The Detailed Chemical Abundance Patterns of M31 Globular Clusters

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Motivation: Detailed Chemical Abundances

Stellar populations are key to studying galaxy formation

- Abundances of old stars trace galaxy formation histories
  - gas enrichment
  - star formation rates
  - supernovae rates/yields

But: The only large galaxy studied is the Milky Way

Individual stars are only accessible using high resolution spectra in nearby dwarf galaxies (i.e. within ~250 kpc)

\( \alpha \) elements: O, Si, Ca, Ti, Mg
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High resolution integrated light spectra (ILS) of GCs: accessible to ~4 Mpc today!
Low resolution spectra and line index techniques are powerful but
  – poor resolution in $\alpha$ and Fe at low $[\text{Fe/H}]$
  – info on other $[\text{X}/\text{Fe}]$ sparse
  – relies on calibration to local stars

Why High Resolution Spectra of Globular Clusters?


Caldwell et al (2011)

Puzia et al (2005)
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Our ILS Abundance Analysis Method

- Based on standard RGB star abundance analysis
- Use isochrones to represent entire cluster population
- Constrain Age and Z using EWs of 30-150 available Fe I lines
- Also measure 20+ $\alpha$, Fe-peak, neutron capture, and light elements!

- Demonstrated accuracy of ±0.1 dex in [Fe/H], [X/Fe]:

- Milky Way GCs with a range of [Fe/H], $\sigma_v$, $M_{v_{total}}$, HB morphology

- Large Magellanic Cloud GCs with a range in age of 0.01 Gyr to >10 Gyr
  (Colucci et al. 2011, Colucci et al. 2012, Colucci & Bernstein 2012)

***Not a calibration!***
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M31 Sample

- Data from Keck/HIRES
- Resolution ~ 24,000
- 3500-8500 Å wavelength coverage
- SNR > 60

The Clusters:
- V Magnitudes of 14-17
- Galactocentric Radii of 2-117 kpc
- Metallicities of -2.2 to -0.1
- Velocity dispersions of 6 to 30 km/s

27 GC spectra to date
Initial Results: Fascinating if true!

- intermediate ages found at high [Fe/H]
- What about Blue Horizontal Branch stars?
- What else can we learn and how can we take advantage of our unique data?

Strong constraints required better tools!
Developing Better Tools:

Two Subtleties Uncovered:

#1. Analysis of high [Fe/H] and high velocity dispersion GCs is really sensitive to line blending.

Synthesize all Fe Lines for these GCs!
BHB stars are only present in a limited range in [Fe/H] and age in the isochrones

Put in BHB ad hoc!

Two Subtleties Uncovered:

#2: high [Fe/H] and a blue horizontal branch (BHB) can affect age measurement

Developing Better Tools:

![Graph showing [Fe/H] vs Age with data points and isochrones.]

Colucci et al. (2009)

This work

Partial BHB

Complete BHB
A simple method for evaluating (missing) blue flux

Example: Milky Way GC NGC 6752

- \([\text{Fe/H}] = -1.6, 13 \text{ Gyrs}\) (i.e low \([\text{Fe/H}]\) with BHB)

- Blue Lines most sensitive to BHB

- New result: Same age, better solution!

- In M31 high \([\text{Fe/H}]\) GCs ages can be more affected
M31 Globular Cluster Fe and Age Results

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- B029: A young metal-rich GC
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- High $[\text{Fe/H}]$ GCs with BHBs!
Results: First Individual Ca, Ti, Si measurements for M31 GCs
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Beyond $\alpha$-elements!

- 10 measurements of Eu, 7 upper limits
- Knee in Eu, rising and flattening/declining Ba a signature of s-process enrichment by high metallicity AGB stars
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Stay tuned for O, Na, Al, Mg, Ni, Sc, V, Co, Mn, Cu, Cr, Y, Sr, La, Nd, Sm!

and more detailed horizontal branch morphology constraints!