The formation of the Inner Milky Way

I. Observations

Manuela Zoccali
- P. Universidad Católica, Santiago
- Millennium Institute of Astrophysics
the Inner Milky Way (hereafter “bulge”)
The G. bulge is massive (~1/3 the disk)

Bulge Stellar Mass

\( M_B = 2 \times 10^{10} \, M_\odot \)  
Valenti & MZ (2016)

\( M_B = 1.5 \times 10^{10} \, M_\odot \)  
Portail+2015

\( M_B = 2.4 \times 10^{10} \, M_\odot \)  
Simion+2017

\( M_B = 1.8 \times 10^{10} \, M_\odot \)  
Cao+2013

[...]
The G. bulge is *mainly* old (\(\sim 10\) Gyr)

adapted from Renzini+2018  HST-WFC3 data

Disk foreground and/or BSS:
e.g.: Clarkson+2008  
Renzini+2018  
Surot+2019

Young/Interm age stars

e.g.: Bensby+2017  
Bernard+2018  
Schultheis+2017  
Haywood+2016

Feltzing & Gilmore (2000), Kuijken & Rich (2002), MZ+2003,  
Valenti+2013  
Barbuy+2018 for a review
The inner Milky Way hosts a bar

from Shen & Zheng 2020

known since
de Vaucouleurs (1964)

see also
Blitz & Spergel (1991)
Stanek +1994
Rattenbury+2007
...

Credit: Xing-Wu Zheng & Mark Reid BeSSeL/NJU/CFA
The main Galactic bar

Saha+2019

Red Clump

extinction corrected

Wegg & Gerhard (2013)  VVV data
The main Galactic bar

axis ratio \( \approx (1 : 0.45 : 0.30) \)
semi-major axis \( \approx 0.7 \text{ kpc} \)
angle \( \phi = 20^\circ - 30^\circ \)

see also: Cao+2013, Simion+2017, Paterson+2020

MZ & Valenti (2016) for a review
The B/P structure (X-shape)

See also:
McWilliam & MZ (2010); Nataf+2010; Saito, MZ+2011; Cao+2013; Gonzalez, MZ+2015, Ness & Lang (2016); Simion+2017; Paterson+2020
The Thin Long Bar

Wegg+2015

Patsis+2002
Athanassoula (2005)

VVV data

N-body simulations
The Thin Long Bar

VVV data

Wegg+2015

N-body simulations

Patsis+2002
Athanassoula (2005)
There are (at least) two components

MZ+2017  GIBS data

b~−1
MP/tot=0.53

b~−2
MP/tot=0.49

b~−3.5
MP/tot=0.33

b~+4.5
MP/tot=0.45

b~−6
MP/tot=0.51

b~−8.5
MP/tot=0.73

see also:
Hill+2011
Ness+2013  ARGOS
Rojas-Arriagada + 2017  GaiaESO
Rojas-Arriagada + 2020  APOGEE
The two components have different spatial distribution

**Metal poor stars (48%)**

**Metal rich stars (52%)**

MZ + 2017, 2018
MP stars are **not in a bar** (nor a B/P)

- **Red Clump**
- Extinction corrected

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**Blanco DECam Bulge Survey**

**Lim+2020**

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Johnson+2020
MP stars are not in a bar (nor a B/P)
MP stars are **not in a bar** (nor a B/P)
Two components also in \([\text{Mg/Fe}] \text{ vs } [\text{Fe/H}]\)

Rojas-Arriagada, MZ + 2019    APOGEE
The two components have different spatial distribution

Queiroz+2020  APOGEE+GaiaDR2  StarHorse
The two components have different spatial distribution

Queiroz+2020   APOGEE+GaiaDR2   StarHorse
The two components have different kinematics.
The two components have different kinematics

Rojas-Arriagada + 2020   APOGEE
The two components have different kinematics

Rojas-Arriagada + 2020   APOGEE

see also MZ+2017,   Ness+2013
(partial) Summary:

APOGEE  7900 stars
1.7°<|b|<6°

only old  
only + ?
only + ?

spheroidal  
bar + B/P  
bar + B/P

high [α/Fe]  
low [α/Fe]  
low [α/Fe]

rotates slower  
rotates faster  
rotates faster

constant σ_{RV}  
gradient σ_{RV}  
gradient σ_{RV}

Rojas-Arriagada+(2020)
(partial) Summary:

Rojas-Arriagada+ (2020)

APOGEE 7900 stars
1.7° < |b| < 6°

- only old spheroidal high $\alpha$/Fe rotates slower constant $\sigma_{RV}$

- old + ? bar + B/P low $\alpha$/Fe rotates faster gradient $\sigma_{RV}$
What can we learn from Variable Stars?

**RR Lyrae** stars: certainly $> 10$ Gyr

**Du+2020:** $\sim 12,300$ “clean” RRL in GaiaDR2 + OGLE

**Mira** variables: age / Period relation

**Grady+2020** $\sim 8,500$ O-rich Miras in GaiaDR2+OGLE+2MASS with $|b|>5^\circ$
RR Lyrae  (a pure old population)

adapted from Du+2020 and Rojas-Arriagada + 2020

see also:
Kunder + 2015, 2020
Pietrukowicz+2015
Dékány+2013
Do RRL and metal-poor RC trace the same parent population?

Probably yes. However, RRL are contaminated by the halo especially at the metal-poor, outer end of their distribution (see Du+2020 and Kunder+2020)
The Bulge $\rightarrow$ Halo Transition

Arentsen+2020 PIGS

metallicity
O-rich Miras: age slicing the inner MW

Grady+2020

**old Miras (~10 Gyr)**

**young Miras (5-7 Gyr)**
Summary

N components?

or perhaps a continuum?

- elongation
- rotation
- fast SFR
- slow
- age
- 10 Gyr
- 6 Gyr?
Summary

N components? or perhaps a continuum?

- elongation
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Red Clump Lim+2020