Interferometric Observations of a Transiting Planet

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Modern Astronomical Optics Project 2
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Project Goal: Directly image a transiting exoplanet

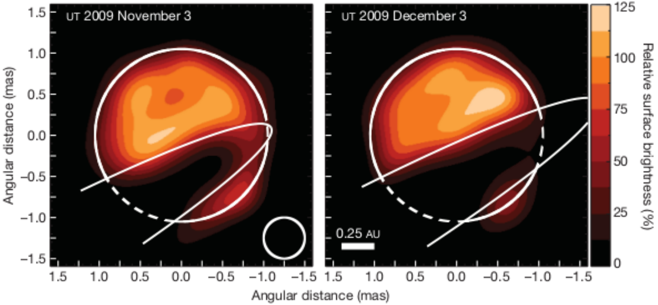
Challenges:

- Long baselines
- Short wavelengths
- Ground or Space?

Science:

- First direct image of a transit
- Information on planet shape
- Information on planet moons/rings

Previous Work in High Resolution Interferometry



Inspired by direct image of transiting binary ϵ Aurigae (Kloppenborg et al, 2010)
H-band, 0.5 mas resolution

Resolution Goals

- 3 Largest apparent sizes of known exoplanets: 0.056 mas, 0.036 mas, 0.026 mas
- 18 planets with apparent size $\geq$0.01 mas
- Goal: resolve 4x smaller than size of planet

Existing Interferometers

- CHARA: 0.5 mas resolution
- Keck: 5 mas resolution
- VLTI: 4 mas resolution
- Eliminate radio: 0.056/4 mas with 1cm wavelength requires an interferometer larger than Jupiter

Design Considerations

- Wavelength Considerations
  - UV, Visible, or NIR
- Telescope Size Requirement
- Baseline Requirement
- Cophasing Requirement
- Beam Combination Requirement

Wavelength Considerations-UV

- Advantages
  - Smaller baseline requirement
- Disadvantages
  - More difficult cophasing requirement
  - Must go to space
  - Most target stars less bright in the UV than optical

Wavelength Considerations-NIR

- Advantages
  - Easier cophasing requirement
- Disadvantages
  - Longer baseline required
  - Most target stars less bright in the NIR than optical

Wavelength Considerations-Visible

- Advantages
  - Cophasing and baseline requirements moderate, but achievable
  - Very advanced technology and detectors (minimal readout noise)
    - Cophasing measurements can be used for science
    - Disperse 1D fringes onto 2D detector for dispersion correction and wavelength-dependent information
  - Cheaper
    - Well-established technology
    - Ground-based
- Disadvantages
  - Not as high resolution given the same baseline as in the UV

Telescope Size / Adaptive Optics

Telescope size is determined by photon flux needed.
$$flux = 10^{-0.4*V} * 3640 * 0.16 * \pi * (\frac{D}{2})^2 * 1.51 * 10^7 \frac{1}{1000*10}$$

- Transit photometry for 91.6% of all previous RV detections achievable with $< 1m$ telescope.
- Cophasing requires 100 photons/millisecond
- Only 10% of signal reaches interferometer due to losses in delay line
- For a V=15 star, we need a 12 meter telescope
- For a V=12 star, we need a 3 meter telescope
- For a V=10 star, we need a 1.2 meter telescope

Telescope Size / Adaptive Optics

The Fried parameter indicates the size of telescope that can operate at the diffraction limit. Any telescope larger than the Fried parameter is seeing-limited, and any telescope smaller can be diffraction limited.

$r_0 = (0.423k^2 \sec\psi \int C_n^2(z)\, dz)^{-3/5}$

where $C_n^2(z)$ is the atmospheric turbulence profile as a function of altitude

$k = \frac{2\pi}{\lambda}$

ψ is the angle of the telescope

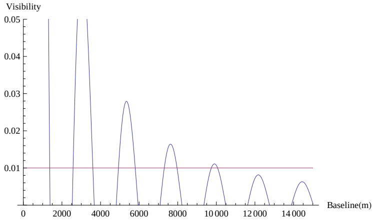
The Fried parameter is approximately 10cm in the visible, so we will need AO for the telescopes to be diffraction limited.

Baseline Requirements

- Planet's apparent size determines the baseline (size of planet / distance to star)
- Assume we need four resolution units for each planet (λ / D)
- Absolute minimum baseline to resolve the largest planet (0.056mas) is 7.4km
- We can resolve 5 currently known transits with a 25km baseline (3 have Vmag < 10)
- We can resolve 18 currently known transits with a 40km baseline (11 have Vmag < 10)
- We can resolve 48 transits with a 80km baseline (17 have Vmag < 10)

Cophasing Requirement

- Require precision of $\frac{\lambda}{40}$
- Kolmogorov turbulence (KT) dominates
  - 3D KT goes as $\sigma \sim B^{5/6}$
  - Ali et. al. (2010) show that past $\sim 22m$, KT flatlines
  - CHARA performs cophasing in optical on 300m baselines
- Fringe tracking becomes difficult when we resolve the star
  - Minimum of 1% visibility needed for tracking
  - $V = \frac{2J_1(\frac{\pi\theta B}{\lambda})}{\frac{\pi\theta B}{\lambda}} = 0.01$ for star of $\sim 1mas$ size gives a 10km cophasing baseline requirement.



Beam Combination Requirement

- Can we digitally record?
  - Vband $\nu \sim 500 THz$
  - Fastest processors only $5.2 GHz$
  - Most accurate clock, HI maser at $1420.405752 MHz$, has high noise when multiplied to $500 THz$
  - No phase sensors available
- Must physically beam combine
  - Fibers or vacuum tubes?

Location Considerations

Factors that are acknowledged:

- Light pollution shouldn't be an issue considering the brightness of the stars to be observed
- Atmosphere imposes limitations on achievable precision of ground-based measurements

Points to high elevation locations with corresponding low-level turbulence accommodating a 40 km baseline; preferential locations would be larger plateaus allowing for an L or T shaped interferometer array.

- low difficulty

Structural Considerations

Large baselines drastically complicates general structure.

- Cannot position telescopes onto a common mount
- The delay lines are proportional to the baseline therefore are driven up
- Use of beam steering becomes necessary
- Mounting larger baseline complications can be addressed using a circular rail
    - Having movable telescopes eliminates the need for additional delay-lines to bring signal in time
    - With given baseline, diameter of track would still be rather large
    - Additionally, would not be prudent for the number of telescopes we wish to use

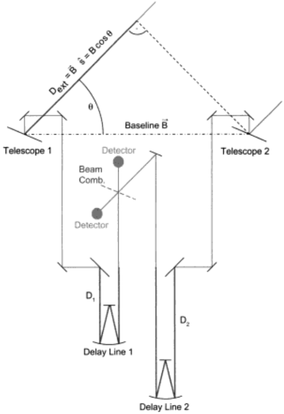
Delay Line Considerations

The external delay between the two telescopes are compensated by the internal delay of the interferometer

Delay related to baseline by:

$$D = \vec{B} \cdot \hat{s}$$

Shows relationship between internal OPD and angle between telescopes (θ)



Vacuum Tube vs. Fiber Optic

Vacuum tubes would serve as better delay lines than fibers for reasons including:

- With delay lines on the order of km, attenuation, dispersion and λ-dependent pathlengths will play a large role in fibers
  - Temperature dependent
- To make fibers work would require R&D. With testing around the 1 km range, fibers not feasible.
- Vacuum tubes may be difficult to build but will get the job done

Telescope Positions

Each group of two telescopes give access to *one sample* in the **UV-plane** $\Leftrightarrow$ the Fourier transform of the object.
Goal : *How to choose the telescope pattern?*

Position of the telescopes : $(x_i; y_i)_{i \in N}$.

The UV plane :

$$\begin{bmatrix} u \\ v \end{bmatrix} = \frac{1}{\lambda} \begin{bmatrix} x_i - x_j \\ y_i - y_j \end{bmatrix}$$

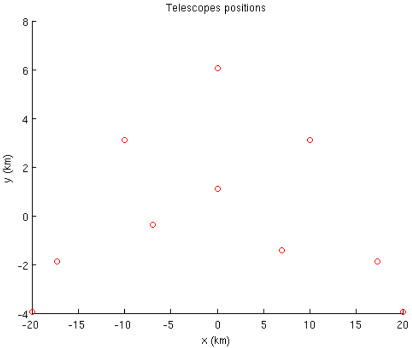
N telescopes span K baselines, with :

$$K = \binom{N}{2} = \frac{N!}{2!(N-2)!} = \frac{N(N-1)}{2}$$

For $N = 6$, there are 15 baselines available at the same time.

We can also fill the **UV plane** with time-multiplexing measurement : the local orientation of the observatory with regard to the object gives access to new samples.

Random telescope positioning with the largest baseline being 40km and having a chain between all telescopes of < 10km :

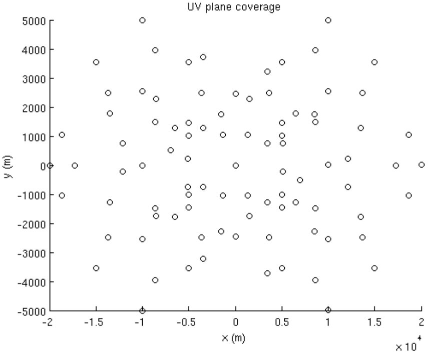


Maximum available frequency content at $\lambda = 550 \quad nm$:

$$\frac{\lambda}{D} \approx 0.003 \quad marcsec$$

UV Plane coverage

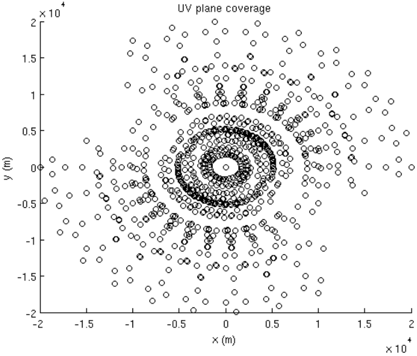
Instantaneous **UV-Plane** coverage :



Not normalized in wave number

UV Plane coverage

UV-Plane coverage taking into account earth rotation, and doing 10 measurements over a 120^o arc:



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Fourier Reconstruction

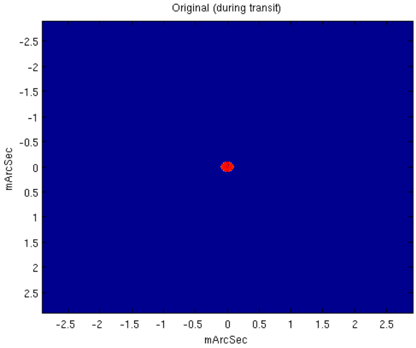
To reconstruct the image, we will use the fourier transform of the object plane (wavefront decomposition).

$$Img = \left| \mathcal{F}^{-1} \left\{ \mathcal{F} \left\{ Obj \right\} \times UV_{plane} \right\} \right|^2$$

The next step in the reconstruction is the deconvolution process : Wiener filter, TV filter, *etc*. For those, we need to know the *mean object spectra* and the *mean nosie spectra*.

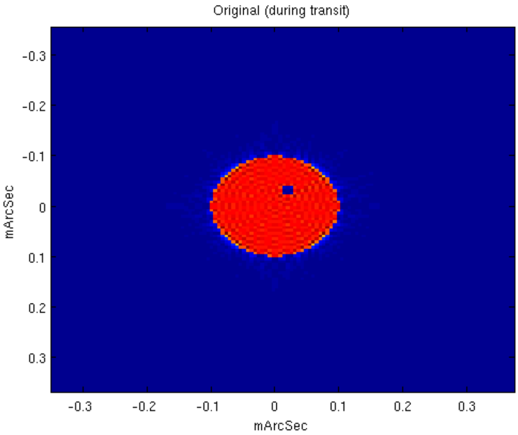
Simulation for an equivalently sized telescope

For a $D = 40$km telescope looking at a 0.2mas star and a 0.02mas transiting planet located at $(-0.03; 0.02)$ mas.

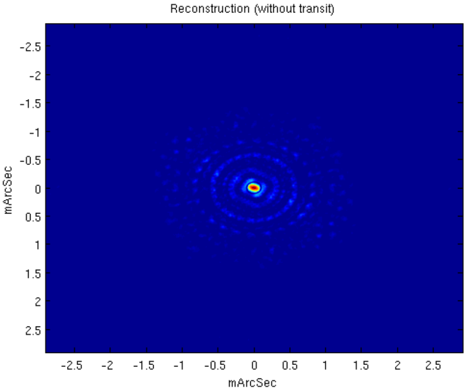


Not including noise, atmospheric perturbation nor deconvolution process.

Simulation for an equivalently sized telescope



Simulation for the current array



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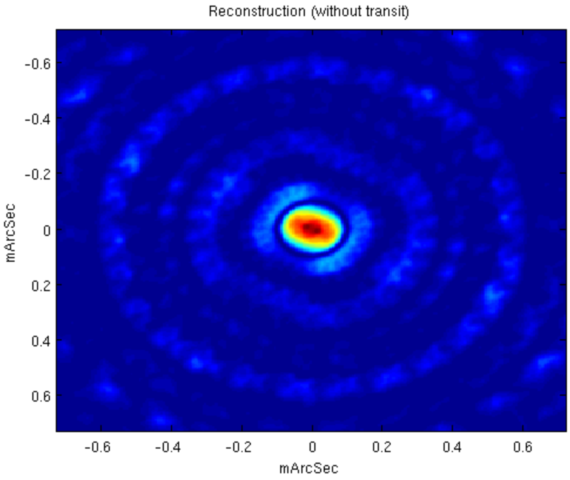

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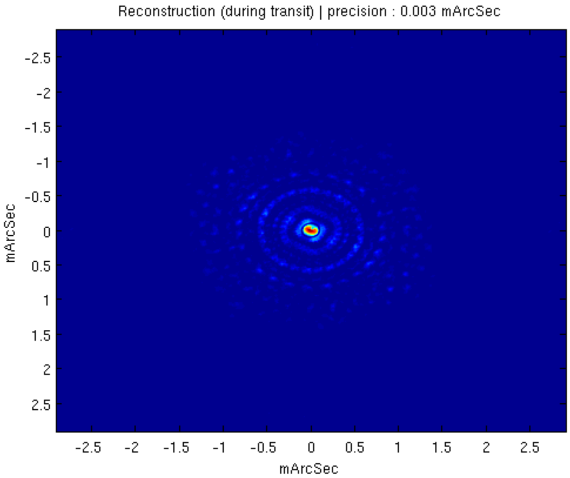

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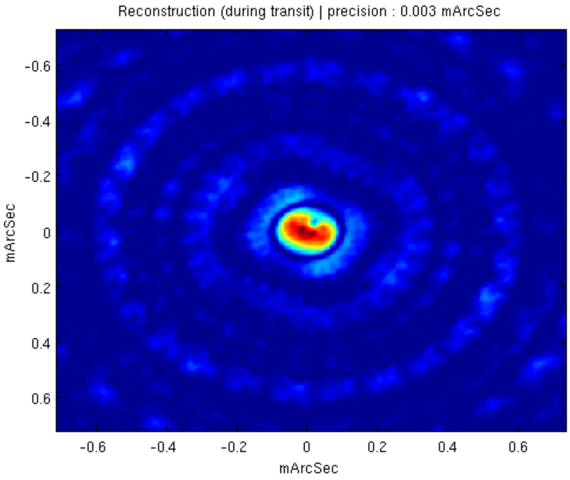

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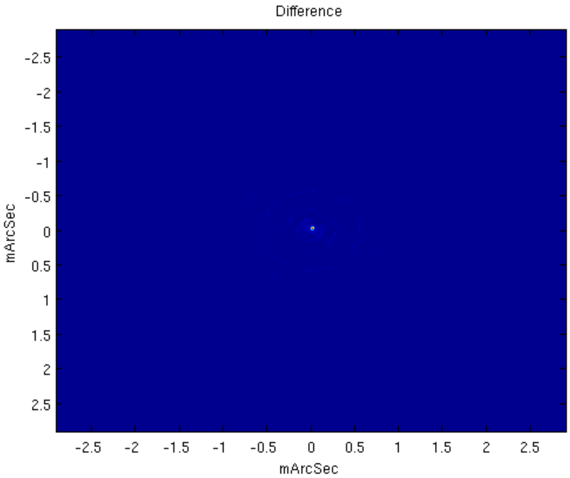

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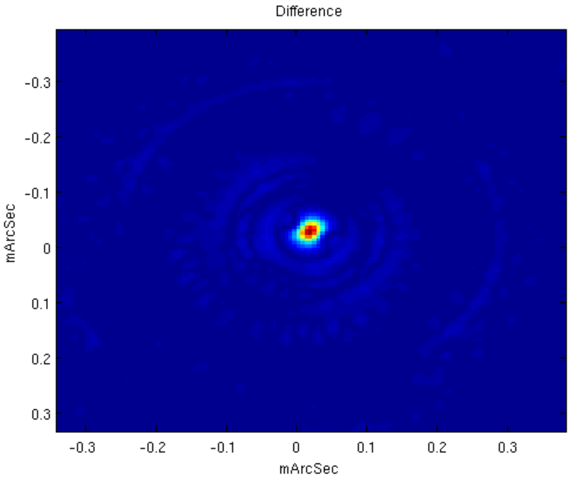

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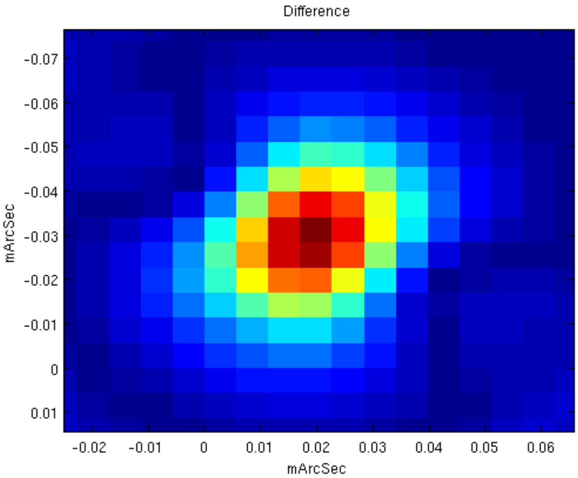
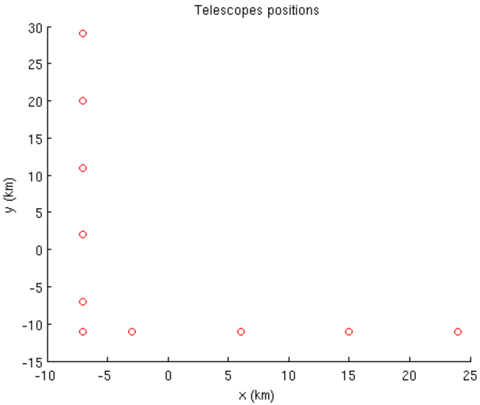


"L-Shape"

Cosidering a *L-Shape*



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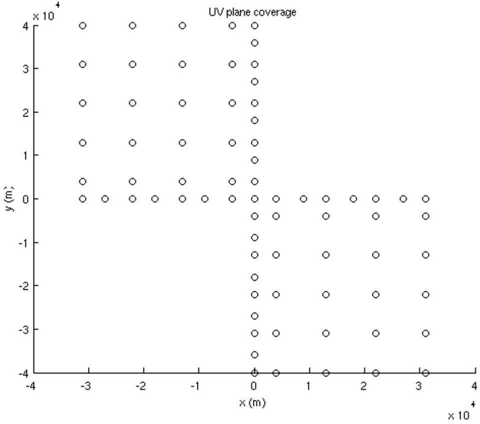

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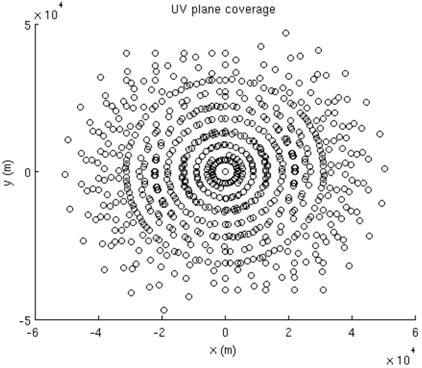

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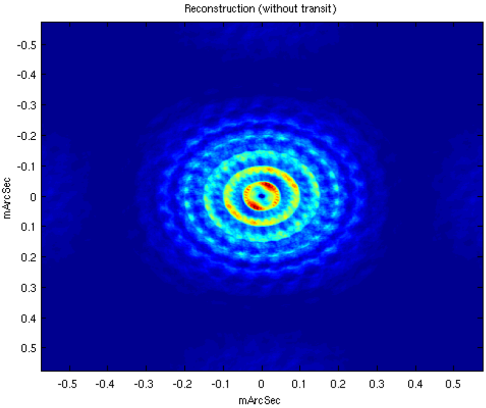
Simulation for the "L-Shape" array



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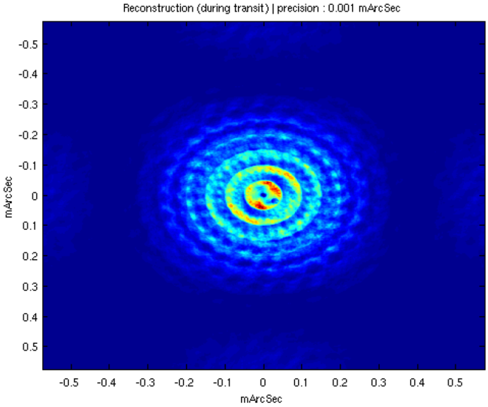

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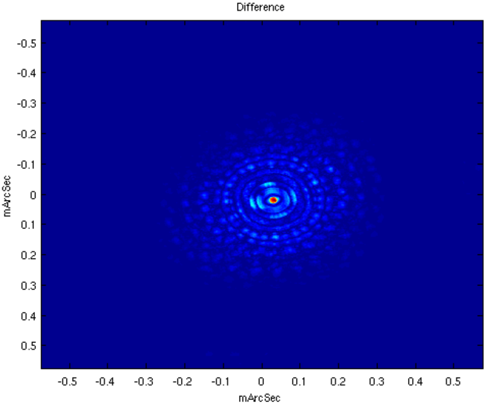
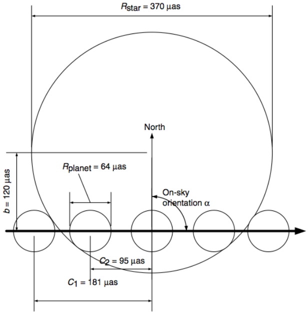


What Additional Information Can We Recover?

- Inclination and Orientation of planetary orbit
- Refined angular diameter measurements of planet and star
- Oblateness
- Satellites: Rings and Moons

Closure Phase

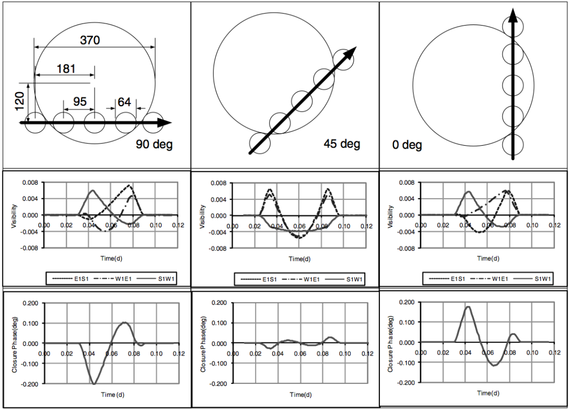
HD 189733



van Belle, 2008

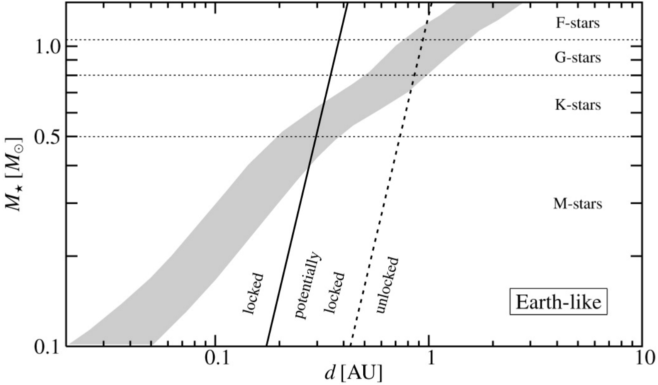
- On-sky orientation of transit chord presently unknown.
- Closure phase quantifies degree of asymmetry in an image.
- We can recover: r_{star}, planet-to-star radius ratio, orbit orientation upon the sky, α, impact parameter, b, zero time of transit event, velocity of planet disk across stellar disk

Closure Phase



van Belle, 2008

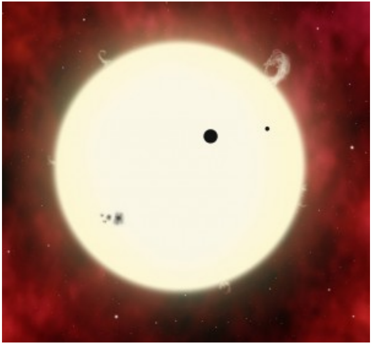
Oblateness: Caused by rotation, or tidal forces?



Grießmeier et al., 2008

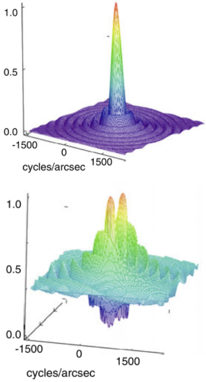
Could We Detect Oblateness or Satellites?

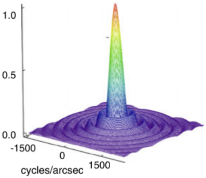
- Oblateness: If the tidal forces are large enough, could possibly detect directly.
- If satellite is big enough ($r_{satellite} > \frac{1}{4} r_{planet}$) we can image it directly.
- With difference imaging, we can detect smaller features than our resolution limit.

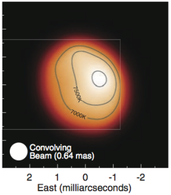


http://www.eurekalert.org/multimedia/pub/26513.php

Difference Imaging: Oblateness & Satellites



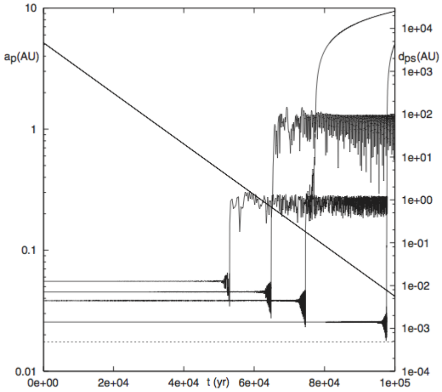




Use different models to look for subtle asymmetries.

Monnier et al., 2007

Do we expect to see satellites?



Namouni, 2010

- Most of our targets probably migrated inward.
- Jovian satellites would all have been ejected in this scenario.

Can we observe transits of planets in the habitable zone around nearby M-dwarf stars?

- Closest known transit around an M-dwarf is GJ436b, it can be imaged with a 11.6km baseline but it is not in the habitable zone.
- Closest star is Proxima Centauri. We could observe a Jupiter-size planet around this star with a 0.56km baseline, or an Earth-size planet with a 6.32km baseline.
- We could image a Jupiter-size planet around the ten nearest M-dwarfs with a 1.5km baseline, or an Earth-size planet with a 16.3km baseline.
- The probability of transit is greater because the stars are closer, but there are no known transits around these stars.

Secondary Science Goal-Direct Imaging

- Optical wavelength search for reflected starlight from planets
  - Preferentially detect hot Jupiters in small orbits around bright stars.
- Limiting factor–Photon noise or fringe visibility contrast?

Photon Noise Limited Case

- 579 total confirmed planets from exoplanets.org
- 91 out of the total 124 planets with known radii and V_{mag} are potentially observable

Table: Planets with the highest SNR for detection with known parameters

Name	V_{mag}	a (AU)	$R_{pl}(R_{Jup})$	SNR
WASP-33 b	8.3	0.026	1.497	81.2
WASP-18 b	9.39	0.020	1.106	43.1
HD 189733 b	7.67	0.031	1.138	42.6
WASP-12 b	11.69	0.023	1.79	31.3

- 106 out of 455 known planets with unknown radii or V_{mag}, are expected to be observable
  - When no V_{mag} was available, 8.60 (average V_{mag}) was used.
  - When no radius was available, 1 Jupiter radius was used.

Fringe Visibility Contrast Limited Case

- Looking only at planets with known radii and stellar magnitudes with 10 telescopes, we obtain:
  - Best contrast: $5.7 * 10^{-4}$
  - Median contrast: $6.0 * 10^{-5}$
- Techniques to improve success in this limit:
  - Search for planet visibility near minima of stellar visibility function
  - Use fringes dispersed by wavelength to search for planet visibility function

Conclusions

Directly observe a transiting exoplanet

- 11 targets
- Optical Interferometer, 40km baseline
- 1.2 m telescopes
- Will be able to determine planet radius, position w.r.t. star, oblateness, and potentially moons
- Secondary Science: potentially directly image 197 planets