Challenges Related to Interferometric Imaging

Brian Kloppenborg

May 24, 2010

Outline

ϵ Aurigae

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- So, what is causing the eclipse?

Epsilon Aurigae

- Largest star in the universe
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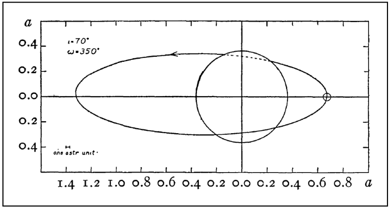

Image Credit: Kuiper et. al. 1937

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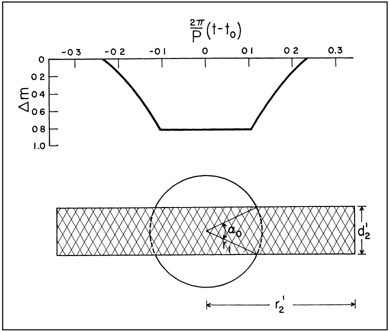

Image Credit: Huang, 1965

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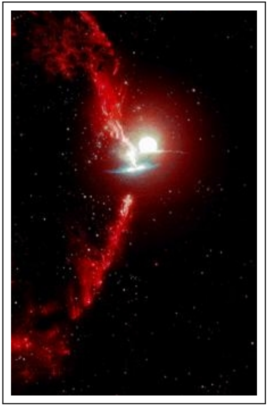

Image Credit: Dan Weeks

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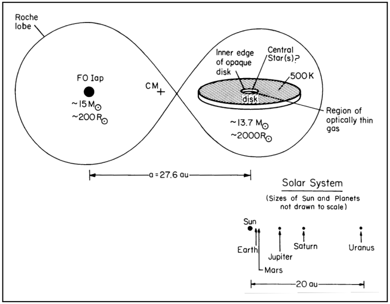

Image Credit: Carroll, S. et. al 1991

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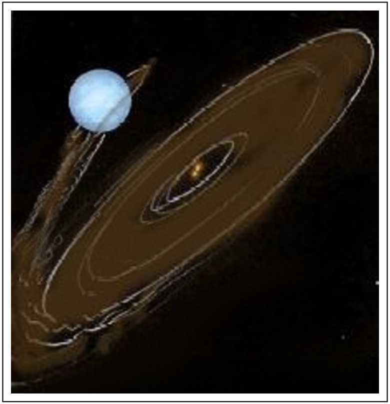

Image Credit: M. Carroll and Robert Stencel 2008

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- Binary or a trinary?
  (Lissauer, 1984)
- Low mass system

  (Webbink, 1985)

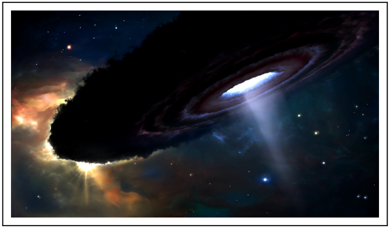


Image Credit: Brian Thieme

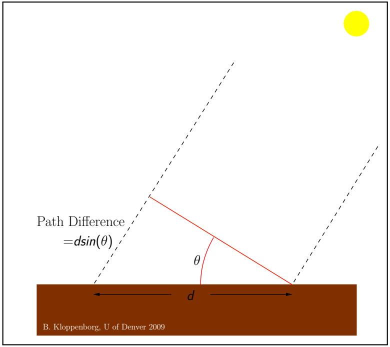
Scientific Relavance

- Simple Binary Stars
  - Period
  - Luminosity
  - Radii
  - Temperatures
- Something new or interesting?
  - Massive $\Longrightarrow$ luminous, where is the companion?
  - Large Obscuring Object: Dark Matter, black hole?
  - New Evolutionary state for stars or PN?

Why do we need interferometry?

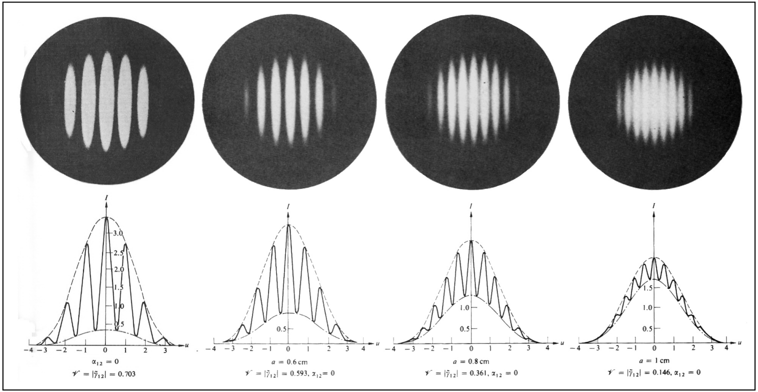
- Previous observations give models, no confirmation.
- Biggest telescopes lack sufficient resolution:
  - Keck Telescopes: 10 m, 55 mas (268 nrad)
- Need direct observations to continue developing theory.

An Interferometer: CHARA



Mt. Wilson Today, Credit: Georgia State University

Visibility



Fringes as seen by an Interferometer (Hecht, 2002)

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

Closure Phase

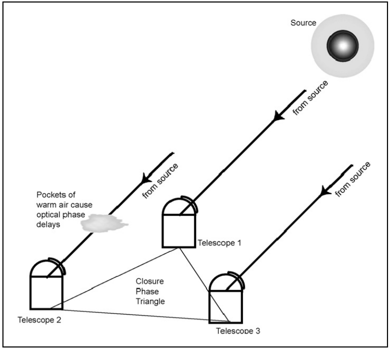


Image Credit: John D. Monnier, 2007

$$\begin{aligned}\Phi_{ijk} &= \phi_{ij} + (\phi_{jk} + \phi_{atm}) \\ &\quad +(\phi_{ki} - \phi_{atm}) \\ &= \phi_{ij} + \phi_{jk} + \phi_{ki}\end{aligned}$$

UV Coverage

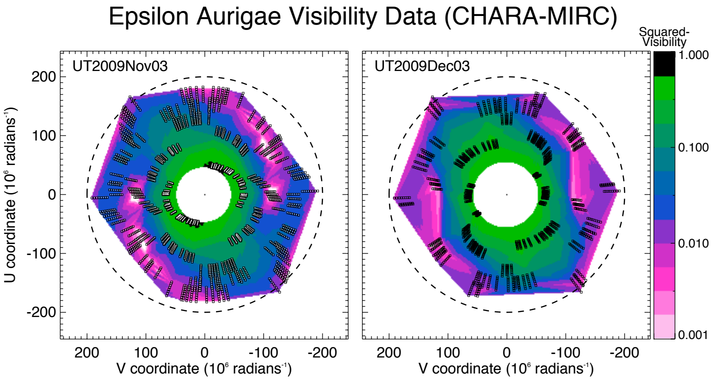


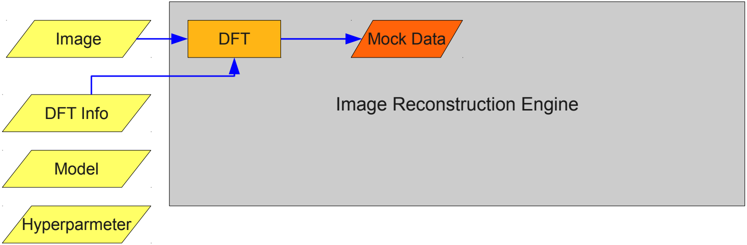
Image Credit: Kloppenborg et. al. 2010

The Premise

A minimization problem:

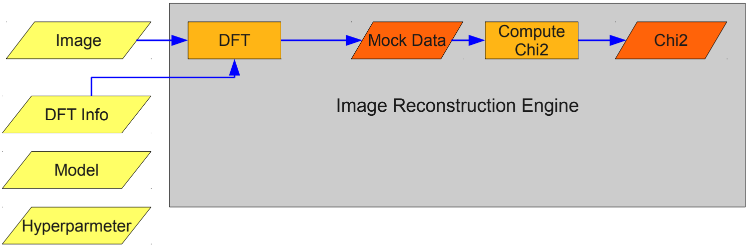
$$C' = \chi^2 - \alpha S$$

The Engine



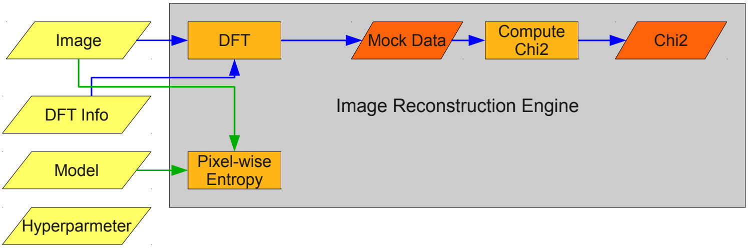
$$
\begin{aligned}
V_k &= \sum_i^x \sum_j^y I_{ij} e^{2\pi ip\, uv_u(k) + 2\pi jp\, uv_v(k)} \\
P_{ij} &= (V_{ij})^2 \\
B_{ijk} &= V_{ij} V_{jk} V_{ki} e^{i(\phi_{ij} + \phi_{jk} + \phi_{ki})}
\end{aligned}
$$

The Engine



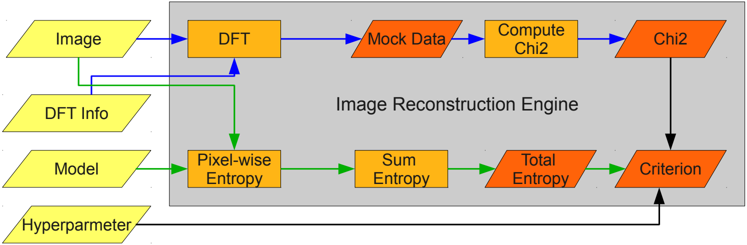
$$\chi^2 = \sum_i^{n_{data}} \frac{(D_i - D_i')^2}{D_{err\ i}}$$

The Engine



$$S_{ij} = I_{ij} - M_{ij} - I_{ij} \ln \left(\frac{I_{ij}}{M_{ij}} \right)$$

The Engine



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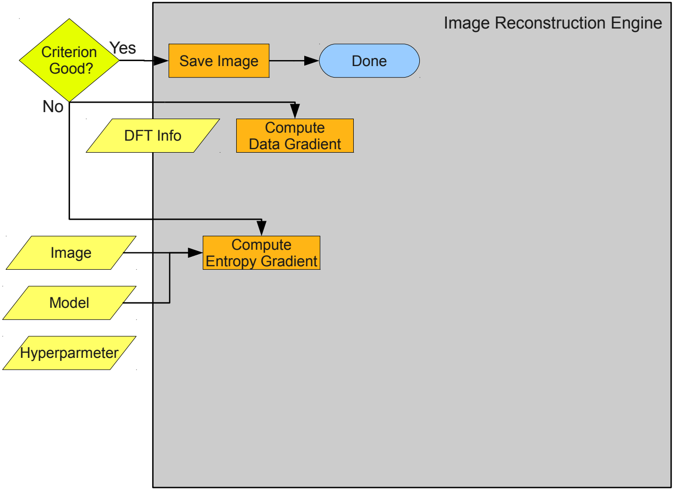
Image Reconstruction Engine
Criterion Good?
Yes
No
Save Image
Done
DFT Info
Compute Data Gradient
Image
Model
Hyperparmeter
Compute Entropy Gradient

The Engine

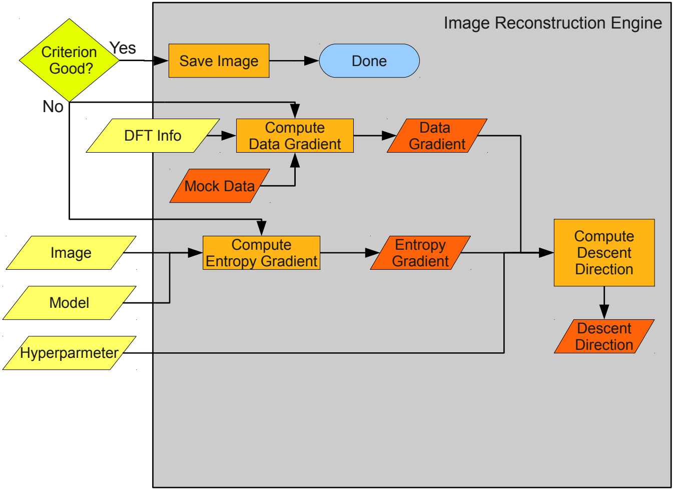
Image Reconstruction Engine
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Compute Data Gradient
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Mock Data
Image
Model
Hyperparmeter
Compute Entropy Gradient
Entropy Gradient
Compute Descent Direction
Descent Direction

The Engine

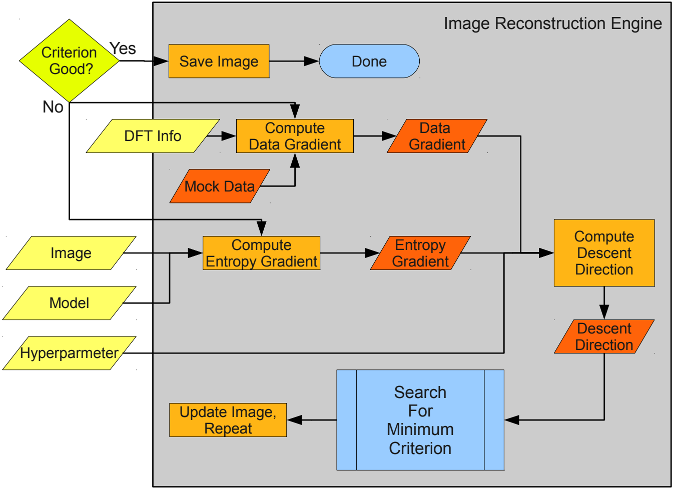
Image Reconstruction Engine
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Yes
No
Save Image
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DFT Info
Compute Data Gradient
Data Gradient
Mock Data
Image
Model
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Compute Entropy Gradient
Entropy Gradient
Compute Descent Direction
Descent Direction
Search For Minimum Criterion
Update Image, Repeat

New Knowledge

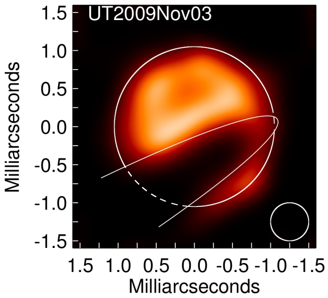
nature Vol 464|8 April 2010|**doi:10.1038/nature08968**

LETTERS

Infrared images of the transiting disk in the ε Aurigae system

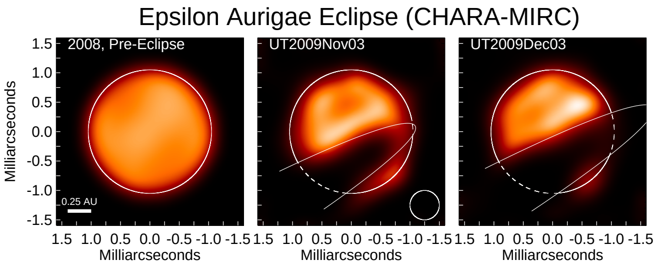
Brian Kloppenborg[1], Robert Stencel[1], John D. Monnier[2], Gail Schaefer[3], Ming Zhao[4], Fabien Baron[2], Hal McAlister[3], Theo ten Brummelaar[3], Xiao Che[2], Chris Farrington[3], Ettore Pedretti[5], P. J. Sallave-Goldfinger[3], Judit Sturmann[3], Laszlo Sturmann[3], Nathalie Thureau[5], Nils Turner[3] & Sean M. Carroll[6]

Simple Parameters



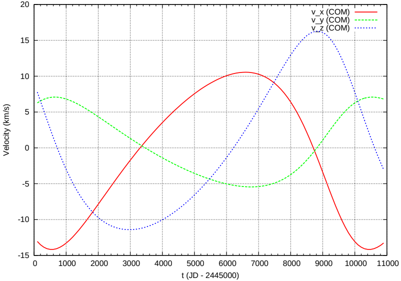
Star Diameter:	1.51 ± 0.02	AU
Disk Semi-Major Axis:	3.81 ± 0.01	AU
Disk Semi-Minor Axis:	0.38 ± 0.01	AU
Minimum Disk Inclination:	84.30 ± 0.15	deg.
Maximum Disk Thickness:	0.76 ± 0.02	AU
Disk Tilt Position Angle:	119.80 ± 0.74	deg.
Disk Volume:	1.16 ± 0.03	1E35 m^3
Disk Mass:	2.22 ± 1.57	1E-7 M_0

Orbital Parameters

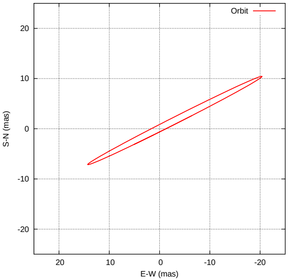


Disk Orbit Position Angle:	296.82 ± 6.85	deg.
Disk Above Orbit Tilt:	2.98 ± 6.89	deg.
Disk Motion:	0.43 ± 0.08	AU
Disk Relative Speed:	25.10 ± 4.65	km/s

Velocities and Mass Ratios



Red line from Stefanik et. al. 2010



	Ours	Literature	
Disk Speed:	9.66 ± 4.67		(km/sec)
Mass Ratio (Disk + B5V : F-Star):	0.62 ± 0.12		
Mass Ratio (F-Star : Disk + B5V):	1.63 ± 0.30		
F-Star Mass:	3.63 ± 0.68	3.15 ± 0.25	$M_\odot$
Mass Function:	2.26 ± 0.32	2.51 ± 0.12	

* Literature values from Stefanik et. al. 2010 and Hoard et. al. 2010.

Acknowledgements

- Dr. Robert Stencel
- Bequest of William Herschel Womble
- CHARA Collaborators
- Dr. Fabien Baron

Data Gradient

$$dV_k = \sum_{k}^{N_{pow}} 4 \left(D_{err\ k}\right)^2 \left(M_k - D_k\right) Re\left(V_k^* \left(e^{2\pi ip\, uv_u(k) + 2\pi jp\, uv_v(k)} - V_k\right)\right)$$

Entropy Gradient

$$dS_{ij} = -ln\left(\frac{I_{ij}}{M_{ij}}\right)$$