Assembling the Milky Way Bulge from Globular Clusters: Evidence from the Double Red Clump

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Double Red Clump (RC) in the MW Bulge

Discovery of Two RCs (lblr > 5.5 deg):
McWilliam & Zocalli 2010; Nataf et al. 2010 → only among metal-rich ([Fe/H] > -0.5) stars

RC stars = metal-rich counterpart of core-He-burning HB stars
A Giant X-Shaped Bulge in the Milky Way?

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

McWilliam & Zocalli 10; Nataf+10, 15; Shen, Kormendy+10; Ness, Freeman+12, 13; Li & Shen 12; Wegg & Gerhard 13; Vasquez+13; Rojas-Arriagada+14; Gonzalez+15; Ness & Lang 16... 140+ papers

→ Even high latitude field of the bulge has bar (pseudo bulge) characteristic

But, a drastically different interpretation has been suggested! (Y.-W. Lee+2015)
Discovery of Multiple Populations in Globular Clusters

letters to nature

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

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The discovery tidally disrupted view that the by the accretion contains sever as its nucleus associated with ω Centauri distinct stellar. The most n younger than that ω Centauri more than ω quite surpris more massive Sagittarius d probably we Galaxy and ω

Lee et al. 1999
Bedin+2004 for MS

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; Yono+14; Piotto+15; Milone+15; Lim+15; Jang+Lee 15; Han+15. Renzini 2015; Bastian+Lardo 2018...

700+ papers!

G1: Normal He
G2+G3: He, Na, N.. (Fe, Ca..) enriched by AGB, WMS, (SNe) & O, Mg depleted

Unique phenomenon observed only in GCs!
In the metal-rich regime..

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

**Synthetic HB models**
Y.-W. Lee & S. Jang 2016
(using Yonsei-Yale evolutionary tracks)

$\Delta Y = 0.13$

*Explains metallicity dependence of double RC!*
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

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

\( \rightarrow \) Brighter RC is younger (Ferraro+2009; 2016) and super-He-rich (D’Antona+2010; Lee+2015; Joo+2017)

\( \rightarrow \) Very analogous to the double RC in bulge!
Multiple Population Models for the Double Red Clump in the Milky Way Bulge

Synthetic HR diagrams using He & N enhanced Yonsei-Yale ($Y^2$) HB evolutionary tracks & isochrones

**G1: normal-He**

$\Delta Y/\Delta Z = 2$

$Y = 0.27$ at $[\text{Fe/H}] = -0.1$

**G2: enhanced-He**

$\Delta Y/\Delta Z = 6$

$Y = 0.39$ at $[\text{Fe/H}] = -0.1$

(cf. Renzini 1994; Nataf+2013)

Lee, Joo & Chung 2015
Lee & Jang 2016
Joo, Lee & Chung 2017

(see also Lopez-Corredoira 2016, 2017)
Our chemical evolution models predict a strong metallicity dependence of $\Delta Y(G2-G1)$! (J. Kim & Y.-W. Lee 2018, ApJ)

This is mostly due to the winds of metal-rich massive stars (Maeder 92; Meynet 08)

Also consistent with the observed spreads in [Na/Fe] & [N/Fe] in MW bulge
In the metal-poor regime, our models can also reproduce..

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

Our model
(Lee & Jang 2016)

$<[\text{Fe/H}]> = -1.1$

$\Delta Y \ (G2-G1) = 0.012$
Two scenarios predict different placements of bRC & fRC stars in K magnitude vs. CN index diagram!

Chemical tagging with CN-band:
Most GCs host CN-strong G2 & CN-normal G1 stars
→ CN traces N
→ N-rich G2 stars also enhanced in He & Na

Unique phenomenon observed only in GCs!

Talk by Dongwook Lim
Bright RC stars are CN-enhanced!!

$\Delta \delta CN = 0.13 \ (5.3\sigma)$
$\Delta \delta CN(G2+, G1) = 0.43$
(similar to GCs: Lim+15)

Similar results from CN4142 LCO 2.5m spectroscopy

CN, Na, & He enhanced stars are discovered only in GCs! $\rightarrow$ Well-established chemical tagging (e.g., Martell+2011)

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

Y.-W. Lee, Hong, Lim+2018 (See Poster by S. Hong)
Unlike CN, the differences in CH and Ca abundances are negligible between the stars in two RC zones → Consistent with GC-origin!

Y.-W. Lee, Hong, Lim+2018 (See Poster by S. Hong)
Na bimodality of bulge RGB stars! (data from Johnson+12, 14) 
→ Smoking gun evidence for G1 & G2+ from GCs!

Y.-W. Lee et al., in prep.
(True) Bulge stars are not from the bar or disk! (data: Johnson+12, 14)

Y.-W. Lee et al., in prep.
Recent cosmological hydro-N-body simulations predict GC-origin bulge with rotation (e.g. Kruijssen 2015; Pfeffer+2017; Renaud+2017; Kravtsov & Gnedin 2005)
Proto-GCs could form in a clump in “clump-origin bulge”

“Clump-origin bulge” (Noguchi+1999; Elmegreen+2008; Inoue+Saitoh 2012) → reproduces observed rotation & boxy bulge

“Clumps” with $\sim 10^7 - 10^8 M_\odot$ are observed at high-z (Vanzella+2017; Johnson+2017; Dessauges-Zavadsky+2017; Cava+2018)

“Clump” = cluster of many GCs (Shapiro+2010; Bekki 2017; Elmegreen 2018)
Summary & Implications

1. Most stars in the **true** MW bulge (best found at $|bl| > 6$ deg) were provided by disrupted globular clusters!!

2. Current view on the 3D structure of the MW bulge (e.g., Wegg & Gerhard 2013) should be re-examined, as it is based on previous interpretation of double RC!

3. Early-type galaxies would be similarly prevailed by G2 & G1 originated in proto-globular clusters! (Chung, Yoon, Lee 2011, 2017; Talks by Chung & Schiavon)

   → Massive ETGs & their GCs are also CN & Na enhanced!! (e.g., Worthey 1998)

4. Gaia distances & spectroscopy can provide further test!

See also **AAS Nova**, 27 July 2018

“Red Clump Stars and the History of the Galactic Bulge”
Composite Bulge:
Bar embedded in “GC-origin Bulge”
(cf. Babusiaux et al. 2010; Hill et al. 2011; Erwin et al. 2014; Rojas-Arriagada et al. 2014, Zoccali et al. 2014; K. Saha 2015)

Latitude dependence
$\rightarrow$ Bar/Bulge = $f(b)$

Longitude dependence
$\rightarrow$ Tilted Bar embedded in Bulge

Bar: monomodal in gray
Bulge: bimodal
Bar + GC-origin-Bulge: blue

Double RC = $f(b, l)$

Lee, Joo & Chung 2015
Ness & Lang 2016: X from WISE residual map?
When an ellipsoid is subtracted from a boxy structure, an artificial X-shaped structure always remains (Han & Lee 2018)
Observed kinematics are consistent with composite bulge (Bar + GC-origin bulge)!

- **Cylindrical rotation at lbl < 6** (Ness+13; Zoccali+14): low lat. is dominated by bar

- **Some ΔVr (bRC – fRC) at b = -6** (Vasquez+13): Bar + Bulge at low lbl, & bar is in streaming motion

- **No ΔVr (bRC – fRC) at b = -8, -10** (De Propris+11; Uttenthaler+12; Rojas-Arriagada+14): Consistent with our GC-origin bulge dominated scenario at high lbl
**Observed kinematics at |b| > 6 are consistent with GC-origin bulge!**

- **Rotation at |b| > 6** (Zoccali+2014, 15..)

  (1) Empirically, metal-rich GCs show significant rotation (~168 km/s; Zinn 1985, Y.-W. Lee+2007).

  (2) Theoretically, “clump-origin bulge” (Noguchi+1999; Elmergreen+ 2008; Inoue+Saitoh 2012) naturally shows significant rotation.

  (3) Recent cosmological hydro-N-body simulations predict GC-origin bulge with rotation (e.g. Kruijssen 2015; Pfeffer+2017; Renaud+2017).

  (4) “Classical bulge” even could absorb some angular momentum from the bar (K. Saha+2012, 15).
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)
Chemical Evolution Models (J. Kim & Y.-W. Lee 2018)

Major assumptions/ingredients:

1. SN blast waves undergo blowout without expelling the leftover gas

   → Chemical evolution is dictated by AGB & WMS (winds of massive stars)

2. Star formation & enrichment 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. No “mass budget problem”
J. Kim & Y.-W. Lee 2018
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 2018).
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! (Lee, Hong, & Lim 2018)
5. The Na bimodality among bulge RGB stars! Na-rich stars are also Al-rich, which is exactly the behavior we would expect from stars originated in GCs. The Na spread in the true bulge is 2-3 times larger than that of the disk (bar) population. Population ratio $G2/G1 = \sim bRC/fRC$!
6. Our models can reproduce key observations: double RC = $f([Fe/H], b, l)$ (Lee+2015; Joo+2017)
7. Our (composite bulge) model is consistent 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 2018).
9. The observed difference in I magnitude between the RR Lyrae stars and the RC ($\sim 0.55$ 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, & RR Lyraes (Lopez-Corredoira 2016, 2017; Pietrukowicz+2015).