Direct Observations of Rotationally Distorted Stars

Gerard van Belle

Interferometry Science Center
California Institute of Technology

IAU 215: Stellar Rotation

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Acknowledgements

- Co-I's: David Ciardi (U. Florida), Bob Thompson (U. Wyoming/JPL), Rachael Akeson (IPAC)
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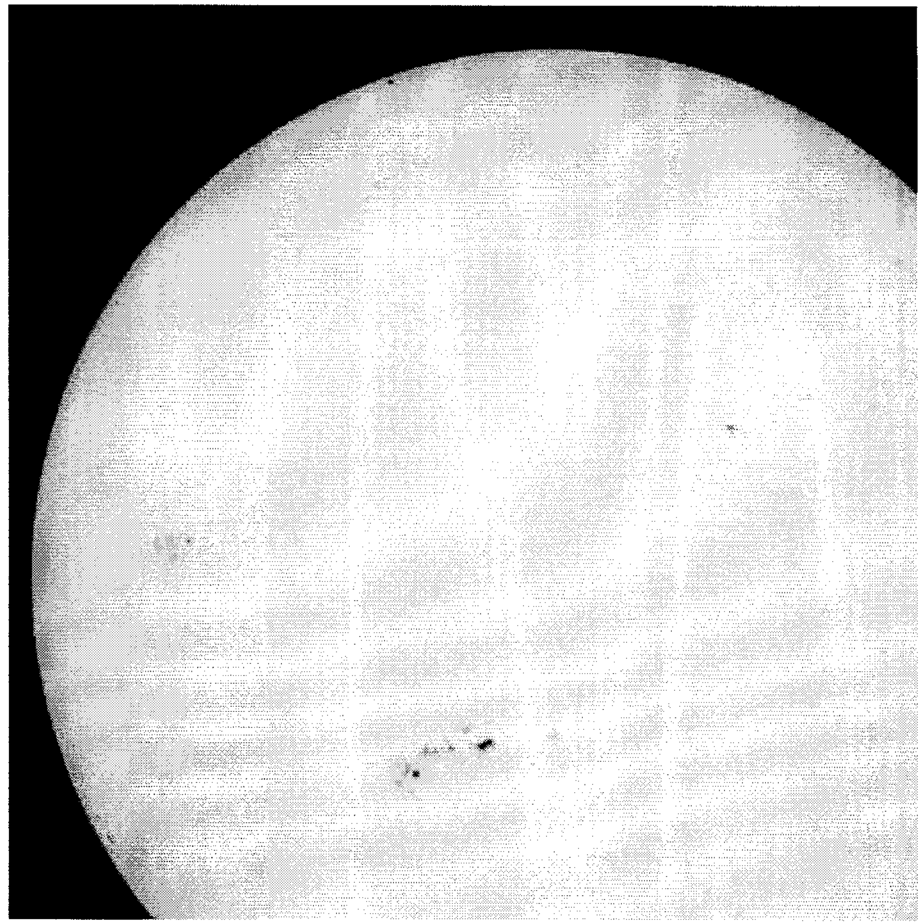
- Steve Howell (Planetary Sciences Institute), Francis Wilkin (JPL/Caltech)

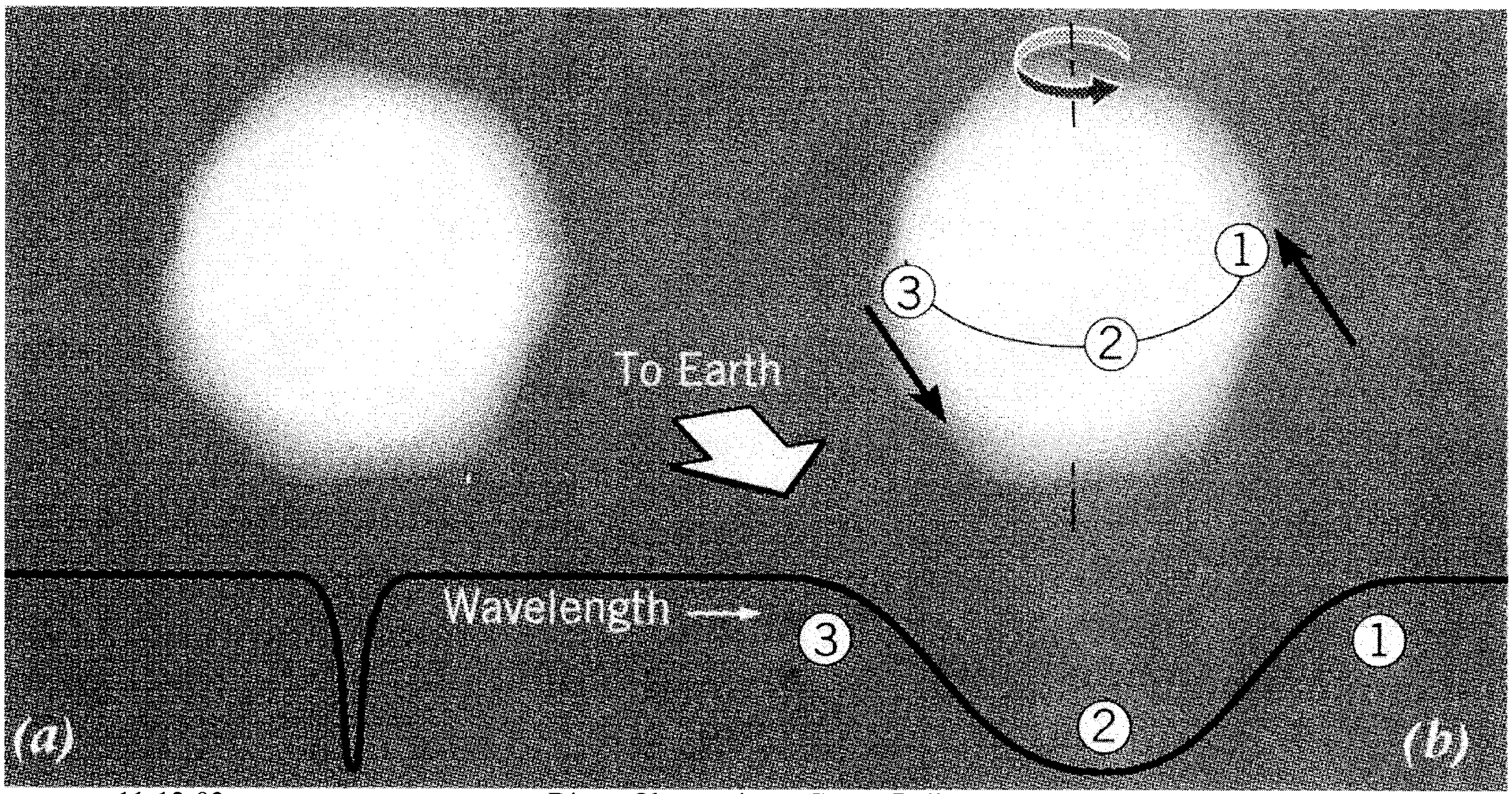
Really High Resolution Stellar Observations

- Observations of the sun
  - Roughly 1,000,000× closer than any other star
  - SOHO observations of the Sun
- Interesting structure
  - Sun spots
  - Phlages
  - Prominences
  - Mass ejections
- Interactions with the surrounding environment
- Wish to extend these observations to other stars



Dynamics of the Stars

- Rapidly rotating stars show line broadening



Firsts in Stellar Rotation: Theory

- Capt. W. de W. Abney (1877)
  - First to suggest axial rotation of stars could be observed from spectral line rotation
- Suggestion was swiftly rebuked by Vogel (1877)

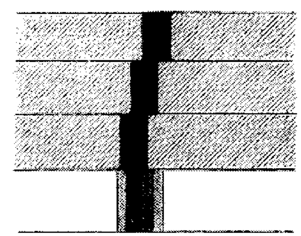
Effect of a Star's Rotation on its Spectrum.

By Capt. W. de W. Abney.

Having privately asked our President at the last meeting if he had considered the effect that would be produced by the rotation of a star on its spectrum, and having received a negative answer, I have ventured to bring the subject before the Society to provoke discussion if possible.

The light which radiates from every part of the visible surface of the star will fall on the slit of the spectroscope; hence a separate spectrum due to every portion of it will be formed. The advancing limb—supposing there is a rotation of the star—will cause the absorption lines to move towards the violet end, and the receding limb towards the red end of the spectrum; whilst the central portion will cause them to occupy their normal positions, provided there be no motion of the star in space.

As an example of what would occur, let us suppose the star's disk to be divided into three equal parts; one of which is advancing towards us, another receding at the same rate, and the third motionless. If we draw an exaggerated diagram of a small part of the spectra given by the light radiating from these three surfaces, we should get a result as shown.



There would be a total broadening of the line, consisting of a sort of double penumbra and a black nucleus. If the displacement was equal to half of the breadth of the line, the double penumbra alone would remain; whilst, if it were equal to the total breadth of the line, there would be only one penumbra. If we suppose the stellar surface to be equally bright throughout, we should get a graduated shade forming the penumbra; which would gradually melt off into the blacker nucleus which would form the line. I have calculated what the shade would be; but I have not thought it necessary to bring forward the formulæ to-night.

It seems, supposing the surface of a quickly rotating star

Firsts in Stellar Rotation: Obsv'ns

- Schlesinger (1909,1911) measured limb effect in eclipsing variables δ Librae and λ Tauri

Rotation of Stars about their Axes. By Frank Schlesinger.

(Communicated by the Secretaries.)

In the May number of the *Monthly Notices* (vol. lxxi. p. 578) Professor Forbes calls attention under this title to an additional displacement of lines in the spectrum of an Algol variable. This occurs towards the beginning and towards the end of the minimum phase, and is due to the partial eclipse of the rotating brighter star. It is interesting to note that this effect has actually been observed in the case of at least one of these variables, namely, δ Libræ. In the *Publications of the Allegheny Observatory*, vol. i. p. 134, the present writer showed that in this case the velocities at these phases were such as to indicate that the bright star is rotating in the same direction as the orbital motion.

Professor Forbes suggests that it may be possible to determine the speed of rotation by this means, but the practical difficulties in the way of such an attempt are very great. Furthermore, it would be necessary to know the law of diminution of brightness as we go from the centre to the limb of the eclipsed disc. Tidal considerations make it very probable that both bodies in an Algol system rotate in the same direction and in the same time as that of their orbital revolution. If we wished to make this assumption, it would therefore be possible to determine roughly the relative brightness of the eclipsed disc at various distances from its centre. But it would appear to be well-nigh hopeless, with present-day appliances at least, to attempt to determine both this and the rate of rotation from observational material alone.

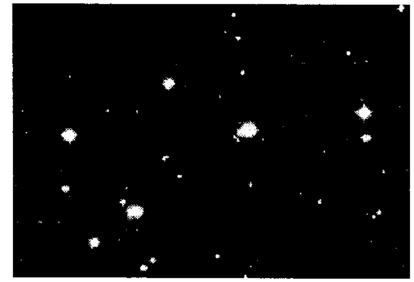
Allegheny Observatory:
1911 *July* 5.

The Auto-Collimating Spectroheliograph of the Kodaikánal Observatory. By John Evershed. (Plates 19, 20.)

The spectroheliograph in daily use at the Kodaikánal Observatory for photographing the calcium flocculi and prominences in "K" light is one of the type in which a transverse uniform motion is imparted to the whole instrument, the collimator slit traversing a stationary solar image, and the camera slit moving at the same rate across a fixed photographic plate. The movement is effected by means of a heavy weight attached to the framework of the spectroheliograph by a steel tape passing over a pulley, and the necessary uniformity and smoothness of motion is attained by mounting the spectroheliograph on three steel balls running on horizontal plane surfaces. The movement is controlled and regulated by attaching part of the framework to a large plunger working in a cylinder of oil, with a valve to regulate the flow of oil through a small aperture in the plunger.

Stellar Angular Sizes

(Back of the envelope)



- Use the sun as our prototype
- Solar vs. bright star apparent brightness:

$$V_\Theta - V_* = -2.5\log\left(I_\Theta / I_*\right)$$

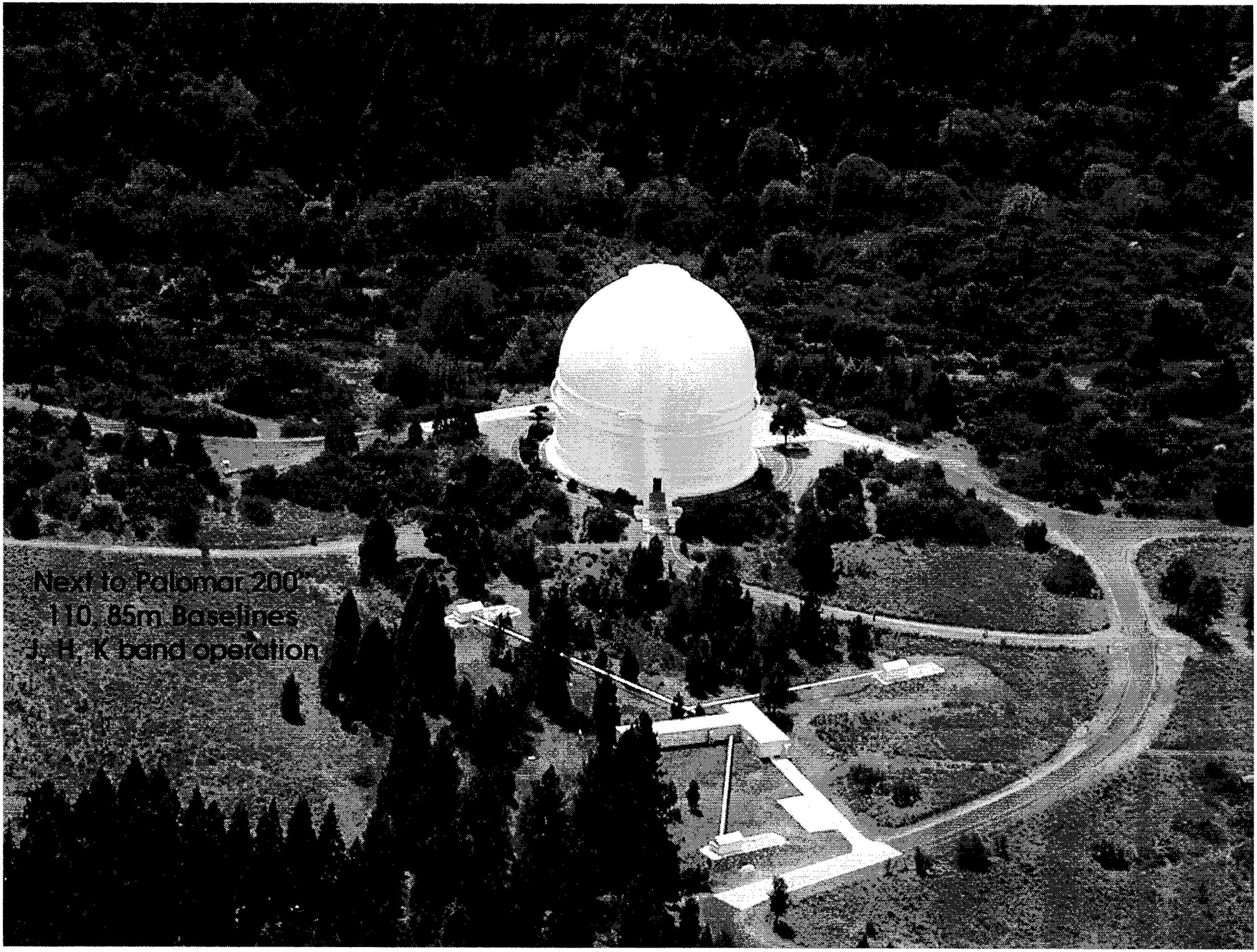
$\rightarrow 2.5 \times 10^{10}$ change in apparent brightness

- Since brightness scales with disk area:

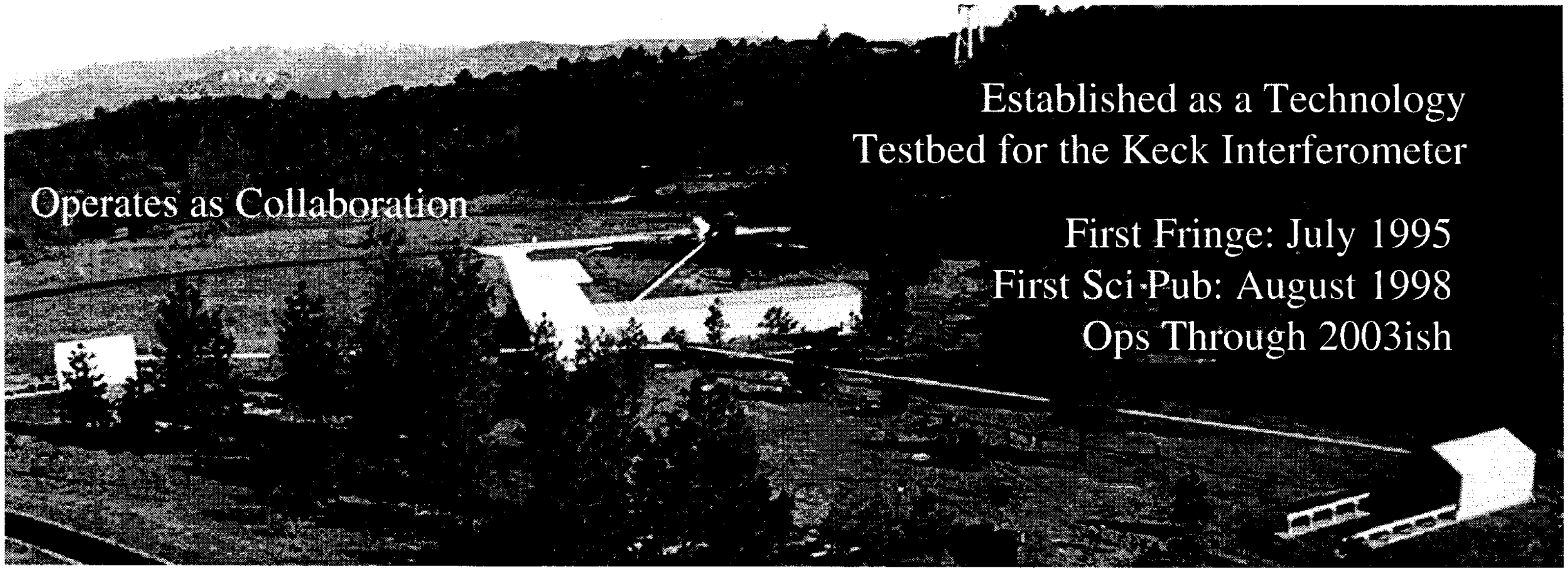
$$\frac{I_\Theta}{I_*} = \frac{A_\Theta}{A_*} = \frac{\omega_\Theta}{\omega_*} = \left(\frac{\theta_\Theta}{\theta_*}\right)^2 \rightarrow \theta_* = \theta_\Theta \times \sqrt{I_*/I_\Theta}$$

Since the sun is ~30' $\rightarrow \theta_* = 12$ mas

- Realized by Newton


Next to Palomar 200"
110, 85m Baselines
J, H, K band operation

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

The PTI Collaboration

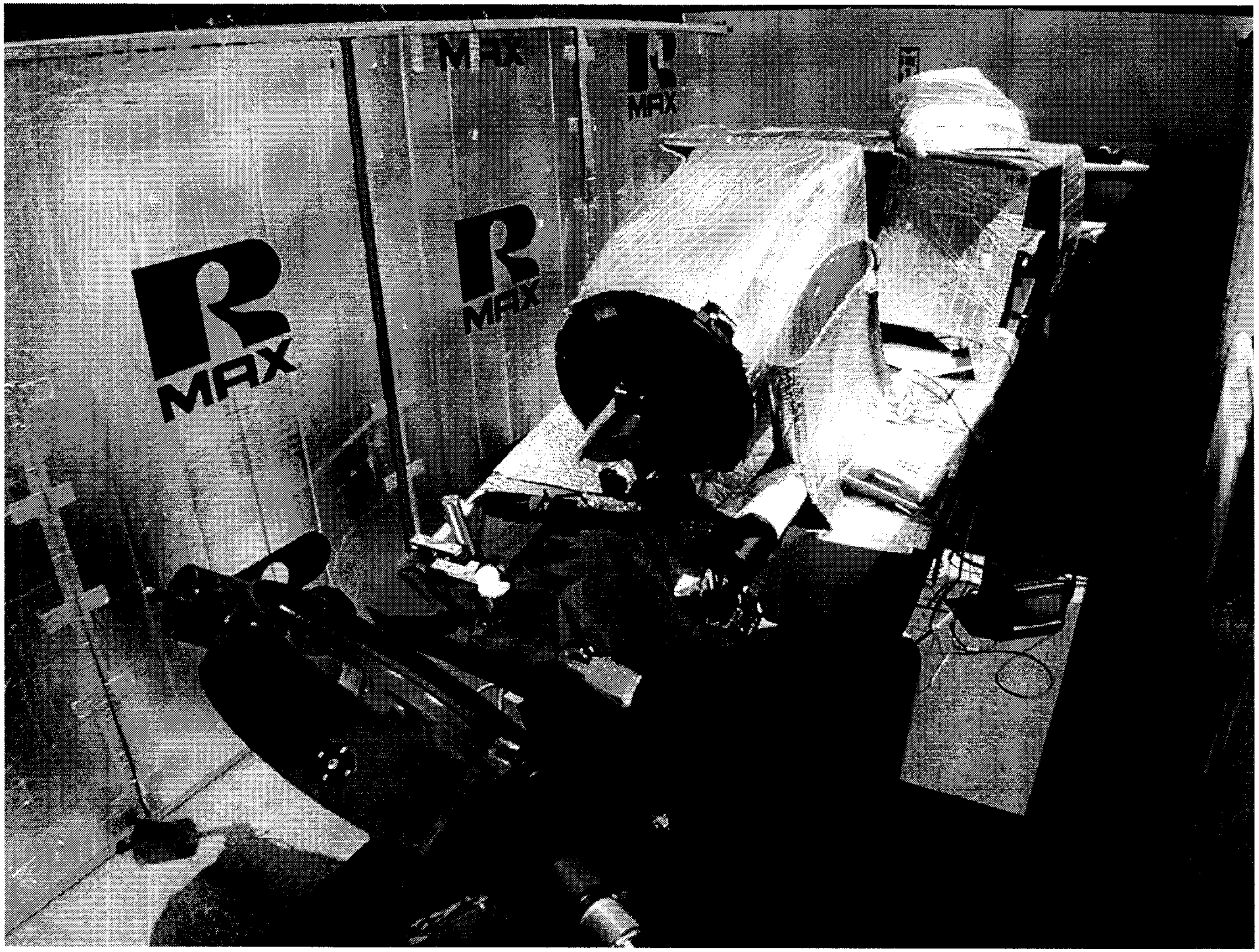
Collaboration Members:

R. Akeson (ISC)
R. Bambery (JPL)
A. Boden (ISC)
M. Colavita (JPL)
M. Creech-Eakman (JPL)
S. Kulkarni (CIT)
B. Lane (CIT)
P. Lawson (JPL)
C. Koresko (IPAC)
K. Rykoski (CIT)
M. Shao (JPL)
M. Swain (JPL)
R. R. Thompson (JPL)
G. van Belle (ISC)

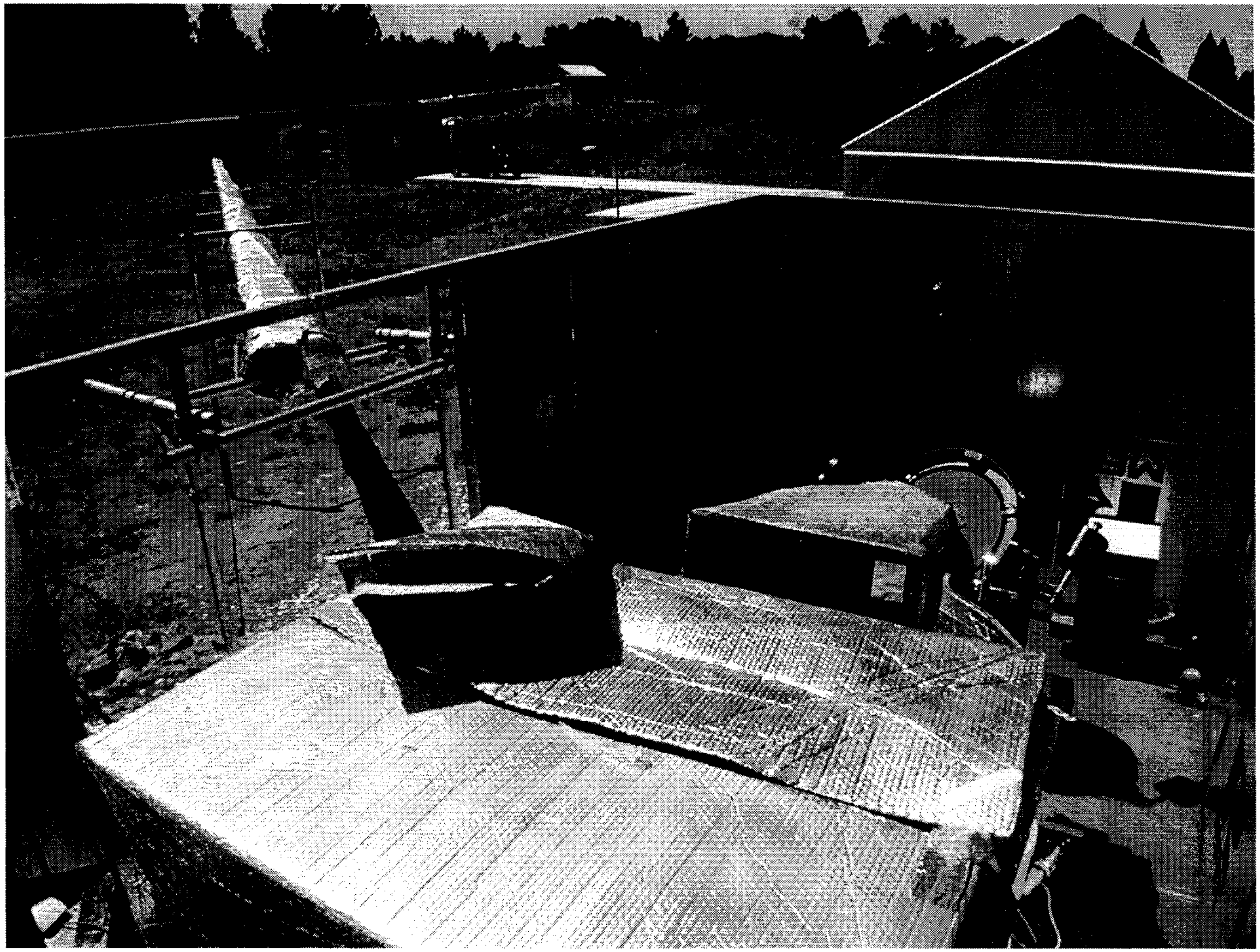
PTI Photo Tour

PTI Siderostats

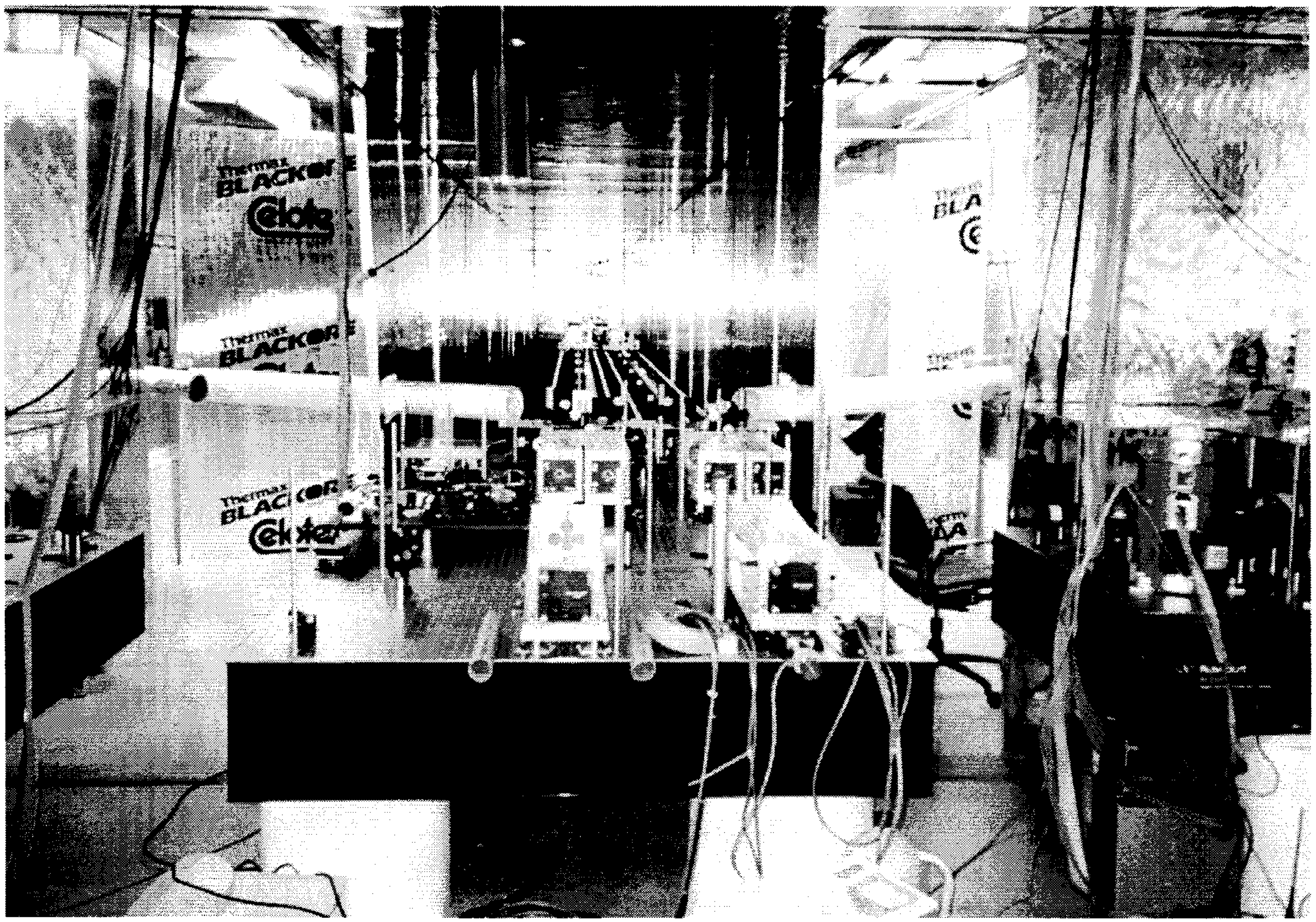
PTI Sidereostats



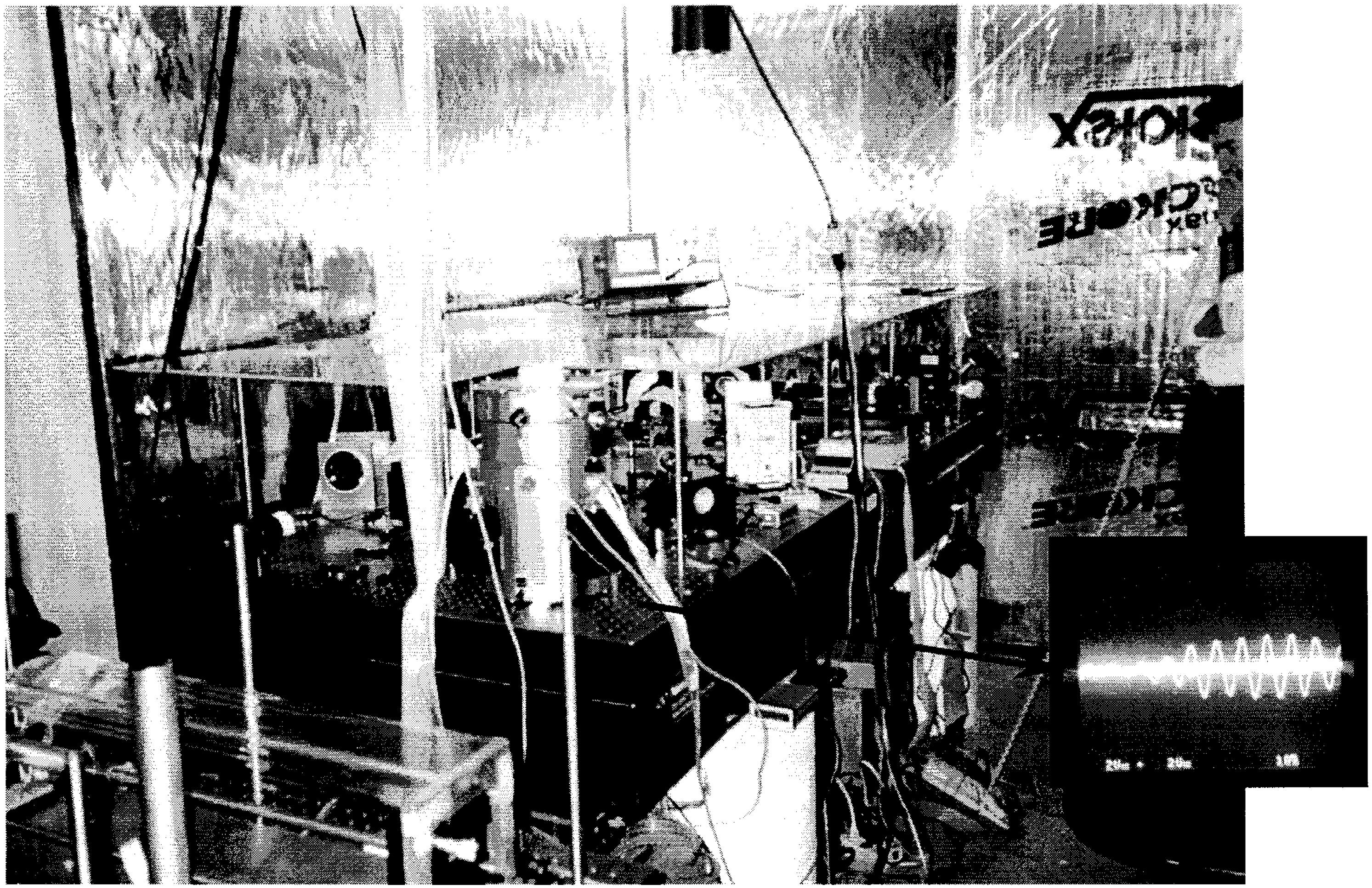
PTI Vacuum Tubes



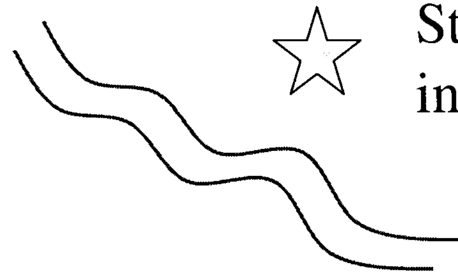
PTI Delay Lines



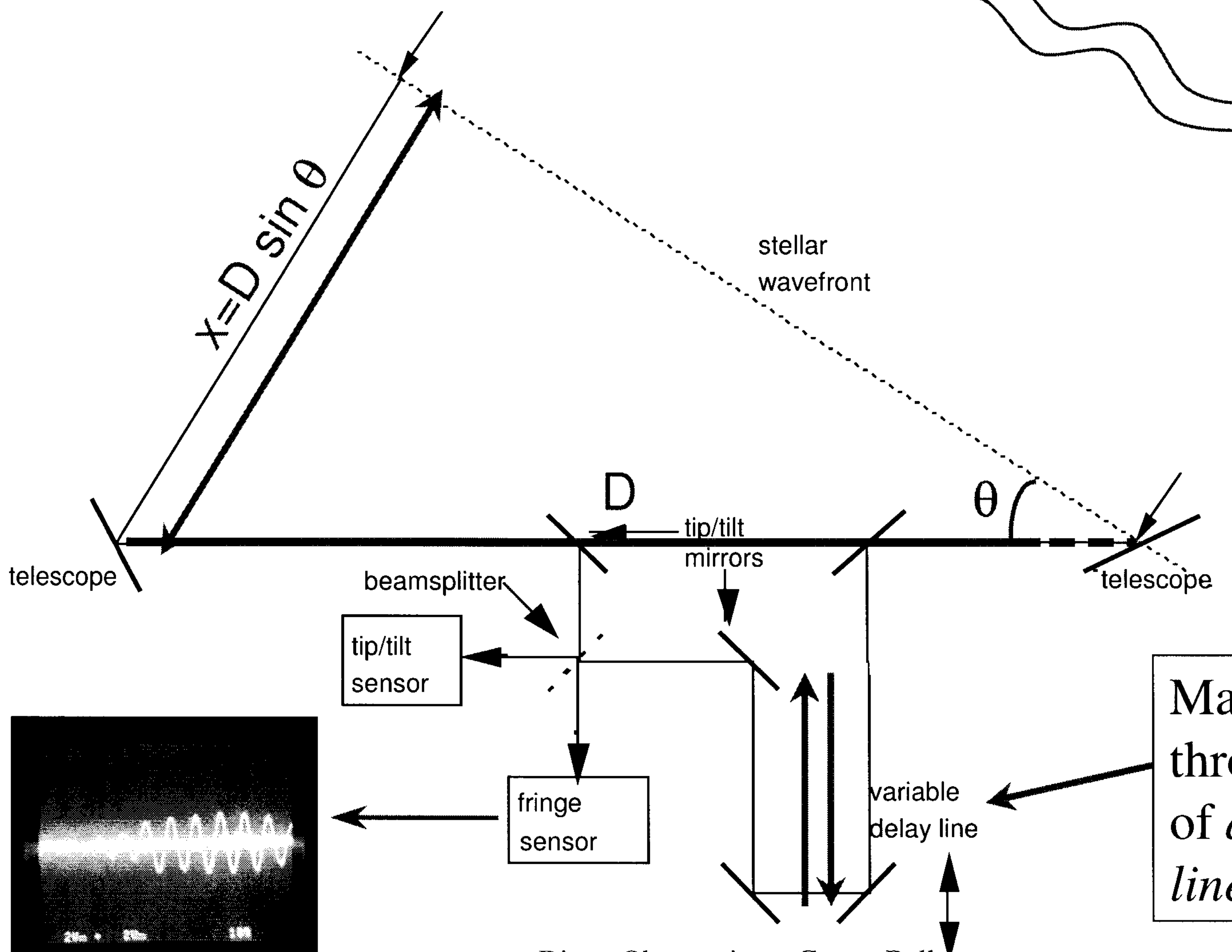
PTI Primary Recombination Table



Michelson Interferometer



Star is at infinity



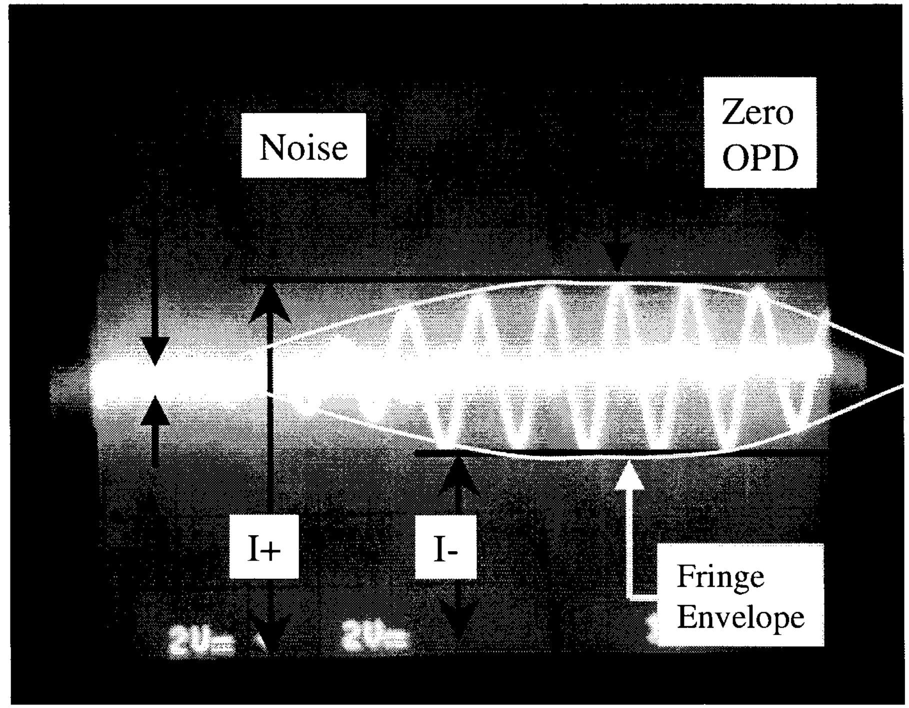
Match paths through use of *delay lines*

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:

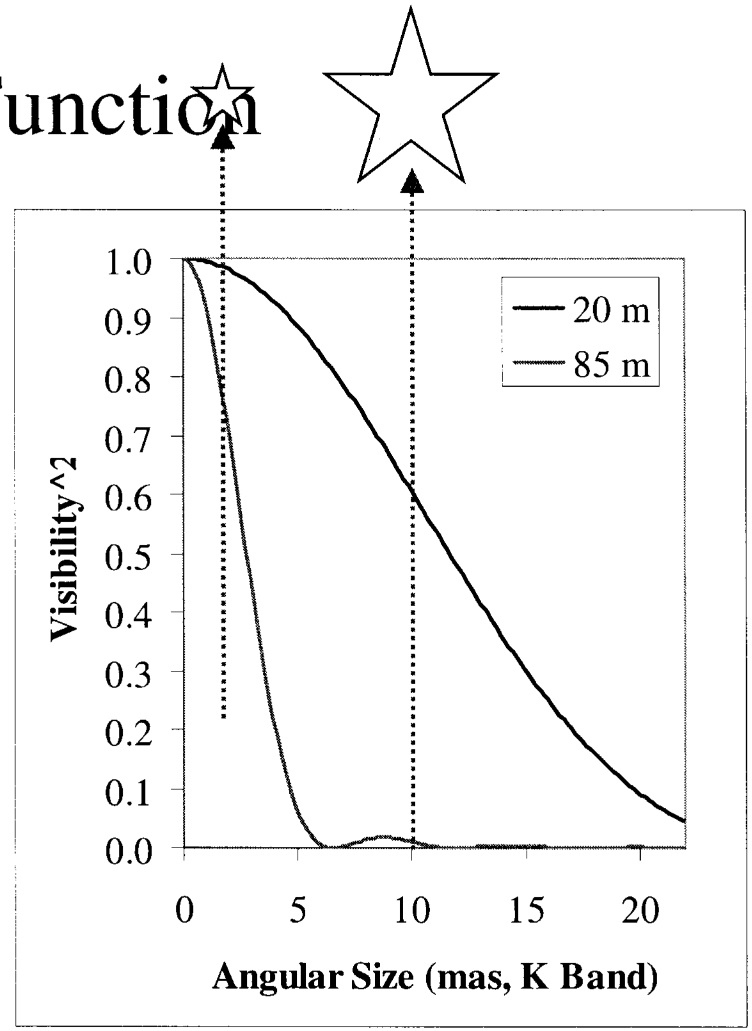
$$V = \frac{J_1(x)}{x} \quad \text{where} \quad x = \frac{\pi\theta B}{\lambda}$$

  B is the projected baseline

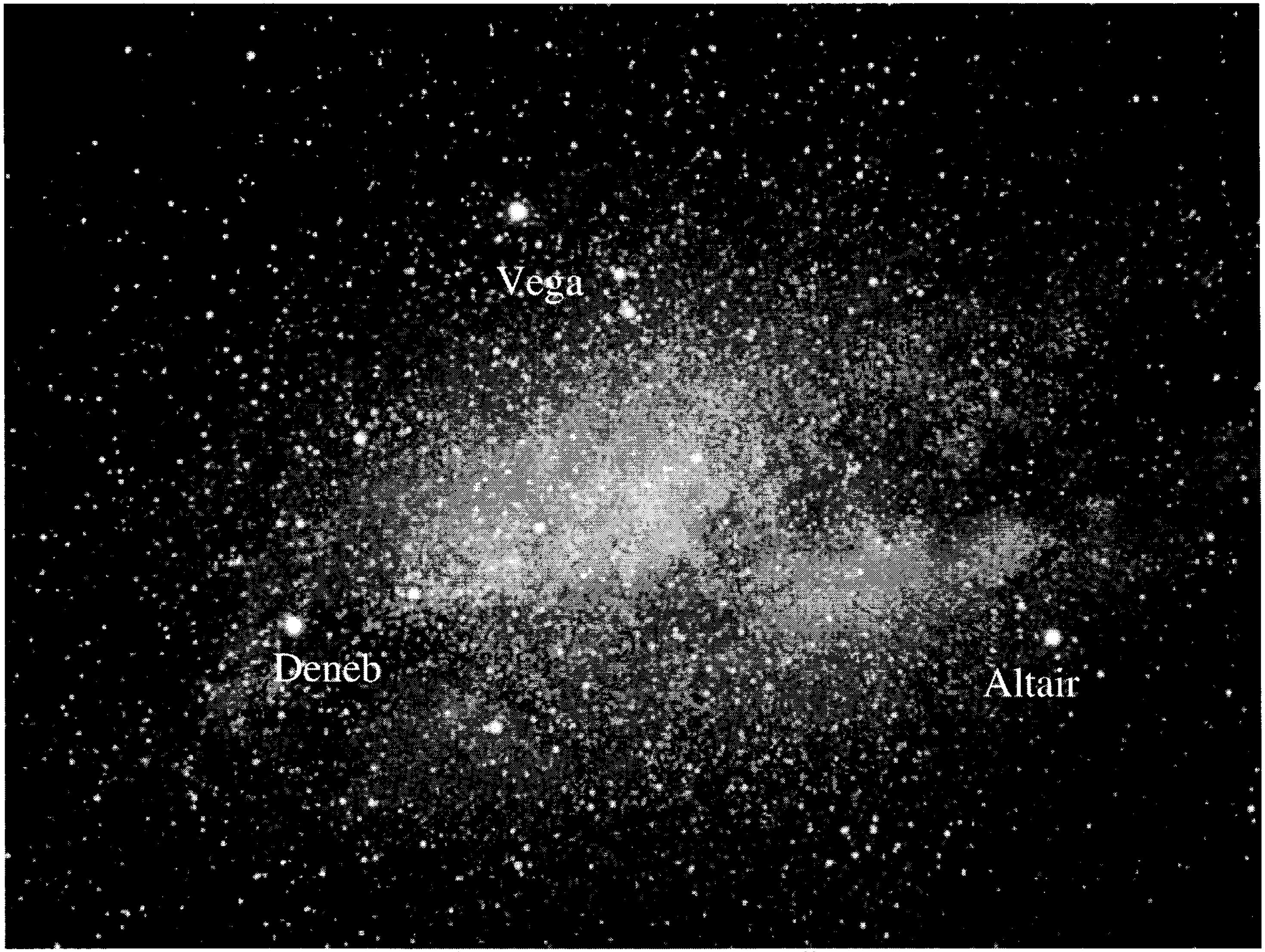
  θ is the stellar disk size

  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)

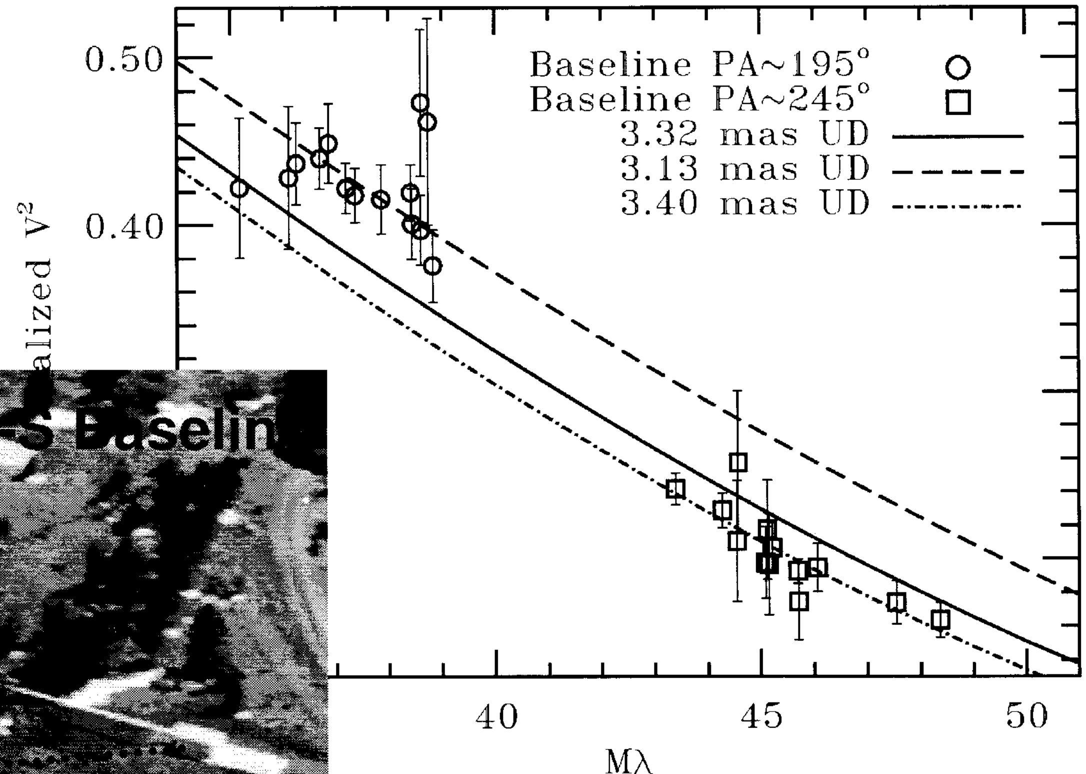


Seeking High Resolution in Familiar Places



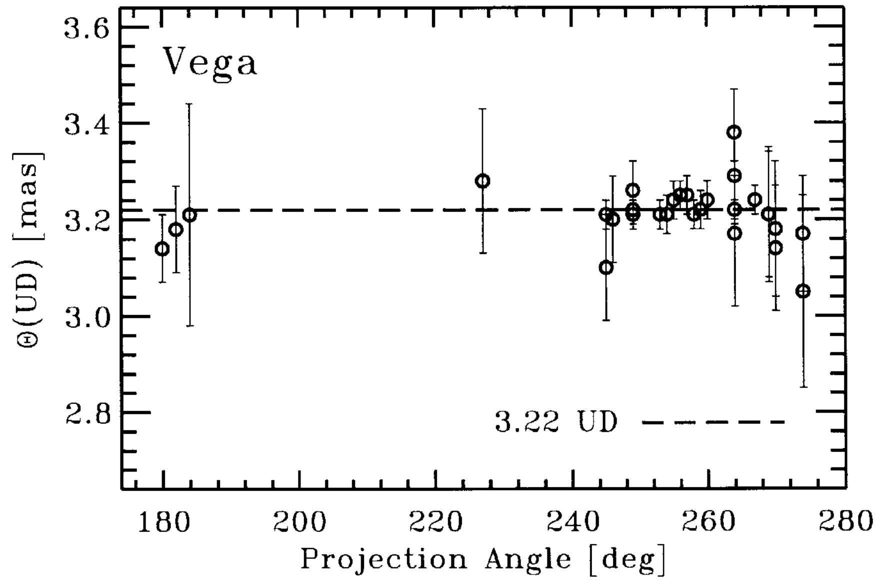
Initial Indications of Something Interesting with Altair

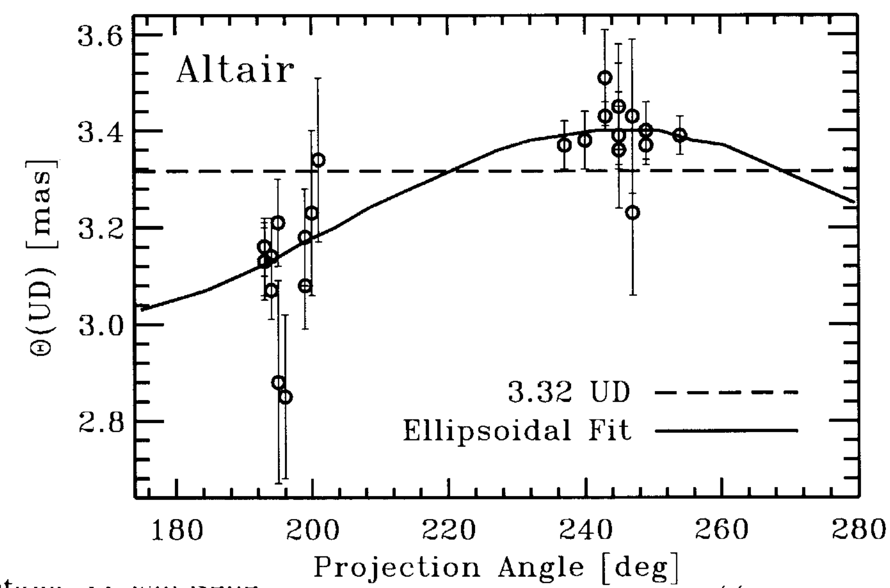
- Use of the PTI N-S and N-W baselines gave different angular sizes



Contemporaneous Measurements Appear Normal

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



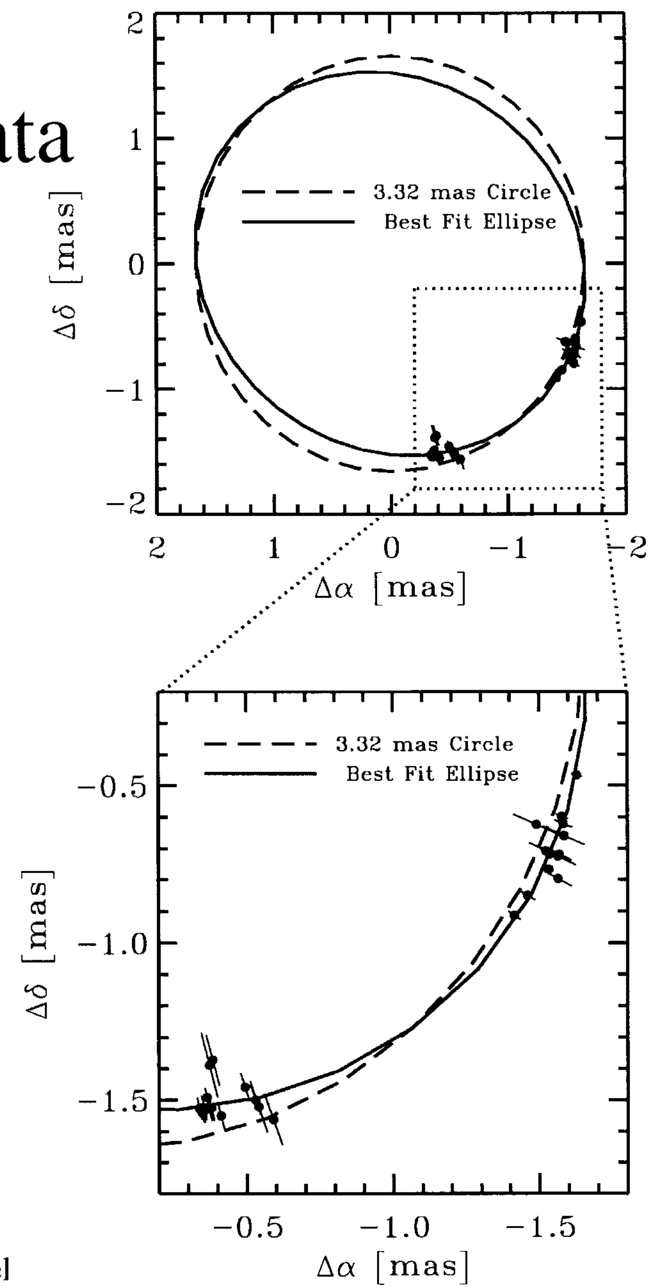


Ellipsoidal Fit to Altair Data

- 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:

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

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



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:

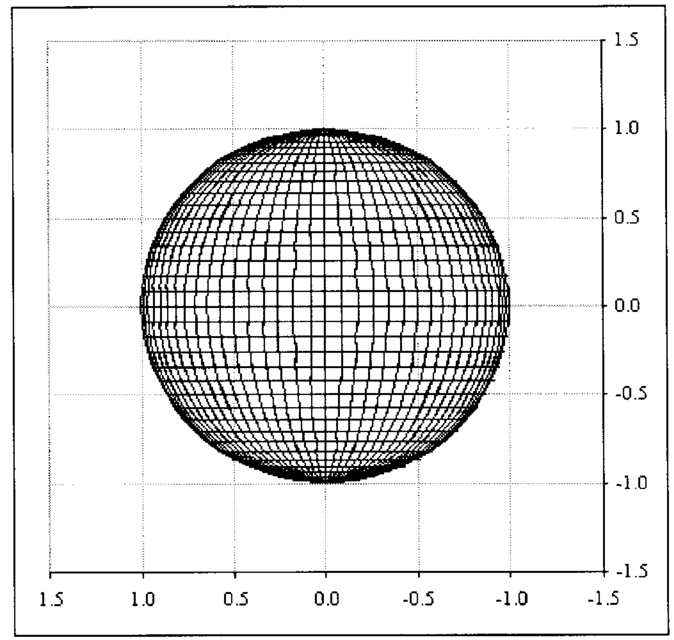
$$r(\theta,u)=\frac{R(\theta,u)}{R_p}=\frac{3}{u\sin\theta}\cos\left[\frac{\cos^{-1}(-u\sin\theta)+4\pi}{3}\right]$$

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

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

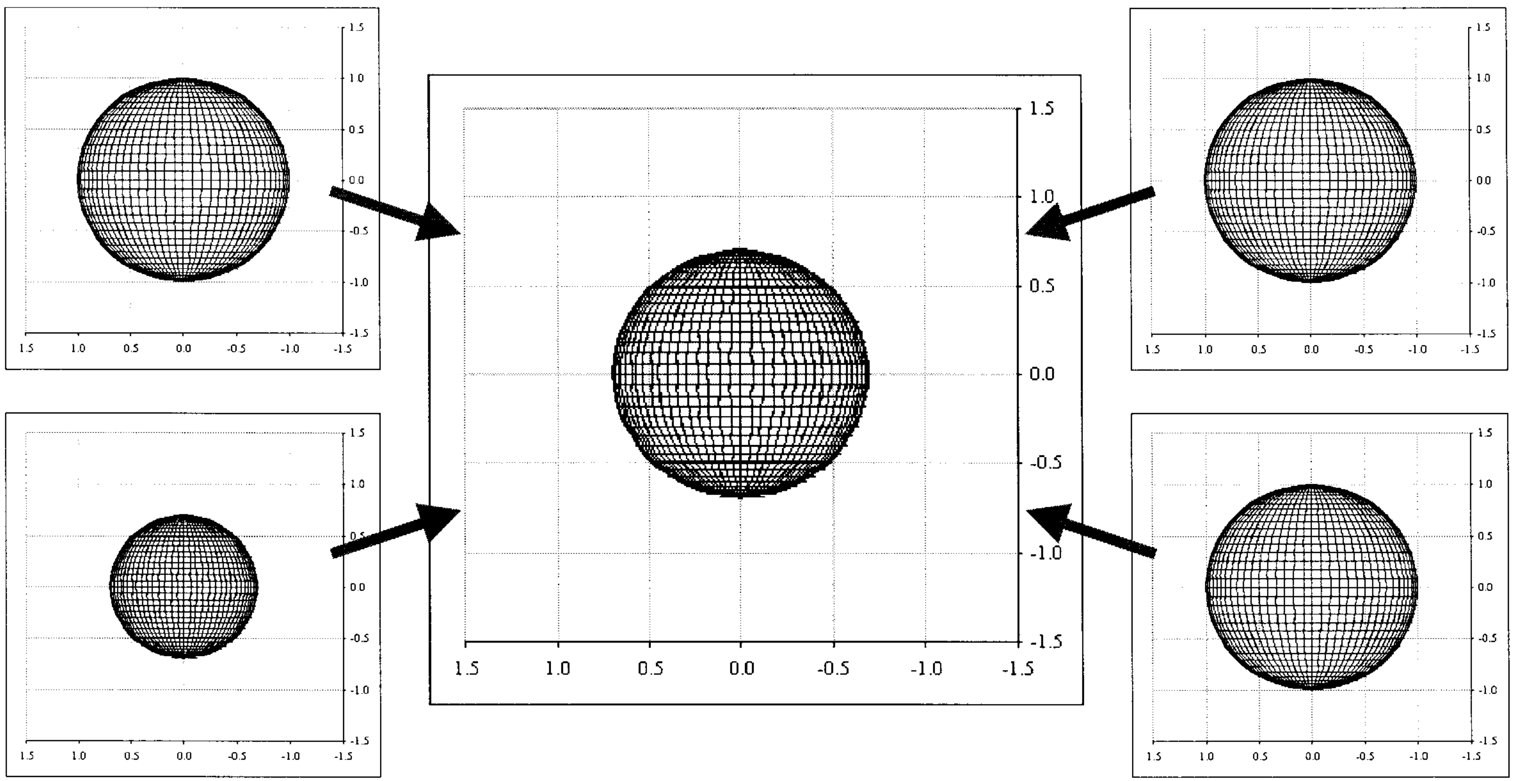
Elements of a Roche Model. I

- 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



Elements of a Roche Model. II

- For a fast rotator, these degenerate parameters become unique

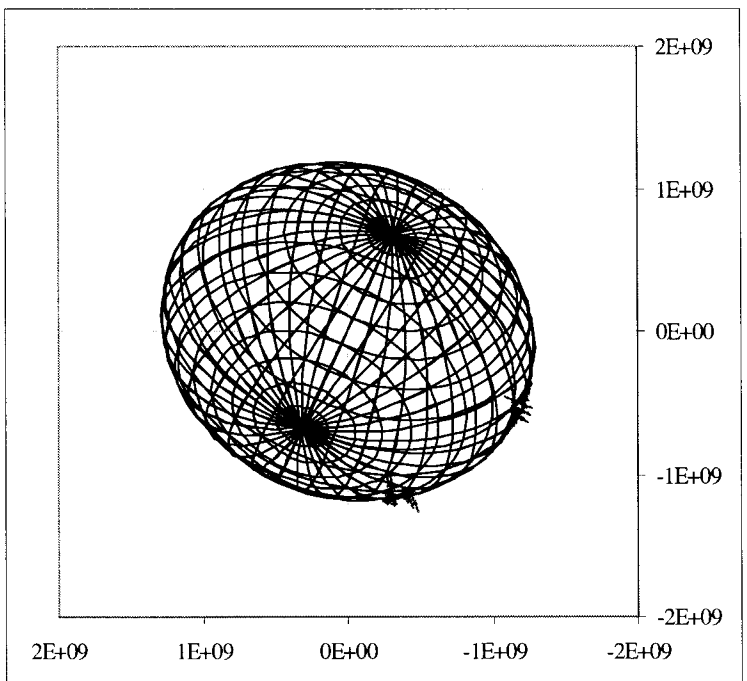


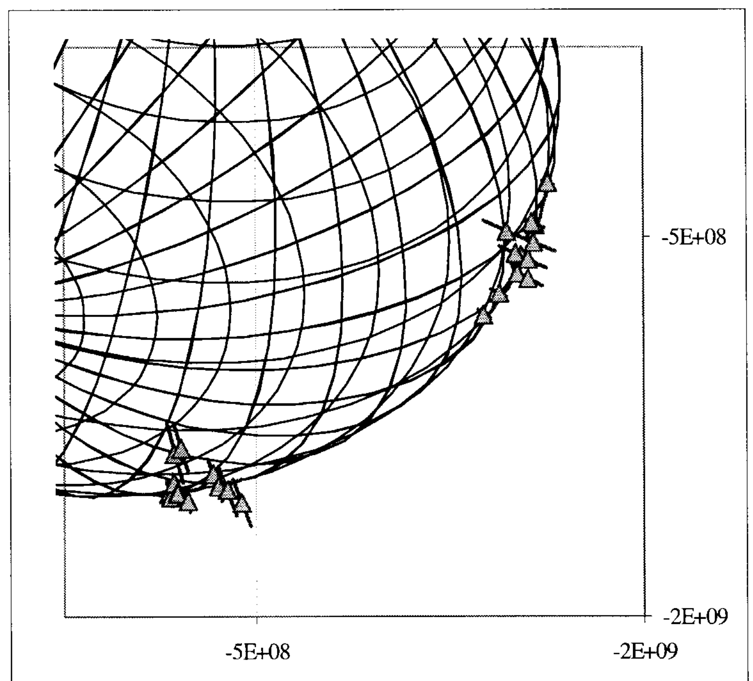
Noteworthy Assumptions

- 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



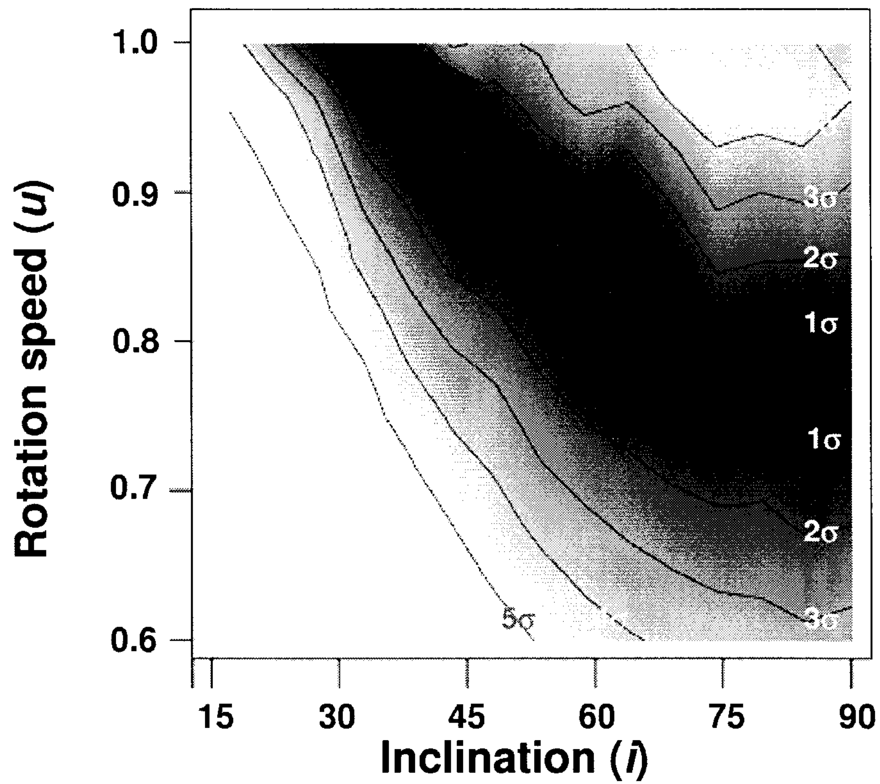


Results of the Minima Search

- 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 $\{i,u\}$

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

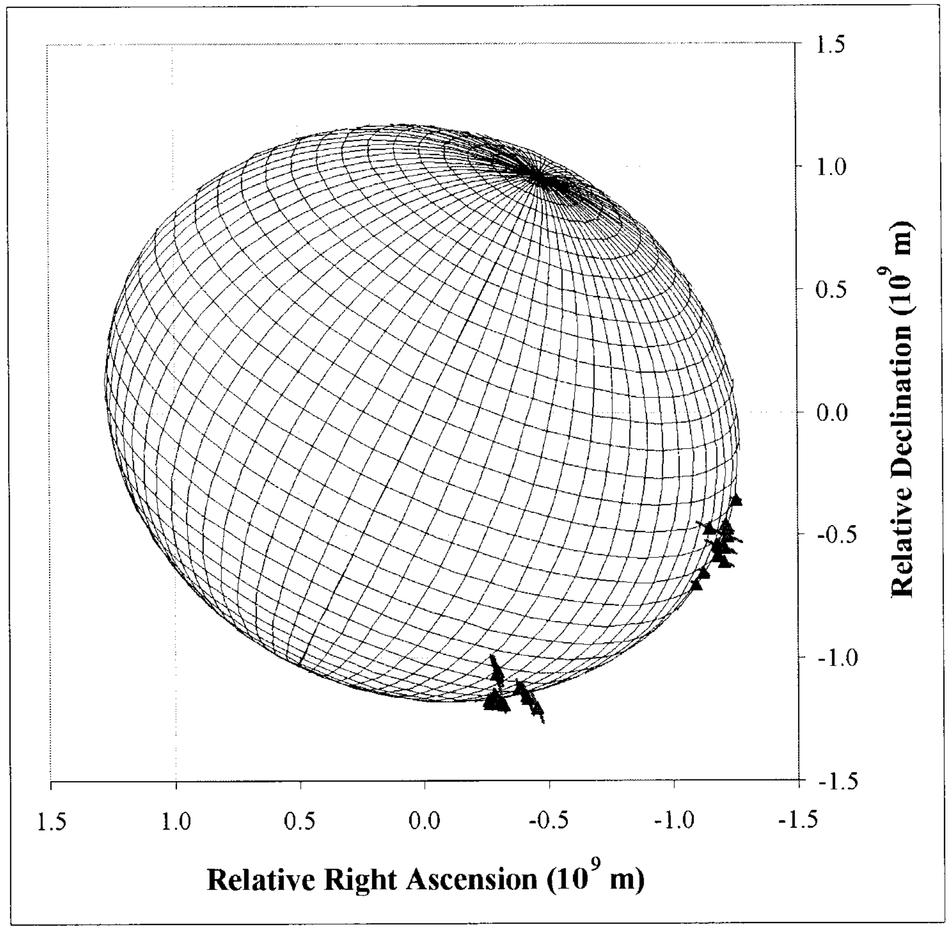
- No inclination less than 30° is allowed, no speed less than 210 km/s



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 (von Zeipel effect)
- Main limitation – resolution
  - Need 250 or more meters to have a large (10+) sample size
  - New interferometers (CHARA, NPOI) will make this possible

Rapid Rotator Study Recently Awarded Time on the VLTI

The End