High-contrast imaging using today’s infrared interferometers

10.2 milliarcseconds

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Why imaging?

- Complete orbital elements
  - Inclination removes sin i degeneracy in mass
- Movie of orbit can reveal temperature differences on planet surface
- Low resolution spectroscopy
- Direct measurement of stellar diameter

Planet-induced Phase Shift

\[ |V| \approx 1 - 2\alpha \sin^2 \left( \pi \frac{\vec{b}}{\lambda} \cdot \vec{\delta} \right) \]

\[ \Phi_V \approx \alpha \sin \left( 2\pi \frac{\vec{b}}{\lambda} \cdot \vec{\delta} \right) \]

Fringe from Bright Source
Fringe from Faint Source

2 sine waves interfere to form new fringe with smaller Visibility and small phase shift
Atmosphere Corrupts the Phase

Point source at infinity

Incoming plane waves

\[ \Delta \phi \]

\[ \Delta \phi \]
The “Closure Phase” Is Not Corrupted

<table>
<thead>
<tr>
<th>Observed</th>
<th>Intrinsic</th>
<th>Atmosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Phi(1-2) = \Phi_i (1-2) + [\phi(2)-\phi(1)] )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Phi(2-3) = \Phi_i (2-3) + [\phi(3)-\phi(2)] )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Phi(3-1) = \Phi_i (3-1) + [\phi(1)-\phi(3)] )</td>
<td></td>
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</tbody>
</table>

Closure Phase

\( (1-2-3) = \Phi_i (1-2) + \Phi_i (2-3) + \Phi_i (3-1) \)
Closure Phase Method

- Need angular resolution to resolve star to planet separation (~2 milliarcseconds for nearby cases)
- Need many photons to beat down photon noise
  - 51 peg provides \( \sim 10^6 \) photons per 0.1 sec per 0.05 mu BW at H band for 1 m telescopes
- Uncertainty: calibration
  - Must use special combiners
- Who: CHARA, VLT Interferometers
  - must have at least 3 telescopes and LONG > 100m baselines to resolve hot Jupiter systems
### Table 1. Hot Jupiter candidates for CHARA-MIRC

<table>
<thead>
<tr>
<th>Star Name</th>
<th>Dist. (pc)</th>
<th>H Mag</th>
<th>K Mag</th>
<th>Period (day)</th>
<th>e</th>
<th>Semimajor Axis (AU)</th>
<th>Semi-major Axis (mas)</th>
<th>T0 (JD)</th>
<th>R* (mas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>v And</td>
<td>13.5</td>
<td>2.957</td>
<td>2.859</td>
<td>4.6170</td>
<td>0.034</td>
<td>0.059 (4.42)</td>
<td></td>
<td>2450088.64</td>
<td>0.569</td>
</tr>
<tr>
<td>τ Boo</td>
<td>15.6</td>
<td>3.546</td>
<td>3.507</td>
<td>3.3128</td>
<td>0.018</td>
<td>0.049 (3.13)</td>
<td></td>
<td>2451653.968</td>
<td>0.45</td>
</tr>
<tr>
<td>51 Peg</td>
<td>15.4</td>
<td>4.234</td>
<td>3.911</td>
<td>4.2310</td>
<td>0.01</td>
<td>0.051 (3.31)</td>
<td></td>
<td>2450203.947</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Planet/Star Flux Ratio: ~$10^4$:1

(Sudarsky et al. 2003)
Closure Phase is Boosted since CHARA resolves the central stars of the brightest Hot Jupiter systems.
IOTA Interferometer:

statistical
+/- 0.07 degs

Systematic
+/- 0.20 degs

Monnier et al.
VLTI Interferometer:

- statistical
  +/- 0.06 degs
  [Differential phase]

- statistical
  +/- 0.6 degs
  [Closure Phase]

Segransan et al.; Millour et al. 2005
The CHARA Array
Mount Wilson, CA

CHARA: Six 1-m telescopes, 15 baselines from 34m to 331m, 20 closure triangles

Built and operated by Georgia State University (McAlister et al. 2005; ten Brummelaar et al. 2005)
MIRC: Michigan Infrared Combiner

- Uses single mode fibers
- Image plane combination

=>$ stable and precise closure phase

(Monnier et al. 2004)
Short triangle ~ 0.8 mas resolution

 UT2007Nov16  Telescope Triangle : E2-W1-W2  CH=0

Averaged 3 files  Mean CP (degs): 0.327±0.753

Time (Hrs)
Short triangle ~ 0.8 mas resolution
Short triangle ~ 0.8 mas resolution

Averaging the whole 1.7 hours=> 0.045°
Averaging the whole 1.4 hours => 0.066°

Short triangle ~ 0.8 mas resolution
Long triangle \( \sim 0.5 \) mas resolution

Averaging the whole 1.7 hours => 0.3

Need 6x S/N for 3\( \sigma \) detection!

Zhao 2009
Significant CP correlations with telescope az and/or alt suggest polarization (or dispersion) effects.
On the horizon…

- We have established precision at $10^{-3}$ level.
  - Need another factor of 10
  - Still not sure the cause of drifts (polarization?)

- Active efforts to detect hot Jupiters
  - VLTI: HD 189733, Tau Boo,..
  - CHARA: Ups And, Tau Boo
  - New Campaign planned this fall, with improved CHARA/MIRC performance

See 2009 PhD by Ming Zhao (U. Michigan -> JPL)