Interferometric Observations and Modeling of the Close Binary Star Spica (Alpha Virginis)

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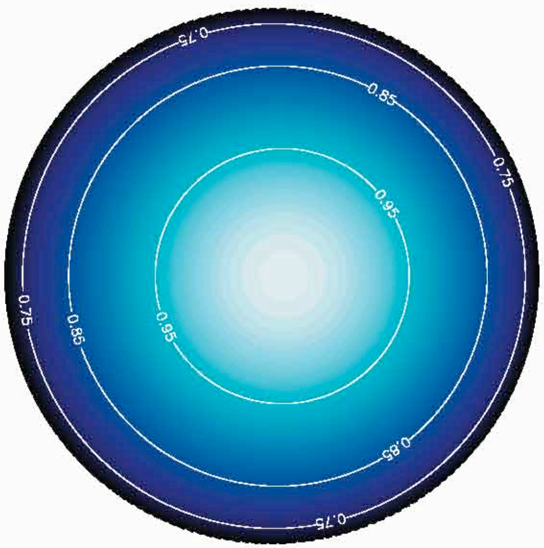

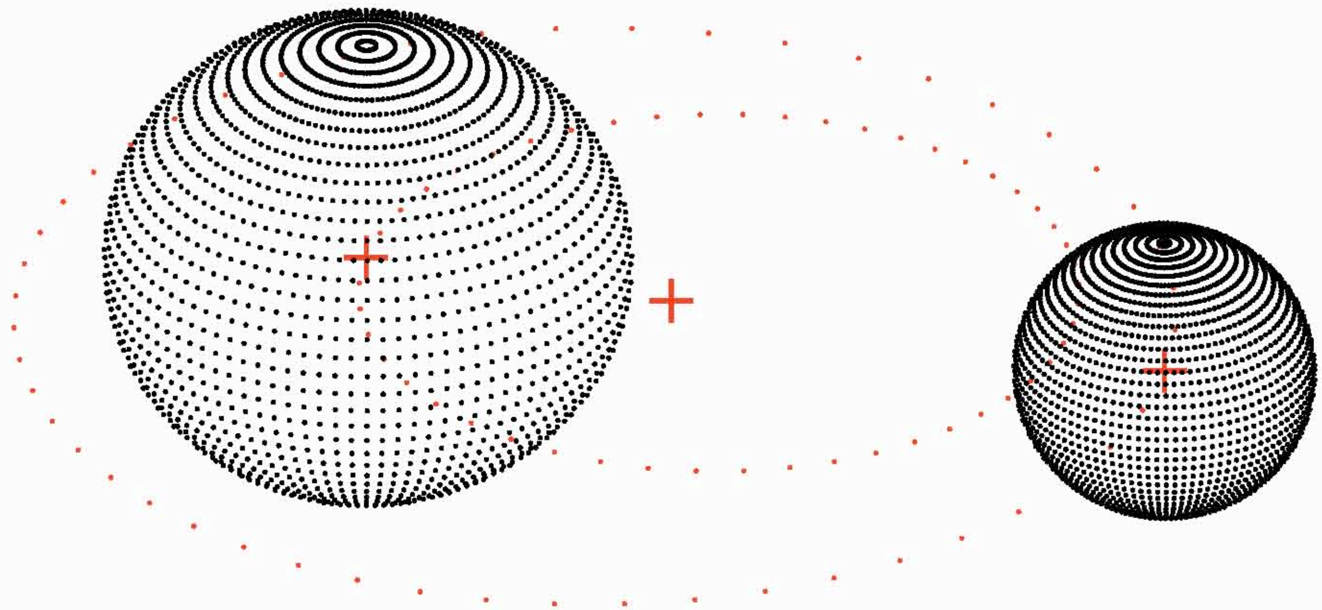

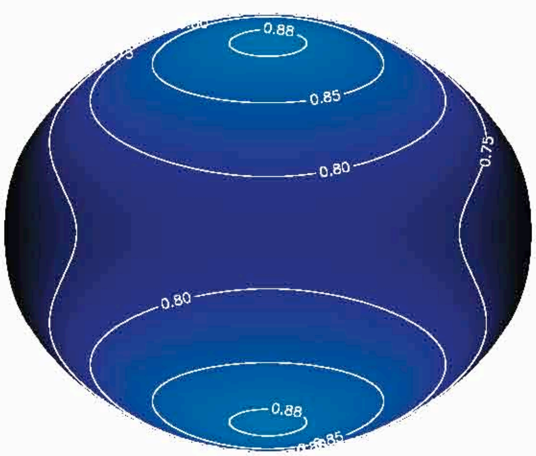

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What's to Come....

- Rapidly Rotating Stars: A hot topic in astronomy!

- What characterizes the surface of a rapid rotator?

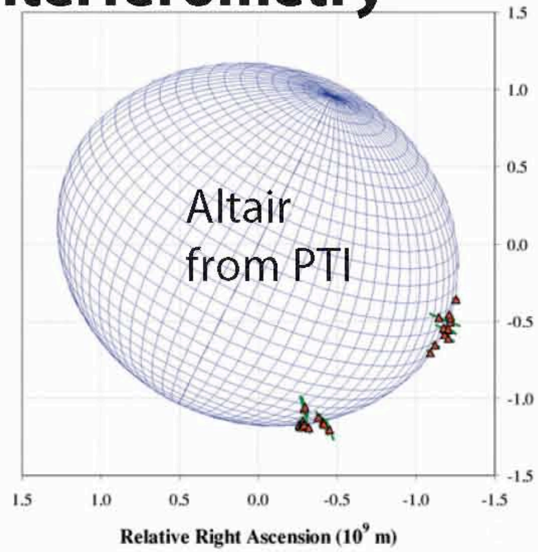
- Vega: a pole-on view of a rapid rotator

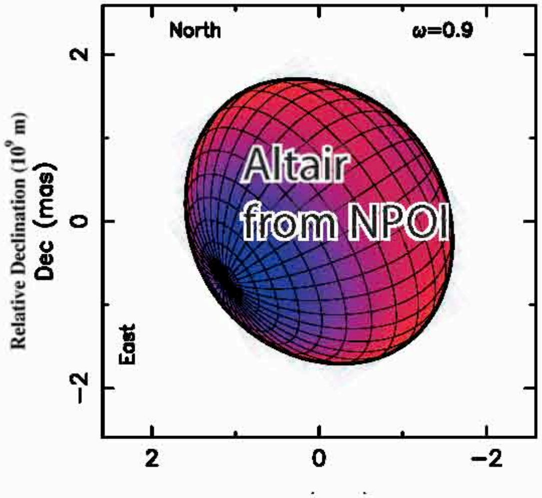
- Spica: Rapid rotation times two!

    History of Spica
    Spica's a binary!
    Apsidal Motion: What's that?!
    Spica components resolved!
    Building a model of Spica
    Preliminary Analysis
    Conclusions

Resolved Rapid Rotators from Interferometry

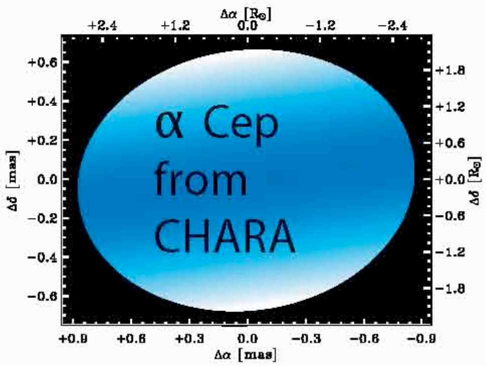
*Disk of **Altair** (A7 V) resolved as ellipsoid by the Palomar Testbed Interferometer (van Belle et al. 2001) Axial ratio: 1.140±0.029



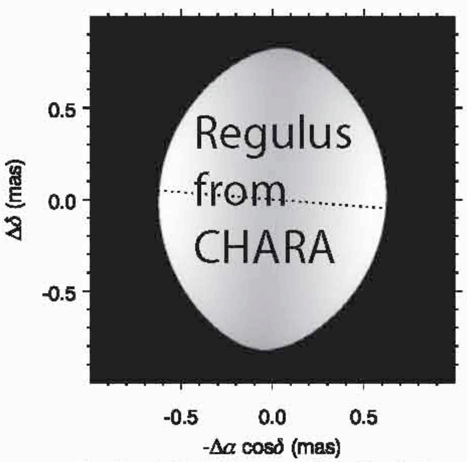


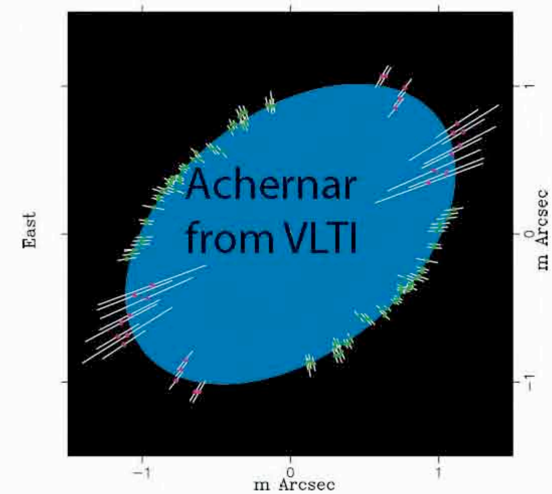
Peterson et al. (2006) ApJ, 636, 1087

*Disk of **Alderamin** (A7 IV-V) resolved as an ellipsoid by CHARA (van Belle et al. 2006). Axial ratio: 1.298±0.051



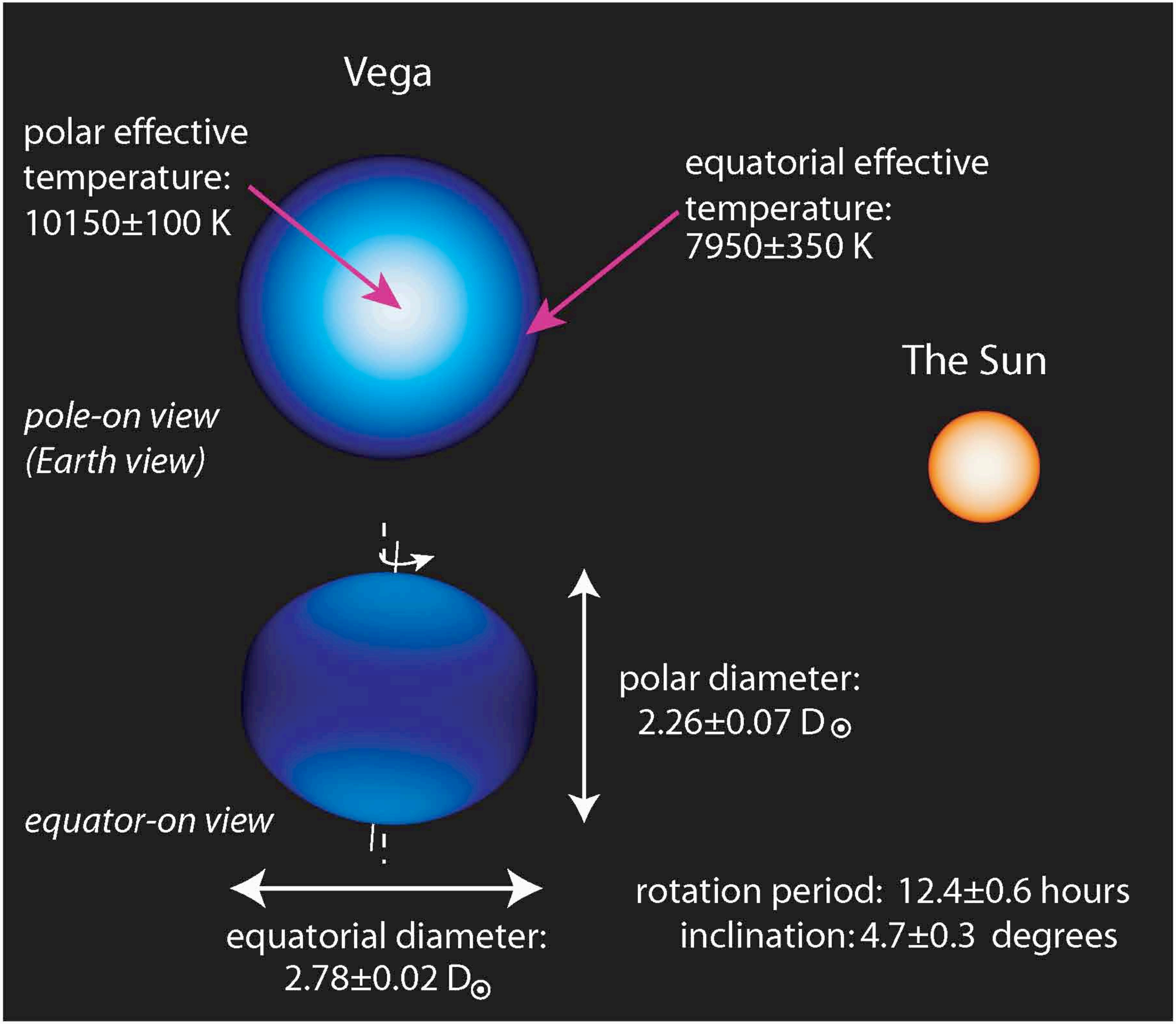
*Disk of **Regulus** (B7 V) resolved as ellipsoid by CHARA (McAlister et al. 2005). Axial ratio: 1.32±0.02





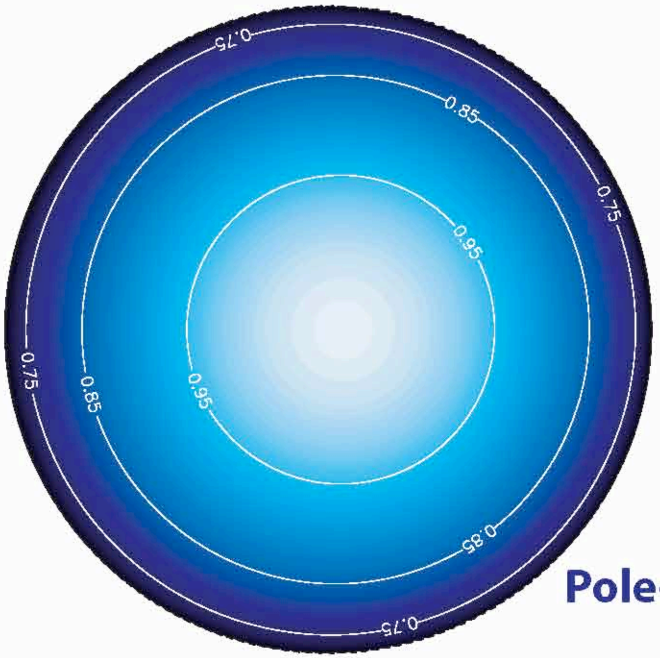
*Disk of **Achernar** (B3 Vpe) resolved as ellipsoid by VLTI (A. Domiciano de Souza et al. 2003). Axial ratio: 1.56±0.05

A Pole-on Rapid Rotator: Vega



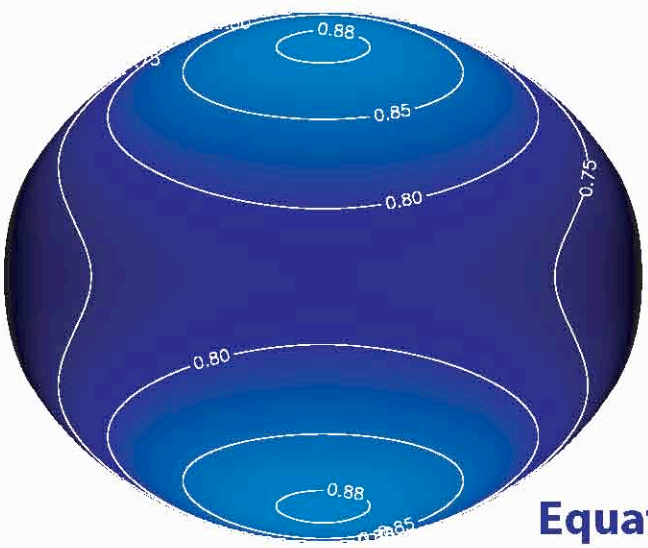
Rotating Stars: Limb Darkening and Gravity Darkening

Rapidly Rotating Model with both Limb and Gravity Darkening



Pole-on view

Limb darkening: *An observer-dependent effect in which the intensity across a stellar surface varies due to a radial or depth-dependent temperature gradient. Measured on the Sun in the late 19th century.*



Equator-on view

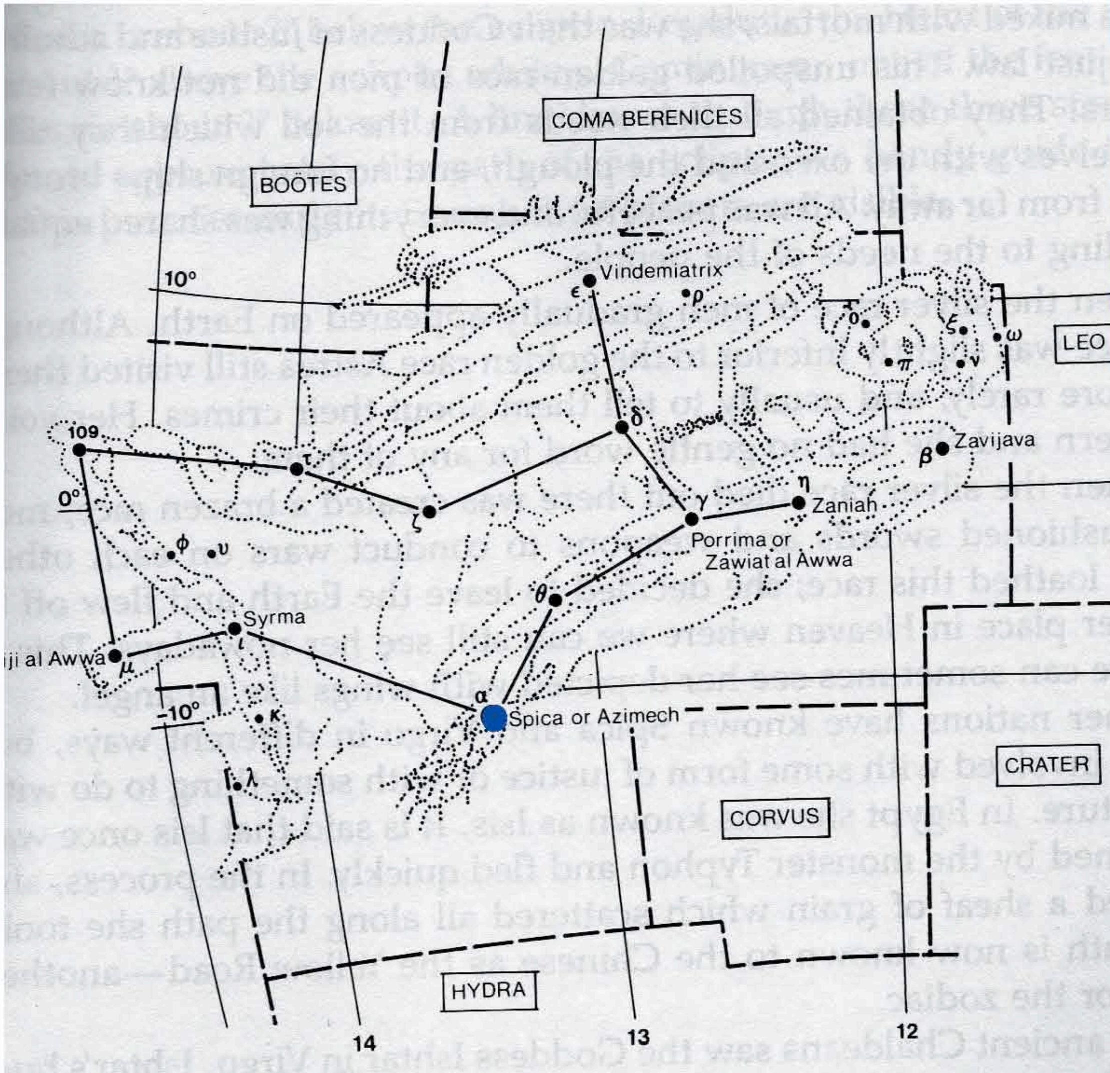
Gravity darkening: *Intrinsic to the star, a pole to equator effective temperature gradient resulting from rapid rotation. Local surface temperature on correlates with local gravity. First worked out by Hugo Von Zeipel in 1924. Observation evidance in the 1930s.*

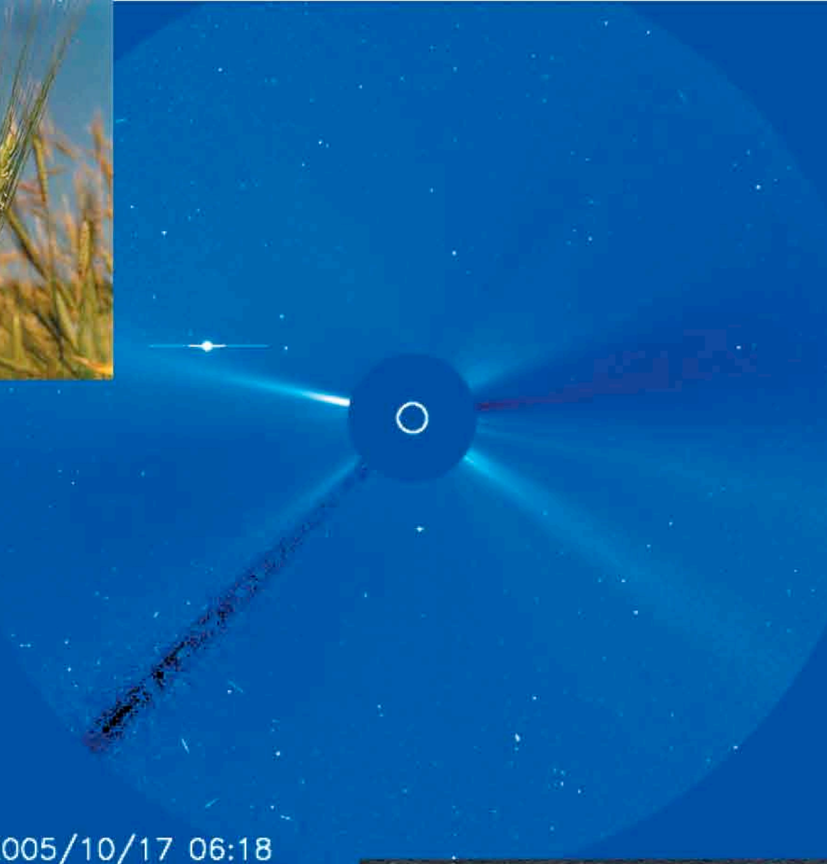
Aufdenberg et al. (2006) ApJ, 645, 664

Why not try two rapidly rotating stars at once!

SPICA

Now for some background ...





Spica (from the Latin for 'ear of wheat') lies in the zodical constellation Virgo and appears near the Sun during harvest time. Hipparchus (190 BC - 120 BC) used observations of Spica is discover the precession of the equinoxes.

Spica announced as binary star (radial velocity variable) in 1890 by H.C. Vogel
Spectrum of second star confirmed by A.C. Maury in 1897.

H.C. Vogel

A.C. Maury

Radial Velocity Curve for Spica A & B (Struve et al.)

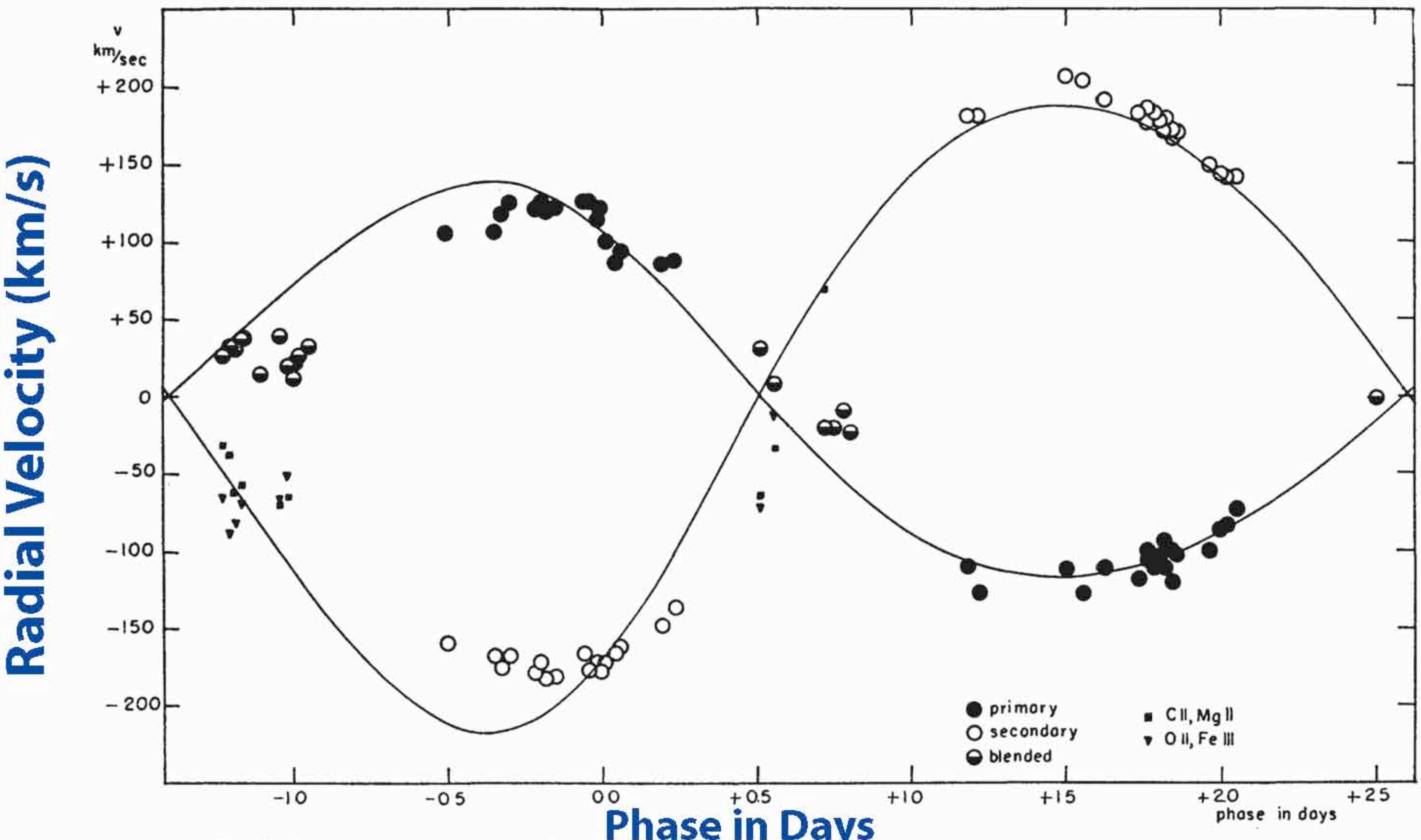
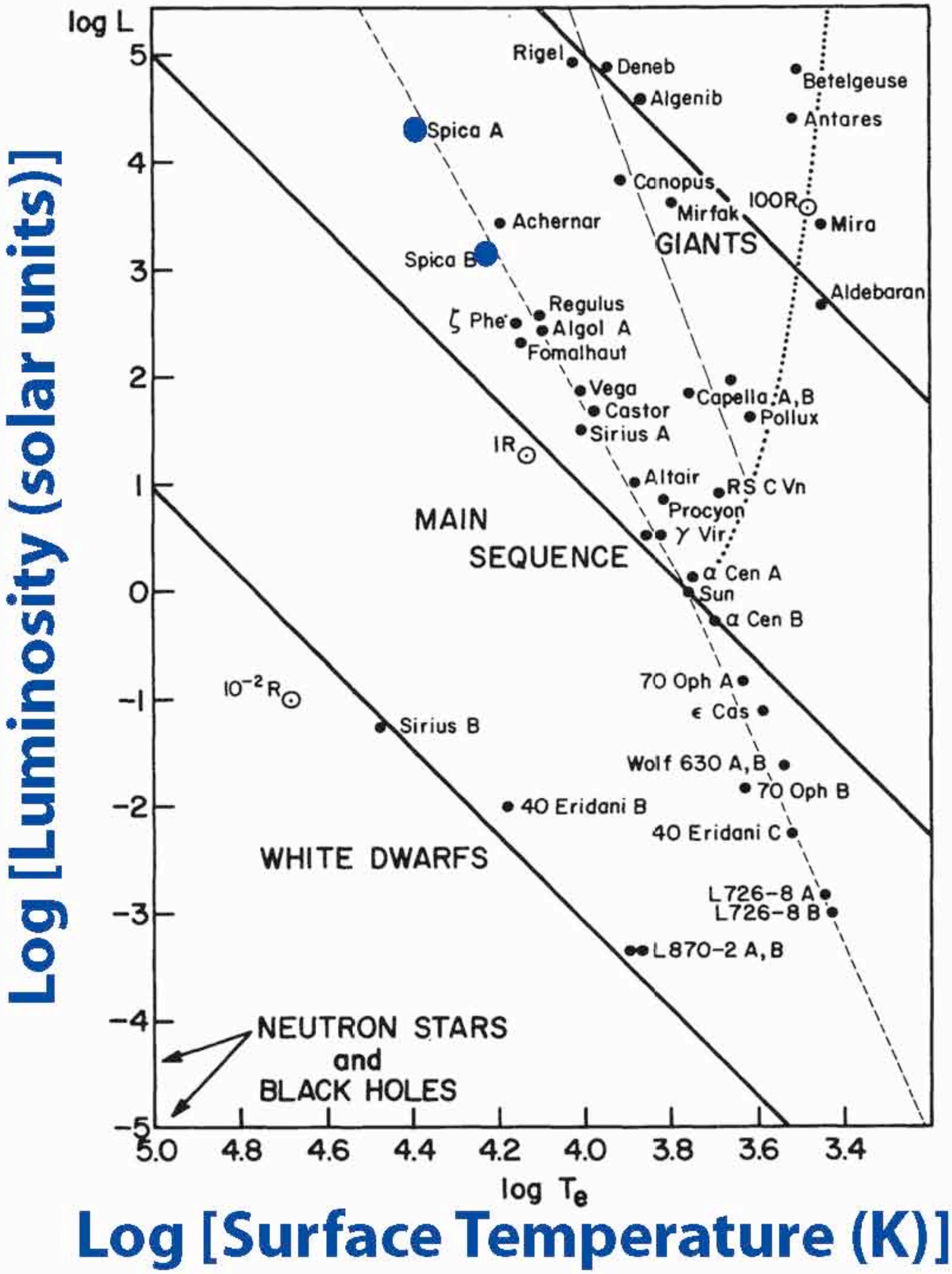


FIG. 1.—Radial velocities of α Virginis derived from the 1956 material The velocity-curve is that Struve and Ebbighausen (1934).

Spica and other bright and/or nearby stars on a theortician's Hertzsprung-Russell diagram.



Orbital Elements of a Binary Star

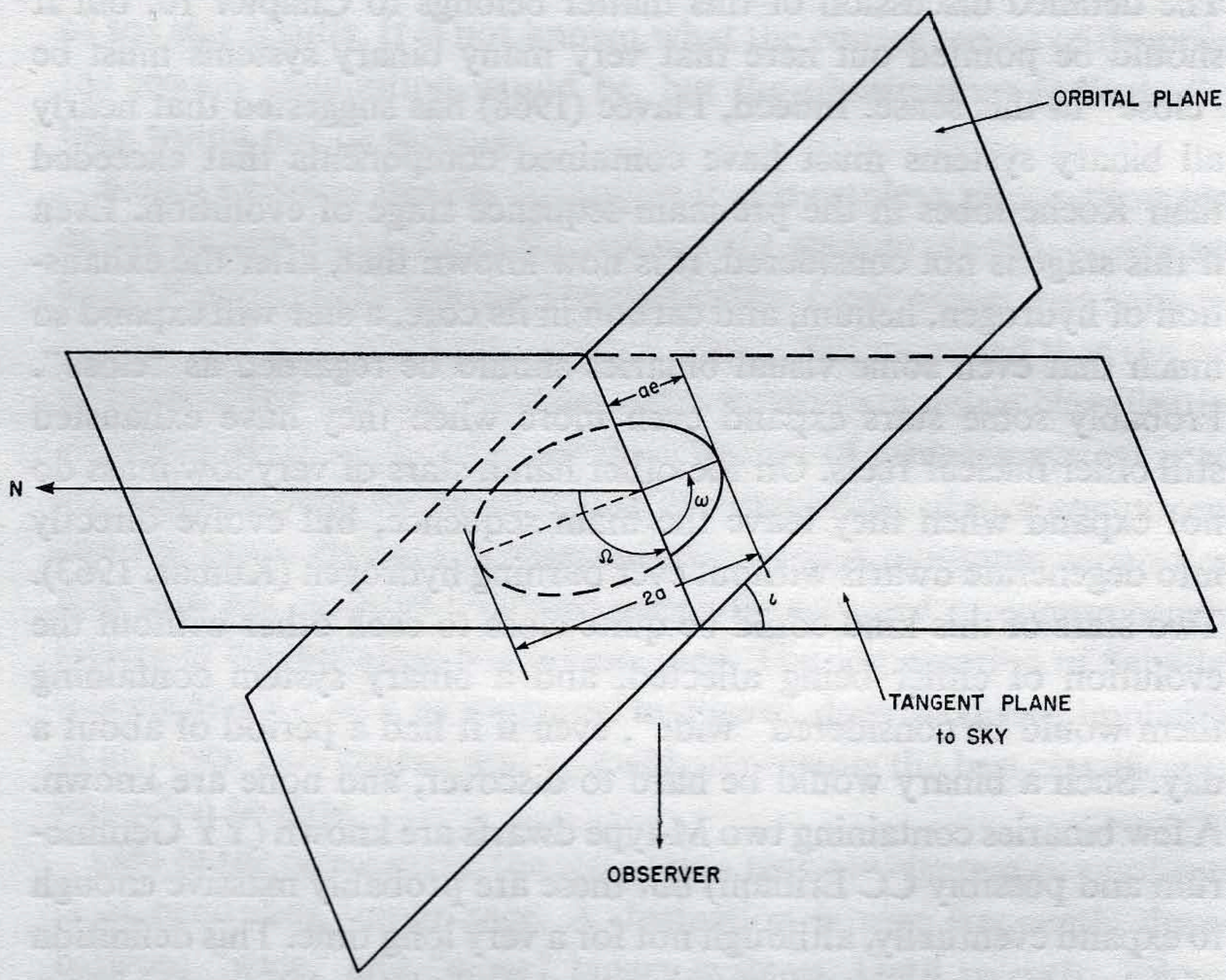
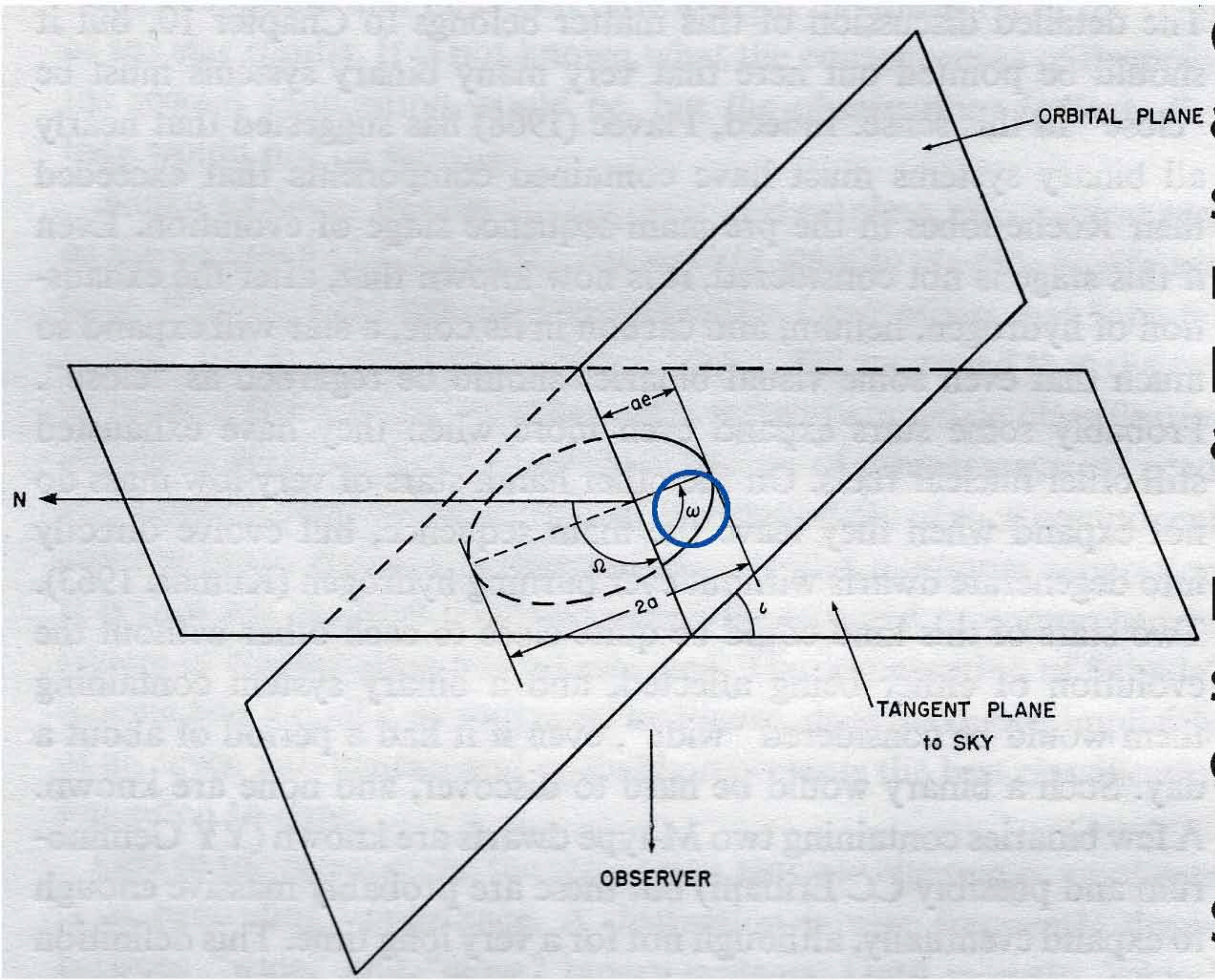


FIG. 1.3. Orbital plane and the tangent plane to the sky illustrating the significance of the orbital elements.



Orbital elements are not constant if stars are not point masses or more precisely if they are not spherical.

Rotation distorts stars, close stars distort each other.

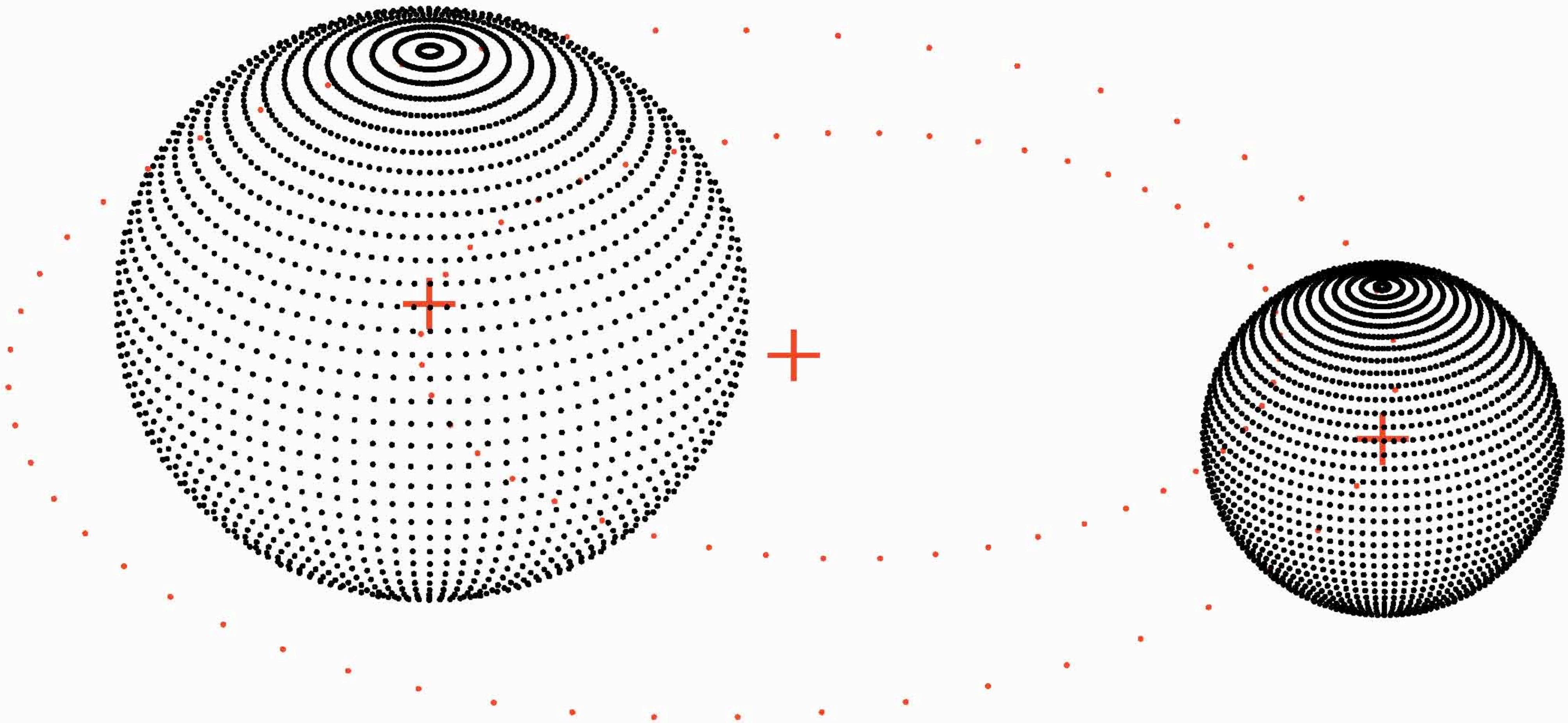
So... ω advances with time. Both non-relativisitic and relativistic terms.

$$\omega = \text{longitude of periastron}$$

= direction of the major axis

= lines of apsides

For one thing*, these stars aren't spherical!



*Other complexities include:

Asynchronous rotation, mutual irradiation, limb and gravity darkening , non-radial oscillations in Spica A

Apsidal Motion Theory

Potential of distorted star 1 at the center of 2,

$$\left\{\frac{R_1}{a}\right\}^5 k_{12}\left\{\frac{Gm_2}{R^6}+\frac{\omega_1^2}{3R^3}\right\}$$

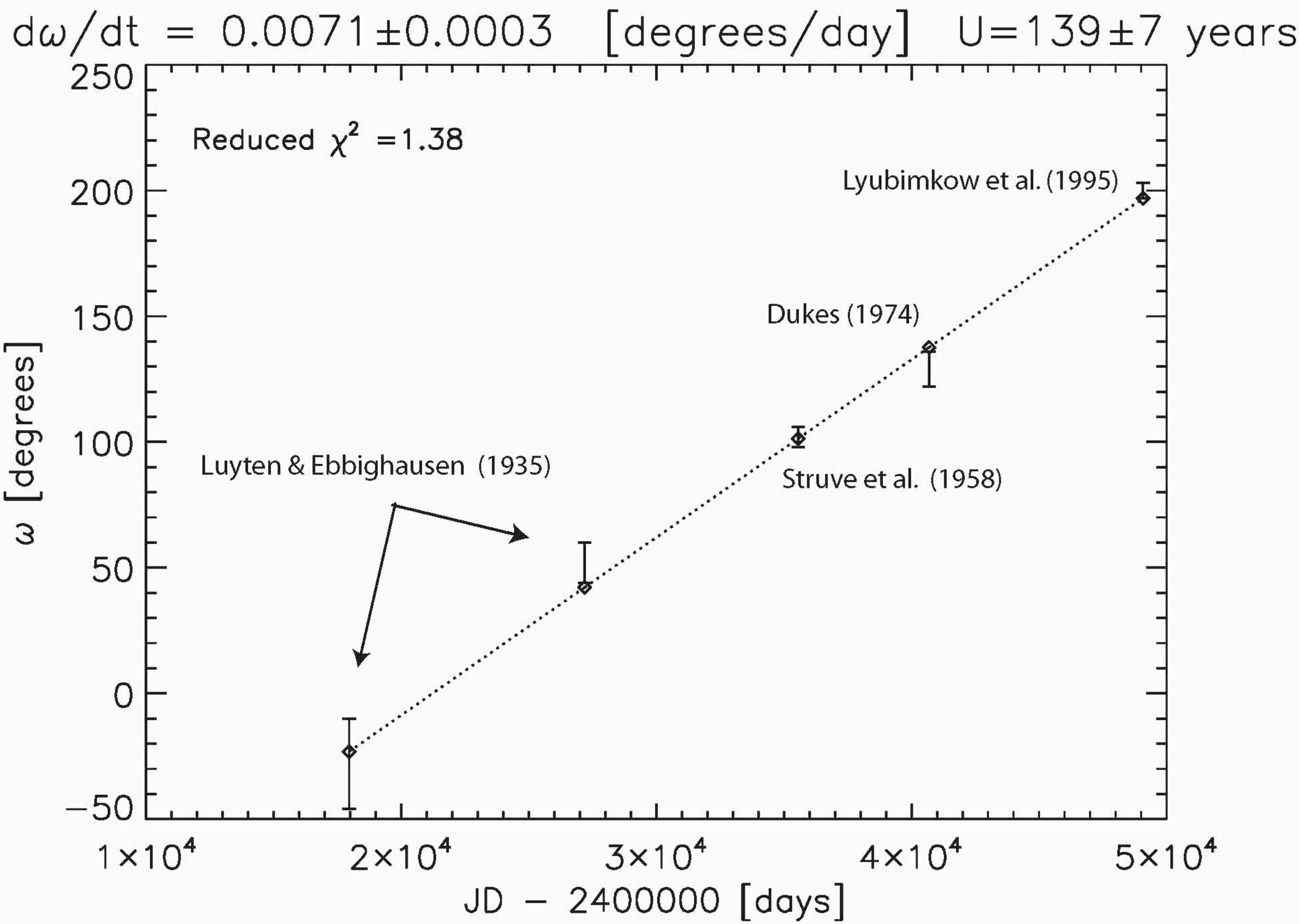
$$k_{12}=\frac{3-\eta_2(r_1)}{4+2\eta_2(r_1)}$$

$$r\frac{d\eta_2}{dr}+\eta_2^2-\eta_2-6+\frac{6\rho}{\bar{\rho}}(\eta_2+1)=0$$

$$\frac{\Delta\omega}{2\pi}=k_{12}\left[\frac{m_2}{m_1}\left(\frac{R_1}{a}\right)^5 f(e)\right]$$

k_{12} **tells you about the run of density with stellar radius**

Apsidal Motion Observation



Why Binaries Are So Important: Masses and Radii

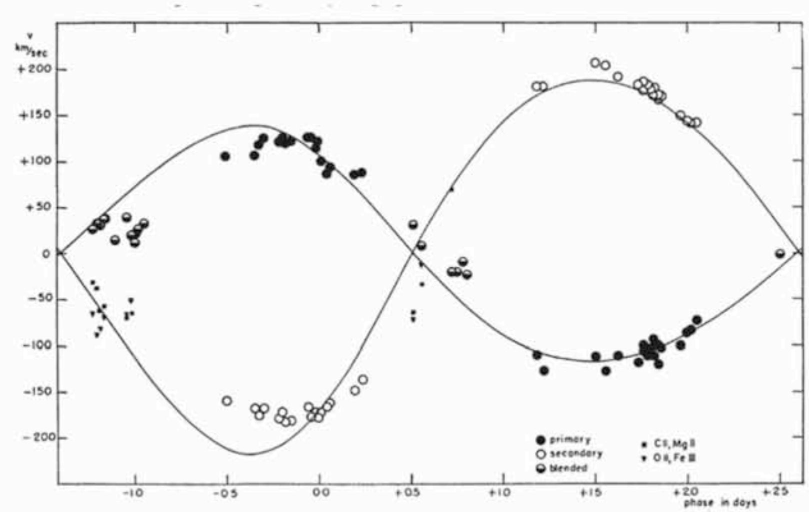


FIG. 1.—Radial velocities of α Virginis derived from the 1956 material The velocity-curve is that Struve and Ebbighausen (1934).

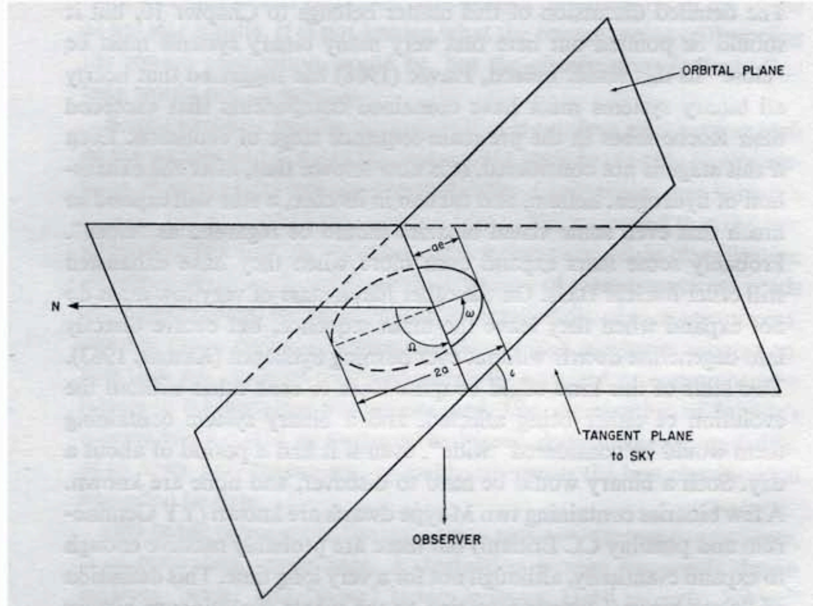


FIG. 1.3. Orbital plane and the tangent plane to the sky illustrating the significance of the orbital elements.

$$P^2 = \frac{4\pi^2}{G(M_1 + M_2)} a^3$$

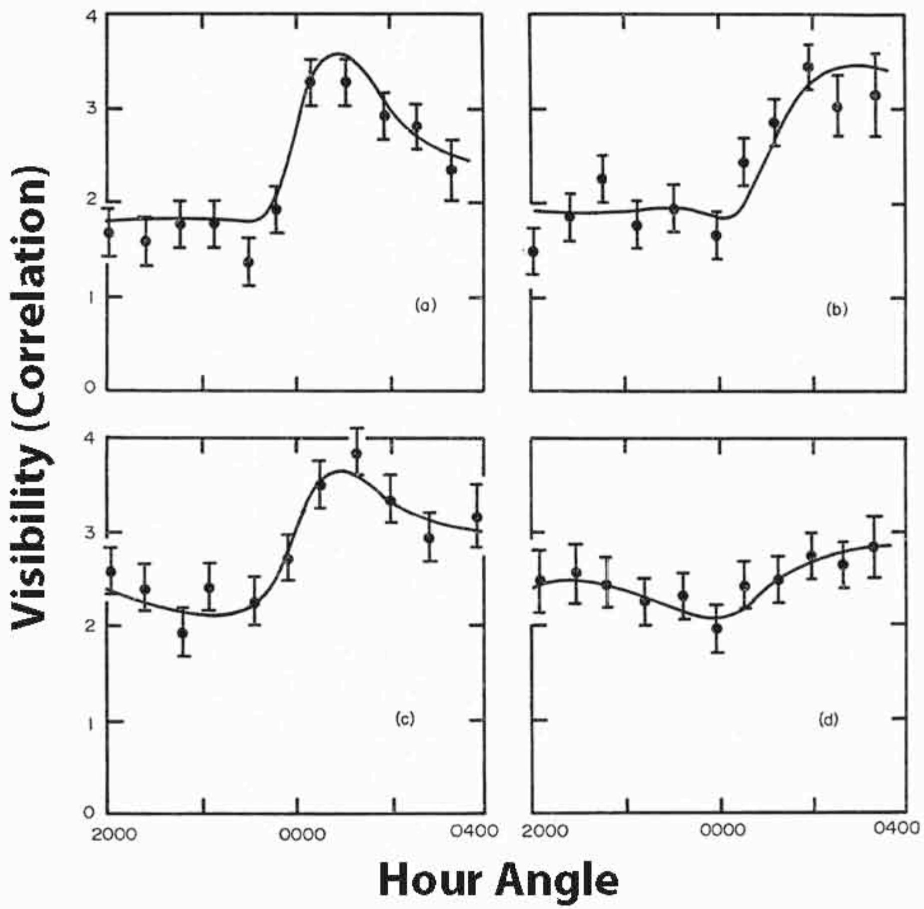
Don't know a^3 if you don't know the inclination.

$$K_2/K_1 = M_1/M_2$$

The projection of the 'true ellipse' on the sky is the apparent ellipse.
Binary orbit must be resolved!

Spica's Components Resolved by the Intensity Interferometer in 1971

Hebrison-Evans et al. (1971)

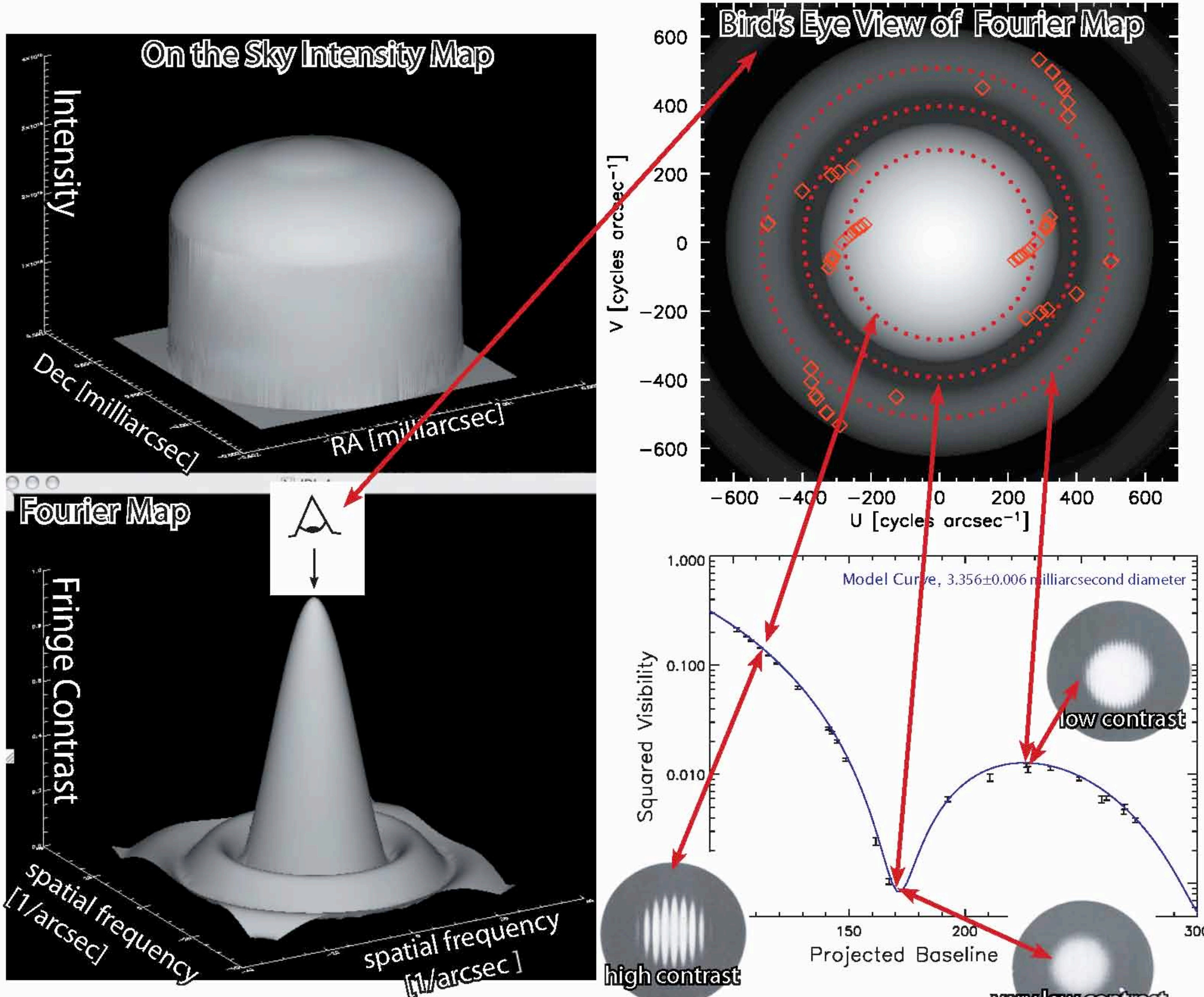


Narrabri Stellar Intensity Inteferometer
New South Wales, Austrailia

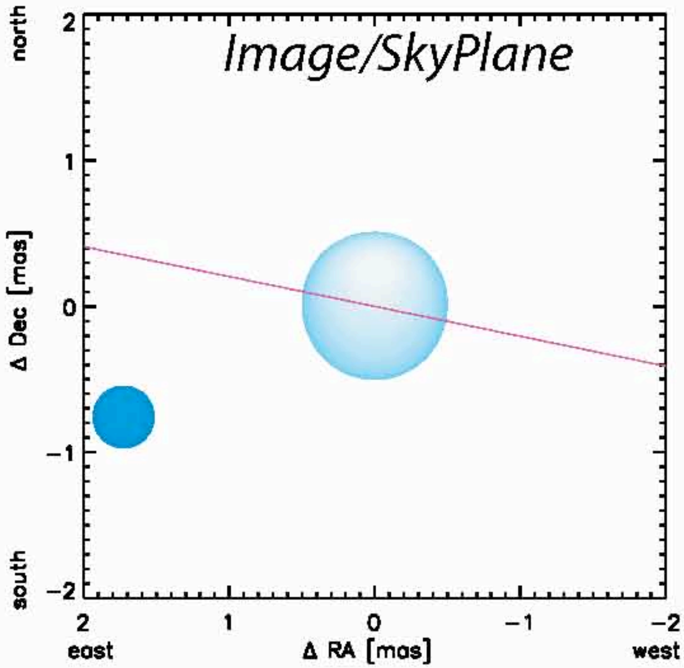
***Spica, the second spectroscopic binary to be resolved interferometrically (Capella 1st)**

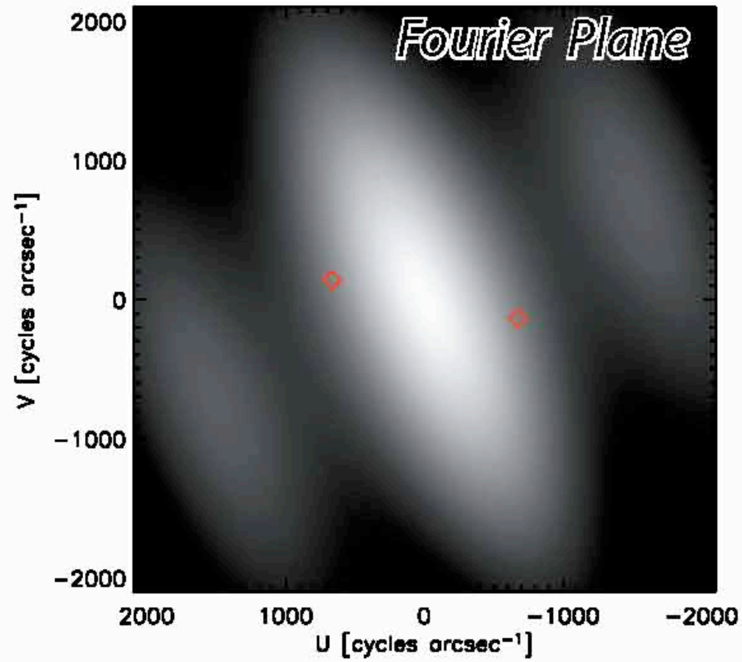
***Find inclination ~ 63° , semi-major axis, a ~ 1.8 mas, distance = 80 parsec = 261 light-years**
***Massive components: Spica A ~11 Msun and ~7 Msun**

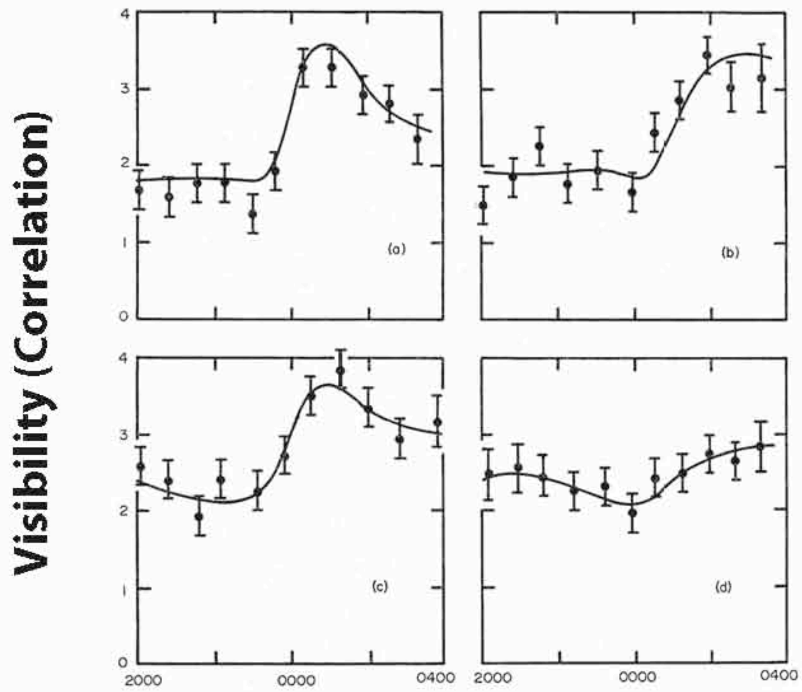
How Does an Interferometer See a Single Star?



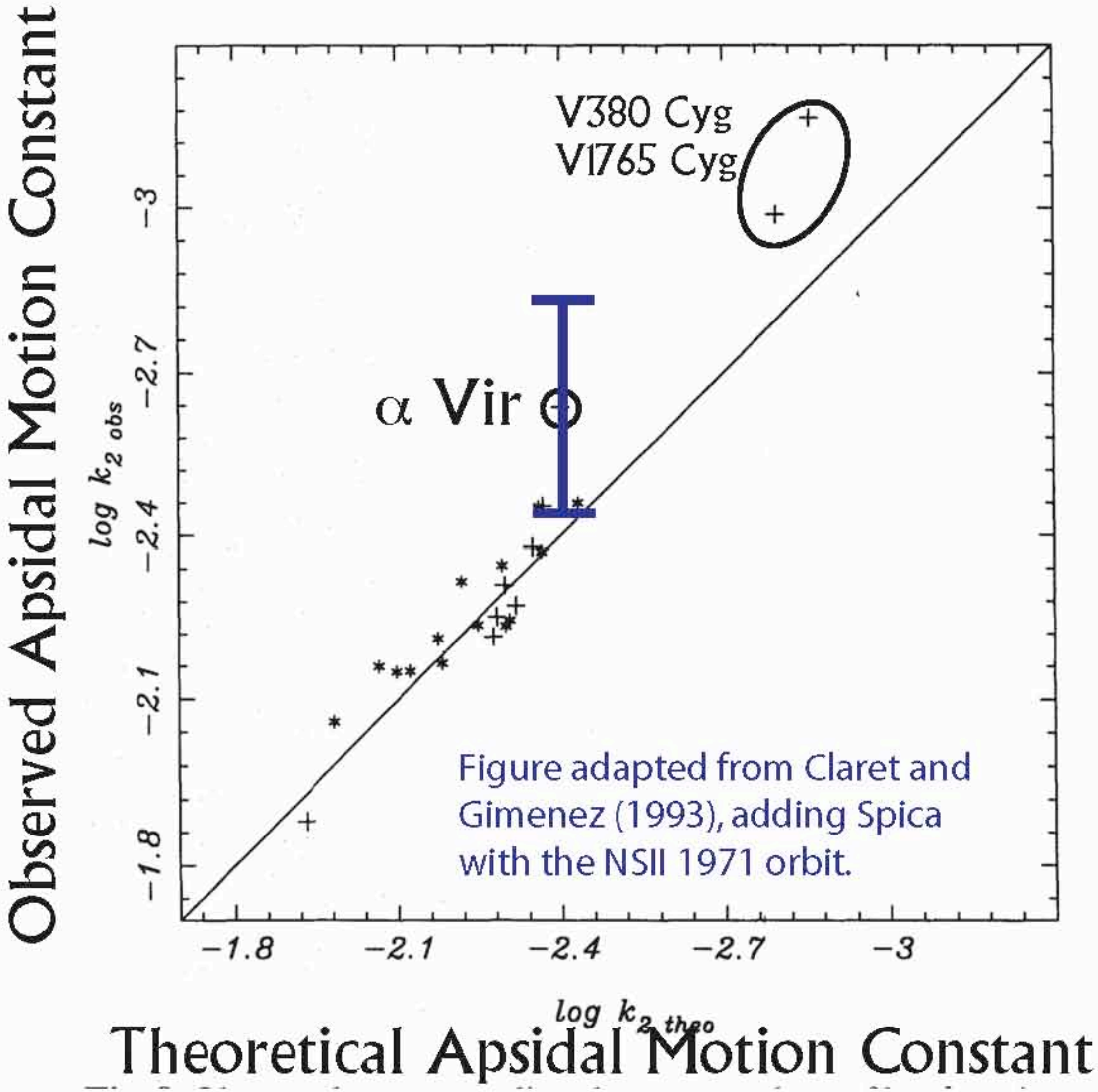
How Does an Interferometer See a Double Star





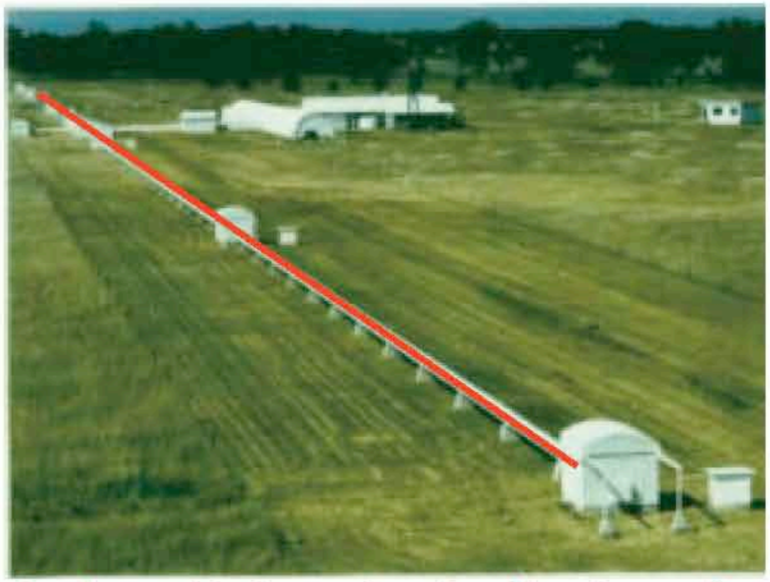


Spica just agrees with theory, but the error bar is big!

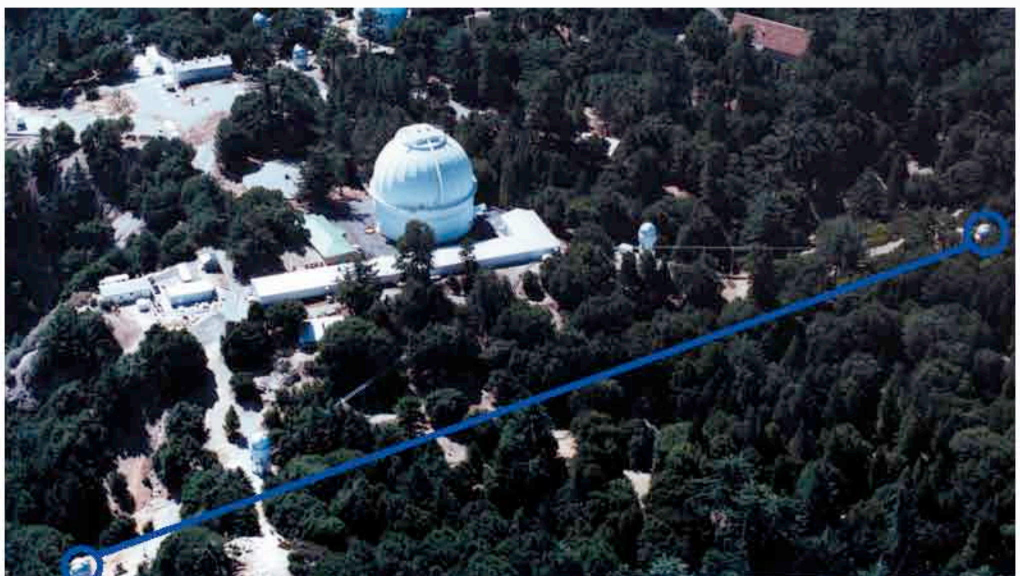


We want to reduce the observational error bar. This means a better interferometric orbit and more sophisticated analysis.

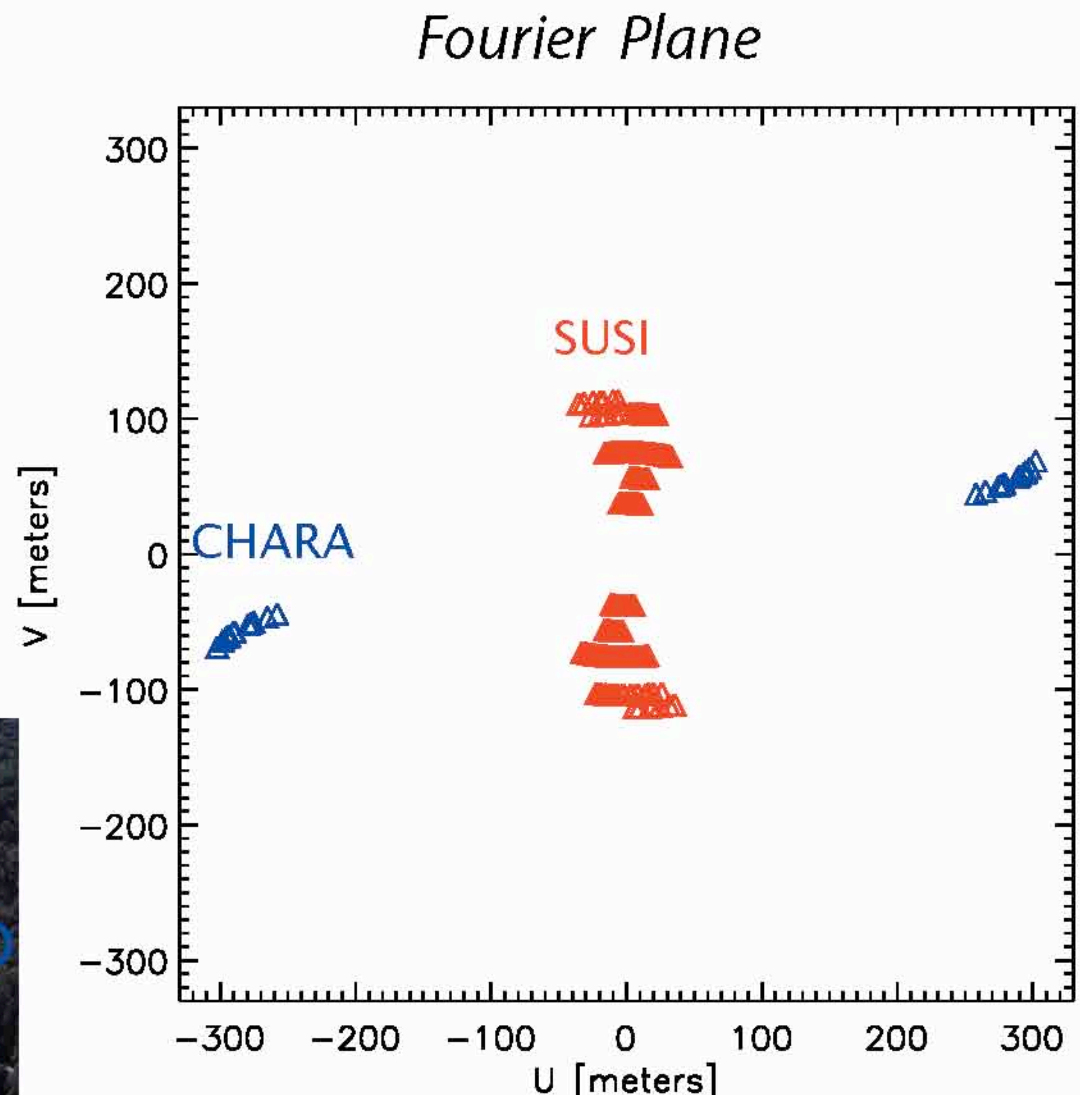
New Observations! Fourier Coverage of Spica from SUSI and CHARA



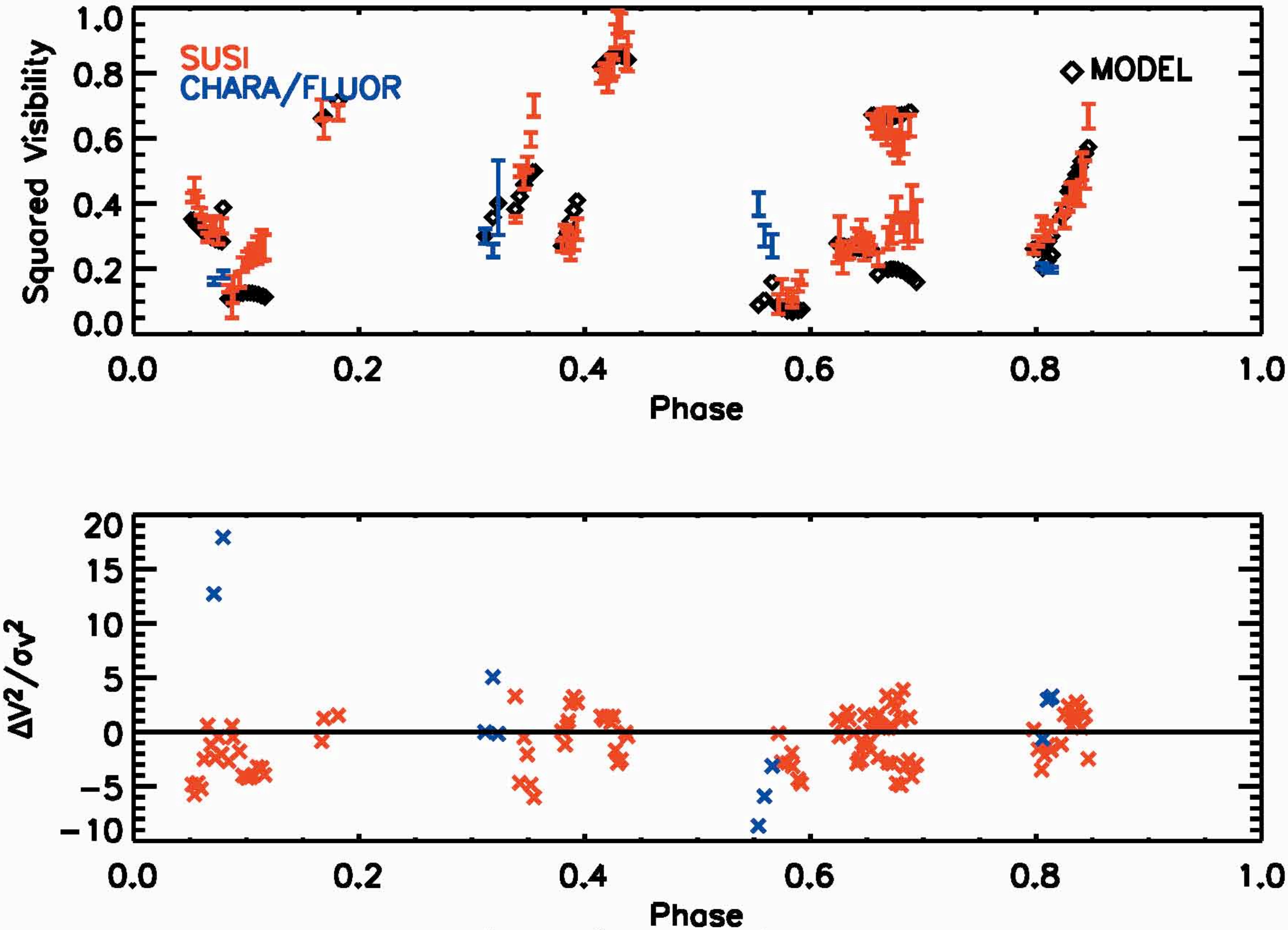
Sydney University Stellar Interferometer North-South Baselines (up to ~ 100 m)



Center for High Angular Resolution Astronomy Array East-West Baseline (~ 313 m)



Preliminary Model Comparison to SUSI+CHARA Visibility Data

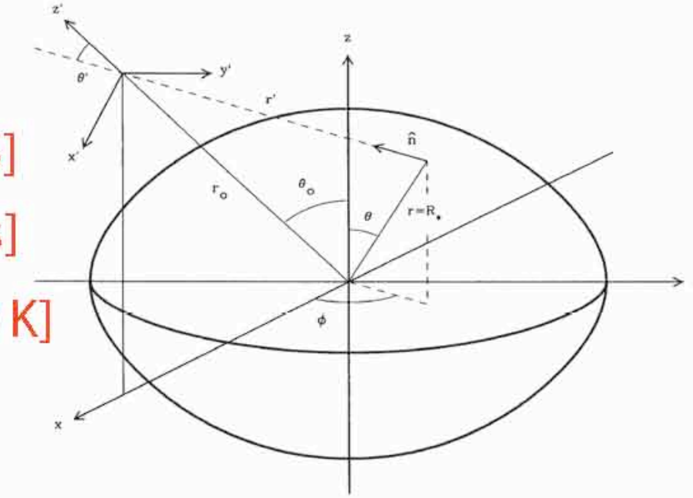


Phase from Periastron

Building a Binary Model for Spica

very preliminary values

ω	Fraction of the angular break-up speed [0.50, 0.25]
θ_{equ}	Equatorial angular diameter [1.076 mas , 0.45 mas]
$T_{\rm eff}^{\rm pole}$	Effective temperature at the pole [25900 K, 20850 K]
$g_{\rm pole}$	Surface gravity at the pole (Spica A) 3.67
β	Von Zeipel exponent [0.25, 0.25]
P	Period (periastron to periastron) 4.01459 days
T_0	Epoch of periastron 2440678.09
ω_0	Longitude of periastron at T_0 138°
U	Apsidal period 116 years
i	Orbital inclination 63.7°
Ω	Longitude of the line of nodes 121.3°
θ_α	Angular size of the semi-major axis 1.82 mas
K_1	Semi-amplitude velocity of Spica A 124 km/s
K_2	Semi-amplitude velocity of Spica B 199 km/s
γ	Radial velocity of the center of mass -5.8 km/s
π	Orbital parallax (distance) 13.3 mas



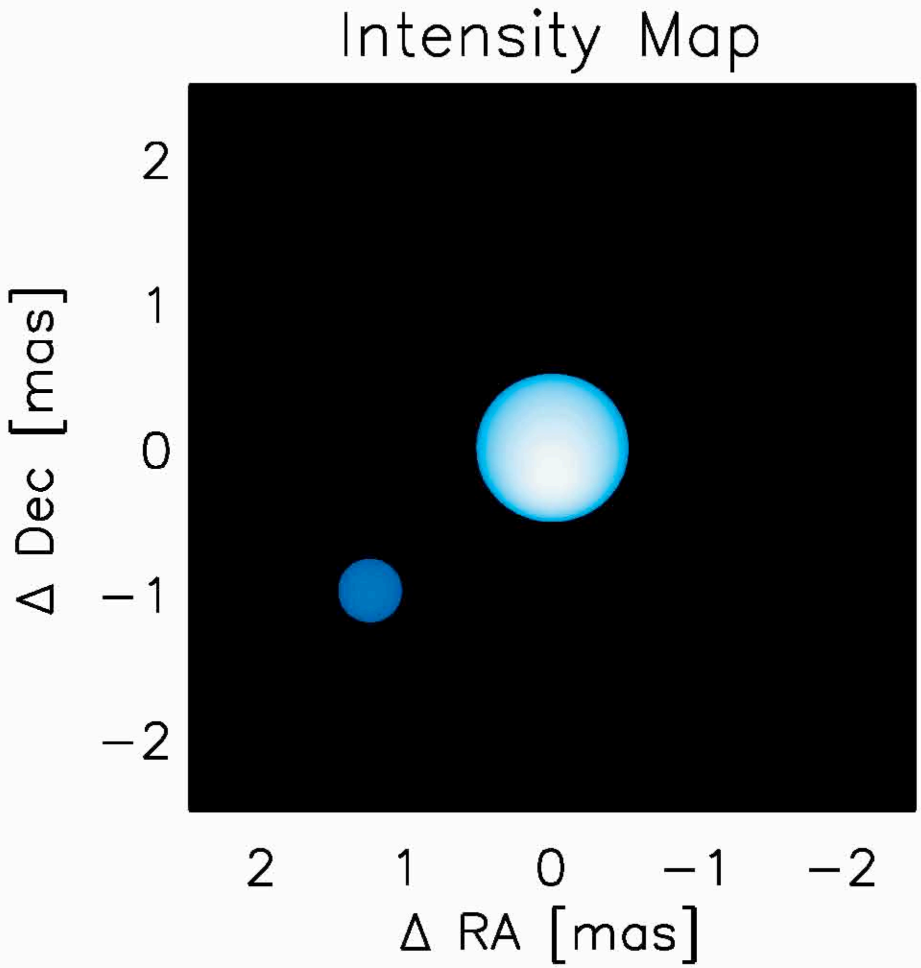
$$\frac{T_{\rm eff}(\vartheta)}{T_{\rm eff}^{\rm pole}} = \left(\frac{g(\vartheta)}{g_{\rm pole}}\right)^{\beta}$$

The intensity at each latitude, longitude point is interpolated from a grid of ~200 1-D non-LTE PHOENIX (Hauschildt et al.) model atmosphere radiation fields.

Interpolate I_λ at each Teff, log(g), λ, μ

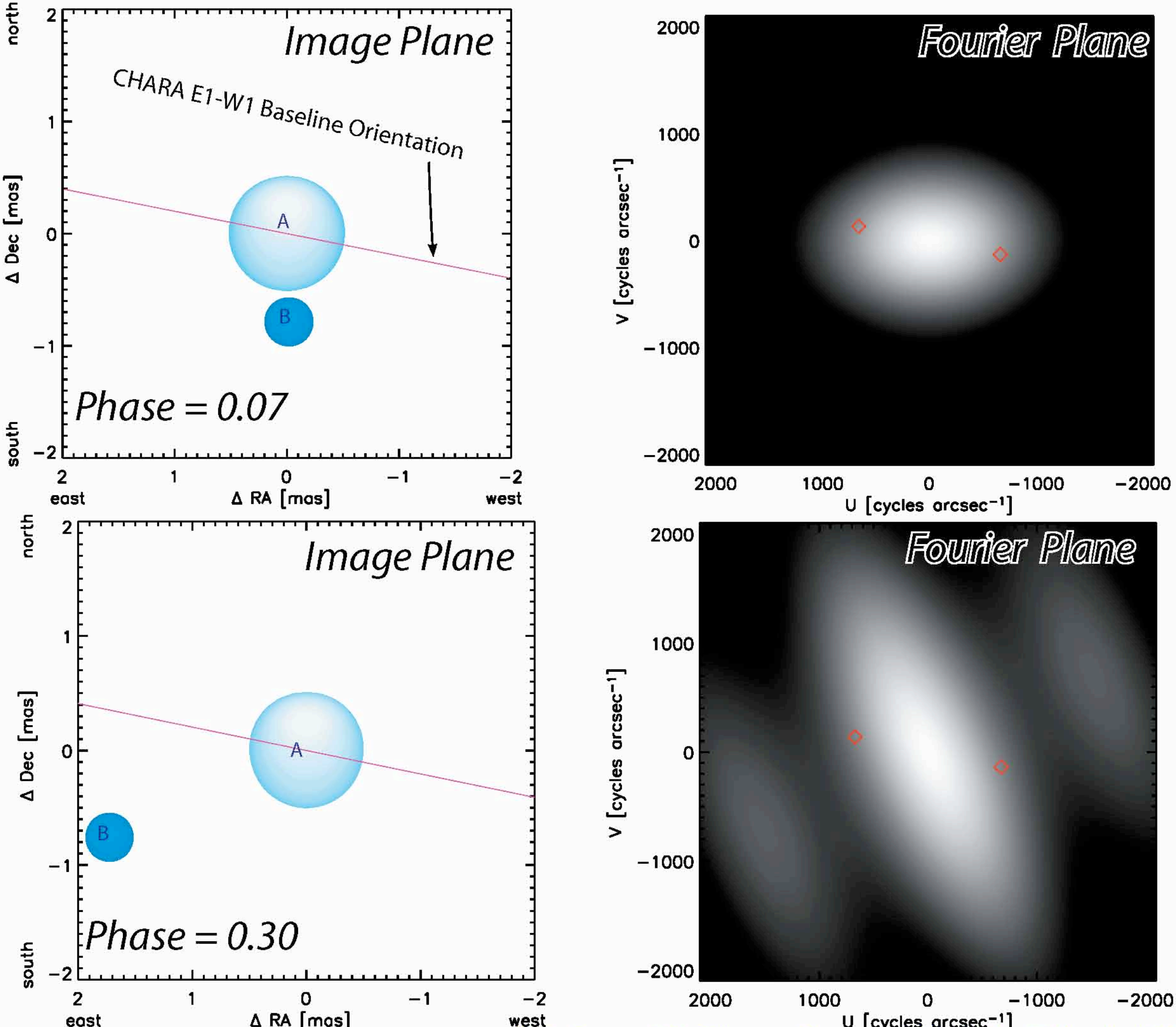
Computation of Synthetic Images

including rotational distortion, limb and gravity darkening

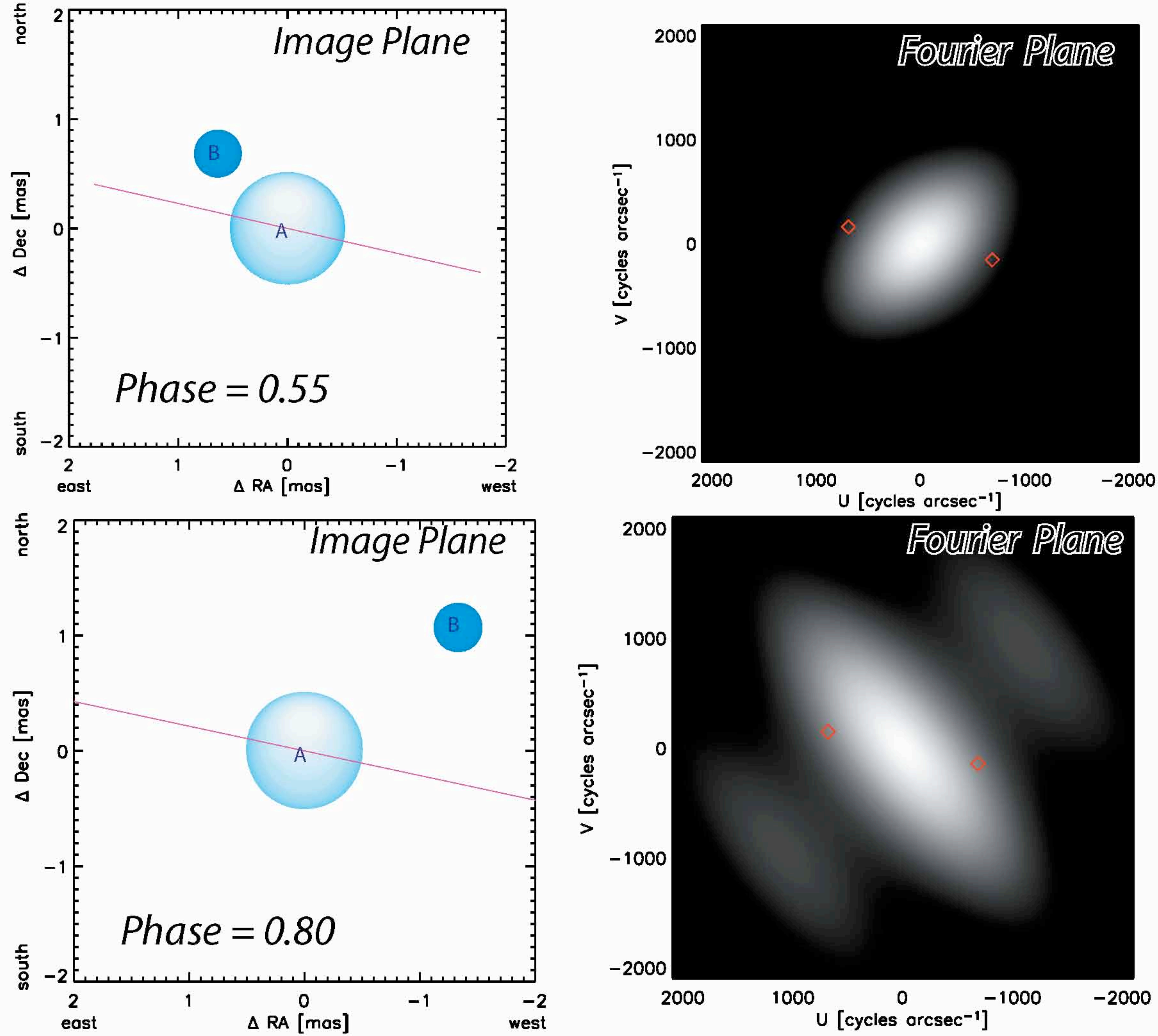


Specific Fouier components of this synthetic image are computed for a visibility simulation

Interferometric Simulation

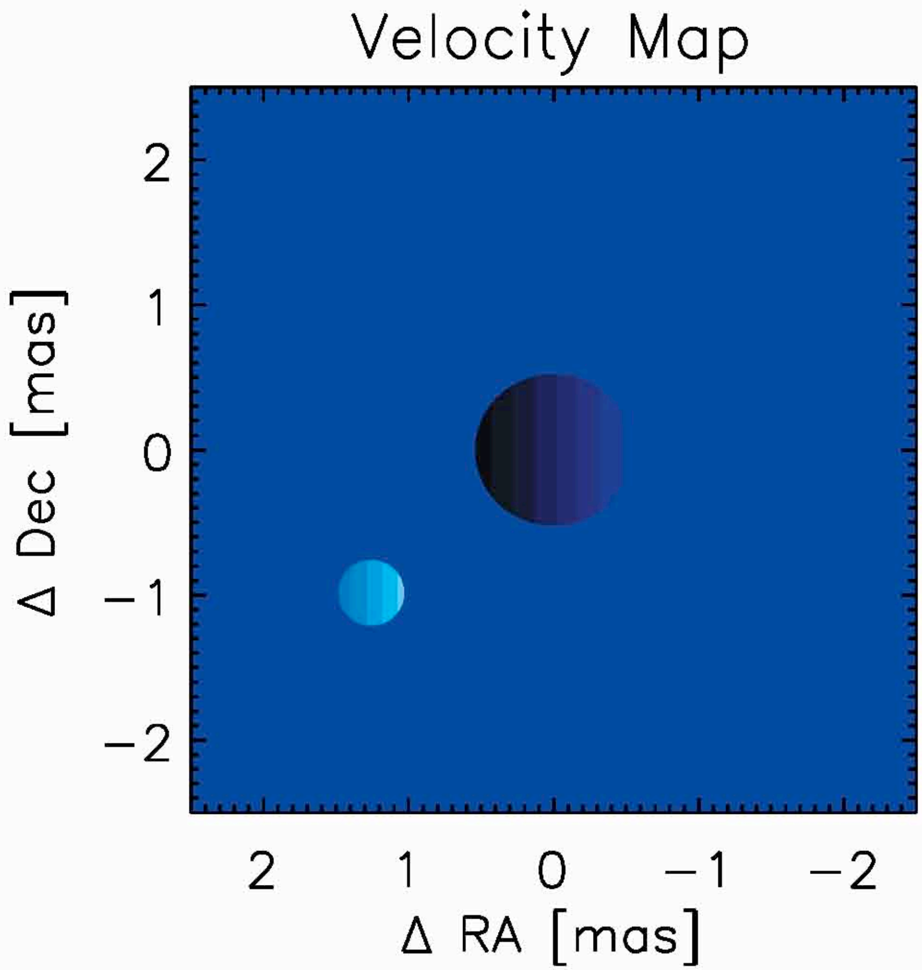


Interferometric Simulation



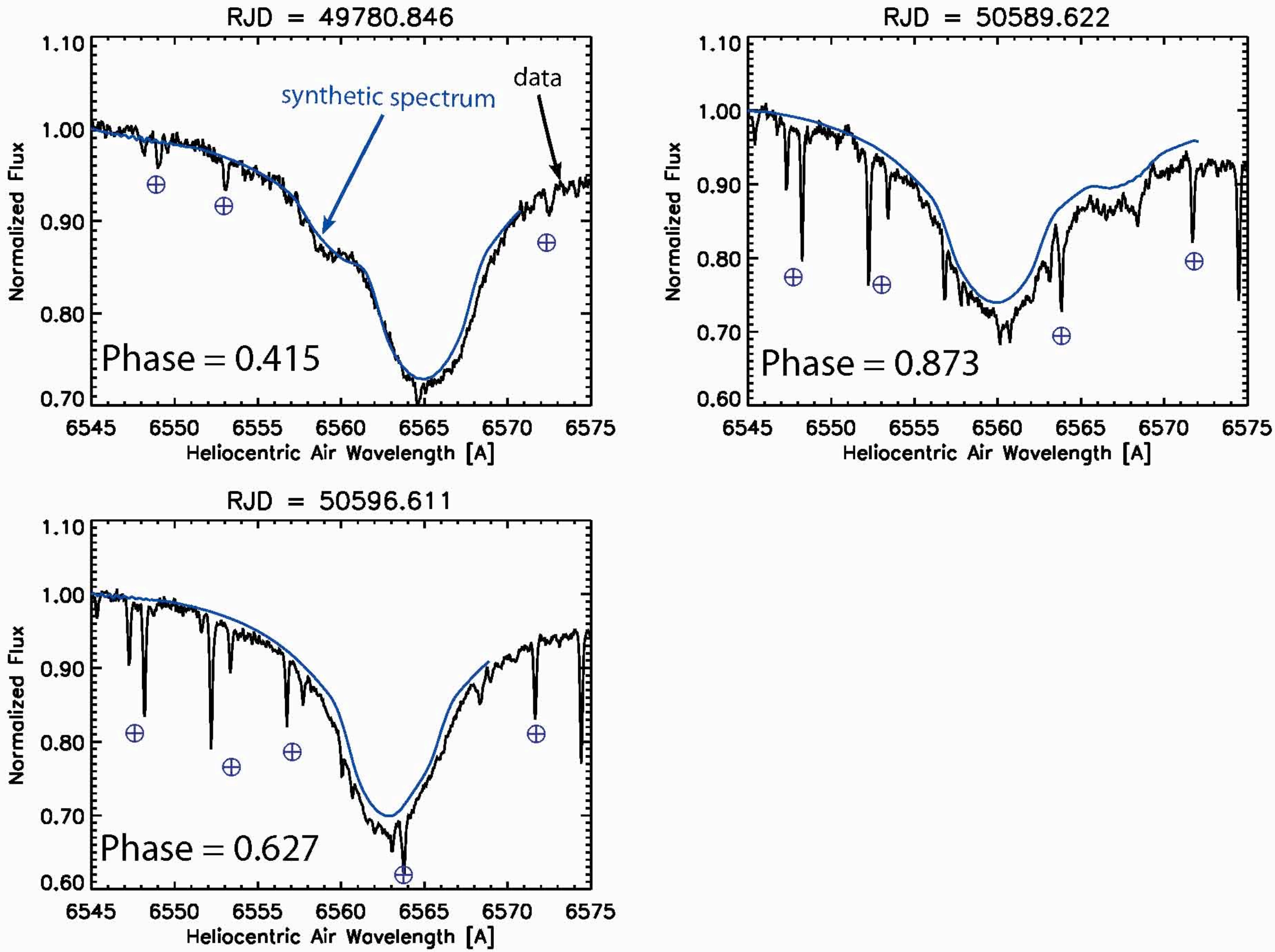
Modeling the Orbital and Rotational Velocity Field

including rotational distortion, limb and gravity darkening



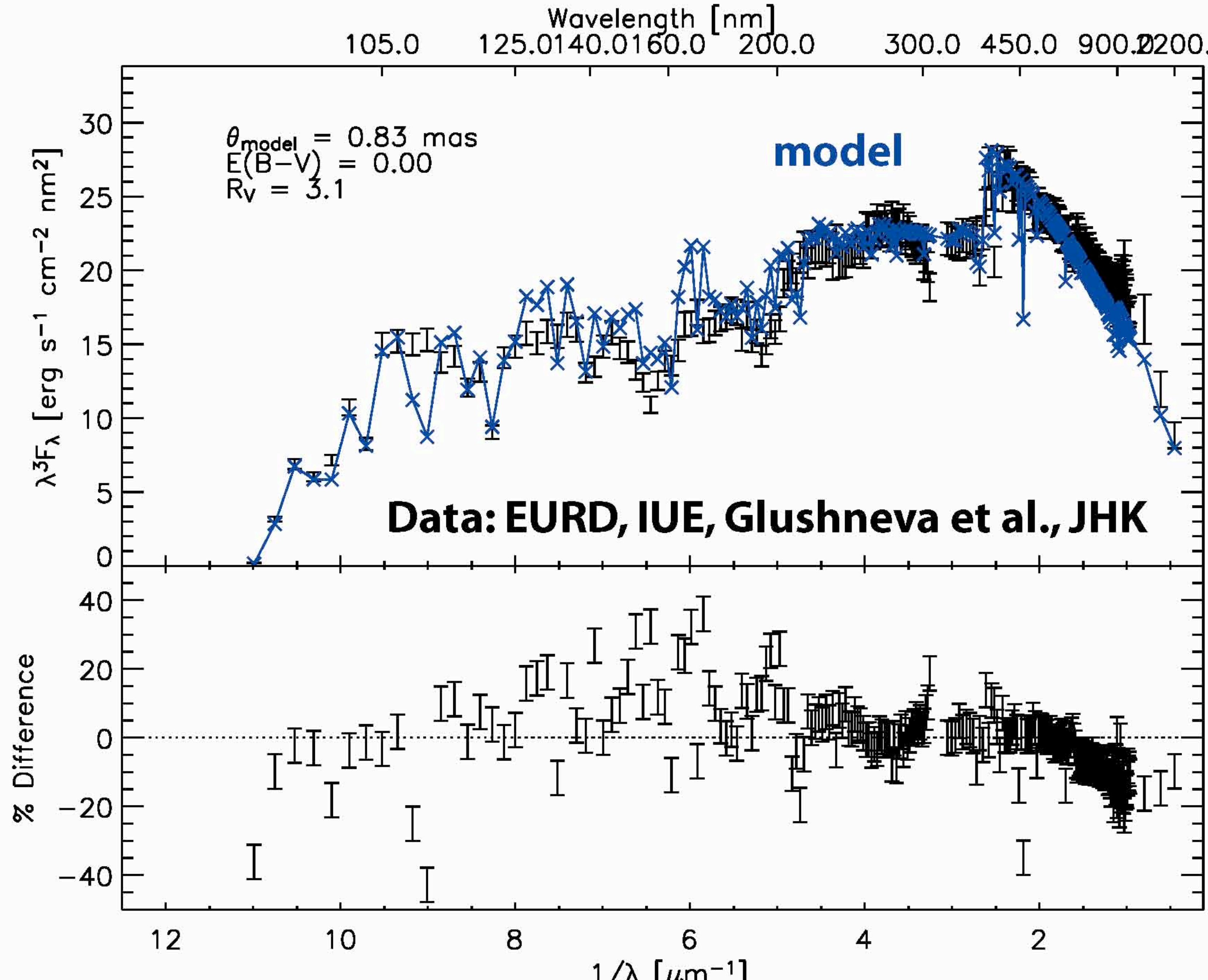
Rest frame wavelengths on the stars are mapped to observer's frame for a high dispersion spectrum simulation

Model Comparison to High Dispersion Spectroscopy



Data: Ritter Astrophysical Observatory (U. of Toledo)

Finally, A Model Comparison to Spectral Energy Distribution



Conclusions and Work to be Done

2-D atmospheric surface effects are beginning to be probed in binaries with long-baseline interferometry.

Detailed atmospheric modeling required for analysis.

Rich interferometric data sets (such as Spica) to have great potential for increasing our fundamental knowledge of close binaries and their internal structure.

Next steps:
1) including tidal distortion and irradiation effects
2) complete spectroscopic analysis, refine orbital parameters
3) reduce error bar on apsidal constant k_{12}!
4) compare results with asteroseismology!