Adventures in Interferometry

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Outline

Modern Interferometry
- Motivation
- Nomenclature
- Why Use Interferometry?
- Palomar Testbed Interferometer

Data Analysis
- Model Selection
- Analysis Methods
- Results

Plans for the Future

Acknowledgments

Simple Eclipsing Binary

Theoretically, we can describe a star by five quantities: Mass, Radius, Temperature, Chemical Composition, Time (age).

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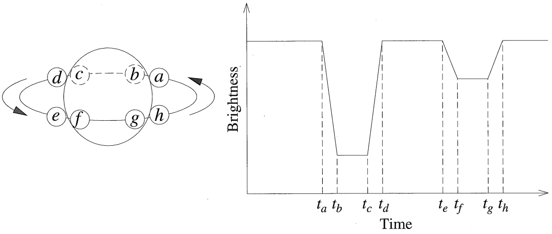

Figure: The (ideal) light curve of an eclipsing binary (Ostlie, 1996)

ϵ Aurigae

The Light Curve of ϵ Aurigae suggests it is an eclipsing binary, except:

- The Eclipse happens once every 27 years
- The Eclipse lasts for two years
- The Spectrum looks like a 15 $M_{\odot}$ F-Super giant star.
- No Significant evidence for the companion star.
- So, what is causing the eclipse?

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Current Model of ϵ Aurigae

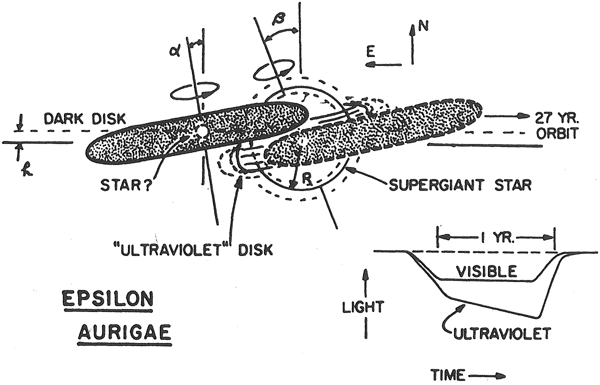

Figure: Model of Epsilon Aurigae System (NASA, 1985)

Astronomical Nomenclature

Angular Measurements

- 1 Radian $= 180/\pi \approxeq 57.3$ degrees
- 1 Degree $= 60$ arc-minutes $= 60^2$ arc-seconds
- 1 arc-second $\approxeq 5 * 10^{-6}$ rad $= 5$ micro-radians
- 1 milli arc-second $\approxeq 5$ nano-radians

Astronomers also speak of the angular resolution of a telescope. Often this is defined by the Rayleigh Diffraction Criterion:

- $\theta = 1.22\frac{\lambda}{D}$

where λ is the wavelength and D is the diameter of the telescope.

Why Build an Interferometer?

Figure: Betelgeuse (α Orionis), has an angular diameter of 223 nrad (46 mas).

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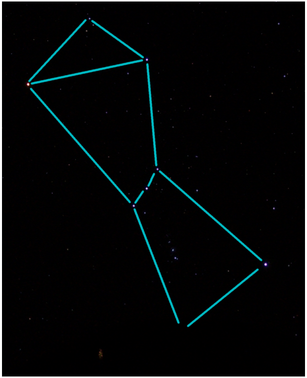

Figure: Betelgeuse (α Orionis), has an angular diameter of 223 nrad (46 mas).

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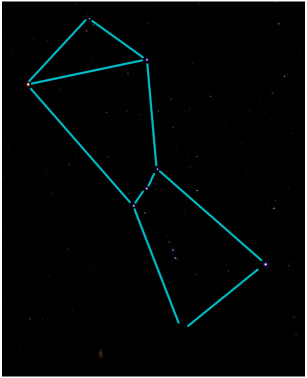
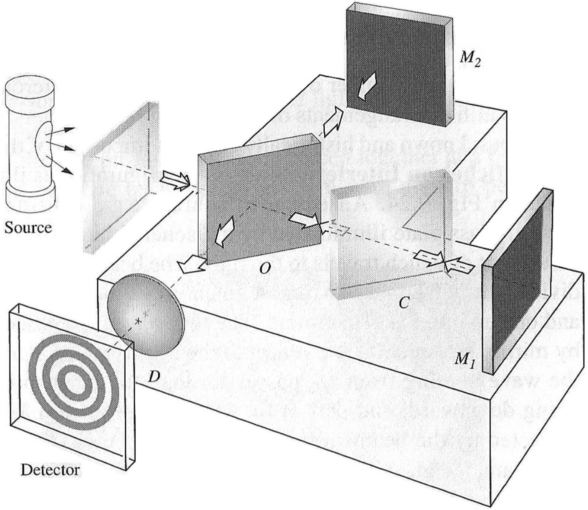


Figure: Betelgeuse (α Orionis), has an angular diameter of 223 nrad (46 mas).

- The Largest Telescopes Lack Sufficient Resolution
  - Keck Telescopes: 10 m
  - 268 nrad (55 mas)
- Large Mirrored Telescopes are expensive

The Michelson Interferometer



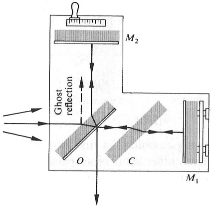


Figure: Schematic Drawings of a Michelson Interferometer (Hecht, 2002)

Fringes

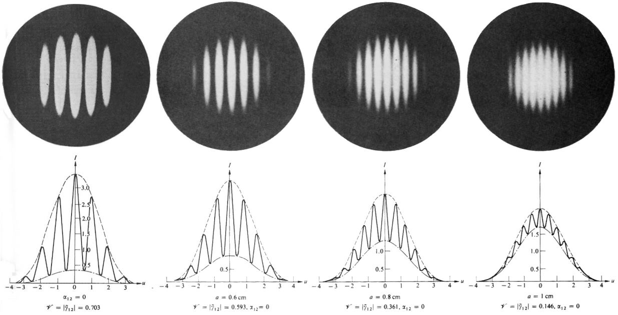


Figure: Fringes as seen by an Interferometer (Hecht, 2002)

Visibility Squared:

$$V^2 = \left(\frac{I_{max} - I_{min}}{I_{max} + I_{min}} \right)^2$$

Palomar Testbed Interferometer

Figure: Aerial View of PTI and the 200" Palomar Telescope (Gerald van Belle)

- PTI Operated by the Michelson Science Center on behalf of CalTech and NASA-JPL
- Maximum Baseline, 110 meters
- Resolution 8.1 - 10.5 nrads (1.67 - 2.18 mas)

PTI Schematic Drawing

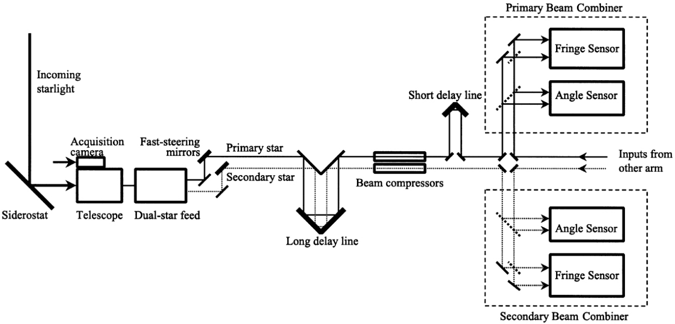
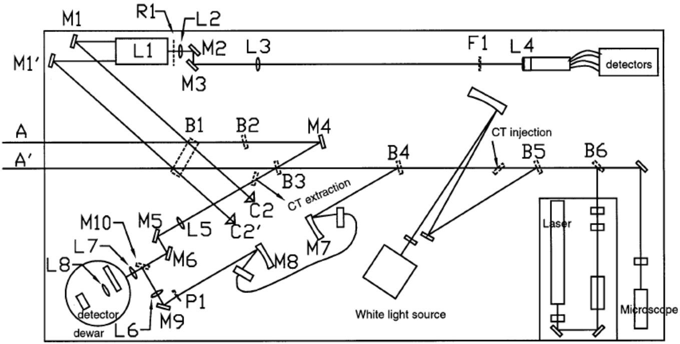


Figure: Schematic Drawing of PTI (Colavita, 1999)

PTI Schematic Drawing



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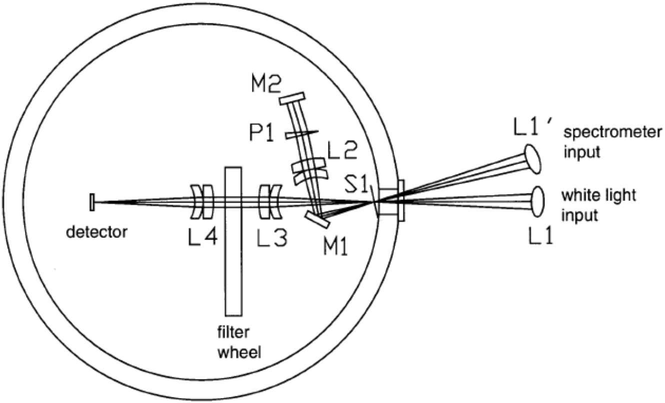

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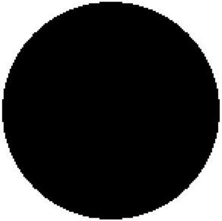
Model Selection

- Uniform Disk
- Limb-Darkened
- Others



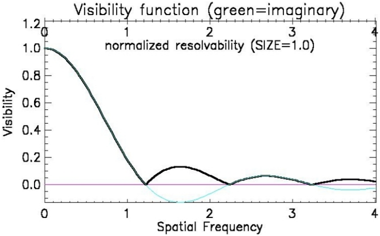


Figure: Disk Models (Meisner, J.)

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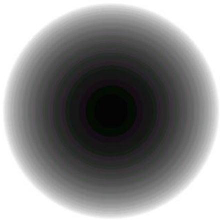

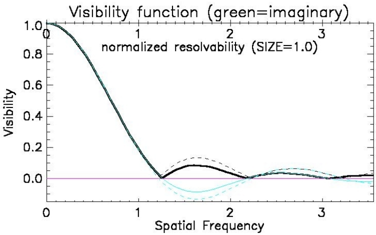

Figure: Disk Models (Meisner, J.)

Model Selection

- Uniform Disk
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- Others

- Uniform Disk with a hole
- Ellipse
- Gaussian (with or without a hole)
- Binary Star (with or without a transit)
- Central "Hotspot"

Uniform Disk

Visibility squared readings from the interferometer are matched to an angle using a model. In our case, we considered the uniform disk model:

$$V^2(\theta, B, \lambda) = \frac{(2 * J_1(\pi\theta B/\lambda))^2}{(\pi\theta B/\lambda)} \quad (1)$$

where B is the projected baseline and $J_1(x)$ is a Bessel function of the first kind.

Bessel Function Approximation

Unfortunately, my version of Excel does not have a Bessel function built-in, so I wrote one. Using Arfken's definition:

$$J_\nu(x) = \sum_{s=0}^{\infty} \frac{(-1)^s}{s!(s+\nu)!} \left(\frac{x}{2}\right)^{\nu+2s} \tag{2}$$

I wrote a macro that takes the first n-terms of the expansion:

$$J_\nu(n,x) = \sum_{s=0}^{n} \frac{(-1)^s}{s!(s+\nu)!} \left(\frac{x}{2}\right)^{\nu+2s} \tag{3}$$

I elected to use the first seven terms from the expansion so that the maximum error that could be contributed by the next term in the series was below 5×10^{-9}.

The Lookup Table

Solving for the angular diameter, θ, in the visibility squared equation is not easily done:

$$\frac{\left(2 * J_1\left(\pi\theta B/\lambda\right)\right)^2}{\left(\pi\theta B/\lambda\right)} = V^2$$

Therefore I elected to create a lookup table that takes values of $(\pi\theta B/\lambda)$ between ≈ 0.45 and ≈ 2.55 in 3.2×10^{-5} increments.

- Produces V^2 values between 0.14 and 0.95 in 2×10^{-5} increments.
- Consists of 65534 rows

Obtaining Results

The lookup table facilitates our analysis by allowing us to match the V^2 values from PTI with a corresponding value of $(\pi\theta B/\lambda)$. After that, it's simply algebra:

$$\theta = \frac{\lambda X}{\pi B} \tag{4}$$

Where X is the (numerical) value for $(\pi\theta B/\lambda)$ in the lookup table.

Results

UTDate JD-2450000	Baseline [m]	UDD [mas]	Error [mas]
2007Oct19 4393	NS	2.18	0.06
2007Oct20 4394	NS	2.02	0.13
2007Oct21 4395	NS	2.52	0.08
2007Dec23 4458	NS	2.36	0.16
2007Dec24 4459	NS	2.24	0.14
Archival Data			
1997Oct22 0744	NS	2.35	0.18
1997Nov09 0762	NS	2.33	0.15
1998Nov07 1125	NS	2.09	0.14
1998Nov25 1143	NS	2.66	0.16

Table: Angular Diameters obtained from Wide-Band Visibility mode data using the uniform disk model

Interferometric Image Synthesis

Radio Astronomers can build images from interferometric data, can we do that with near-optical data too?

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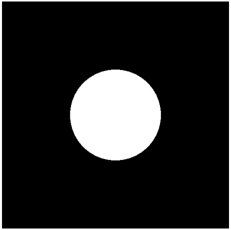

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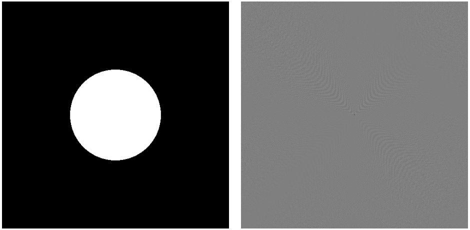

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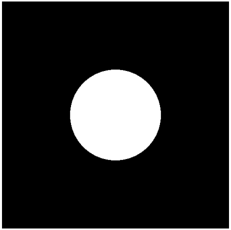
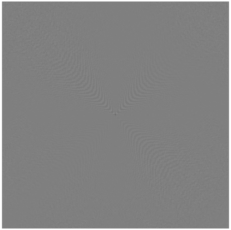
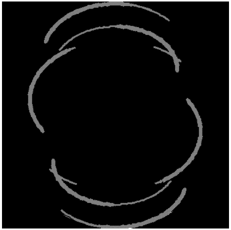

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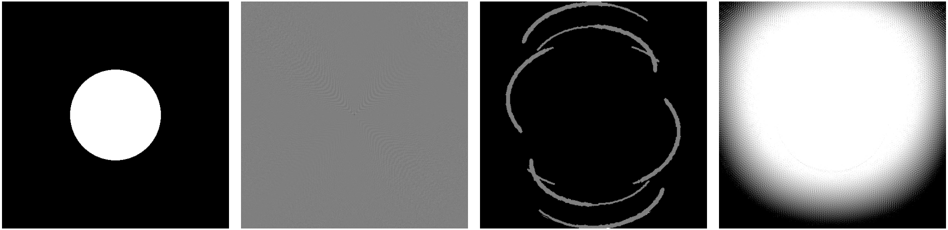

Future Observations

When we go back, what will we look for?

- ϵ Aurigae exhibits large changes in brightness over very short time periods. Is this a form of pulsation? Can it be detected by PTI?
- Is this star really a F-supergiant? Could it be a Post Asymptotic Giant Branch Star (AGB)?
- More Pre-eclipse Data. How does the system change before and after eclipse?
- How does the angular diameter change as the disk passes? Does the disk divide the star in two?

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Acknowledgments

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