Review of Interferometric Measurements and Prospects for Single Stars

John Davis

Chatterton Astronomy Department

School of Physics

University of Sydney

The Narrabri Stellar Intensity Interferometer

- Angular diameters of 32 early-type stars leading to effective temperature scale.
- First interferometric-spectroscopic study of a double-lined spectroscopic binary (α Vir).
- A number of exploratory experiments:
  - Angular size of emission envelope around Wolf-Rayet star γ^2 Vel in ionised carbon lines.
  - Study of limb-darkening effects.
  - Attempt to measure extended corona around β Ori in orthogonal polarisations.
  - Study of effects of rapid rotation on shape and brightness distribution across star.
  - Discovery of unsuspected binary systems.

Measured Stellar Angular Diameters (Early 1997)

(Ref: Davis, IAU Symposium 189, p.31, 1997, Kluwer)

(1) Measurements regardless of accuracy

Range in Spectral Type	Luminosity Class I	II	III	IV	V
O	3				1
B0-B4	2	2	3	2	2
B5-B8	2		1	1	1
A0-A3	1			2	5
A5-A7			1		1
F0-F5	3			1	
F8	2				
G0-G5	2	1	2	3	
G7-G9.5	2	1	12		
K0-K3	3	10	16		
K3-K7	1	1	7		
M0-M4	5	6	17		
M5-M8	1	2	13		
TOTAL:	27	23	72	9	10

(2) Measurements with uncertainty < ±5%

Range in Spectral Type	Luminosity Class I	II	III	IV	V
O					
B0-B4			1	1	1
B5-B8	1				1
A0-A3	1			1	3
A5-A7					1
F0-F5	3			1	
F8	2				
G0-G5	2	1		3	
G7-G9.5	2	1	11		
K0-K3	3	7	11		
K3-K7	1		6		
M0-M4	5	6	15		
M5-M8	1		9		
TOTAL:	21	15	53	6	6

Status of Interferometrically Measured Stellar Angular Diameters

1997

Range in Spectral Type	Luminosity Class				
	I	II	III	IV	V
O	3				1
B0-B4	2	2	3	2	2
B5-B8	2		1	1	1
A0-A3	1			2	5
A5-A7			1		1
F0-F5	3			1	
F8	2				
G0-G5	2	1	2	3	
G7-G9.5	2	1	12		
K0-K3	3	10	16		
K3-K7	1	1	7		
M0-M4	5	6	17		
M5-M8	1	2	13		
TOTAL:	27	23	72	9	10

Ref: Davis (IAU Symposium No. 189, 1997)

1999

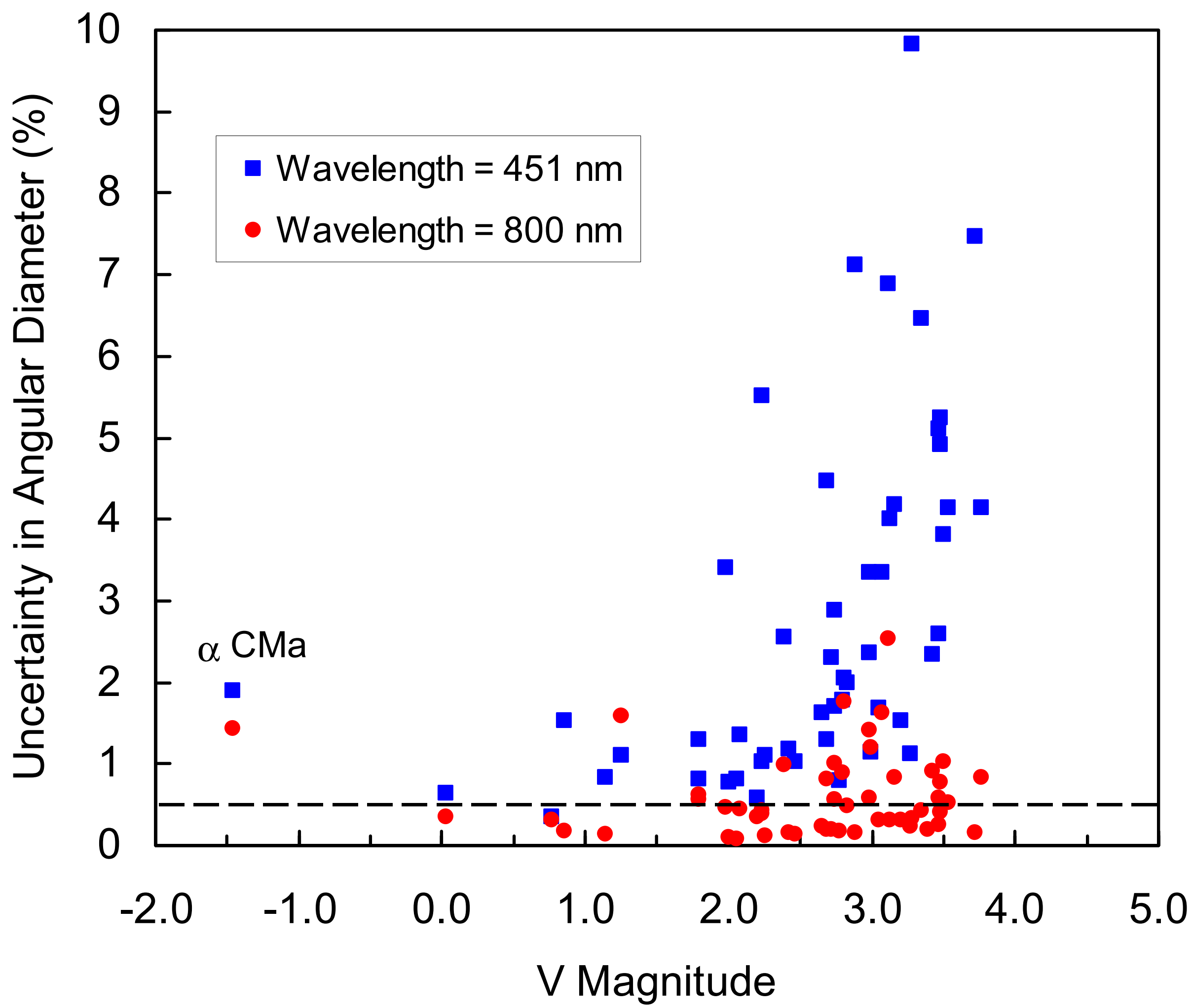
Range in Spectral Type	Luminosity Class				
	I	II	III	IV	V
O	3				1
B0-B4	2	2	3	2	2
B5-B8	2		1+1	1	1
A0-A3	1			2	5
A5-A7			1		1
F0-F5	4	1		1	
F8	2				
G0-G5	3	1	2	3	
G7-G9.5	2	1	22		
K0-K3	5	16	31		
K3-K7	3	1	14		
M0-M4	12	13	70		
M5-M8	1	2	31		
TOTAL:	40	37	176	9	10

Evolved Stars	
Carbon	22
M Miras	37
C Miras	5
S Miras	4
TOTAL:	68

Ref: van Belle (Michelson Summer School, 1999)

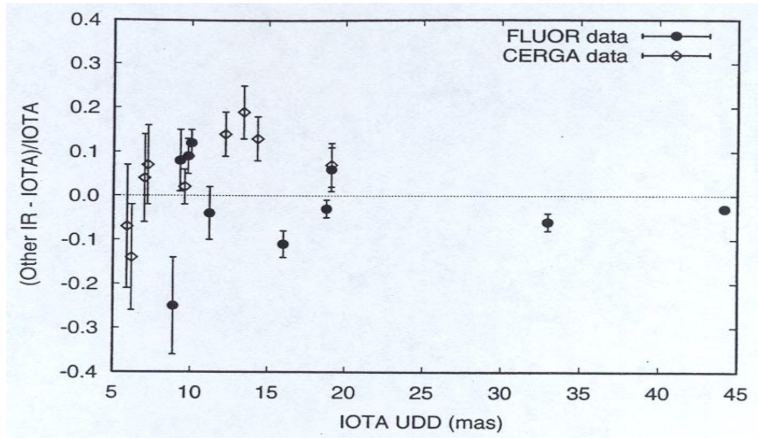
Comparison of Uncertainties in Interferometric Angular Diameter Measurements at Blue and Red Wavelengths with the Mark III Interferometer

(Courtesy of D. Mozurkewich)

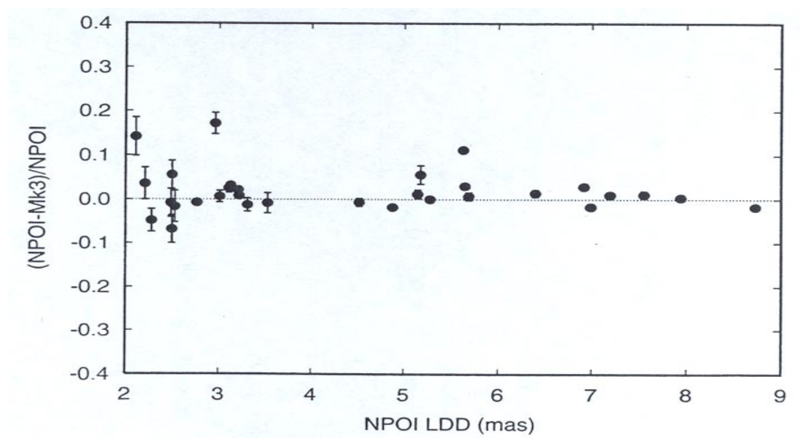


Comparisons of Angular Diameter Measurements

Copied from M. Dyck, 1999 Michelson School



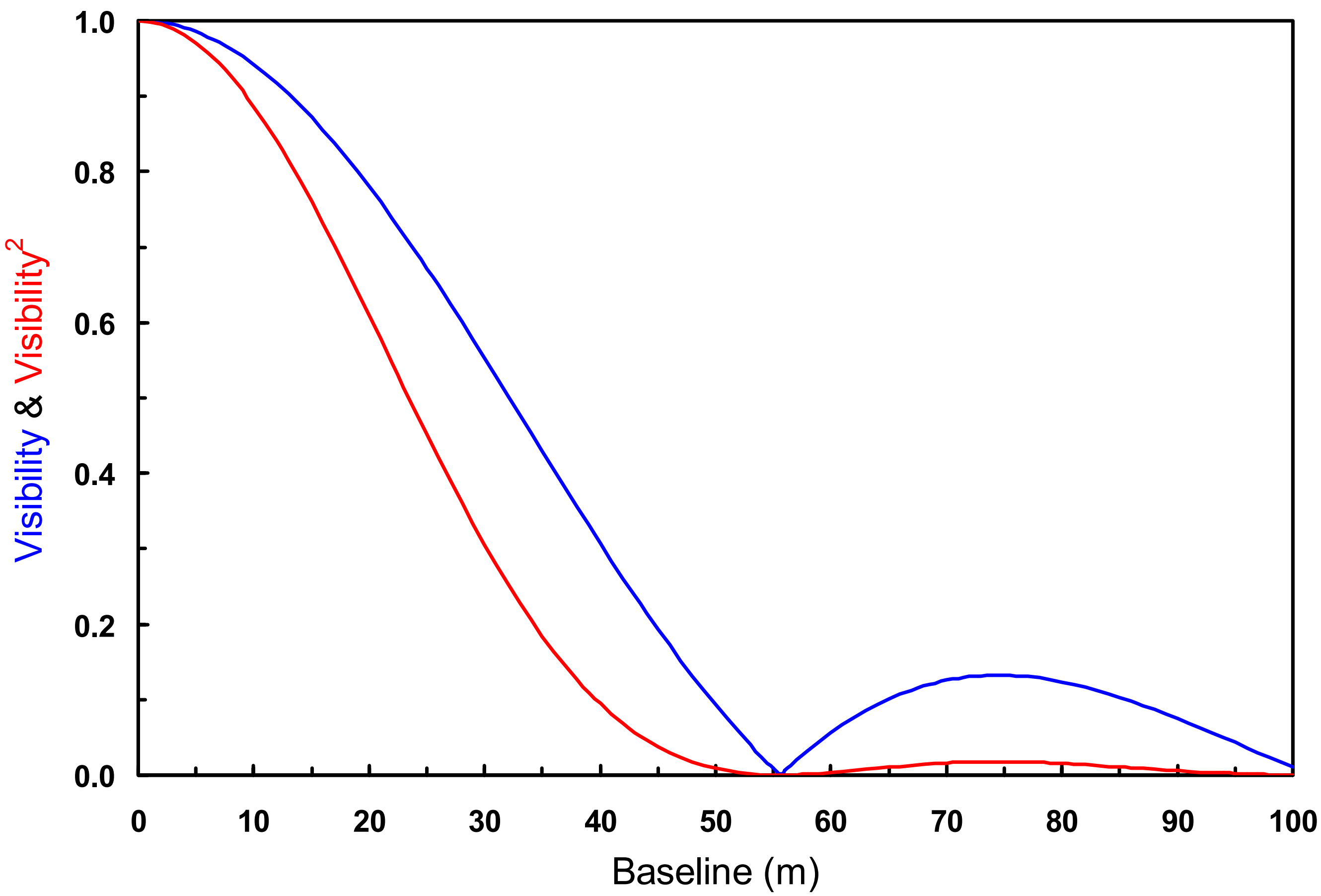
A comparison of 2.2 um uniform disk diameters measured with IOTA to those measured with CERGA and FLUOR

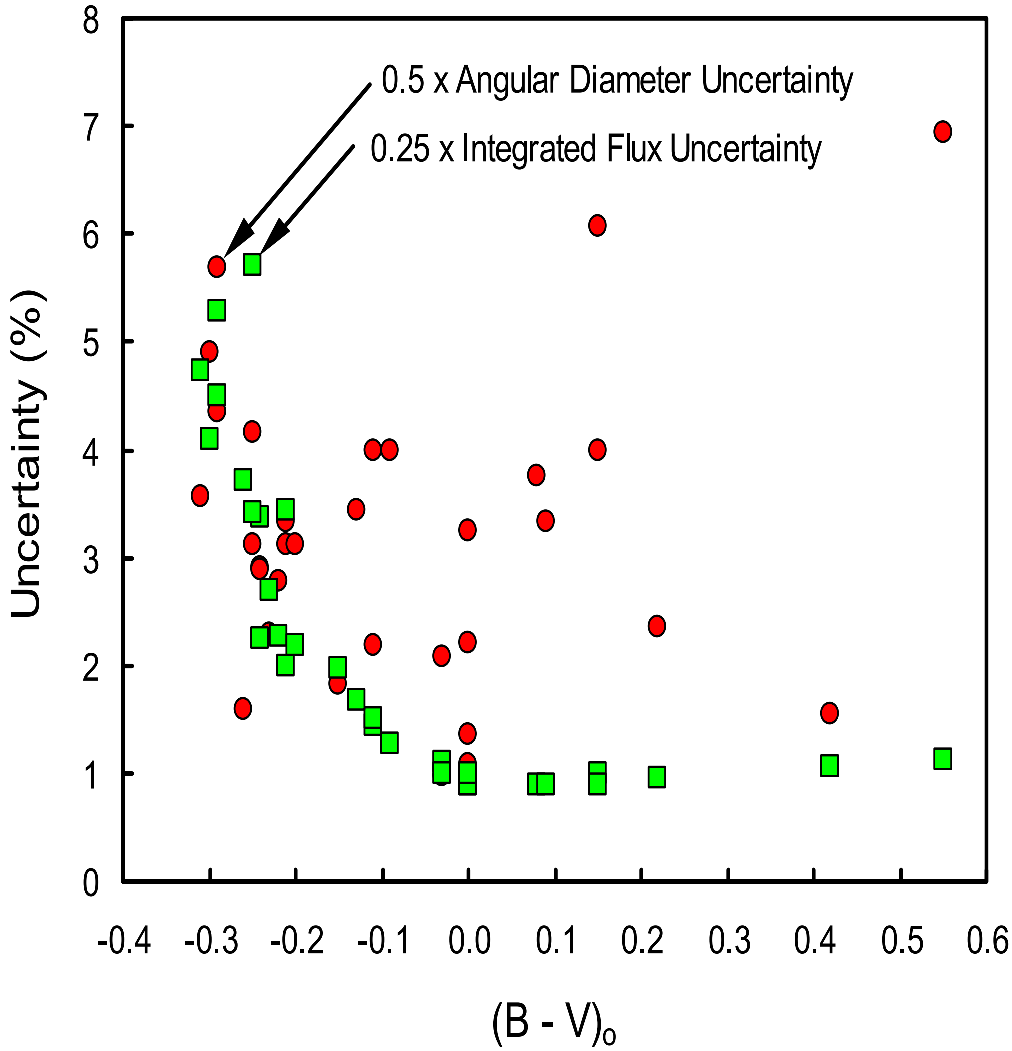


A comparison of limb-darkened angular diameters measured at NPOI and the Mark III at red wavelengths

Visibility v. Baseline for a Uniformly Illuminated Disk

(Angular Diameter = 2.0 mas: Wavelength = 442 nm)



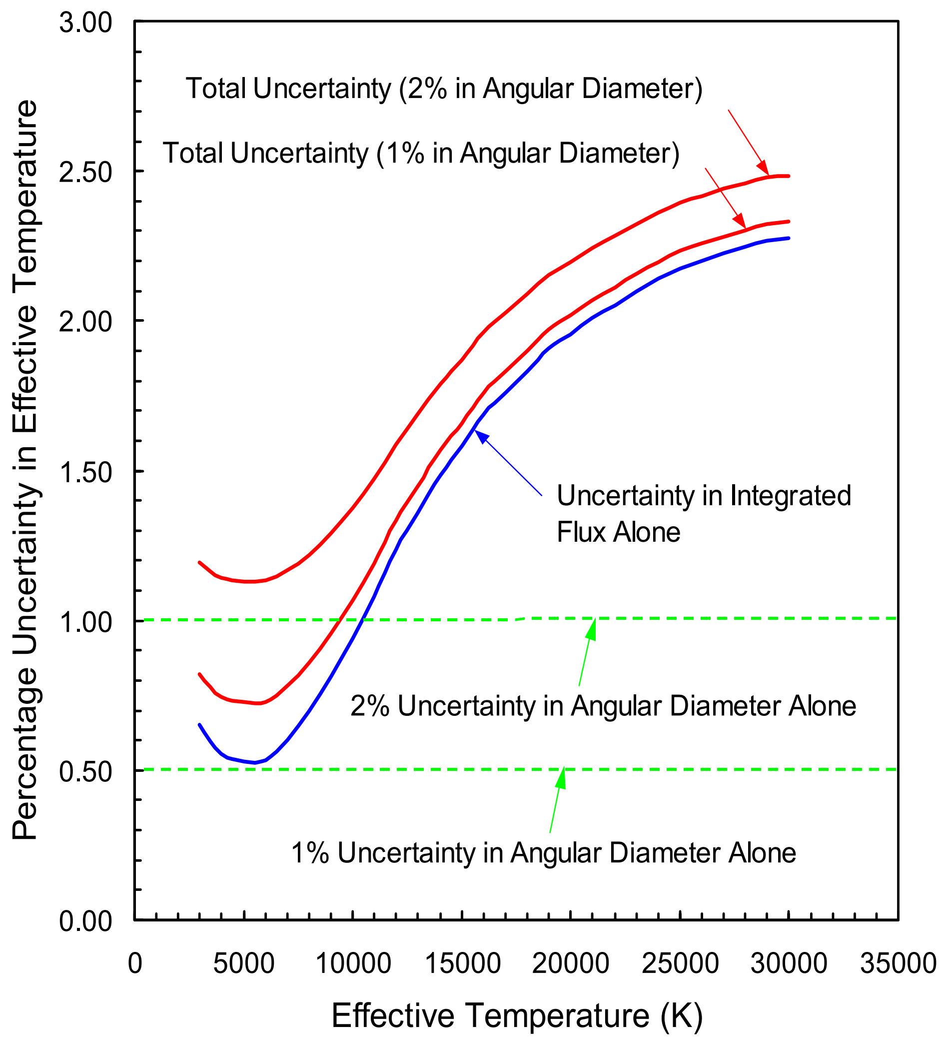


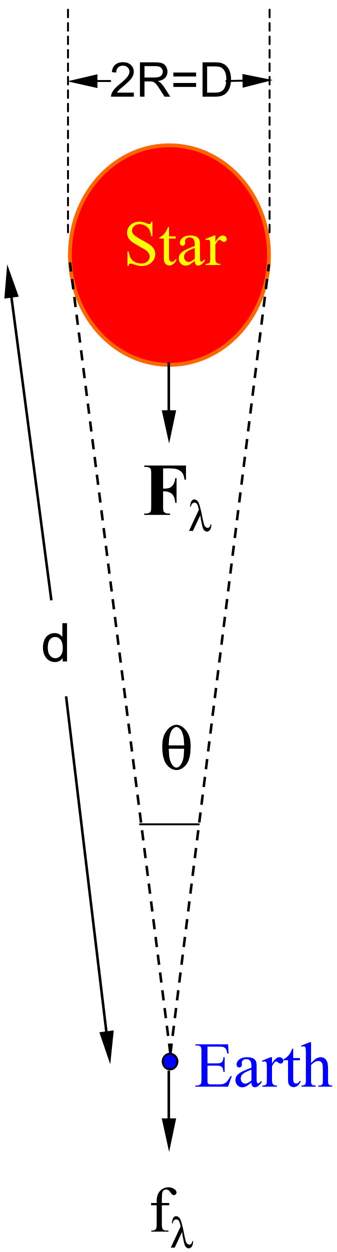
NSII: 32 Stars

$$\sigma T_e^4 = \frac{4f}{\theta^2}$$

$$\therefore \quad T_e \propto f^{0.25}\,\theta^{-0.5}$$

Uncertainty in Effective Temperatures





Angular diameter plus flux data:

$$4\pi R^2 \mathbf{F}_\lambda = 4\pi d^2 f_\lambda$$

$$\therefore \quad \mathbf{F}_\lambda = \frac{4}{\theta^2} . f_\lambda$$

Emergent Flux

$$\int_0^\infty \mathbf{F}_\lambda . d\lambda = \int_0^\infty \frac{4}{\theta^2} . f_\lambda . d\lambda = \sigma T_e^4$$

Effective Temperature

If the distance is known:

$$2R = D = d\,\theta$$

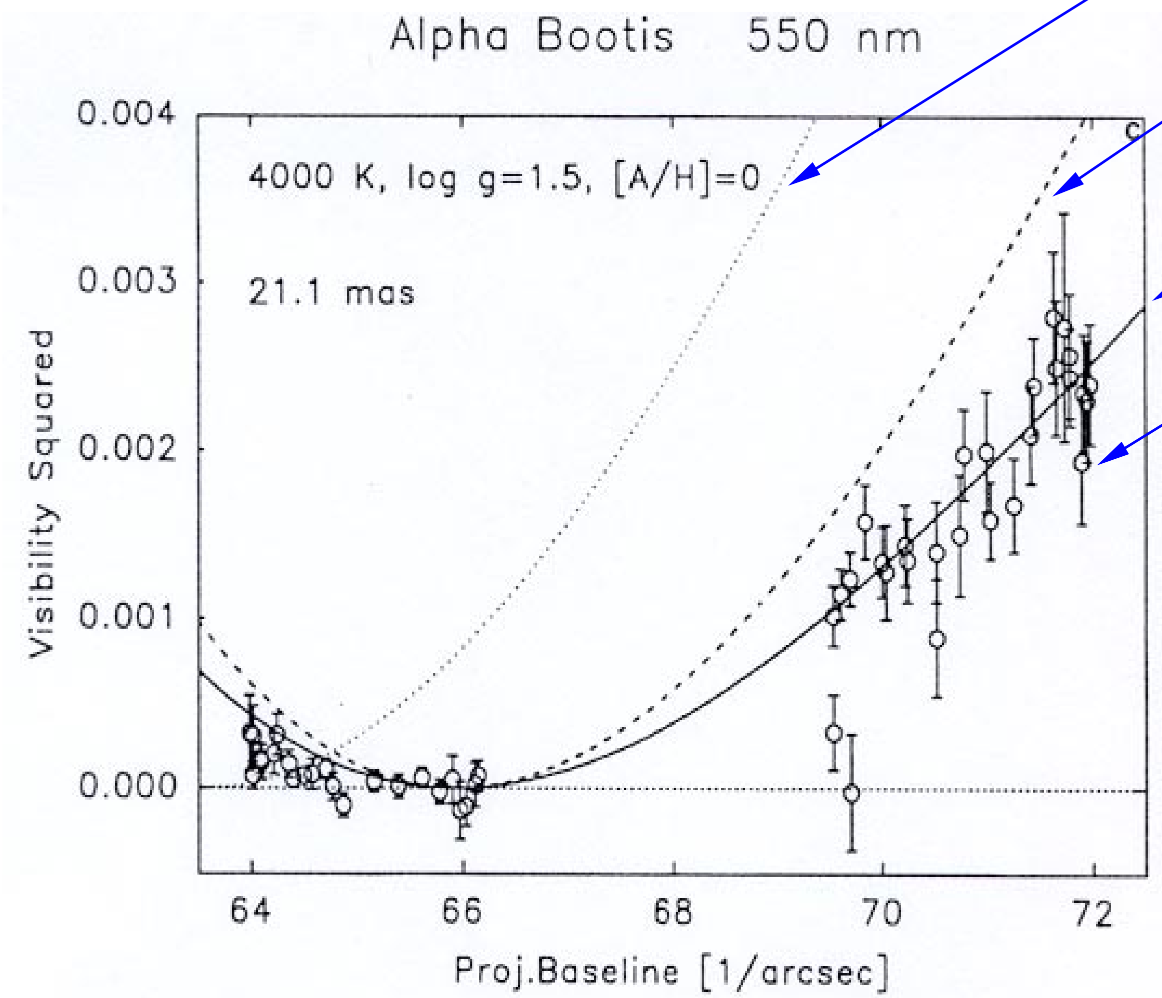
Radius

and $$L = 4\pi R^2 \sigma T_e^4$$

Luminosity

Limb Darkening for Arcturus

(Ref: Quirrenbach et al., A&A, 312, 160, 1996)



θ_{UD} = 19.18 mas: best fit at short baseline

θ_{UD} = 18.50 mas: null matched to model

Model (Manduca et al., A&A, 61, 809, 1977)

Mark III Data

A Whole Lot More!

Examples include:

•Pulsating stars - e.g. Cepheids, Miras

•Rotation - absolute, distortion

•Pre-main sequence objects

•Young stars - structure and morphology

•Extended corona

•Hot star emission envelopes, shells, winds etc.

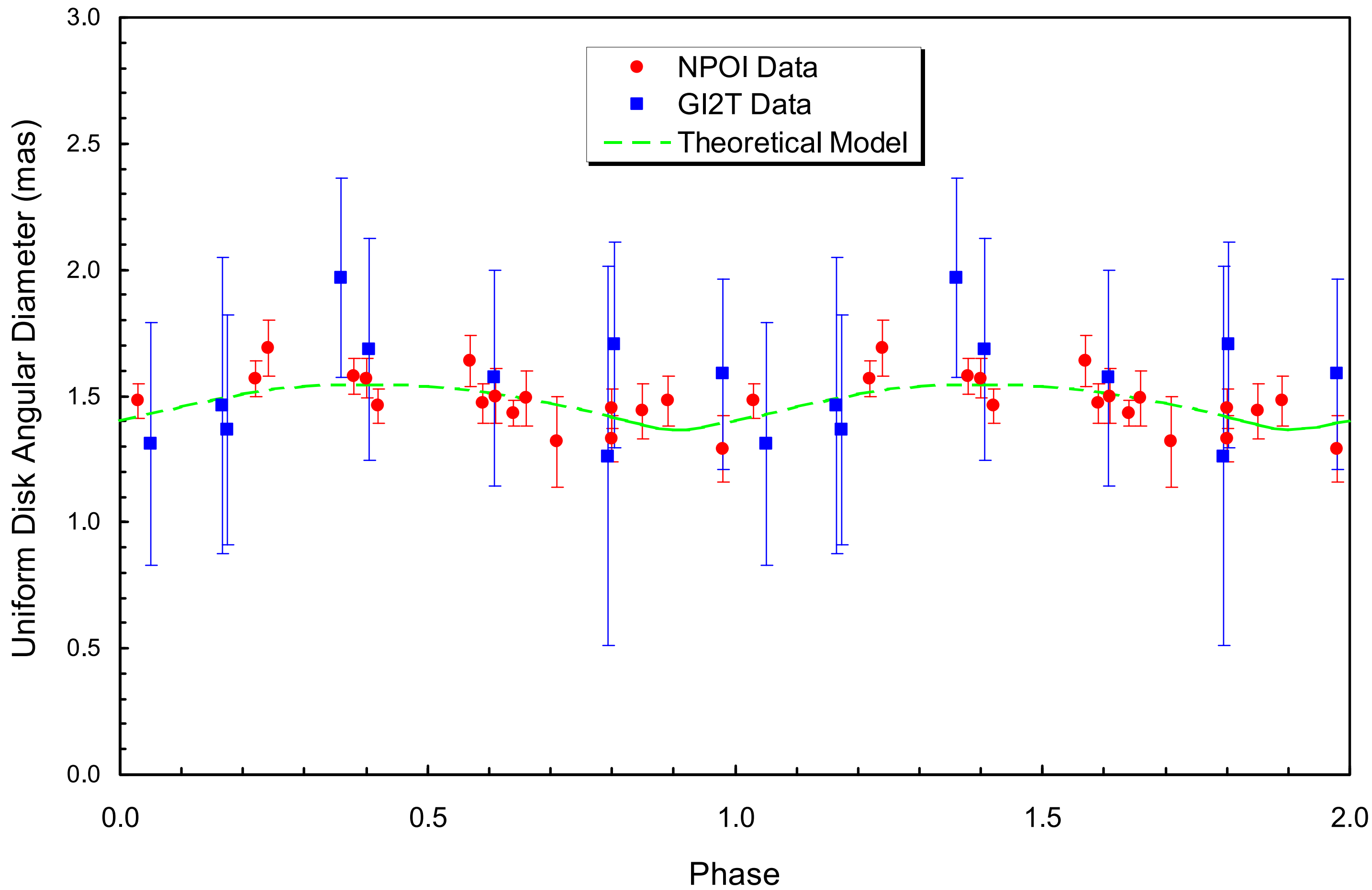
•Cool star circumstellar dust shells

•Novae/Supernovae

•Images - stellar surface features plus several of the above items

•etc.

Interferometric Observations of δ Cephei



Mean limb-darkened disk diameter = 1.520 ± 0.014 mas but variation only at ~1.5 σ level

Cepheids

Distance $d = 2\Delta R/\Delta\theta$

Interferometry: Measure θ and $\Delta\theta$

For $\sigma_\theta = \pm 1\%$:
$\sigma_{\Delta\theta} = \pm 5\%$ to $\pm 15\%$ depending on $\Delta R/R$

Spectroscopy: Measure ΔR

Difficulties

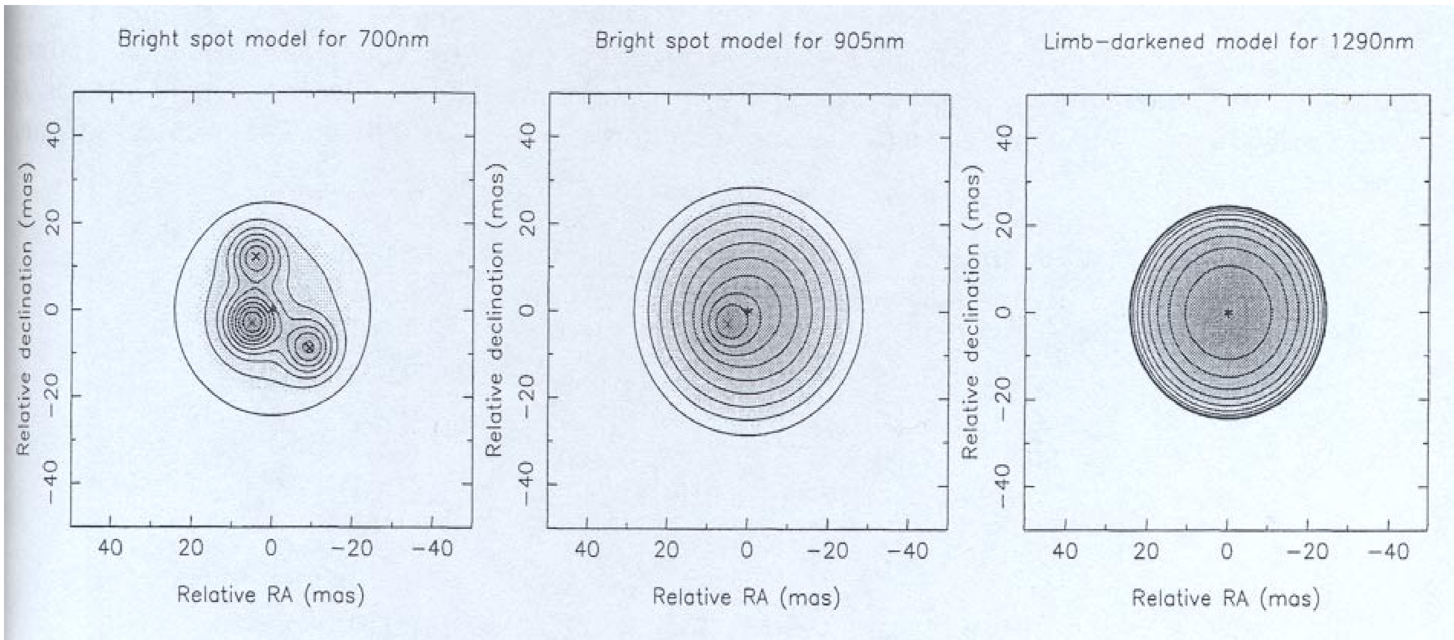
- Ideally the ΔR and $\Delta\theta$ values would have comparable percentage errors but there are difficulties:
  - Pulsation factor
  - Radial velocity measurements – velocities depend on lines measured, the measurement technique, the velocity gradient in the atmosphere, etc.
  - Limb darkening
  - Differences in velocities in line and continuum forming regions

Conclusions

- ΔR will limit the accuracy of distance determinations
- Need hydrodynamic, non-LTE, pulsational models of Cepheid atmospheres to reproduce observed velocity curves, line asymmetries etc.
- Measurement of many Cepheids would improve accuracy and give an independent calibration of the zero point of the Cepheid luminosity scale

Brightness distributions for Betelgeuse

Ref: Young et al, SPIE 4006,472-480, 2000



WHT COAST COAST

Ground-Based Long-Baseline Optical/IR Interferometers

Instrument Acronym	Institution	Location	Aperture Diameter (m)	Maximum Baseline (m)	Wavelength Range (μm)	Status
NSII	Sydney U.	Narrabri, Australia	2×6.8	188	0.44	C
SUSI (P'type)	Sydney U.	Sydney, Australia	2×0.10	11	0.4-0.5	C
Mark III	NRL/MIT/CfA	Mt. Wilson, USA	2×0.05	32	0.45-0.8	C
I2T	CERGA	Calern, France	2×0.26	144	Visible	C
GI2T	CERGA	Calern, France	2×1.5	65	Visible/IR	W
COAST	Cambridge U.	Cambridge, UK	5×0.4	100	Red/near IR	W
SUSI	Sydney U.	Narrabri, Australia	2×0.14	640	0.4-0.9	W
IOTA	CfA	Mt.Hopkins, USA	3×0.45	38	Visible/IR	W
ISI	UC Berkeley	Mt. Wilson, USA	2×1.65	70	10	W
NPOI	USNO/NRL	Anderson Mesa, USA	2×6.17	435	0.45-0.9	W
PTI	JPL/Caltech	Mt. Palomar, USA	2×0.4	110	2.2	W
CHARA	Georgia St. U.	Mt. Wilson, USA	6×1.0	350	0.45-2.4	UC
Keck	CARA	Mauna Kea, USA	2(4)×10(1.5)	165	2.2-10	UC
VLTI	ESO	Cerro Paranal, Chile	4(3)×8(1.8)	200	0.45-20	UC

KEY: C = Closed; W = Working; UC = Undergoing commissioning or under construction