What's the Matter with Vega?: The Next Generation of Model Atmospheres for Rapidly Rotating Stars

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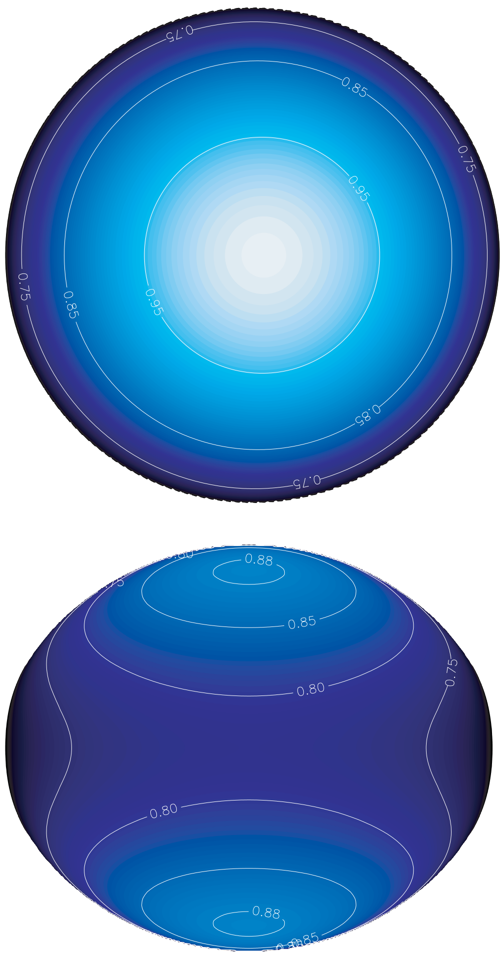
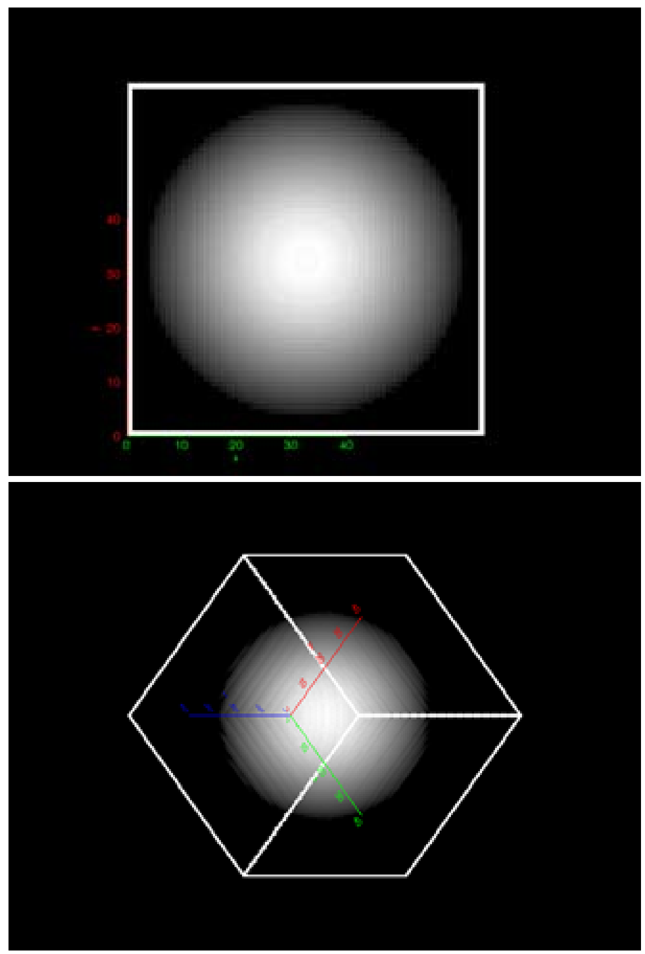
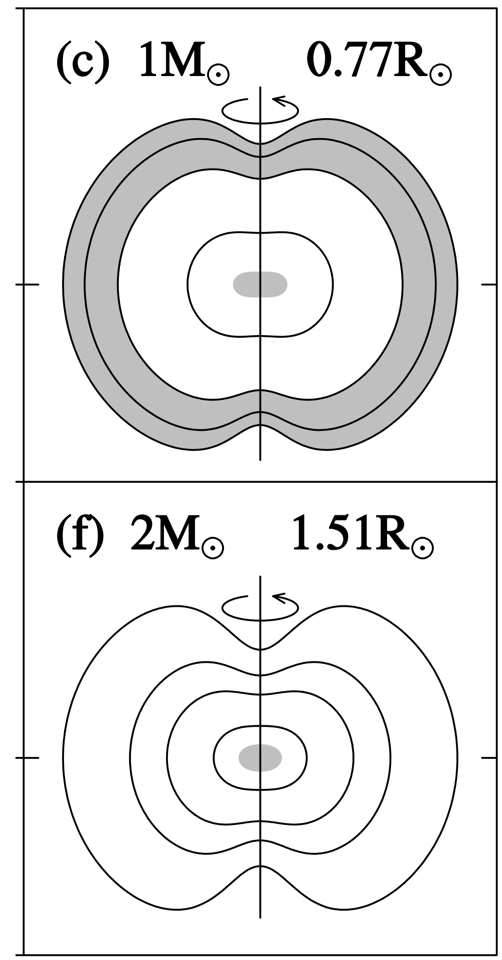


Aufdenberg et al. (2006) ApJ, 645, 664

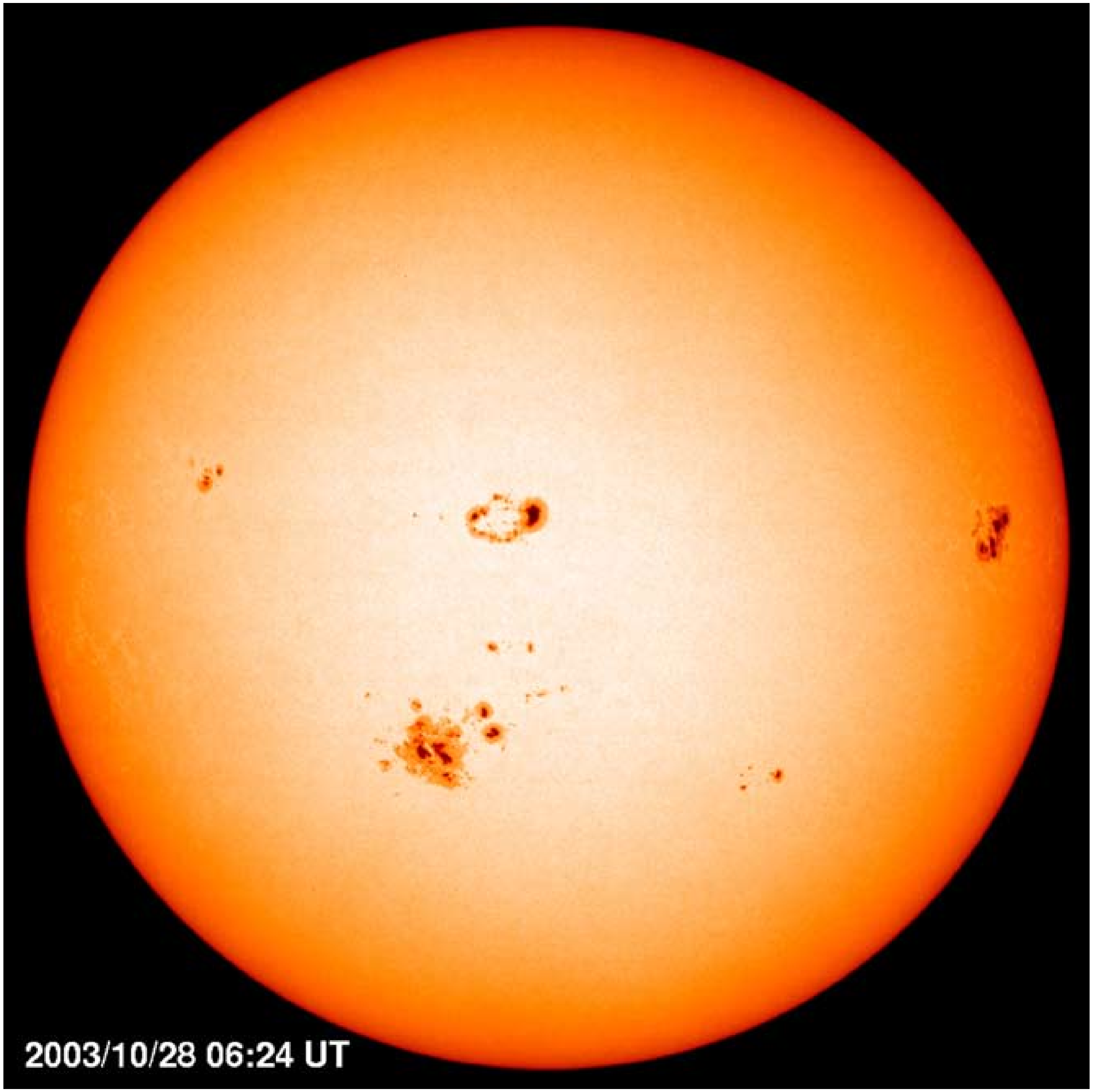


Hauschildt, P. H. and Baron, E. (2006) A&A, 451, 273



MacGregor et al. (2007) ApJ, 663, 560

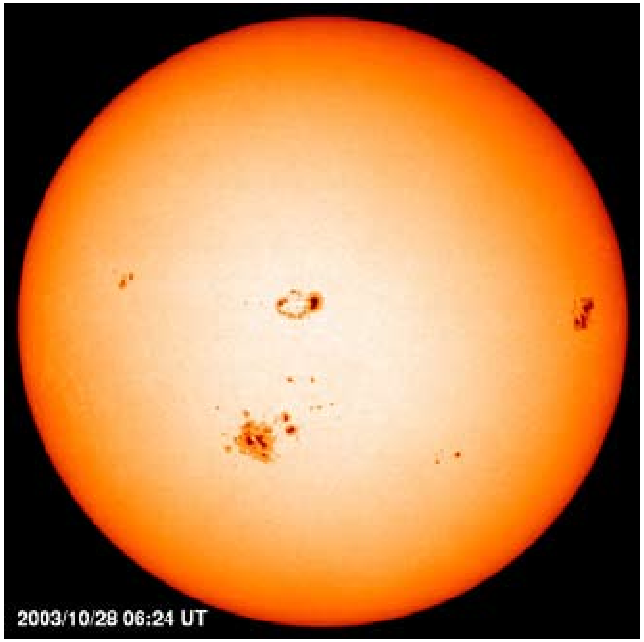
Solar and Heliospheric Observatory (SOHO)
Michelson Doppler Imager (MDI)

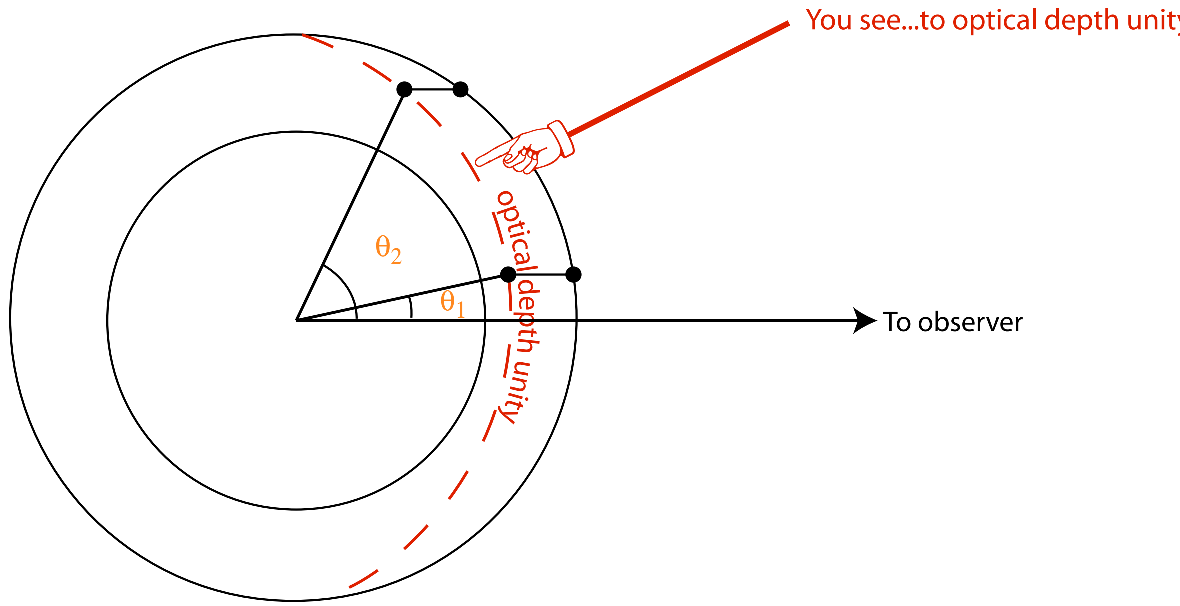


http://sohowww.nascom.nasa.gov/bestofsoho/images/large/mdi20031028.jpg

Very narrow band
Ni I 6768 Å

Limb Darkening Basics

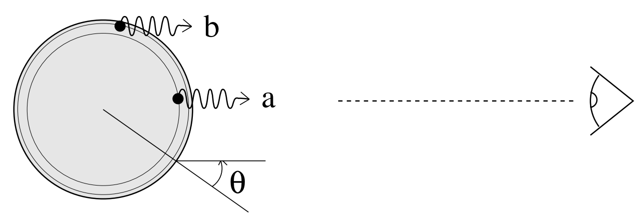




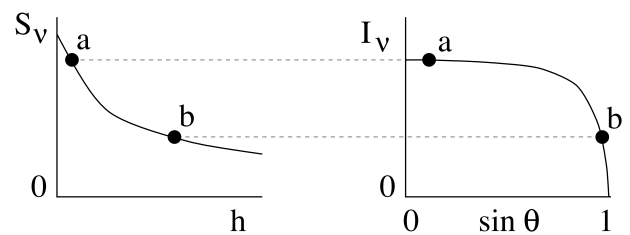
(a) Deeper, hotter layers are visible near the disk center

(b) Shallower, cooler layers are visible near the disk limb

isothermal atmospheres do not exhibit limb darkening



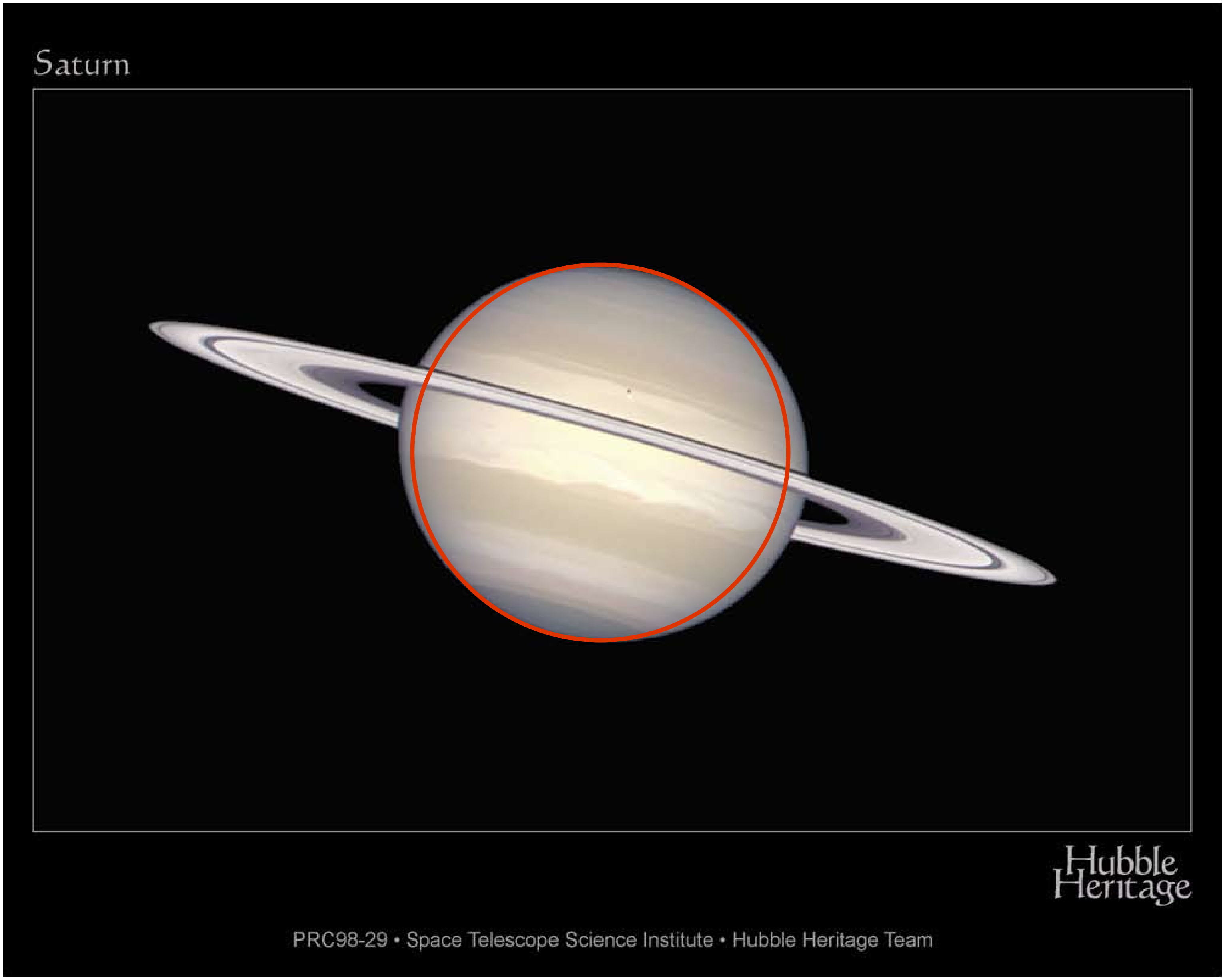
Rutten (2003)



source function as a function of depth

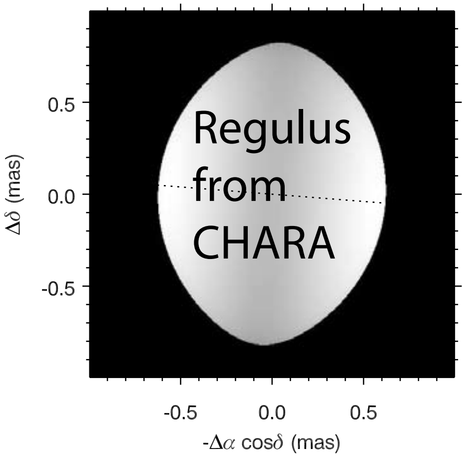
center to limb intensity profile

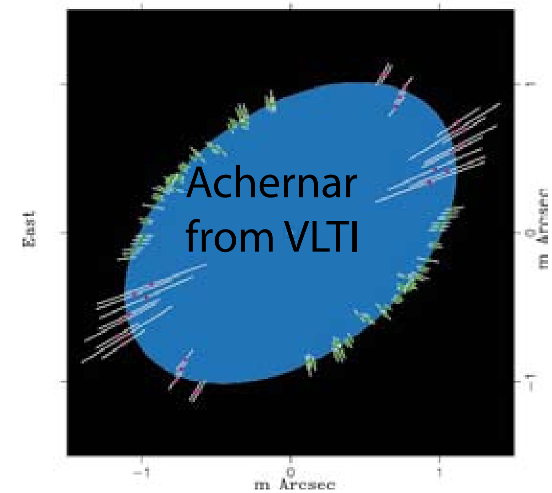
Oblate Saturn Viewed from the Hubble Space Telescope



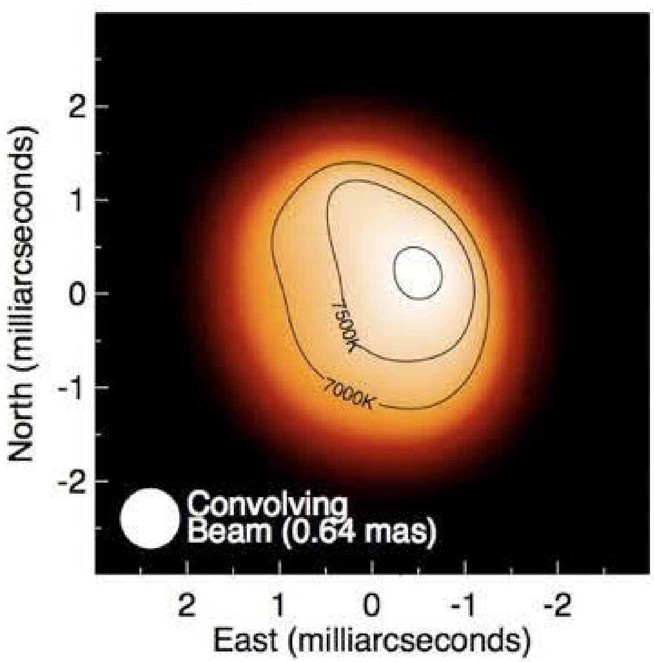
Resolved Rapid Rotating Stars from Interferometry

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

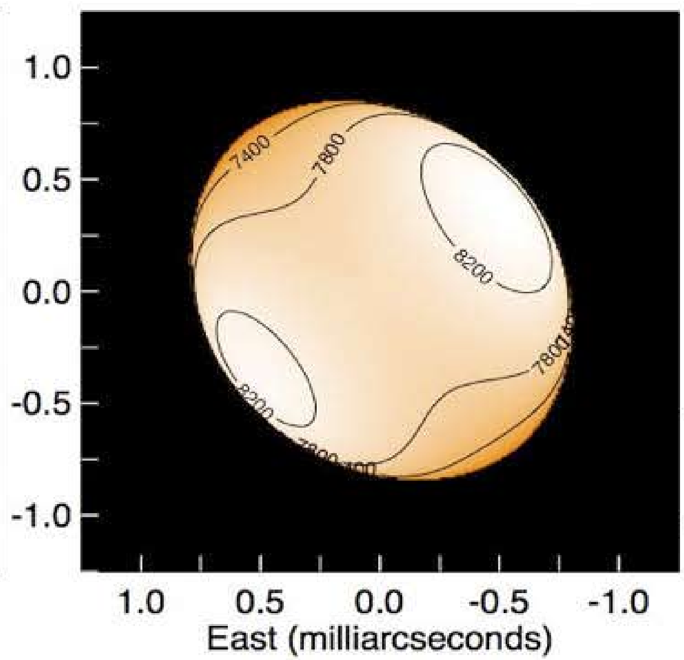




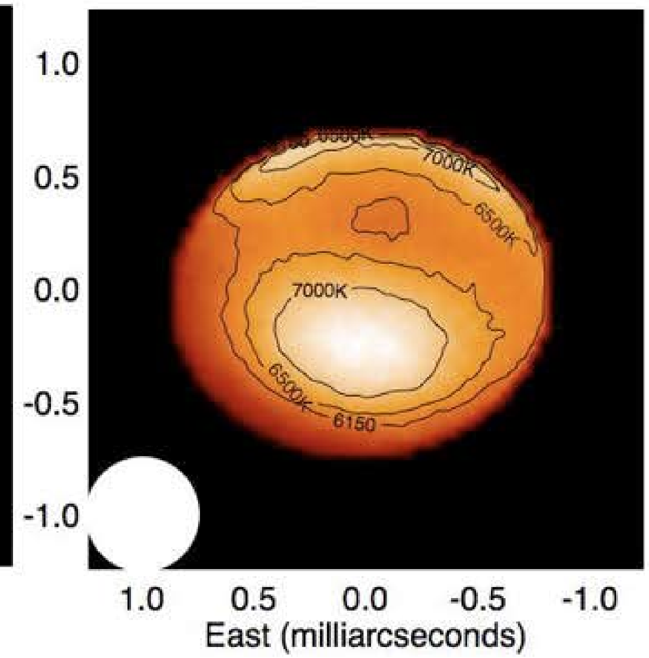
*Disk of **Achernar** (B3 Vpe) resolved as ellipsoid by VLTI (A. Domiciano de Souza et al. 2003). Axial ratio: 1.56±0.05



*Disk of **Altair** (A7 V) resolved by CHARA (J. Monnier et al. 2007).



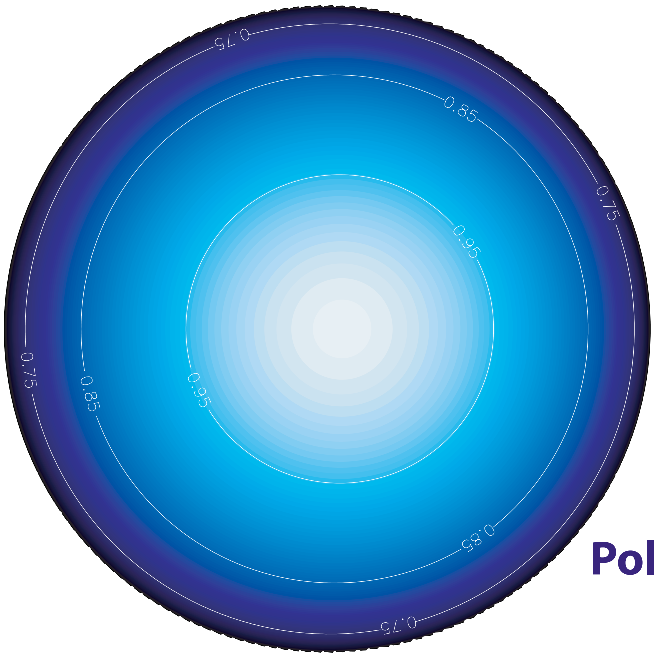
*Disk of **Rasalhague** (A5 III) resolved by CHARA (M. Zhao et al. 2009).



*Disk of **Alderamin** (A7 V) resolved by CHARA (M. Zhao et al. 2009).

Gravity Darkening vs. Limb Darkening

Rapidly Rotating Model with Intensity Contours

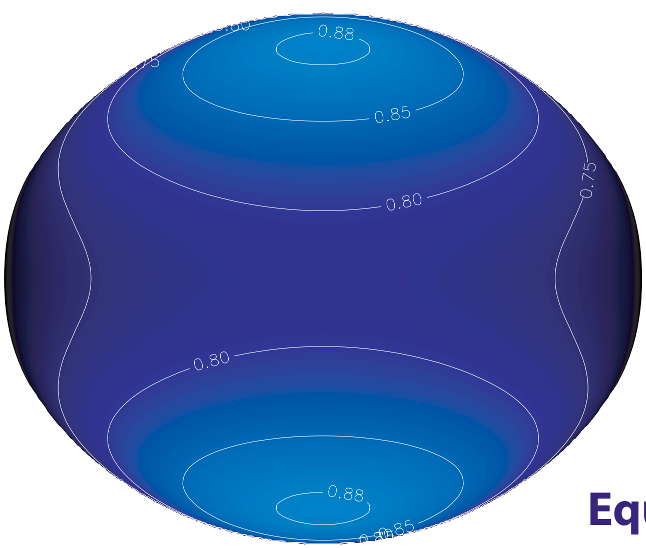


Pole-on view

Gravity darkening: *Intrinsic to the star, a pole-to-equator effective temperature gradient resulting from rapid rotation. Local Teff on surface correlates with local gravity (e.g., $T_{eff} \propto g^{1/4}$)*

Limb darkening:

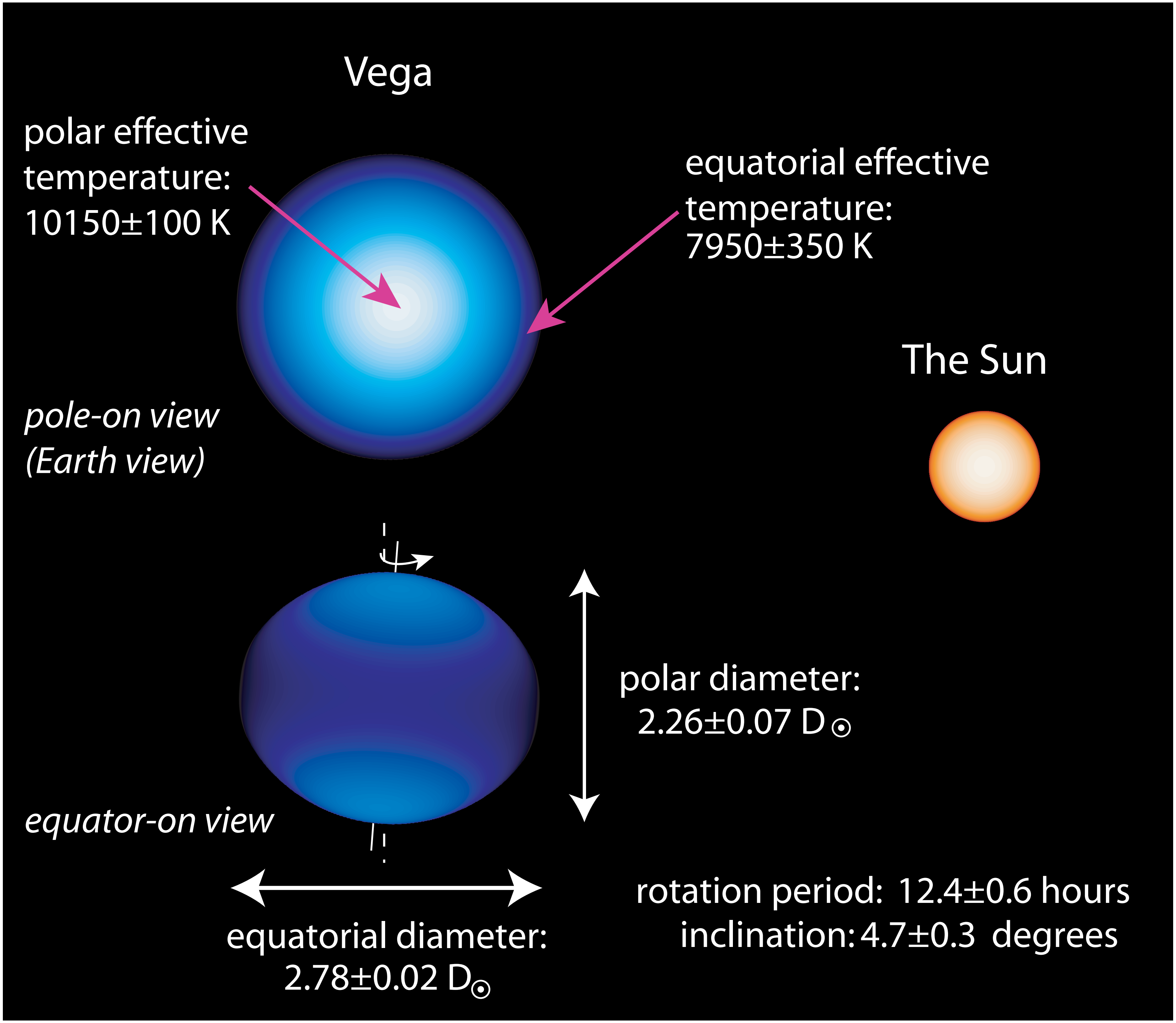
An observer-dependent effect in which the intensity across a stellar surface varies due to a radial or depth dependent temperature gradient.



Equator-on view

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

A Pole-on Rapid Rotator: Vega (Aufdenberg et al. 2006)

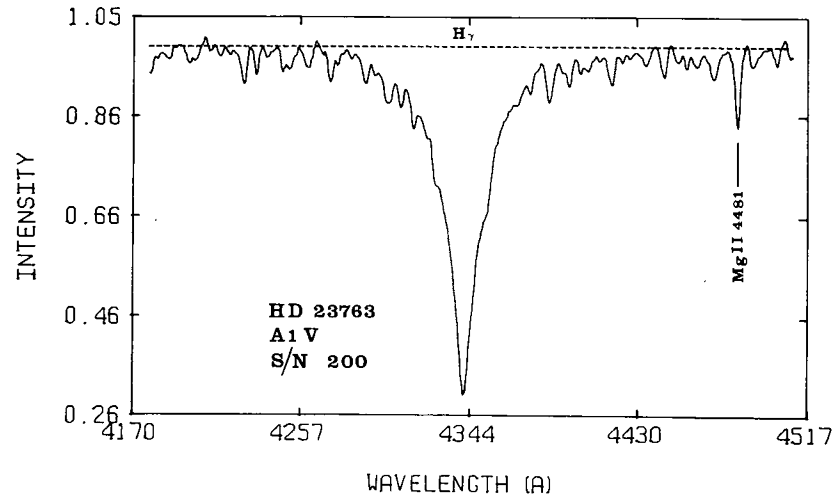


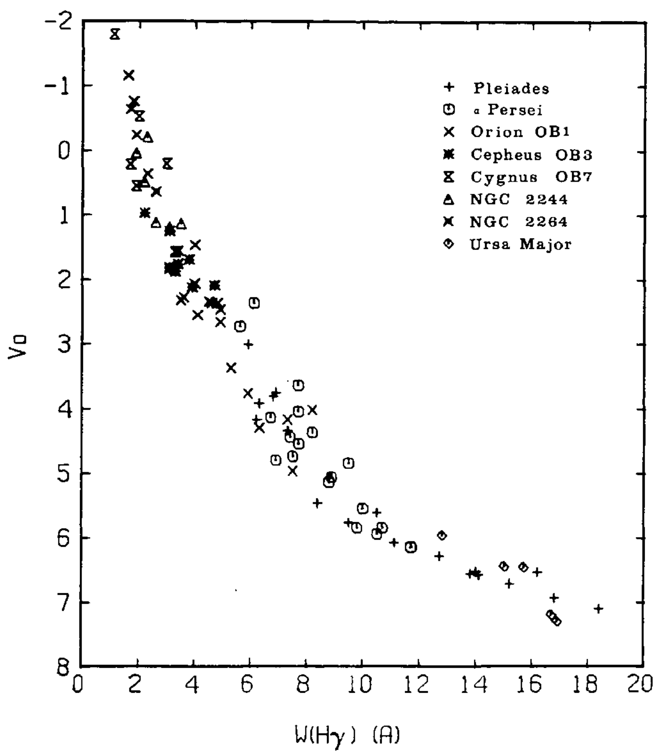
Vega is 47% more luminous than expected for its spectral type (A0 V)

AN EMPIRICAL Hγ LUMINOSITY CALIBRATION FOR CLASS V–III STARS

(1985)

CHRISTOPHER G. MILLWARD AND GORDON A. H. WALKER
Geophysics and Astronomy Department, University of British Columbia





Vega brighter than mean W(Hγ)- M_V relation

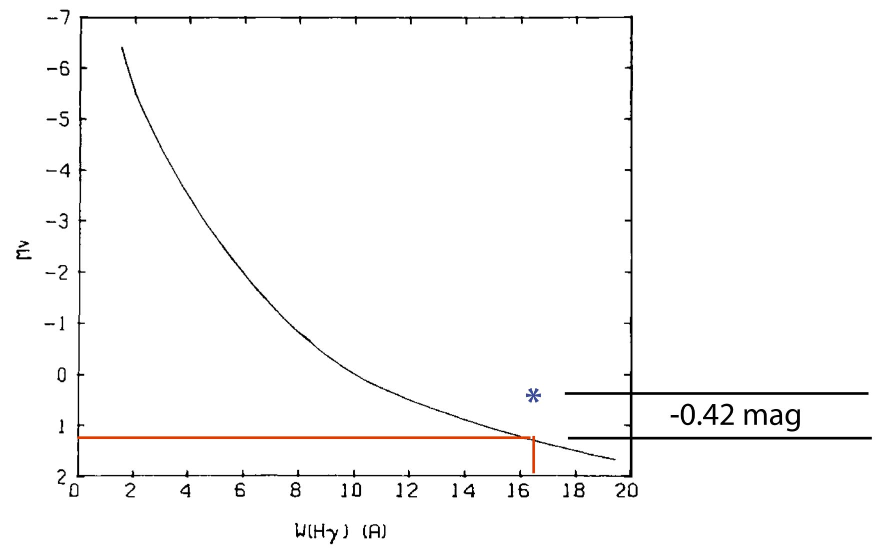
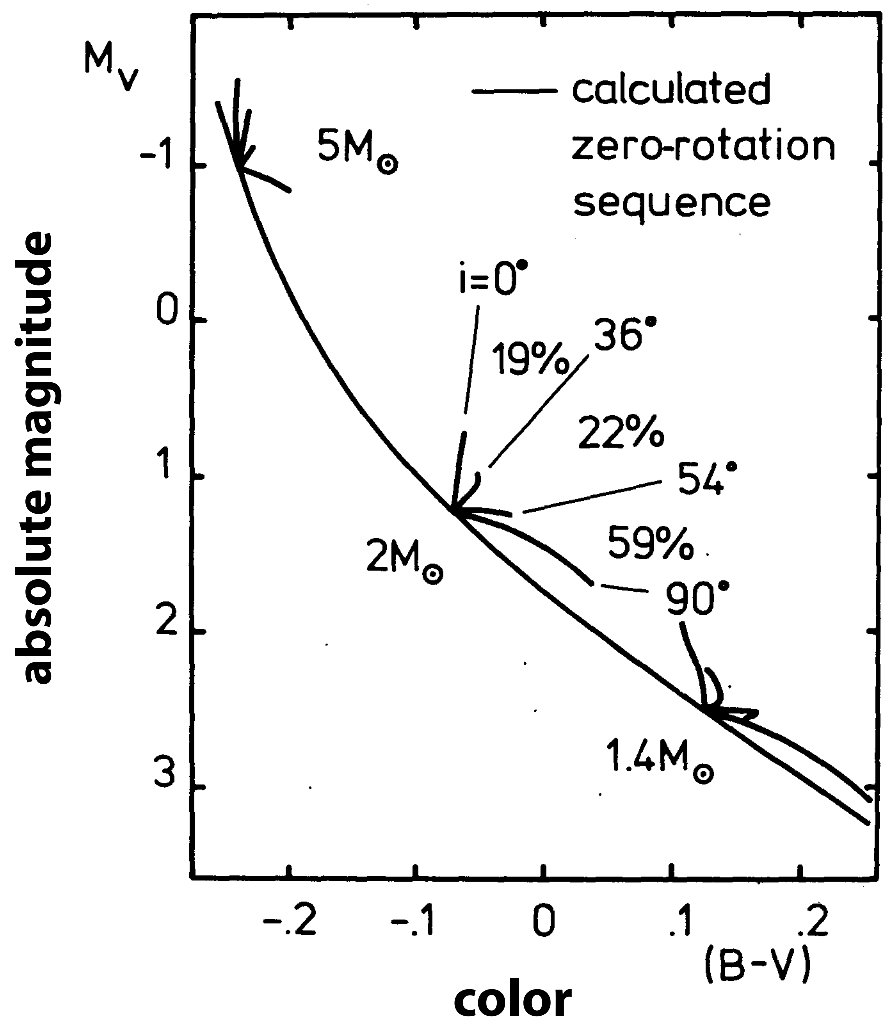


FIG. 6.—Mean $W(H\gamma) - M_v$ relation

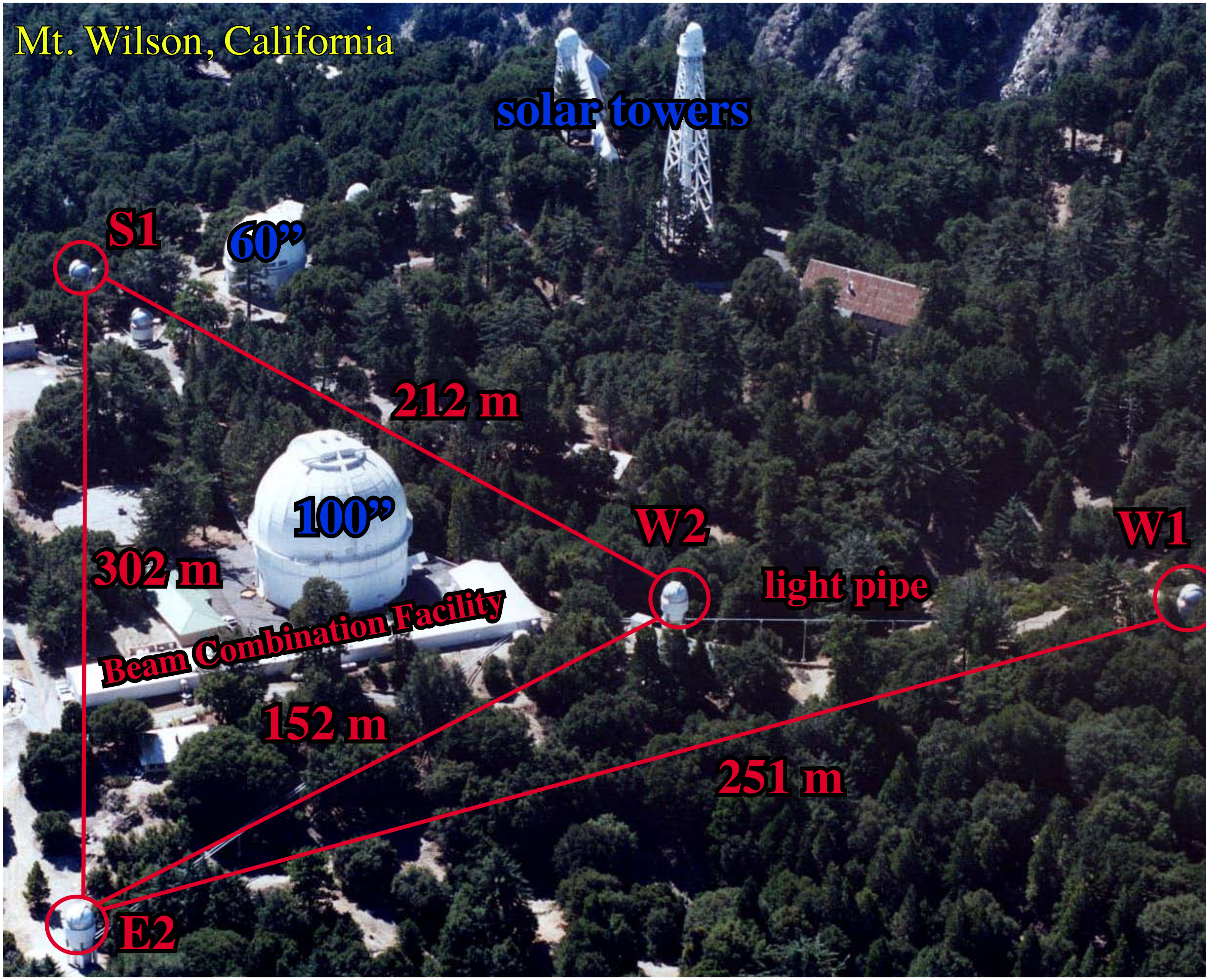
Vega is a Pole-on Rapid Rotator (R. Gray 1985, 1988)

Pole-on rapid rotators appear more luminous, have same color as slow rotators



From Tassoul (1978) "Theory of Rotating Stars"
originally from Maeder & Peytremann (1970)

CHARA (Center for High Angular Resolution Astronomy) Array



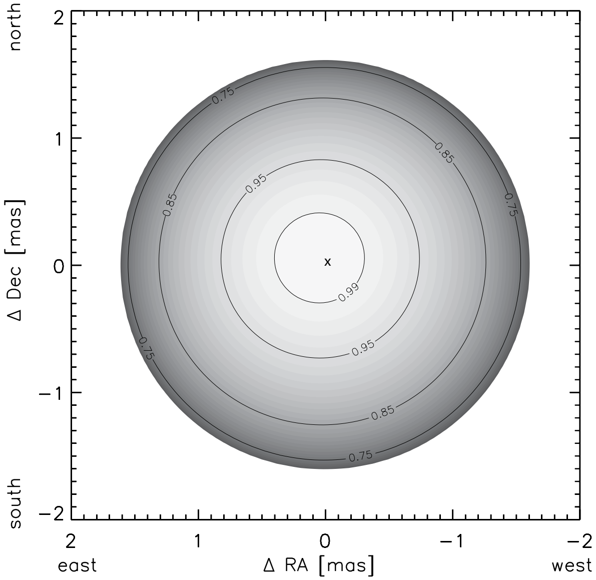
http://www.chara.gsu.edu/CHARA/Slides/CHARAoverview.pdf

Vega Observations
May, June2005

K-band
λ = 2.2 μm

Fiber
Linked
Unit for
Optical
Recombination

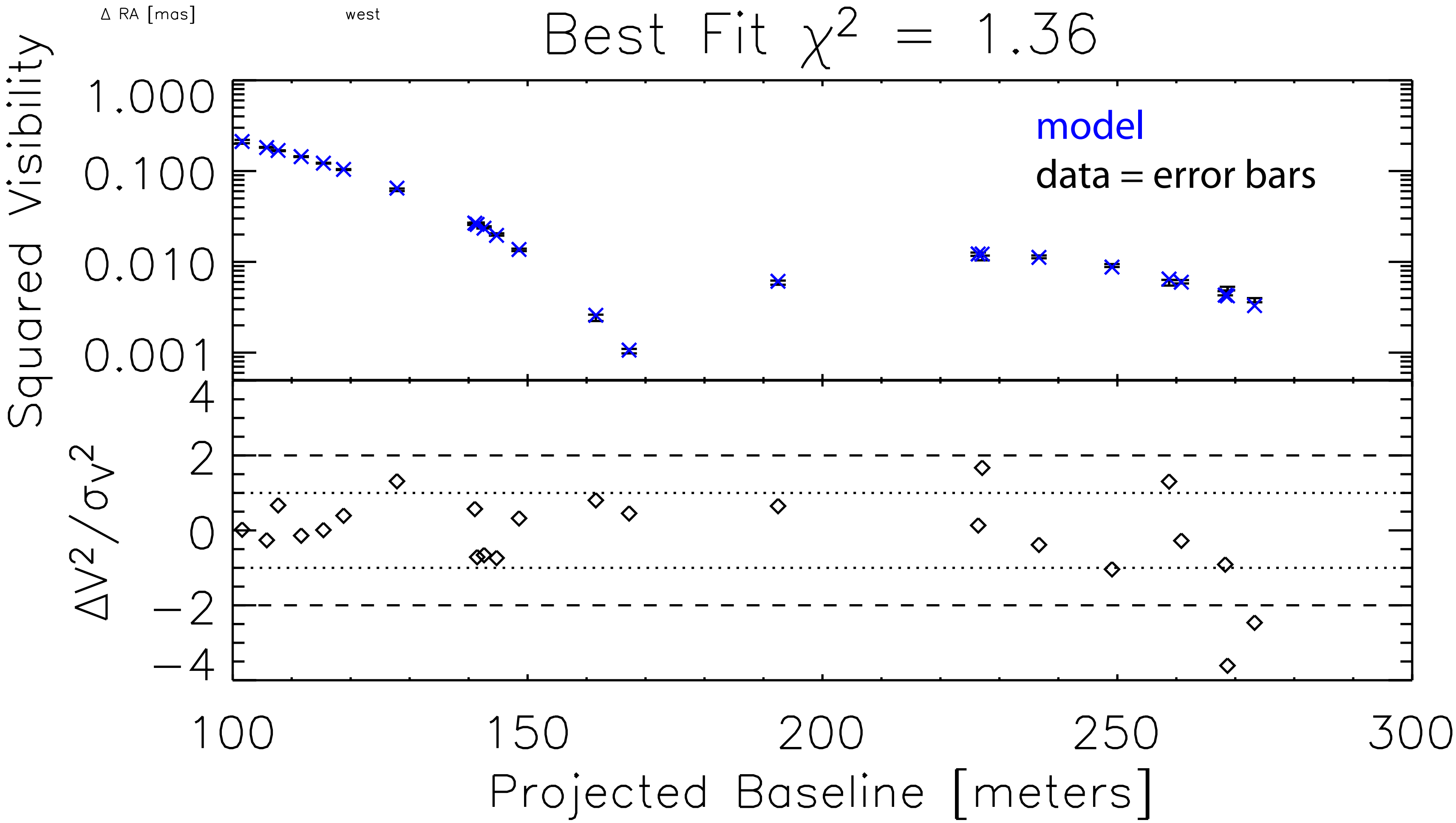
beam combiner



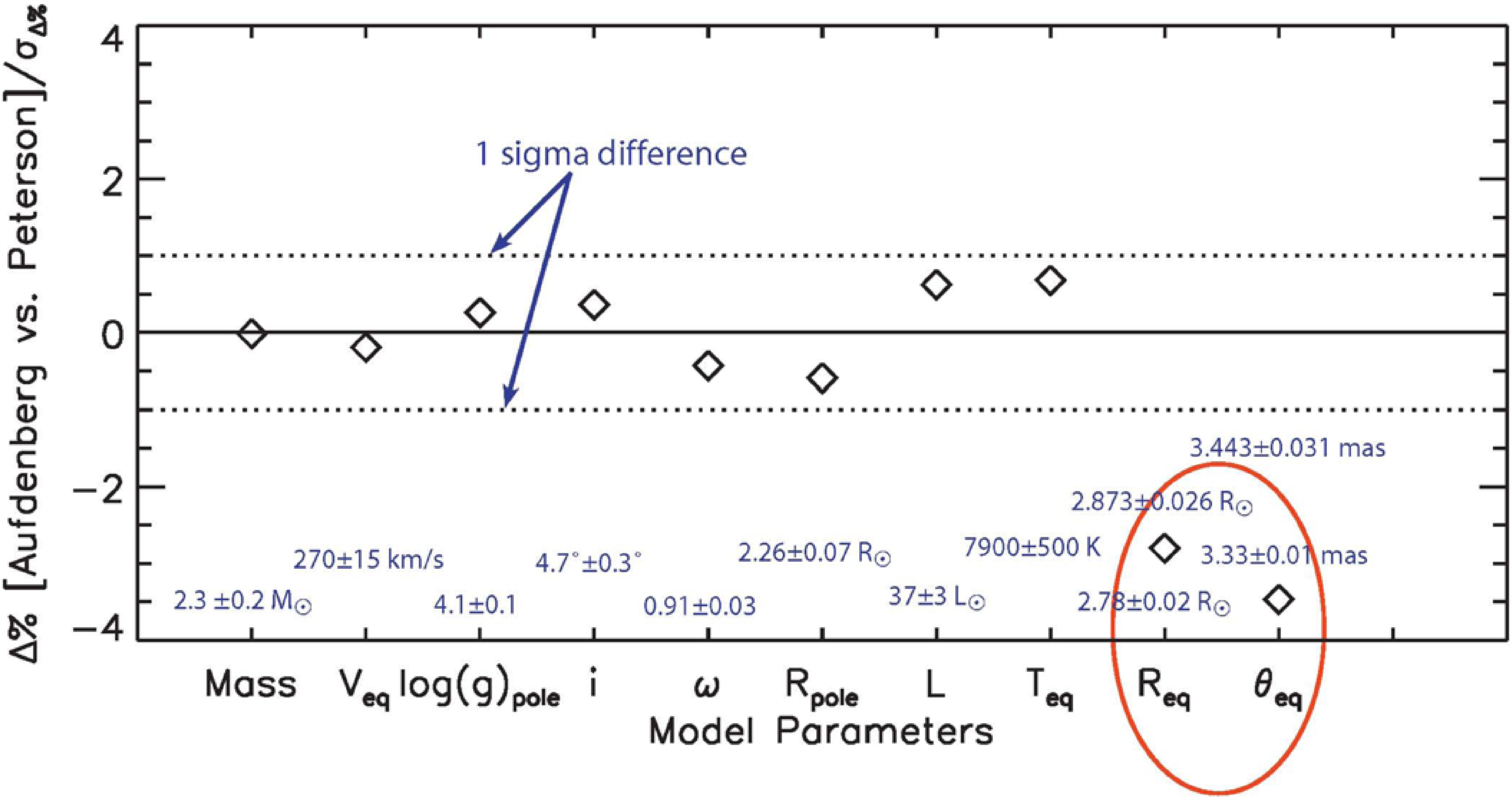
A Rotating Model Fit to the Visibility Data

Best Fit Parameters

T_{eff} (pole)	= 10250 K	B9 spectral type
T_{eff} (equator)	= 7900 K	A8 spectral type
Log(g) (pole)	= 4.10	
ω (angular break-up fraction)	= 0.91±0.03	
$\theta_{equator}$	= 3.33±0.03 milliarcsecs	



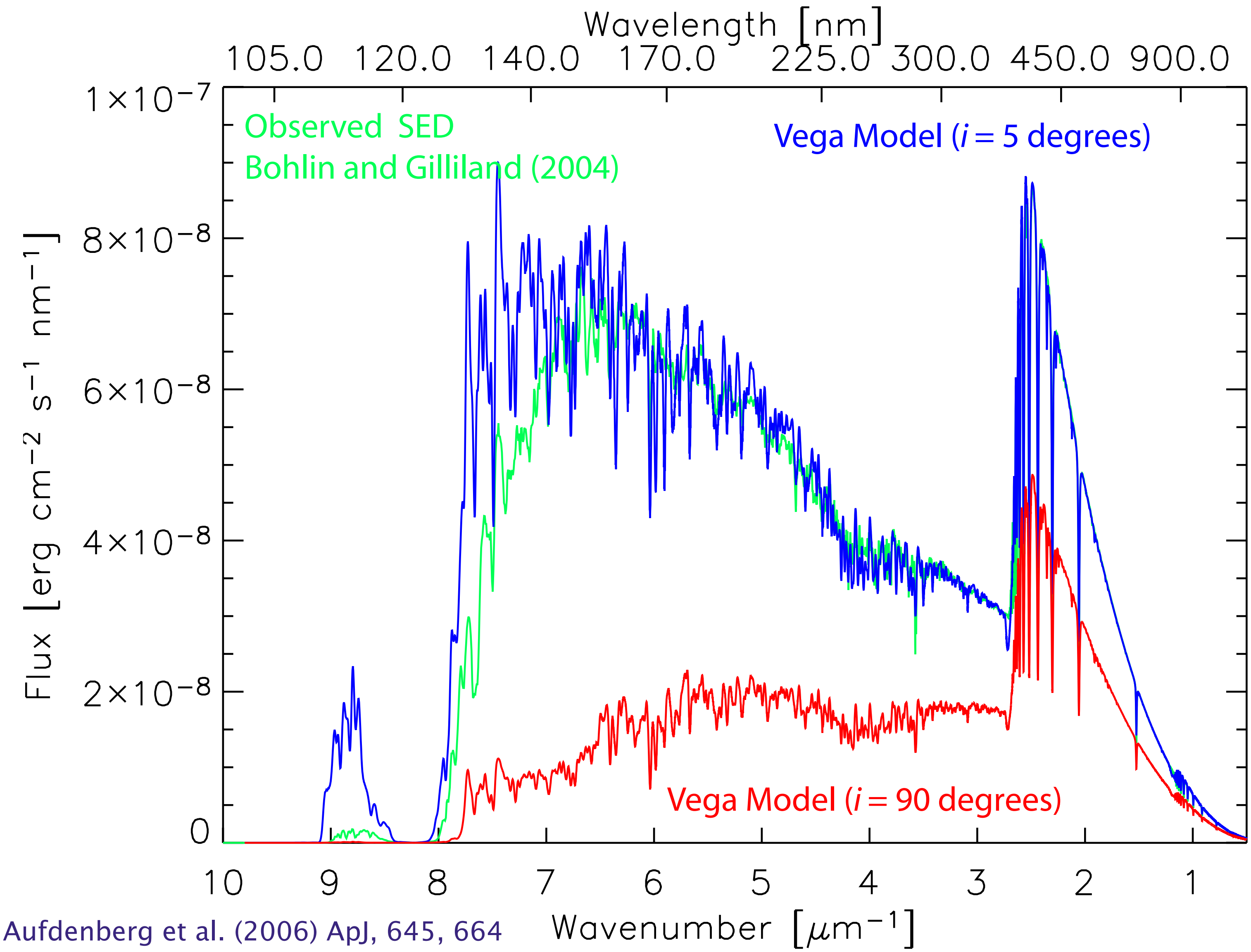
A Comparison of Parameters for Vega from Aufdenberg et al. and Peterson et al.



The equatorial radii derived from CHARA (IR) and NPOI (Visible) data are inconsistant

Vega's Spectrum from Different Points of View

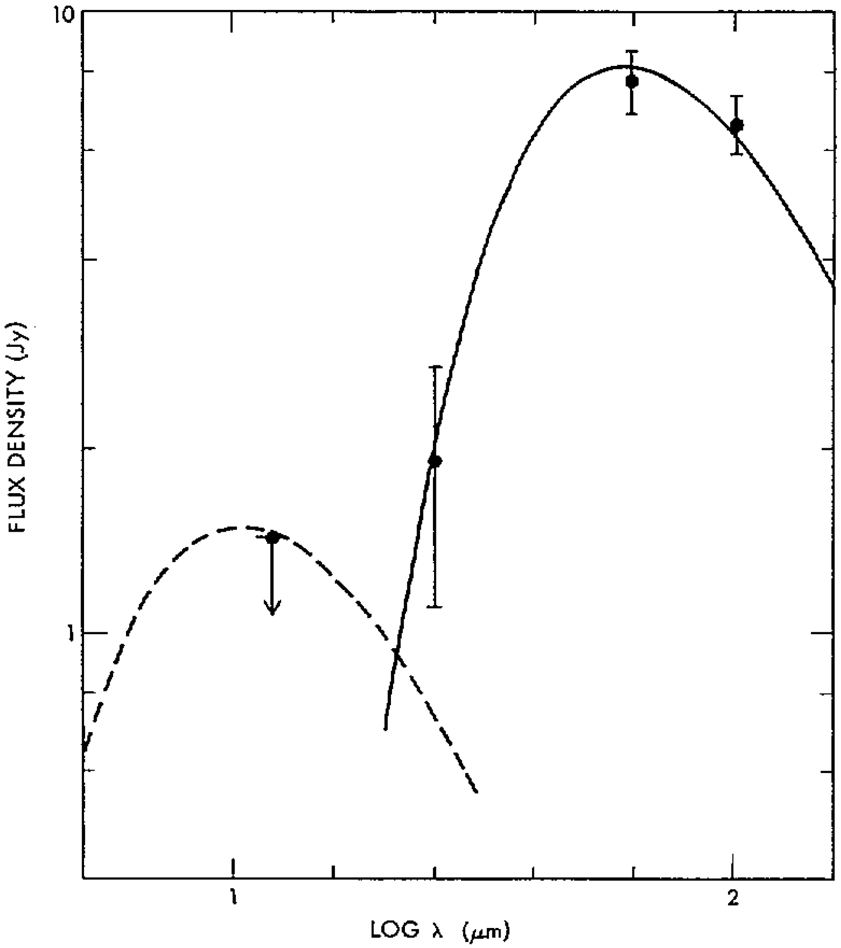
T_{eff} (pole) = 10250 K B9 spectral type
T_{eff} (equator) = 7900 K A8 spectral type



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

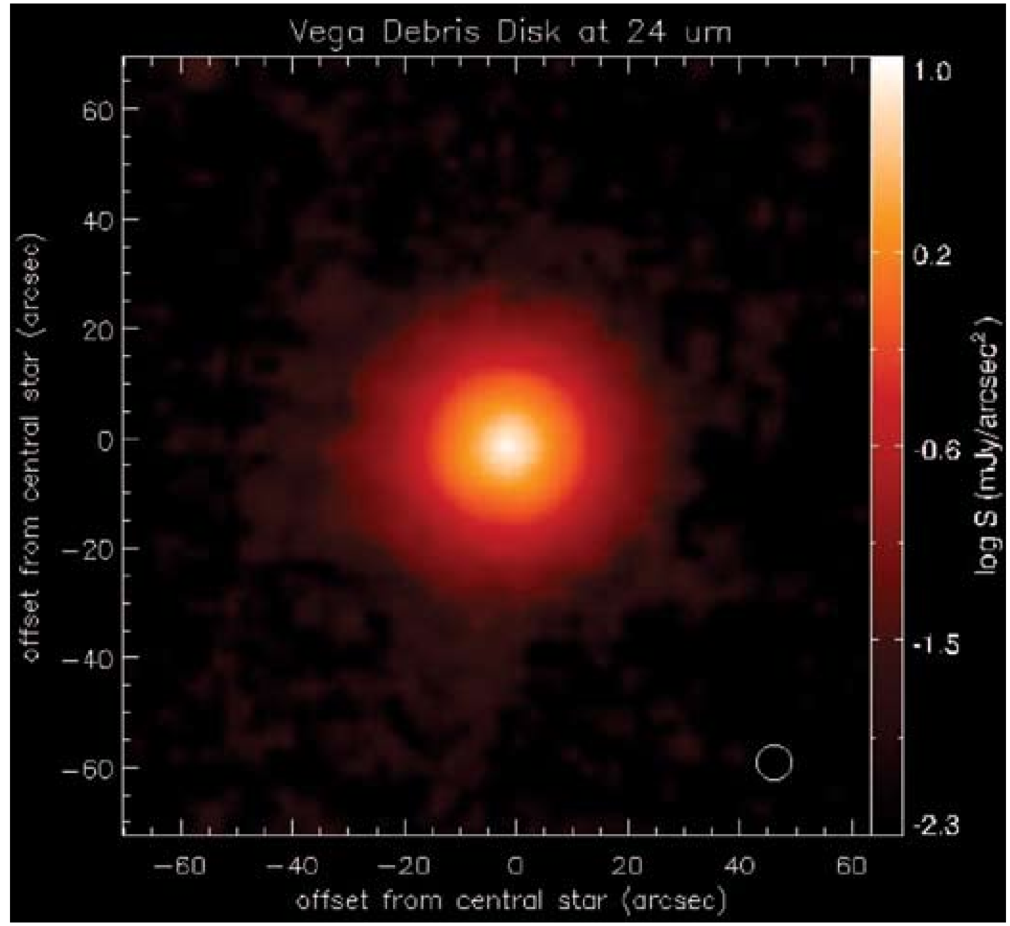
Vega's Disk

IRAS



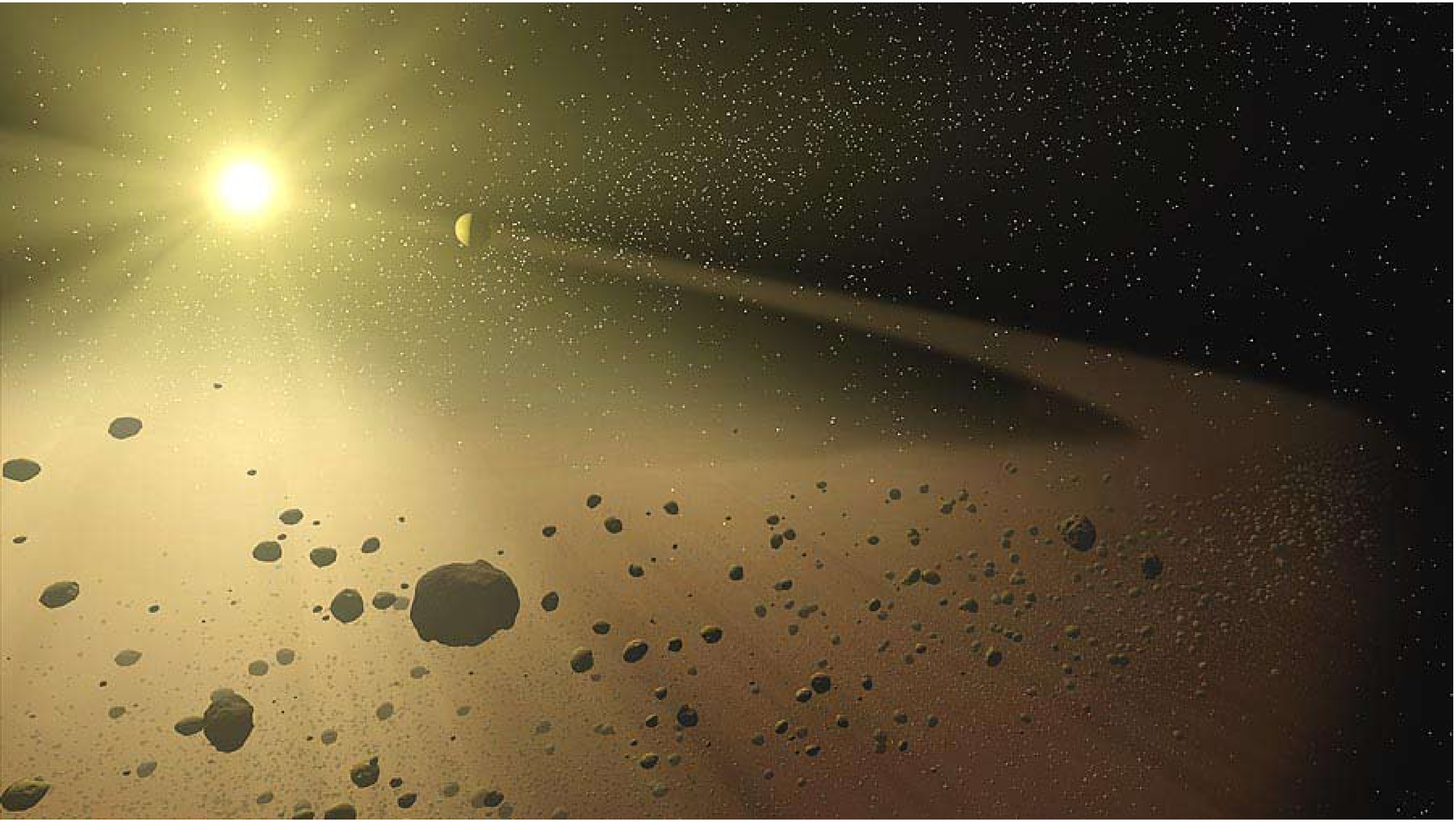
Aumann et al. (1984)

Spitzer Space Telescope



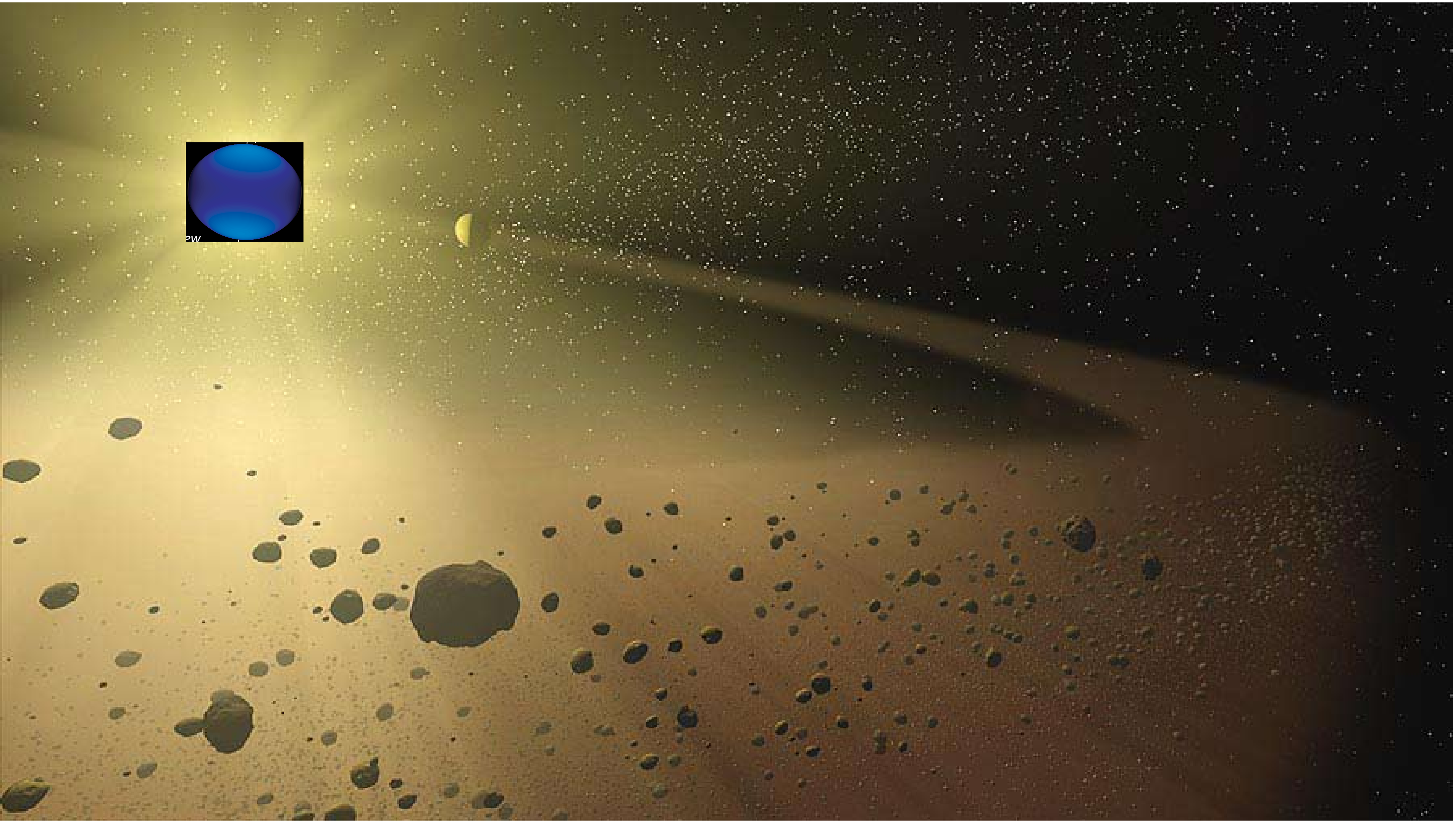
Su et al. (2005)

A Debris Disk Around a Young Star (artist conception)



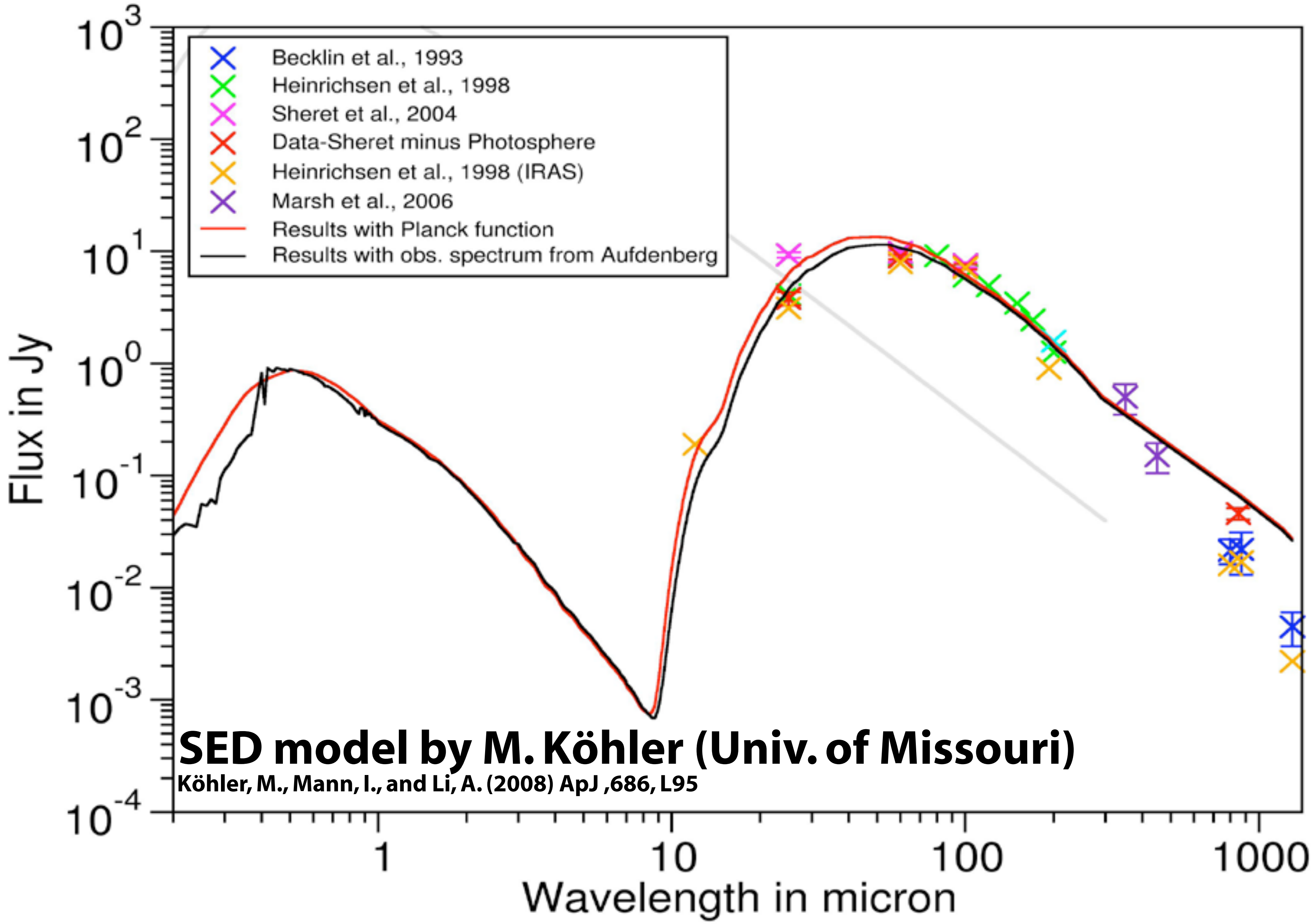
NASA/JPL-Caltech/T. Pyle

A Debris Disk Around a Rapidly Rotating Young Star

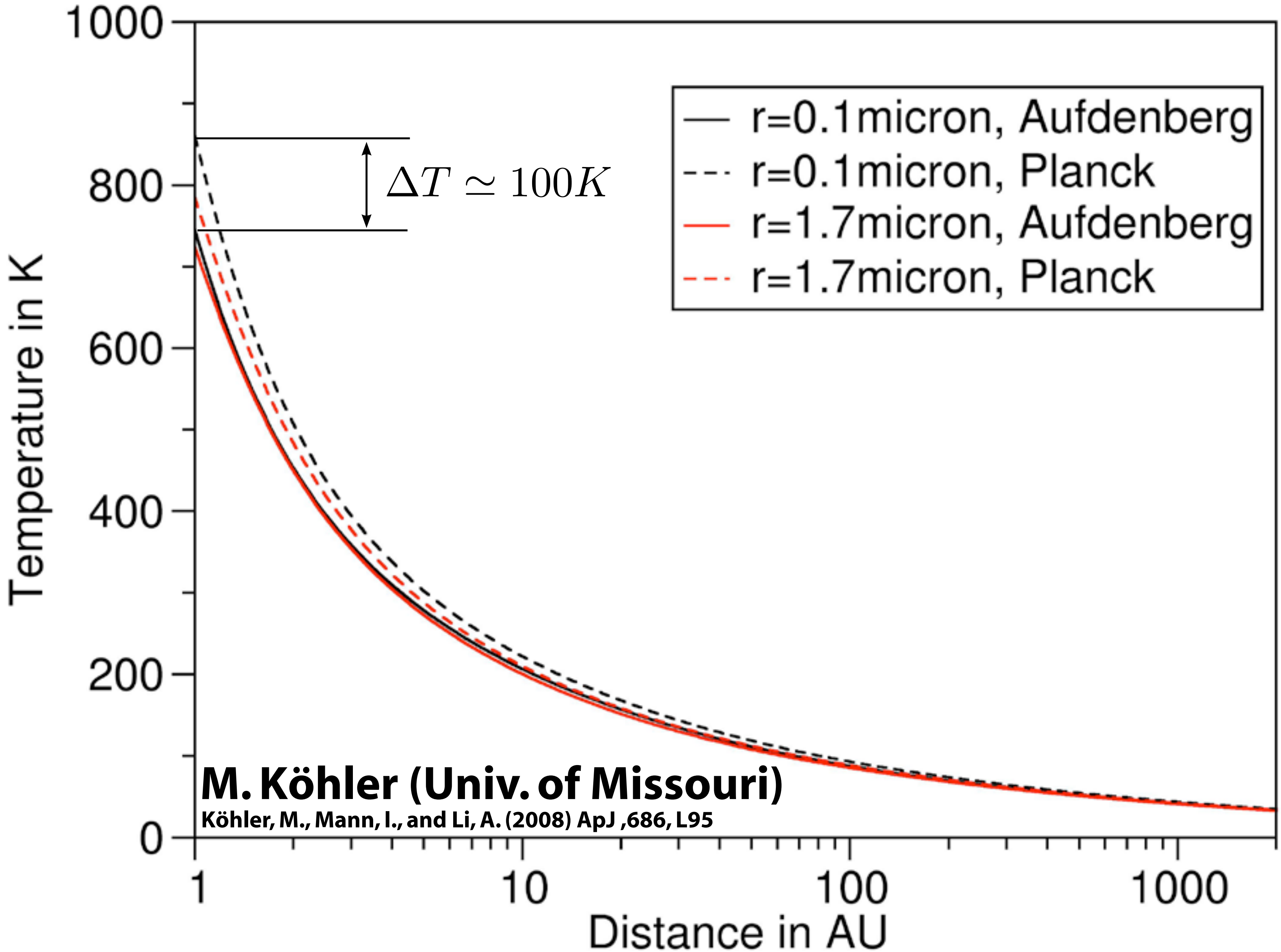


NASA/JPL-Caltech/T. Pyle

Amorphous Silicate Illuminated by Vega (Equatorial) Model Spectrum



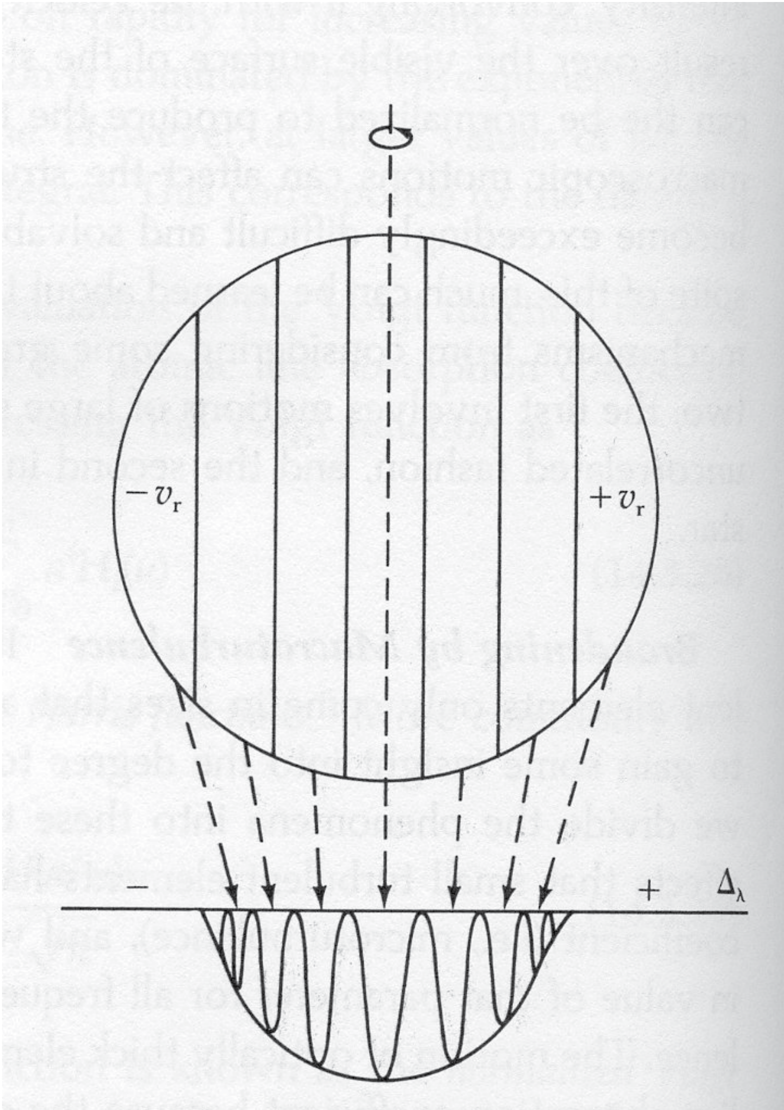
Amorphous Silicate Illuminated by Vega (Equatorial) Model Spectrum



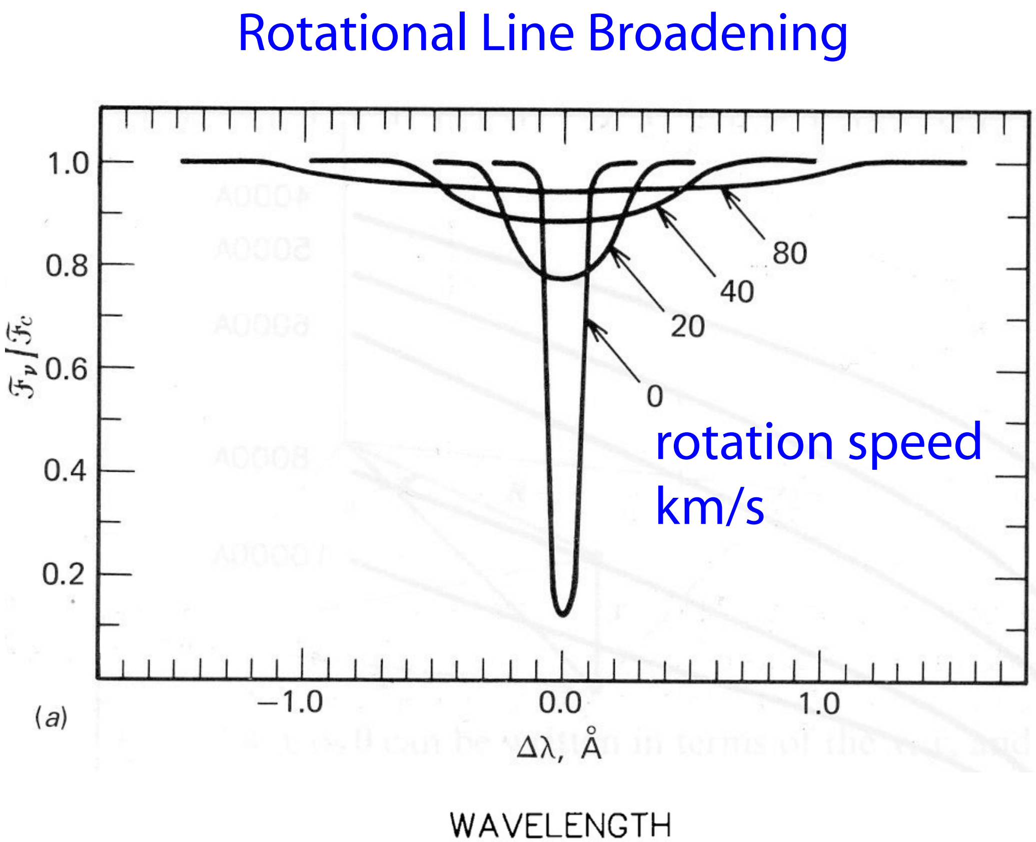
M. Köhler (Univ. of Missouri)

Köhler, M., Mann, I., and Li, A. (2008) ApJ ,686, L95

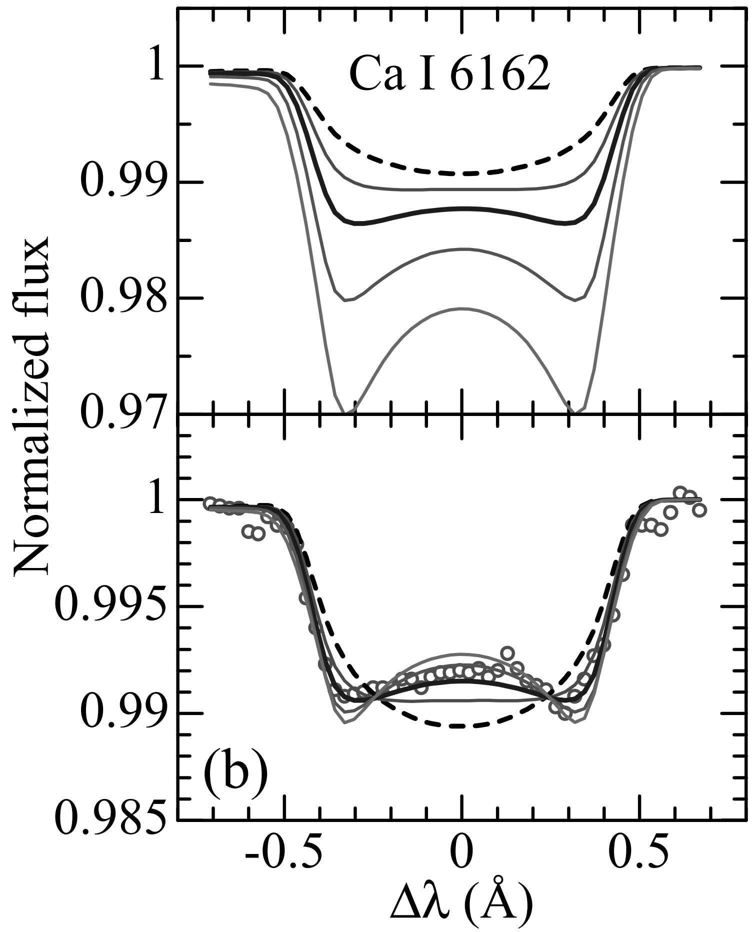
Clues from Rotational Broadening of Spectral Lines



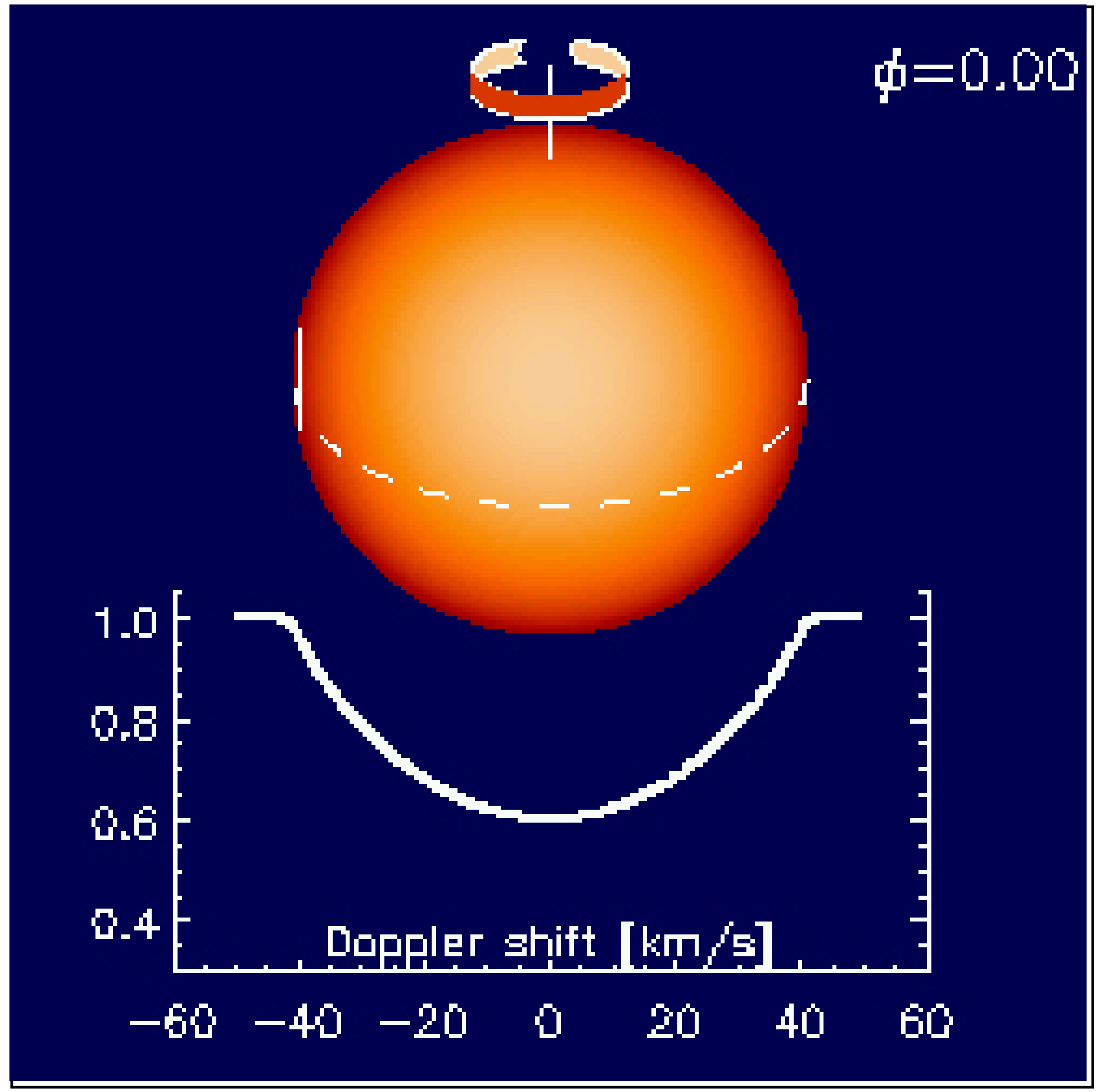
From Collins (1989)



Takeda et al. (2008) find 175 km/s Equatorial Velocity

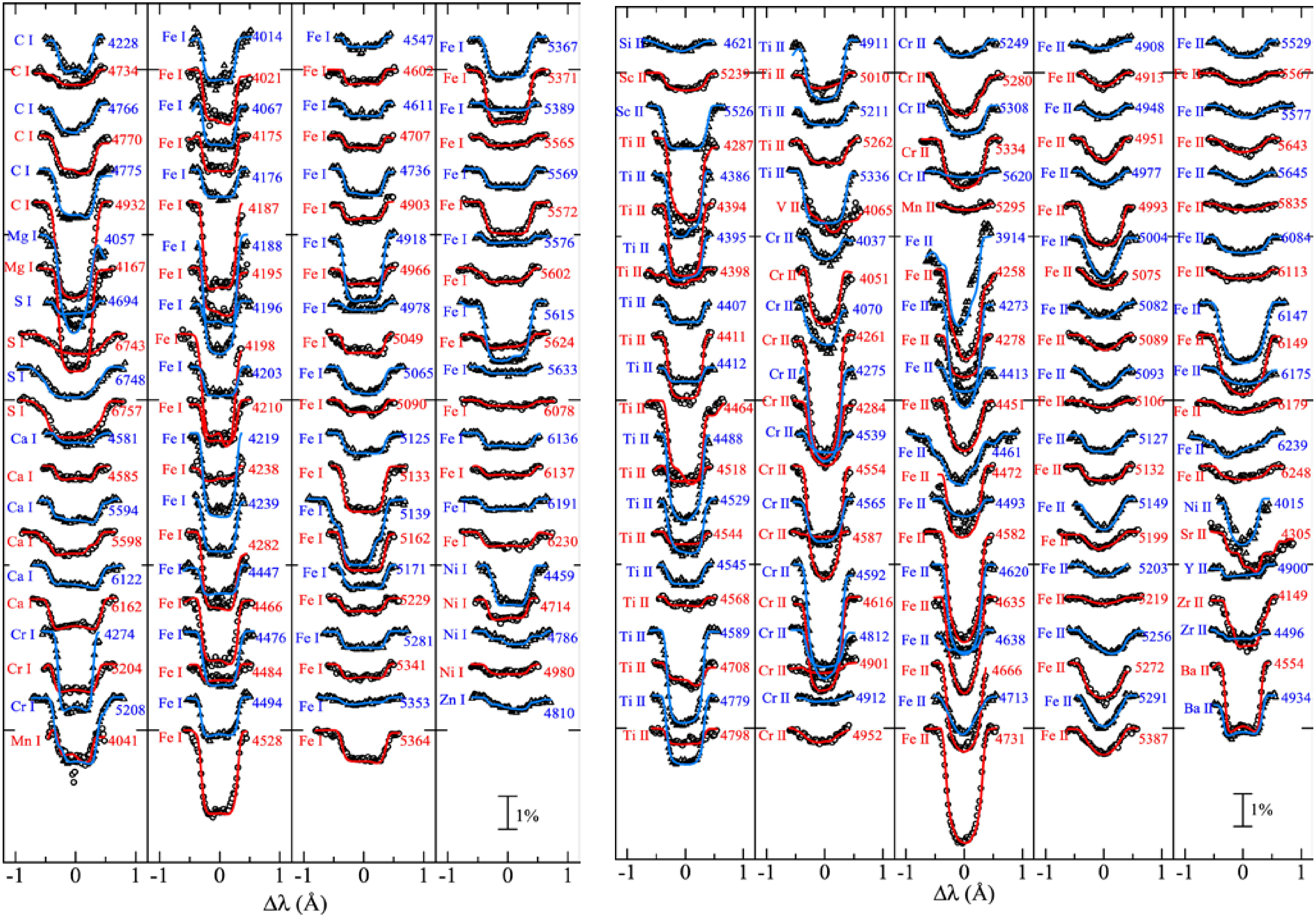


Takeda, Y., Kawanomoto, S., and Ohishi, N. (2008). Rotational Feature of Vega Revealed from Spectral Line Profiles. ApJ , 678, 446–462.



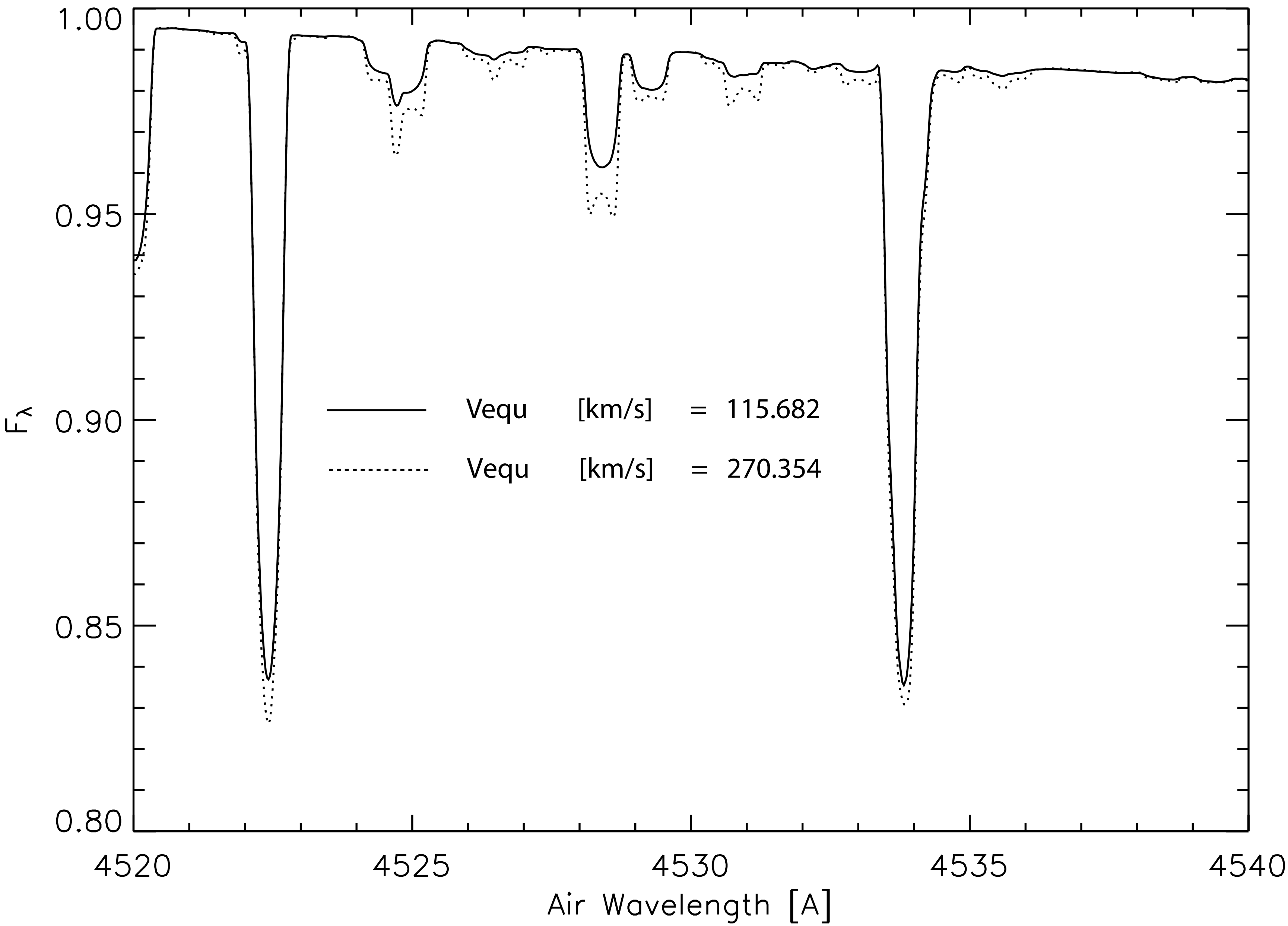
http://www.astro.uu.se/~oleg/structures.html

Takeda et al. (2008) Model Fits Many Neutral and Singly Ionized Lines



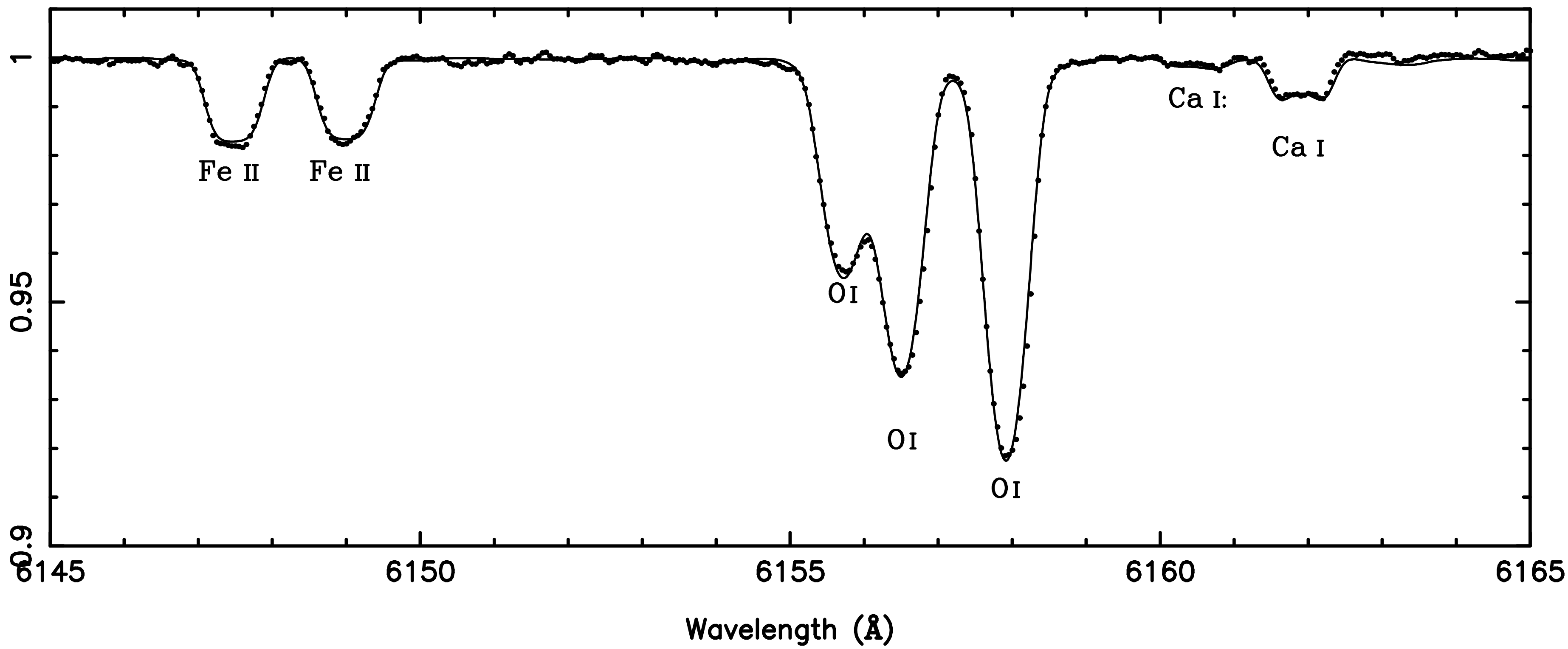
Takeda, Y., Kawanomoto, S., and Ohishi, N. (2008). Rotational Feature of Vega Revealed from Spectral Line Profiles. ApJ , 678, 446–462.

Our calculations indicate 270 km/s equatorial speed too high



... But Yoon et al. (2008) find 275 km/s Equatorial Velocity

Yoon, J., Peterson, D. M., Zagarello, R. J., Armstrong, J. T., and Pauls, T. (2008). The Effect of Rotation on the Spectrum of Vega. ApJ , 681, 570–578.



The difference is additional macro-turbulence broadening of 10 km/s.

Meridional Circulation May Provide "Macro-turbulence"

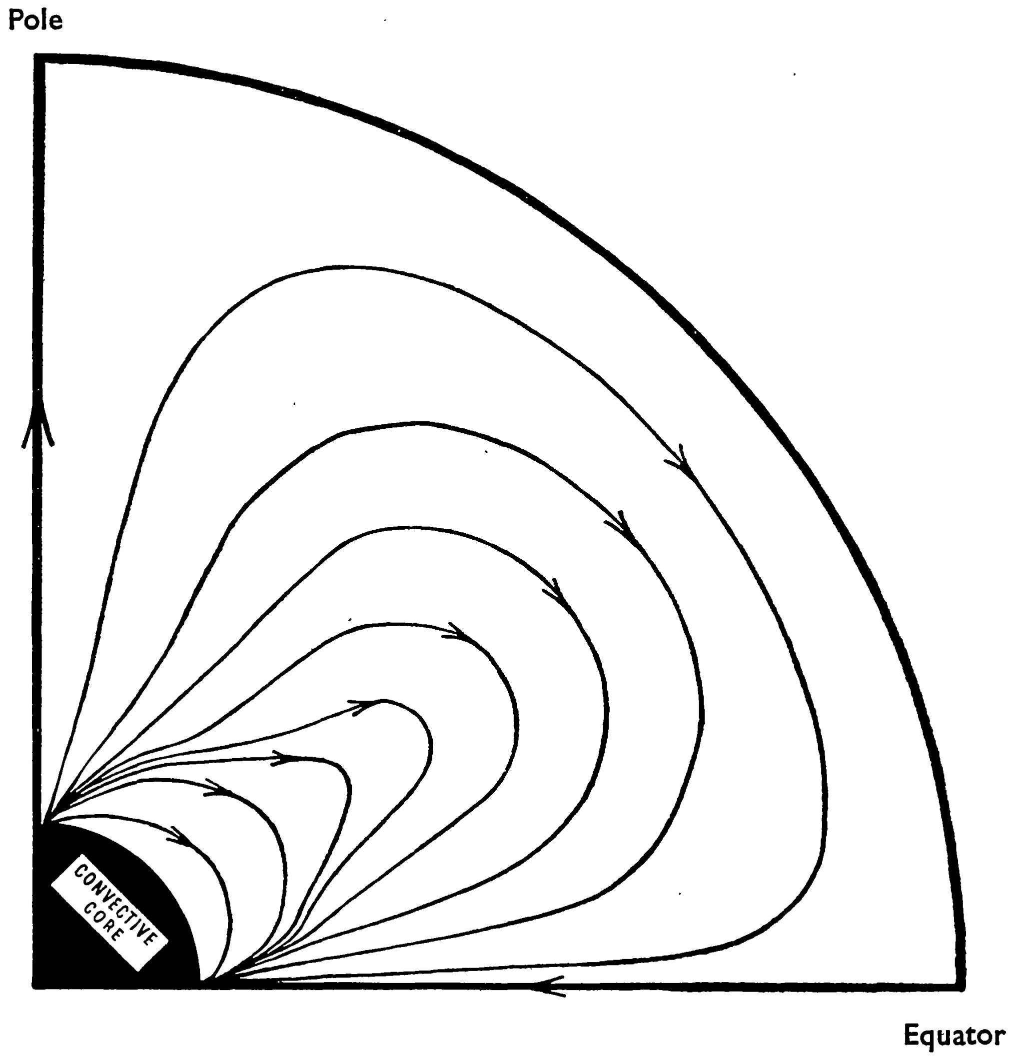
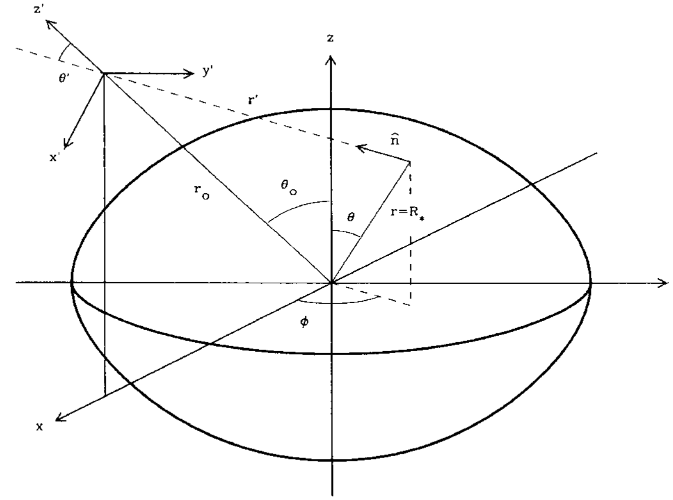


FIG. 1.—*Circulation in a uniformly rotating star.*

Sweet (1950). The Importance of Rotation in Evolution, MNRAS, 110, 548.

Gridding 1-D models on to 3-D stars neglects velocity shear between latitudes.

Standard Roche-Von Zeipel Model Atmosphere



- ω Fraction of the angular break-up speed
- $\theta_{\rm equ}$ Equatorial Angular Diameter
- $T_{\rm eff}^{\rm pole}$ Effective Temperature at the pole
- $g_{\rm pole}$ Surface gravity at the pole

$$R_{\rm equ} = 107.48 \frac{\theta_{\rm equ}}{\pi_{\rm hip}}$$

$$R_{\rm pole} = \frac{\omega\, R_{\rm equ}}{3\,\cos\left[\frac{\pi + \cos^{-1}(\omega)}{3}\right]}$$

$$R(\vartheta) = 3\frac{R_{\rm pole}}{\omega \sin\vartheta} \cos\left[\frac{\pi + \cos^{-1}(\omega\sin\vartheta)}{3}\right]$$

Standard Rotating Star Model

1. **Point-mass approximation for the potential**
2. **Uniform (non-differential) rotation**
3. **Stellar shape is an equipotential surface, the sum of gravitational and centrifugal potentials**
4. **Von Zeipel gravity darkening law**
5. **Interpolated 1-D atmosphere models**

$$\Omega = \omega\Omega_{\rm crit} = \omega\left[\frac{8}{27}\frac{GM}{R_{\rm pole}^3}\right]^{1/2}$$

$$g(\vartheta) = \left[g_r(\vartheta)^2 + g_\vartheta(\vartheta)^2\right]^{1/2}$$

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

$$V_{\rm equ} = R_{\rm equ}\,\Omega$$

$$g_r(\vartheta) = \frac{-GM}{R(\vartheta)^2} + R(\vartheta)(\Omega\sin\vartheta)^2$$

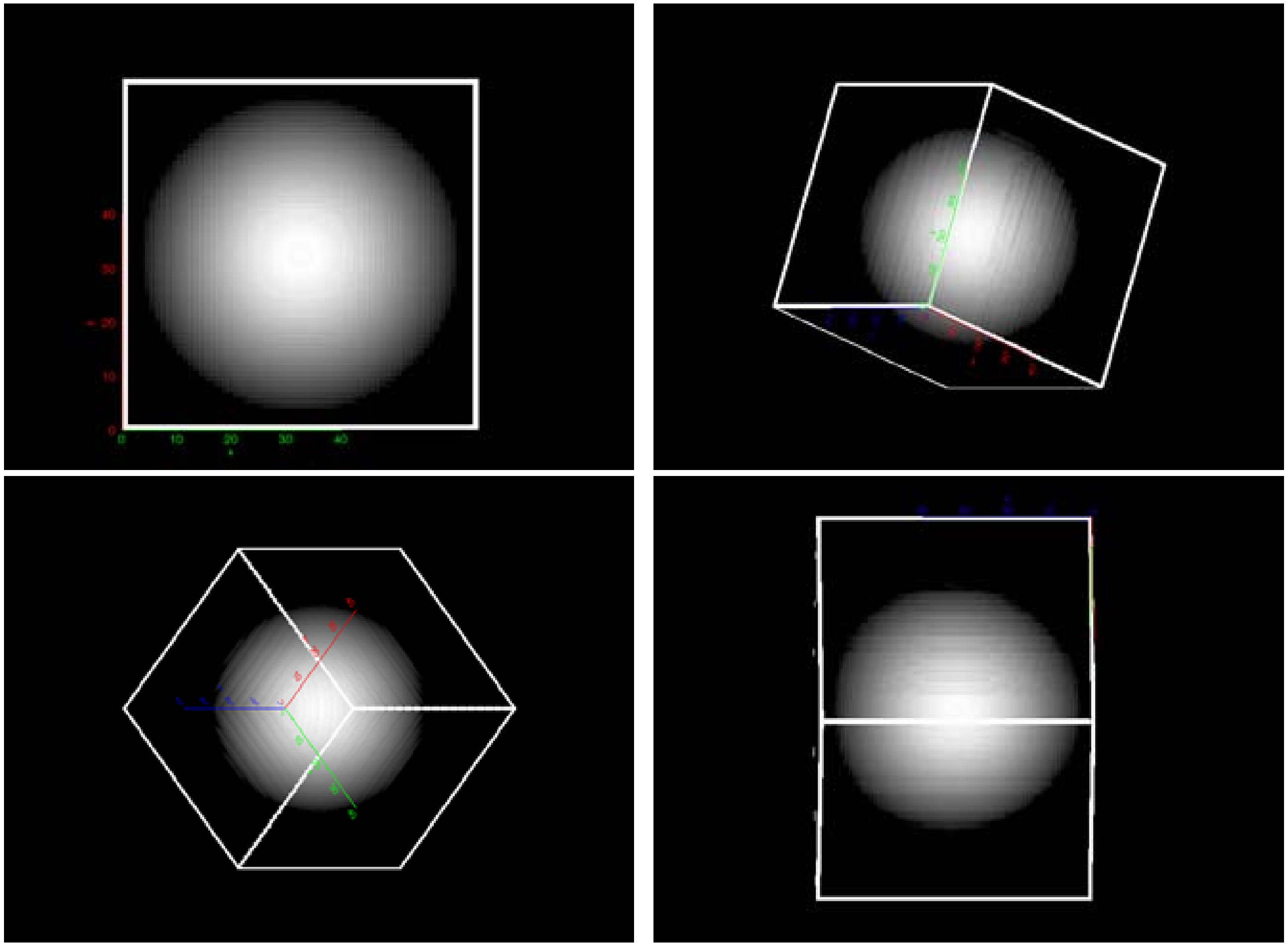
$$i = \sin^{-1}\left[\frac{v\sin i}{V_{\rm equ}}\right]$$

$$g_\vartheta(\vartheta) = R(\vartheta)\Omega^2\sin\vartheta\cos\vartheta$$

$$\Sigma \approx 4\pi GM\left[1.0 - 0.19696\,\omega^2 - 0.094292\,\omega^4 + 0.33812\,\omega \right.$$
$$\left. - 1.30660\,\omega^8 + 1.8286\,\omega^{10} - 0.92714\,\omega^{12}\right]$$

$$M = \frac{g_{\rm pole}\,R_{\rm pole}^2}{G} \qquad L = \frac{\sigma\Sigma(T_{\rm eff}^{\rm pole})^4}{g_{\rm pole}}$$

Three-Dimensional Radiative Transport Required to Simulate Spectrum



Visualization of the results from the PHOENIX 3-D code (Hauschildt & Baron)

The voxel (volume element) grid has 65^3 elements.

The intensity image is shown for $(\theta, \varphi) = (0°, 0°), (45°, 45°), (140°, 250°)$ and $(89°, 139°)$.

The intensities are mapped linearly to 255 shades of gray.

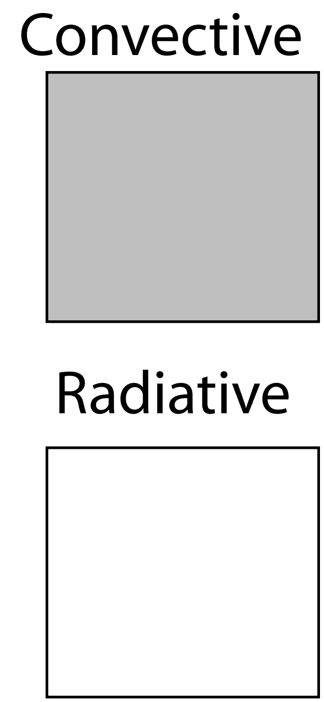
In spherical coordinates $(n_r, n_\theta, n_\varphi) = (65, 33, 65)$ voxels, an angular resolution on the stellar surface of about 5.5 degrees.

Hauschildt, P. H. and Baron, E. (2006). A 3D radiative transfer framework. I. Non-local operator splitting and continuum scattering problems. A&A, 451, 273–284.

Self-Consistent Field (SCF) Model for a Rotating Star
Mass Distribution is Fully Self-Consistent with Effective Potential

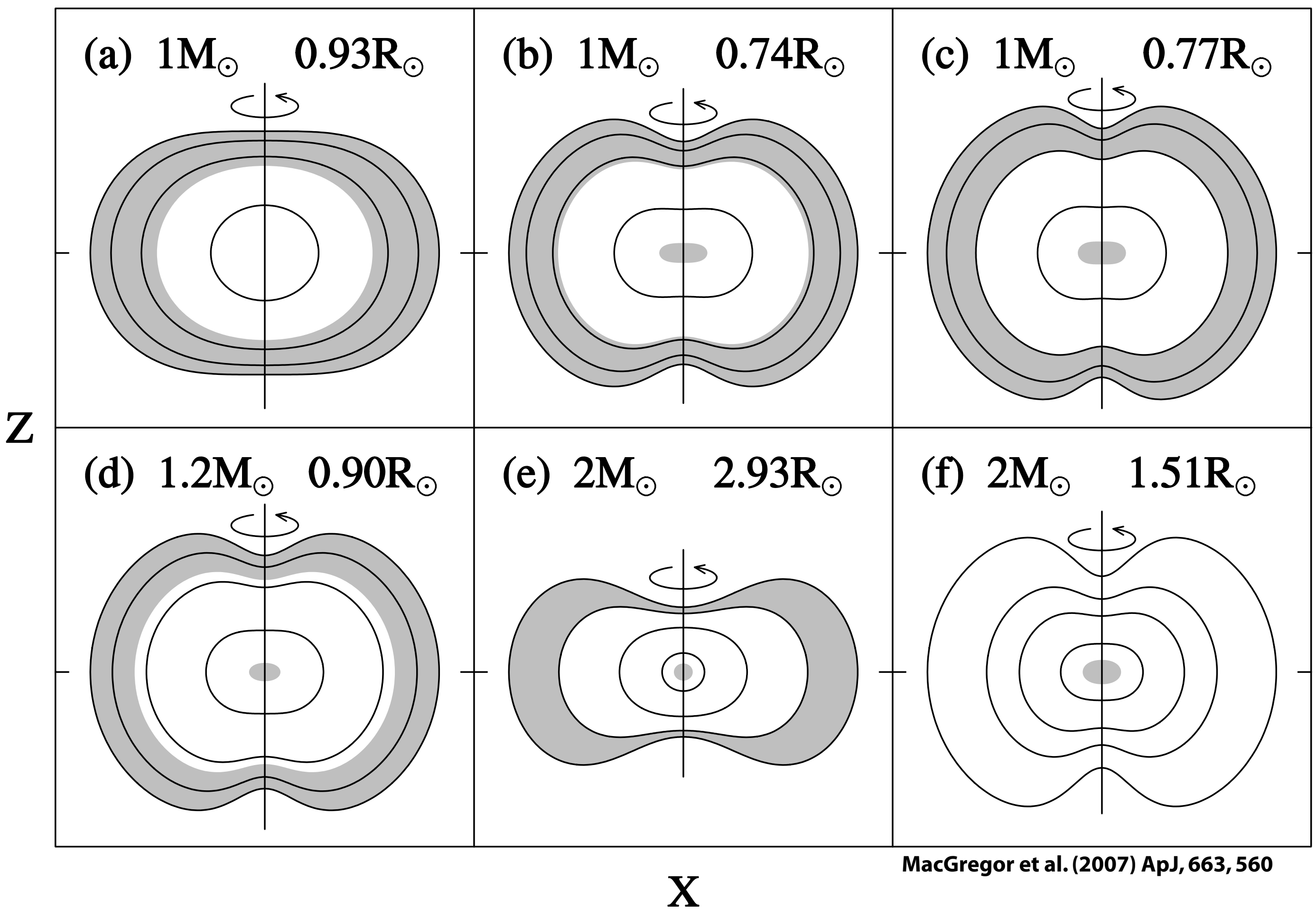
$g = \nabla\Psi$	Effective gravitational acceleration
$\Psi = \Phi + \Phi'$	Effective potential
$\nabla^2\Phi = -4\pi G\rho$	Gravitational potential (Poisson's Equation)
$\Phi' = \int_0^{\varpi} \Omega^2(\varpi)\varpi \, d\varpi$	Centrifugal potential
$\eta = \Omega_0/\Omega_{\rm cr}$	Ratio of the angular velocity at the pole to the critical angular velocity
$\Omega_e/\Omega_0 = 1/(1+\alpha^2)$	Ratio of the angular velocity at the equator to the angular velocity at the pole (differential rotation)
$\Omega(\varpi) = \frac{\Omega_0}{1+(\alpha\varpi/R_e)^2}$	"Anti-solar" rotation: pole spins faster than equator
$\Omega(\varpi) = \Omega_0\left[1+(\alpha\varpi/R_e)^2\right]$	"Solar" rotation: equator spins faster than pole

One to Two Solar Mass SCF Differentially Rotating Models



M, α, η

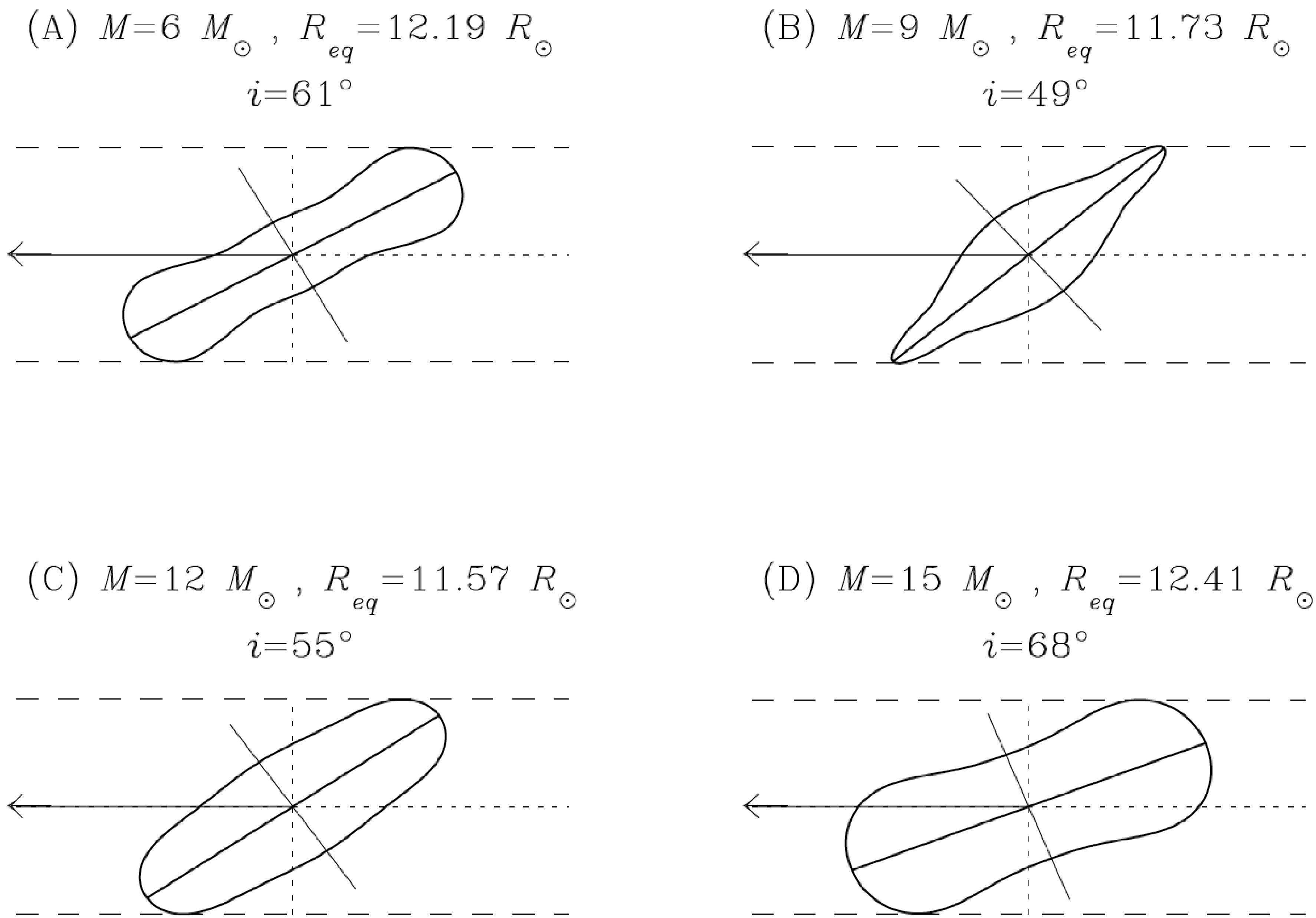
$1\,M_\odot$, 1.5, 1.55 | $1\,M_\odot$, 3.75, 3.58 | $1\,M_\odot$, 5, 4.15



MacGregor et al. (2007) ApJ, 663, 560

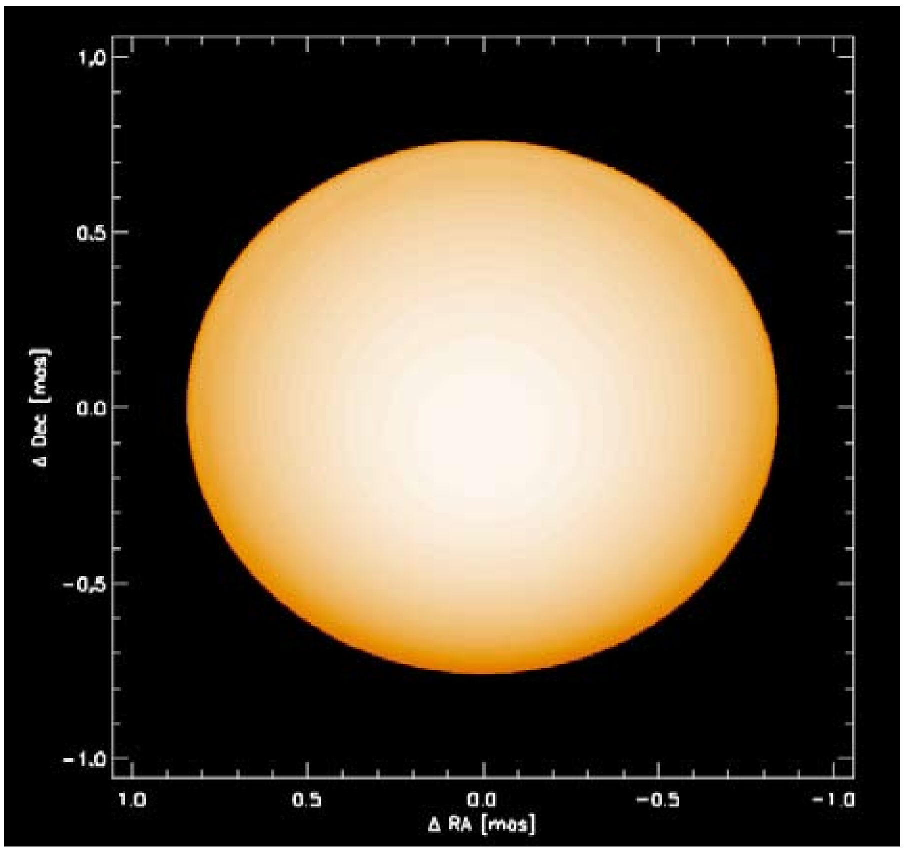
$1.2\,M_\odot$, 4, 3.74 | $2\,M_\odot$, 3, 5.64 | $2\,M_\odot$, 4.75, 5.9

More Massive SCF Models for Alpha Eri (Jackson et al.)



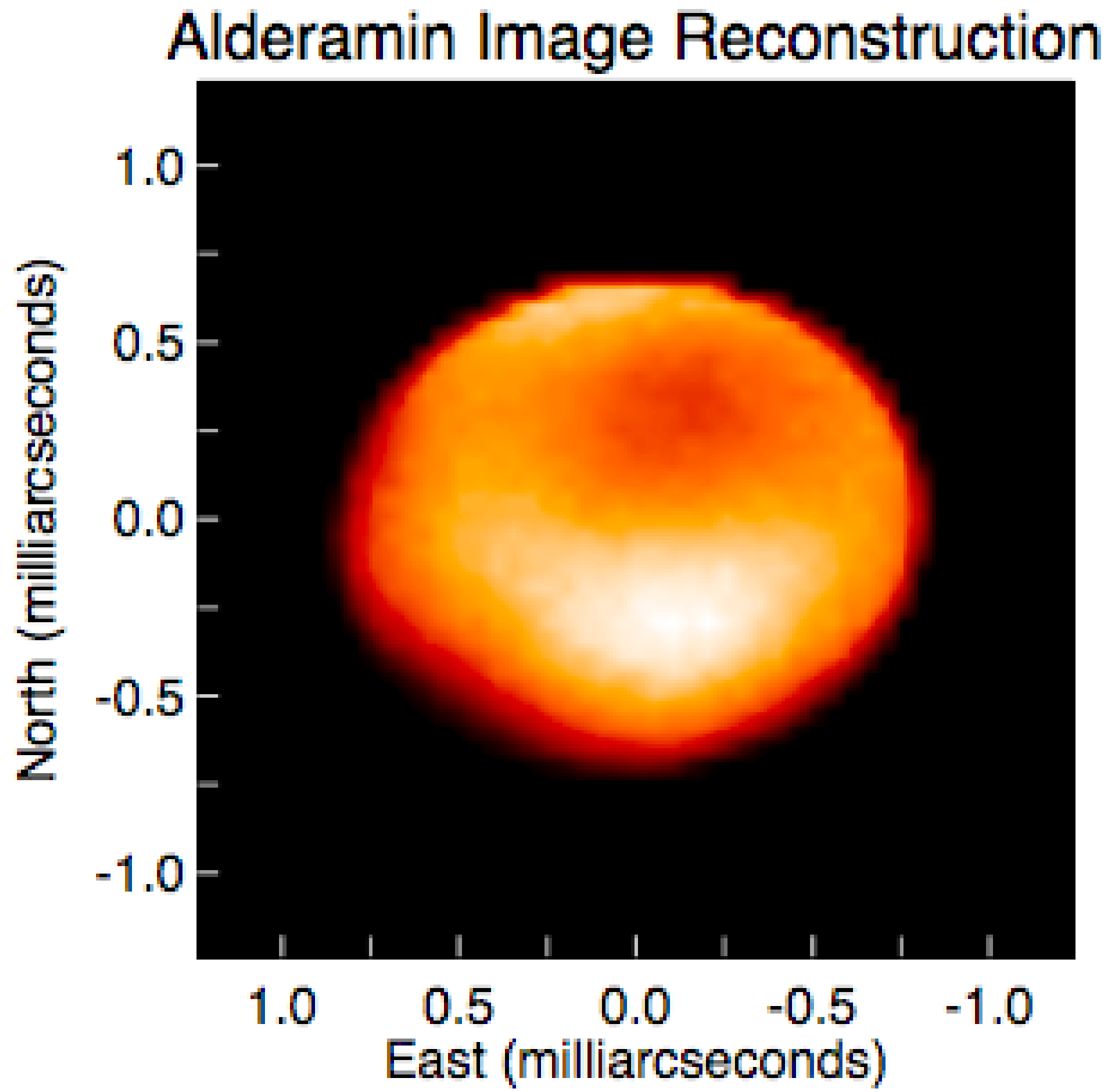
Jackson, S., MacGregor, K. B., and Skumanich, A. (2004). Models for the Rapidly Rotating Be Star Achernar. ApJ , 606, 1196–1199.

Trial SCF Model for Alderamin (Alpha Cep)

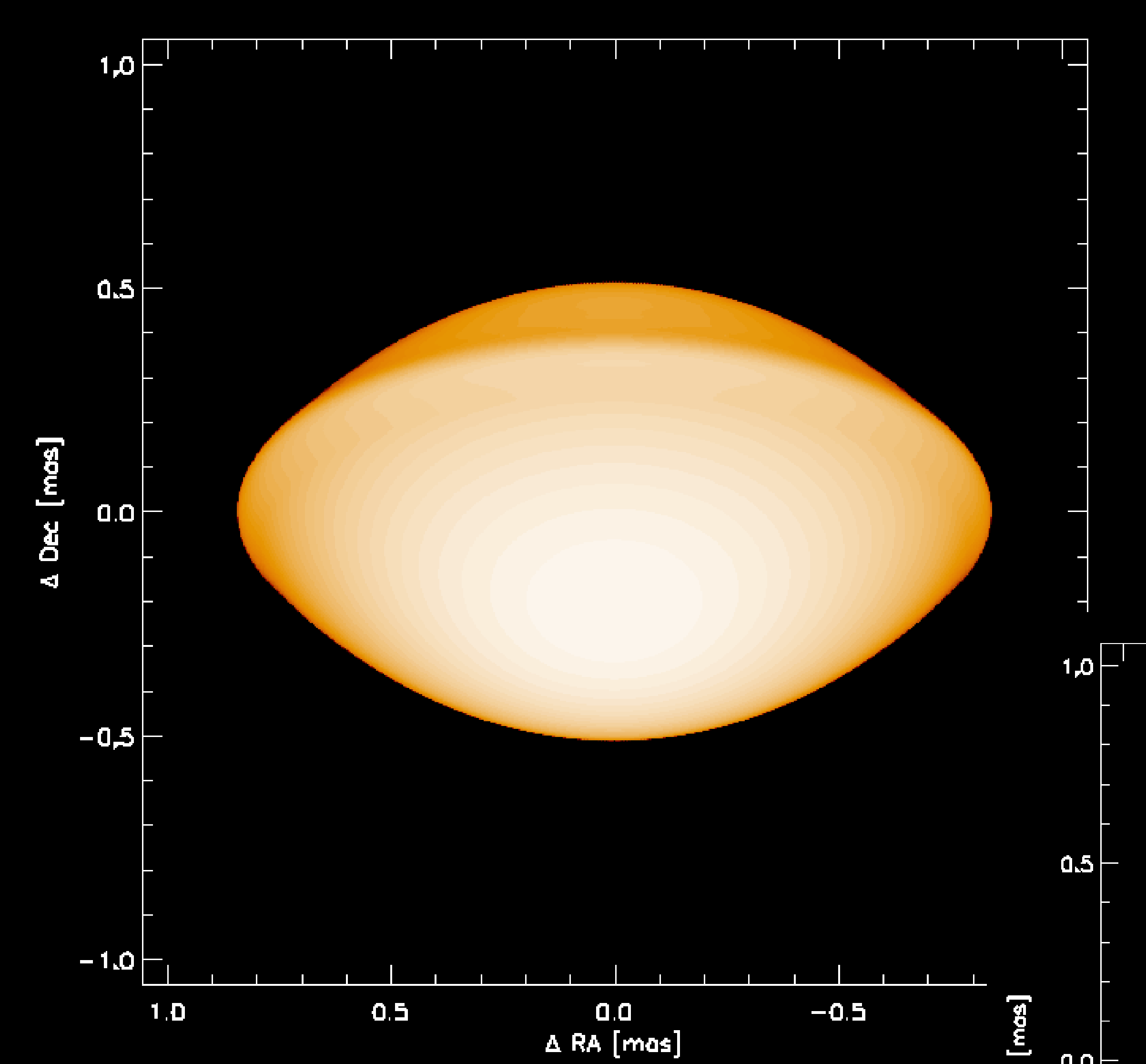


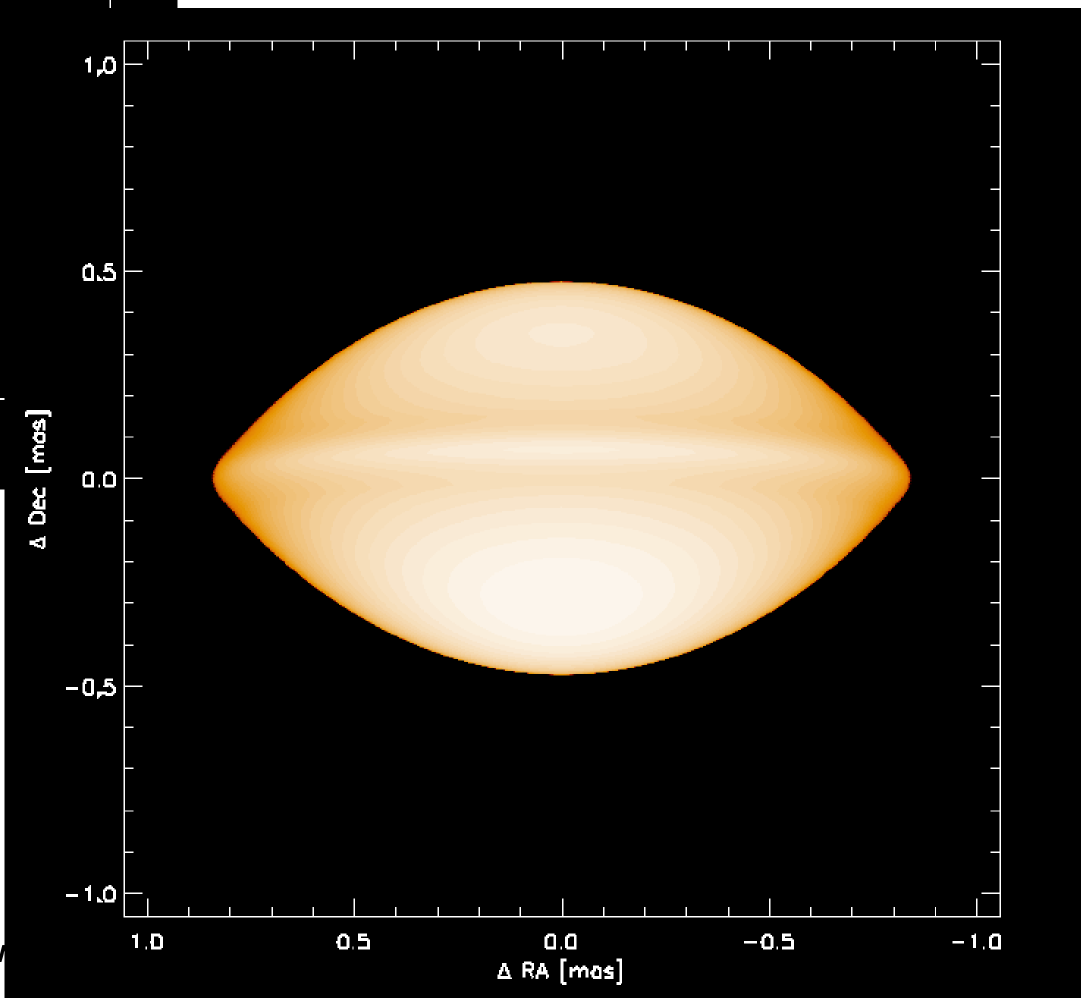
$\mathrm{M} = 1.9 M_{\odot}, \eta = 1.60, \alpha = 0.08$

i=26.5° at 1.6 microns

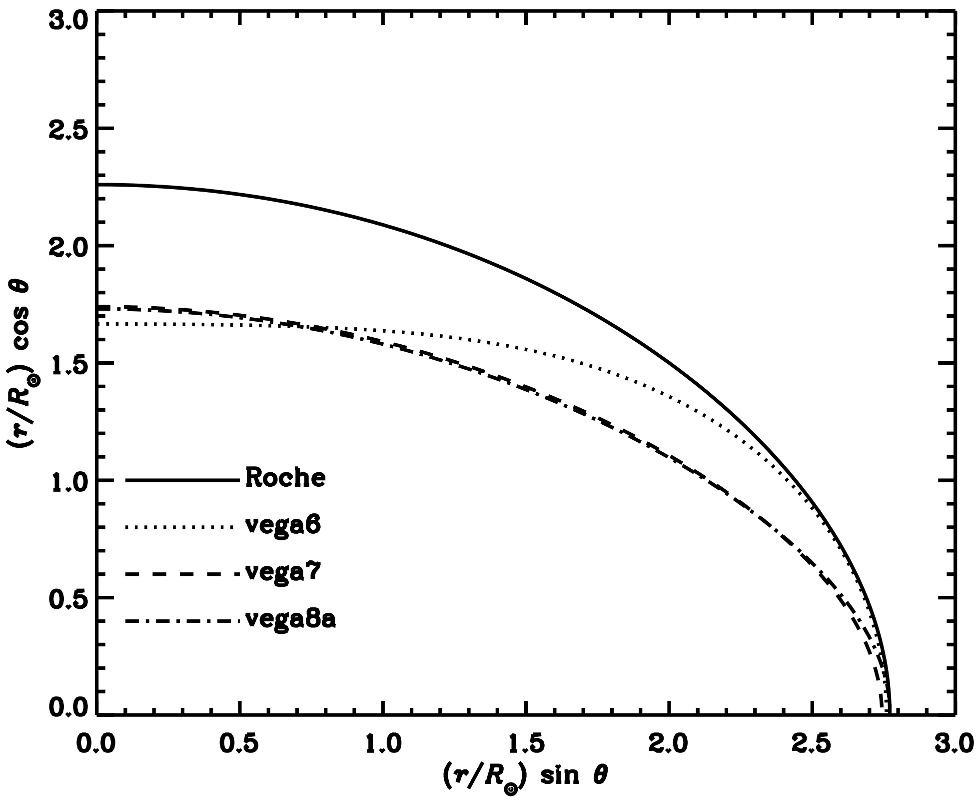


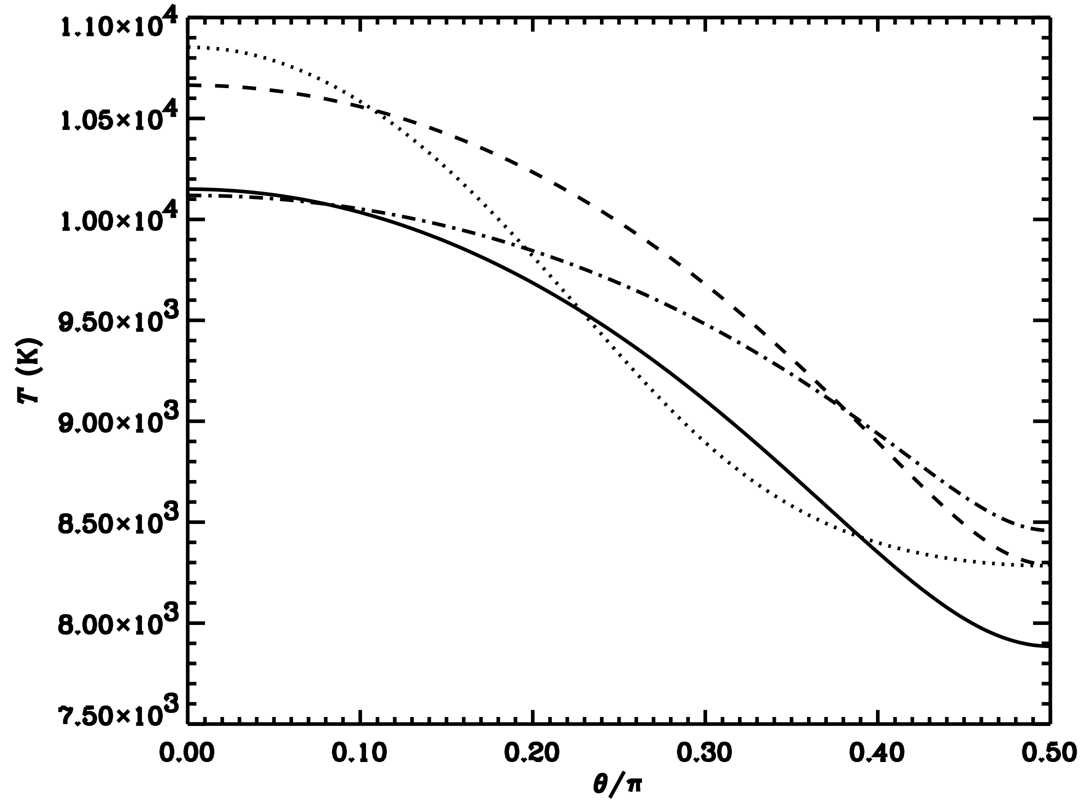
Trial SCF Model at higher inclinations





Searching for a Vega Model
SCF Model Shapes and Pole-to-Equator Temperature Profiles





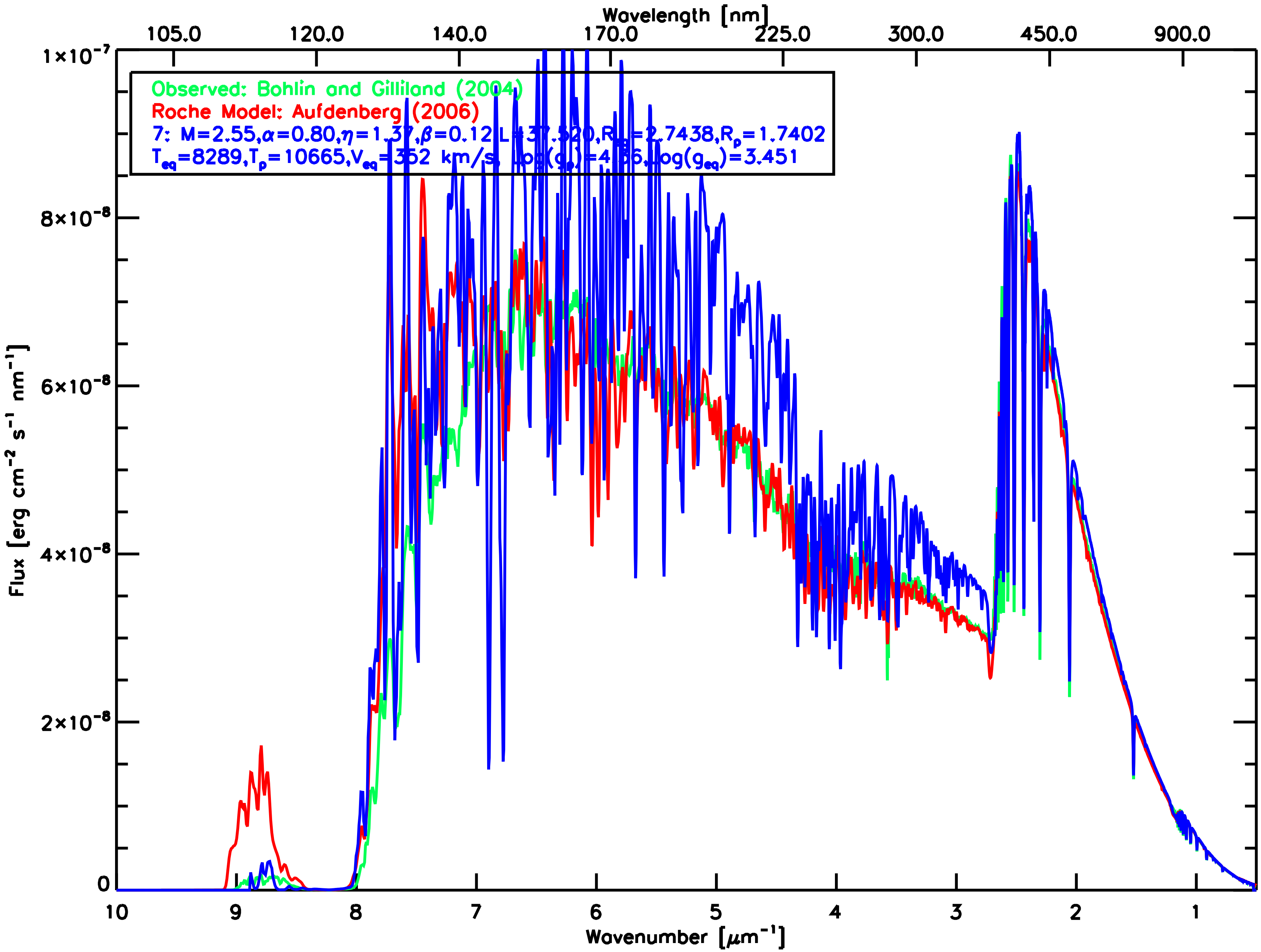
$$6: \mathrm{M} = 2.55 M_\odot, \eta = 2.05, \alpha = 1.50, \beta = 0.18$$

$$7: \mathrm{M} = 2.55 M_\odot, \eta = 1.37, \alpha = 0.80, \beta = 0.12$$

$$8a: \mathrm{M} = 2.52 M_\odot, \eta = 1.40, \alpha = 0.80, \beta = 0.08$$

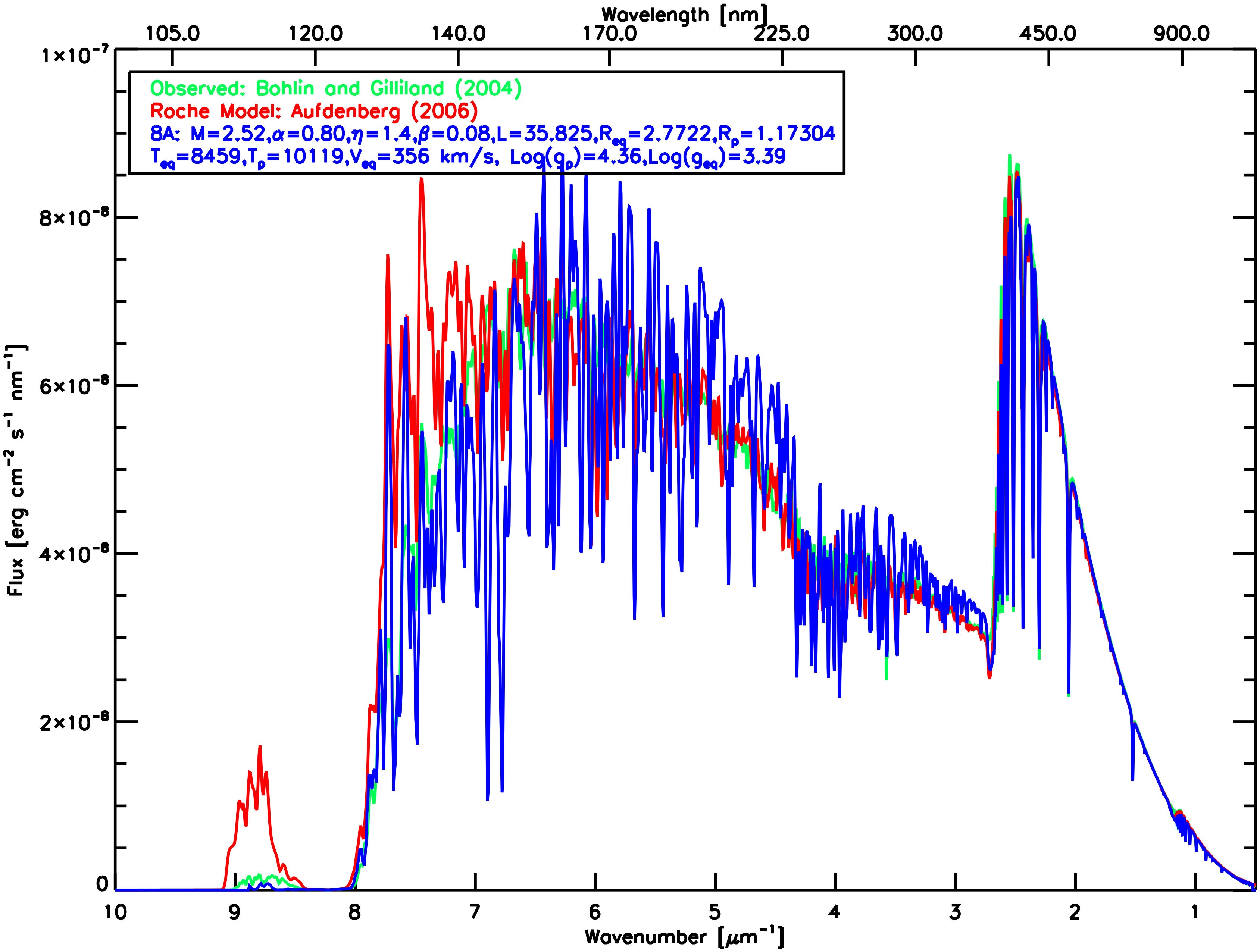
$$7 : \mathrm{M} = 2.55 M_{\odot}, \eta = 1.37, \alpha = 0.80, \beta = 0.12$$

Too much UV flux, Temperature profile too hot



$$8a : \mathrm{M} = 2.52 M_{\odot}, \eta = 1.40, \alpha = 0.80, \beta = 0.08$$

Better UV Match; line blanketing is too strong



Future Work

1. Identify and quantify which radiative features are sensitive to which model features.

2. Find a best fit match of the SCF models to the spectrophotometric, spectroscopic, and interferometric data sets.

3. Include main-sequence evolutionary effects in the SCF rotating models.

4. Improve performance of parallel atmosphere interpolation algorithms.