Tracing the stellar halo with BHB stars

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Stellar Halos Across the Cosmos

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Blue horizontal branch stars in the Canada-France Imaging Survey I. The stellar halo of the Milky Way traced to large radius

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ABSTRACT
We present the stellar density profile of the outer halo of the Galaxy traced over a range of Galactocentric radii from $15 < R_{GC} < 250$ kpc by blue horizontal branch (BHB) stars. These stars are identified photometrically using $u$-band imaging from the new Canada-France-Imaging-Survey (CFIS), which reaches 24.5 mag, combined with $griz$ bands from Pan-STARRS 1, covering a total of $\sim 4200~\text{deg}^2$ of the northern sky. We present a new method to select BHB stars that has low contamination from blue stragglers and high completeness. We use this sample to measure and parameterize the three dimensional density profile of the outer stellar halo, using both a simple power-law with a constant flattening, and a flattening that varies as a function of Galactocentric radius. In the case of a constant flattening, we find that the density profile is well described by a slope of $\gamma = 3.42 \pm 0.02$ and an oblateness of $q = 1.06 \pm 0.2$, consistent with the recent result of Fukushima et al. (2017). In the case of the radius-dependent flattening, we find that the inner halo is more oblate ($q_{\text{in}} = 0.96 \pm 0.03$) than at large distance ($q_{\text{out}} = 1.25_{-0.06}^{+0.07}$), and has a power-law slope of $\gamma = 3.60 \pm 0.04$. With these two models, the profile of the stellar halo trace by BHB stars is shallower than when traced by RR Lyrae, a surprising result given the similarity of these stellar populations.

Key words: stars: horizontal branch – stars: distances – stars: statistics – Galaxy: structure – Galaxy: halo

1 INTRODUCTION
It is now generally accepted that large galaxies, like the Milky Way, have been formed by a succession of mergers and via the accretion of smaller galaxies, in a process called hierarchical formation. In the case of accretions, the smaller galaxy is disrupted due to the tidal effects generated by the larger (host) galaxy. This leads to the formation of stellar streams clearly visible around many massive galaxies of the Local Group (e.g. Martínez-Delgado et al. 2010; Martin et al. 2013; Grillmair & Carlin 2016; Bernard et al. 2016; Malhan et al. 2018). Although these structures stay spatially coherent for many Gyr (Johnston et al. 2008), they tend to be eventually destroyed by mixing effects and are in turn assimilated to form part of the “smooth” stellar halo.
CFIS & UNIONS
CFIS

- \textbf{\textit{u-band}} : 10,000 deg$^2$
- \textbf{\textit{r-band}} : 5,000 deg$^2$

\textit{Ibata et al., 2017}

- \textit{\textbf{\textit{u-band}}} : 3 mag deeper than SDSS
- $u$-band: 10,000 deg$^2$
- $r$-band: 5,000 deg$^2$

Ibata et al., 2017

- $u$-band: 3 mag deeper than SDSS
UNIONS

The Ultraviolet Near-Infrared Optical Northern Survey

- MoU between CFIS and Pan-STARRS
- u W r i z photometric bands
What is the stellar halo?

How does it form?
How was the Stellar Halo formed?

- **In-situ stars**: formed initially in the stellar halo or kicked out of the disc
  * **metal rich** ([Fe/H] > -1.0)
  * dominant < 20 kpc

- **Accreted stars**: coming from the accreted galaxies/globular clusters
  * **metal poor** ([Fe/H] < -1.0)
  * dominate the **outer stellar halo**

*Bullock & Johnston 2005*
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“...a study of these subsystems allows us partially to reconstruct the Galactic past...” Olin Eggen

Bullock & Johnston 2005
How was the Stellar Halo formed?

- **Correlation** between the **slope** of the stellar halo and the **total mass** of a galaxy
- **Correlation number** of principle **progenitors**

*Pillepich et al., 2014, 2018*
How was the Stellar Halo formed?

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Pillepich et al., 2014, 2018

- Find substructures
- Presence of substructures → bias the slope

Ibata et al., 2014
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Need accurate distance

Pillepich et al., 2014, 2018

Ibata et al., 2014
The BHB stars

How to use them as distance tracers?
The BHB stars

- The Blue Horizontal Branch stars:
  - Hot stars $7400 < T_{\text{eff}} < 9300$ K
  - Member of the Horizontal Branch

→ Accurate photometric distance
  $(5\% \text{ of precision})$
The BHB stars

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  - **Hot stars** $7400 < T_{\text{eff}} < 9300$ K
  - **Member of the Horizontal Branch**
  
  → **Accurate photometric distance**
  (5% of precision)

- **Contaminated** by the Blue Stragglers (BS)
The BHB selection with CFIS

- **Disentangle** the BHB and the BS with **hydrogen lines** sensitive to the **surface gravity**:
  - Balmer lines: *u-band*
  - Paschen lines: *z-band*
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- Bell et al., 2010 :
  74% pure and 57% complete (*ugr*)

- Vickers et al., 2012 :
  77% pure and 51% complete (*griz*)
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- **Principal Component Analysis (PCA)**
  - 75% pure and 71% complete
  - Deeper thanks to CFIS (up to 240 kpc)
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The BHB stars

Radial profile of the stellar halo
The radial profile of the BHBs

- Find the radial profile that fit the BHB distribution:

\[
p(D_i|\theta) = \frac{\rho_{\text{BHB}}(D_i|\theta) |J| S(l_i, b_i, D_i)}{\int \int \int \rho_{\text{BHB}}(l, b, D|\theta) |J| S(l, b, D) \, dl \, db \, dD}
\]
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\]

- Selection function:
  - **Footprint**
    \[S_{\text{area}}(l, b) = \begin{cases} 1 & \text{if } (l, b) \text{ in CFIS} \\ 0 & \text{otherwise} \end{cases}\]
  
  - **Distance** (15 < \(R_{GC}\) < 240 kpc)
    \[S_{\text{outer halo}}(R_{GC}) = \begin{cases} 1 & \text{if } 15 < R_{GC} < 240 \text{ kpc} \\ 0 & \text{otherwise} \end{cases}\]

  - **Presence of the Sgr stream**
    \[S_{\text{Sgr}}(l, b) = \begin{cases} 0 & \text{if } |\vec{B}| < 10.0 \text{ deg} \\ 1 & \text{otherwise} \end{cases}\]

- Contamination of compact objects

\[S_{\text{conta}}(l, b) = \begin{cases} 0 & \text{if } d_{M31} < 4.0 \text{ deg} \\ 0 & \text{if } d_{M33} < 2.0 \text{ deg} \\ 0 & \text{if } d_{NGC5466} < 0.4 \text{ deg} \\ 0 & \text{if } d_{\text{Draco}} < 0.5 \text{ deg} \\ 1 & \text{otherwise} \end{cases}\]

- Completeness

\[S_{\text{comp}}(l, b, r_{\text{helio}}) = C_z \left( z_{\text{BHB}} - z_{\text{lim}}(l, b) + z_{\text{lim, ref}} \right) \]
The radial profile of the BHBs

Two models with a single power law:

- **Constant oblateness**
  
  \[
  \gamma = 3.42 \pm 0.02 \\
  q = 1.06 \pm 0.02
  \]

- **\( q(R_{GC}) \)**:
  
  \[
  \gamma = 3.60 \pm 0.04 \\
  q_0 = 0.96 \pm 0.03 \\
  q_\infty = 1.25^{+0.07}_{-0.06} \\
  r_q = 46.4^{+12.0}_{-8.3}
  \]
The radial profile of the BHBs

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Comparison with previous results

[Graph depicting the comparison of densities with previous results from various studies.]

- Watkins et al., 2009 (RR Lyrae)
- De Propris et al., 2010 (BHB)
- Deason et al., 2014 (BHB)
- Xue et al., 2015 (K-giants)
- Slater et al., 2016 (Giants)
- Cohen et al., 2017 (RR Lyrae)
- Fukushima et al., 2017 (BHB)
- Hernitschek et al., 2018 (RR Lyrae)
- Power law (BHB)
Profile traced by the **BHB** is **closer** to the profile traced by the **giants** than by the **RR Lyraes**
Profile traced by the BHB is closer to the profile traced by the giants than by the RR Lyraes.
Conclusions

- Identified the BHBs with an unprecedented precision by their photometry.
- Radial profile of the stellar halo traced by the BHB is similar to the halo traced by the giants ...
- Traced the radial profile of the stellar halo up to ~240 kpc.
- ... but shallower than traced by the RR Lyrae.
Conclusions

● Identified the BHBs with an unprecedented precision by their photometry

● Radial profile of the stellar halo traced by the BHB is similar to the halo traced by the giants ...

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● ... but shallower than traced by the RR Lyrae

Future works

● Compare the distribution of these different populations with cosmological simulations (Auriga?) and/or the Galactic Besançon Model

● Study the dynamics of the BHBs => Mass of the MW and the 3D distribution of the DM halo at large distances
Completeness of the sample

- Assume that the limiting magnitude is not the $u$-band
- Studied the completeness of the $griz$ bands via HSC-SSP
Completeness of the sample

- Assume that the **limiting magnitude** is not the $u$-band
- Studied the **completeness** of the $griz$ bands via HSC-SSP

Limiting magnitude = $z$-band
Completeness of the sample

- Assume that the limiting magnitude is not the $u$-band
- Studied the completeness of the griz bands via HSC-SSP

Field of reference

- Used the Luminosity Function to see the spatial variation of the completeness