The Bulge Radial Velocity/Abundance Assay

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My other telescope is a 0.5m... GALEX

Mira Tail  Martin, Seibert et al. 2007, Nature, 448, 780
Motivation

- “Spheroids” 50-70% of stellar mass in local Universe. (Fukugita et al. 1998)
- Lyman-break (z > 3) galaxies **metal-rich** star formation and evidence for metal-rich **winds**. Chemical evolution.
- **Epoch, population** of bulge formation?? EROs? BzK, LBG? Other?
- Unique formation history, stellar population (link to extragalactic spheroids, high Mg$_2$ index (Worthey et al. 1993)
- **Bulges host supermassive black holes**. Formation process still unknown. Related to bulge formation? (Gebhardt et al., Ferrarese et al., Ghez et al.).
- Metal rich halos are widespread: M31 (Durrell 1994, Rich 1996) other galaxies (Mouhcine et al. 2005).
- ~15 hot Jupiter transit planets discovered using HST imaging of Bulge field (Sahu et al. 2006).
Composition is a window into galaxy formation and chemical/dynamical evolution

- Type II supernovae are produced by massive stars (>8 $M_\odot$) on very short ($10^7$ to $10^8$ yr) timescales.
- Type I supernovae produce Fe-peak elements on longer ~$10^9$ yr timescales.
- Produce large amounts of the elements through the Fe-group ($Z < 31$) and probably some r-process.
- Known for high $\alpha$-element (O, Mg, Ne, Si, S, Ar, Ca, Ti) to Fe yields.
- Detailed production dependent on progenitor mass:
  - O, Mg primarily produced by $M > 25$ $M_\odot$ progenitors.
  - Si, S produced in the 15-25 $M_\odot$ range.
  - Ca, Ti through Zn produced over nearly all masses.
High \([O/Fe]\) reflects early burst of star formation

Matteucci et al. 1999

Matteucci et al. 1999

\[ [\alpha/Fe] \] vs. \([Fe/H]\) plot with data points and fitting curves.
Imelli et al. 2004 - major merger origin
Clumps dissipate rapidly into bulge

*Multiple star forming clumps might produce kinematic groups with distinct chemical fingerprints.*
UV-Luminous Galaxies in the Local Universe
(Lyman Break Galaxy Analogs)

Overzier et al. 2007
Bar dissolves due to central mass (Norman et al. 1996)

Vertical thickening of the bar into a bulge would leave no abundance gradient in the z-direction.
Do some bulges populate halos?
Do bulge debris populate halos?

Mouhcine, Ferguson, Rich, Brown, Smith 2005

Koch et al. 2007
Bulge in Context

2MASS

Oph SFR (foreground)

Sgr dSph (28 kpc)

Baade's Window

Wood et al. (1987)
Baade’s Window

- Located at \((l,b)=(-1^\circ, 4^\circ)\)
- “Low” reddening:
  \[E(B-V) = 0.45 \pm 0.10\]
  \[A_V = 1.3\ \text{to}\ 1.6\ \text{mag}\]
- Line of Sight passes
  \(~500\ \text{pc} (~1\ \text{scale length})\) from Galactic Center.
- Has been heavily studied (OGLE, low-res, etc.).
The Inner Bulge < 200 pc: A complex picture

Outside of 200 pc the bulge is dominated by old stars; bar angle ~20° (Gebhardt et al. 2002); bar has 3 kpc length

The Galactic Center region has star formation, supermassive black hole

Serabyn & Morris (1996) argue that the nuclear region is dominated by the r^-2 cusp. Launhardt et al. 2002 map it.

Nuclear region has continuous star formation but has some old stars.
the inner Galaxy: the bulge ...

structure:
- $-20^\circ < |l| < +20^\circ \Rightarrow 3 \text{ kpc}$
- $-10^\circ < b < +10^\circ \Rightarrow 1.5 \text{ kpc}$
triaxial/oblate

inner bulge (COBE-DIRBE)
- $-10^\circ < |l| < +10^\circ$
- $-5^\circ < b < +5^\circ$
boxy/peanut shaped $\Rightarrow$ barred

physical parameters:
- $L_{bol} \equiv 5 \times 10^9 \ L_\odot \ (25\%)$
- $M \equiv 2 \times 10^{10} \ M_\odot \ (20\%)$

Bar angle $\sim 20^\circ$

(See Babusiaux & Gilmore 05, reviews by Gerhard 02, new work by Benjamin (GLIMPSE))

dsurface brightness:
- power-law (large $r^{1/4}$ bulges) or
- exponential (small bulges in late type galaxies) ?

Dwek et al. 2005
Bar structure from red clump distance; Babusiaux & Gilmore 2005
Stellar Evolution in the Bulge

- PNe
- Horizontal Branch (HB)
  - RR Lyr
  - EHB
- ?? Far-UV
- Main sequence
  - ~10^10 yr
  - H-burning
- Red clump
- Red Giant Branch (RGB)
  - ~ 5x10^7 yr
- TiO bands can cause RGB tip to be faint
- AGB
  - 10^7 yr
  - (Mira, gM O)
Simple model fit (Rich et al. 07) to Zoccali et al. 2008 data at -6°
BRAVA
First proposal 2003

Strategy: Use M giants brighter than clump that can be observed even in high extinction fields

Select M giants from 2MASS survey (excellent, uniform, astrometry and photometry; ease of developing links to spectra for a public database)

Clear red giant branch easily seen in 2MASS data

Cross correlation from 7000 - 9000A (include Ca IR triplet)

Abundances from either future IR studies or from modeling of optical spectra

3x10 min exposures with Hydra fiber spectrograph at CTIO Blanco 4m; ~100 stars/field R~4000

All stars pass through K/M giant phase; avoid region of CMD with overlap from disk and nearby red clump

[Fe/H]=-1.3 and +0.5 RGB
Adjust selection for reddening
Full sample, dereddened
Sample BRAVA spectra
Fig. 2.—(l, b) distributions for the Survey fields only sample (top panel) and the Survey fields + Catalogue sample (lower panel).
Zhao (1996) self-consistent Rotating Bar model

Schwarzschild method

Surf brightness, dynamics constrain orbit families

Can populate N-body bar with particles launched according to the model prescription

Model can be modified to respond to new data
Solid body rotation not present at $-4^\circ$; Zhao model needs more retrograde orbits.
Rebinned Beaulieu data (light open crosses) show Pne agree well with rotation curve but dispersion curve low.

Pne data courtesy S. Beaulieu
Kinematics does not change with color, luminosity.
-4° velocity distributions
Larger samples have not confirmed 2 stream candidates; all candidates will be followed up. Reitzel et al. (2007) simulations suggest ~1 “real” stream candidates. Stream followup important. Possible origins from disrupted globular clusters or dwarf galaxies, groups of stars in unusual orbit families; all candidates presently assumed to be Poisson statistics caused.
Cold streams?

No coincidence with Sgr dwarf at +140 k/s

Disk l=-30; sigma 46 km
Summed and shifted data show no departure from Gaussian: No evidence of cold (disky) or hot (halo-like) subcomponents

Minor axis, \(N=822\)

Minor + \(b=-4^\circ\) major, \(N=30\)
l-v plot also shows no cold (disk) or hot (spheroid) components
New Results at -8°
The $-8^\circ$ field has a clear bulge-like population, even at the corners.
BRAVA data at -8° (1kpc): Evidence of cylindrical rotation? Also note solid-body like rotation field at -8°.

Howard et al. 2008
Contradiction: Abundance gradient in the outer bulge

Cylindrical rotation a characteristic of pseudobulges, but should not exhibit abundance gradient, since buckling models are not dissipative. Location on Binney plot similar to NGC 4565.
No minor axis rotation; more data needed

Goal: Grid of fields at 1 deg intervals, covering 10x10 deg box, pushing as close to plane as possible
Bulge Spectroscopy Before Keck

Low resolution spectroscopy; challenging due to high extinction, stellar crowding, high metallicity.

High resolution spectroscopy almost impossible (McWilliam & Rich 1994 analyzed CTIO echelle spectra of 11 giants). R=16,000, S/N=30

Galactic globular clusters, disk, and halo composition well understood; bulge remains as last frontier.
Bulge Spectroscopy After Keck

HIRES: $R=45,000$ and higher, $S/N\sim60$: metal rich giants feasible

NIRSPEC: $R=25,000$ cross-dispersed infrared echelle, opens both cool red giants and optically obscured stars

Note: NIRSPEC remains as the only cross-dispersed infrared echelle spectrograph with $R>20,000$ on an 8-10m class telescope. Need for atmospheric dispersion standard star, flat field, arcs, for each wavelength setting makes other IR echelles (Phoenix, CRIRES) far less efficient, especially for faint stars.
Sample Spectra:

Sun [Fe/H] = +0.0 Teff = 5770 K

α Boo [Fe/H] = −0.6 Teff = 4290 K

μ Leo [Fe/H] = +0.3 Teff = 4540 K
Keck Bulge Giants: Baade’s Window

II–166 \([\text{Fe/H}] = -1.8\) \(\text{Teff} = 4500\ \text{K}\)

III–152 \([\text{Fe/H}] = -0.6\) \(\text{Teff} = 4250\ \text{K}\)

I–025 \([\text{Fe/H}] = +0.4\) \(\text{Teff} = 4475\ \text{K}\)
A New Approach to Abundance Analysis

- Use the thick disk giant Arcturus, not the Sun, as the abundance standard.

- Issues like non-plane parallel atmosphere, mass loss, CN molecule opacity, etc. are similar between Arcturus and the bulge giants.

- Derive Arcturus-based gf values for weak iron lines that remain on the linear part of the curve of growth even in metal rich stars. Confirm the line list with the local metal rich giant mu Leo.

- Result: robust iron abundance scale, and confirmation of stars with [Fe/H]=+0.5

- Method also adopted by Lecureur et al. 2007.
Fulbright, McW, Rich 2006

definitive bulge iron abundance relative to Arcturus.

New linelist is usable over the full abundance range of our sample.

<table>
<thead>
<tr>
<th>Element</th>
<th>Temperature</th>
<th>$T_{\text{eff}}$</th>
<th>$m/H$</th>
<th>Fe I</th>
<th>m/H</th>
<th>Relative Intensity</th>
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<tbody>
<tr>
<td>Fe I</td>
<td>4531 K</td>
<td>+0.22</td>
<td>-1.22</td>
<td>2119</td>
<td>-1.22</td>
<td>0.32</td>
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<tr>
<td>Fe I</td>
<td>4556 K</td>
<td>-0.40</td>
<td>-0.40</td>
<td>4047</td>
<td>0.32</td>
<td>0.51</td>
</tr>
<tr>
<td>Fe I</td>
<td>4554 K</td>
<td>-1.22</td>
<td>0.51</td>
<td>1039</td>
<td>0.32</td>
<td>0.51</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wavelength (Å)</th>
<th>Relative Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>5520</td>
<td>1.2</td>
</tr>
<tr>
<td>5522</td>
<td>1.0</td>
</tr>
<tr>
<td>5524</td>
<td>0.8</td>
</tr>
<tr>
<td>5526</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Graph showing spectra with labels for elements and temperatures.
Sample Continuum Regions & Lines:

IV-003 [Fe/H] = -1.34 Teff = 4433 K

III-152 [Fe/H] = -0.46 Teff = 4157 K

I-025 [Fe/H] = +0.46 Teff = 4340 K

Fe I 6820.37  Fe I 6828.59  Fe I 6827.01
NEW [Fe/H] scale (FMR 2006) leads to.. Fulbright, McWilliam, & Rich 2007

[O/Fe]

[SiCaTi]/Fe]

[Mg/Fe]

[Al/Fe]
Confirmation: Lecureur et al. 2007

Mg confirms McWilliam & Rich 1994
What is the matter with Oxygen?

• Wolf-Rayet stars are believed to be evolved, very massive ($M > 30 \, M_\odot$) and metal-rich ($> 1/3 \, Z_\odot$).
• Extreme mass loss ($dM/dt$ up to $10^{-4} \, M_\odot/yr$) at high velocities (up to 2000 km/s). Total mass loss can be a significant fraction of the ZAMS mass.
• Occurs during He-core burning, so later burning stages are affected. Could this stop O production?
Mass loss in metal rich massive star progenitors (Maeder 1992) may explain the $[\text{O/Fe}]$ decline.

Maeder models have lower O yields, due to mass loss of outer layers, preventing He, C from being synthesized to O.

Infrared Spectroscopy of Bulge M giants
L. Origlia, E. Valenti  Bologna Obs.
Keck II with Nirspec/ echelle R=25,000, 1.6μm
Region has OH lines and Fe, Mg, Si, Ca

Origlia et al. ’02,’04,’05,’08

Extend abundance analysis to cool stars, obscured regions.
Spectrum synthesis using Johnson, Bernat, Krupp (1991) atmospheres and Origlia code

Verified using NEXTGEN atmospheres

Full error analysis Origlia & Rich 2002

Multiple OH line advantage, but other alpha element lines are on damping part of the curve of growth.

Need phot for stellar parameters
First detailed abundances of bulge M giants in Baade’s Window and (l,b)=(0,-1)


Open circles; Baade’s Window (1,-4)
Filled circles: (0,-1): no composition gradient

No gradient between fields
NGC 6791 (Origlia et al. 2006) is metal rich and has low (disk-like) alphas; why no bulge M giants this metal rich? Are most metal rich stars truncated by mass loss?
Bulge globular clusters and field stars show similar enhancement in all light elements. However, our samples lack metal rich bulge M giants (we do not see O decline).
Pushing abundance analysis toward the Galactic Center

Figer et al. 2004
Rich, Origlia, Valenti in prep.

$\log g = 0.5$, $\xi = 2$ km/s, $T_{\text{eff}} = 3800$ K

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

$[\text{O, Si, Ti/Fe}] = +0.3$

$[\text{Al/Fe} = +0.4]$
M giants appear to lack the most metal rich stars

Blue: Lecureur et al. 2007
Black: Rich, Origlia, Valenti
Is there a problem with bulge abundances?

Cohen et al. 2008 observe a microlensed metal rich ([Fe/H]=+0.51) bulge dwarf. 2 other bulge dwarfs, also microlensed, are metal rich (but 3 other bulge dwarfs are Solar and metal poor).

Cohen proposes that most metal rich giants are not present, not represented, due to mass loss.

Bulge actually has [Fe/H]~+0.3?
Figures from Cohen et al. 2008

3 added lensed bulge dwarfs from Cavallo et al. 2002
Kalirai et al. (2007) suggest that mass loss may deplete RGB in metal rich populations, helping to account for UV-bright populations. Only marginal effect and NGC 188 has Solar metallicity while 6791 is +0.4 - same RGB LF.

We disagree with Cohen et al. 2007; we believe that there is no problem with a red-giant derived abundance scale in the bulge.
Conclusions (Abundances)

1. Concluding a six year effort, Fulbright et al. (2006) develop a new iron abundance scale for the bulge. A new line list of weak iron lines, with Arcturus-based gf values, is used to verify the abundance scale at the metal rich end.

2. Fulbright et al. (2007) confirms original abundance trends (enhanced alphas) found in McWilliam & Rich (1994) are confirmed; oxygen is an enhanced but far less than Mg/Fe (analysis in progress).

3. The bulge and halo are separated in \(<\text{Ca+Si+Ti}>/\text{Fe}\) vs \([\text{Fe/H}]\)

4. \([\text{Al/Fe}]\) ranks cleanly the bulge, Solar vicinity, and Sgr dwarf.

5. New studies of M giants 100 pc from the nucleus find no abundance or composition gradient relative to Baade’s Window, but metal rich M giants are lacking.

6. We believe that K giant studies have adequately and correctly sampled bulge abundance distribution.
Hot Jupiter population discovered orbiting M dwarfs, at similar irradiation levels (but smaller orbits)

Sahu et al. 2006: Ultra-short Period Planets in the bulge
OSIRIS in M31 Bulge

M31 bulge 300 pc S of the nucleus (roughly Equivalent to the Sgr I window in the Milky Way Obtained in Hbb (1.6 um). K=16 mag giants

Spectrum synthesis (Origlia at R=3,800)