Direct imaging and Spectroscopy of Exo-Planets

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www.exoplanet.de  www.astro.uni-jena.de
Friedrich-Schiller-Universität Jena
The brown dwarf desert: 20 to 50 Jup masses

Objects below \( \sim 35 \) Jup masses form differently, i.e. planets …
Objects with mass below 13 Jupiter masses are planets (non-fusors), if born in orbit around a fusor.
Neuhäuser, …, Hauschildt A&A 2005

Chauvin et al. 2005

Subaru CIAO L-band 2002

New companion candidates

c1

c2

paper in preparation
Determination of mass

By comparison with evolutionary models & tracks (hot start)

Observables:
Luminosity $L$
Temperature $T$
Gravity $\log g$
Radius $R$
Age (of host star)

Model yields mass of the companion

Example given here:
GQ Lup b and Burrows et al. 1997 models
$\Rightarrow$ 20-25 M$_{jup}$ (4 to 36 M$_{jup}$), figure from Andreas Seifahrt PhD thesis (red: 25 Jup)
Calibrating tracks with eclipsing double-lined brown dwarf – brown dwarf binary (2M0535 in Orion region, i.e. few Myr)

→ Masses from Kepler 3rd law:
  
  A has 59.5 \ 4.8 \text{ M}_{\text{jup}} \text{ but spots}
  
  B has 37.5 \ 2.9 \text{ M}_{\text{jup}}

(Stassun et al. 2007 Nat. & ApJ)
<table>
<thead>
<tr>
<th>Object name</th>
<th>Luminosity log(L$<em>{bol}$/L$</em>{D}$)</th>
<th>Magnitude $M_K$ [mag]</th>
<th>Temperature $T_{eff}$ [K]</th>
<th>Age [Myr]</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>2M0535 A</td>
<td>$-1.65 \pm 0.07$</td>
<td>$5.29 \pm 0.16$</td>
<td>$2715 \pm 100$</td>
<td>0.1-3</td>
<td>Stassun 07</td>
</tr>
<tr>
<td>B</td>
<td>$-1.89 \pm 0.07$</td>
<td>$5.29 \pm 0.16$</td>
<td>$2820 \pm 105$</td>
<td>0.1-3</td>
<td>Stassun 07</td>
</tr>
</tbody>
</table>

Directly detected planet candidates:

<table>
<thead>
<tr>
<th>Object name</th>
<th>$L$</th>
<th>$T$</th>
<th>$K$</th>
<th>Age</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>DH Tau b</td>
<td>$2.75 \pm 0.10$</td>
<td>$3.11 \pm 0.23$</td>
<td>$2750 \pm 100$</td>
<td>0.1-4</td>
<td>Itoh 05</td>
</tr>
<tr>
<td>GQ Lup b</td>
<td>$-2.38 \pm 0.25$</td>
<td>$7.67 \pm 0.26$</td>
<td>$2650 \pm 100$</td>
<td>0.1-3</td>
<td>Neuh. 05</td>
</tr>
<tr>
<td>2M1207 A</td>
<td>$-2.76 \pm 0.05$</td>
<td>$8.35 \pm 0.05$</td>
<td>$2425 \pm 100$</td>
<td>5-12</td>
<td>Chau. 05a</td>
</tr>
<tr>
<td>b</td>
<td>$-4.75 \pm 0.06$</td>
<td>$13.33 \pm 0.12$</td>
<td>$1690 \pm 280$</td>
<td>5-12</td>
<td>Chau. 05a</td>
</tr>
<tr>
<td>AB Psc b</td>
<td>$-3.76 \pm 0.06$</td>
<td>$10.85 \pm 0.11$</td>
<td>$2940 \pm 100$</td>
<td>20-40</td>
<td>Chau. 05b</td>
</tr>
<tr>
<td>CT Cha b</td>
<td>$-2.68 \pm 0.21$</td>
<td>$8.83 \pm 0.50$</td>
<td>$2600 \pm 250$</td>
<td>0.1-4</td>
<td>Schmidt 08</td>
</tr>
<tr>
<td>1RXS J1609 b</td>
<td>$-3.57 \pm 0.15$</td>
<td>$10.38 \pm 0.35$</td>
<td>$2750 \pm 100$</td>
<td>0.1-4</td>
<td>Schmidt 08</td>
</tr>
<tr>
<td>HR 8799 b</td>
<td>$-5.1 \pm 0.1$</td>
<td>$12.68 \pm 0.11$</td>
<td>$2900 \pm 100$</td>
<td>30-1000</td>
<td>Mar. 08</td>
</tr>
<tr>
<td>c</td>
<td>$-4.7 \pm 0.1$</td>
<td>$11.74 \pm 0.09$</td>
<td>$2900 \pm 100$</td>
<td>30-1000</td>
<td>Mar. 08</td>
</tr>
<tr>
<td>d</td>
<td>$-4.7 \pm 0.1$</td>
<td>$11.56 \pm 0.26$</td>
<td>$2900 \pm 100$</td>
<td>30-1000</td>
<td>Mar. 08</td>
</tr>
<tr>
<td>Fom b</td>
<td>$\leq -6.5$</td>
<td>$M_K \geq 23.5$</td>
<td>$100-300$</td>
<td></td>
<td>Mar. 08</td>
</tr>
<tr>
<td>$\beta$ Psc b</td>
<td>$M_K = 9.8 \pm 0.3$</td>
<td>$8-20$</td>
<td></td>
<td></td>
<td>Lagr. 09</td>
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</table>

Model derived masses:

<table>
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</thead>
<tbody>
<tr>
<td></td>
<td>(L, age)</td>
<td>(L, T, K, age)</td>
<td>(L, T, K, age)</td>
<td>(≥ 10 Jup)</td>
<td>(≥ 10 Myr)</td>
</tr>
<tr>
<td>2M0535 A</td>
<td>50 (45-60)</td>
<td>55 (30-60)</td>
<td>50 (45-60)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>27 (32-46)</td>
<td>46 (40-60)</td>
<td>43 (40-65)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

true 37.5 jup

Itoh et al. Subaru

(Schmidt, RN, Seifahrt, Conf. Proc., astro-ph)
HR 8799

Keck H-band July 14, 2004UT

Keck JHK-band (July-Sept. 2008)

Gemini CH4S Oct. 17, 2007UT

b 1.73" = 68 AU

c 0.95" = 38 AU

d 0.63" = 24 AU

Marois et al. 2008
SED and disk around HR 8799

Companions and dust rings stable, only if masses are low, hence planets.

Inner ring at 3 to 15 AU.

(Reidemeister, Krivov, …, Neuhäuser 2009 A&A 503, 247)
(Close et al. 2007)

Unstable?  
stable  
stable  
stable  
unstable?
(Schmidt, Neuhäuser, Seifahrt, 2009, AIP Conf. Proc. 1158, 231, also on astro-ph)
CT Cha (< few Myrs)

Sep = 2.67 arc sec
440 AU at 165 pc
Common proper motion!

Schmidt, Neuhäuser, Seifahrt, … Hauschildt 2008 A&A
Schmidt, Neuhäuser et al. 2009 Cool Stars XV Proceedings
Problem:
Hot-start model tracks may not be valid for objects younger than ~ 10 Myrs.
CT Cha b
and Drift-Phoenix
(Helling, Hauschildt):

\[ T = 2600 \text{ K} \quad 250 \text{ K} \]

\[ A_V = 5.8 \quad 0.8 \text{ mag} \]

**Log g = 4.0 \quad 0.5 \text{ dex}**

⇒ Mag, \( A_V \) and distance
give luminosity \( L \)

⇒ \( L \) and \( T \) give radius
\(~ 2.2 \quad 0.7 \text{ R}_\text{jup} \)

Schmidt, Neuhäuser, Seifahrt, … Hauschildt, 2008 A&A
GQ Lup: VLT / Sinfoni JHK-band spectra: R=4000, S/N > 100

Effective temperature $T = 2650 \pm 100$ K and surface gravity $\log g = 3.7 \pm 0.5$ dex

$Lum. L$ and $T$ give radius: $3.5 \ R_jup$ ($2.5 – 5.0 \ R_jup$)

$Log g$ and radius give mass: $4$ to $36 \ M_jup$ (upper mass limit as compared to eSB2 BD 2M0535)

[McElwain et al. 2007 and Marois et al. 2007: 5 to 40 M_Jup]


Compare to Hauschildt GAIA model (synthetic spectra)
Conclusion:
Given the age ranges and all models, Planet status is dubious in all cases but maybe Fomalhaut b and HR 8799 bcd.

Problem:
Hot-start models differ a lot and may not be valid below ~ 10 Myrs.

Solution:
Fitting higher-resolution spectra to model atmospheres ⇒ T, Av, and g Mag, Av, and distance give luminosity L L & T give radius R then R & g give mass

Problem here:
Gravity determination not yet precise enough (0.5 dex).

Direct imaging planets can constrain and probe

⇒ Planet formation time-scale (youngest star with planet)
⇒ Migration scenarios (most exo-Jupiters at snow line?)
The disk around classical T Tauri star CT Cha (companion at 440 AU separation)

New recent detection of CT Cha with ATCA at 3 mm (93 & 95 GHz), 7.2 mJy total, 5 mJy peak (Schreyer et al., in prep.)
Another classical T Tauri star with sub-stellar companion (planet or brown dwarf) and with IR excess, i.e. (gas) disk. 

GQ Lup

Strong IR excess in both CT Cha and GQ Lup ➔ massive large disks (?) ➔ wide sub-stellar companions could form in disk instability (?)

Disk inclination ~ 22 to 32 deg (Broeg et al., Hügelmeyer et al.)
Summary:

- Direct detection of planets is possible (wide separations)
- Mass determination still very challenging (model dependent)
- JHK spectra and model atmospheres yield T, g, R, then mass
- Direct imaging of young planets can constrain planet formation time-scale and migration theories
NB 1:

PZ Tel – new brown dwarf companion

JHK colors give spectral type (late M) ➔ brown dwarf of ~ 40 Jup masses (at age and distance of host star)
PSF subtraction

PZ Tel B @ 0.3'' (15AU)

NB 2:

Planet transit observations in Jena
90-cm telescope in Großschwabhausen (GSH) near Jena

Three telescopes with four instruments for imaging, photometry, Lucky Imaging, and spectroscopy
Wasp-10: 9 light curves of 8 transits from 4 different observatories

Relative photometry rms +/- 1.1 to 2.7 milli-mag
Mid-transit times error +/- 18 to 45 sec  Maciejewski et al. 2010b MNRAS in press
Wasp-10: 2 different frequencies: $f=0.183/P$ (poor) and $f=0.175/P$ (good) i.e. $5.473 \times P_b (=5:3 \text{ MMR})$

Period $P_b = 3.09$ days

Maciejewski et al. 2010b MNRAS in press
Wasp-10: after removing Wasp-10b from RadVel data, one new frequency: 12 days (rotation period of star)

12 day rotation period also seen in WASP photometry (Christian et al. 2009)

Peak-to-peak photometric variation ~ 20 milli-mag, typical for spotted star

Gyro-chronology: 12 day rotation for K5 dwarf star gives Age 200 to 350 Myrs (intermediate between Pleiades and Hyades)

i.e two quite young planets

Youth can also explain the large radius of Wasp-3b (1.3 Jup radii for 3 Jup masses) a 10% effect!

Maciejewski et al. 2010b MNRAS in press
Wasp-10: TTV best explained by additional planet Wasp-10c with 0.1 Jup mass in outer 5:3 MMR with 5.23 day period

(Wasp-10b: 2 Jup mass With 3.09 day period)

Maciejewski, Dimitrov, Neuhäuser, ..., Tachihara, Takahashi, ... 2010b MNRAS in press
Young Exo-planet Transit Initiative (YETI)

network of telescopes at all longitudes to observe 24 / 7 in order not to miss a transit
Gunma Astronomical Observatory

- 1.5-m telescope
- Kengo Tachihara et al.
Transit search in young clusters started with Schmidt Teleskop Kamera (STK) at 90 cm: Few Myrs cluster Trumpler-37 with 18000 stars.

Other clusters later.

Other telescopes around the world are participating to cover all longitudes to observe 24 / 7.
IRCS+AO188 Observation

Quick Recap

2MASS 21385604+5711345

0''.3

20mas Camera (H-band; 3''.15x3''.15)

Rad Vel follow-up with Keck on 26 & 28 Feb 2010
Summary:

- Direct detection of planets is possible (wide separations)
- Mass determination still very challenging (model dependent)
- JHK spectra and model atmospheres yield T, g, R, then mass
- Direct imaging of young planets can constrain planet formation time-scale and migration theories

- New brown dwarf companion found to PZ Tel

- Planetary Transit Timing Variations find new planets in Wasp-3 & -10

- Young cluster monitoring to find very young transiting planets