Testing Models of Substellar Evolution with Dynamical Masses

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Art credit: R. Hurt (IPAC)
Main-sequence stars

Brown dwarfs

> M6

L

T

M6–L2
L2.5–L9
L9.5–T4
T4.5–T9


Masses: Leinert et al. (2001), Lane et al. (2001), Bouy et al. (2004), Zapatero Osorio et al. (2004), Simon et al. (2006), Stassun et al. (2006)*
Main-sequence stars

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\[ > \text{M6} \]


Masses: Leinert et al. (2001), Lane et al. (2001), Bouy et al. (2004), Zapatero Osorio et al. (2004), Simon et al. (2006), Stassun et al. (2006)*

\[ = \text{dynamical masses in 2007} \]
What are field brown dwarfs’ physical properties (mass, etc.)?


Masses: Leinert et al. (2001), Lane et al. (2001), Bouy et al. (2004), Zapatero Osorio et al. (2004), Simon et al. (2006), Stassun et al. (2006)*

Main-sequence stars

Brown dwarfs

> M6

M6–L2
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★ = dynamical masses in 2007
$M_{\text{tot}} = \frac{a^3}{P^2}$

$p \sim 10-20 \text{ yr}$
Cool Stars 18

Determine the orbital period probability distribution from observations.

We have developed a novel Monte Carlo technique to improve astrometric errors by a factor of 5–10 years later.

Archival data from 5 to 10 years ago enables precise orbit determination observed between discovery and our first Keck data.

In order to estimate the period probability distribution, we ran a Monte Carlo simulation of model observations, assuming the approach described in the text, we randomly drew orbital elements for 100,000 model observations.

The orbital period, and thus the monitoring scope time. The orbital period, and thus the monitoring scope time.

Companions to a young solar analog (G2V, 0.8 Sun, T5.5, Oranges inferred from model color–magnitude diagrams will be in error for such objects.

Supporting the idea that the temperature estimated from atmospheric models and evolutionary models are consistent between the atmospheric model-derived temperatures.

First dynamical mass benchmark at the L band.

Tom left: 2MASS J22062952AB is the first T dwarf binary with a dynamical mass faster with a limited amount of telescope time.

Consistency between the atmospheric model-derived temperatures estimated from model color–magnitude diagrams will be in error for such objects.

2MASS J1728+3948AB (L5+L8)

For the ultra-cool binaries, observing epochs. The distribution of periods of these orbits is the period probability distribution. This method can, but is not limited to, investigating the approach described in the text.

Orbital period probability distribution

We have re-analyzed archival data from 5 to 10 years ago and are critical for dynamical masses from visual binaries given the shortest period ultracool binaries have previously published parallaxes, so our program targeting these objects of their measured masses.

This implies that masses are likely to beerror for such objects.

We have re-analyzed archival data from 5 to 10 years ago and are critical for dynamical masses from visual binaries given the shortest period ultracool binaries have previously published parallaxes, so our program targeting these objects of their measured masses.

The method allows for a greatly expanded sample of masses.

M\text{tot} = \frac{a^3}{P^2}

P \sim 10–20 \text{ yr}

\alpha \sim 0.1”
We have developed a novel Monte Carlo technique critical for accurate orbit determination (e.g., [11], [14]).

10 years ago, improving astrometric errors by a factor of 100.

In order to estimate the period probability distribution from a single observation, one must assume that the period is the period probability distribution. This method can, but does not necessarily, result in a narrower range of orbital parameters, so our program targeting objects of their measured masses [9]. This implies that mass functions, or ages inferred from model color–magnitude diagrams will be in error for such objects.

The orbital period distribution using only the discovery epoch (black) is the period probability distribution. This method can, but does not necessarily, result in a narrower range of orbital parameters, so our program targeting objects of their measured masses [9]. This implies that mass functions, or ages inferred from model color–magnitude diagrams will be in error for such objects.

Our Keck LGS AO data combined with discovery and monitoring observations, and even with these assumptions the period probability distribution reveals incongruities, so our program targeting objects of their measured masses [9]. This implies that mass functions, or ages inferred from model color–magnitude diagrams will be in error for such objects.

\[ M_{\text{tot}} = \frac{\alpha^3 d^3}{P^2} \]

\[ P \sim 10-20 \text{ yr} \]

\[ \alpha \sim 0.1'' \]
**Orbital monitoring**

0.5 mas (median)
0.10–3 mas (90%)

$\sigma_x/x < 1\%$

**Parallax measurements**

0.9 mas (median)
0.7–1.5 mas (90%)

$\sigma_d/d < 3\%$

*Keck Laser Guide Star Adaptive Optics*

*Canada-France-Hawaii Telescope*

see poster by M. Liu (#259)
Leinert et al. (2001)  
Lane et al. (2001)  
Bouy et al. (2004)  
Zapatero Osorio et al. (2004)  
Simon et al. (2006)
Leinert et al. (2001)
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Bouy et al. (2004)
Zapatero Osorio et al. (2004)
Simon et al. (2006)
Liu et al. (2008)
Dupuy et al. (2009abc, 2010)
Konopacky et al. (2010)
Dupuy (2010 thesis)

M7−L1.5  L2−L9  T0−T5
mean in $M_{\text{Jup}}$

89  84  67  60  38
Directly Measured:

$M_{\text{tot}}$

$L_{\text{bol},1}$  $L_{\text{bol},2}$

evolutionary models

Model-derived:

$T_{\text{eff},1}$ & $T_{\text{eff},2}$

age

etc.
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<table>
<thead>
<tr>
<th>Spectral type</th>
<th>Effective temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M5</td>
<td>1000</td>
</tr>
<tr>
<td>L0</td>
<td>1500</td>
</tr>
<tr>
<td>L5</td>
<td>2000</td>
</tr>
<tr>
<td>T0</td>
<td>2500</td>
</tr>
<tr>
<td>T5</td>
<td>3000</td>
</tr>
</tbody>
</table>

Precisely calibrated temperature scale (typical error $\approx 40$ K)
Directly Measured:

- $M_{\text{tot}}$
- $L_{\text{bol},1}$
- $L_{\text{bol},2}$

Model-derived:

- $T_{\text{eff},1}$ & $T_{\text{eff},2}$
- age
- etc.

evolutionary models
Saumon & Marley (2008) "hybrid" tracks
Saumon & Marley (2008) “hybrid” tracks
$\log\left(\frac{L_{\text{bol}}}{L_\odot}\right)!$

Mass ($M_\odot$)

Saumon & Marley (2008) “hybrid” tracks

![Graph showing the relationship between measured luminosity and mass for stars of different ages. The graph includes lines for 100 Myr, 300 Myr, 1 Gyr, 3 Gyr, and 10 Gyr. There is a star indicating the measured luminosity and mass.](image-url)
How accurately can brown dwarfs with masses be used as clocks?

Saumon & Marley (2008) “hybrid” tracks
Can brown dwarfs with dynamical masses be used as accurate clocks?
HD 130948BC
- 47 AU projected separation from G1-type host star
- 790 Myr (±0.08 dex) gyro age
- [Fe/H] = 0.05
- L4+L4 spectral types

Gliese 417BC
- 1970 AU projected separation from G0-type host star
- 750 Myr (±0.08 dex) gyro age
- [Fe/H] = 0.09
- L4.5+L6 spectral types

Fig. 1.— Contour plots of our Keck LGS AO images from which we derive astrometry and flux ratios (Table 1). Contours are in logarithmic intervals from unity to 7% of the peak flux in each band. The image cutouts are all the same size and have the same native pixel scale, and we have rotated them such that north is up for display purposes.
determine the orbital period probability distribution from archival data from 5 to 10 years ago enables precise orbit determination and evolutionary models and supporting the idea that the temperature estimates from atmospheric model-derived temperatures and even with these assumptions the derived masses are consistent between the atmospheric model-derived temperatures and infrared parallax program at the Canada France Hawaii Telescope.

**HD 130948BC**
- 47 AU projected separation from G1-type host star
- 790 Myr (±0.08 dex) gyro age
- \([\text{Fe/H}] = 0.05\)
- \(L4+L4\) spectral types

**Gliese 417BC**
- 1970 AU projected separation from G0-type host star
- 750 Myr (±0.08 dex) gyro age
- \([\text{Fe/H}] = 0.09\)
- \(L4.5+L6\) spectral types
Age (Gyr)  

$L_{bol}(L_\odot)$

B component

C component

Tucson

Lyon

Models are $\approx 2 \times$ under-luminous

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Fig. 4.— Probability distributions of the difference between the system masses measured dynamically and those derived from evolutionary models using component luminosities and system gyrochronology ages for the brown dwarf binaries Gl 417BC (violet) and HD 130948BC (blue). Multiplying these two distributions gives the joint constraint (black). For both systems, the directly measured masses are systematically lower than predicted by all three models. This is an alternative way of viewing the same discrepancy shown in Figure 3, caused by model-predicted luminosities that are too low at this mass ($\approx 45–60 M_{\text{Jup}}$) and age ($\approx 800 \text{ Myr}$).

Measured masses 15%–25% smaller than expected.
Saturn is ≈2x more luminous than state-of-the-art substellar evolutionary models.
Luminosity vs. Time

L$_{bol}$ (L$_{Sun}$)

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Crossfield et al. (2014) introduced the concept of a "weather map" for brown dwarfs. Saumon & Marley (2008) noted that brown dwarfs can have cloudy weather phases, followed by cloud-free periods. Trent Dupuy (UT Austin) presented this graph at Cool Stars 18 to illustrate the temporal evolution of brown dwarfs' luminosity with age.
What is the age distribution of the brown dwarf field population?
stars (not brown dwarfs) that are on the main sequence

old (>10 Gyr)
brown dwarfs
Observed age distribution (Kaplan-Meier estimator)
constant star formation history up to 10 Gyr

Observed age distribution (Kaplan-Meier estimator)
Conclusions

> 50 ultracool dwarfs with precise dynamical masses unveil the physical properties of the field population.

Substellar evolutionary models appear under-luminous by a factor of $\approx 2$, possibly related to cloud clearing.

A novel test using brown dwarfs as clocks shows that the field population is inconsistent with a constant star formation history.