First results from the UKIDSS Galactic Cluster Survey

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Outline of my talk

1. What are in brown dwarfs?
2. Overview of techniques and searches to find brown dwarfs
3. Why do we study the substellar IMF?
4. Quick overview of the UKIDSS Galactic Cluster Survey
5. The Upper Scorpius association
6. The Alpha Per open cluster
7. The Pleiades
8. Future work and perspectives
The realms of brown dwarfs

- Brown dwarfs have masses < 0.072 $M_\odot$ at solar metallicity (Baraffe et al. 1998)
- Core temperature and pressure insufficient to ignite hydrogen
- Luminosity and temperature decrease inexorably with time
- Radii of extrasolar planets larger than those of brown dwarfs

<table>
<thead>
<tr>
<th>$M$</th>
<th>$L$ ($L_\odot$)</th>
<th>$T_{\text{eff}}$ (K)</th>
<th>$R$ ($R_{\text{jup}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.03 $M_\odot$</td>
<td>$10^{-2}$</td>
<td>2800</td>
<td>4.3</td>
</tr>
<tr>
<td>1 Myr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Gyr</td>
<td>$6 \times 10^{-6}$</td>
<td>1900</td>
<td>1.0</td>
</tr>
</tbody>
</table>

- If $M > 0.013 \ M_\odot$ brown dwarfs burn deuterium
- If $M > 0.065 \ M_\odot$ brown dwarfs burn lithium shortly
- Atmospheres composed of H, He, C, O, N
The formation of brown dwarfs

- Controversy over the formation mechanisms of brown dwarfs
  - Jeans mass in molecular clouds larger than the mass of a brown dwarf
  - Accretion should be interrupted to keep the mass below 0.072 M☉

- Proposed formation mechanisms
  - Turbulence in molecular clouds  
    Klessen (2001); Padoan & Nordlund (2002)
  - Irradiated pre-stellar cores  
  - Disk instabilities  
    Boss (1998, 2000); Li (2002); Watkins et al. (1998a, 1998b); Boffin et al. (1998)
  - Ejection of the least massive component from multiple systems  
    Reipurth & Clarke (2001)
  - Formation in circumstellar disks  
    Papaloizou & Terquem (2001)  
    Armitage & Bonnell (2002)

- Observational tests
  - Brown dwarfs and stars share the same formation mechanism in disagreement with N-body simulations  
    (Kroupa 2001)
Searches for brown dwarfs I

- First unambiguous brown dwarfs discovered in 1995
  Nakajima et al. (1995)
  Rebolo et al. (1995)
- Isolated brown dwarfs in the field

  - All-sky surveys:
    - 2MASS (Kirkpatrick et al. (2000))
    - DENIS (Delfosse et al. 1997, 1999)
    - SDSS (Fan et al. 2002; Schneider et al. 2002)
    - UKIDSS ...

  - Proper motion surveys:
    - LHS and NLTT catalogues (Luyten 1979, 1980)
    - Solar vicinity within 8 pc (Reid and collaborators)
    - Extension of the NLTT catalogue (Lépine and collaborators)
    - Calán-ESO database (Ruiz et al. 1997)
    - Our proper motion survey (Scholz et al. 2000; Lodieu et al. 2005)

- Serendipitous discoveries:
  - Cuby et al. 1999; Liu et al. 2002; Kendall et al. 2003
Searches for brown dwarfs II

- Brown dwarfs as companions to stars
  - High-resolution imaging with adaptive optics
    - Close et al. (2002, 2003); Freed et al. (2003); McCaughrean et al. (2004)
  - High-resolution imaging with the Hubble space telescope
    - Martín et al. (1999); Reid et al. (2001); Burgasser et al. (2003); Gizis et al. (2003); Bouy et al. (2003)
  - Binary fraction ~20%
  - Separations < 20 AU with a peak around 8 AU
  - Mass ratios around unity

- Radial velocity surveys
  - Mayor et al. (1992); Tokovinin et al. (1994); Mazeh et al. (1996)
  - Marcy et al. (1999), Udry et al. (2002)

=> Less than 0.5% of solar type stars have BD companions
Searches for brown dwarfs III

- **Brown dwarfs in star-forming regions:**
  - Trapezium Cluster (*Muench et al. 2002; Slesnick et al. 2004*)
  - Sigma Orionis (*Béjar et al. 2001; Barrado y Navascués et al. 2004a*)
  - IC 348 (*Luhman et al. 2003*)
  - Taurus (*Briceño et al. 2002*)
  - Rho Ophiuchus (*Luhman et al. 2000*)
  - Chameleon (*Comerón et al. 1999, 2000*)
  - Serpens (*Lodieu et al. 2002; Klotz et al. 2004*)

- **Brown dwarfs in young open clusters:**
  - Pleiades (*Martín et al. 1998; Dobbie et al. 2002; Moraux et al. 2003*)
  - Alpha Per (*Barrado y Navascués et al. 2002*)
  - IC 2391 (*Barrado y Navascués et al. 2004b*)
  - NGC 2547 (*Jeffries et al. 2004*)
  - IC 4665 (*de Wit et al. 2005*)
  - Collinder 359 (*Lodieu et al. 2005*)

=> Determination of the IMF in the substellar regime
The Initial Mass Function

- Understand the origin of stars and brown dwarfs

- Definition of the IMF:
  - Salpeter definition: \( \xi(\log M) = \frac{dN}{d\log M} \propto M^{-x} \)
  - Mass spectrum definition: \( \xi(m) = \frac{dN}{dM} \propto M^{-\alpha} \)

- Determination of the IMF:  
  - \( M > 1 \, M_\odot \): \( \alpha = 2.7 \)
  - \( M = 1-0.5 \, M_\odot \): \( \alpha = 2.2 \)
  - \( M = 0.5-0.08 \, M_\odot \): \( \alpha = 1.3 \)
  - \( M < 0.08 \, M_\odot \): \( \alpha = 0.5-1.0 \)

Kroupa 2002
New wide-field NIR survey with WFCAM on UKIRT (Lawrence et al. 2006)
- Pipeline-processed by CASU in Cambridge (Irwin et al. 2006, in prep)
- WFCAM Science Archive (Hambly et al. 2006, in prep)
- 5 components: LAS, GCS, GPS, DXS, and UDS
- Typical 5 sigma completeness limit is $K = 18.1$ mag (Vega)

Galactic Cluster Survey (GCS)
- ZYJHK observations
- 1000 square degrees
- 10 star-forming regions and open clusters
- 2 epochs in the K-band
- 5 sigma completeness limits: $Z = 20.0$, $J = 18.6$, $K = 17.5$
The Upper Scorpius association


1) Scorpius Centaurus = nearest OB association

- Area ~ 120 square degrees
- Age = 5 Myr (kinematic + isochrone fitting)
- Distance = 145 pc (Hipparcos)
- Region free of extinction (Av < 2 mag)

Blaauw (1964)

2) Previous surveys:

- X-rays studies (Walter et al. 1994; Preibisch et al. 1998, Argiroffi et al. 2006)
- Hipparcos astrometry (de Bruijne 1997)
- Deep optical (RI) surveys (Ardila et al. 2000, Slesnick et al. 2006)
- Optical (I) + near-infrared (JK) (Martin et al. 2004)
- Near-infrared (ZYJHK): UKIDSS GCS SV & EDR (Lodieu et al. 2006a, b)
Coverage in Upper Sco

Coverage based on 6.5 deg$^2$ (SV data) and 9.3 deg$^2$ (EDR data)

- △ Preibisch et al. (1998)
- ◆ Ardila et al. (2000)
- □ Martin et al. (2004)
- * Slesnick et al. (2006)
- ● Lodieu et al. (2006a, b)
Selection of members (I)

164 sources selected with $Z = 11.5\text{-}20.5$ mag

Cluster sequence well separated from field stars

Mass scale from the NextGen and DUSTY models

(Baraffe et al. 1998; Chabrier et al. 2000)
Lower-mass brown dwarfs with no Z detection can be selected from this colour-magnitude diagram: 6 new candidates (open red triangles)
Selection of members (III)

5 filters are available => rejection of photometric candidates from various colour-magnitude diagrams

- 18 candidates (squares) rejected
- 146+6 good candidates (red dots)
Proper motion selection

Photometry is usually not enough for membership assessment
=> Proper motion available from the GCS/2MASS cross-correlation

Upper Sco mean PM
(-11, -25) mas/yr

- Limit @ $J = 15.8$ mag
- 2 sigma circle selection
- 23 rejected PM non-members
- 129 good candidates

Level of contamination = 25%
Optical spectroscopy

Optical spectra (6400-8500 Å) obtained with ESO3.6-m/EFOSC2 18 photometric+proper motion selected candidates in the EDR 15 spectroscopic members and 3 non-members => 83% success

Halpha: EW = -30 to -4 Å => youth indicator
Weak NaI doublets (EW = 2-4 Å) => low gravity indicator
Initial Mass Function

We derived the IMF based on the NextGen and DUSTY models, assuming an age = 5 Myr and a distance of 145 pc.

Slope of the power law is $\alpha = 0.6 \pm 0.1$ in the $0.3-0.01 \, M_\odot$ mass range.
The Alpha Per open cluster

Properties of Alpha Persei

- Age = 90+/-10 Myr
- Distance = 182 pc
- Extinction < 0.3 mag
- PM = (23, -25.5) mas/yr
- Low galactic latitude
- Extended: 6 deg²

> KPNO/MOSA
  => 13 fields in R, I
  => ~3 sq. deg.

UKIDSS GCS DR1
=> 9 sq. deg. in ZYJHK
APer: Coverage

Red boxes: optical coverage (3 deg$^2$) in $R, I$ \cite{Barrado y Navascues et al. 2002}

Blue boxes: Infrared coverage (9 deg$^2$) in $ZYJHK$ from GCS \cite{Lodieu et al. 2006}
APer: CMDs

**Cluster Centre**
- 212,396 sources in 6.1 deg$^2$
- 963 photometric candidates

**Control Fields**
- 99,052 sources in 2.9 deg$^2$
- 389 photometric candidates
APer: Selection of candidates

A) Cluster centre
➢ 963 bright photometric candidates
➢ 192 bright proper motion members
➢ 60 (25) faint ZJ candidates
➢ 5 faint YJ candidates
➢ 4 faint JK candidates

B) Control fields
➢ 389 photometric candidates
➢ 29 bright proper motion members
➢ 35 (3) faint ZJ candidates
➢ 4 faint YJ candidates
➢ 10 faint JK candidates
APer: Luminosity function

- Cluster centre
- Centre + Control fields
- Centre – Control fields

M7/M8 gap @ J=16 mag

M/L transition @ J=17.5 mag?
APer: Mass function

- Cluster centre
- Centre + Control fields
- Centre – Control fields

M7/M8 gap @ $M \sim 0.08$ Msun

M/L transition @ $M \sim 0.04$ Msun

$=> \alpha = 0.35 +/- 0.20$ in the 0.3-0.03 Msun mass range
The Pleiades

Lodieu, Dobbie, Hodgkin, Hambly, Jameson, Moraux, Bouvier
Pleiades: overview

- $d = 130$ pc
- Age = 125 Myr
- $E(B-V) = 0.03$
- PM = (+19.7,-45.5) mas/yr

Teide+Calar (*Rebolo, Martin, Zapatero Osorio*)

SuperCOSMOS (*Deacon & Hambly 2004*)

CFHT (*Bouvier, Moraux*)

INT (*Dobbie, Pinfield, Jameson*)

and many other surveys...
Pleiades: selection of candidates (I)

- 97158 sources in 12 sq. deg.
- 0.5-0.03 Msun mass range

- 1095 bright photometric cand
  - 518 PM members
  - 31 PM NM
  - 542 photometric NM

- 105 faint ZJ cand
  - 19 PM members
  - 35 photometric members
  - 8 PM NM
  - 43 photometric NM
Pleiades: selection of candidates (II)

22 faint YJ cand
- 5 PM members
- 8 photometric members
- 2 PM NM
- 6 photometric NM

25 faint JK cand
- 1 PM members
- 7 photometric members
- 6 PM NM
- 11 photometric NM
Pleiades: coverage

GCS coverage: 12 sq. deg.

CFHT + INT coverage

=> Large number of stellar and substellar with accurate optical-to-infrared proper motions
Pleiades: proper motion

239 out of 1200 photometric candidates are common to the optical (INT+CFHT) and GCS.

Pleiades cluster well defined

Proper motions available from the 2MASS/GCS cross-correlation down to $J = 15.8$ mag (60 Mjup)
Pleiades: binary fraction

Selection of photometric multiple systems from the \((Y-K, Y)\) CMD

\[
BF = \frac{N_B}{N_S + N_B} = \frac{40}{65+40} = 38\%
\]

- 26 single stars with PM
- 24 binary systems with PM
Pleiades: IMF

- $d = 130$ pc
- Age = 125 Myr
- No reddening correction

- Total number of candidates is 534
- About 100 BDs
- J = 12.0-20.0 mag
- Mass range = 0.52-0.025 Msun
- Lyon group models
- 1 mag bin by steps of 0.5 mag
- Correction for binarity

IMF: all cand (filled circles) single stars only (squares)
Future plans and outlook

1) The Upper Sco cluster

- The full Upper Sco association will be covered by the GCS
- 2\textsuperscript{nd} epoch in $K$ to get proper motion for all candidates
- Spectroscopic follow-up with AAT, ESO 3.6-m, and VLT
- Spectroscopic follow-up with Gemini/GNIRS
- Deeper optical $Z$ data to find lower-mass brown dwarfs
- VLT NACO LGS for planetary-mass binaries
- Study \textit{accretion} and \textit{variability} timescale (Jayawardhana, Mohanty et al.)

2) Pleiades and Alpha Per

- Full coverage after 7 years by UKIDSS GCS
- Spectroscopic follow-up with Gemini/GNIRS
- Deeper optical $Z$ data to find lower-mass brown dwarfs
- VLT NACO LGS for brown dwarf binaries
The power of the GCS

Upper Scorpius

s Orionis

Pleiades

A Persei