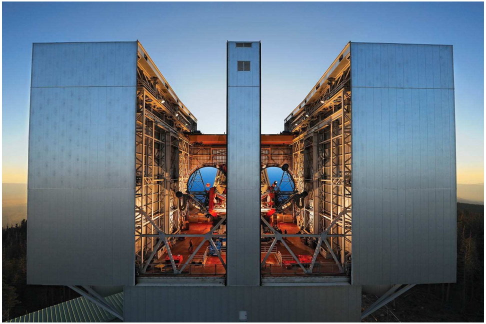
Detection and Characterization of Hot Jupiters with LBTI Interferometry



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Modern Astronomical Optics Team Project 2

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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

What is Hot Jupiter?

Very close to host star

↕

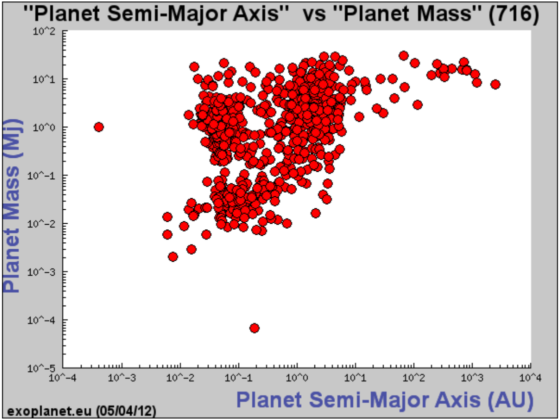
Hot Jupiter

↕

Close to Jupiter mass

Discovered Hot Jupiters

- Creates large transiting signal, thus easy to detect



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

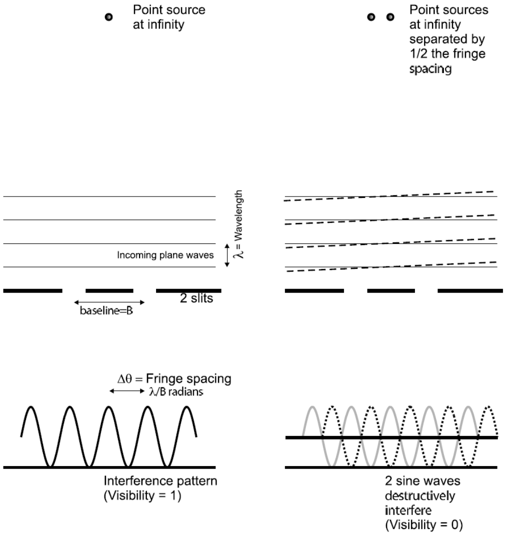
- 0.2 AU -> 10 mas at 20 parsecs

Row ID	Host Name	Semi-Major Axis [AU]	Planet Mass [Jupiter]	Distance [parsec]	V (Johnson)	Angular sepration (arcsec)
		<0.5	>0.9	<20		
27	70 Vir	0.484±0.028	7.49±0.61	18.11±0.24	4.98	0.026
69	GJ 3021	0.49	3.37±0.09	17.62±0.16	6.582±0.010	0.028
86	Gl 86	0.1130±0.0065	3.91±0.32	10.91±0.07	6.12	0.010
87	Gliese 876	0.211	2.64	4.70±0.05	10.191±0.015	0.045
300	HD 189733	$0.03099^{+0.00060}_{-0.00063}$	1.13±0.03	19.25±0.32	7.676±0.010	0.001
353	HD 217107	0.073±0.001	1.33±0.05	19.72±0.29	6.16*	0.004
524	HIP 79431	0.36	> 2.1	14.90±0.75		0.024
631	rho CrB	0.22	1.04	17.43±0.21	5.4	0.012
634	tau Boo	0.046	3.9	15.60±0.17	4.5*	0.003

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



Monnier and Allen (2012)

Key Interferometry Metrics

Angular Resolution of a Telescope

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

Angular Resolution of an Interferometer

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

Number of independent Fourier components measured

$\frac{N(N-1)}{2}$

Interferometric Measurement of Source Intensity Distribution

$\tilde{V} = |V|\, e^{i\phi_\nu} = \int_{sky} A_N(\vec{\sigma}) I(\vec{\sigma}) e^{-\frac{2\pi i}{\lambda}\vec{B}\cdot\vec{\sigma}} d\Omega,$

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

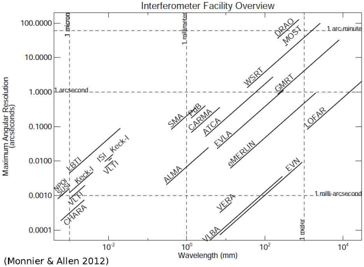
A_N is correction factor for large fields (usually not needed for O/IR interferometry)

$\vec{B}$ 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

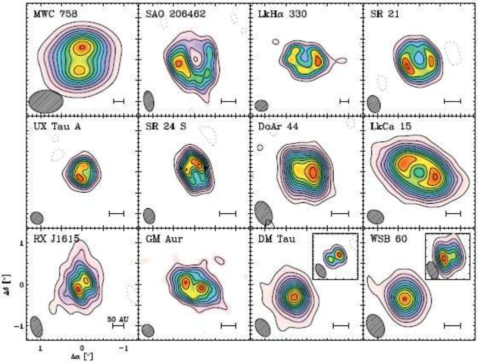
Currently Existing Inferometers



(Monnier & Allen 2012)

- 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).

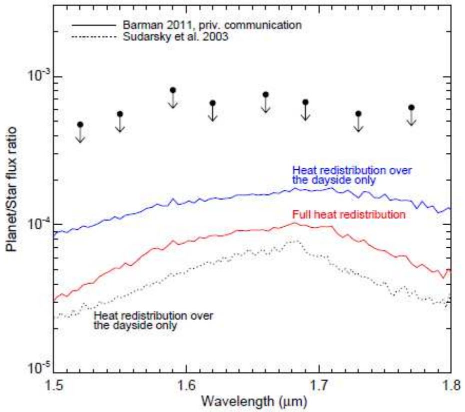
Studies of protoplanetary systems



- 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

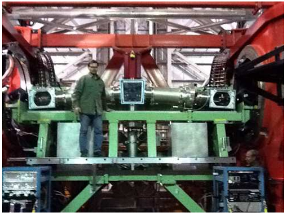
- Orbiting (and perhaps transiting) planets evolve quickly such that coadding signals over a long observing baseline does not offer any beneficial gains in sensitivity.
- A technique used by Zhao et al. (2011) for the CHARA array and also by Absil et al. (2011) for VLTI/PIONEER capitalizes on planetary 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 υ 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 v 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 μm
- NOMIC
  - 8-13 μm



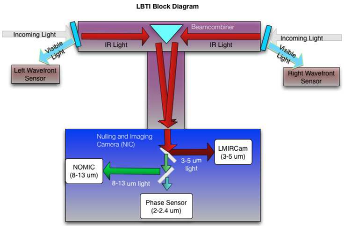
LMIRCam

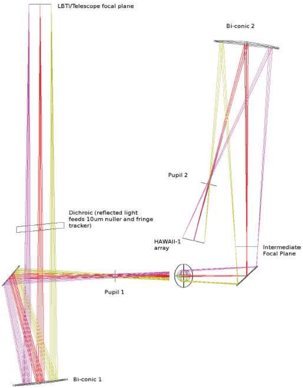
- Modes of Operation
  - Single/Dual Aperture Imaging
  - Single/Dual Aperture Interferometry
    - This what we care about!
  - Coronography
  - Single Grism Spectroscopy
    - This is also what we care about!

LMIRCam

- Interferometric Mode
  - $\sim$ 26 mas resolution, non-redundant masking
  - Adaptive Optics
- Spectroscopy
  - Grism (Grating+Prism) spectroscopy of Dual-Mirror PSF

LMIRcam Optical Layout





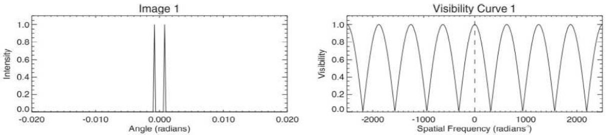
LMIRcam: an L/M-band imager for the LBT combined focus

Beyond LBTI

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

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 LBT 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:

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

Parameters	Estimation
Ratio planet/star brightness	10^{-4}
m_V	5
K-band: $\lambda = 2.2\ \mu m\ (\pm 20\%)$	$F_0 = 4.38\ 10^9\ ph.m^{-2}.s^{-1}.\mu m^{-1}$
Exposure time	10 min
Telescope diameter	8.4 m
Interferometer baseline	22.8 m
Throughput	10%

$$SNR = 24$$
$$\delta_x = 0.13 \text{ mas}$$

Planet Name	70 Virginis b
Orbital Period (days)	116.67
Semi-major Axis (AU)	0.48
Eccentricity	0.43
Argument of Periapse (degrees)	2.1
Inclination (degrees)	
Discovery Method/Date Code	RV96
Planet Mass (in Jupiter masses)	6.6
Planet Radius (in Jupiter radii)	
Planet Density (in grams/cc)	
Number of Planets in System	1
Star Name	70 Virginis
Alternative Star Name	
Star Mass (in solar masses)	0.92
Star Radius (in solar radii)	1.968
Stellar Spectral Type	G4V
Star Brightness (Visual Magnitudes)	5

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.

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

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

$$T = \sqrt{\frac{4\pi^2 a^3}{G M_{star}}} \Rightarrow a \Rightarrow F_{planet} = F_{star} * \frac{2d}{a}$$

Precision

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

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

We assume that at

$\lambda \gg \lambda_0$ (*wavelength emission of the star*), F_{star} *is significantly decreased*:

$$\delta F_{planet} = 2\, d \frac{F_{star}}{a} \delta\theta \approx \frac{1}{a}(\delta(\text{aF}) - \text{F}_{\text{planet}}\ \delta a) = 4.27\ 10^3\ ph.s^{-1}.m^{-2}\mu m^{-1}$$

TOO HIGH

Solutions:

1. Increase exposure time
2. Increase baseline by a factor of 10: $B \approx 200\ m$

Other Sources of Error

- Sky background (1500 ph/ms) [$\Delta t = 10$ min: $N_{ph} = 9 \times 10^8$]
- Telescope background (15000 ph/ms) [$\Delta t = 10$ min: $N_{ph} = 9 \times 10^9$]

  –> **Negligible for bright sources** $m_v < 7$
- Atmospheric perturbations
  Variance of measurement at an angle θ*:*
  $\sigma^2 = \frac{16\pi^2}{B^2 t} \int_0^\infty dh v^{-1}(h) \int_0^\infty d\kappa \phi(\kappa, h)[1 - \cos B\kappa][1 - \cos \theta\kappa h]$
  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

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