Direct Observations of Rotationally Distorted Stars

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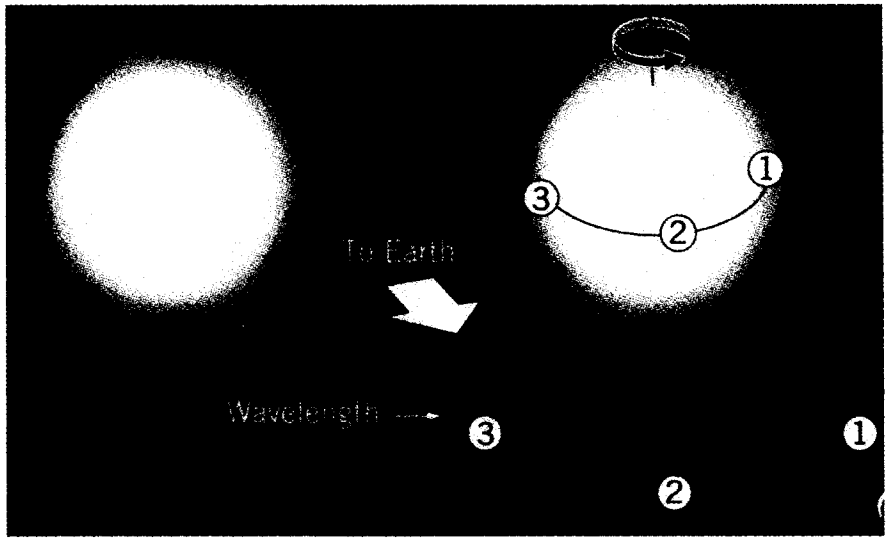
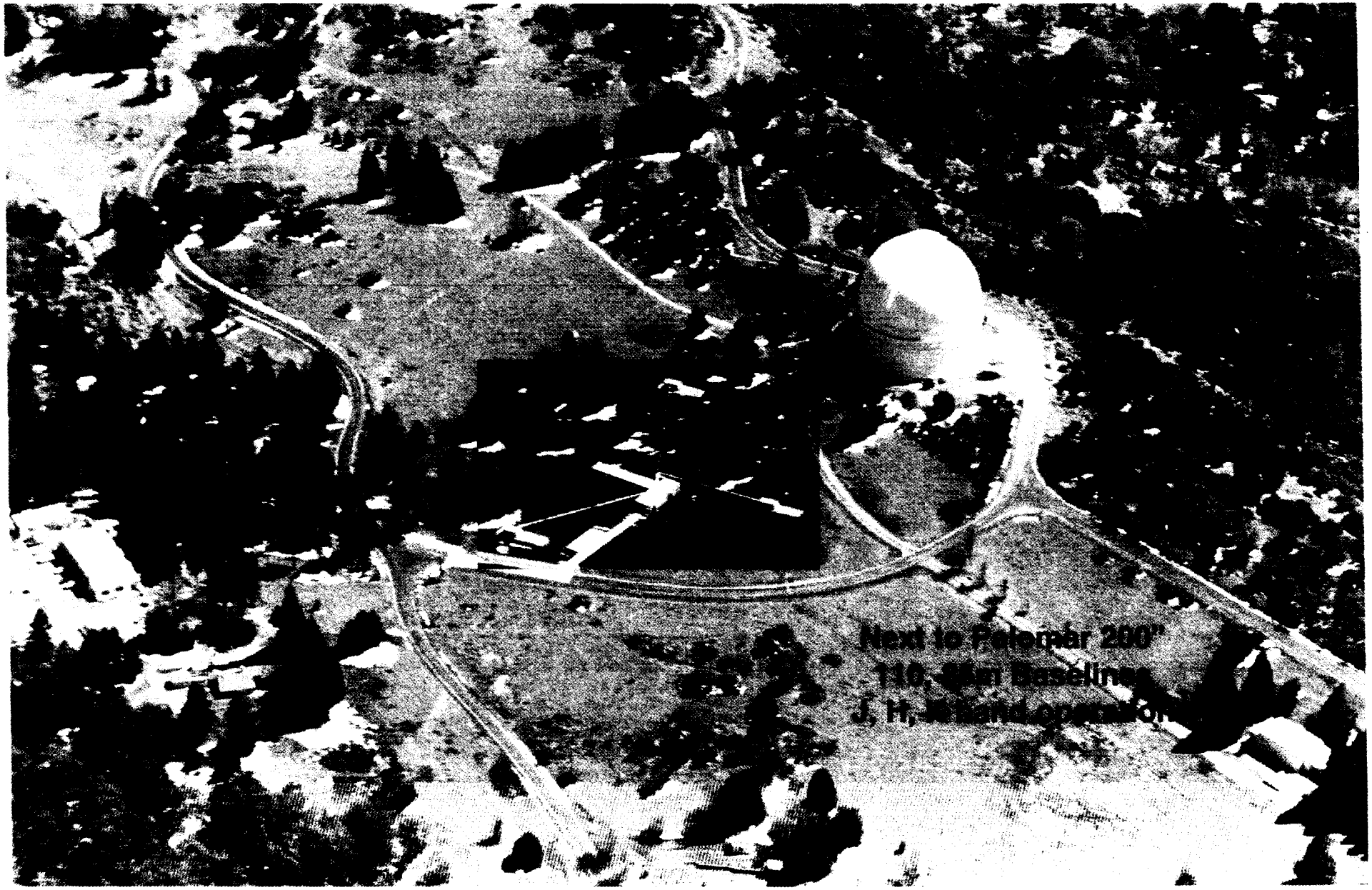
Spectral Inference of Rapid Rotation

- Rapidly rotating stars show line broadening
- Provides a independent check of our interferometric results
- Extreme rapid rotators can be difficult to characterize spectroscopically due to excessive line smearing



The Palomar Testbed Interferometer



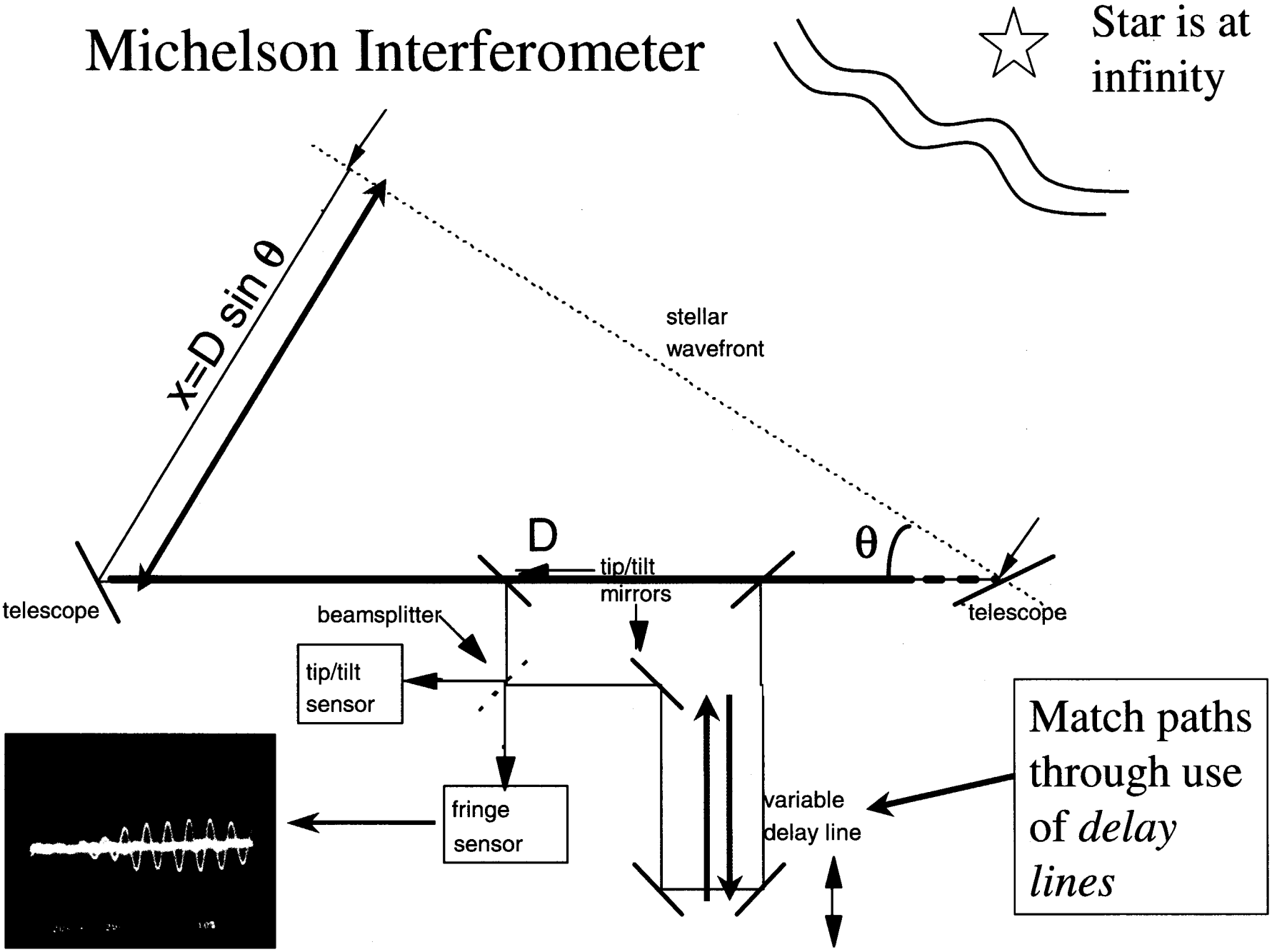
Palomar Testbed Interferometer (PTI)

- PTI is a Near-IR (K & H-band) single-baseline interferometer
  - NS and NW baseline combination
  - NICMOS array combiner
  - Point Src Limiting Mag K ~ 6.5
  - Scientific Limiting Mag K ~ 5.7

http://huey.jpl.nasa.gov/palomar

- Single and Dual-Beam Interferometry:
  - Visibility (V^2) measurement => modelling (simple morphology like one or two stars)
  - Simultaneous fringe tracking on two nearby stars => differential astrometry

Michelson Interferometer

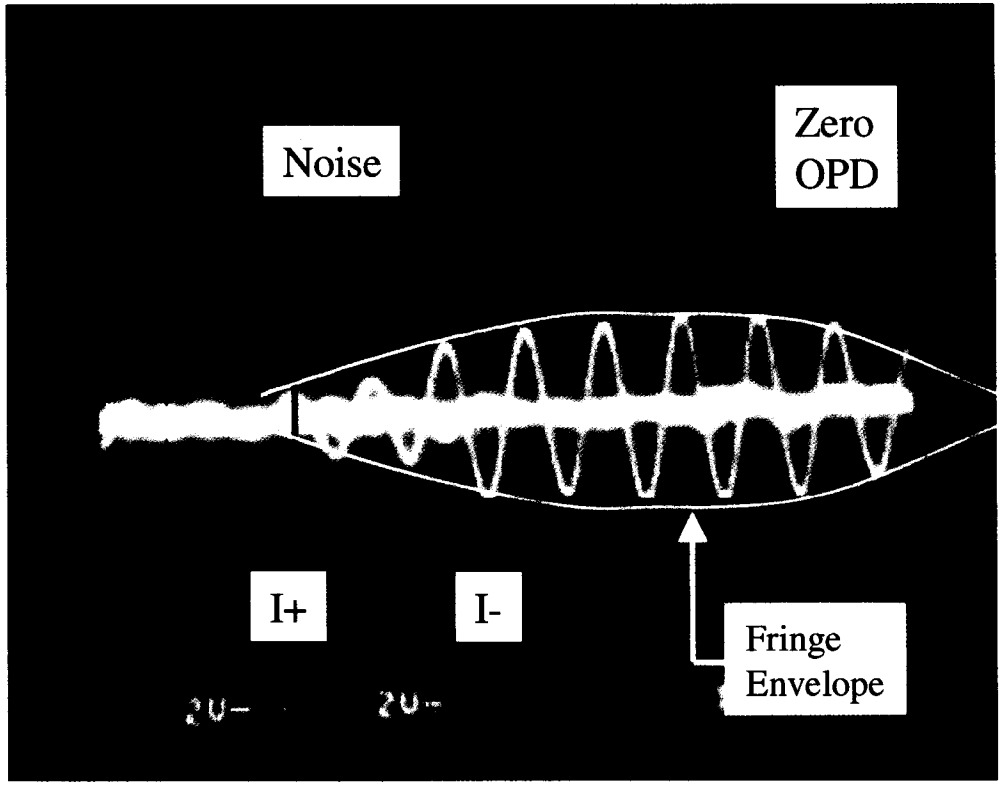


Fringe Visibility

- Constructive & destructive interference of light
- Fringe contrast or visibility:

$$V = \frac{I^+ - I^-}{I^+ + I^-}$$

- Calibration issues
  - Detector linearity
  - Zero point measm't
  - Noise characterizat'n



Actual starlight fringes from IOTA - β And
Photo credit: R.R. Thompson

Visibility Function

- For a 'uniform disk', visibility matches:

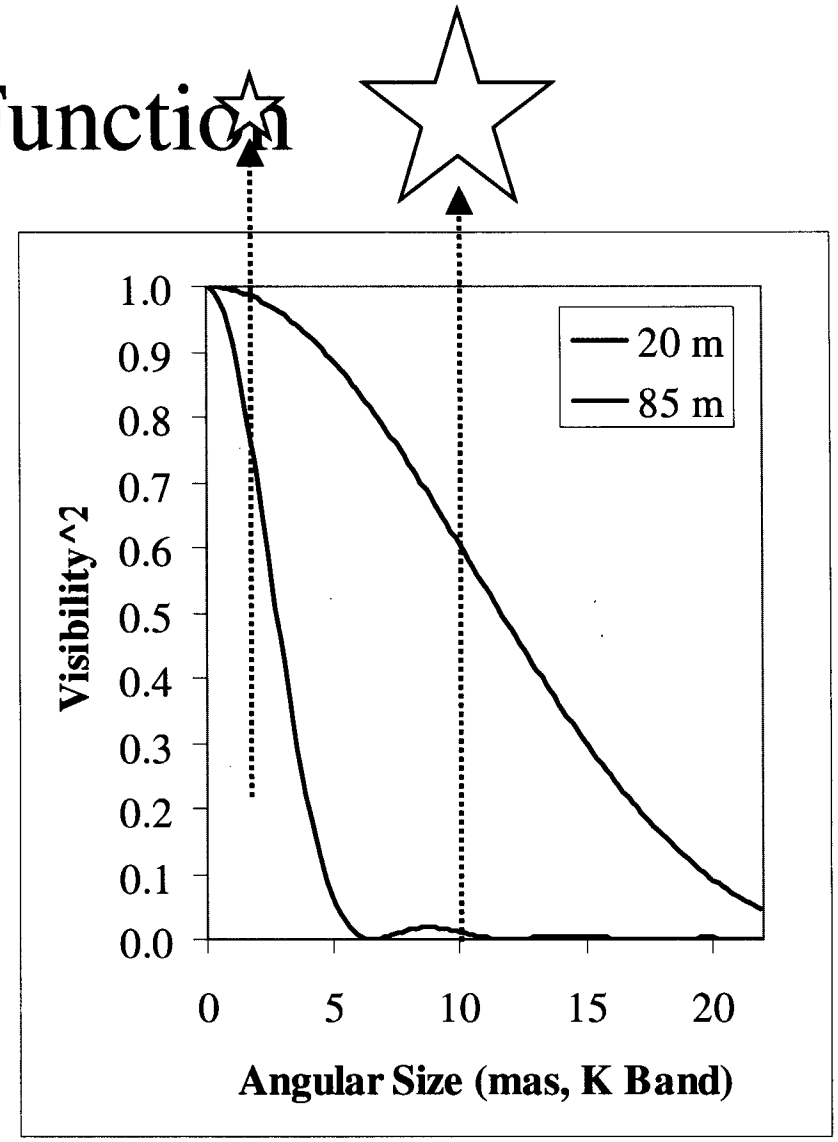
$$V = \frac{J_1(x)}{x} \quad \text{where} \quad x = \frac{\pi\theta B}{\lambda}$$

B is the projected baseline

θ is the stellar disk size

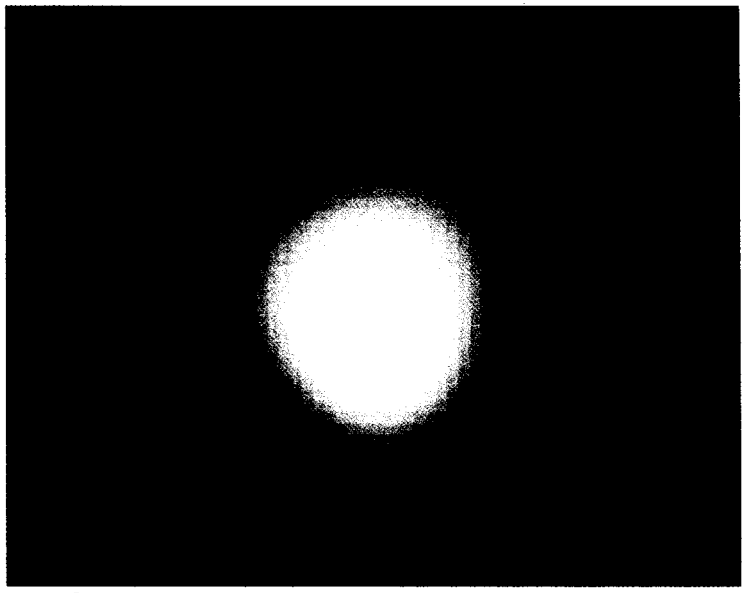
λ is the instrumental wavelength

- Baseline, wavelength known
  - Can solve for θ
- Use V^2 instead of V
  - Unbiased estimator of visibility
  - See Colavita (1999)

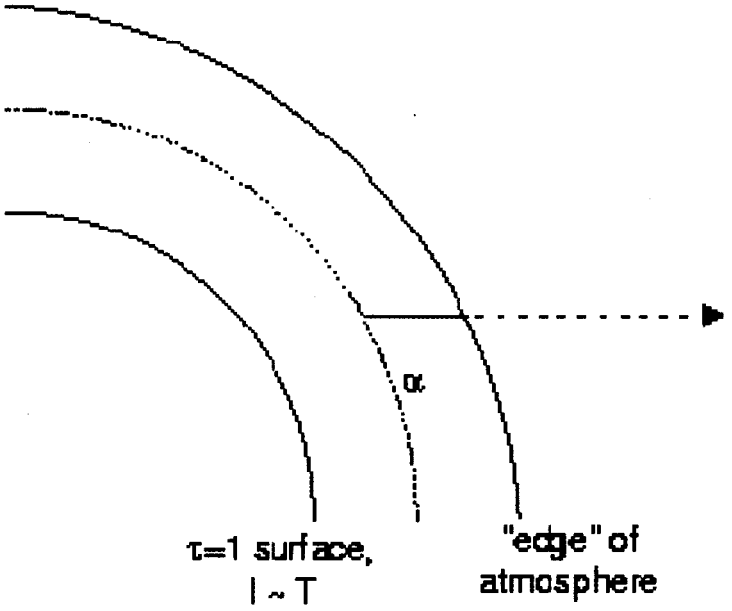


Limb darkening

- Stars are *not* uniform disks
- Gaseous, not solid, sphere
  - End up looking 'into' the star
- Good and bad
  - Have to account for this
  - Measuring this can be used to characterize internal structure of star
  - Direct probe of internal temperature stucture

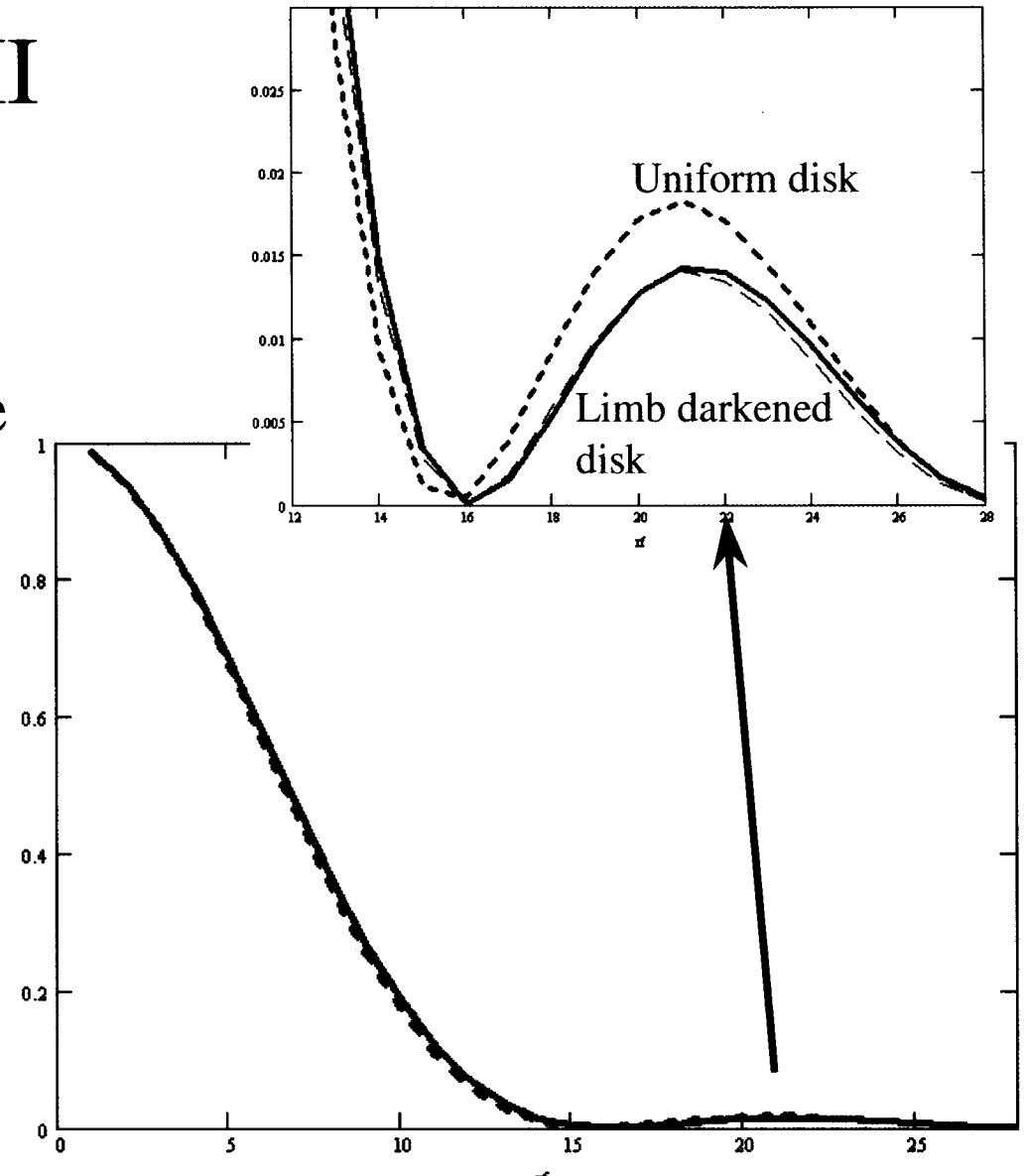


HST Image of α Ori - Betelgeuse



Limb darkening. II

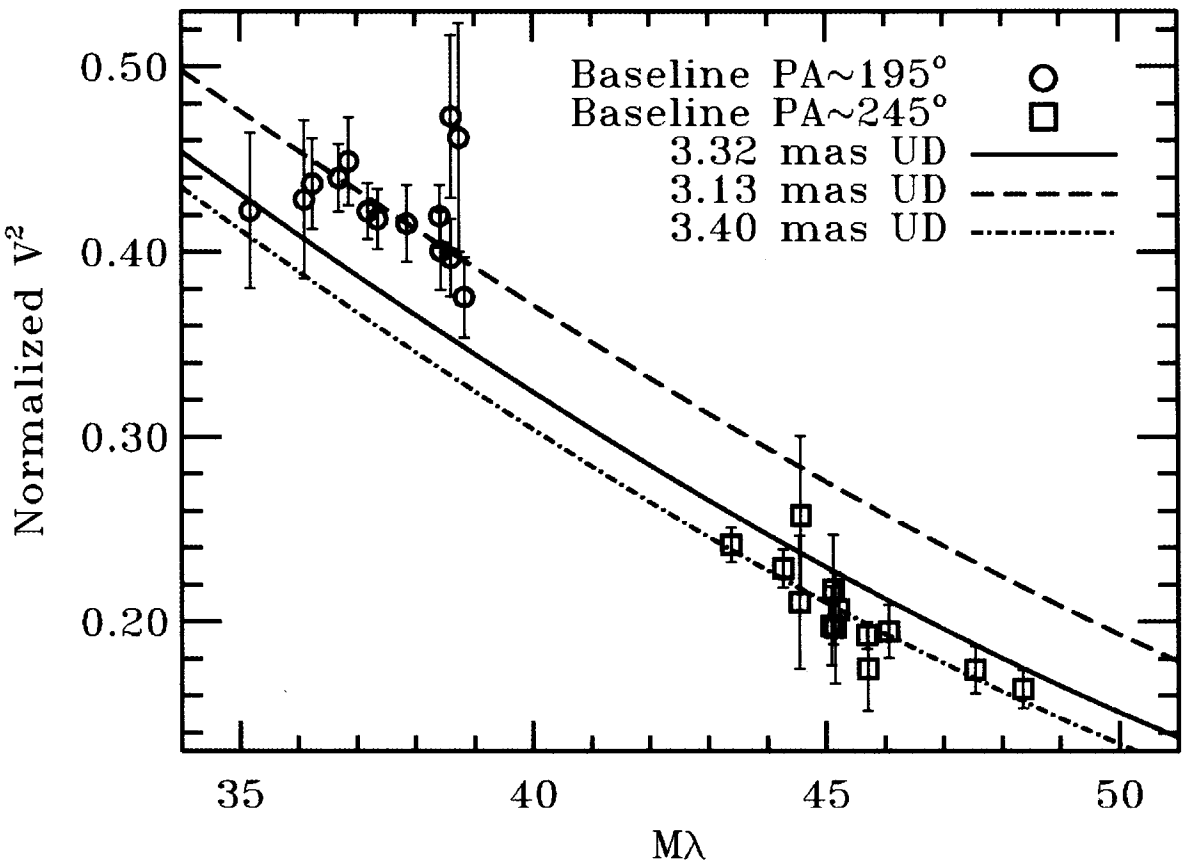
- Effects are less striking in the near-IR
- Most of the effects are seen at the higher spatial frequencies
- Acceptable to do a UD fit, and scale
  - Corrections are ~1.5% for main seq.
  - Higher for evolved stars
  - Gives the size of the mean radiating surface



A-type Star Model (Claret et al. 1995)

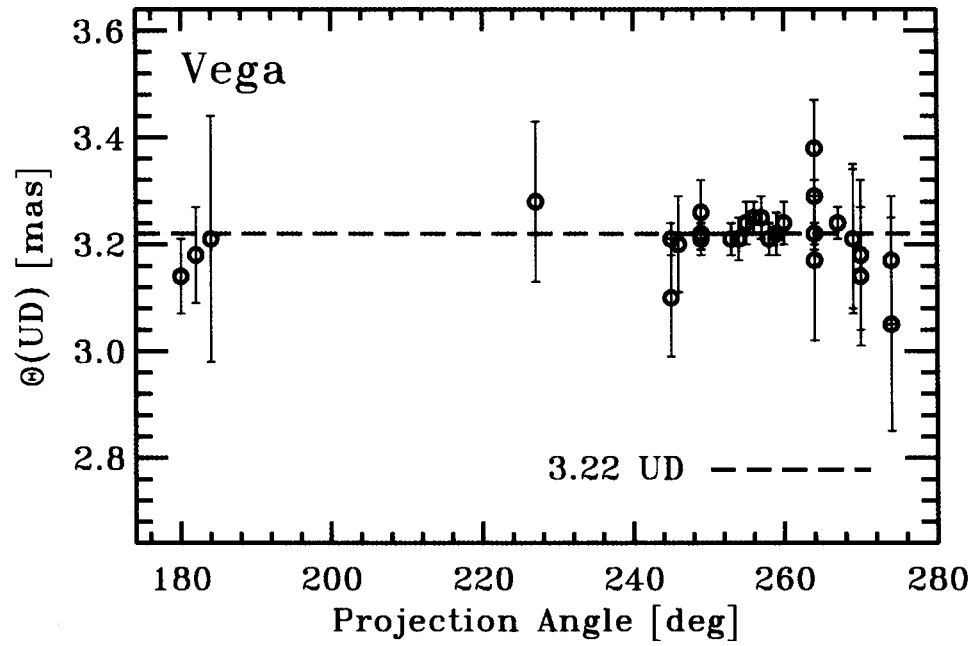
Initial Indications of Something Interesting with Altair

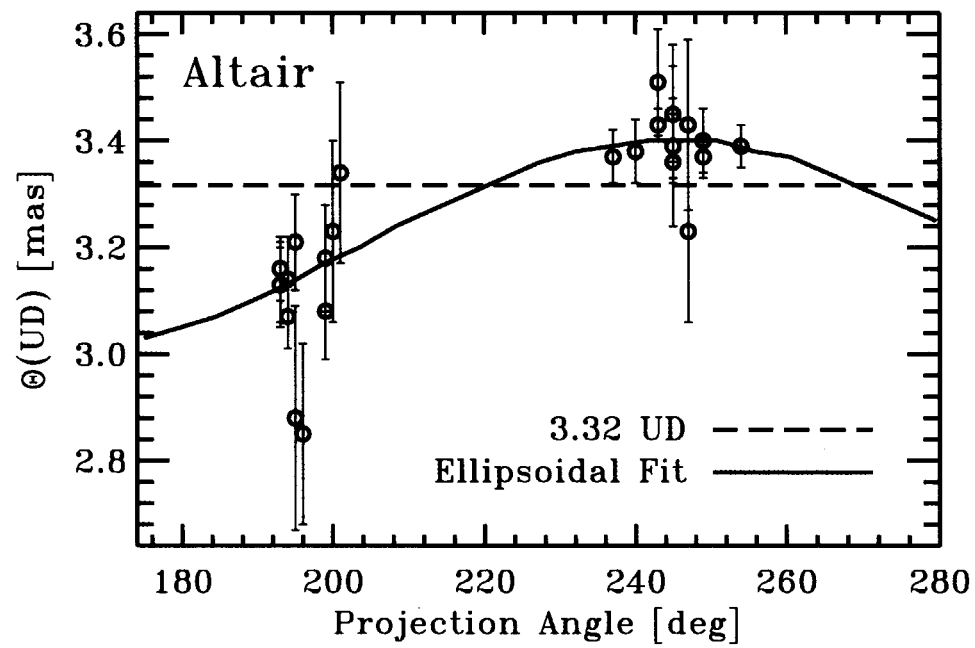
- Use of the PTI N-S and N-W baselines gave different angular sizes
- Not explainable in terms of limb darkening, spotting



Contemporaneous Measurements Appear Normal

- Vega had been observed on the same nights, at the same time
- No apparent θ(UD) evolution with projection angle



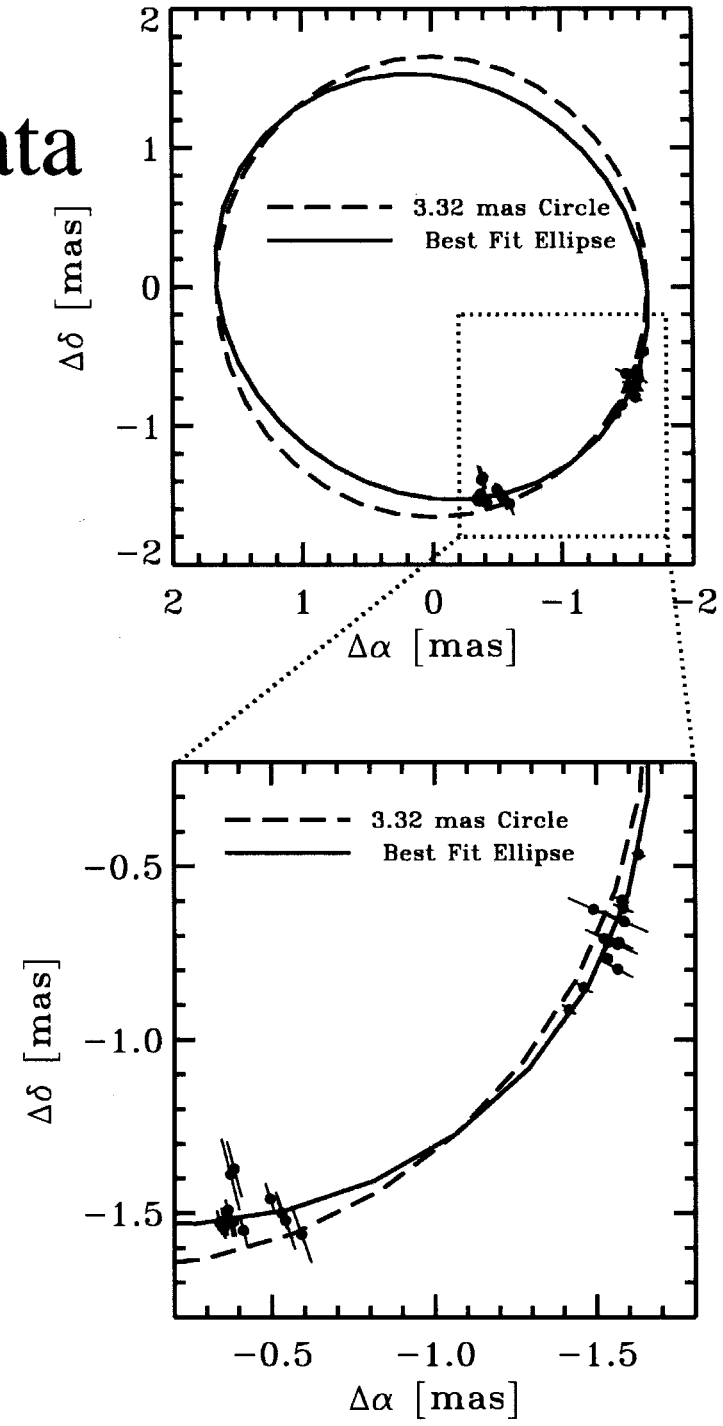


Ellipsoidal Fit to Altair Data

- Measurement of Altair's angular size with PTI's N-S and N-W baselines
  - ~50° between the baselines
- Best fit is an ellipse
  - a/b = 1.140±0.029
  - a-b = 424±79 μas
- Star is a known rapid rotator
  - Can derive rotational velocity:

$$v \sin i = \sqrt{\frac{2GM}{R_b}\left(1 - \frac{R_b}{R_a}\right)}$$

  - $v \sin i = 224 \pm 28$ km s^{-1}



The Roche Model

- Shape defined by local radius $R(\theta,\omega)$ of an equipotential surface:

$$\Phi = const \quad = \frac{GM}{R} + \frac{1}{2}\omega^2 R^2 \sin^2\theta$$

$$= \frac{GM}{R_p(\omega)}$$

where θ is the colatitude and $R_p(\omega)$ is the polar radius

Solving for the Roche Model

- A solution for the colatitude- and rotation speed-dependent radius:

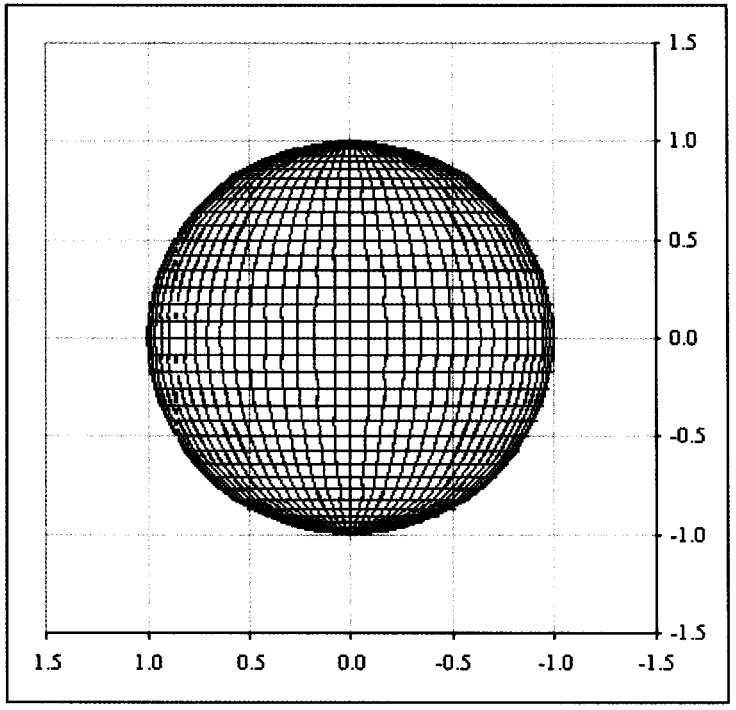
$$r(\theta,u)=\frac{R(\theta,u)}{R_p}=\frac{3}{u\sin\theta}\cos\left[\frac{\cos^{-1}(-u\sin\theta)+4\pi}{3}\right]$$

where u is the fractional rotation speed and $r(\theta,\omega)$ is the normalized radius. u is defined as:

$$\omega^2=u^2\frac{8}{27}\frac{GM}{R_p^{\,3}(\omega)}$$

Elements of a Roche Model. I

- Four independent parameters define Roche model on the backdrop of the sky
  - i – inclination
  - α – orientation
  - R_p – polar radius
  - u – fractional rotational speed
- Assumes a mass M and distance d for the object is known

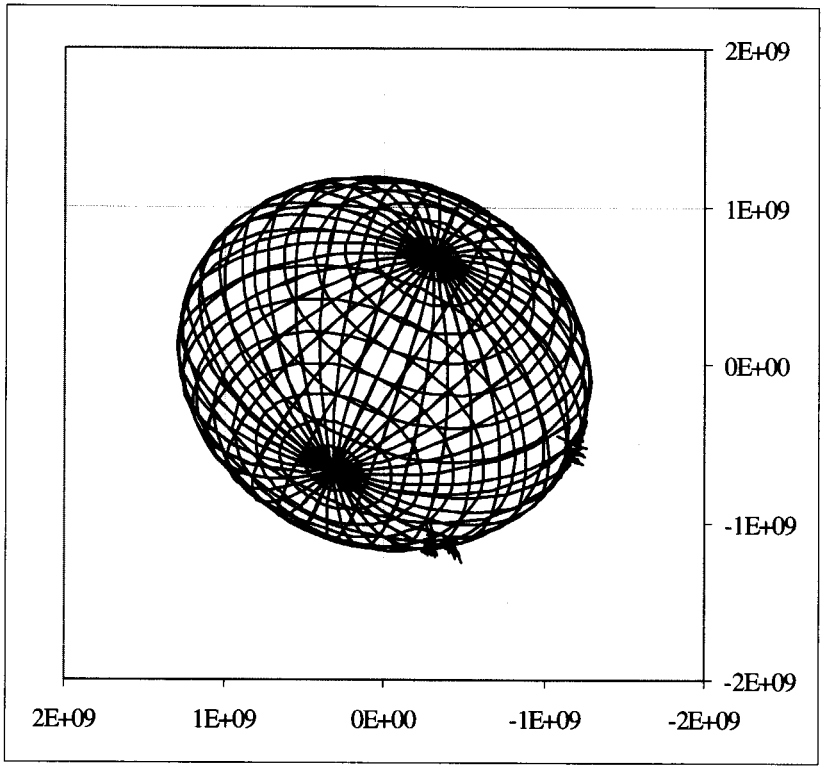


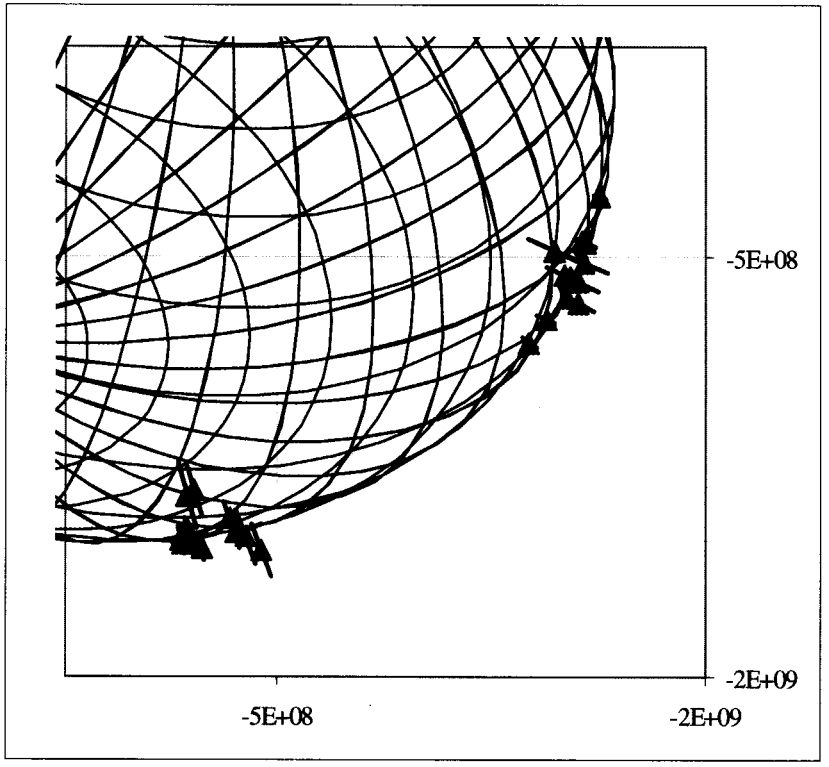
Noteworthy Assumptions

- Rigid rotation
  - Poor assumption for most stars
  - But actually not bad for A-type stars
- Uniform disk illumination
  - Again, poor assumption for most stars
  - Expected gravity darkening will be low contrast for Altair in near-IR
  - Again, actually not bad for A-type stars
- Working in image space, not Fourier space
  - Downright dangerous assumption
  - Will change the analysis in future experiments

Monte Carlo Fitting

- Can randomly generate values for $\{i, \alpha, R_p, u\}$ and examine χ^2 of fit
- Brute-force examination of $\chi^2(i, \alpha, R_p, u)$ can reveal global minima in χ^2 space



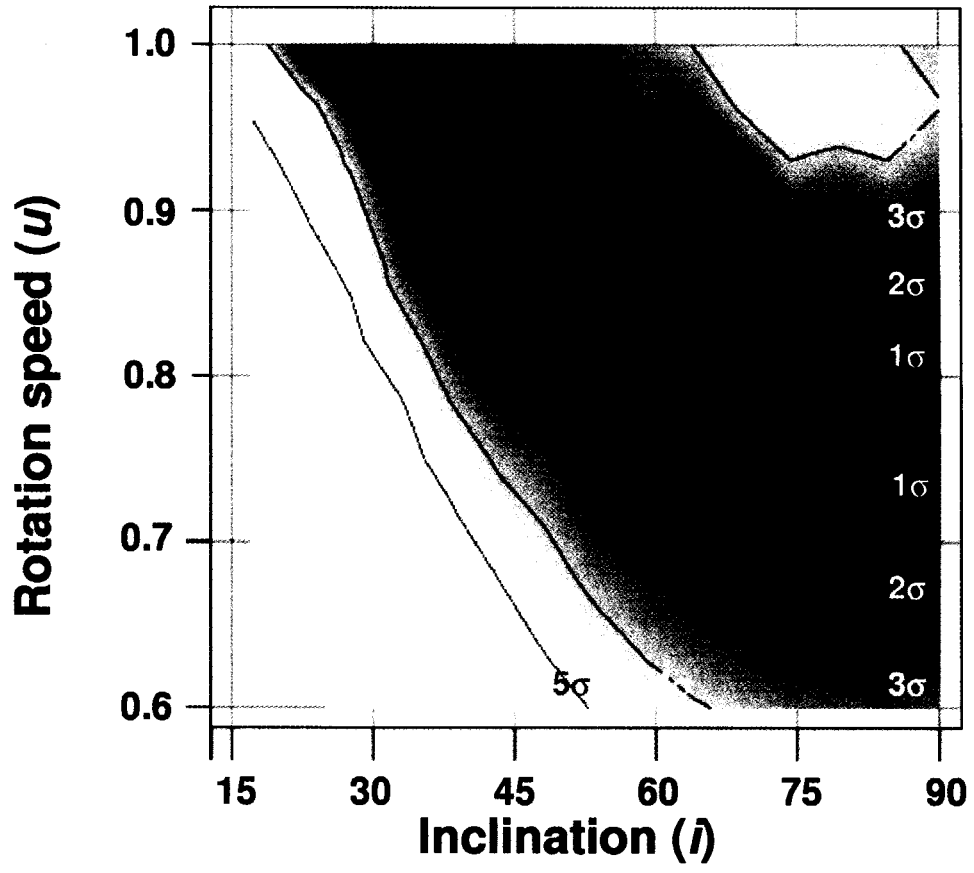


Results of the Minima Search

- No statistically significant global minima found for $\{i, \alpha, R_p, u\}$
  - For rich enough inteferometric data sets, unique solutions *are* possible
- However, a minima 'trough' found in $\{i,u\}$

$$u = 4.961\times10^{-5}(90-i)^2 + 1.116\times10^{-3}(90-i) + 0.762$$

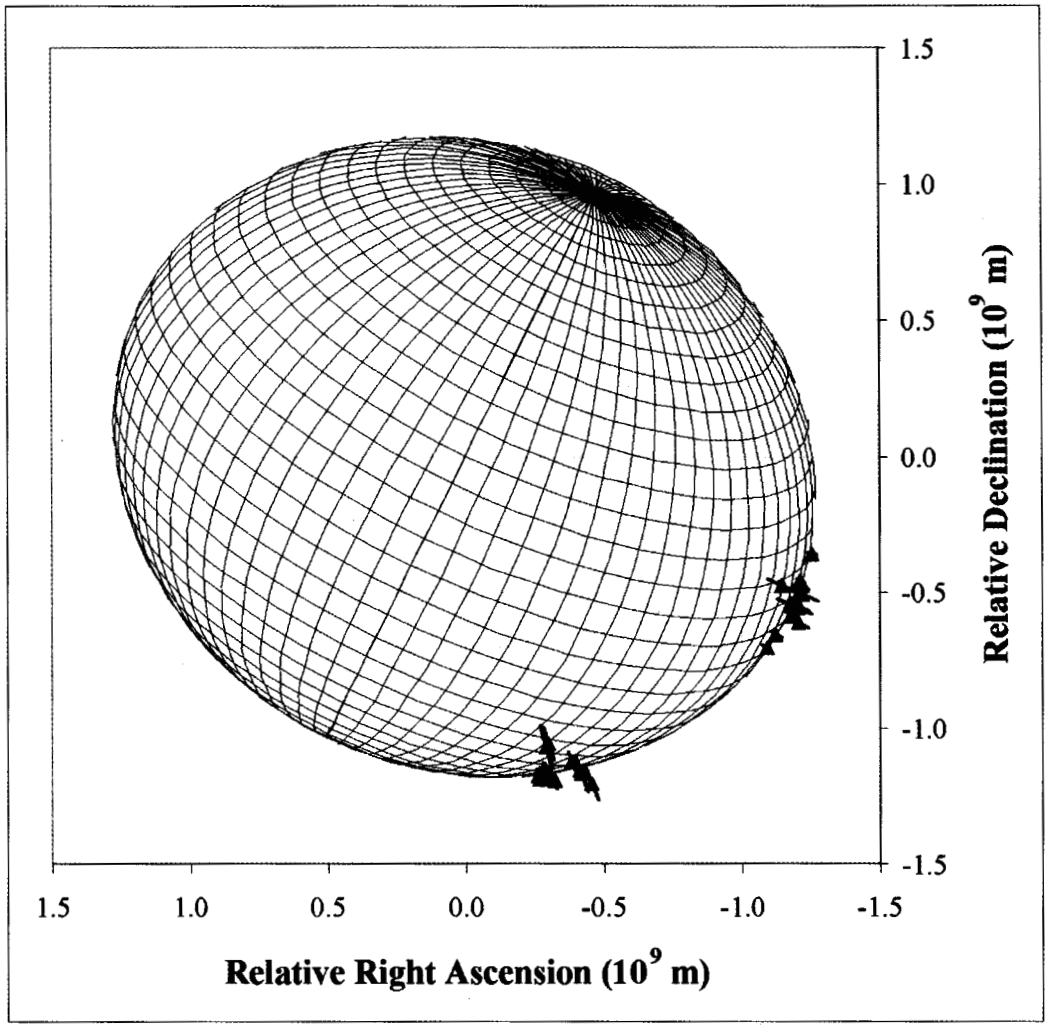
- No inclination less than 30° is allowed, no speed less than 210 km/s



Altair χ^2 in $\{i,u\}$ subspace

Unique Apparent Rotational Velocity

- Family of models appear to fit data
  - A single projected rotation velocity agrees with these models
- Unique solution for $v \sin i = 210 \pm 12$ km/s
  - Independent of, and agrees with, $v \sin i$ from spectra
- Finding not inconsistent with NPOI data



Altair best fit: u=0.82, i=70°

Future Directions

- Other large (nearby) rapid rotators
  - eg. Regulus, eps Sgr
- Multiwavelength observations
  - Combine PTI, NPOI data in near-IR, visible
  - Directly probe latitude dependencies of radius and temperature
- Main limitation – resolution, not sensitivity
  - Need 250 or more meters to have a large (10+) sample size
  - New interferometers (CHARA, NPOI) will make this possible

Basic Parameters from Angular Diameters (θ)

- *Direct observation* of fundamental stellar parameters
- Effective temperature is defined as: $L = 4\pi\sigma R^2 T_{\mathrm{EFF}}{}^4$,

  which can be rewritten as: $T_{\mathrm{EFF}} = 1.316\times10^7 \left(\frac{F_{\mathrm{BOL}}}{\theta_{\mathrm{R}}^2} \right)^{1/4}$

  - F_{BOL} is the bolometric flux (W cm^{-2}), θ_{R} is the Rosseland mean stellar angular diameter (mas)
- Linear radius is simply: $R = \frac{1}{2}\theta \times d$
  - Hipparcos (Perryman et al. 1997) distances now available
  - Uncertainties in parallax (typically ~15-20%) still largest contribution to error