The WFC3 Galactic Bulge Treasury Program

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Outline

• Historical perspective
• Overview of program
• Images, photometry, astrometry
• Preliminary ages & metallicities in the bulge populations
• Metallicities of exoplanet hosts
• Implications
Bulge Formation - Historical Paradigm

Protogalactic collapse

Internal secular evolution
driven by bar instabilities, dark matter halos, bars and oval distortions, spiral structure, nuclear black holes, galactic winds & fountains, etc.

common processes
star formation, gas recycling, metal enrichment, energy feedback via SNe, etc.

Galaxy mergers, RAM-pressure stripping of gas

Environmental secular evolution
driven by prolonged gas infall, minor mergers, galaxy harassment, etc.

Kormendy & Kennicutt (2004)
Conflicting evidence

- Bulge morphology implies prolonged evolution from secular instabilities

Boxy, peanut-shaped

- Bulge populations imply rapid formation (see also Ferreras et al. 2003)

Old

Metal-rich

Alpha-enhanced

New paradigm emerging

- IFU observations of z~2 galaxies reveal large, rotating, gas-rich, disks (Genzel et al. 2008; Forster Schreiber et al. 2009)
- Gas-rich & clumpy disks prone to instabilities that can drive bulge formation faster & earlier than traditionally associated with secular processes (Immeli et al. 2004; Elmegreen et al. 2009)
Program Goals

• Map the detailed star-formation history of the Galactic bulge in four distinct windows

• Calibrate a new HST photometric system for stellar population studies, using star clusters

• Measure accurate temperatures and metallicities for tens of thousands of stars in each bulge field, including 11 exoplanet hosts

• Calculate stellar mass function of a pure bulge population as a function of metallicity and position

• Obtain proper motions in each field for bulge/disk decomposition and kinematics
Deep HST bulge observations already exist - why do we need new ones?

- Observations did not provide wide wavelength coverage
- Bands could not distinguish the effects of reddening, age, and metallicity
- Different fields observed in different bands
- Most fields have single-epoch observations (no proper motions)
Main sequence = clock

horizontal branch

RGB

subgiant branch

6 Gyr

10 Gyr

14 Gyr

turnoff

main sequence

V-I (ABMAG)

I (ABMAG)
CMD also indicates metallicity.

$[\text{Fe/H}] = -1.31$

8 Gyr
10 Gyr
12 Gyr

$[\text{Fe/H}] = -0.71$

8 Gyr
10 Gyr
12 Gyr
With only 2 bands, it is difficult to disentangle age and metallicity in a highly reddened environment like the bulge.
Reddening-free indices of temperature & metallicity

- Temperature index using: $V$, $J$, $H$

$$[t] = (V - J) - (J - H) \frac{E(V-J)}{E(J-H)}$$

$$[t] = (V - J) - 5.8 (J - H)$$

- Metallicity index using: $C$, $V$, $I$

$$[m] = (C - V) - (V - I) \frac{E(C-V)}{E(J-H)}$$

$$[m] = (C - V) - 0.9 (V - I)$$

Reddening-free indices of temperature & metallicity

\[ [t] = (V - J) - 5.8 (J - H) \ (\text{mag}) \]

\[ [m] = (C - V) - 0.9 (V - I) \ (\text{mag}) \]

\[ [\text{Fe/H}] = -0.8 \]

\[ A_V = 1.8 \ \text{mag} \]

\[ 4 \ < \ \text{age} \ < \ 14 \ \text{Gyr} \]

Reddening-free indices of temperature & metallicity

\[ [t] = (V - J) - 5.8 (J - H) \text{ (mag)} \]

\[ [m] = (C - V) - 0.9 (V - I) \text{ (mag)} \]

Reddening-free indices of temperature & metallicity

\[ [t] = (V - J) - 5.8 (J - H) \text{ (mag)} \]

\[ [m] = (C - V) - 0.9 (V - I) \text{ (mag)} \]

\[ [\text{Fe/H}] = -2.3, -1.8, -1.4, -1.1, -0.8, -0.6, -0.4, -0.2, 0.0, 0.2, 0.4, 0.5 \]

1.2 < A_v < 2.4 mag
4 < age < 14 Gyr

### WFC3 Fields

**2MASS image (Skrutskie et al. 2006)**

<table>
<thead>
<tr>
<th>Field</th>
<th>$l$ (deg)</th>
<th>$b$ (deg)</th>
<th>$R_{min}$ (kpc)</th>
<th>$A_V$ (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stanek's Window</td>
<td>0.25</td>
<td>-2.15</td>
<td>0.32</td>
<td>2.6</td>
</tr>
<tr>
<td>SWEEPS</td>
<td>1.25</td>
<td>-2.65</td>
<td>0.43</td>
<td>2.0</td>
</tr>
<tr>
<td>Baade's Window</td>
<td>1.06</td>
<td>-3.81</td>
<td>0.58</td>
<td>1.6</td>
</tr>
<tr>
<td>OGLE29</td>
<td>-6.75</td>
<td>-4.72</td>
<td>1.21</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Stanek’s Window

156x150 arcsec

6.5x6.1 pc

$R_{\text{min}} = 0.32$ kpc

$A_v = 2.6$ mag
SWEEPS

156x150 arcsec

6.5x6.1 pc

R_{min}=0.43 kpc

A_V=2.0 mag
Baade’s Window

156x150 arcsec
6.5x6.1 pc
$R_{\text{min}} = 0.58$ kpc
$A_V = 1.6$ mag
OGLE29

156x150 arcsec

6.5x6.1 pc

$R_{\text{min}} = 1.21$ kpc

$A_v = 1.5$ mag
SWEEPS

156x150 arcsec

6.5x6.1 pc

$R_{\text{min}} = 0.43 \text{ kpc}$

$A_v = 2.0 \text{ mag}$
SWEEPS CMD (motions in disk direction)
SWEEPS CMD (motions opposite disk direction)
All fields (IR)  

Brown et al. (2010, ApJL, sub.)

Stanek's Window

SWEEPS

Baade's Window

OGLE29

10 Gyr  
[Fe/H]=0

10 Gyr  
[Fe/H]=0

10 Gyr  
[Fe/H]=0

10 Gyr  
[Fe/H]=0

J - H (mag)

J (mag)
Bulge stars on upper main sequence

Stanek’s Window
- $R_{\text{min}} = 0.32$ kpc
- [t] = (V - J) - 5.8 (J - H) (mag)

SWEEPS
- $R_{\text{min}} = 0.43$ kpc
- [t] = (V - J) - 5.8 (J - H) (mag)

Baade’s Window
- $R_{\text{min}} = 0.58$ kpc
- [t] = (V - J) - 5.8 (J - H) (mag)

OGLE29
- $R_{\text{min}} = 1.21$ kpc
- [t] = (V - J) - 5.8 (J - H) (mag)
Bulge stars & isochrones on upper main sequence

\[ [m] = (C - V) - 0.9 (V - I) \text{ (mag)} \]

\[ [t] = (V - J) - 5.8 (J - H) \text{ (mag)} \]

\[ R_{\text{min}} = 0.32 \text{ kpc} \quad \text{Stanek's Window} \]

\[ R_{\text{min}} = 0.43 \text{ kpc} \quad \text{SWEEPS} \]

\[ R_{\text{min}} = 0.58 \text{ kpc} \quad \text{Baade's Window} \]

\[ R_{\text{min}} = 1.21 \text{ kpc} \quad \text{OGLE29} \]

Brown et al. (2010, ApJL, sub.)
Metal-rich exoplanet hosts in SWEEPS field

- $R_{\text{min}} = 0.32 \text{ kpc}$
- Stanek’s Window
- $[\text{Fe/H}] = +0.5$

- $R_{\text{min}} = 0.43 \text{ kpc}$
- SWEEPS

- $R_{\text{min}} = 0.58 \text{ kpc}$
- Baade’s Window

- $R_{\text{min}} = 1.21 \text{ kpc}$
- OGLE29

Brown et al. (2010, ApJL, sub.)
Implied metallicities for bulge fields

- **Stanek’s Window**
  - $R_{\text{min}} = 0.32$ kpc
  - metallicities range from $[Fe/H] = -2$ to $0$

- **SWEEPS**
  - $R_{\text{min}} = 0.43$ kpc
  - metallicities range from $[Fe/H] = -2$ to $0$

- **Baade’s Window**
  - $R_{\text{min}} = 0.58$ kpc
  - metallicities range from $[Fe/H] = -2$ to $0$

- **OGLE29**
  - $R_{\text{min}} = 1.21$ kpc
  - metallicities range from $[Fe/H] = -2$ to $0$

*Brown et al. (2010, ApJL, sub.)*
Bulge fields and metallicities

\[ [M] = (C - V) - 0.9 (V - I) \text{(mag)} \]

\[ [t] = (V - J) - 5.8 (J - H) \text{(mag)} \]

R\(_{\text{min}}\) = 0.32 kpc
Stanek’s Window

[Fe/H] = +0.5

R\(_{\text{min}}\) = 0.43 kpc
SWEEPS

R\(_{\text{min}}\) = 0.58 kpc
Baade’s Window

R\(_{\text{min}}\) = 1.21 kpc
OGLE29

Brown et al. (2010, ApJL, sub.)
Implications

- Bulge is dominated by old (10 Gyr) stars at all positions.
- Bulge exhibits declining metallicities at increasing radius.
- Preliminary analysis of bulge consistent with:
  - Classical dissipative collapse, or
  - Early, rapid evolution driven by instabilities in a gas-rich clumpy disk.
- Inconsistent with secular processes traditionally associated with peanut-shaped bulge.
- Exoplanets preferentially found at high metallicity in bulge (as in solar neighborhood; Fischer & Valenti 2005).
- Exoplanets may preferentially form in metal-rich environment.