Orbital Motion and Multi-Wavelength Monitoring of LkCa15 b

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LkCa 15 A+b: K. Teramura (UH/IfA)
Young planets are primordial
Planets migrate based on interactions with the protoplanetary gas disk (left; Armitage & Rice 2005) or other planets and planetesimals

Young planets are bright(er)
Hot start or cold start aside, young planet should be orders of magnitude brighter (below; Marley et al. 2007; Baraffe et al. 2003).

BUT: Young Stars are far away (5AU=0.05")
Correct the turbulence introduced by the atmosphere, and hence concentrate the light of the primary star away from the planet.
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Solution: Maybe LOCI?

- At larger separations (~4 times the diffraction limit), Angular Differential Imaging and “LOCI” have been very successful.
- But a speckle at \((x,y)\) has amplitude \(
|E_0(x,y) + E_\sigma(x,y)|^2\)
  \(,\) with

  \[
  E_\sigma = \mathcal{F} \left[ \varepsilon(u,v) \right]
  \]

- Speckles are \textit{first-order} in pupil-plane phase errors \(\varepsilon\).
Solution: Maybe Coronagraphy?

- Coronagraphy eliminates the off-axis diffraction-limited electric-field $E_0$.
- Errors are *second-order* in pupil-plane phase-abberation $\varepsilon$... if the coronagraph is perfect.

(From Sivaramakrishnan et al 2001)
Solution, Part 2: Kernel Phase

There is always more phase information in the \((u,v)\)-plane than the pupil-plane. This information is the Kernel-Phase (Martinache 2010) and is \textit{third-order} in phase errors.

At least \textit{half} of the Fourier phase info. is independent of pupil phase (1\textsuperscript{st} order)

\[
\Phi_F = A \cdot \Phi_P
\]
Nonredundant Mask Interferometry (NRM): Place an aperture mask in the pupil plane, turning the single mirror into a sparse array.

(A. Kraus talk on Friday for more details including large surveys….)
Kernel-Phase Versus SAM/NRM
Poor Strehls: Aperture-Masking Wins

NGAO or L/M bands: Kernel-phase wins
Back to Astronomy...
Following the Signposts of Planet Formation

If we’re going to find planets anywhere, transitional disks are the places to look!

Observe at reddest possible wavelength (L’), and invest 4+ hours per target. We want to hit the contrast limit of our current capabilities.
One of the best-studied transitional disks –
A ~50 M\textsubscript{J} disk, a ~46 AU gap, a 1 M\textsubscript{\odot}, 2-3MYr star.

Andrews et al. (2011)
SMA, Sub-mm Image
(Dusty Outer Disk)

Thalmann et al. 2010
HiCIAO, H-band Image
(Interpreted as inner Disk Wall)
K&I 2012: Image Reconstruction

LkCa 15 disk

50 AU

Andrews et al. (2011)
SMA, Sub-mm Image
Dusty Outer Disk

LkCa 15 b

11 AU (76 mas)

(Deprojected radius ~20 AU)

Reconstructed Multicolor Image
Blue=K’, Red=L’
Planet + Co-orbital material?

Planet + Co-orbital material?
New Observations

Poor weather since 2010 has meant different filters taken at different times...

<table>
<thead>
<tr>
<th>Date</th>
<th>Filters</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008 Dec</td>
<td>K (shallow)</td>
</tr>
<tr>
<td>2009 Nov</td>
<td>L</td>
</tr>
<tr>
<td>2010 Nov</td>
<td>K,L</td>
</tr>
<tr>
<td>2012 Jan</td>
<td>H,M</td>
</tr>
<tr>
<td>2012 Aug</td>
<td>L</td>
</tr>
<tr>
<td>2012 Dec</td>
<td>K,L</td>
</tr>
</tbody>
</table>
H-band (Jan 2012, nearly 6 hours)

$\Delta = 7.2$ mag (noise peak)

Window Function
M-band (Jan 2012)

- Kernel-phase (full pupil) imaging
- Contrast $\Delta = 3.5$ mag
- $\sim 80$ milli-arcsec arc similar to L-band
Orbital Motion? (K’ filter)

~6 degrees/year motion (3-4 degrees deprojected) – consistent with Keplarian rotation (~100 year period for 1 M☉, 20 AU).
Orbital Motion

- Imaging with super-resolution has artifacts: better to fit.
- For epochs fit well by 3 additional point-sources, all show clockwise rotation.
- 4 out of 6 blob/colour combinations are statistically significant (up to 10 sigma)
Orbital Motion + CO 2-1

Simon et al (2001), IRAM

Image Rotation + Doppler velocities uniquely determine disk orientation.

The preferred Thalmann (2010) orientation is confirmed – reflection not forward scattering to the NW.

Simon et al (2001), IRAM
Luminosities and Colors

- The hot-start models (i.e., disk instability) predicted $6 \, M_{\text{jup}}$ for the central source. It’s way too bright for cold-start models.
- The integrated luminosity of $3 \times 10^{-3} \, L_{\odot}$ is of course more luminous, but very red.

Points show all free-floating Taurus members from Luhman (2010). The point sources fall at the very faint end (or below).
Three clouds of dust ~3AU in size (large planet Hill-sphere) can just intercept enough starlight to explain the L-band emission (albedo=1), but would struggle at M-band…

Emission is very red. Exotic/bright scattering needs a forward scattering geometry. We don’t have this luxury.

<table>
<thead>
<tr>
<th>Dust Type</th>
<th>$\tau=0.5$</th>
<th>$\tau=1$</th>
<th>$\tau=2$</th>
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<tbody>
<tr>
<td>Dirty Ice</td>
<td>4.1</td>
<td>4.2</td>
<td>4.15</td>
</tr>
<tr>
<td>Silicate</td>
<td>1.35</td>
<td>1.02</td>
<td>0.95</td>
</tr>
<tr>
<td>“K Dark” dust</td>
<td>0.42</td>
<td>0.33</td>
<td>0.32</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Filter</th>
<th>Contrast (mags)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>$&gt;6.8$</td>
</tr>
<tr>
<td>K</td>
<td>4.8-5.6</td>
</tr>
<tr>
<td>L</td>
<td>4.1-4.7</td>
</tr>
<tr>
<td>Ms</td>
<td>3.5</td>
</tr>
</tbody>
</table>
Thermal Emission

- Small Grains - Radiation Heated
- 900K, 1e-5 fill-factor
- 900K, Thin Small Grains

Luminosity ($10^{-3}L_\odot \mu$m$^{-1}$) vs Wavelength (µm)
In core accretion, the luminosity should spike as it rapidly accretes its envelope; this phase corresponds to gap formation in the disk. The transition disk stage is exactly the right time to look for planets, when even Jupiters might be detectable.
Lessons...

- Interpretation is hard, but would have been impossible without:
  1. mm CO disk measurements.
  2. mm disk continuum measurements.
  3. Medium resolution IR spectra.
  4. Detections at multiple wavelengths.
  5. Detections with the resolution to tell point-emission from extended emission.
  6. Orbital monitoring.
What comes next?

- Deep H-α observations (e.g. L. Close poster)
- Polarimetry + aperture-masking or kernel-phase.
- ALMA with resolutions smaller than 50 milli-arcsec (cycle 2, bands 7 and 9)

Remember: Point-source planets are Boring – the real action happens at formation!