Science Opportunities in Stellar Physics

Douglas R. Gies

CHARA, Georgia State Univ., gies@chara.gsu.edu

and the

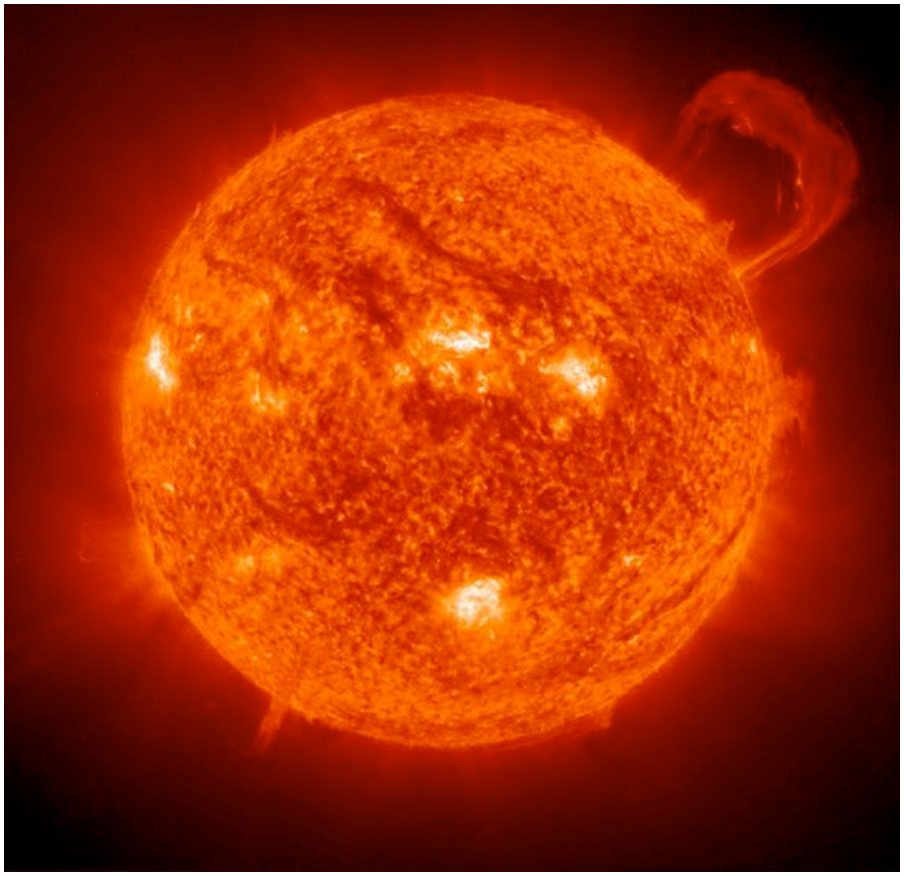
Stellar Physics Working Group

Future Directions for Interferometry

AURA • NIO • NOAO • CHARA

General Themes

- Fundamental properties
- Interior structure and evolution
- Surface features
- Mass loss and outer regions
- Companions



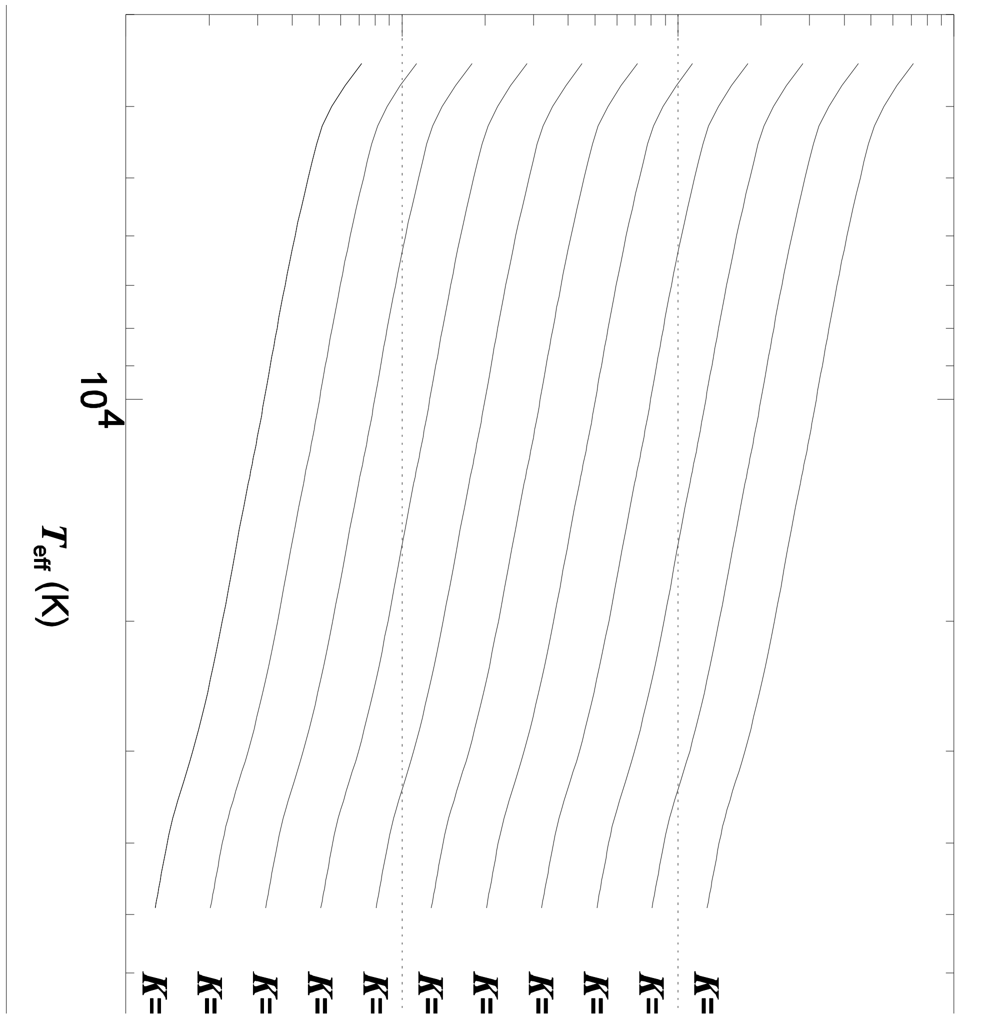
Good Reviews

- Various contributions at the 2006 Michelson Summer Workshop
  http://msc.caltech.edu/workshop/2006/agenda.html
- Monnier 2003, Reports on Progress in Physics, 66, 789

Fundamental Properties of Stars

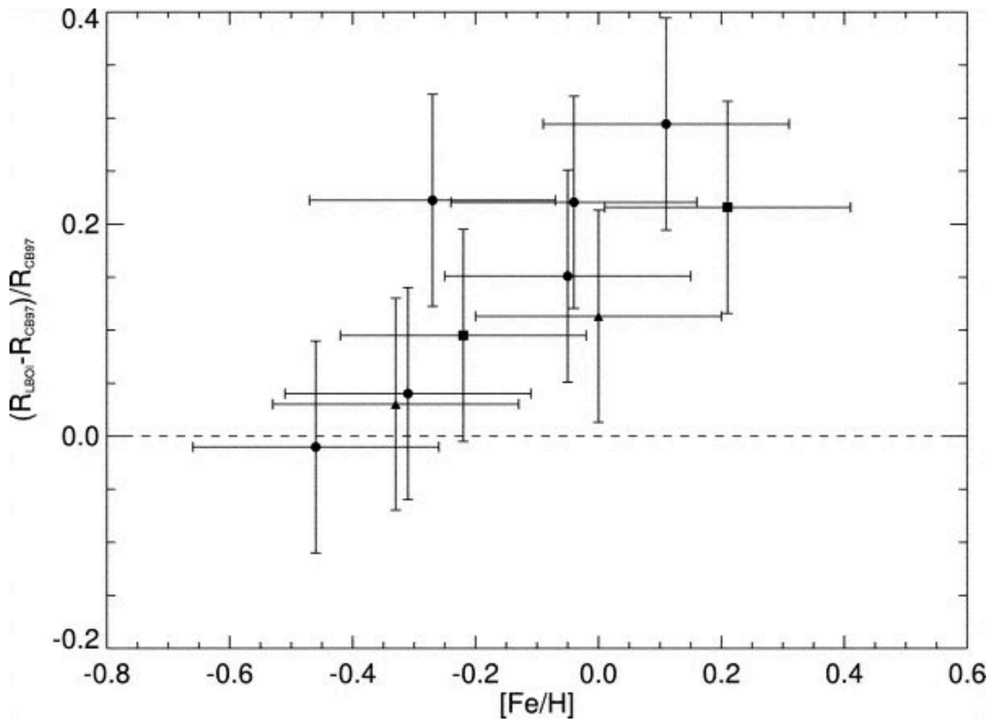
- Angular Diameters: best way to determine stellar T_{eff} using
  - monochromatic flux + model
  - wavelength integrated flux
- Parallax (*Hipparcos*, USNO, etc.) yields radii → luminosity
- Recent measurements better than 1% (cool giants, supergiants, solar type)

Needed: Sub-mas Resolution for Hot Stars and Small Stars (L, T dwarfs)



Work Ahead

- Need high-precision and spectrally dispersed measurements
- Multi-wavelength data to explore opacity effects and check model atmospheres
- Huge potential for hot stars and cool dwarf stars

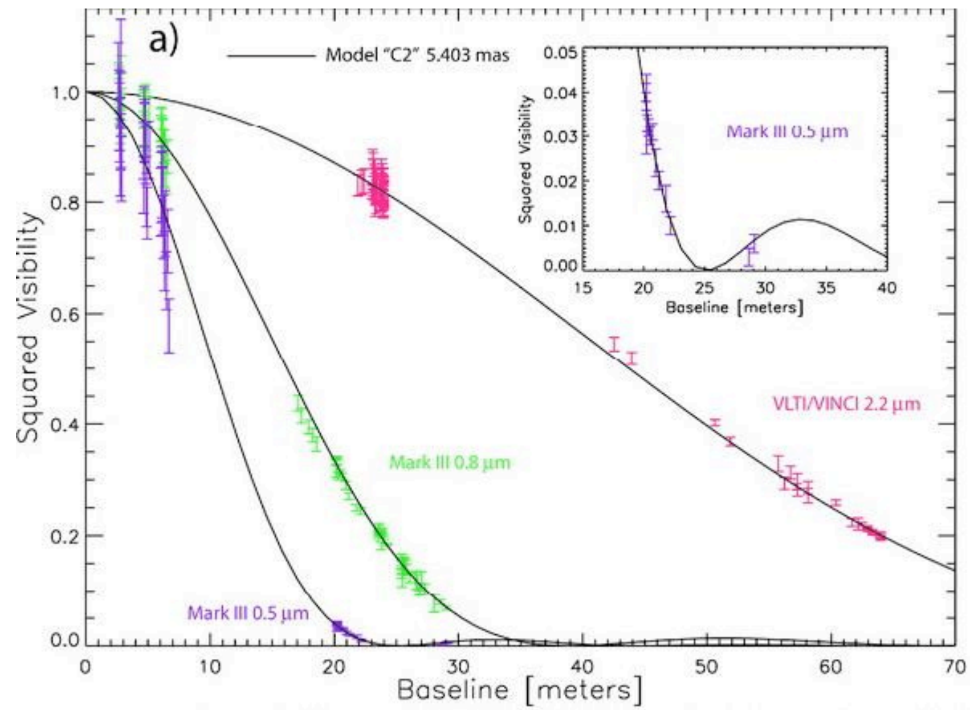


M-dwarfs: Berger et al. 2006, ApJ, 644, 475

Important Complications

- Temperature gradient in outer atmosphere → *limb darkening*
- Granulation, convection, extended atmosphere, …
- 3D radiation hydro.

Procyon (F5 IV)



Aufdenberg et al. 2005, ApJ, 633, 424

Stellar Interiors: Radius

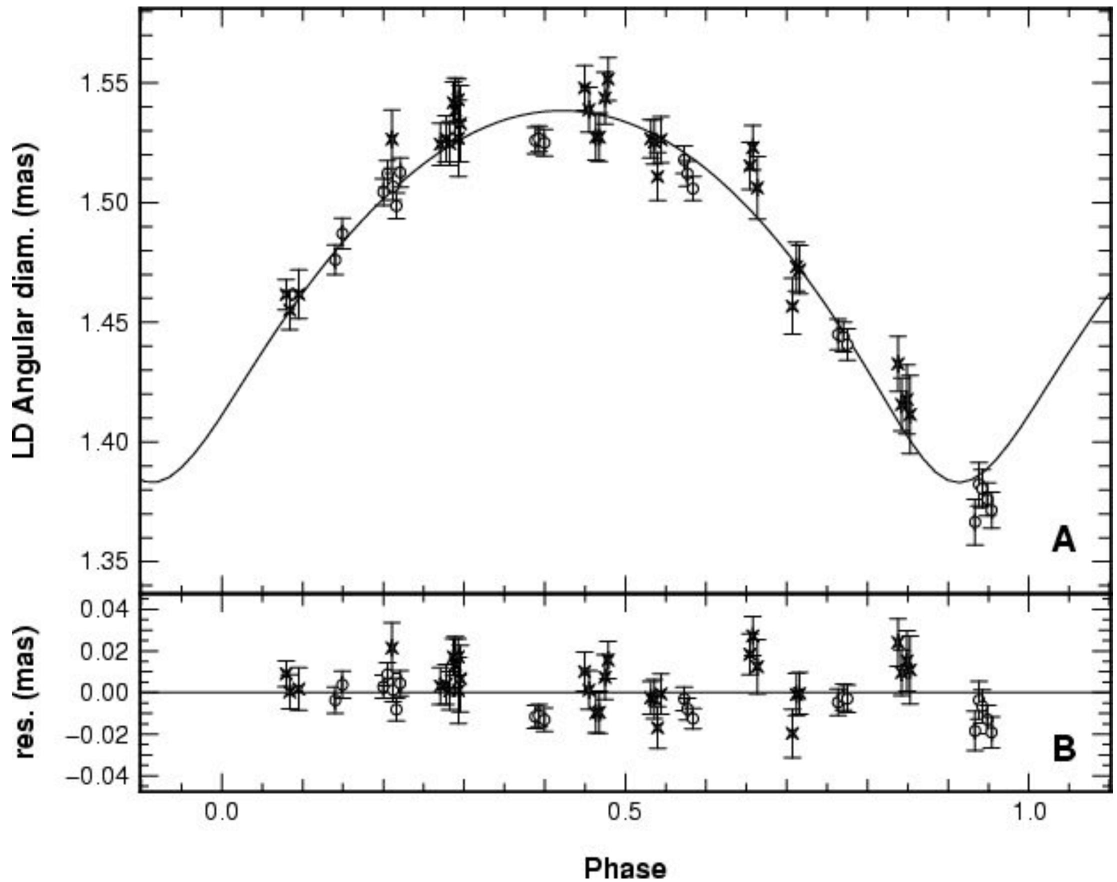
- Microvariability observed from orbit → pulsation periods for asterosiesmology
- Radius, T_{eff} from interferometry (Thévenin et al. 2006,MmSAI, 77, 411) Example: η Boo (van Belle et al. 2006)
- Apsidal motion in binaries: $P/U \sim kR^5$ Example: α Vir (Aufdenberg et al. 2006)

COROT launch scheduled for 22/12/2006

MOST

Stellar Interiors: Radial Pulsation

- **Cepheids:**
  direct measurement of angular diameter variations
- Indirect measurement through photocenter flux change in spectral lines (Mourard & Nardetto 2004)



δ Cep: Mérand et al. 2005, A&A, 438, L9

Stellar Interiors: Radial Pulsation

- **Cepheids:** Calibrate the period - luminosity relation
- Calibrate the surface brightness – color relation

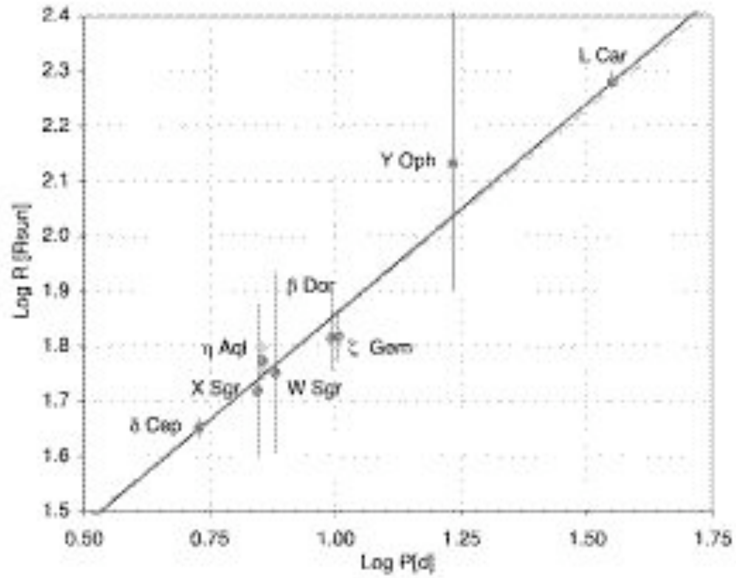
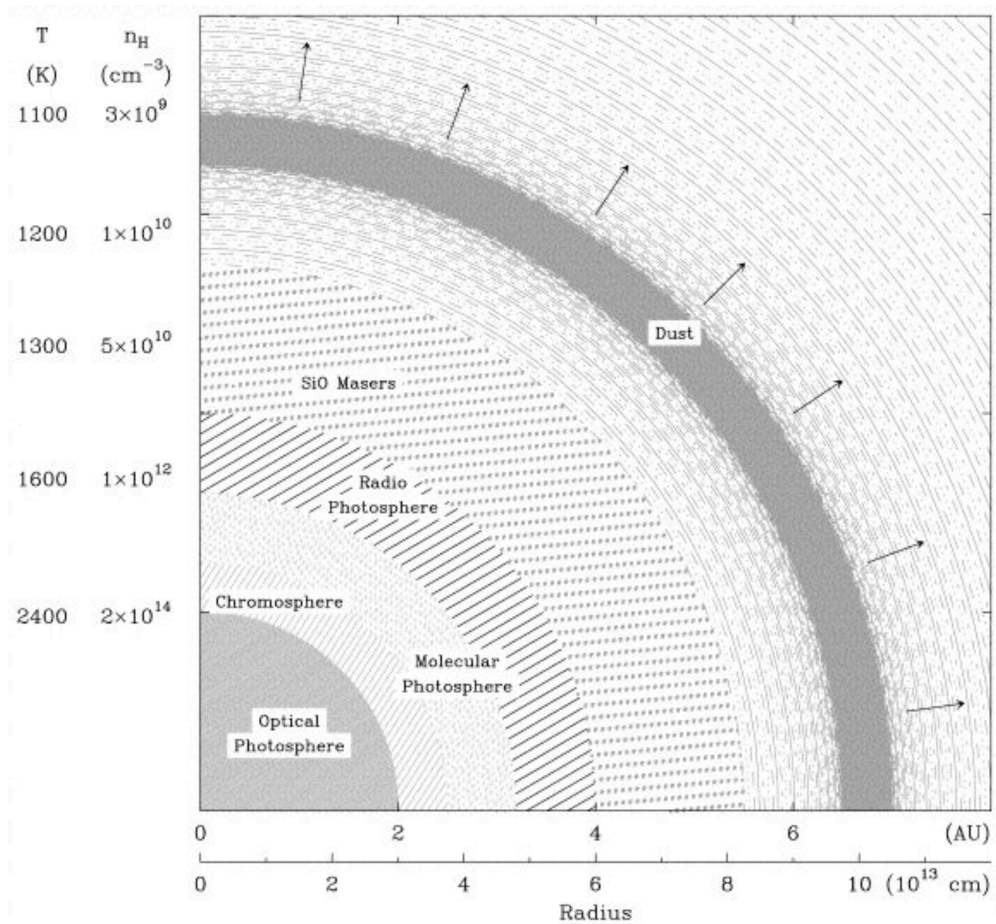


Fig. 2. Period-Radius relation deduced from interferometric measurements of Cepheids. The solid line results from the simultaneous fit of the zero point and slope of the line. The dashed line assumes the slope from GFG98, fitting only the zero point.

Kervella 2006, MmSAI, 77, 227

Stellar Interiors: Radial Pulsation

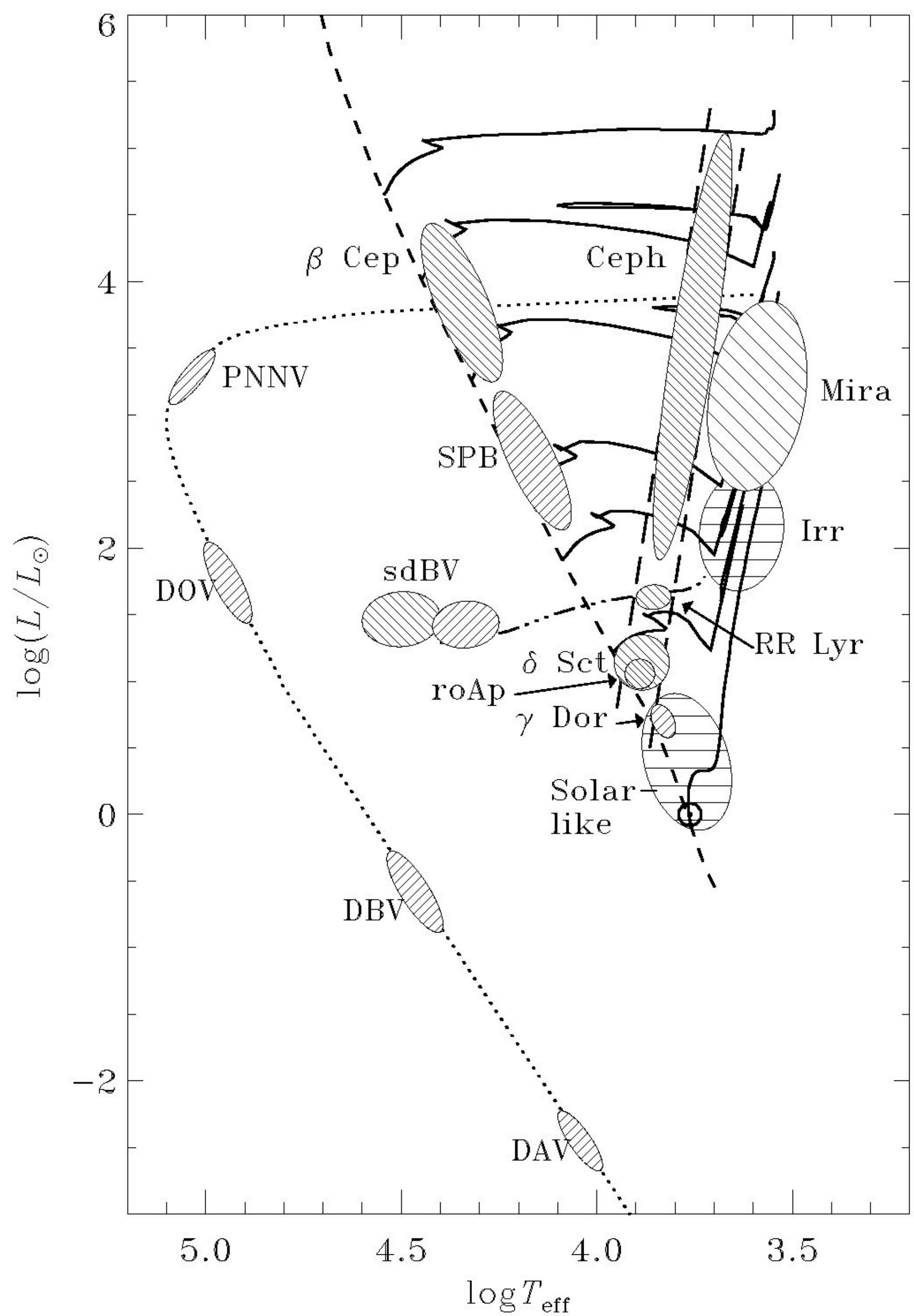
- **Miras:**
  different sizes at different λ for specific layer and opacity
- Fundamental mode pulsators:
  Perrin et al. 2004, A&A, 426, 279
- Temporal/geometric changes with cycle:
  Thompson & Creech-Eakman 2004 (PTI)
- Asymmetric shapes:
  Ragland et al. 2006 (astro-ph/0607156)



Reid & Menten 1997, ApJ, 476, 327

Others

- Many other kinds of pulsators await investigation



Stellar Interiors: Nonradial Pulsation

- Interferometry can potentially provide radius, rotation, oblateness, inclination, and mode identification
- Nonradial modes (low to intermediate order) will display photocenter variations within spectral lines (need to observe many lines)

Stellar Interiors: Nonradial Pulsation

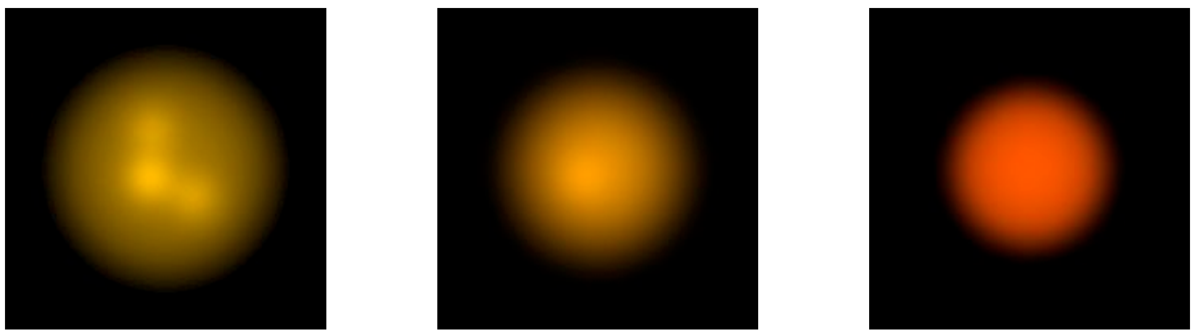
- Requires long term, high resolution observing programs (avoiding daily alias problems); Schmider et al. 2005, Bull.SRS Liege, 74, 115

	Differential Visibilities	Differential Phase	Imaging
	Radius Oblateness	Differential rotation Mode identification Intermediate degree $2 < l < 6$	High degree imaging $2 < l < 100$
Baseline	1-2 km		1-10 km
Telescopes	> 3 (boot-strapping)	3	$> 36 (\approx l)$
Wavelength Resolution Magnitude Precision	 $M_V = 13$ $\sigma_V = 10^{-3} - 10^{-4}$	420-840nm 120000 $M_V = 10$ $\sigma_\varphi = 10^{-5} rd$	 IFTS $M_V = 7$

Stellar Interiors: Convection & Granulation

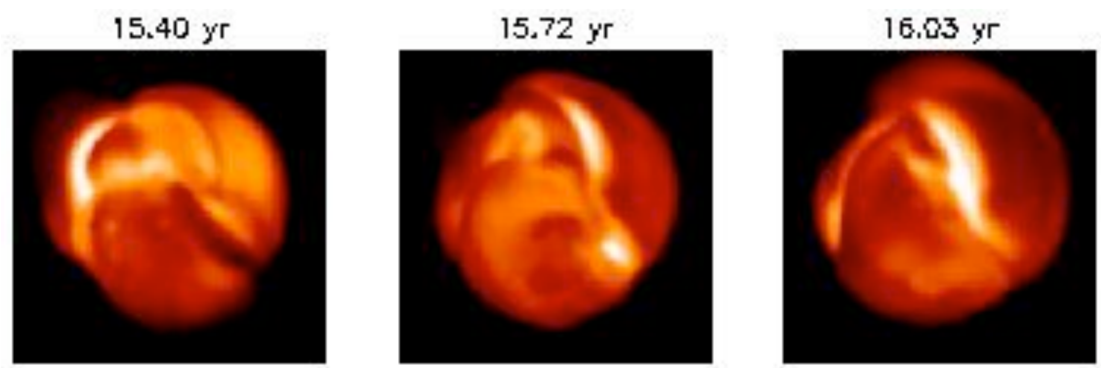
- Spatial scale of granules varies with pressure scale height; large in supergiants like Betelgeuse (Young et al. 2000, MNRAS, 315, 635)

700 nm | 905 nm | 1290 nm



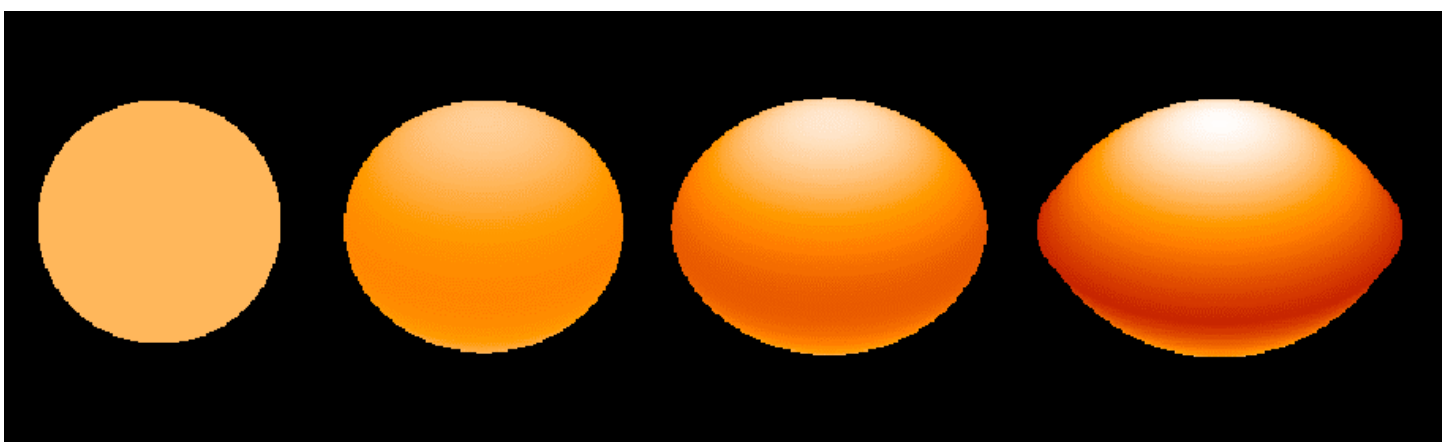
Opacity holes in molecular envelope?

3D hydrodynamical simulation by Freytag (2003)



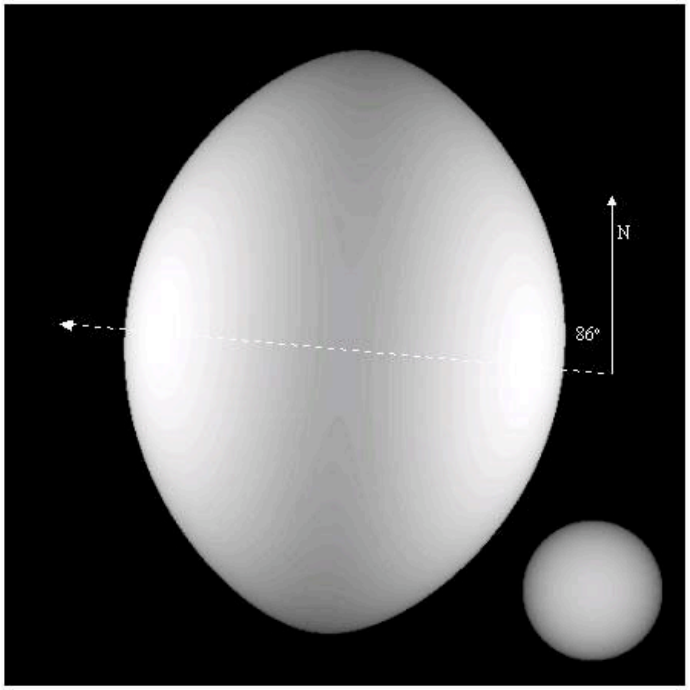
Rotation: Shape & Gravity Darkening

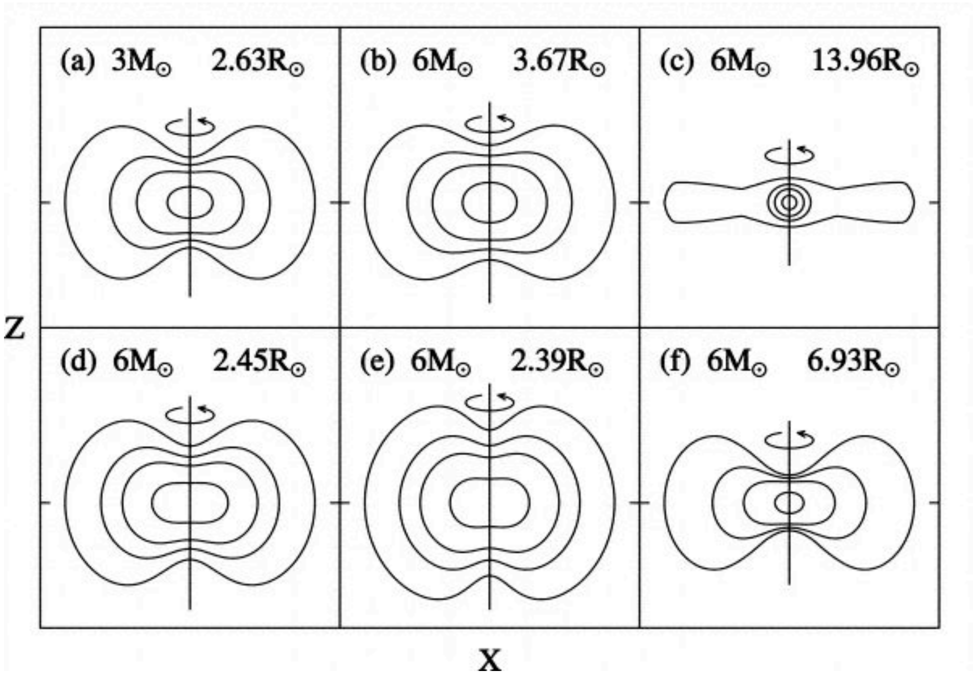
- Rapid rotation found among main sequence A-stars
  - Altair (van Belle et al. 2001)
  - Alderamin (van Belle et al. 2006)
  - Pole-on Vega (Peterson et al. 2006; Aufdenberg et al. 2006)



Rapid Rotation in Hotter Stars

- Regulus (B7 V)
  McAlister et al. (2005)
- Need models to estimate solid angle integrated luminosity





- How close to critical do stars rotate?

Jackson et al. 2005, ApJS,156, 245

Stellar Surfaces

- von der Lühe (1997): resolution prospects much better for large, evolved stars

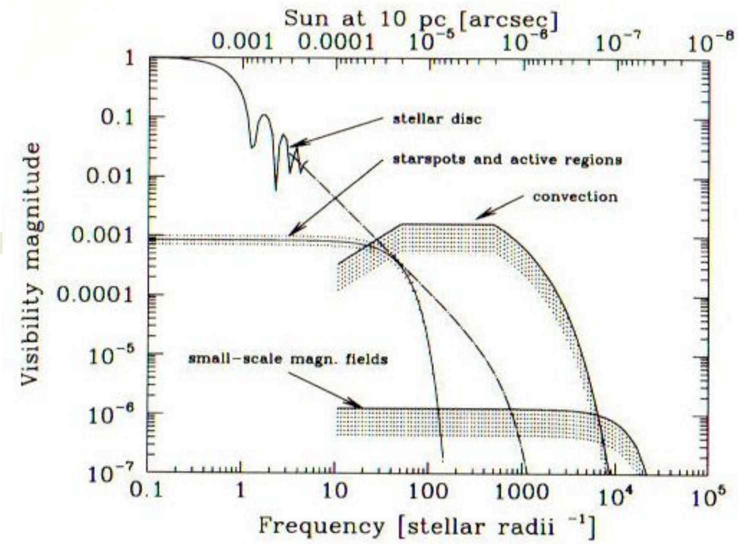


Fig. 3. Visibility magnitude for a solar type star.

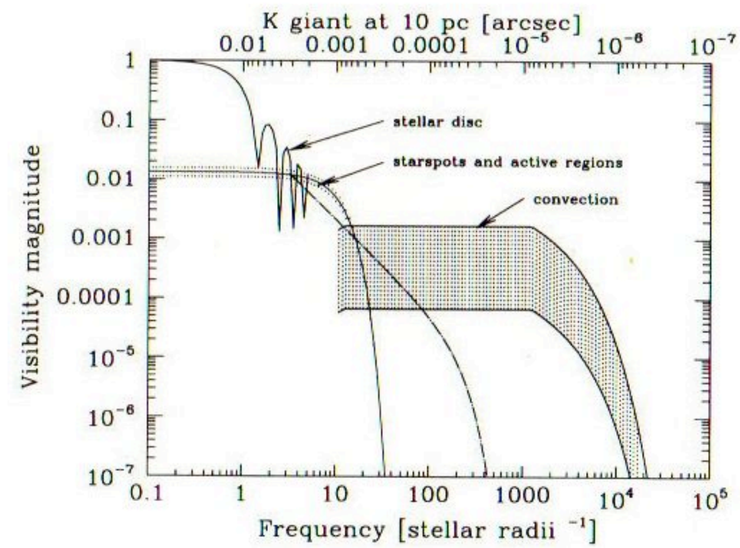


Fig. 4. Visibility magnitude for a giant star.

Magnetic Phenomena

- Spots
- Chromospheres, extended atmospheres
- Activity cycles
- Origin, evolution of stellar dynamos
- BY Dra, FK Com, UV Cet (flare) stars
- RS CVn, W UMa binaries

Magnetic Phenomena

Ideally need near simultaneous, multiwavelength light curves to construct "comprehensive" (as opposed to "ad hoc") models of these objects which combine all regions (photosphere, corona, circumbinary environment)

- radio - modeling size, temperature, and mechanism of quiescent emission
- near-IR through optical - constrain spot sizes and temperatures
- ultraviolet and X-ray - related to radio emission
- visible spectra - tomography to model spot sizes and temperatures
- Narrow band (Ca II K) imaging with interferometry

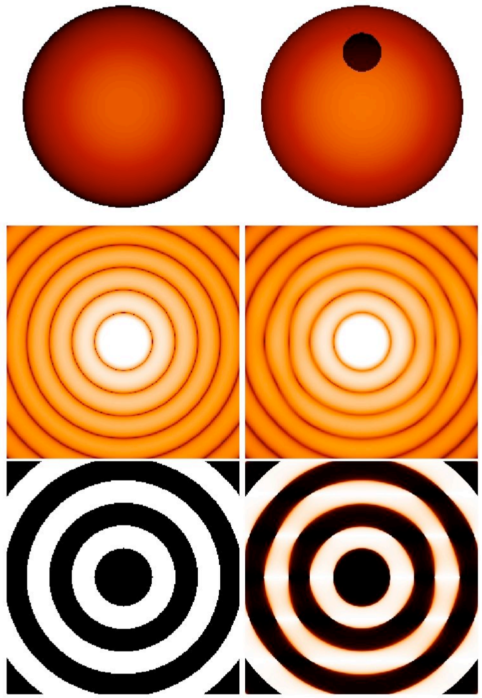


Fig. 1. Illustration of our model star. Shown are the image (top), the visibility amplitude (middle), and the visibility phase (bottom) of our model star (right), compared to the same star without a surface spot (left). Model parameters were used as given in Tab. 2. The $\times$-symbol on the image of the model star denotes the position of the stellar pole. Visibility amplitude values $\in [0, 0.2]$ are shown in logarithmic scale. The spatial frequency range for the visibility amplitudes and phases is $[-2000, 2000]$ cycles/arcsec, corresponding to an angular resolution of up to 0.5 mas, i.e. up to a projected baseline of 400 m at a wavelength of 1 μm. The VLTI with a maximum baseline of ~ 200 m operating at a wavelength of 1 μm can use half of the range shown here. As another example, the NPOI with a maximum baseline of 437 m operating at a wavelength of about 750 nm can use $\sim$ 1.5 times the shown range for bright stars. Horizontal and vertical cuts through the different panels are shown in Fig. 2.

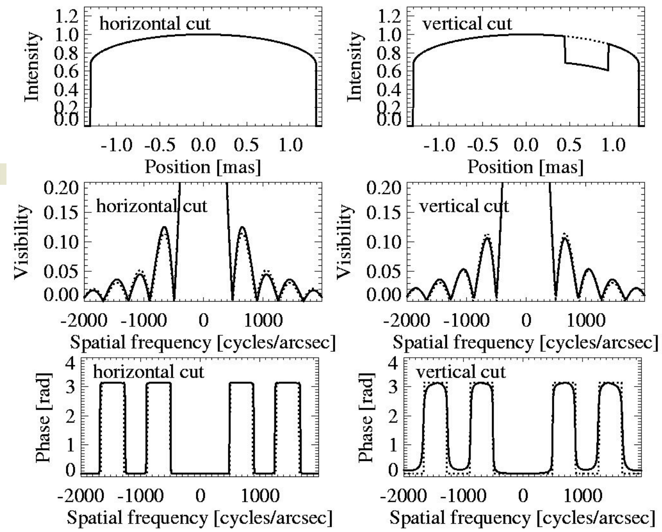


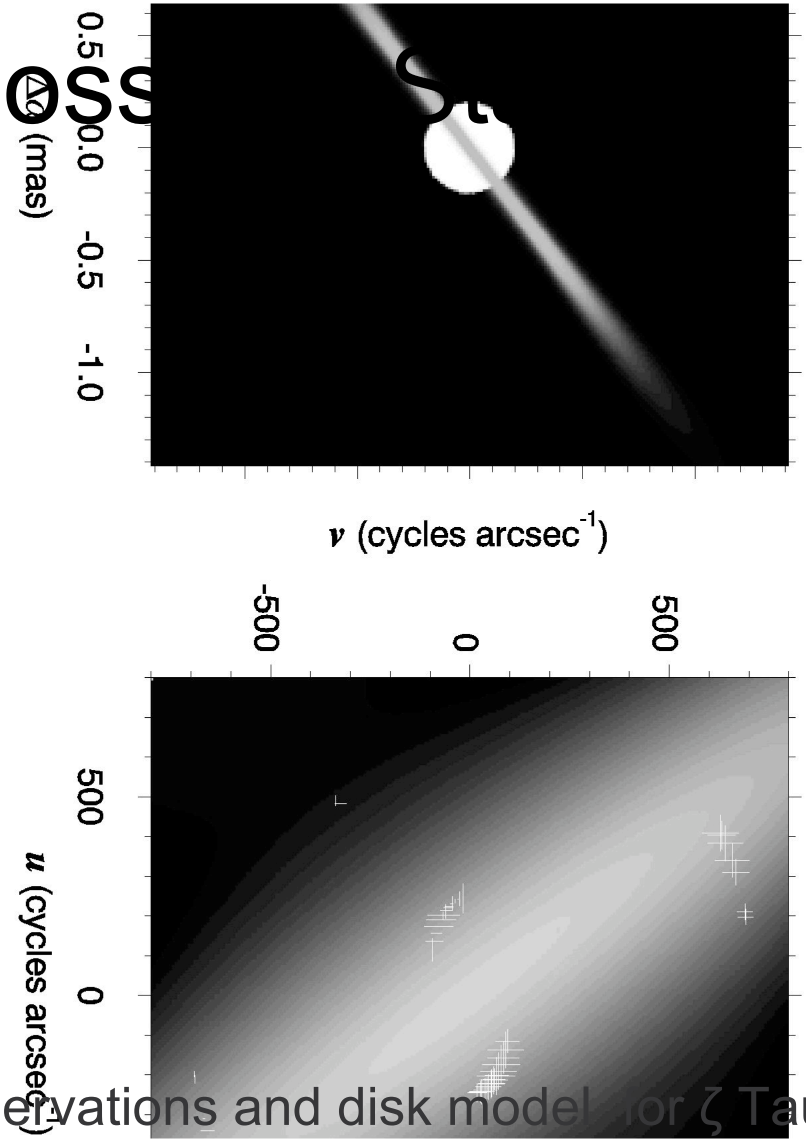
Fig. 2. Horizontal (left) and vertical (right) cuts through the different panels of Fig. 1, i.e. through the model images (top), visibility amplitudes (middle), and visibility phases (bottom). The solid lines denote our used model star, and the dotted lines the same star without a surface spot.

- Wittkowski et al. 2002, AN, 323, 241
- Simulation for active, single giant star
- Need θ_{LD} > 2 mas for VLTI/Amber

Mass Loss: Be Stars

- Be stars are rapid rotators with out-flowing circumstellar disks
- Disks observed in emission lines,
IR continuum excess, polarization
- Ideal environments to study processes near critical rotation: mass loss, disk dynamics, disk growth and dissipation cycles
- Need: imaging, velocity mapping across emission lines, interferometric polarimetry

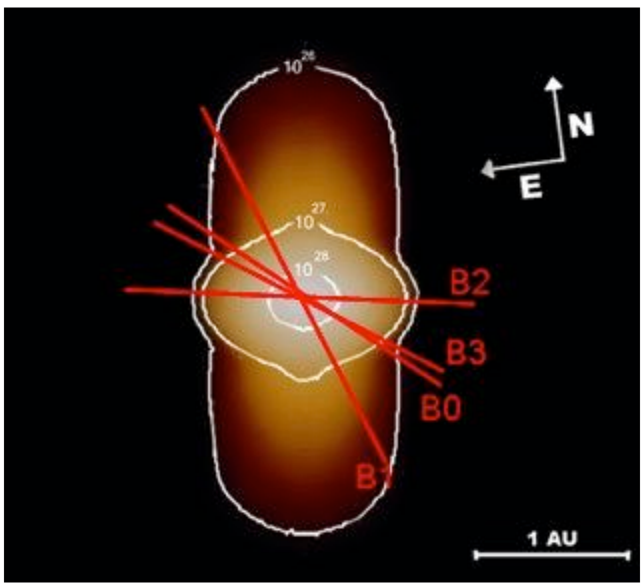
Mass Loss … St

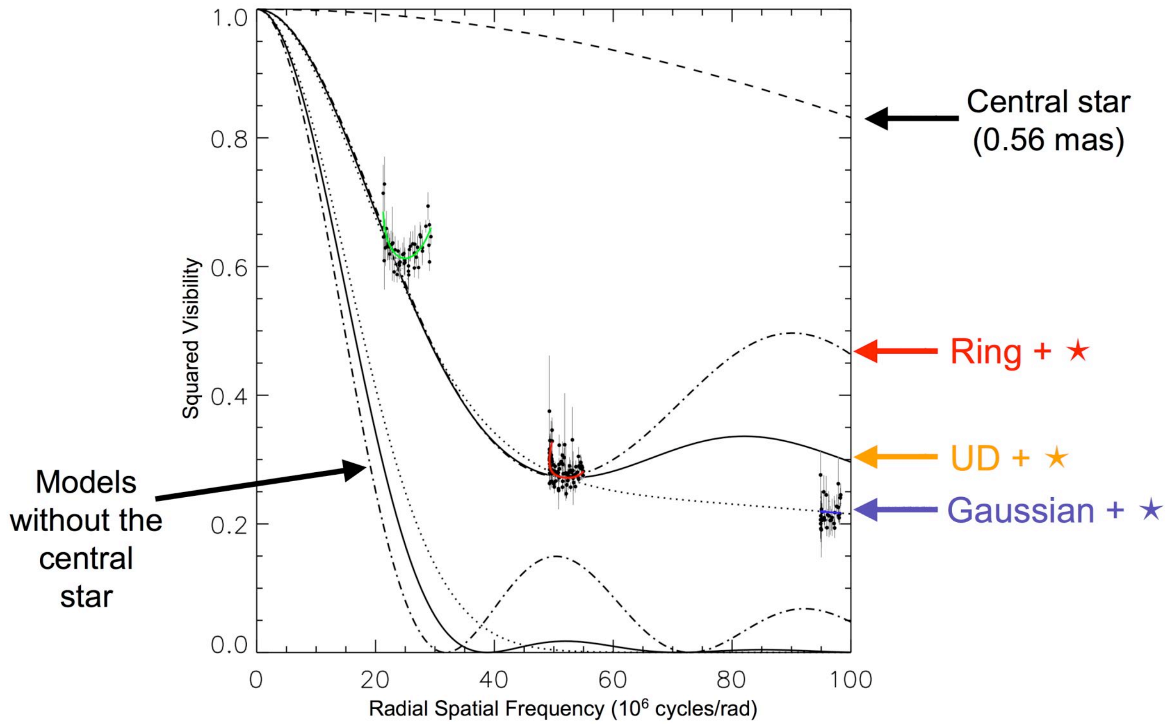


CHARA *K*-band observations and disk model for ζ Tau (Gies et al. 2007)

Mass Loss: Be Stars

K-band model of disk plus wind for α Ara [VLTI/Amber] (Meilland et al. 2006; astro-ph/0606404)

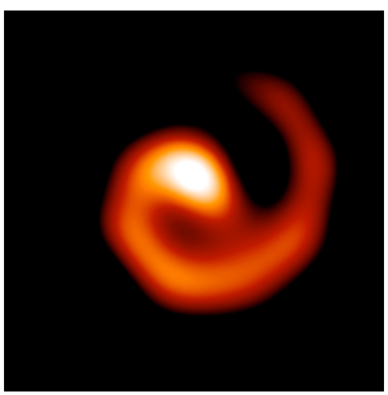


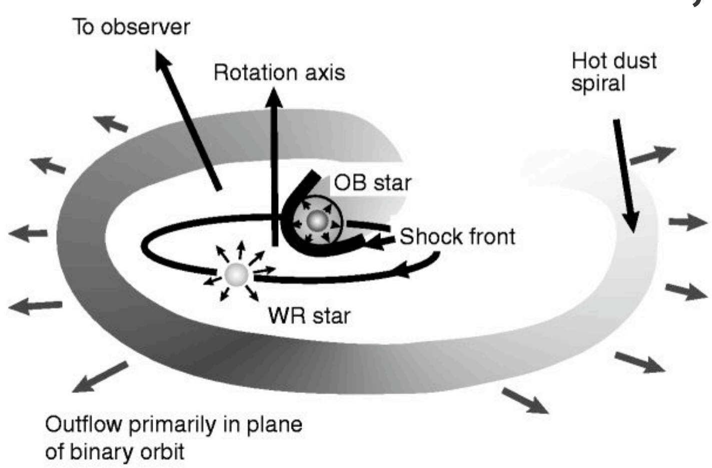


Hα visibility of γ Cas from NPOI (Tycner et al. 2006, AJ, 131, 2710)

Mass Loss: Massive Stars

- Stellar winds of massive stars, especially the most luminous (Luminous Blue Variables: η Car, P Cyg)
- Produce emission lines, IR excess, and, in case of WC binaries, dust emission



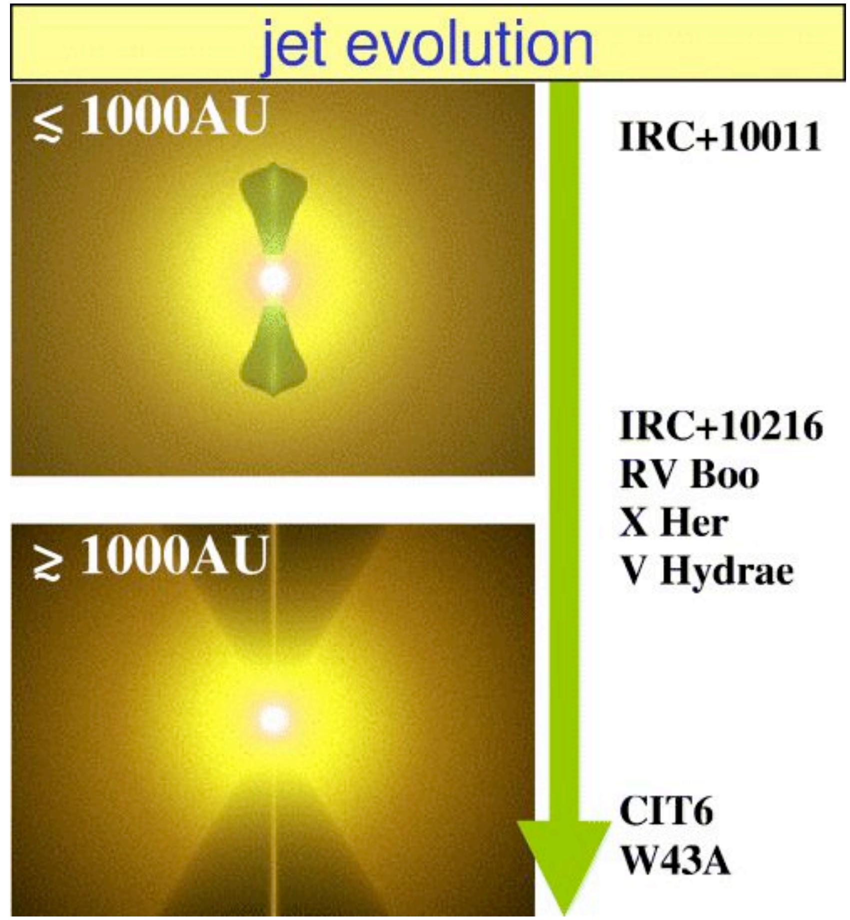


Pinwheel nebula surrounding WR 104, formed in colliding winds of close binary;

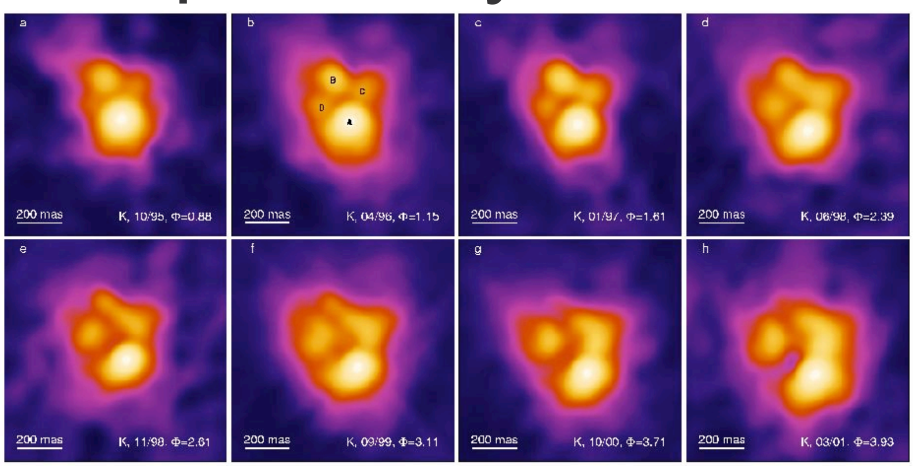
Tuthill et al. 1999, Nature, 398, 487

Mass Loss: Old Stars

- Dust envelopes around cool, evolved stars
- AGB and young planetary nebulae



Vinković et al. 2004, MNRAS, 352, 852



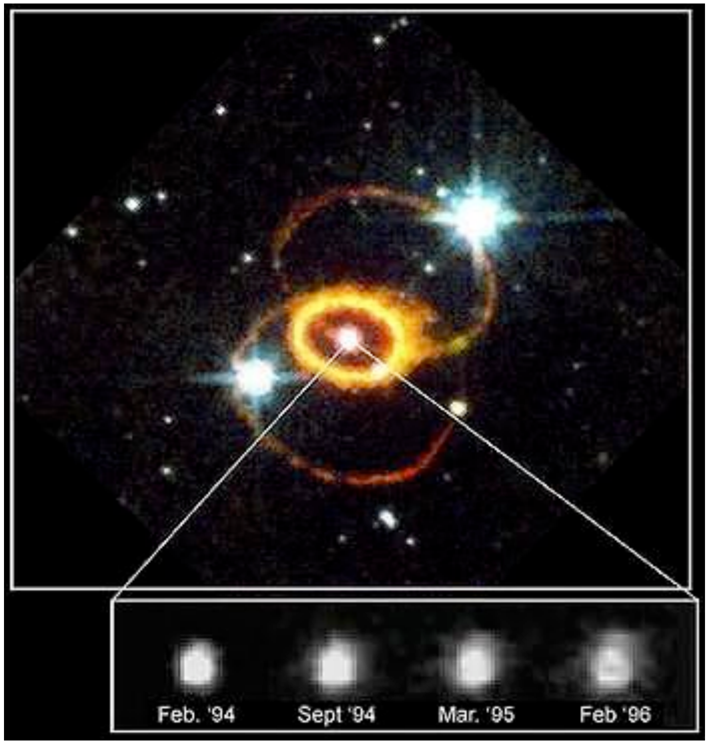
IRC+10216 at 2.2μm, 1995-2001
(Weigelt et al. 2002, A&A, 392,131)

Mass Loss: Novae

- V1663 Aql
  Lane et al. (2006; astro-ph/0606182): followed expansion of expansion of the nova photosphere
- RS Oph
  Monnier et al. (2006; astro-ph/0607399): partially resolved binary or circumstellar disk (constant during outburst)

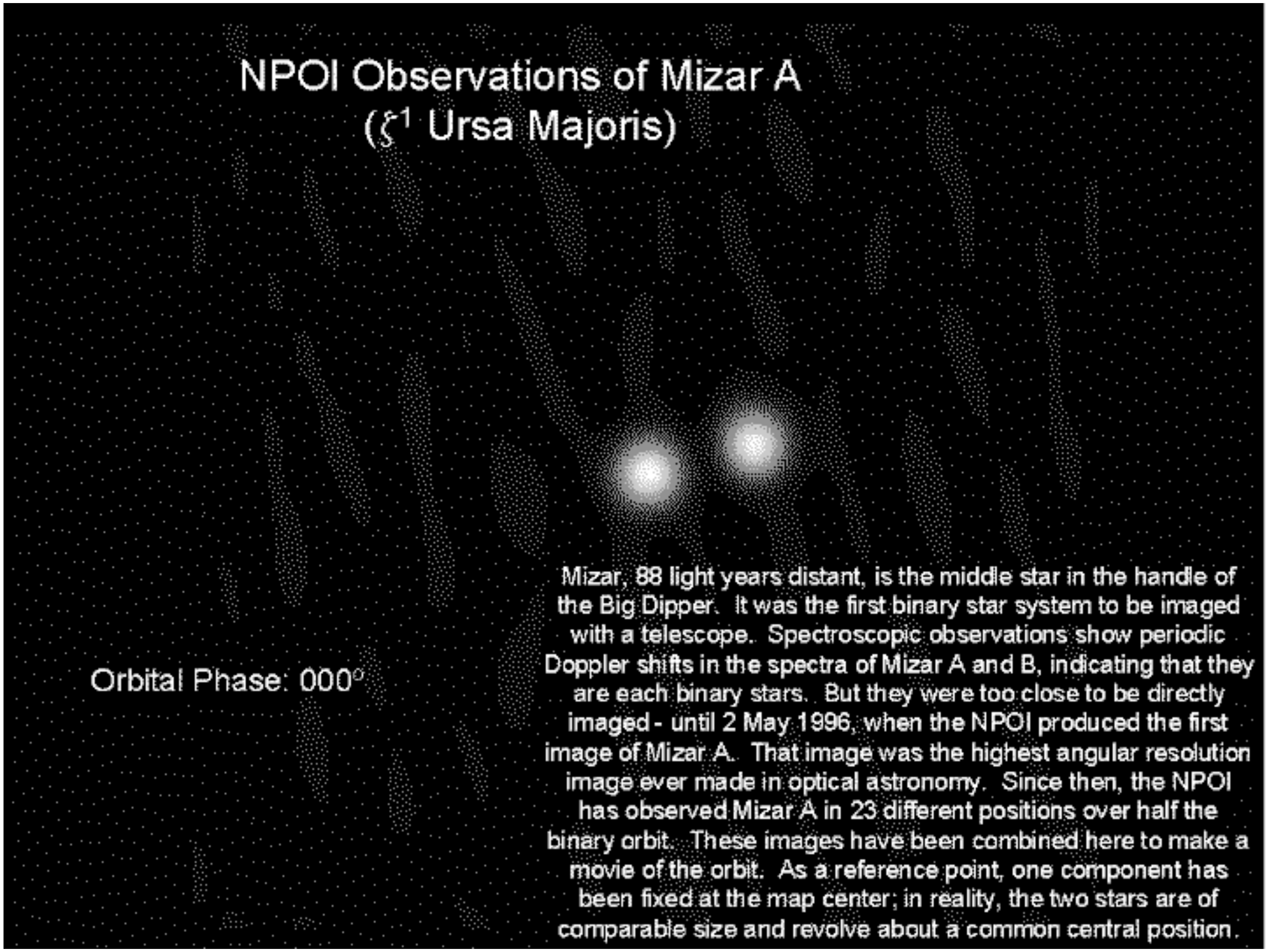
Mass Loss: Supernovae

- SN1987A photosphere grew from 0.7 mas (2 d) to 2.6 mas (100 d) → would have been resolved by VLTI/Amber
- Central clouds at 200 mas resolved by HST after 7 years



Binary Stars

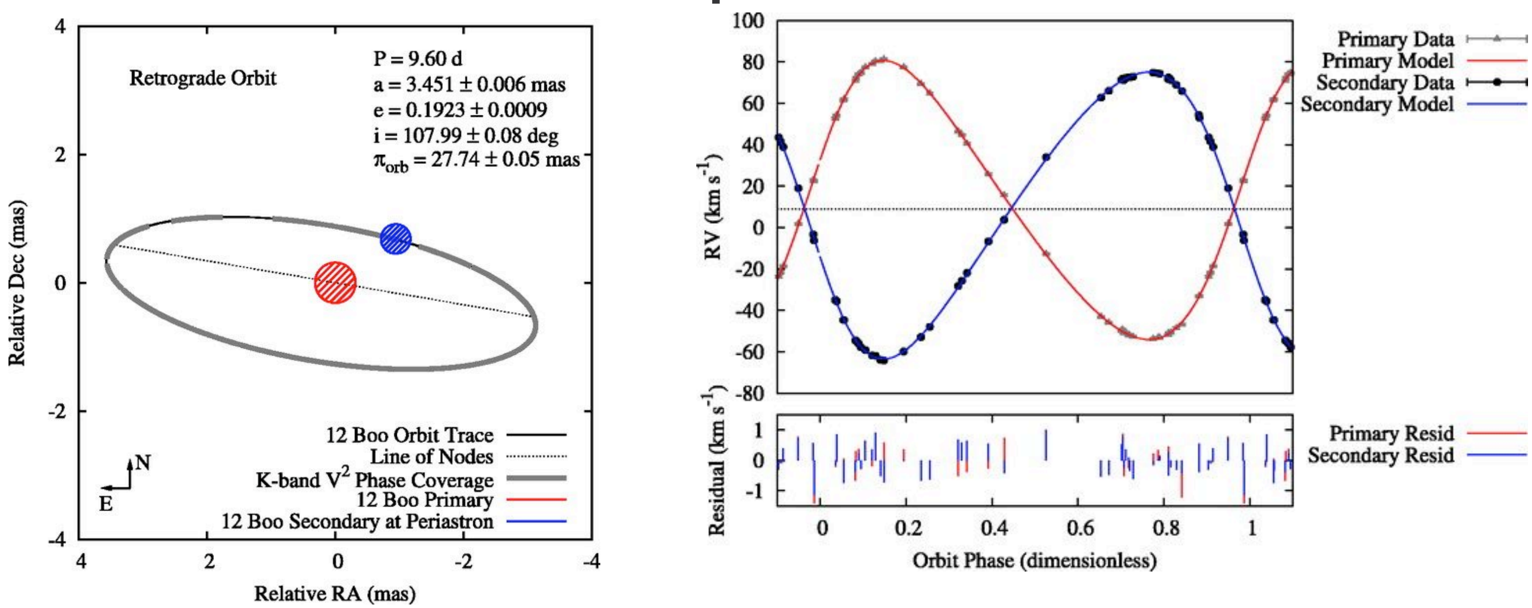
Hummel et al. 1998, AJ, 116, 2536



Binary Stars

- Masses and distances (+spectroscopy)
- Duplicity surveys (e.g. GC clusters)
- Low mass companions

12 Boo (Boden et al. 2005 ApJ, 627, 464)



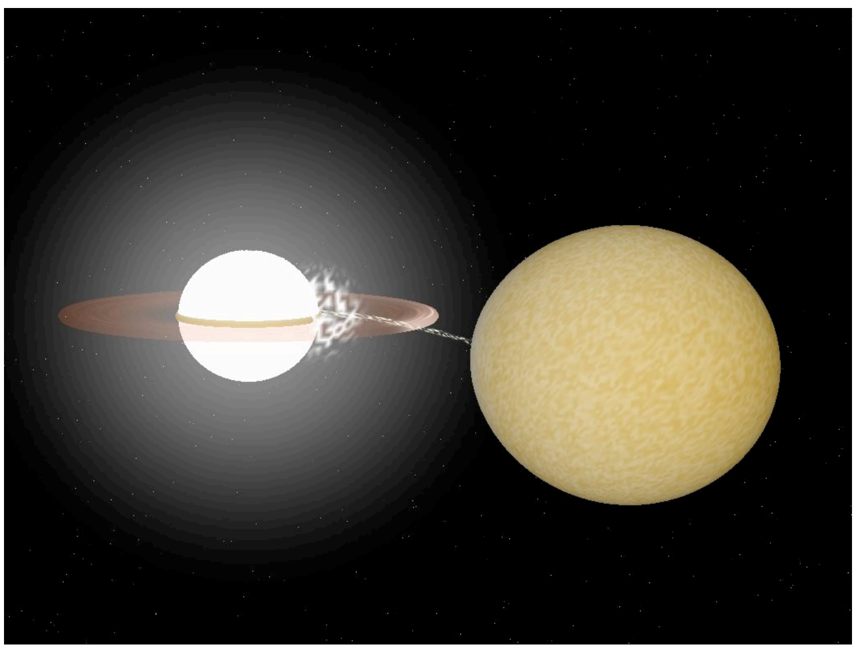
Binary Stars

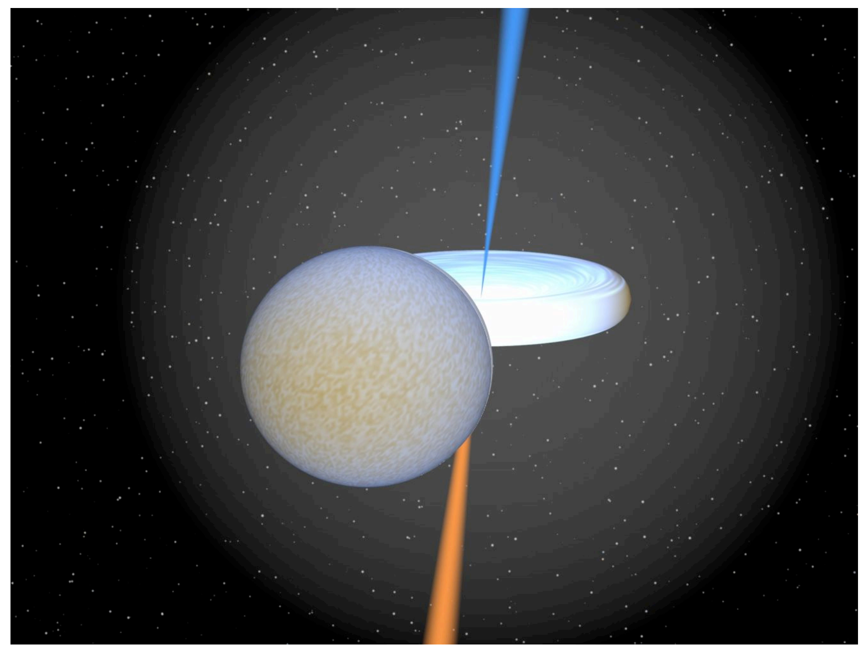
- Interacting: mass transfer by RLOF, wind accretion, or both
- Symbiotics: Mira

Karovska et al. 2005, ApJ, 623, L137

Binary Stars

- Algols, Cataclysmic Variables
- X-ray binaries: disks, jets near neutron stars and black holes



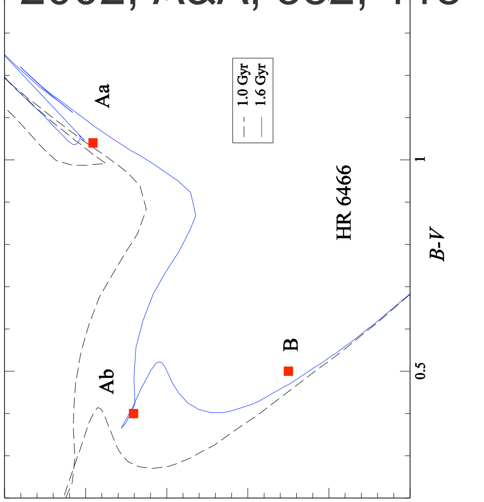


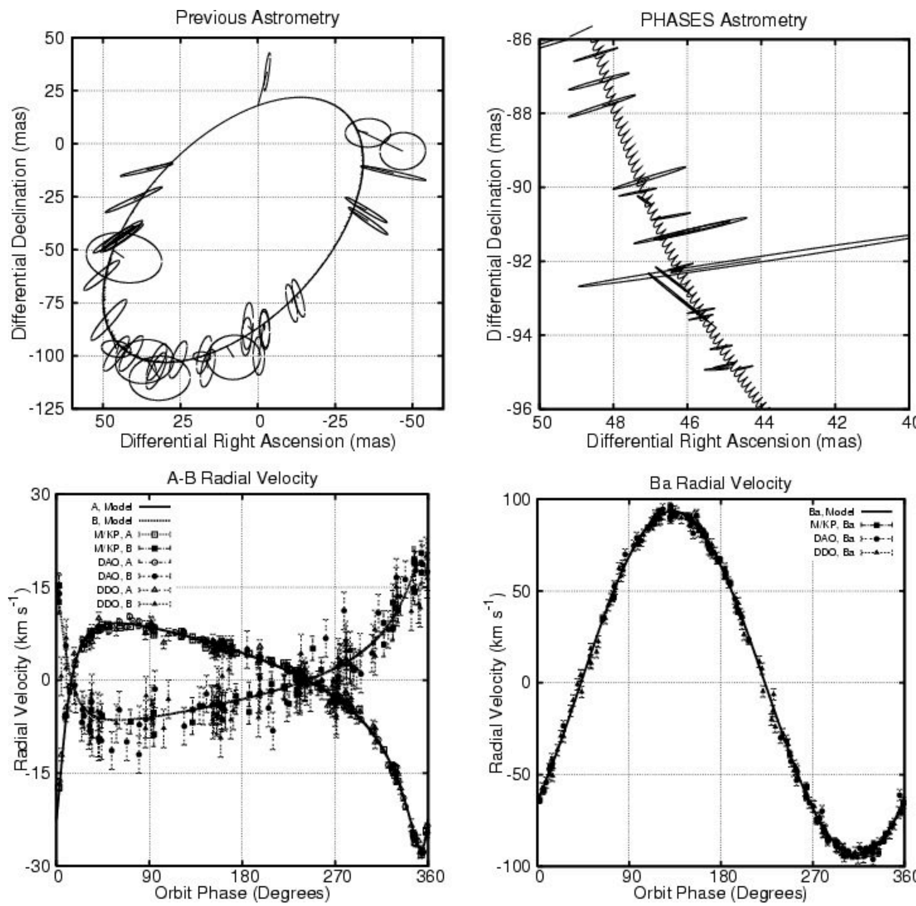
Multiple Stars & Dynamics

- Formation, orientation, evolution of close triples

V819 Her:
Muterspaugh et al.
2006, A&A, 446, 723

Tokovinin & Smekhov
2002, A&A, 382, 118





Technical Requirements

- Baselines: > 1 km
- Number of elements: many (imaging)
- Field of View: small
- Sensitivity: 100x greater
- Dynamic range: large
- Spectral resolution: dispersed, filtered
- Critical time scales: pulsation