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Detection and Characterization of Hot Jupiters with LBTI Interferometry


Modern Astronomical Optics Team Project 2

April 5, 2012
Project Objectives

- Use interferometric techniques to detect and characterize Hot Jupiters
  - Use fringe visibility to show presence of planet
  - Look for photocenter changes as function of color
  - Embark on hot Jupiter spectroscopy
- Can this be done at the LBT with LBTI?
- Discuss current facilities and expected science capabilities
Detection and Characterization of Hot Jupiters with LBTI Interferometry

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What is Hot Jupiter?

Very close to host star

Hot Jupiter

Close to Jupiter mass
Discovered Hot Jupiters

- Creates large transiting signal, thus easy to detect

![Planet Semi-Major Axis vs Planet Mass](exoplanet.eu) (716)
Interesting Hot Jupiter Physics

- **Tidally Locked:**
  - How heat transfers from day side to night side and how efficient it is

- **May have migrated:**
  - To confirm this migration thus understanding planet formation; Atmospheric chemical make-up can help understand this

- **Atmosphere temperature inversion:**
  - Why do all hot Jupiters not have inversion layer; correlation with parent star activity?

- **Eccentricity of the orbit, retrograde orbit, etc.**

-> Hot Jupiters are easier to observe and model than super Earths and super Neptunes at this time—>brighter and atmosphere in thermodynamic equilibrium.
**Difficulty to Resolve**

- $0.2 \text{ AU} \rightarrow 10 \text{ mas at 20 parsecs}$

<table>
<thead>
<tr>
<th>Row ID</th>
<th>Host Name</th>
<th>Semi-Major Axis [AU]</th>
<th>Planet Mass [Jupiter]</th>
<th>Distance [parsec]</th>
<th>V (Johnson)</th>
<th>Angular separation (arcsec)</th>
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<td>634</td>
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<td>0.046</td>
<td>3.9</td>
<td>15.60$\pm$0.17</td>
<td>4.5*</td>
<td>0.003</td>
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</table>
Review of Interferometric Techniques

- The process by which an electromagnetic wave is separated and recombined to gain information about the original wave
- Pros: an angular resolution \( \sim \) distance between apertures, lower cost compared to one equivalent (angular resolution) telescope
- Cons: limited in the amount of photons collected, sensitive to OPL (rotation of the Earth, atmosphere, etc)
**Basic Interferometer Layout**

- **Point source at infinity**
- **Point sources at infinity separated by 1/2 the fringe spacing**

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**Monnier and Allen (2012)**
Key Interferometry Metrics

**Angular Resolution of a Telescope**

\[ \Theta = 1.22 \frac{\lambda}{D} \text{ (in radians), where } D \text{ is the telescope diameter} \]

**Angular Resolution of an Interferometer**

\[ \Theta = \frac{1}{2} \frac{\lambda}{B} \text{, where } B \text{ is the baseline between interferometer apertures} \]

**Number of independent Fourier components measured**

\[ \frac{N(N-1)}{2} \]

**Interferometric Measurement of Source Intensity Distribution**

\[ \tilde{V} = |V| e^{i\phi} = \int_{\text{sky}} A_N(\vec{\sigma}) l(\vec{\sigma}) e^{-\frac{2\pi i}{\lambda} \vec{B} \cdot \vec{\sigma}} d\Omega, \]

(from Monnier and Allen (2012)) \( \vec{\sigma} \) is vector from center of FOV to a given point in celestial sphere.

\( A_N \) is correction factor for large fields (usually not needed for O/IR interferometry).

\( \vec{B} \) is vector defining baseline of interferometer.
Astronomical Applications

- Interferometry is used in astronomy to measure size and position to high accuracy
- Exoplanets/hot Jupiters can be detected in the near-IR and thermal IR
- High resolution images can be achieved through aperture synthesis imaging (requires complex visibility measurement)
- Can use direct and indirect imaging techniques
Currently Existing Inferometers

▲ CHARA offers longest baselines (great resolution) for a O-IR telescope array, but operation is limited to near-IR. Small apertures and lack of AO limit sensitivity.

▲ Keck-I offers two large 10 m apertures with a long 85 m baseline, for high angular resolution.

▲ VLTI/PIONEER uses four 10 meter telescopes in fixed configuration for high sensitivity.

▲ LBTI benefits from the ease of motion due to the LBT’s modern light-weight construction and also superb throughput design (no bulkly relay optics).
Studies of protoplanetary systems

- Work in the sub-millimeter probes protoplanetary disk evolution. SMA interferometer on Mauna Kea gives first glimpse of work to be done at more powerful ALMA array.
- Andrews et al (2011) showed signs of large cavities in protoplanetary disk which may be the construction zone of new planets.
Modeling Fitting to Known Systems

- Orbiting (and perhaps transiting) planets evolve quickly such that coadding signals over a long observing baseline does not offer any beneficial gains in sensitivity.

- A technique used by Zhao et al. (2011) for the CHARA array and also by Absil et al. (2011) for VLTI/PIONEER capitalizes on planetary systems with well known orbits. Through model fitting in CHARA’s case, the star/planet flux ratio can be found by using observation of many epochs.

- We can start by targeting planets with well known orbits. A primary candidate would be the v And system. (for system parameters see Zhao et al. (2011))
Calibration is very challenging for long baseline O/IR interferometers.

Above are the best measurements to date by the CHARA array of $\nu$ And b showing upper limits on the star/planet flux ratio.

CHARA particularly challenged by spectral dispersion.
Interferometry at the LBT

- LBT Interferometer (LBTI)
  - Combines light from both 8 meter apertures
- LMIRCam
  - 3-5 \( \mu \text{m} \)
- NOMIC
  - 8-13 \( \mu \text{m} \)
LMIRCam

- Modes of Operation
  - Single/Dual Aperture Imaging
  - Single/Dual Aperture Interferometry
    - This what we care about!
  - Coronography
  - Single Grism Spectroscopy
    - This is also what we care about!
LMIRCam

- Interferometric Mode
  - \( \sim 26 \) mas resolution, non-redundant masking
  - Adaptive Optics

- Spectroscopy
  - Grism (Grating+Prism) spectroscopy of Dual-Mirror PSF
Detection and Characterization of Hot Jupiters with LBTI Interferometry

LMIRcam Optical Layout

LMIRcam: an L/M-band imager for the LBT combined focus.
Beyond LBTI

- Higher Resolution Spectrography
- Investigation of Spectrography using aperature masking
  - Current instruments use Fizeau mode, planet located at null of PSF
- Use GMT
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Interferometric Spectroscopy

- Split fringes out in wavelength
- View ratio of stellar light to planet light as a function of wavelength
- Get spectrum!

J. Monnier, Optical Interferometry in Astronomy
Design Limitations using LBTI

- Must work within the 22.8 meter baseline
- Adaptive optics is required to reach full potential
- 26 mas interferometric resolution
  - At 10 pc: 0.26 AU resolution
  - At 20 pc: 0.52 AU resolution
- Observation technique are unproven
  - Will expected performance be achieved?
Will LBTI work for us?

- Hot Jupiters: 0.015 - 0.5 AU from parent star
- Resolution is limited to within 19.2 pc
- Number of stars within 20 pc: about 2100
  -> LBTI will work for these stars
Can we do better?

- Assuming LBTI performs as expected, improving performance provides no benefit.
- Interferometer baseline would need to be larger than LBTI provides.
- "Warm" Jupiters could be detected.
  - distance > 20 pc and > 0.5 AU from parent star.
Measurement’s precision

\[ \delta_x = \frac{1}{2\pi} \frac{\lambda}{B} \frac{1}{SNR} \]

Let’s assume the system is only subjected to photon noise, in the worst case when we capture both lights from the host star and Hot Jupiter:

\[ SNR = \frac{N_{ph, planet}}{\sqrt{N_{ph, star}}} \]
\[ N_{ph} = F \Delta t \pi \left( \frac{D}{2} \right)^2 \Delta \lambda \]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio planet/star brightness</td>
<td>(10^{-4})</td>
</tr>
<tr>
<td>(m_v)</td>
<td>5</td>
</tr>
<tr>
<td>K-band: (\lambda = 2.2 \mu m) (±20%)</td>
<td>(F_0 = 4.38 \times 10^9 \text{ ph.m}^{-2}.s^{-1}.\mu m^{-1})</td>
</tr>
<tr>
<td>Exposure time</td>
<td>10 min</td>
</tr>
<tr>
<td>Telescope diameter</td>
<td>8.4 m</td>
</tr>
<tr>
<td>Interferometer baseline</td>
<td>22.8 m</td>
</tr>
<tr>
<td>Throughput</td>
<td>10%</td>
</tr>
</tbody>
</table>

\[ SNR = 24 \]
\[ \delta_x = 0.13 \text{ mas} \]
Application to *Virginis 70 B*

If we look at the interference pattern for different wavelengths, the photocenter will move approaching the planet for higher wavelengths, indeed assuming the planet much colder than its host star, at higher wavelength the photocenter will be closer to the planet.

$$\theta = \frac{1}{2} \frac{a}{d} \frac{F_{\text{planet}}(\lambda)}{F_{\text{star}}(\lambda_0)}$$

where $a$, semi major axis, $d$, distance observation to planet, $F_{\text{planet}}(\lambda)$, flux from the planet at long wavelength, $F_{\text{star}}(\lambda_0)$, flux from the star at short wavelength.

If we look at the star for several months, we can deduce from the period of the signal the semi major axis using Kepler’s law and therefore the flux of the planet:

$$T = \sqrt{\frac{4 \pi^2 a^3}{G M_{\text{star}}}} \quad a \quad F_{\text{planet}} = F_{\text{star}} \times \frac{2 d}{a}$$
Precision

If we assume an uncertainty on the period only of about 10% we have

\[
\delta a = \frac{2}{3} T^{-1/3} \delta T \left( \frac{G M_{\text{star}}}{4 \pi^2} \right)^{1/3} = 0.032 \text{ AU} = 6.67\% a
\]

We assume that at
\[
\lambda \gg \lambda_0 \text{ (wavelength emission of the star), } F_{\text{star}} \text{ is significantly decreased:}
\]

\[
\delta F_{\text{planet}} = 2 a \frac{F_{\text{star}}}{a} \delta \theta \approx \frac{1}{a} (\delta(aF) - F_{\text{planet}} \delta a) = 4.27 \times 10^3 \text{ ph.s}^{-1}.\text{m}^{-2}.\mu\text{m}^{-1}
\]

TOO HIGH

Solutions:
1. Increase exposure time
2. Increase baseline by a factor of 10: \( B \approx 200 \text{ m} \)
Other Sources of Error

- Sky background (1500 ph/ms) \( [\Delta t = 10 \text{ min}: N_{ph} = 9 \times 10^8] \)
- Telescope background (15000 ph/ms) \( [\Delta t = 10 \text{ min}: N_{ph} = 9 \times 10^9] \)
  \[ \rightarrow \text{ Negligible for bright sources } m_v < 7 \]

- Atmospheric perturbations
  Variance of measurement at an angle \( \theta \):
  \[
  \sigma^2 = \frac{16\pi^2}{B^2 t} \int_0^\infty dh v^{-1}(h) \int_0^\infty d\kappa \psi(\kappa, h)[1 - \cos B_\kappa][1 - \cos \theta_\kappa h] 
  \]
  where \( B \): baseline; \( h \): altitude, \( v \): wind speed at \( h \); \( \psi(\kappa, h) \): 3D spatial power spectrum of the refractive index, \( t \): integration time.

- WFE variations
Mitigating sources of error

- Use of fringe tracking to get rid of atmospheric perturbation
  - Use of color filter: NIR light is analyzed into the fringe tracker at a sampling rate of 1000 Hz
  - NIR light is subjected to an exposure time of 10 min
- Additional WFE variations cancelled out by Adaptive Optics (AO) systems on telescope mirrors
Summary

- Interferometric techniques are necessary to begin to resolve exoplanets in close in orbits.
- Ongoing work is showing promise; many facilities are attempting to detect exoplanets/Hot Jupiters with interferometric techniques.
- LBTI has two interferometric cameras good for exoplanet characterization.
- As long as LBTI performs as expected, hot Jupiter spectroscopy should be possible.
References

- Lecture notes, OPTI 416/516 2012: astrometry and interferometry
- Seager, S. and R. Dotson. "Exoplanets"