Galactic Archeology With Ultracool Dwarfs

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4. Northwestern
5. Space Telescope Institute
6. U of Louisville
7. U of Delaware

Credit: R. Hurt (Caltech/IPAC)
Outline

Introduction: UCDs and Galactic Archeology

Finding UCDs in Deep Parallel WFC3 Surveys (Aganze+ 2022a)

Measuring Galactic Structure with UCDs (Aganze+ 2022b)

Looking Ahead: JWST, Rubin Observatory, Euclid and The Nancy Grace Roman Telescope (Aganze+ 2023 in prep.)
Guiding Science Questions

(1) Are the chemical compositions and kinematics of halo UCDs consistent with main-sequence FGK stars?

(2) Is the number fraction of halo/disk for UCDs similar to main-sequence FGK stars?

(3) What drives kinematic heating in the disk, does this process change with lowest-mass stars and brown dwarfs?

(4) Does metallicity affect the hydrogen-burning minimum mass?

(5) Are low-mass stars in the solar neighborhood (<100 pc) unusual?
What are Ultracool Dwarfs?

M dwarfs < 3500 K
L dwarfs < 2200 K
T & Y dwarfs < 1200 K
Jupiter 125 K

Low-mass stars and brown dwarfs (< 0.1 Msun)

The bottom end of the initial mass function (>20 % of all “stars”, Reyle+ 2021)

Image credit: Robert Hurt
What are Ultracool Dwarfs?

- **Stars**
- **Brown dwarfs**
- **Planets?**
Spectra of UCDs Show Rich Chemistry

Colder objects

Burgasser 2009
UCDs are Extremely Common

Distribution of objects within 10 pc

Reyle+ 2021
UCD Discoveries are Local (<100 pc)

Volume-limited sample within < 20 pc

UCD Discoveries are Local (<100 pc)

Credit: Adrian Price-Whelan, https://adrian.pw/aas237/
The Halo is Dominated by Accreted Populations

Koppelman+ 2018, Helmi 2020
Halo Stars Are Chemically Distinct from Disk Stars

Mackereth+ 2019
Halo UCDs Are Rare

SDSS J1256-0224 (sdL3.5)

[Fe/H] = -1.8 +/- 0.2 (Gonzales + 2021)

Radial velocity: -130 km/s
Local L Dwarfs Are Highly-Dispersed

Faherty+ 2012, Burgasser+ 2015

Hsu+2021
Why Study the Galaxy with UCDs?
Guiding Science Questions

(1) Are the chemical compositions and kinematics of halo UCDs consistent with main-sequence FGK stars?

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Part 1: Finding Distant UCDs with HST/WFC3
Distant Color-Selected Samples

HST/ACS
15 fields
28 L & T dwarfs candidates
Identification by $z$ mag and $i-z$ color

Ryan Jr. + 2005
Deep HST/WFC3 Spectroscopic Samples are Small

HST/WFC3

3 T dwarfs (identified by eye)
Distant UCDs in Deep Surveys

2 Surveys (WISPS & 3D-HST) conducted using parallel observations with the Hubble Space Telescope WFC3 Instrument with an area ~ 0.5 sq deg

Both surveys provide spectra of > 250,000 objects

Galactic Distribution of all the pointings

Atek+ 2011, Momcheva+ 2015
Data

F160W Image

G141 Spectrum
Selection by Spectral Indices
Selection by Spectral Indices

\[ \prod (\text{micron}) \]

\[ \text{Normalized Flux} + \text{offset} \]

\[ \begin{align*}
\text{H}_2\text{O} - 1 & \text{ J-cont} \\
\text{H}_2\text{O} - 2 & \\
\text{H-contCH}_4 & \\
\text{M}7.0 & \\
\text{L}5.0 & \\
\text{T}0.0 & \\
\text{T}5.0 & \\
\text{Y}0.0 & \\
\end{align*} \]

\[ \begin{align*}
\text{H}_2\text{O} & \text{ °1} \\
\text{H}_2\text{O} & \text{ °2+} \\
\text{CH}_4 & \\
\text{H-cont} & \\
\end{align*} \]

Aganze + 2022a
Selection by Spectral Indices

Aganze + 2022a
Selection by Spectral Indices

\[
\prod_{i=1}^{n} (\text{micron})
\]

Normalized Flux + offset

\[
\begin{align*}
\text{H}_2\text{O-1} & \quad \text{J-cont} \\
\text{H}_2\text{O-2} & \quad \text{H-contCH}_4
\end{align*}
\]

\[
\begin{align*}
\text{L7.0} & \quad \text{T0.0} \\
\text{T5.0} & \quad \text{Y0.0}
\end{align*}
\]

\[
\begin{align*}
\text{H}_2\text{O} & \quad \text{CH}_4
\end{align*}
\]

Aghanze + 2022a
Selection by Spectral Indices

Aganze + 2022a
Alternative: Supervised Machine Learning
Training Students to Use Machine Learning Methods

Photometric classification

Gutierezz+ 2021 (RNA), Gong + 2021 (RNA)

Finding spectral binaries

Desai+ 2022 (in prep)

10+ students from UCSD + local high schools
Training Sets & Features

Training set

\(~ 3,000\) known ultracool dwarfs spectra (SpexPrism Library, Burgasser 2014)

\(~ 150,000\) objects flagged as galaxies

Prediction set

104,346 objects flagged as point sources

Measurements: spectral indices, S/N ratio and other comparison statistics

Classes: Galaxies, early M, late M, L & T dwarfs
Random Forest

RANDOM FOREST CLASSIFIER

DATASET

DECISION TREE

PREDICTION

PREDICTION

PREDICTION

MAJORITY VOTE TAKEN

FINAL PREDICTION MADE
Selection by Artificial Neural Network
## Comparing Methods

<table>
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<tr>
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<th>M7-M9</th>
<th>L0–L4</th>
<th>L5-L9</th>
<th>T0-T4</th>
<th>T5-Y0</th>
<th>Contaminants</th>
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<tbody>
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<td>Indices</td>
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<td>21</td>
<td>5</td>
<td>7</td>
<td>3</td>
<td>3400</td>
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<tr>
<td>Random Forest</td>
<td>120</td>
<td>21</td>
<td>5</td>
<td>7</td>
<td>3</td>
<td>120</td>
</tr>
<tr>
<td>Neural Network</td>
<td>124</td>
<td>19</td>
<td>5</td>
<td>7</td>
<td>3</td>
<td>124</td>
</tr>
</tbody>
</table>
Example of Discovered UCDs

164 M7-M9 dwarfs up to \( \sim 2 \text{ kpc} \)

26 L dwarfs up to \( \sim 2 \text{ kpc} \)

10 T dwarfs up to \( \sim 500 \text{ pc} \)

Aganze + 2022a
Galactic Distribution of the Sample

Aganze + 2022a
Part 2: Measuring Galactic Structure
Measuring Structure: Monte-Carlo Simulations

- Mass Function
- Galactic Structure
- Spectral Templates
- Survey Parameters
- Local Luminosity Function
- Age Distribution
- Physical Parameters (mass, age, temperature, radius, luminosity, surface gravity, 3D-Positions)
- Binary Statistics
- Evolutionary Models
- Empirical Calibrations
- Observables (magnitude, spectral type, S/N)
- Effective Volume
- Selection Function
- Number Counts Magnitude Distribution Spectral Type Distribution
Comparison with the Local Luminosity Function

\[ \frac{dN}{dT_{\text{eff}}} [ K^{-1} \text{pc}^{-3}] \]

- B01
- B03
- SM08
- M19
- P20
- K20

T_{\text{eff}} [K]

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UCDs Pile up to Low Temperatures Due to Cooling

Burrows+ 2001
Inferring Scaleheight from Counts

$$\rho \propto \exp\left(-\frac{|Z - Z_0|}{H}\right)$$

Density in \((pc^{-3})\)

Scaleheight \((pc)\)

Vertical distance \((pc)\)

Aganze + 2022b
**Constraints on Population Ages**

Velocity dispersion in units [20 km/s]

\[ H = \zeta n \frac{\sigma^2_{20}}{\Sigma_{68}} \]

Scaleheight [pc]

Surface mass density in [68 $M_\odot$ pc$^{-2}$]

\[ \sigma(\tau) = \nu_{10} \left( \frac{\tau + \tau_1}{10\text{Gyr} + \tau_1} \right)^\beta \]

Age (Gyr)

Velocity dispersion in units [km/s]

Van der Kruit 1988, Aumer & Binney 2009, Sharma+ 2021

Van der Kruit 1988, Aumer & Binney 2009, Sharma+ 2021

Age (Gyr)

Simulated

Inferred

Subtype

M7-M9L0-L4 L5-L9 T0-T4 T5-Y0

Aganze + 2022b
We discovered a sample of 164 distant UCDs in deep spectroscopic HST surveys.

We estimate scale heights of \( \sim250 \text{ pc} \) for late Ms, \( \sim150 \text{ pc} \) for L dwarfs and \( \sim180 \text{ pc} \) for T dwarfs.

We estimate median population ages of \( \sim3.6 \text{ Gyr} \) for late Ms, \( \sim2.1 \text{ Gyr} \) for L dwarfs and \( \sim2.4 \text{ Gyr} \) for T dwarfs with additional 1-2 Gyr systematics from AVRs.

Our estimates of scaleheights and ages are consistent with predictions from evolutionary models and reveal complex age structure of UCDs in the Galactic thin disk.
Part 3: Predictions for the Next Generation of Surveys
Looking Ahead: the JWST PASSAGE Survey

124 parallel fields
Area: 500 arcmin$^2$ (0.14 deg$^2$)
F115W & F200W = 27

Expect > 100 halo dwarfs (late-M& L)

Aganze + 2022b
Euclid

Euclid J=27
Area/field=40 deg$^2$, deep fields

Expect $\sim 7000$ halo, $10^4$ thick disk

Aganze + 2023 (in prep)
The Nancy Grace Roman Telescope

The High Latitude survey
Area = 2000 deg$^2$
J = 24

Expect $\sim$1000 halo, $>10^4$ thick disk

Aganze + 2023 (in prep)
The Vera Rubin Observatory

Depths:
z= 23 (single epoch)
z= 26 (10 years)
Area/field=18,000 deg²

~ 1 mas astrometric precision

Expect >1000 halo, > $10^4$ thick disk

Aganze + 2023 (in prep)
## Comparing Surveys

<table>
<thead>
<tr>
<th>Survey/Facility</th>
<th>Advantage</th>
</tr>
</thead>
</table>
| JWST           | Spectra in multiple bands *(IR and Mid-IR)*  
*First unambiguous samples of halo UCDs* |
| Euclid         | Depth (> 5-10 kpc for L dwarfs in deep fields)  
Large survey area (>15,000 deg²) |
| Roman          | Large field of view for a single pointing (0.28 deg²)  
Large survey area (>2,000 deg²) |
| Rubin          | Large survey area (>18,000 deg²)  
Optical imaging and 1 mas arcsec precision |
Summary

We found **164 distant UCDs** in deep spectroscopic HST/WFC3 surveys.

We confirmed that **late-M dwarfs are older** than L dwarfs.

The next generation of upcoming surveys will provide **thousands of halo UCDs, tens of thousands of thick disk UCDs**, opening up a new era in galactic archeology with UCDs.
Additional Slides
Limitations of our Simulations

Lack of metal-poor templates to simulate halo and thick disk populations

Lack of metal-poor models to simulate evolution/cooling of metal-poor UCDs

Smooth models of the density structure of the MW, no consideration of asymmetries and disequilibrium
Ultracool Dwarfs as Tracers of Galactic Structure

**Pros**

- They are ubiquitous in the Galaxy (> 20% of all stars)
- They have long lifetimes (> 1 trillion years)
- Their cooling curve directly traces their age
- Fully convective, brown dwarfs probe elemental abundances from progenitor molecular clouds

**Cons**

- Intrinsically faint and cold (10^{-4} solar luminosity for the coldest dwarfs)
  - *Solution: big telescopes in the infrared*
  - Degeneracy between ages and masses
    - *Solution: model populations with Monte-Carlo simulations*
- Their cooling and evolution changes their observable properties (spectra)
  - *Solution: employ empirical calibrations based on local samples*
Disequilibrium in the Disk
RF Parameters & Metrics on Test Set

![Heatmap showing RF parameters and metrics on test set](image-url)

- Aganze + 2022a
Deep Neural Net metrics (Test Set)

CTM: 0.985 0.039 0.006 0.001 0.0 0.008
M7-L0: 0.002 0.908 0.001 0.0 0.0 0.007
L: 0.006 0.028 0.993 0.004 0.0 0.0
T: 0.002 0.0 0.0 0.994 0.096 0.0
Y: 0.001 0.0 0.0 0.001 0.904 0.0
Sd: 0.003 0.026 0.0 0.0 0.0 0.985

True Label
Evaluating Completeness and Contamination
Point Sources vs Galaxies
Selection as Function of S/N
Example Spectra

Momcheva et al. 2016

GOODSN-46-G141 16623

Image

$JH_{IR}=22.49$

2D Spectrum

2D Spectrum - Contamination

2D Spectrum - Contamination - Continuum

Spectrum

$F_x$
Scale height, Velocity Dispersion and Age

\[ \rho \propto sech^2 \left( \frac{-|Z - Z_0|}{2H} \right) \]

- **Scale height (pc)**
- **Velocity Dispersion**
- **Age**
- **Main-sequence lifetime (Gyr)**
- **Density in (pc^{-3})**
- **Scaleheight (pc)**
- **Vertical height above the plane (pc)**

Bovy + 2017
Main sequence lifetime (Gyr)

Vertical velocity dispersion (km/s)

Spectral type

Ryan Jr + 2017