Direct detection of sub-stellar companions in young stars with disks

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Topics:

- Homogeneous mass determination of planet candidates imaged directly
- Stability of star + planet(s) (+ disk) systems, in particular HR 8799
- Sub-stellar companion and disk around CT Cha (new 3mm data)
The brown dwarf desert: 20 to 50 Jup masses

Lineweaver & Grether 2006

Objects below ~ 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.
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 $M_{\text{jup}}$ (4 to 36 $M_{\text{jup}}$), figure from Andreas Seifahrt PhD thesis (red: 25 $\text{Jup}$)

(Burrows et al. tracks for masses 10 to 70 $M_{\text{jup}}$)
Masses from Kepler’s 3rd law:

A has $59.5 \pm 4.8 \text{ M}_{\text{Jup}}$ but spots

B has $37.5 \pm 2.9 \text{ M}_{\text{Jup}}$

(Stassun et al. 2007 Nat. & ApJ)
**Observables:**

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<tbody>
<tr>
<td>2M0535 A</td>
<td>-1.68 ± 0.07</td>
<td>5.29 ± 0.16</td>
<td>2715 ± 100</td>
<td>0.1-3</td>
<td>Stromun 07</td>
</tr>
<tr>
<td>B</td>
<td>-1.83 ± 0.07</td>
<td>5.29 ± 0.16</td>
<td>2820 ± 105</td>
<td>0.1-3</td>
<td>Stromun 07</td>
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**References:**

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

**Model derived masses:**

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<tr>
<td></td>
<td>(L, age)</td>
<td>(L, T, K, age)</td>
<td>(L, T, K, age)</td>
<td>(≥ 20 Jup)</td>
<td>(≥ 10 Myrs)</td>
</tr>
<tr>
<td>2M0535 A</td>
<td>80 (45-60)</td>
<td>85 (30-80)</td>
<td>80 (45-80)</td>
<td></td>
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<tr>
<td>B</td>
<td>87 (35-45)</td>
<td>45 (40-50)</td>
<td>48 (41-65)</td>
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**Directly detected planet candidates:**

<table>
<thead>
<tr>
<th>System</th>
<th>Mass [M⊕]</th>
<th>Age [Myr]</th>
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<tr>
<td>AB Pmc b</td>
<td>-3.76 ± 0.06</td>
<td>20.80 ± 1.0</td>
</tr>
<tr>
<td>CT Cha b</td>
<td>-2.68 ± 0.21</td>
<td>1.05 ± 0.3</td>
</tr>
<tr>
<td>1RXSJ1890 b</td>
<td>-3.87 ± 0.15</td>
<td>3.48 ± 0.03</td>
</tr>
<tr>
<td>HR 8799 b</td>
<td>-6.7 ± 0.1</td>
<td>1.20 ± 0.01</td>
</tr>
<tr>
<td>Poin b</td>
<td>-6.5</td>
<td>Mar 08</td>
</tr>
<tr>
<td>π Psc b</td>
<td>-9.8 ± 0.03</td>
<td>5.20</td>
</tr>
</tbody>
</table>
HR 8799

Keck H-band July 14, 2004UT

Gemini CH4S Oct. 17, 2007UT

Keck JHK-band (July–Sept. 2008)

b 1.73" = 68 AU

c 0.95" = 38 AU

d 0.63" = 24 AU

Marois et al.
2008
Inner ring at 3 to 15 AU.

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

(Reidemeister, Krivov, …, Neuhäuser 2009 A&A 503, 247)
unstable?
CT Cha (< few Myrs)

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

Schmidt, Neuhäuser et al. 2009 Cool Stars XV Proceedings

Schmidt, Neuhäuser, Seifahrt et al. 2008 A&A
Problem:
Hot-start model tracks may not be valid for objects younger than ~ 10 Myrs
CT Cha b
and Drift-Phoenix:

T = 2600 K ± 250 K

A_V = 5.8 ± 0.8 mag

Log g = 4.0 ± 0.5 dex

Mag, A_V and distance give luminosity L

L and T give radius
(~ 2.2 ± 0.7 R_jup)

L, T, R, and g give mass:
~ 17 ± 6 M_Jup

(planet or BD?)

Schmidt, Neuhäuser, Seifahrt et al. 2008 A&A
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 and with IR excess, i.e. (gas) disk

Strong IR excess in both CT Cha and GQ Lup

\( \Rightarrow \) massive large disks (?) \( \Rightarrow \) wide sub-stellar companions could form in disk instability (?)
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 ?)
Rotation period of GQ Lup A

4 week monitoring with 8 min/night at CTIO (2005)

(8.41 day period, but only one spot.

Rotation period, v sin i, and radius
(from Stefan-Boltzmann law with luminosity and temperature)
yield inclination of GQ Lup A (and its disk) to be ~ 27 ± 5 degrees from pole-on
(26 to 39 deg, if up to half the luminosity is from disk accretion).

(Broeg, Schmidt, Guenther, Gaedke, Bedalov, Neuhäuser, Walter, 2007, A&A)
GQ Lup observed with CRIRES, compared to radiative transfer Disk model, gives 22 deg disk inclination (Hügelmeyer et al. 2009 A&A)

At inner disk at 0.052 to 0.5 AU, Accretion rate 3e-9 Msun / yr
Large radio beams

The beam size of APEX: 18″!
Results

(1) APEX

Map in CO 3-2
(total integrated line emission)

with:
CO/H$_2$ = $10^{-4}$,
$T_{\text{ex}} = 15...25$ K,
$\tau \approx 1...10$,
$D = 140$ pc

$\Rightarrow M_{\text{gas}} \approx 0.15$ $M_{\odot}$
Result

(2) ATCA

3mm continuum
DSS image

primary beam

3σ & 4σ rms

GQ Lupi

Schreyer et al.
Results: SED

SED     GQ Lupi System

Overestimate of the cold dust component of the GQ Lupi system

Result: The 38mJy by D. Nürnberger
- does not stem from the GQ Lupi System.
- but is the total integrated cloud emission as in case of the IRAS measurements

Schreyer et al.