Deep near-IR observations of Globular Clusters: Hunting for the coolest and faintest objects in M4

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Deep near-IR HST observations designed to push beyond the end of the H-burning sequence into the regime of brown dwarfs

**Why do we want to study BDs?**

- **Not a star:** $M_{BD} < 0.07 \, M_\odot$ (?)
  - cannot sustain H-fusion
  - cool forever

- **Like a star:** formed in the same way
  - continuous extension of the stellar into the sub-stellar IMF

**But do they really form like stars??**

- **Not a planet:** $M_{BD} > 13 \, M_{\text{Jupiter}}$
- **Like a planet:** Complex atmospheres

→ BDs represent a link between lowest mass stars and planets
Why Brown Dwarfs in Star Clusters??

- Large samples of BDs are known today (SDSS, 2MASS, WISE, UKIDSS, Pan-STARRS etc., also see DwarfsArchive.org and Johnston archive)

- **But:** all of those are rather metal-rich (solar neighbourhood) or metallicity and age are unconstrained

→ determining the physical properties of BDs is difficult and the major hurdle in BD research!

Benchmark BDs at known age, distance & metallicity are crucial if we are to test and improve theories about star/BD/planet formation, evolution, and structure (atmospheres)!!

Finding BDs in **star clusters** can considerably improve the situation

→ BDs have been found in (young & metal-rich) open clusters & star forming regions (e.g. de Oliveira 2013)
Why Brown Dwarfs in Globular Clusters??

Need to find benchmark metal-poor BDs
But: Only very few halo BDs (i.e. old and metal-poor) are known

→ Globular Clusters (GCs) are old (>10 Gyr), massive and metal-poor, and might have produced large numbers of BDs!

• harbour the oldest BDs from the era of star formation in the MW
• GC MF down to and beyond the H-burning limit can tell us about:
  • IMF (universal? breaks?), BD formation
  • dynamics of GC and impact on MF
  • ...
Previous work: 1st epoch NIR CMD of M4

- Apparent/expected end of MS at F110W ≈ 24 mag
- “Best-fit” CMD ≈ 3 mag deeper and well into the BD region
  → the deepest NIR CMD of a GC to date!
- WD and BD cooling sequences cross in the NIR CMD!
Previous work: optical - 1st epoch NIR CMDs

- Photometry redone on F775 optical images: 19,900 detections
  → Proper-motion cleaned optical-nearIR CMD

- Blue: IR matches to optical WD candidates

- 4 sources without optical counterpart
  → estimated(!) F775 mag

But are they cluster members?

2nd epoch NIR observations

F775W ACS  F110W WFC3 1\textsuperscript{st}  F110W WFC3 2\textsuperscript{nd}
2nd epoch NIR observations

- All 4 former BD candidates recovered!
- BD2: only 0.05 px displacement → high-probability cluster member!

What type of source is BD2??
Is BD2 a faint, low-mass MS source?

Theoretical Predictions: The H-burning limit in M4

- Theory predicts bluer SEDs with decreasing metallicity
- Mass estimates at H-burning limit range from $0.065$ to $0.09\ M_\odot$
- No metal-poor sub-stellar models exist!
- Comparison with more metal-rich models (BT-Settl, e.g. Allard et al. 2013)
  \[ \rightarrow \text{H-burning limit } F110W \approx 24 \text{ mag} \]

\[ \rightarrow \text{BD2 too faint to be a MS star} \]

or: the faintest, coolest and lowest-mass MS star ever detected in a GC!

Is BD2 a brown dwarf? – MESA isochrones

- models (solar) predict a „gap“ between the MS and BD cooling sequence
- At the age of GCs (11, 12, 13 Gyr), this gap covers \( \approx 2 \text{ mag} \)
- A new age dating tool, independent of our knowledge of the cluster distance!

Caiazzo et al. 2017, arXiv:1702.00091

→ the first BDs should appear below F110W=26 mag in M4
→ BD2 is probably too bright to be a bona fide single BD
Is BD2 a white dwarf?  **CMDs**

Position in the optical-NIR CMDs, based on previous estimate:

- too red for a DA or He WD
Is BD2 a white dwarf? CMDs

Position in the optical-NIR CMDs, based on previous estimate:
• too red for a DA or He WD

But: we now know BD2 is a cluster member
→ position in optical image
→ aperture photometry
  \( F775 \approx 27 \pm 1 \) mag

→ position in the optical-NIR CMDs agrees more with a faint, cool (< 4500 K) WD!
Conclusions:

• We have recovered all four former BD candidates
• BD2 is a high-probability cluster member (99.55%)
• BD2 is too faint (below the estimated end of the H-burning sequence) to be a MS star in the NIR CMDs
• BD2 is probably too bright to be a bona fide BD, according to MESA…
• New optical estimate suggests that BD2 is indeed a very cool (4500 K) and faint WD at the bottom of the WD cooling sequence
What have we learned?

• Still no BD detected in a GC!

• But we are pushing into the BD regime!

• We need BD models for a range of metallicities and ages!!
  → shape of the BD cooling sequence?