The low mass end of the (I)MF

Catarina Alves de Oliveira
1. Introduction

2. Review of low mass (I)MF studies in our Galaxy
   a. The field
   b. Open clusters
   c. Star forming regions

3. Open questions

4. Possible ways forward
Introduction
Introduction

It’s now 50 years since the theoretical prediction, but less than 20 years from the discovery of the first brown dwarfs

Oppenheimer, Kulkarni, Stauffer 1998, PP IV
“A main-sequence star is to a candle as a brown dwarf is to a hot poker recently removed from the fire”

Whitworth, Bate, Nordlund, Reipurth, Zinnecker 2007 PPV
“(…) brown dwarfs form like stars (…) on a dynamical timescale and by gravitational instability, with an homogeneous initial elemental composition, the same as the interstellar medium from which they form.”
Introduction

Discovery
- Surveys in clusters
- BDs in the field

1995
- 2MASS completed
- start of SDSS
- IRTF/VLT/NTT/Gemini

2000
- 2MASS completed start of SDSS
- Spitzer

2005
- PPV
- UKIDSS CFHTBD

2010
- WISE

Y dwarfs (~300K)

~1500 BDs

Mass functions down to planetary mass regime

today
Introduction

How do brown dwarfs fit into our current knowledge of star and planet formation?

Different from solar-type stars
- Disc fragmentation
- Ejection
- Photo-Erosion

Like solar-type stars
- Turbulence
- Gravity
The mass function: definition

\[ \frac{dN}{dM} \propto M^{-\alpha} \]

\[ \frac{dN}{d\log M} \propto M^{-\Gamma} \]

\[ \alpha = \Gamma + 1 \]
Relevance of mass function studies in the low-mass regime:

a. Shed light on the formation process

b. Probe the universality and continuity of the mass function

c. Drive census of these objects

Recent IMF reviews: Luhman (2012)
Jeffries (2012)
Kroupa et al. (2011)
Bastian, Covey & Meyer (2010)
Mass function: the field
Mass Function: the field

Galactic local field (~ Gyr) ~1300 L, T, Y dwarfs

Methodology

1. Census:
   - Photometric surveys to uncover candidates
   - Extensive spectroscopic follow-up

2. Derive space density:
   - Estimate distances (if no parallax, relations between spectral type and absolute magnitude)
   - Correct observational bias

3. Comparison to statistical model:
   - MC/Bayesian simulations of expected number of L, T, Y dwarfs based on IMF + Galactic birthrate + evolutionary models + binarity
Mass Function: the field

WISE results on the field substellar mass function
(Kirkpatrick et al. 2012, Cushing et al. 2011)

\[-0.5 < \alpha < 0.0\]

Power law may provide a poor fit
### Mass Function: the field

<table>
<thead>
<tr>
<th>Survey</th>
<th>Sample</th>
<th>Limit</th>
<th>Alpha</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>UKIDSS</td>
<td>Late T</td>
<td>Mag limited</td>
<td>$-1 &lt; \alpha &lt; -0.5$</td>
<td>Burningham et al. 2013, Pinfield et al. 2008</td>
</tr>
<tr>
<td></td>
<td>mid-L to mid-T</td>
<td>Mag limited</td>
<td>$-1 &lt; \alpha &lt; 0.$</td>
<td>Day-Jones et al. 2013</td>
</tr>
<tr>
<td>WISE</td>
<td>late-T + early-Y</td>
<td>Vol limited</td>
<td>$-0.5 &lt; \alpha &lt; 0.0$</td>
<td>Kirkpatrick et al. 2012</td>
</tr>
<tr>
<td>CFHTBD</td>
<td>L and T</td>
<td>Mag limited</td>
<td>$&lt; 0$</td>
<td>Reyle et al. 2010</td>
</tr>
<tr>
<td>2MASS/SDSS</td>
<td>T</td>
<td>Mag limited</td>
<td>$\sim 0.0$</td>
<td>Metchev et al. 2008</td>
</tr>
<tr>
<td>2MASS</td>
<td>L</td>
<td>Vol limited</td>
<td>$&lt; 1.5$</td>
<td>Cruz et al. 2007</td>
</tr>
<tr>
<td>2MASS</td>
<td>MLT</td>
<td>Vol/Mag limited</td>
<td>$+0.3 \pm 0.6$</td>
<td>Allen et al. 2005</td>
</tr>
</tbody>
</table>
Mass Function: the field

Limitations:

→ Field brown dwarfs are older, therefore, fainter
→ No mass-luminosity relation can be used directly (age)
→ Distance estimates
→ MF cannot be measured directly: requires comparison to simulations, need to assume Galactic star formation history, dependent on evolutionary models
→ Bias correction

Advantages:

→ Not affected by reddening
→ Physical properties are better understood
→ Assuming population is well mixed, devoid of foreground or background contamination
→ Larger number of nearby benchmark systems
Mass function: open clusters
Mass Function: open clusters

Open clusters (30-100 Myr) ~200 M, L dwarfs

Methodology

1. Census:
   - Surveys to uncover candidates: photometric, kinematic, youth indicators, spectroscopy
   - Assess contamination and completeness

2. Convert observables to fundamental properties:
   - Distance to cluster
   - Convert spectral type to temperature
   - Convert magnitudes to luminosity (with distance and BC correction)
   - HR diagram – convert Teff or Luminosity or both, to mass

3. Construct the IMF histogram with number of brown dwarfs per bin
Mass Function: open clusters

Pleiades (120 Myr)
# Mass Function: open clusters

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Age (Myr)</th>
<th>Alpha</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pleiades</td>
<td>125</td>
<td>0.6 ± 0.11</td>
<td>Moraux et al. 2003, Casewell et al. 2007, Lodieu et al. 2007</td>
</tr>
<tr>
<td>IC 4665</td>
<td>30</td>
<td>~0.6</td>
<td>Wit et al. 2006, Lodieu et al. 2011</td>
</tr>
<tr>
<td>Blanco 1</td>
<td>100</td>
<td>0.69 ± 0.15</td>
<td>Moraux et al. 2007</td>
</tr>
<tr>
<td>Alpha Per</td>
<td>80</td>
<td>0.59 ± 0.05</td>
<td>Barrado y Navascués et al. 2002, Lodieu et al. 2005, Lodieu et al. 2012</td>
</tr>
<tr>
<td>Praesepe</td>
<td>600</td>
<td>No variation</td>
<td>Boudreault et al. 2010</td>
</tr>
<tr>
<td>Hyades</td>
<td>600</td>
<td>BD depleted</td>
<td>Bouvier et al. 2008</td>
</tr>
</tbody>
</table>
Young open clusters MFs consistent within errors with Pleiades lognormal fit in the mass range $\sim0.030-1.0 \, M_\odot$

Little evidence for cluster-to-cluster variations
Mass Function: open clusters

Limitations:
→ Dynamical evaporation of very low mass objects
→ Contamination
→ Mass segregation
→ Uncertainty in mass-luminosity

Advantages:
→ Coeval
→ Distance and age fairly constrained
→ Uniform (low) extinction
→ Rich clusters
→ Compact on sky
Mass function: star forming regions
Mass Function: star forming regions

Young clusters (<5 Myr) ~300 M, L dwarfs

Methodology
1. Census:
   - Surveys to uncover candidates: photometric, kinematic, youth indicators, spectroscopy
   - Assess contamination and completeness
   - Correct for extinction
2. Convert observables to fundamental properties:
   - Distance to cluster
   - Convert spectral type to temperature
   - Convert magnitudes to luminosity (with distance and BC correction)
   - HR diagram – convert Teff or Luminosity or both, to mass
3. Construct the IMF histogram with number of brown dwarfs per bin
Mass Function: star forming regions

Upper Sco
Ophiuchus
Lupus
Orion
Taurus
Perseus
Chamaeleon

Planck / ESA (Galactic thermal dust emission)
### Mass Function: star forming regions

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Age (Myr)</th>
<th>Alpha</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC 348</td>
<td>2</td>
<td>0.7 ± 0.4</td>
<td>Alves de Oliveira et al. 2013, Muench et al. 2007, Luhman et al. 2003</td>
</tr>
<tr>
<td>NGC 1333</td>
<td>1</td>
<td>0.6 ± 0.1</td>
<td>Scholz et al. 2012, Winston et al. 2009</td>
</tr>
<tr>
<td>Sig Ori</td>
<td>3</td>
<td>0.6 ± 0.2</td>
<td>Peña Ramírez et al. 2012, Caballero et al. 2012, Caballero et al. 2009; Béjar et al. 2011</td>
</tr>
<tr>
<td>L Ori</td>
<td>2</td>
<td>~0.3</td>
<td>Bayo et al. 2011</td>
</tr>
<tr>
<td>ONC</td>
<td>1</td>
<td>0.3-0.6</td>
<td>Weights et al. 2009</td>
</tr>
<tr>
<td>Ophiuchus</td>
<td>1</td>
<td>0.7 ± 0.3</td>
<td>Alves de Oliveira et al. 2012, Muzic et al. 2012, Erikson et al. 2011</td>
</tr>
<tr>
<td>Cha I</td>
<td>3</td>
<td>No variation</td>
<td>Muzic et al. 2011, Muench et al. 2008, Luhman et al. 2007</td>
</tr>
<tr>
<td>Taurus</td>
<td>1</td>
<td>No Variation of BDs (but peak IMF)</td>
<td>Luhman et al. 2004</td>
</tr>
</tbody>
</table>
Mass Function: star forming regions

Bayo et al. 2011

Peña Ramírez et al. 2012
Limitations:

- Dust extinction
- Near-IR regime less sensitive to spectral type
- Significant contamination: need spectra
- Circumstellar disks
- Earlier episodic accretion
- Magnetic activity
- Temperature scale and evolutionary models

Advantages:

- Brown dwarfs are brighter when young
- Dependence on star-forming regions
- Closest to IMF
- Distance to clusters relatively well constrained
Open questions
Mass Function: summary

field: \( \alpha < 0 \)
young clusters: \( \alpha \sim 0.6 \)

\[
dN / dM \propto M^{-\alpha}
\]

\[
dN / d\log M \propto M^{-\Gamma}
\]

\[
\alpha = \Gamma + 1
\]
Open questions

Observations: substellar MFs measured from field BDs and clusters seem to differ, but are they comparable?

- Clusters: different methods / spectral typing / evolutionary models / completeness corrections

- Field: different methodology / large spread when fitting entire temperature range

Are the current results mature and accurate enough to claim a difference in the observed substellar mass function?
Open questions

Are the current results representative of our galaxy? Of other galaxies?

NASA/JPL-Caltech/R. Hurt (SSC-Caltech)
Possible ways forward
(One) Way forward

With current resources

FIELD: on-going and complementary surveys will bring a more complete characterization of the brown dwarf population in the Galaxy

CLUSTERS:  
- need for homogenization of methodology
- uniform analysis (temperature scale, evolutionary models, comparison of spectral type functions)
- spectroscopic clean samples down to the lowest mass
Future instrumentation:

- Explore distant clusters, e.g., massive star forming regions, extreme environment

- Characterize planetary mass objects (confirmation, atmospheres, ...)

- Study benchmark young binaries

- Proper motion membership, dynamics

- Extinction maps at high resolution

- Other galaxies: brown dwarfs in the LMC
Thank you.

The low mass end of the (I)MF

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