Uncovering Milky Way Globular Cluster Formation and Evolution with LBC+LUCI

LBC - V, R, and I

LUCI - J, H, and Ks

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HSTPROMO Collaboration (STScI), R. van der Marel, A. Bellini, J. Anderson, L. Watkins
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Preparatory project to enable MPIA LINC-NIRVANA Key Science Project on Milky Way GCs

Aims:
- To determine GC formation histories: Did they form in-situ, or were they accreted?
- How did the multiple stellar populations arise?
- To search for evidence of IMBHs
- To investigate dynamical and stellar evolution: What is the primordial binary fraction?
  How did exotic star types arise? (e.g. blue stragglers)
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Mackey et al. 2010

Origin of galactic GCs?

Leaman, VandenBerg & Mendel (2013)

In-situ vs. accreted GCs

• GCs in disk-like orbits suspected of in-situ origin
• GCs in halo-like orbits and associated with streams suspected of accreted origin

what is the connection with MW stellar halo? and with the internal chemo-dynamics?

Leaman, VandenBerg and Mendel 2013
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Background

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Piotto et al. 2007
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   How did exotic star types (e.g. blue stragglers) arise?
Simulation of a LINC-NIRVANA (in LINC interferometric mode) observation of a MW GC

Exquisite resolution (~20mas @ K), but... spatially varying PSF... and low sky coverage
Simulation of a LINC-NIRVANA (in MCAO mode) observation of a MW GC

**BH Sphere of Influence**

- \( M_{\text{BH}} = 10^{3.5} \, M_{\odot} \) and \( \sigma = 15 \, \text{km/s} \) \( \Rightarrow N_{\text{stars}} = 131 \)
- \( M_{\text{BH}} = 10^{3.5} \, M_{\odot} \) and \( \sigma = 10 \, \text{km/s} \) \( \Rightarrow N_{\text{stars}} = 716 \)
- \( M_{\text{BH}} = 10^{3} \, M_{\odot} \) and \( \sigma = 10 \, \text{km/s} \) \( \Rightarrow N_{\text{stars}} = 72 \)

**Input/Detected Stars**

- Input Stars \( \Rightarrow N_{\text{stars}} = 1500 \)
- Detected Stars \( \Rightarrow N_{\text{stars}} = 1283 \)

Lower resolution (~50mas @ K), but ~constant PSF and can detect all H burning stars in ~a few hours for nearby GCs - perfect for studies of spatial variation in stellar populations, also high sky coverage.
Observations
Selected 6 MW GCs suitable for study with LN.

Northern Hemisphere.

Massive - so IMBH detectable if present

Suspected accreted and in-situ GCs

Range of dynamical properties - w/wo core collapse
Observations:

LBC optical imaging to study large scale distribution of exotic types, and binary fraction.
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+ LUCI imaging to accurately determine structural properties - i.e. exact centre
Observations

LBC

LUCI
Observations:

LBC optical imaging to study large scale distribution of exotic types, and binary fraction.

+ LUCI imaging to accurately determine structural properties - i.e. exact centre

+ LUCI spectroscopy to obtain LOS velocities
Preparatory Observations

LUCI J band spectroscopy of NGC 6341 red giants.

> 90 slitlets per mask, R > 8500
Preparatory Observations

LUCI J band spectroscopy of NGC 6341 red giants.

> 90 slitlets per mask, R > 8500
Confirmed velocity accuracy $<\sim 1.5\ \text{km/s}$
Observations:

LBC optical imaging to study large scale distribution of exotic types, and binary fraction.
  +
LUCI imaging to accurately determine structural properties - i.e. exact centre
  +
LUCI spectroscopy to obtain LOS velocities
  +
HST Proper motions
HST Proper Motions

8 arcmin

Uncovering MW GC Formation | Mark A. Norris | LBT Users Meeting 24/03/2014
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8 arcmin

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Notice missing coverage in central regions
LINC-NIRVANA will resolve this

8 arcmin
Two competing theories for how multiple stellar populations in GCs arise:

1. Multiple periods of star formation

2. Enrichment of lower mass protostars without new star formation.

They predict different kinematic behaviours
Figure 2:
Kinematically distinct components along the main sequence of M15.

Left: Colour magnitude diagram of M15 divided into putative 1st generation (red) and 2nd generation (blue) components. This is further divided into three magnitude bins, corresponding to mean stellar masses of 0.73, 0.64, and 0.50 M☉, labeled 1, 2, and 3, respectively.

Centre: Velocity dispersion profiles for the three magnitude bins. The dispersions of the 2nd-generation component are systematically lower at all magnitudes. In each panel, we indicate the percentage relative difference in the global values of dispersion.

Right: Normalized number count radial profiles for the 1st-generation and the 2nd-generation components. No significant differences are detected in the number count profiles of our samples.

The dispersion between the two populations can be considered as a conservative lower limit since our separation is not based on the actual identification of different populations, but only on a colour-based division criteria.

No globular cluster has previously been shown to harbour distinct kinematic components, except for a colour-dependent anisotropy for 47 Tuc indicating different dynamical properties for He-rich and He-poor stars [22]. A detailed proper motion analysis for !Cen revealed no significant kinematic difference between its multiple populations [23]. Our kinematic detection not only provides additional evidence for the presence of multiple populations in M15, but also constitutes a unique fossil record of the formation mechanism of globular clusters.
Figure 2: Kinematically distinct components along the main sequence of M15. 

Left: Colour magnitude diagram of M15 divided into putative 1\textsuperscript{st} generation (red) and 2\textsuperscript{nd} generation (blue) components. This is further divided into three magnitude bins, corresponding to mean stellar masses of 0.73, 0.64, and 0.50 M\textsubscript{☉}, labeled 1, 2, and 3, respectively.

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Right: Normalized number count radial profiles for the 1\textsuperscript{st}-generation and the 2\textsuperscript{nd}-generation components. No significant differences are detected in the number count profiles of our samples. The difference in dispersion between the two populations can be considered as a conservative lower limit since our separation is not based on the actual identification of different populations, but only on a colour-based division criteria.

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HST Proper Motions

Bianchini, Bellini, Norris, et al. (in prep)

1st generation sample has dispersion $\sim 13\%$ higher than the 2nd generation!

2nd generation is more compact!

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Figure 1: Kinematically distinct components in the Milky Way globular cluster M15. The Hubble Space Telescope images, of which a multi-colour composite is shown (credit: NASA, ESA, http://www.spacetelescope.org/images/heic1321a/), form the basis of the 37,159 proper motion measurements used in this study. Proper motions are analyzed by dividing main-sequence stars into a 1st generation (primordial component) and an enriched 2nd generation (He-enhanced component), using their observed colour. Resulting velocity dispersion maps (bottom panels) and velocity dispersion profiles (top panel) show the presence of distinct kinematics throughout the spatial extent of our sample, corresponding to a difference of 13.5% in the global values of velocity dispersion. We clearly distinguish two distinct component in the system: a dynamically-warm 1st-generation component and a dynamically-cold 2nd-generation component.

Bianchini, Bellini, Norris, et al. (in prep)
Proper Motions

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Dynamical interpretation

\[
\left(\frac{V}{\sigma}\right)_{2^{\text{nd}}} \approx 3 \left(\frac{V}{\sigma}\right)_{1^{\text{st}}}
\]

Supports the idea that GCs had multiple star forming periods - likely formed within dwarf galaxies
Observations:

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+ LUCI spectroscopy to obtain LOS velocities

+ HST Proper motions
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= Exquisitely detailed large scale dynamical and stellar population picture of each GC
Conclusions

Started preparatory and science observations with LBC and LUCI.

HST proper motions reveal the presence of kinematically distinct sub-populations
  - Supports the formation of GCs in dwarf galaxies

LN-MCAO will significantly improve the study of the inner regions of GCs

Full LINC-NIRVANA will revolutionise the study of the inner regions of GCs
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