Observing Strategy & Rotationally Distorted Stars

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Keck Interferometer

Relative Measures in Astronomy

- Photometry
  - Rarely measure absolute flux
  - Typical measure is in reference to some ‘standard’ object
- *Calibration* of utmost importance
  - Even more true in interferometry

Zeroth Rule of Interferometry

"You can get good fringes, or scientifically interesting fringes"

- D. Mozurkewich

(The 'or' in this proposition is an 'exclusive or')

First Rule of Interferometry

If you see something interesting,
it’s probably instrumental

Calibrating around the Rules

- Knowledge of instrument point response needed
- Typically a variable function of:
  - Pointing - Interferometers are big floppy things
  - Time - Seeing varies on short (~minute) timescales
- Experimental approach
  - Periodic observation of point-like or quasi-pointlike sources

(Quasi-)Pointlike Sources

- Need to observe (nearly) unresolved sources
- How to predict source size?
- Chicken and egg conundrum

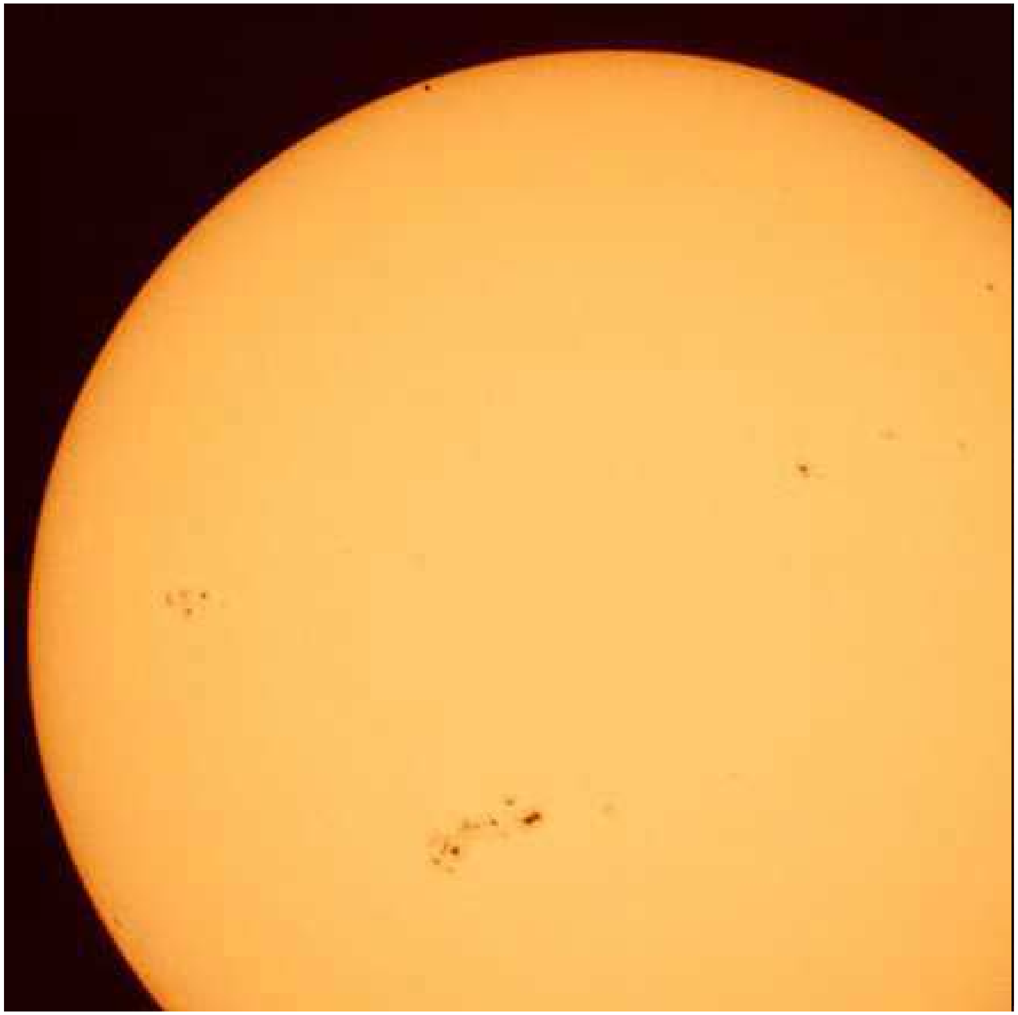
Other Concerns

- Subtle PSF effects
  - As with all telescopes, need to keep an eye out for other instrumental dependencies
- Interferometer red herrings
  - Dynamic range
    - Instrument response a function of SNR?
    - Significant concern if calibrators are dim
  - Pointing sensitivity
    - Instrument response a function of RA, dec?
  - Coupled effects
    - Eg. low SNR + low dec = spurious results, etc.

RAPID ROTATION

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

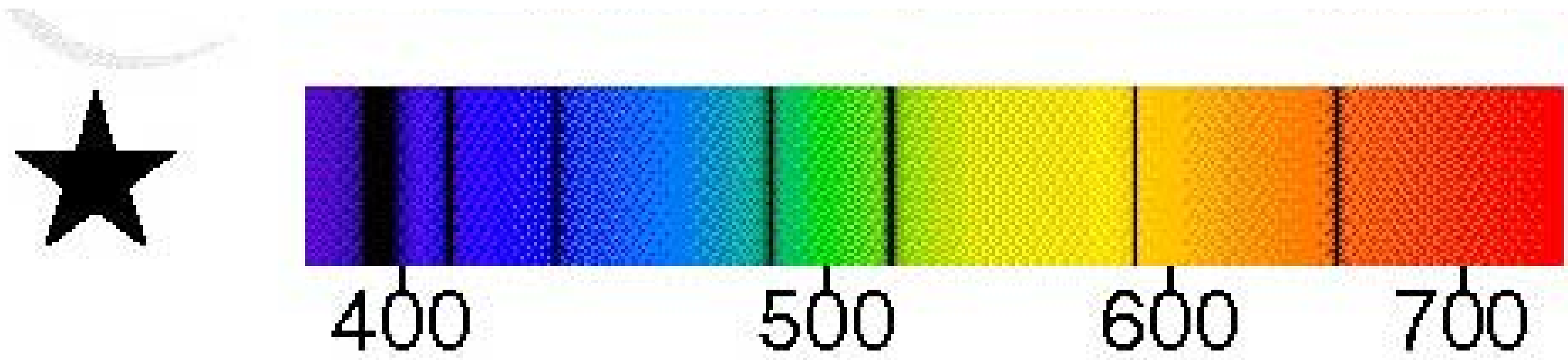


Historical Context

- Stellar rotation first observed by Galileo
  - Observed motion of sunspots
- 1920's: Equations of rotating stars in radiative equilibrium

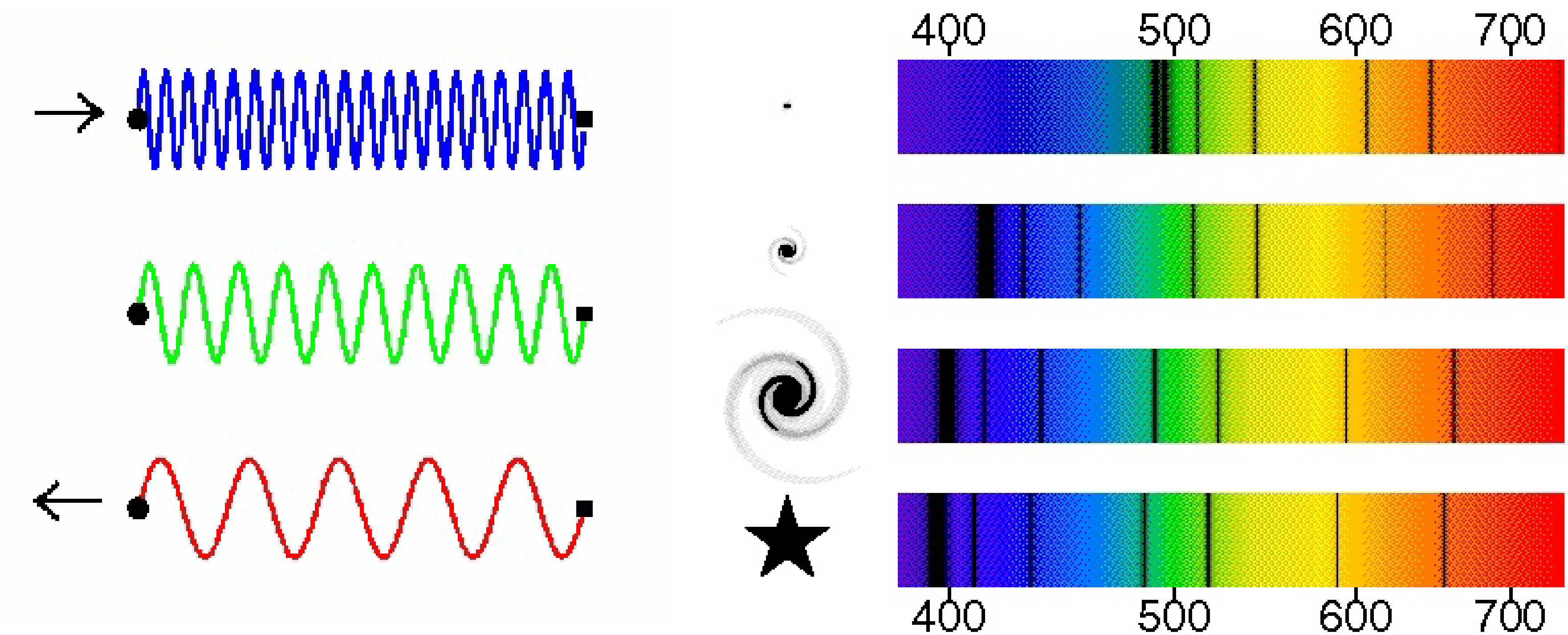
Stellar Spectra

- Solar features noted by Wollaston in 1802
- Fraunhofer cataloged solar lines in 1814
- Huggins (1864)
  - Comparison of stellar spectra with terrestrial samples
  - Opened the door for modern spectroscopy



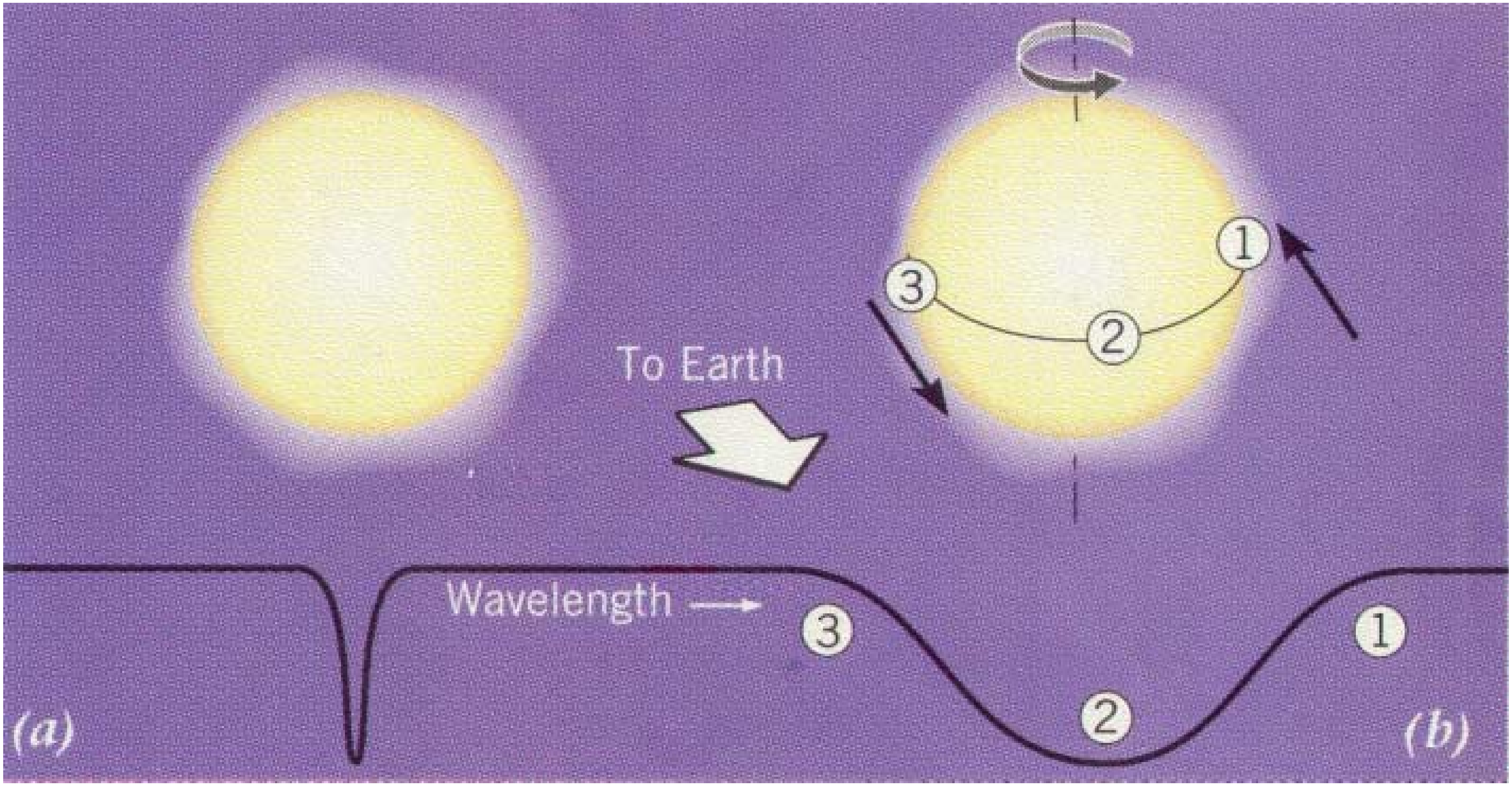
Stellar Dynamics

- Measurement of Doppler shift can establish velocity along line of sight



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)

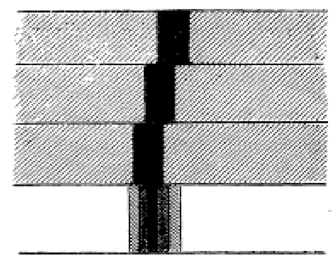
Effect of a Star's Rotation on its Spectrum.

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.

Considerations of Stellar Rotation

- Jeans (1919, 1926)
  - Interior rotation different from exterior rotation
- von Zeipel (1924)
  - Derived effective temperature (T_{EFF}) as a function of latitude
  - H (luminous flux) ~ g (surface gravity)
  - T_{EFF} maximum at the poles, minimum at the equator
- Eddington (1926)
- Shajn & Struve (1929)
  - Predicted line shape

First Generation of Observationalists

- Elvey (1930)
  - First list of rotational velocities published
  - Used Shajn & Struve measures of line contours
- Struve & Elvey (1931)
  - Linked rotation rate to spectral type
  - A-type stars are known to be mean high rotators
- Westgate (1933,1934)
  - Extensive observational catalogs
- Slettebak (1949-1956)
  - Found most rapid rotators among Be stars
  - Established relationship between rotation and mass

Development of Rigid Rotator Theory

- Collins (1963-1965)
  - Explored implications of rapid rotation upon color, luminosity, spectral characteristics
- Jordahl (1972)
  - Ph.D. dissertation on Altair

Pseudo-Metaphysical Questions

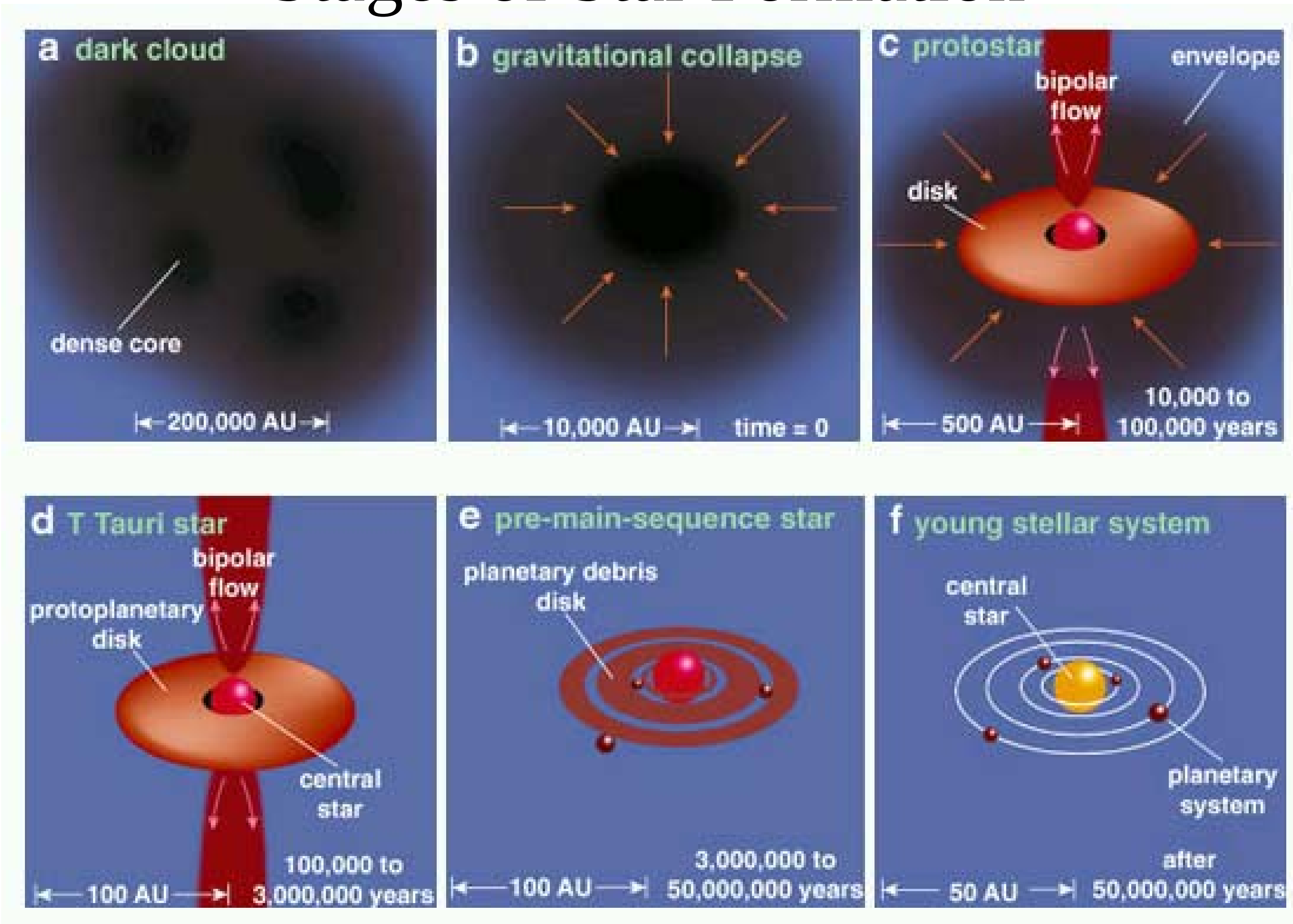
- ~~Why do these stars spin so fast?~~

Wrong Question!

Right Question:

- Why don't all stars spin fast?

Stages of Star Formation



Reference: T.P. Greene, American Scientist, July-August 2001

Interaction of Central Star with Disk

- Rotational braking consistent with evidence that many T Tauri stars have rotational speeds that are only 10% of breakup (Bouvier et al 1993, Shu et al 1994)
- Also, some stars slow down over the course of their main sequence lifetime (Kraft 1967b)

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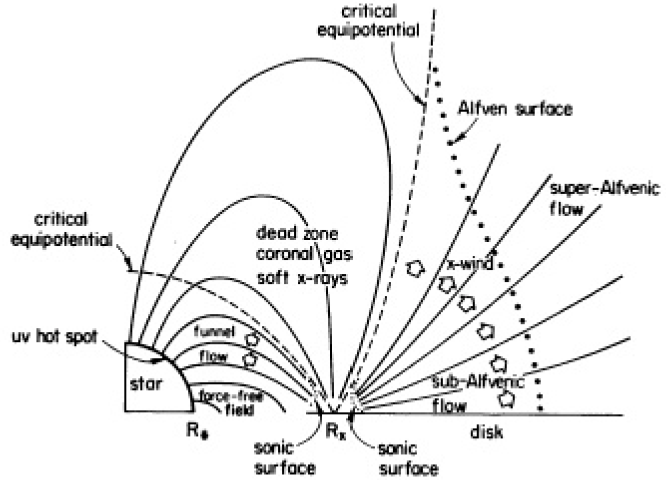
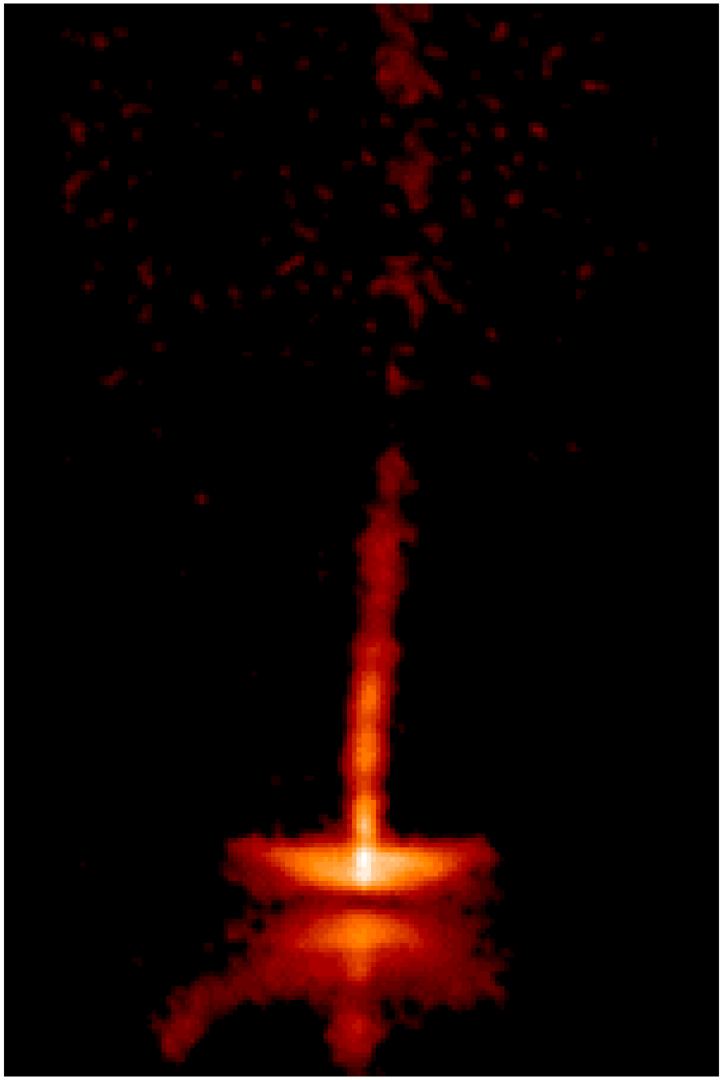


FIG. 4.—Schematic diagram of principal components in a typical CTTS system.

Reference: Shu et al 1994 ApJ 429 781

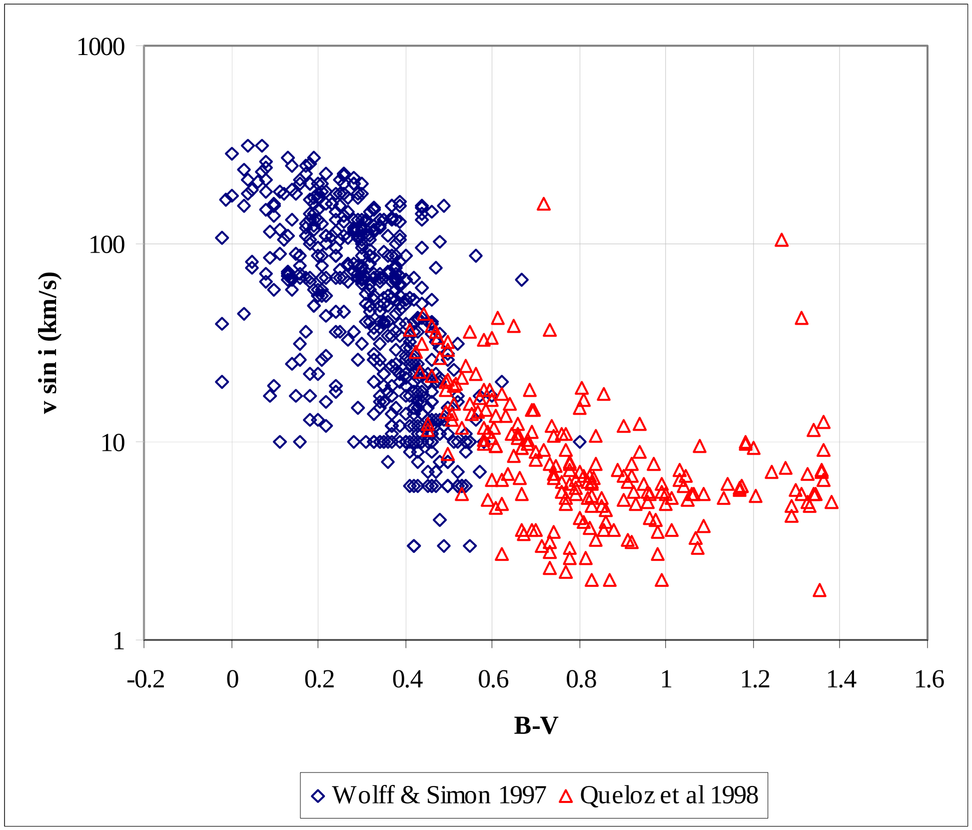
HST Movie of HH30

- Shows bipolar outflows in action
  (Stapelfeldt et al 1999)



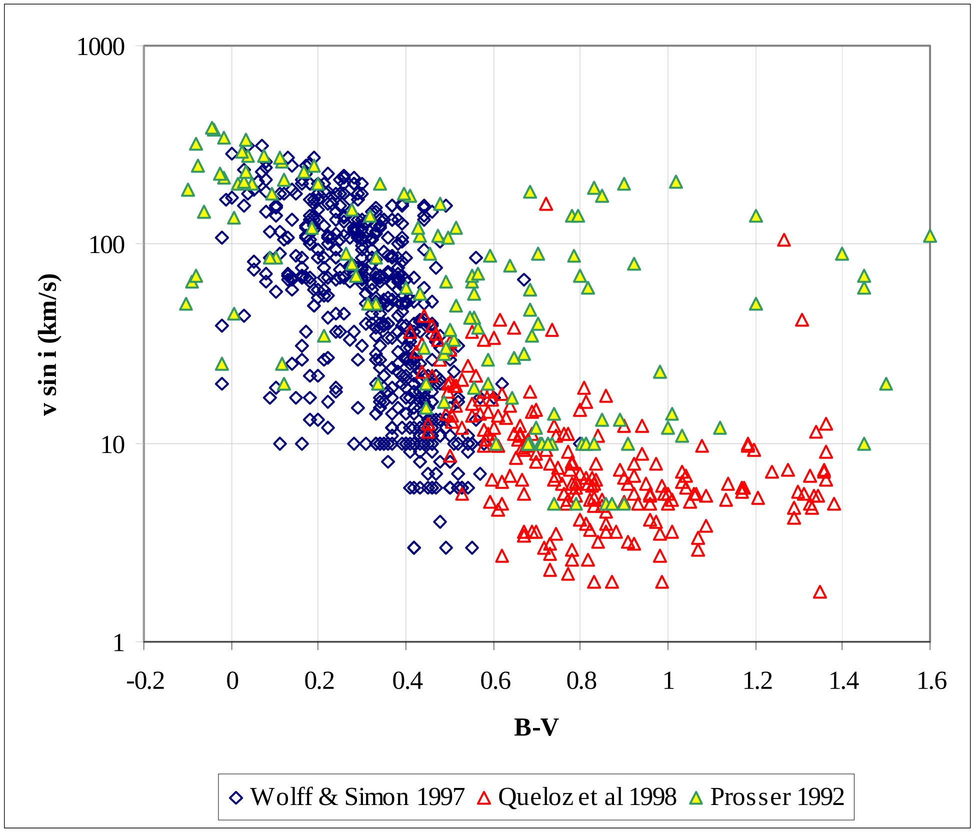
Distribution of MS Rapid Rotators in *B-V*

- Have to go blueward of B-V≈0.5 to find rapid main sequence rotators (eg. Wolff & Simon 1997, Queloz et al 1998)



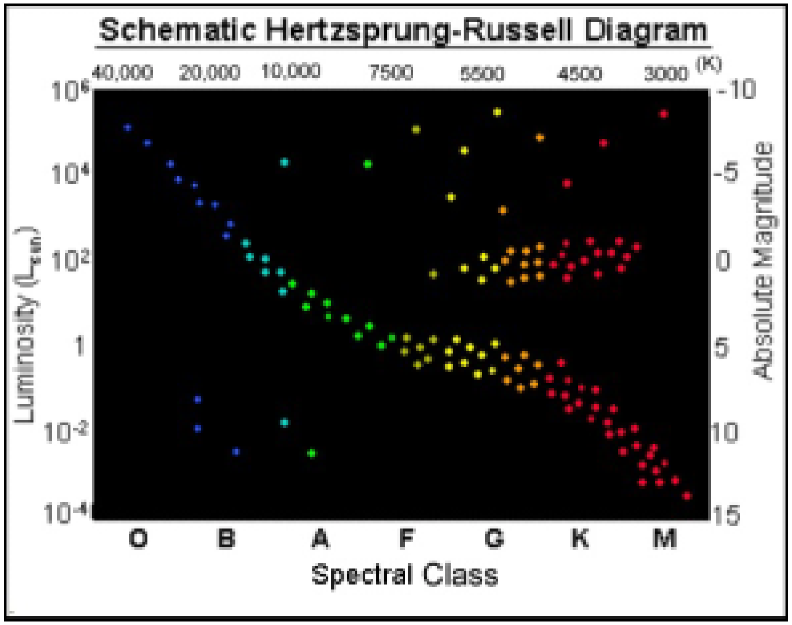
Comparison to α Persei Cluster

- Open cluster α Persei is 'relatively youthful' (Prosser 1992)
- Evidence for rapid rotation among lower mass objects



Sights Set on Our Quarry

- Effects of rotation largest on upper main sequence (Maeder & Meynet 2000)
- Extreme, massive rotators can potentially have a variation in radius of 1.5×
- So, how do we go about observing such a star?
- Key here: *lots* of resolution



Visibility Function

- For a ‘uniform disk’, visibility matches:

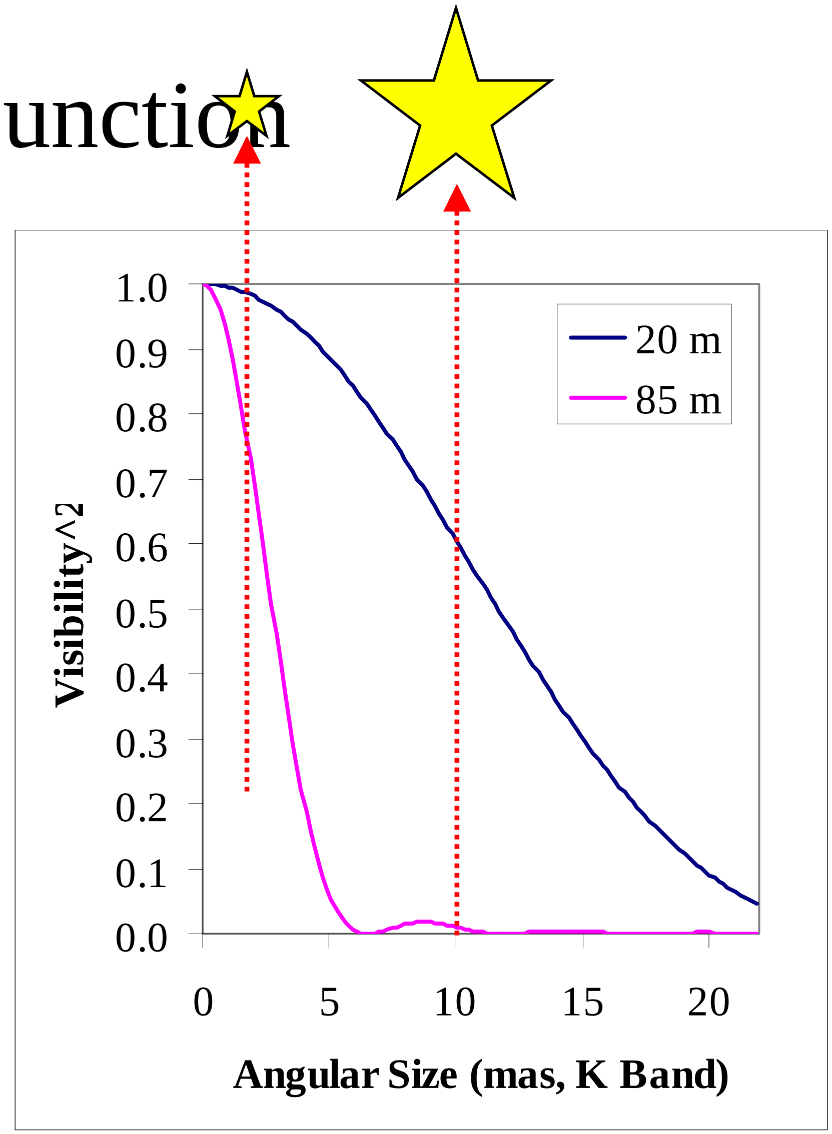
$$V = \frac{J_1(x)}{x} \quad \text{where} \quad x = \frac{\pi\theta B}{\lambda}$$

  B is the projected baseline

  θ is the stellar disk size

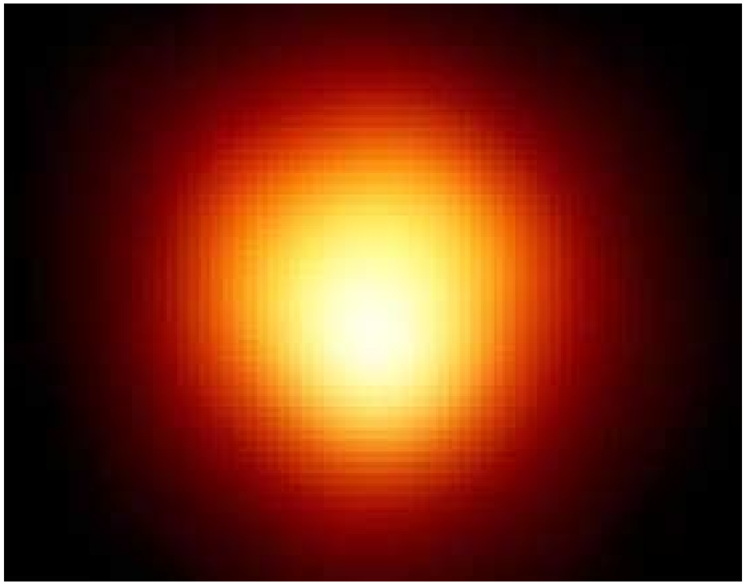
  λ is the instrumental wavelength

- However … *Stars Are Not Uniform Disks*
  - This changes the visibility function
  - “Limb darkening” can be a significant consideration

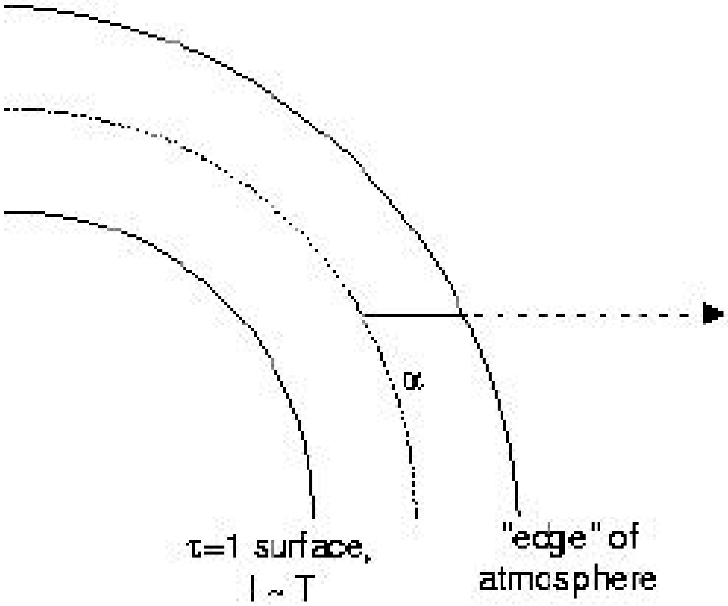


Limb darkening

- 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

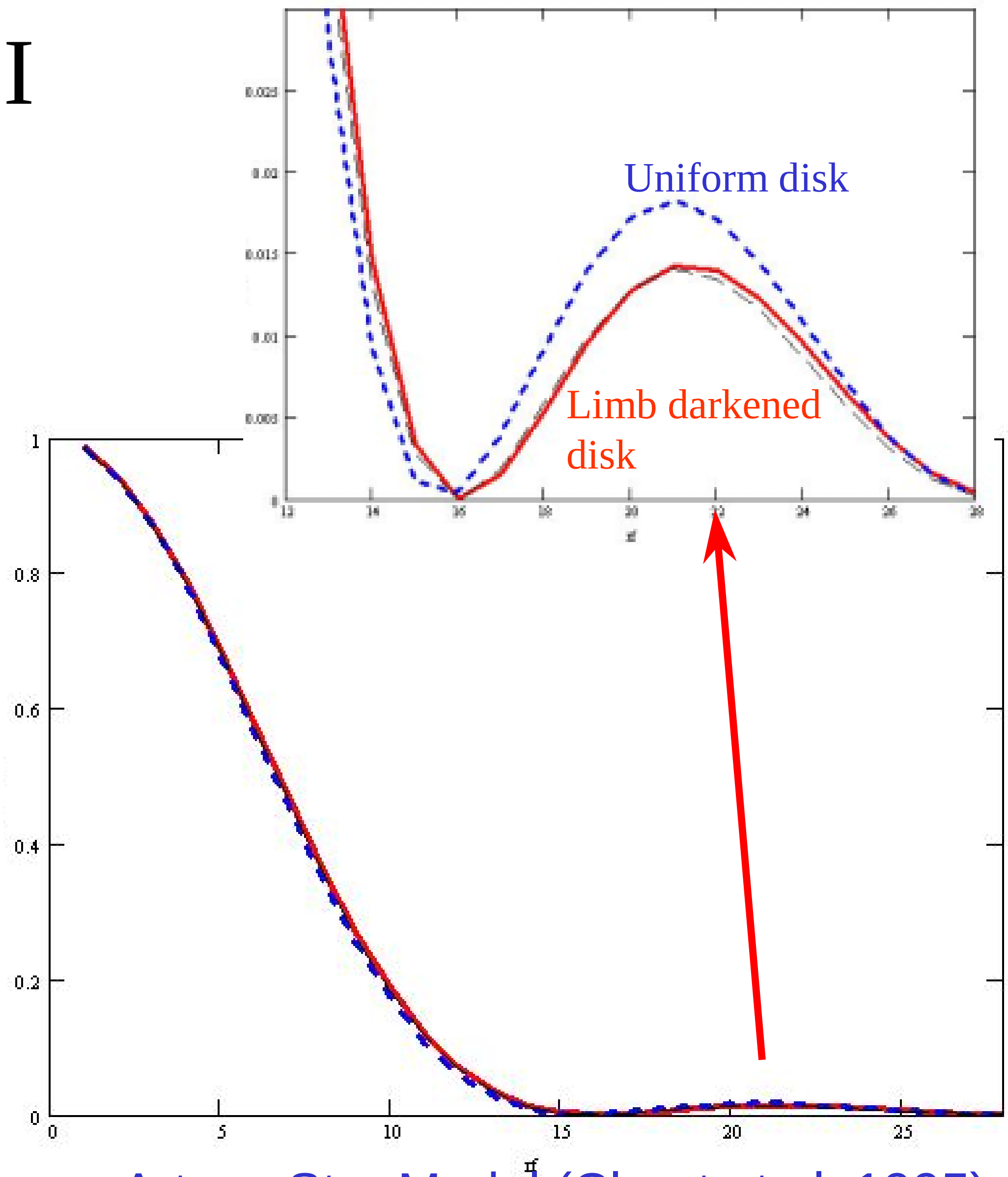


HST Image of α Ori - Betelgeuse



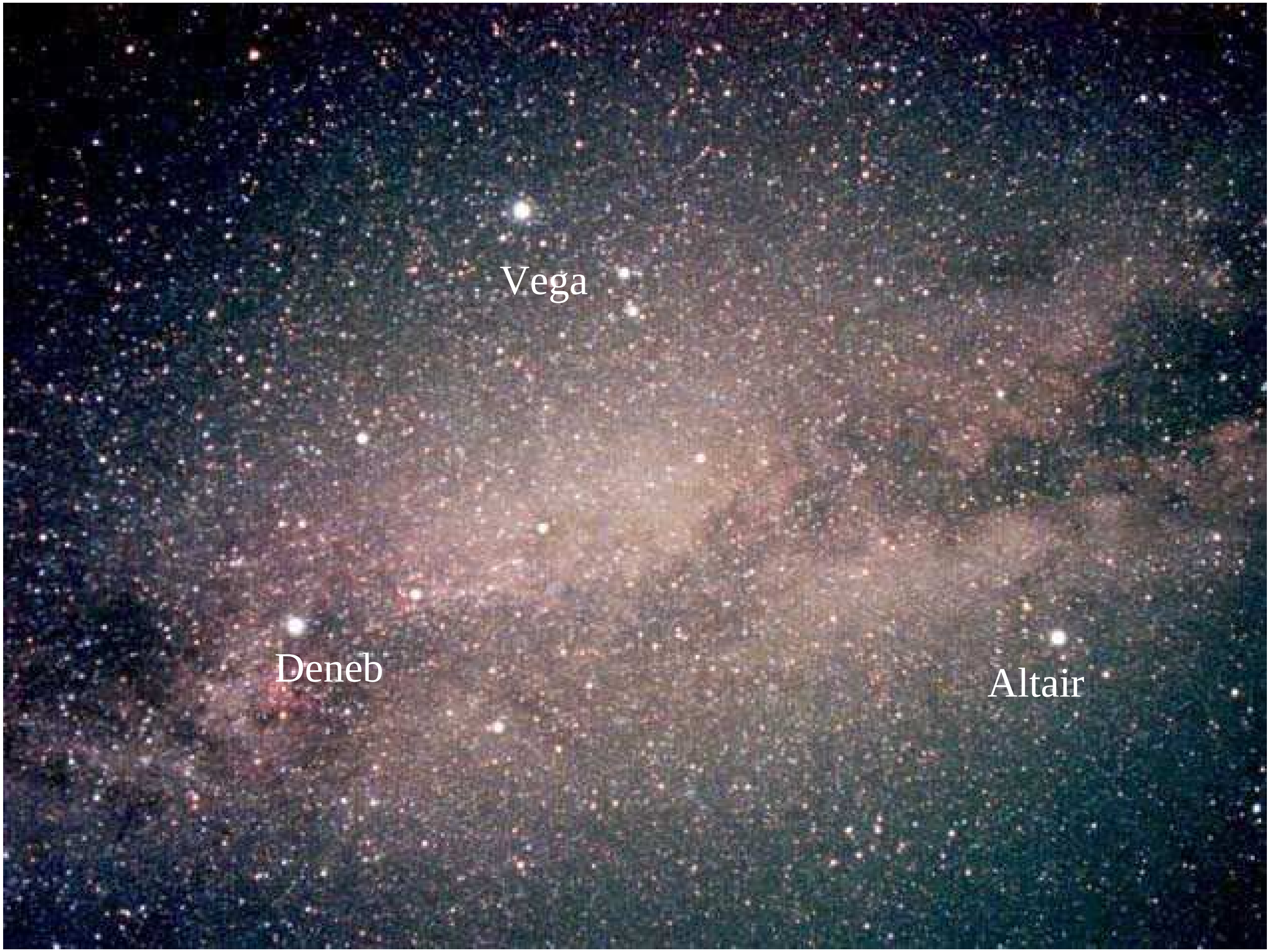
Limb darkening. II

- 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



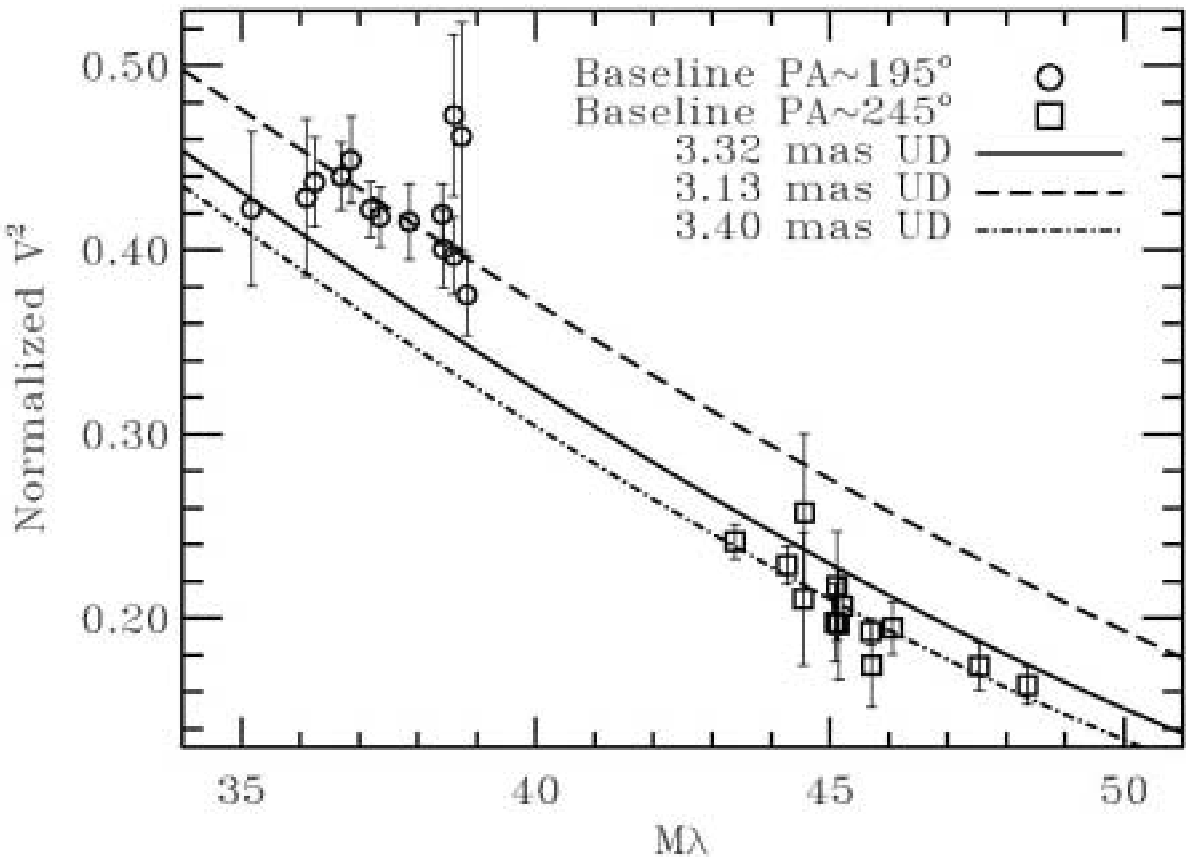
A-type Star Model (Claret et al. 1995)

Seeking High Resolution in Familiar Places



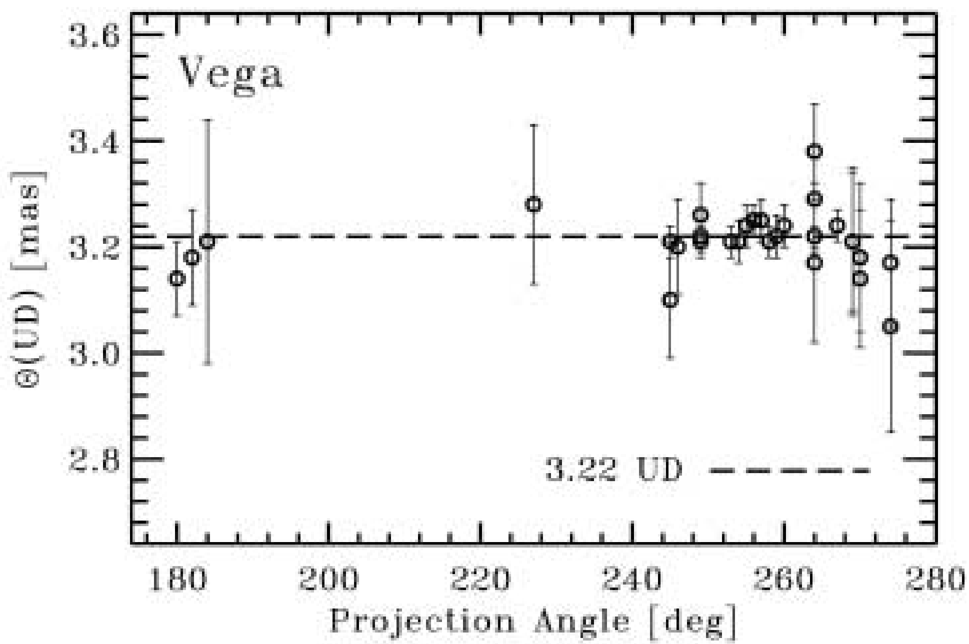
Initial Indications of Something Interesting with Altair

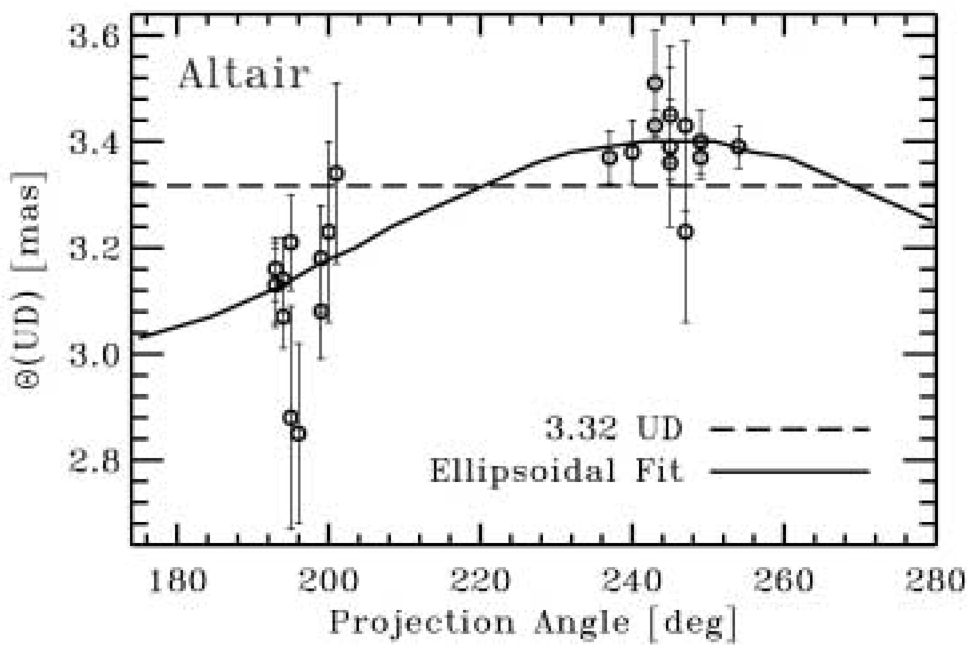
- Use of the PTI N-S and N-W baselines gave different angular sizes
- Not explainable in terms of limb darkening, spotting



Contemporaneous Measurements Appear Normal

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



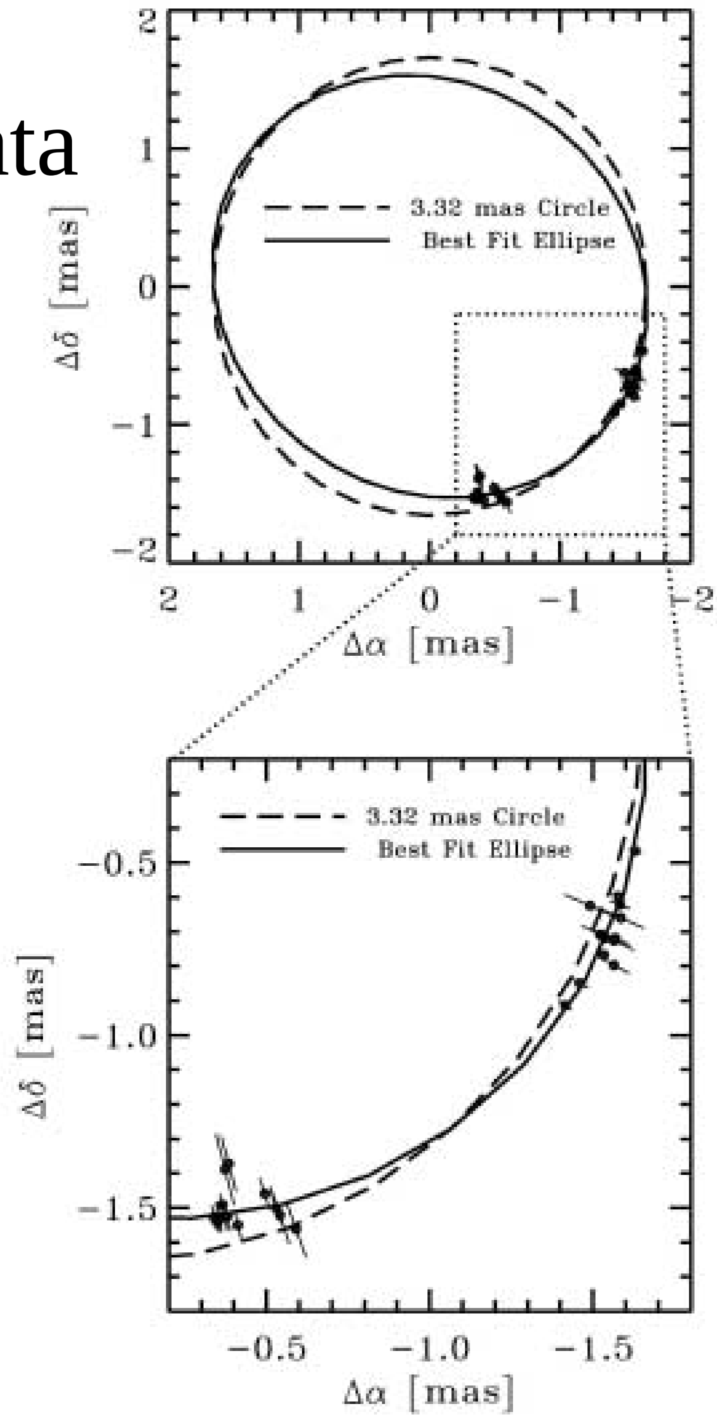


Ellipsoidal Fit to Altair Data

- 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:

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

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



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

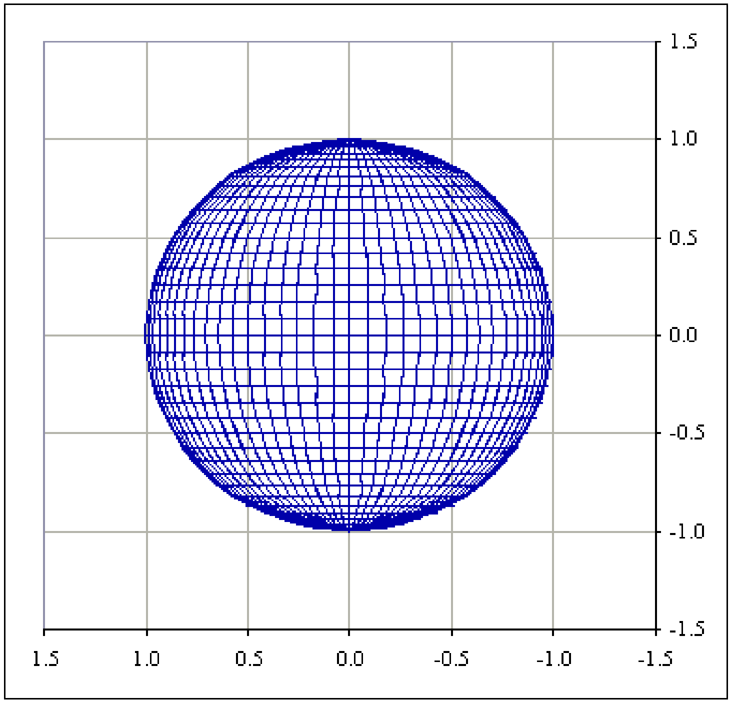
  i – inclination

  α – orientation

  R_p – polar radius

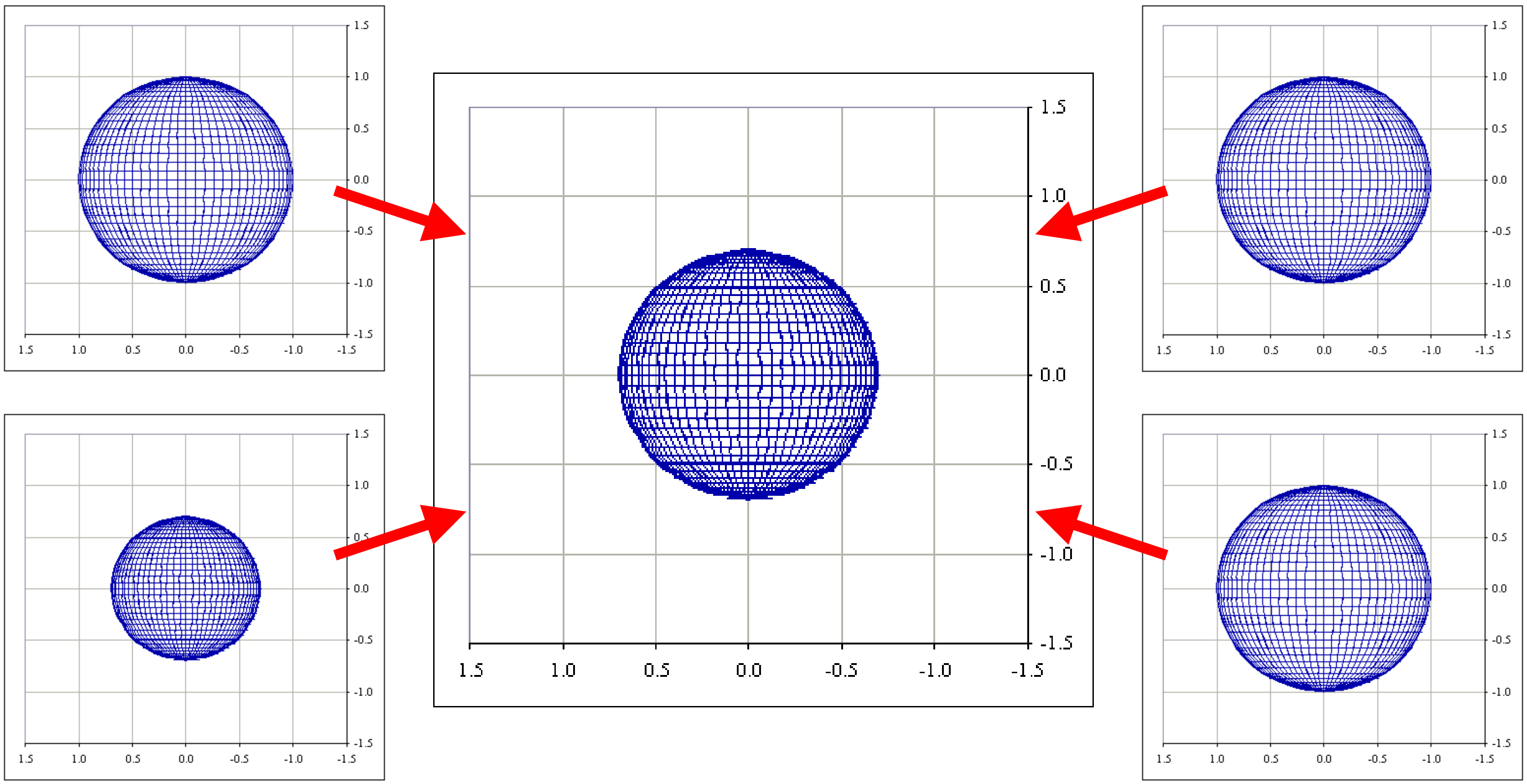
  u – fractional rotational speed

- 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

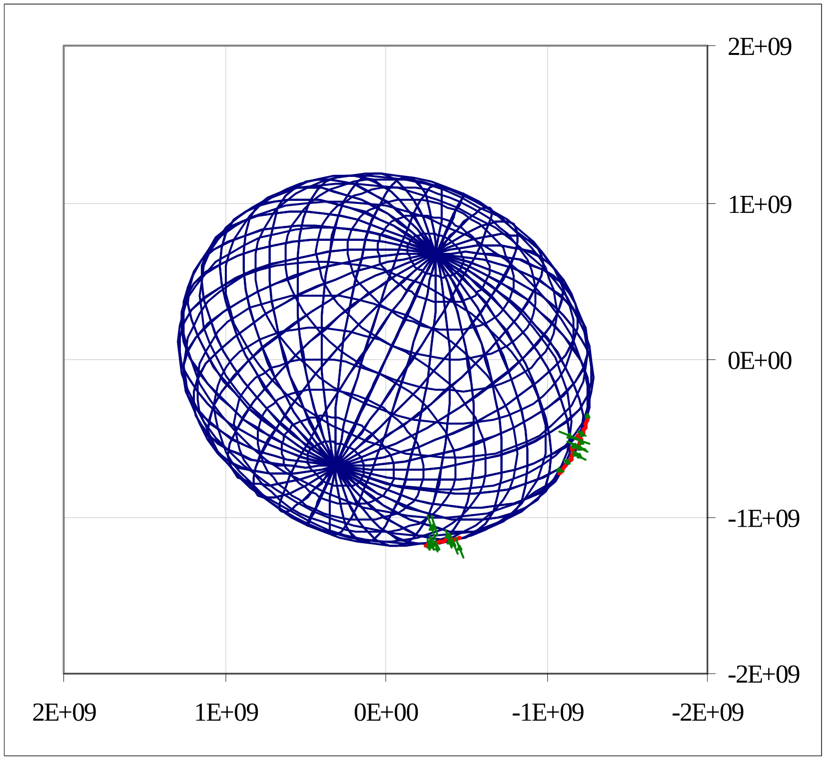


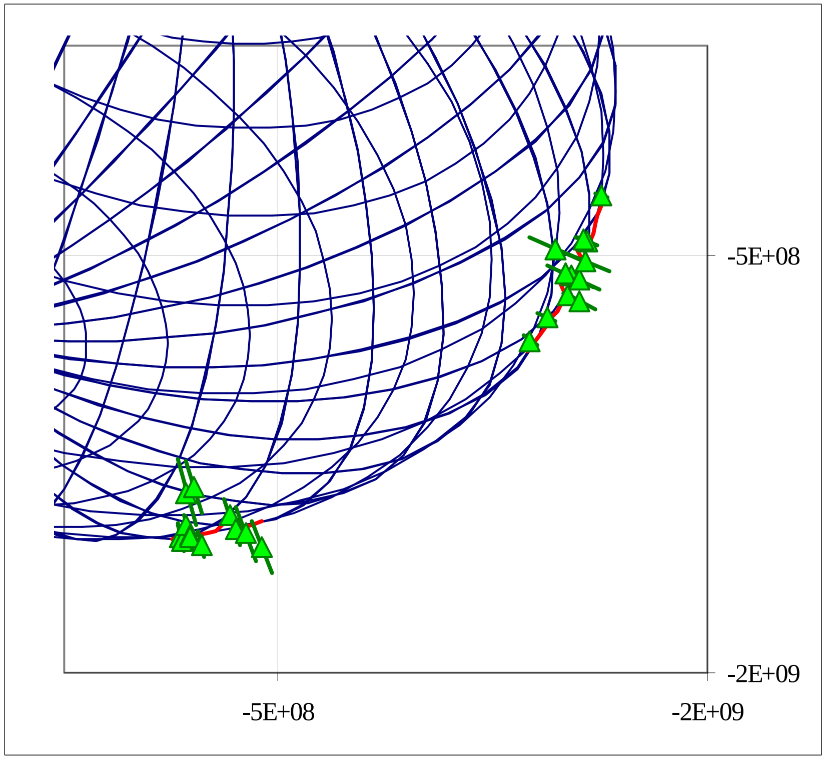
Noteworthy Assumptions

- 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

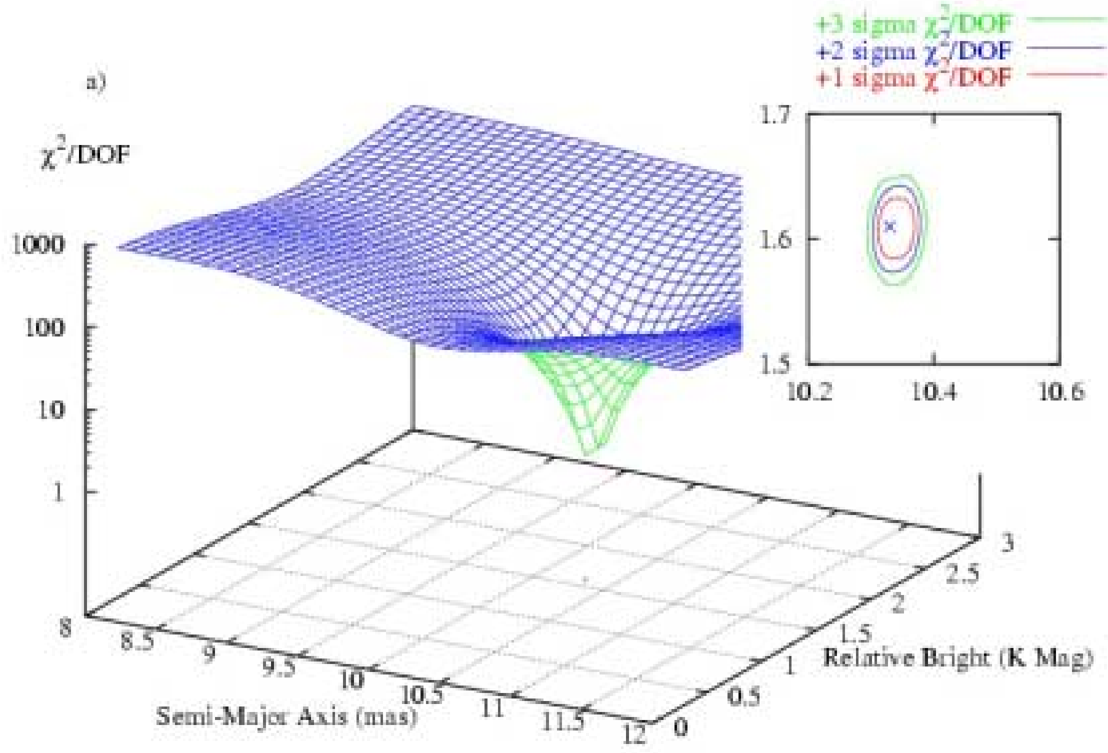
- Can randomly generate values for $\{i, \alpha, R_p, u\}$ and examine χ^2 of fit
- Brute-force examination of $\chi^2(i, \alpha, R_p, u)$ can reveal global minima in χ^2 space





Binary Orbit Determination

- Fit V^2, radial velocity data by seven-element Keplerian orbit model
- Problem is non-linear with local minima

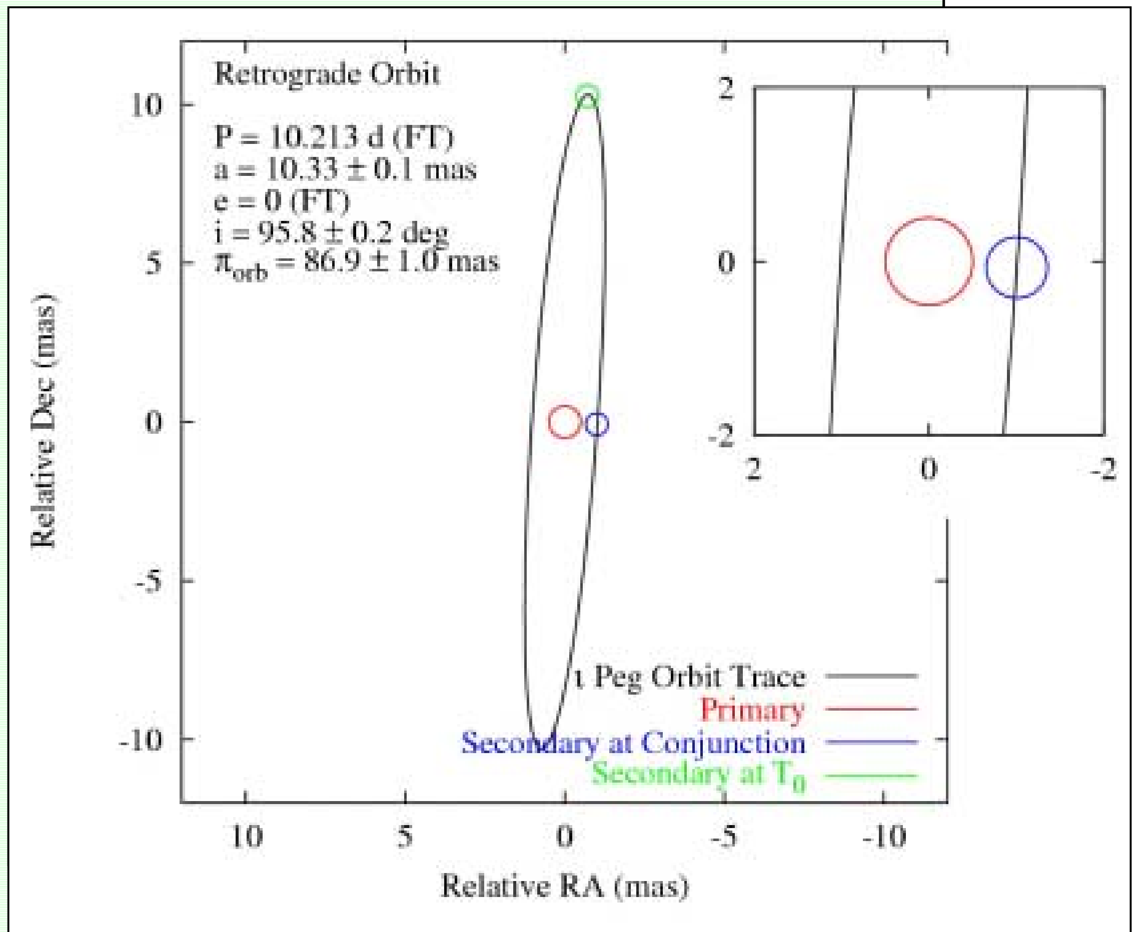


ι Peg χ^2 in *a*/r Subspace

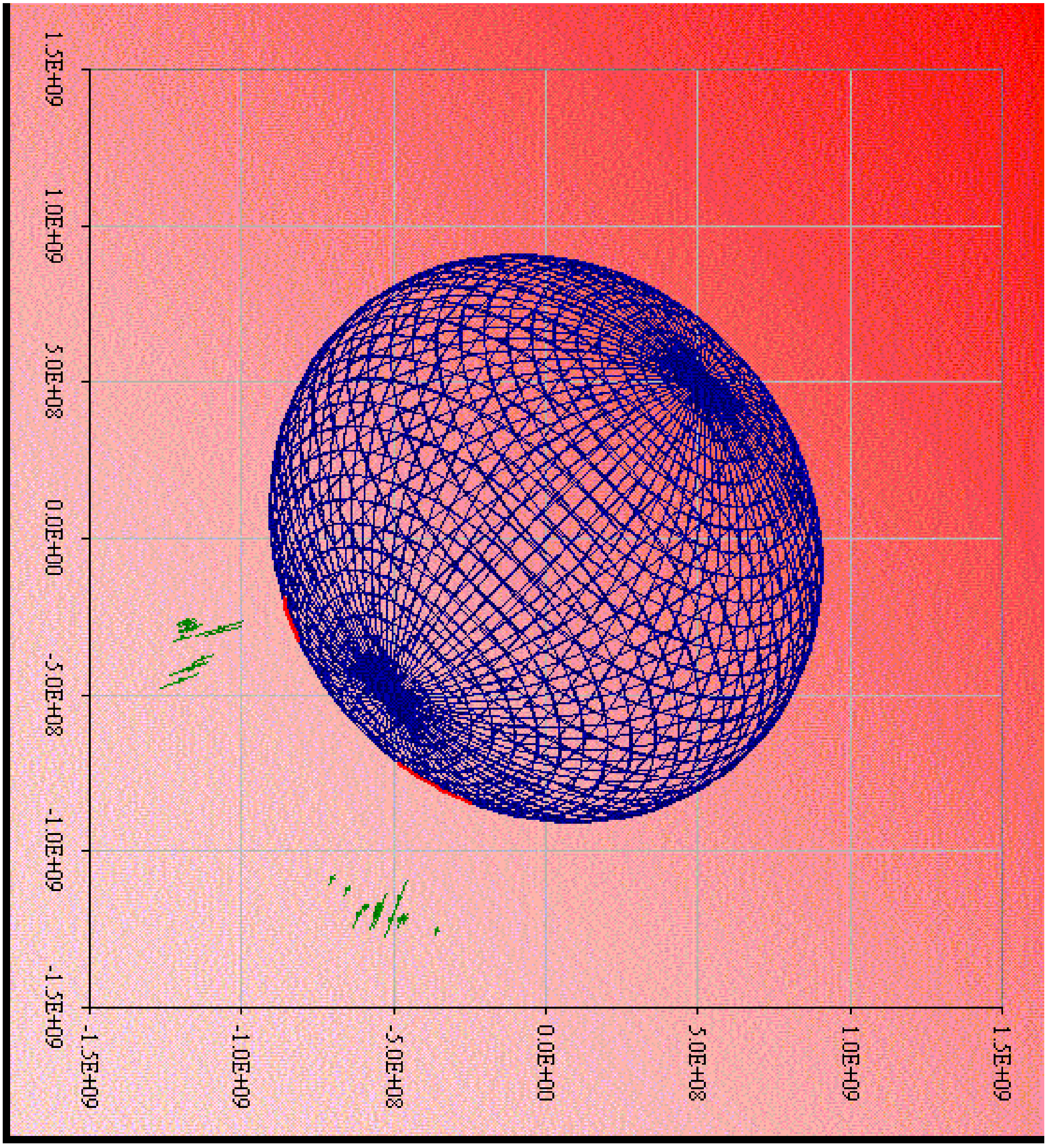
ι Pegasi

One HST WFPC 2 Pixel

- Well-known binary system
- Established as a SB2 by Fekel and Tomkin who inferred the "possibility of eclipses" (1983)
- Average Absolute V^2 Residual 1.4% Over 114 Scans
- Precision photometry : no eclipses (Boden *et al.* 1998 *ApJ*)



Exhaustive Search = Exhausting!

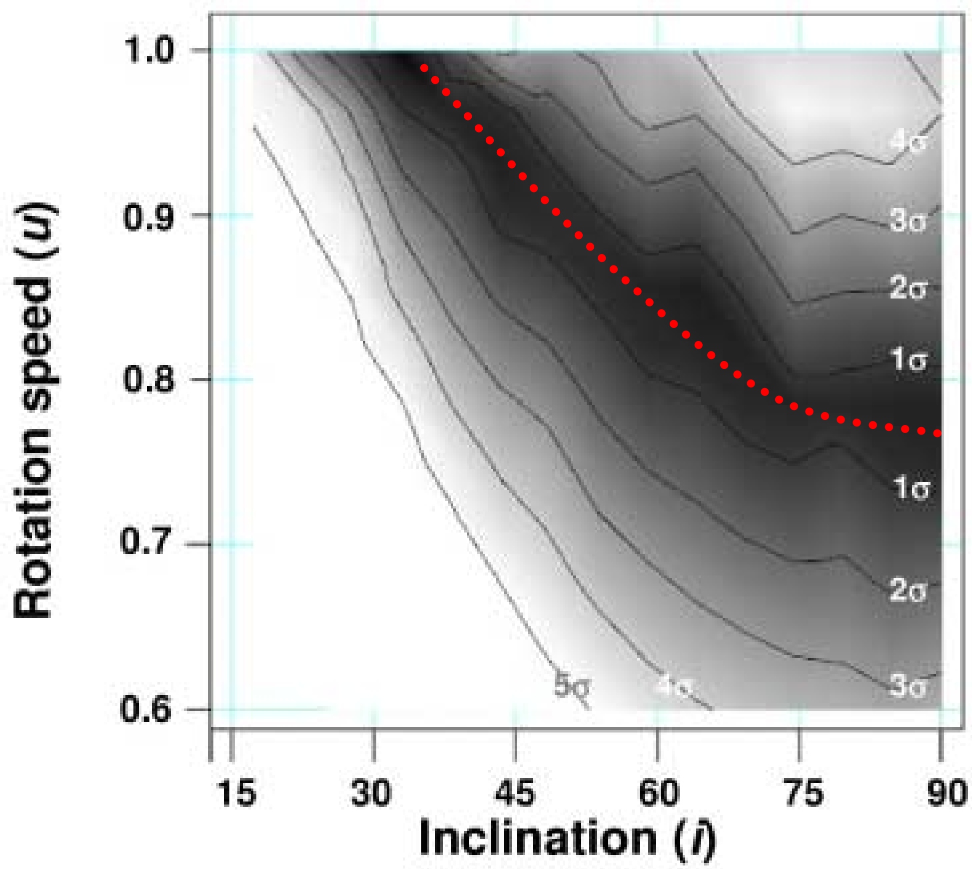


Results of the Minima Search

- 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 $\{i,u\}$

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

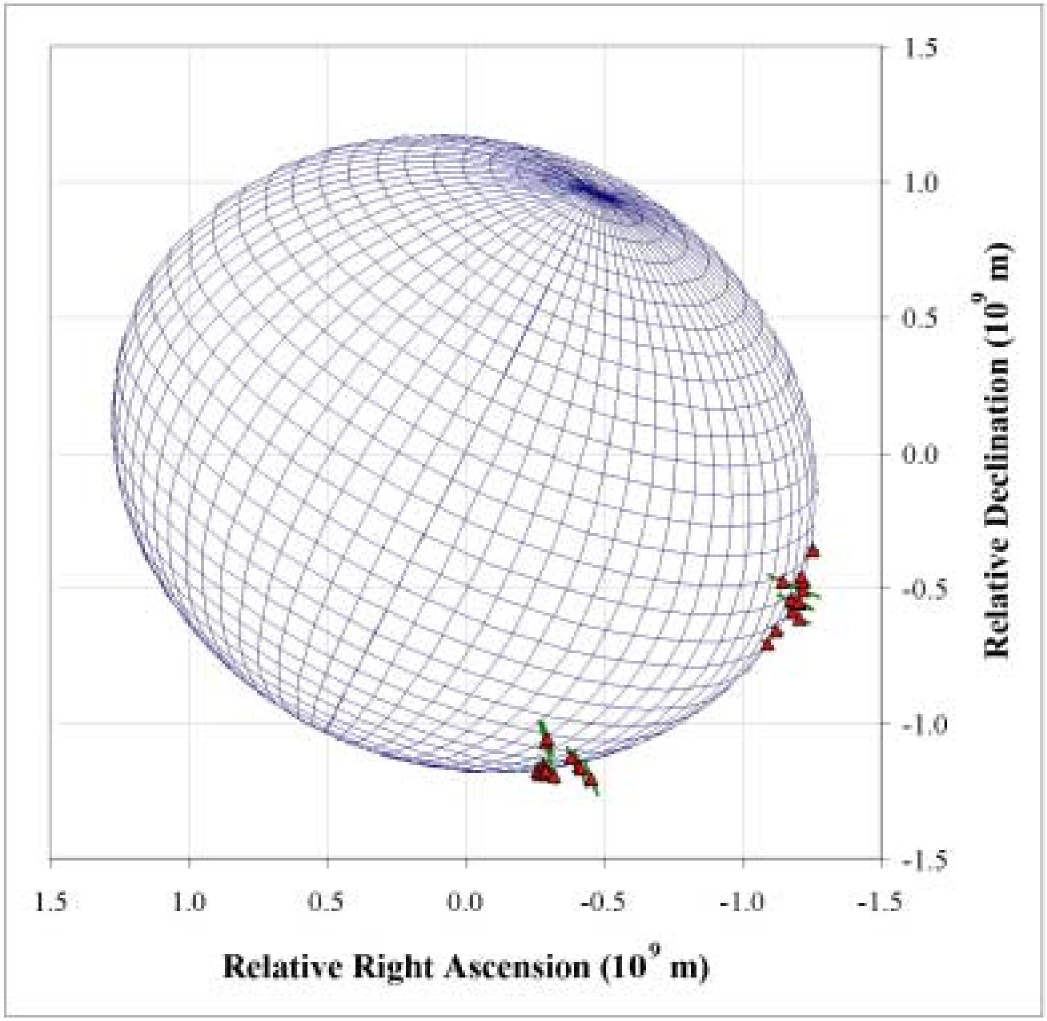
- No inclination less than 30° is allowed, no speed less than 210 km/s



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±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

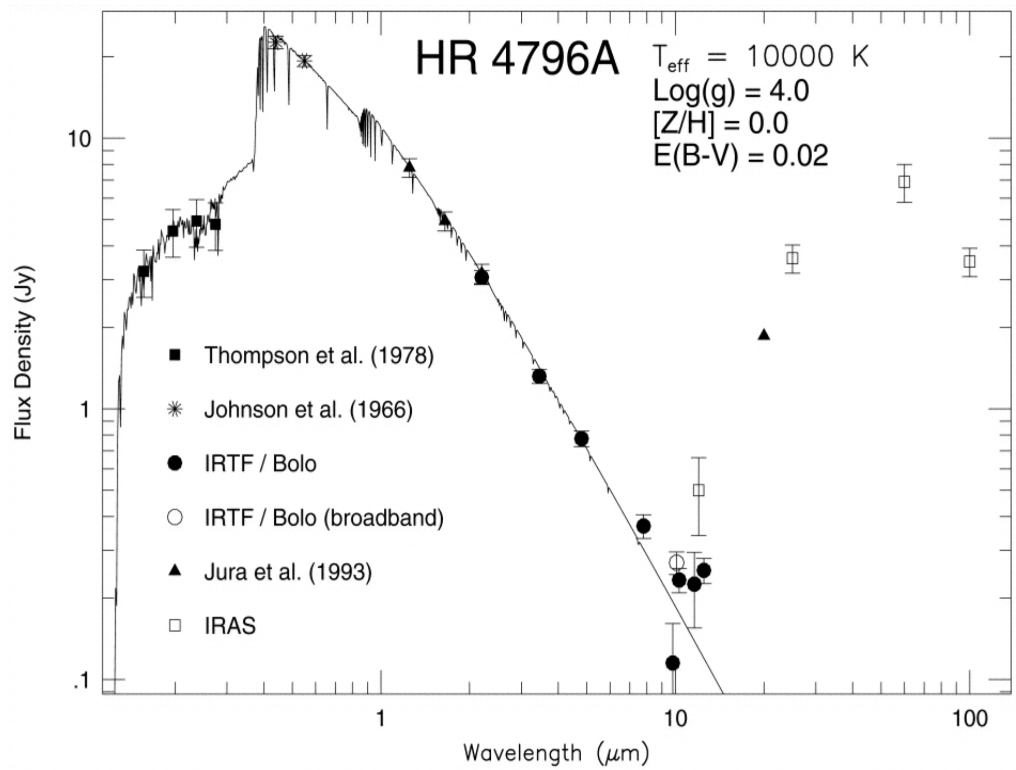
- Other large (nearby) rapid rotators
  - eg. Regulus, eps Sgr
- Multiwavelength observations
  - Combine PTI, NPOI data in near-IR, visible
  - Directly probe latitude dependencies of radius and temperature
- Main limitation – resolution
  - Need 250 or more meters to have a large (10+) sample size
  - New interferometers (CHARA, NPOI) will make this possible

The End

Backup Slides

Vega-like Systems

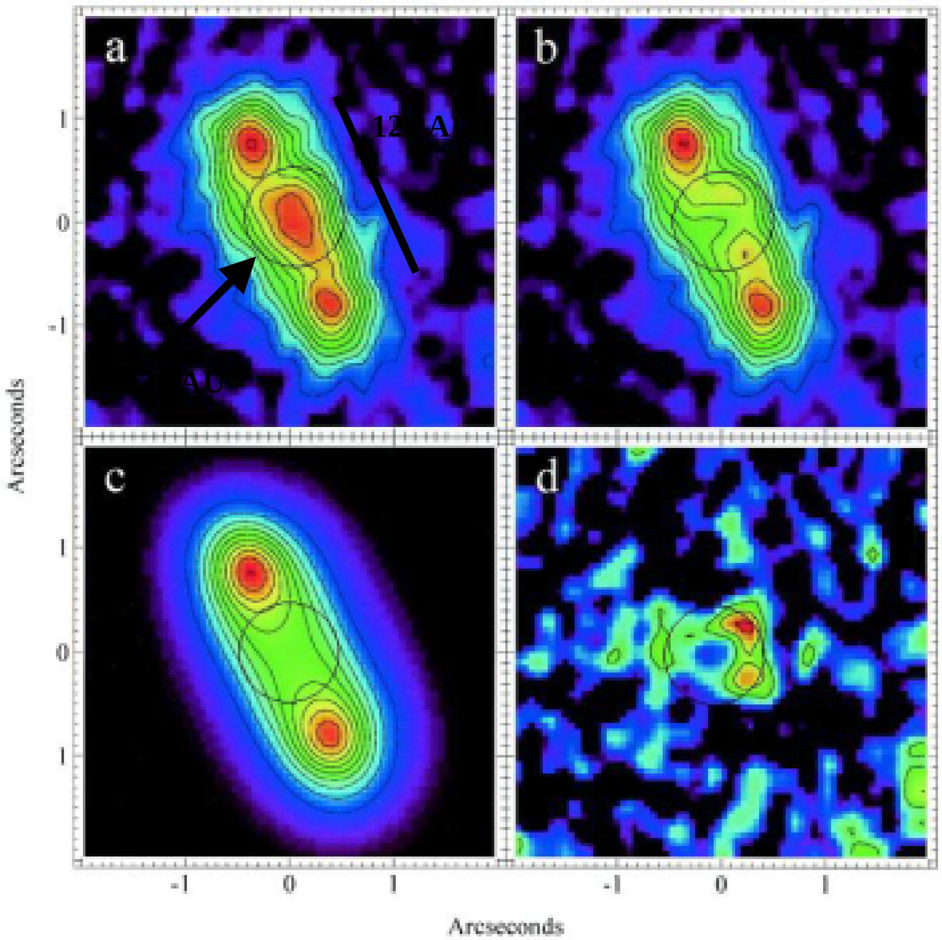
- Young (main sequence) stars with infrared excesses from surrounding dust disk
- Debris Disks analogous to our own zodiacal dust
  - Low luminosity & mass
  - Mostly dust grains
  - Grain lifetime shorter than star lifetime … ***Dust is NOT primordial.***
  - ***Dust must be replenished, probably by a reservoir of larger objects***
  - The existence of a debris disk implies the presence of larger bodies.



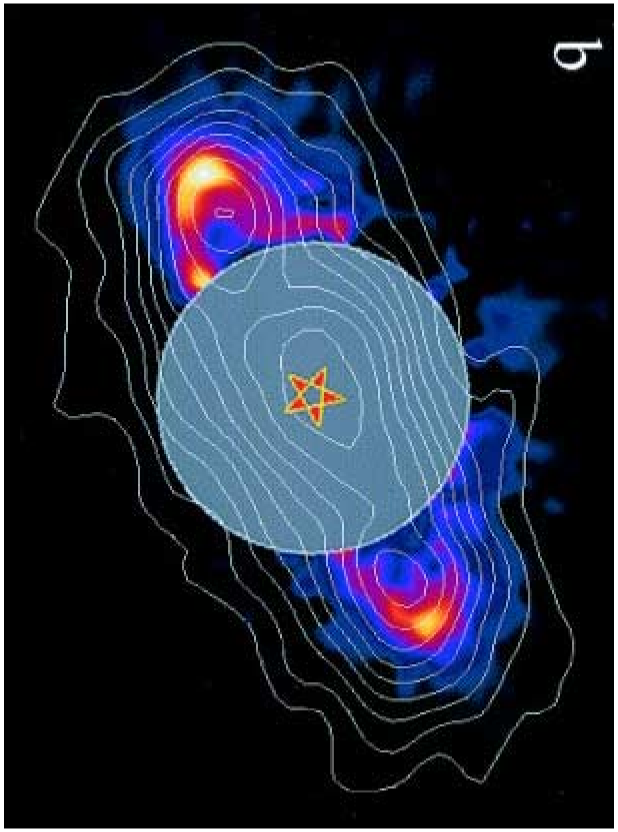
From Fajardo-Acosta, Telesco, & Knacke 1998)

HR 4797A in Mid and NIR-IR

18 μm

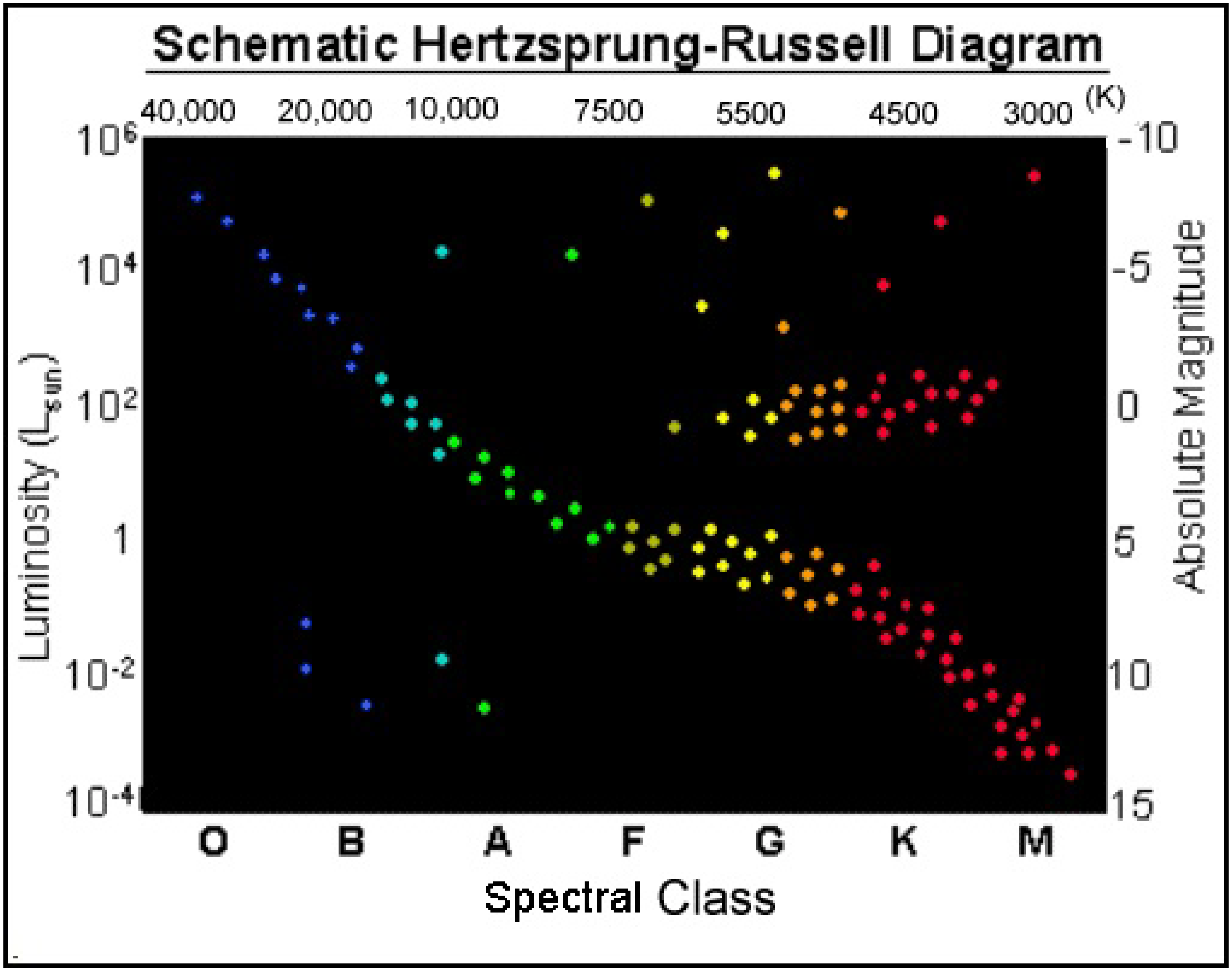


1.1 μm

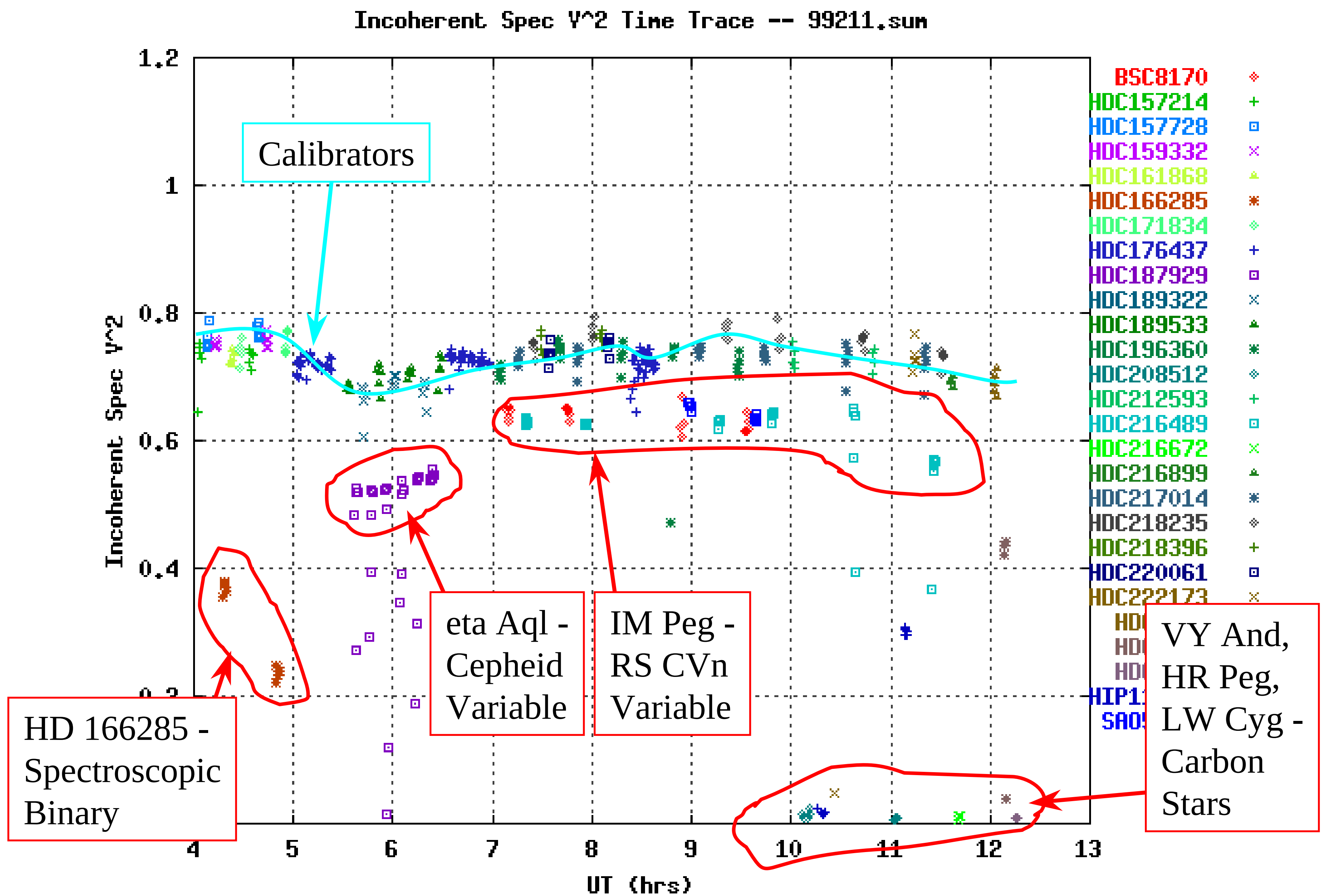


From Telesco et al. 2000

Hertzsprung-Russell Diagram



PTI Visibility Data



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: $T_{\mathrm{EFF}} = 1.316 \times 10^7 \left(\frac{F_{\mathrm{BOL}}}{\theta_{\mathrm{R}}^2} \right)^{1/4}$

  - 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

Current Stock of Results

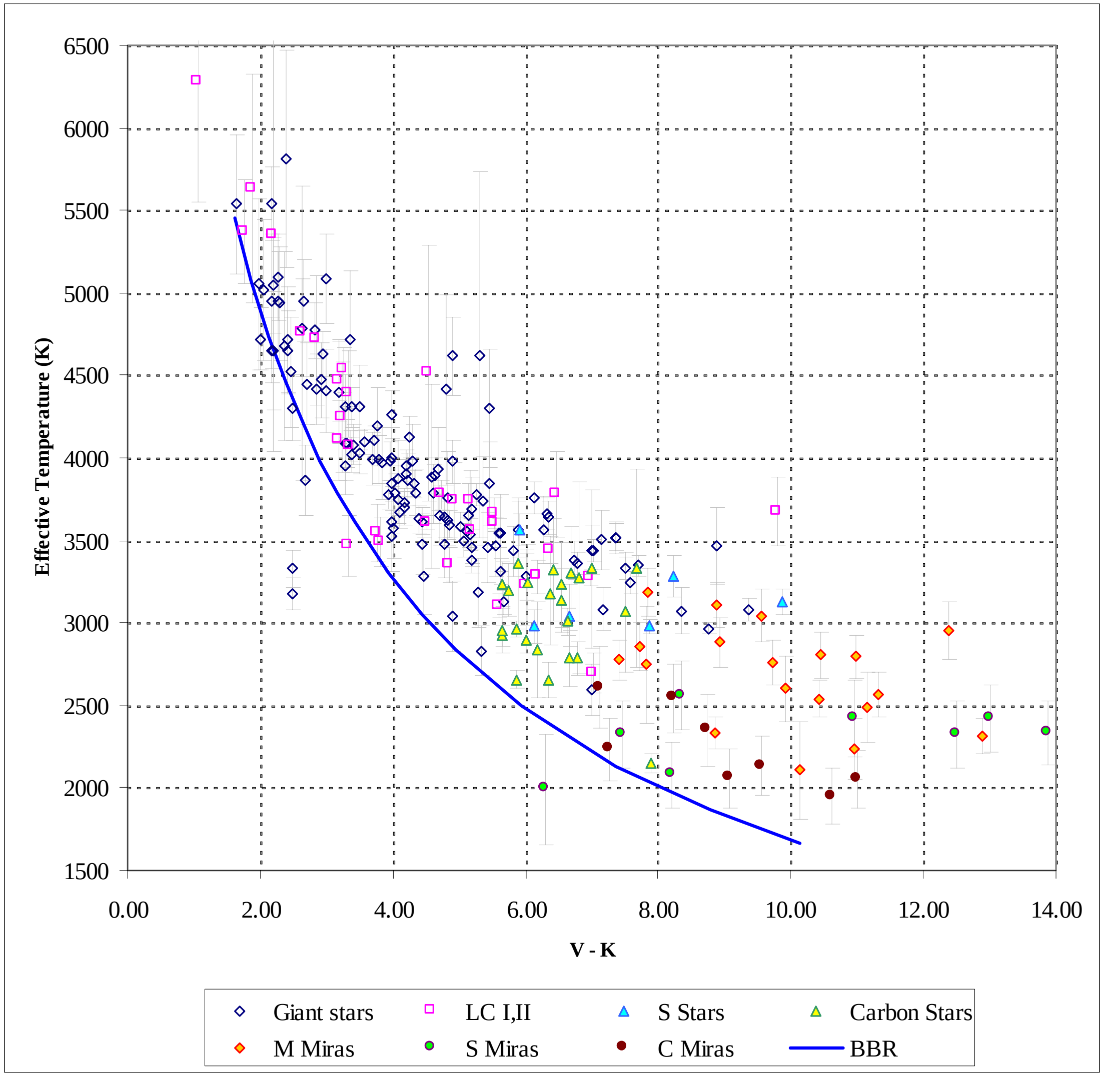
- Borrowing from Davis (1997), increase of 145 to 340 stars in the literature
  - Largely due to sizes published by Dyck & van Belle
  - Noting that 78 of the original 145 are still unpublished
- Notable improvement: Application of interferometry to evolved stars
- Notable area for improvement: *Still* main sequence stars, particularly late-type

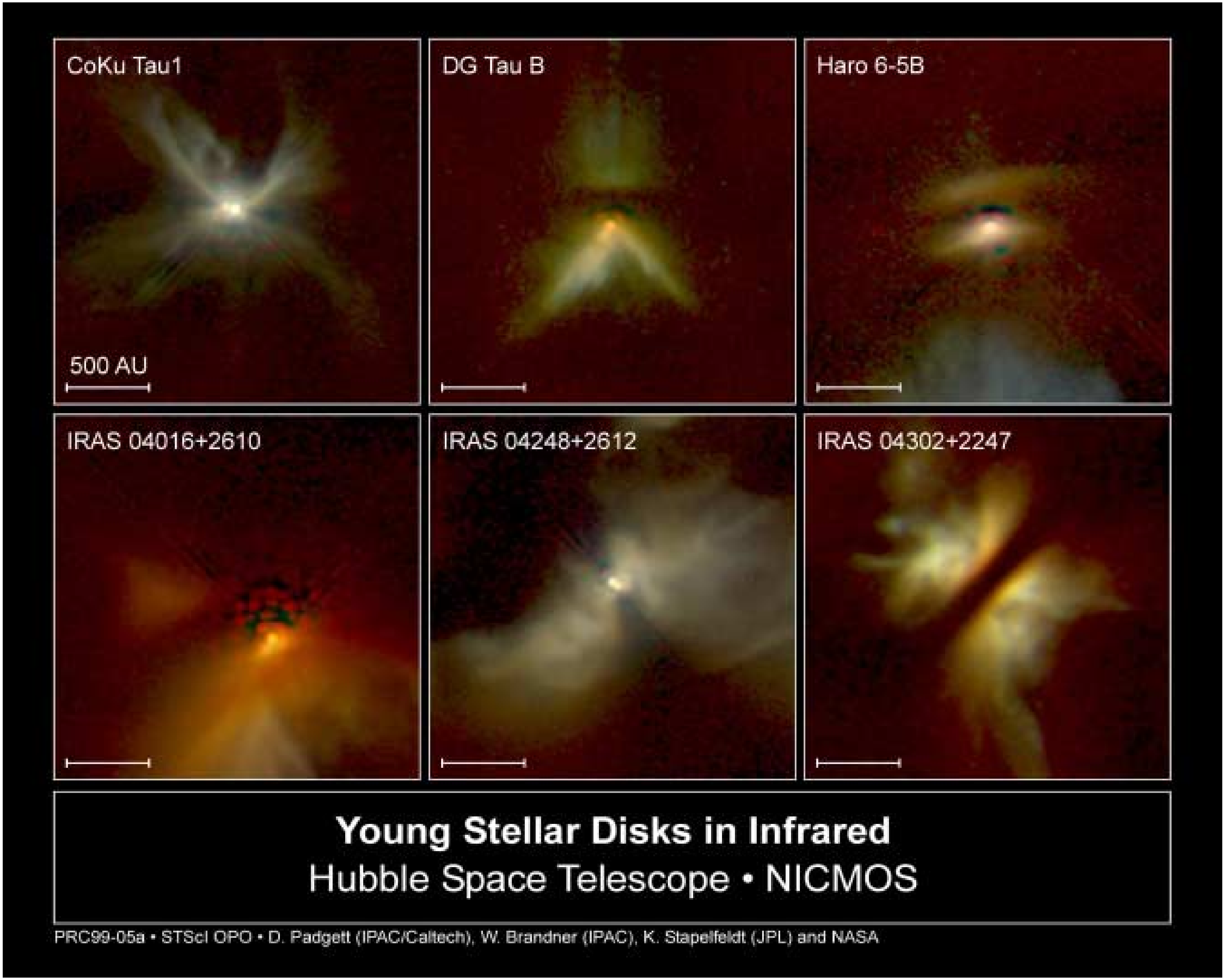
Spectral Type	I	II	III	IV	V
O	3	0	0	0	1
B0-B4	2	2	3	2	2
B5-B8	2	0	2	1	1
A0-A3	1	0	0	2	5
A5-A7	0	0	1	0	1
F0-F5	4	1	0	1	0
F8	2	0	0	0	0
G0-G5	3	1	2	3	0
G7-G9.5	2	1	22	0	0
K0-K3.5	5	16	31	0	0
K4-K7	3	1	14	0	0
M0-M4	12	13	70	0	0
M5-M8	1	2	31	0	0
Totals	40	37	176	9	10

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

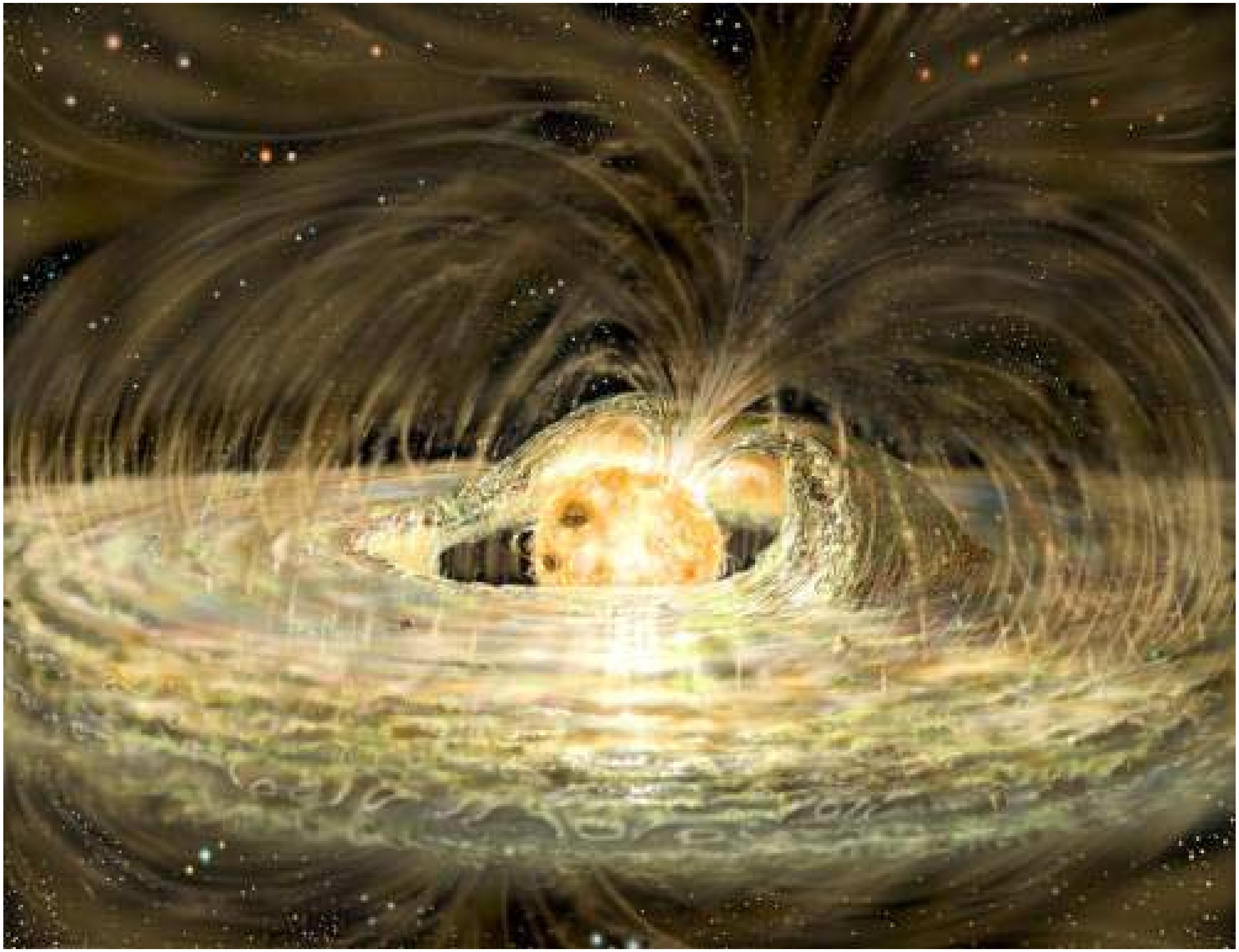
Effective Temperature vs. V-K Color

- Blue: Blackbody behavior
- Indications of increased absorption bands at V at low T_{EFF} (Barbuy *et al.* 1992, Jørgensen 1994)
- Clear separation of the abundance subtypes into regions on the plot




CoKu Tau1
DG Tau B
Haro 6-5B
500 AU
IRAS 04016+2610
IRAS 04248+2612
IRAS 04302+2247
Young Stellar Disks in Infrared
Hubble Space Telescope • NICMOS
PRC99-05a • STScI OPO • D. Padgett (IPAC/Caltech), W. Brandner (IPAC), K. Stapelfeldt (JPL) and NASA

Artist's Concept of T Tauri System



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