr>
<td>Y</td>
<td>0.23, 0.28, 0.33, 0.38, 0.43</td>
</tr>
<tr>
<td>[N/Fe]</td>
<td>0.0, 0.8, 1.6</td>
</tr>
<tr>
<td>([CNO/Fe]</td>
<td>(0.21, 0.31, 0.67)</td>
</tr>
</tbody>
</table>

- **Mass-Loss on RGB**
  - Reimers’ mass-loss parameter $\eta$ calibrated to the HB morphologies of inner halo GCs ($\eta \sim 0.4$)

- **Stellar Pulsation**
  - The blue edge of the instability strip: Tuggle & Iben 1972; Bono et al. 1995
  - $P_{ab}$ and $P_c$: van Albada & Baker 1971; Bono et al. 1997
  - Transition $T_{\text{eff}}$ between c and ab type RRL: Sandage’s (2006) empirical formula
Three distinct subgroups on the HB of M15

M15 (Oo II)
Buonanno+1985; Bingham+1984

3 distinct subgroups on HB:
RR Lyraes, blue HB, & blue tail (extreme BHB).

Assume that they were originated from 3 distinct subpopulations (G1, G2, & G3) in this GC.

Other Oo II GCs, NGC 5466 & 4590, also show gaps between RR Lyraes & blue HB.
Placements of G1, G2, & G3 on the HB of M15

**G1**: Normal Blue HB ([Fe/H] = -2.2, $t = 12.5$ Gyr)

**G2**: RR Lyraes (somewhat enhanced in Helium & CNO, $\approx 1$ Gyr younger)

**G3**: “Blue tail” or Extreme Blue HB (Super-He-rich)

Some evidence for He and CNO enhancements in G2:
- **Theory (IMAGB/FRMS)**: Fenner+2004; Ventura & D’Antona 2009; Karakas 2010; Decressin+2009
  - Need more observations for CNO sum

Both helium and CNO enhancements play a role in increasing the period of RR Lyrae variables!
Effects of $Y$, Age, and $Z_{\text{CNO}}$ on the HB of G2

$[\text{Fe/H}] = -2.2$  \quad $\Delta Y = + 0.015$

$t = 12.5$ Gyr  \quad $\Delta t = -1.1$ Gyr

$Y = 0.23$  \quad $\Delta Y = + 0.015$

$\Delta t = -1.1$ Gyr

$\Delta Z_{\text{CNO}} = +0.00026$

Data: Buonanno+1985

Open Circles: RR Lyraes
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>$\Delta \langle P_{ab}\rangle$</th>
</tr>
</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</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>

$^a[\alpha/Fe] = 0.3$ for G1 & G2, 0.5 for G3.
Period-Shift between Oo groups
→ “Population-Shift” within the instability strip (Jang & Lee 2015)

RR Lyraes produced mostly by
G1 for Oo I,
G2 for Oo II,
G3 for Oo III
When our models are extended to all metallicity regimes...

The Oosterhoff dichotomy reproduced!

**Outer Halo** ($R > 8\text{kpc}$):

$\Delta t (G1-G2) = 1.4 \text{ Gyr}$

**Inner Halo** ($R < 8\text{kpc}$):

$\Delta t (G1-G2) = 0.5 \text{ Gyr}$

$\Delta t (\text{Inner}-\text{Outer}) = 1.2 \text{ Gyr}$

$\Delta Y (G2-G1) = 0.01$

$\Delta Z_{\text{CNO}} (G2-G1) = 0.00035$

*Post-ZAHB evolution effect (Lee+ 90) is still important in the Inner Halo*

Jang & Lee 2015
"Two-stage Jump" in $\langle P_{ab} \rangle$ for the Inner Halo GCs

With decreasing metallicity, contribution from G1 & G2 ZA HBs decrease sequentially

→ Two-stage jump in $\langle P_{ab} \rangle$  (cf. Lee & Zinn 90)

"Population-shift" effect when $\Delta t$ (G1-G2) is small

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

Discovery of Two RCs (lblr > 5.5):
McWilliam & Zocalli 2010; Nataf et al. 2010; Saito et al. 2011
Double RC in MW Bulge: Key Observations

(1) $\Delta K = \Delta I = \sim 0.5$ mag

(2) Two RCs have $\sim$identical mean colors

(3) Double RC $= f([Fe/H])$

Only evident among metal-rich stars, while metal-poor populations show only faint RC

(4) Double RC $= f(b, l)$

Separation vanishes at low latitude, relative strength of two RCs changes with longitude

The X-Shaped Bulge in the Milky Way

X-Shaped Bulge from bar instability: bright RC (foreground) + faint RC (background)

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

But this is most likely an artifact!
Discovery of Multiple Stellar Populations in GCs

**G1:** Normal He

**G2+G3:** He, Na, N.. (Fe, Ca..) enriched by IMAGB, FRMS, (SNe)
For metal-poor GCs,

Super-He-rich subpopulations are on the bluer HB

NGC 2808
Lee et al. 2005

Models & Spectroscopy:
Lee+94; D’Antona & Caloi 04, 08; Lee+05; Cassisi+09; Gratton+11, 12, 13; Chung+11; Dalesandro+11; Joo & Lee 13; Kunder+13; Jang+14; Marino+14; Jang & Lee 15
But in metal-rich system, they are at brighter RC!

Hint from Terzan 5: A metal-rich bulge GC

Metal-rich counterpart of ω Cen

→ Brighter RC is either
  6 Gyr younger (Ferraro+2009) or super-He-rich (D’Antona+2010; Le e+2015)

→ Very analogous to the double RC in bulge!
But dismissed because of the color difference… (McWilliam & Zocalli 2010; Nataf et al. 2010)
Multiple Population Models for the Double RC in Bulge

Synthetic HB models using $Y^2$ evolutionary tracks

G1: normal-He  
$\Delta Y/\Delta Z = 2, \ 12 \text{ Gyr}$

G2: super-He-rich 
$Y = 0.39, \ 10 \text{ Gyr}$

$\Delta [\text{Fe/H}] = 0.2 \text{ dex}$

Explains metallicity dependence!

Lee, Joo & Chung 2015
Multiple Population Models for the Double RC in Bulge

G1: normal-He
\[ \frac{\Delta Y}{\Delta Z} = 2, \ 12 \text{ Gyr} \]

G2: super-He-rich
\[ \frac{\Delta Y}{\Delta Z} = 6, \ 10 \text{ Gyr} \]
\( Y_{\text{Max}} = 0.41 \)

\[ \Delta [\text{Fe/H}] = 0.2 \text{ dex} \]

Explains metallicity dependence!

Joo, Lee+, in prep.
Multiple Population Models for the Double RC in Bulge

G1: normal-He
\[ \frac{\Delta Y}{\Delta Z} = 2 \]
G2: super-He-rich
\[ Y = 0.39 \]
\[ \rightarrow \text{At solar [Fe/H], } \frac{\Delta Y}{\Delta Z} = 6 \]
(by AGB+FRMS+SNe)

\[ \rightarrow \text{Could form ubiquitous } \]
\[ \text{ly in metal-rich syste} \]
\[ \text{m!} \]

\[ \rightarrow \text{Chemical evolution m} \]
\[ \text{odel required} \]

Lee, Joo & Chung 2015
Composite Bulge:
Tilted Bar embedded in a Classical Bulge (CB)

Double RC = \( f(b, l) \)

Latitude dependence
\( \rightarrow \) Bar/CB = \( f(b) \)

Longitude dependence
\( \rightarrow \) Tilted Bar embedded in CB

Bar: monomodal in gray
CB: bimodal
Bar+CB: blue
Observed kinematics are not inconsistent with our scenario!

- **Cylindrical rotation at l|b| < 6** (Ness+13; Zoccali+14): low l|b| is dominated by bar, CB could have absorbed angular momentum from bar (Saha+15; Zoccali+14)

- **Some $\Delta V_r$ ($b_{RC} - f_{RC}$) at $b = -6$** (Vasquez+13): Bar + CB at low l|b|, & bar is in streaming motion

- **No $\Delta V_r$ ($b_{RC} - f_{RC}$) at $b = -8, -10$** (De Propris+11; Uttenthal+12; Rojas-Arriagada+14): Consistent with our CB dominated scenario at high l|b|
At metal-poor regime, our models can also reproduce... Two populations of RR Lyrae variables in the bulge (Pietrukowicz et al. 2014) Our model (Lee & Jang, in prep.)

$<[\text{Fe/H}]> \sim -1.0$

$\Delta Y (G2-G1) \sim 0.015$
Multiple population models can also reproduce...

The Oosterhoff dichotomy: 76 year old problem

Oosterhoff Dichotomy:
"Population-Shift" within the instability strip

RR Lyraes from
G1 for Oo I,
G2 for Oo II,
(G3 for Oo III)
\( \Delta Y (G2-G1) = 0.01 \)

Jang & Lee 2015
Double RC & two populations of RRL in bulge, & Oosterhoff dichotomy are different manifestations of the same phenomenon!!

\[ \Delta Y(G2-G1) = 0.12 \]

\[ \Delta Y(G2-G1) = 0.015 \]

\[ \Delta Y(G2-G1) = 0.01 \]
Summary & Implications

(1) Double RC in MW bulge is another manifestation of multiple populations in metal-rich regime, rather than the distance effect (Lee et al. 2015)
   ➔ *Gaia can confirm this!*

(2) MW bar is not sufficiently buckled to form X-shaped structure
   ➔ *previous studies on the structure of the bulge (based on RC) should be re-examined*

(3) Stars in CB component were provided by disrupted “building blocks” such as Terzan 5 (massive GCs)! NB. γ-ray emission from MW center best explained by MSPs provided by disrupted GCs (Brandt+Kocsis 2015)

(4) Early-type galaxies would be similarly prevailed by super-helium-rich population!! ➔ *Impacts on population synthesis, such as Na enhanced gE (van Dokkum & Conroy 2010) & UV upturn (Chung, Yoon, & Lee 2011)*

(5) The same multiple population models can explain two populations of RR Lyrae variables in the bulge, and the Oosterhoff dichotomy in the halo (Jang & Lee 2015)

(6) *Astronomers repeat the same mistakes:* intrinsically brighter (fainter) population is often misinterpreted as a distance effect
This longitude dependence at $b = -8.5$ is understood by:

1. tilted bar+CB & effect of perspective
2. metallicity effect
Gonzalez et al. 2015
Comparison of our model with observation

2MASS data for $b = -8$ deg:
bulge +
foreground disk contamination
Figure 3. CMDs and brightness distribution with best-fit double clump model for two locations. Left: \((l, b) = (0.27, -5.77)\), the \(\Delta \chi^2 = 26.7\) when a second Gaussian is fit, the parameters are \((m_{RC,1}, \sigma_{RC,1}, N_{RC,1}, m_{RC,2}, \sigma_{RC,2}, N_{RC,2}) = (14.90, 0.18, 166.42, 15.42, 0.10, 98.51)\). Right: \((l, b) = (-0.28, 5.76)\), the \(\Delta \chi^2 = 14.4\). The parameters are: \((m_{RC,1}, \sigma_{RC,1},\)
G2 Y=0.4064 : dY/dZ=6 at [Fe/H]=+0.1

# of stars : G1=G2=10,000

$\Delta M_K = 0.50$ (peak)
0.517 (mean)

$\Delta M_I = 0.40$ (peak)
0.523 (mean)
The HB morphology versus metallicity diagram

[Graph showing the HB morphology versus metallicity diagram with different markers and lines indicating different groups and combinations of groups (e.g., Outer Halo, Inner Halo, G1 + G2, G1 + G2 + G3)].
The image shows a comparison between the Outer Halo and Inner Halo of a celestial object. The graphs display the relationship between the metallicity ([Fe/H]) and the apparent magnitude ($M_V$) at three different metallicity levels: [Fe/H] = -1.0, [Fe/H] = -1.5, and [Fe/H] = -2.0. Each metallicity level has distinct colors and symbols representing different groups (G1, G2, G3). The HBT (Hydrogen to Helium) ratio is also indicated for each metallicity level: HBT = -0.97, HBT = -0.38, and HBT = 0.88, respectively. The B-V color index is shown on the x-axis for both the Outer Halo and Inner Halo plots.
“Population shift”

within the instability strip

→ P-shift

RR Lyraes are produced mostly by G1 for M3 (Oo I), by G2 for M15 (Oo II), & by G3 for NGC 6441 (Oo III), respectively.

NB. Evolution effect is still important for the Oo II GCs in the inner halo (Jang & Lee 2015)
The $Y^2$ Evolutionary Tracks for HB & RC
(RC = metal-rich counterpart of HB)

Credit: Chongsam Na