So What is Speckle Interferometry Good For, Anyway?

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So What is Speckle…

An older (but not the oldest!), much simpler form of interferometry than you've been hearing about this week!

This talk will include:

- brief overview of speckle history and theory
- types of science well-suited to speckle

a bit of background…

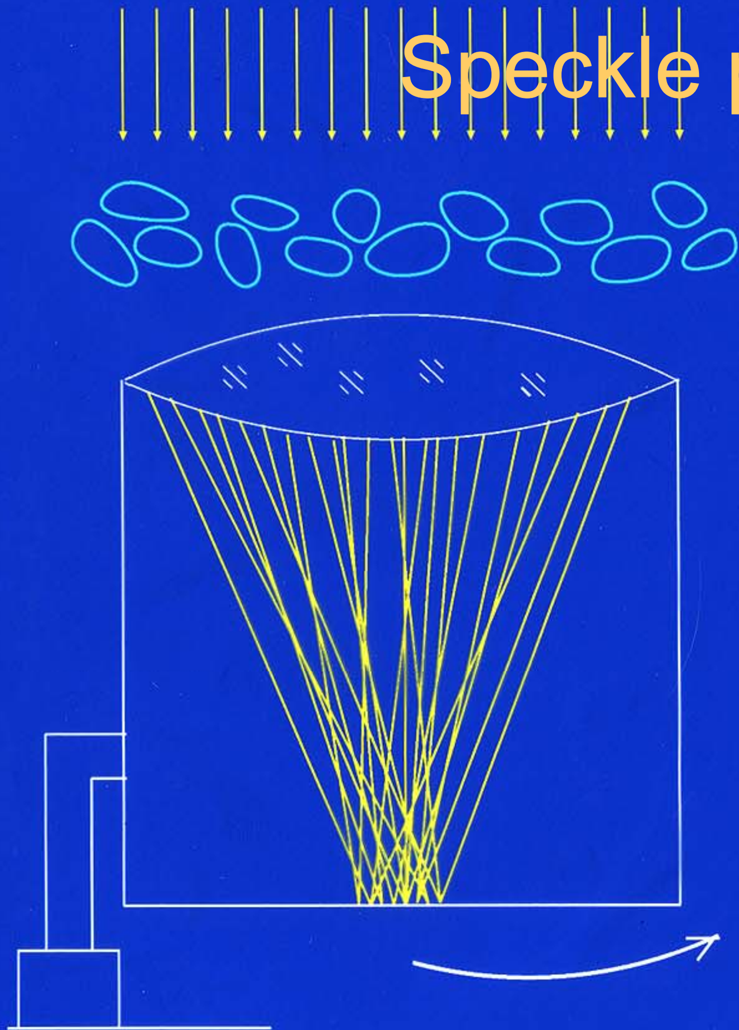
- Earliest interferometry of binaries – Schwartzschild (1895)
- Speckle technique proposed by Labeyrie (1969), first applied 1970 (binaries and stellar diameters)
- 1970’s: photographic speckle programs by French, British, Soviets, Germans, U.S. (esp. McAlister et al.)
- 1980’s: CCDs and other visible/IR detectors → better sensitivity → McCarthy, Leinert, Ghez, Karovska, etc.
- 1990’s: Isobe, Scardia, Horch, USNO
- 2000’s: Docobo; even within grasp of serious amateurs!

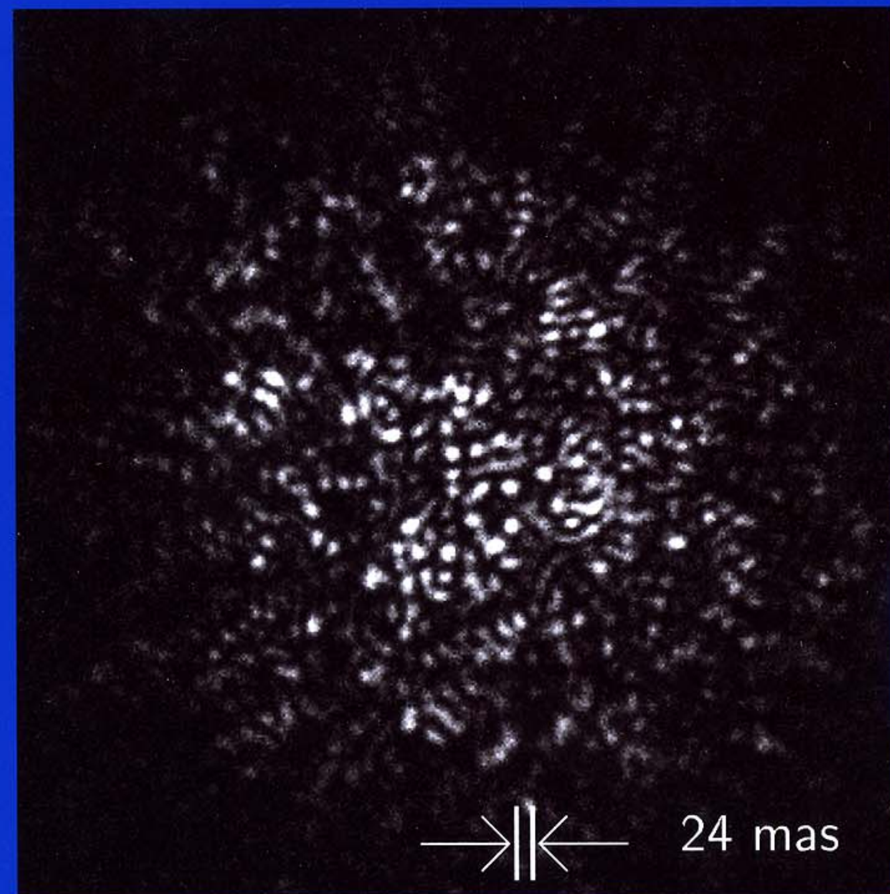
Handwaving speckle theory

- Theoretically, resolution set by wavelength and aperture
- Actually limited by atmosphere to size of turbulent cells (r_0 ~10 – 20cm). Cells move due to wind, change size
- Telescope of aperture *D* sees $(D/r_0)^2$ cells
- Interference of light through cells with same tilt and group delay → "speckle" pattern

(moving cells → "twinkling")

Speckle pattern formation





atmosphere
telescope
speckle interferogram

speckle interferogram
6 m telescope, Gamma Ori, λ=550 nm
field of view 1.84 arcsec

More handwaving…

- Isoplanicity = stars close enough (few arcseconds) for light from both to pass through same coherence cells
- Short exposures needed to "freeze" atmosphere
- Each isolated set of speckle pairs is diffraction-limited image - take multiple exposures and add images

If $I(\alpha,\beta)$ = image intensity distribution

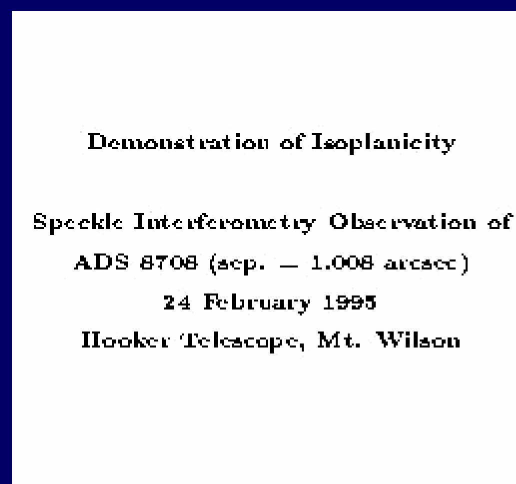
$O(\alpha,\beta)$ = object intensity distribution

$|p(\alpha,\beta)|^2$ = point spread function

$$I(\alpha,\beta) = O(\alpha,\beta) * |p(\alpha,\beta)|^2$$

Mpeg of Speckle data

- STT 256 (discovered by Otto Struve, 1843)
  - sep = 1.008 arcsecs
  - V_A = 7.3
  - V_B = 7.6



More handwaving…

Fourier transform of this intensity →

$$I(x,y) = o(x,y) \ . \ \boldsymbol{A}[P(x,y)]$$

and

$$|I(x,y)|^2 = |o(x,y)|^2 \ . \ |\boldsymbol{A}[P(x,y)]|^2$$

where ***A*** is autocorrelation function

Dividing FT of speckle images by FT of single star is essence of speckle interferometry.

Simple alternative to full power spectrum analysis is

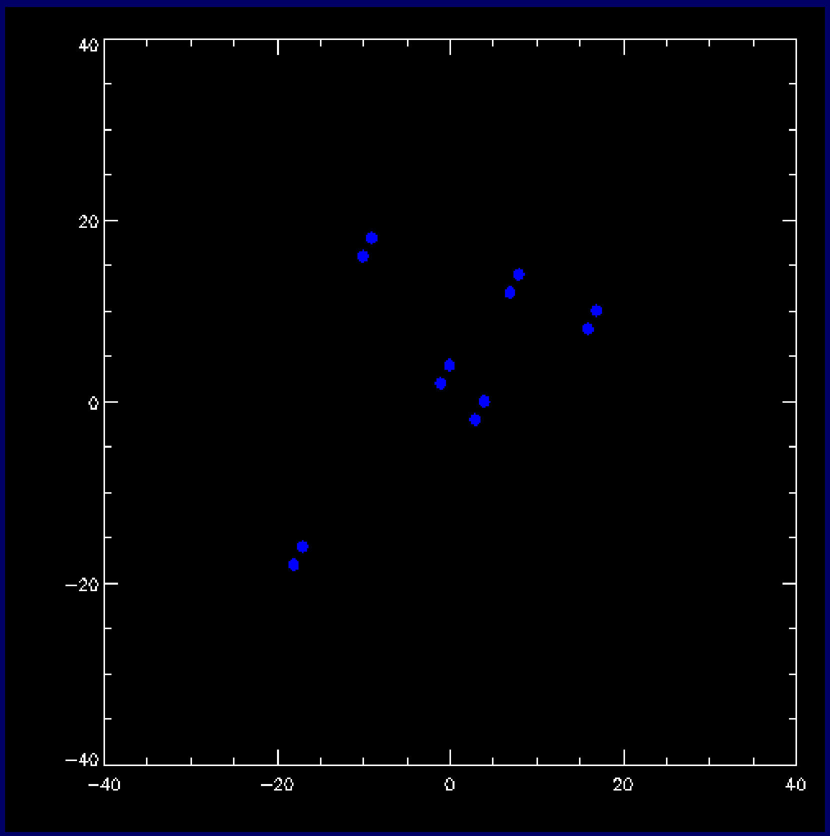
vector autocorrelation

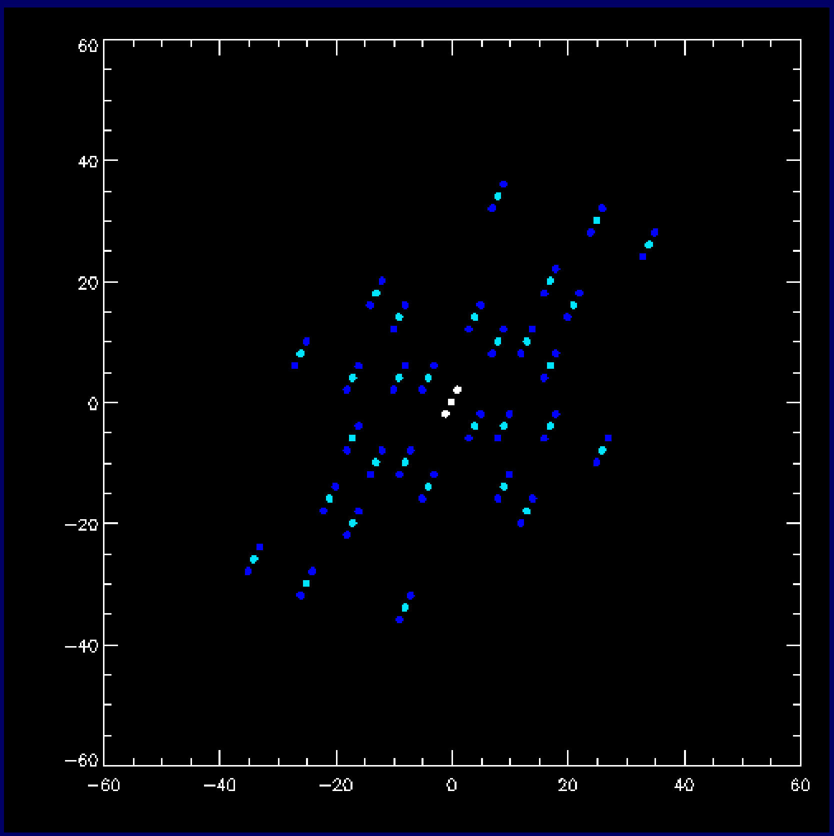
Reducing speckle data

- Triple correlation, etc.
  - Computer- and time-intensive,
    ill-suited to surveys
- Autocorrelation methods
  - straightforward, rapid, high data throughput
  - well-characterized errors, *but*
  - less sensitive to large Δm
  - no full image reconstruction
  - only coarse differential photometry

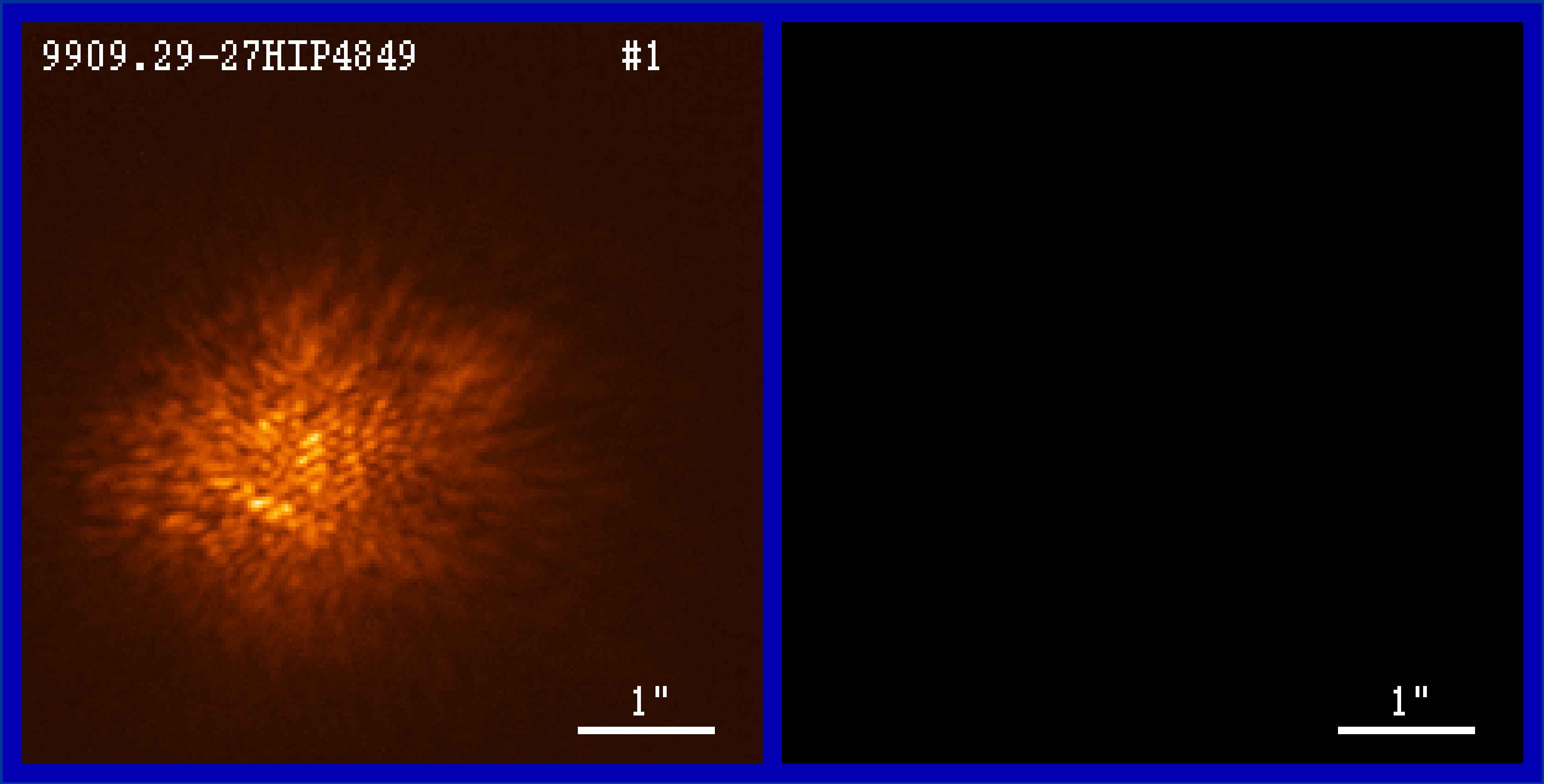
Simple Autocorrelation

speckle frame → autocorrelation





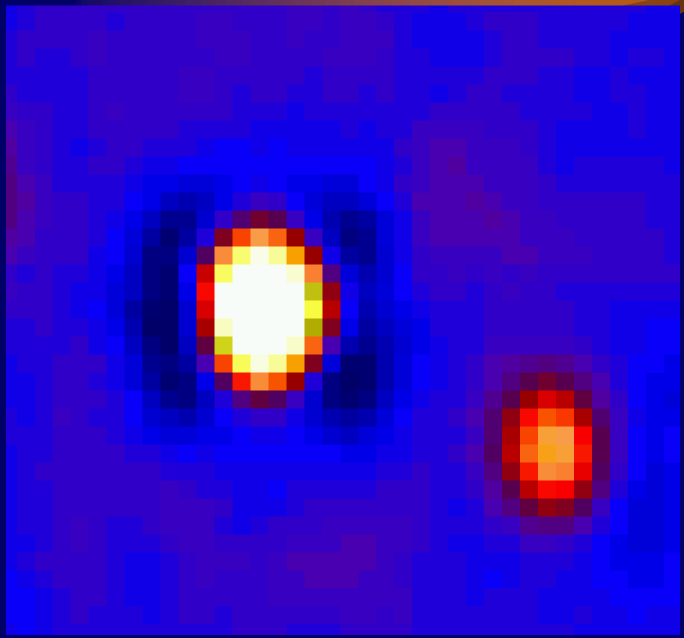
Real Time Bispectrum Speckle Interferometry

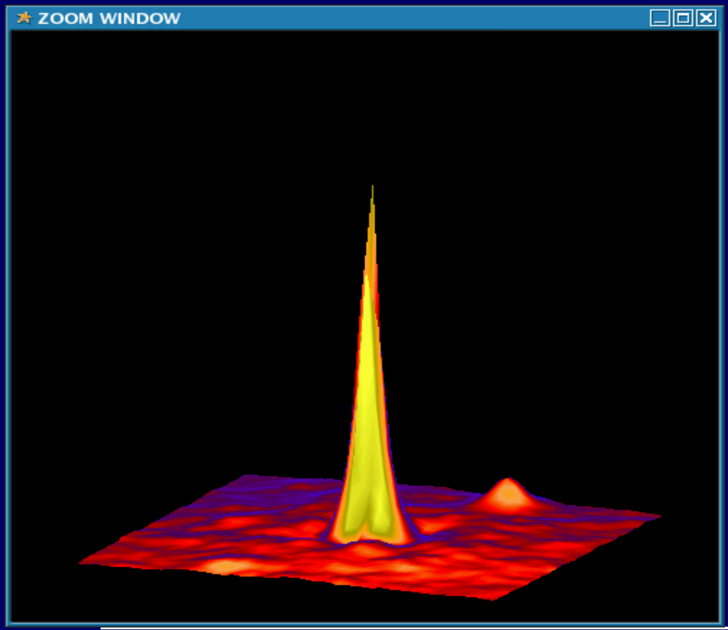


Data recording and data processing: ~ 2 frames/s, SAO 6 m telescope, 2 arcsec K-band seeing, 76 mas resolution (G.Weigelt et al. 2005)

Speckle Binary Examples

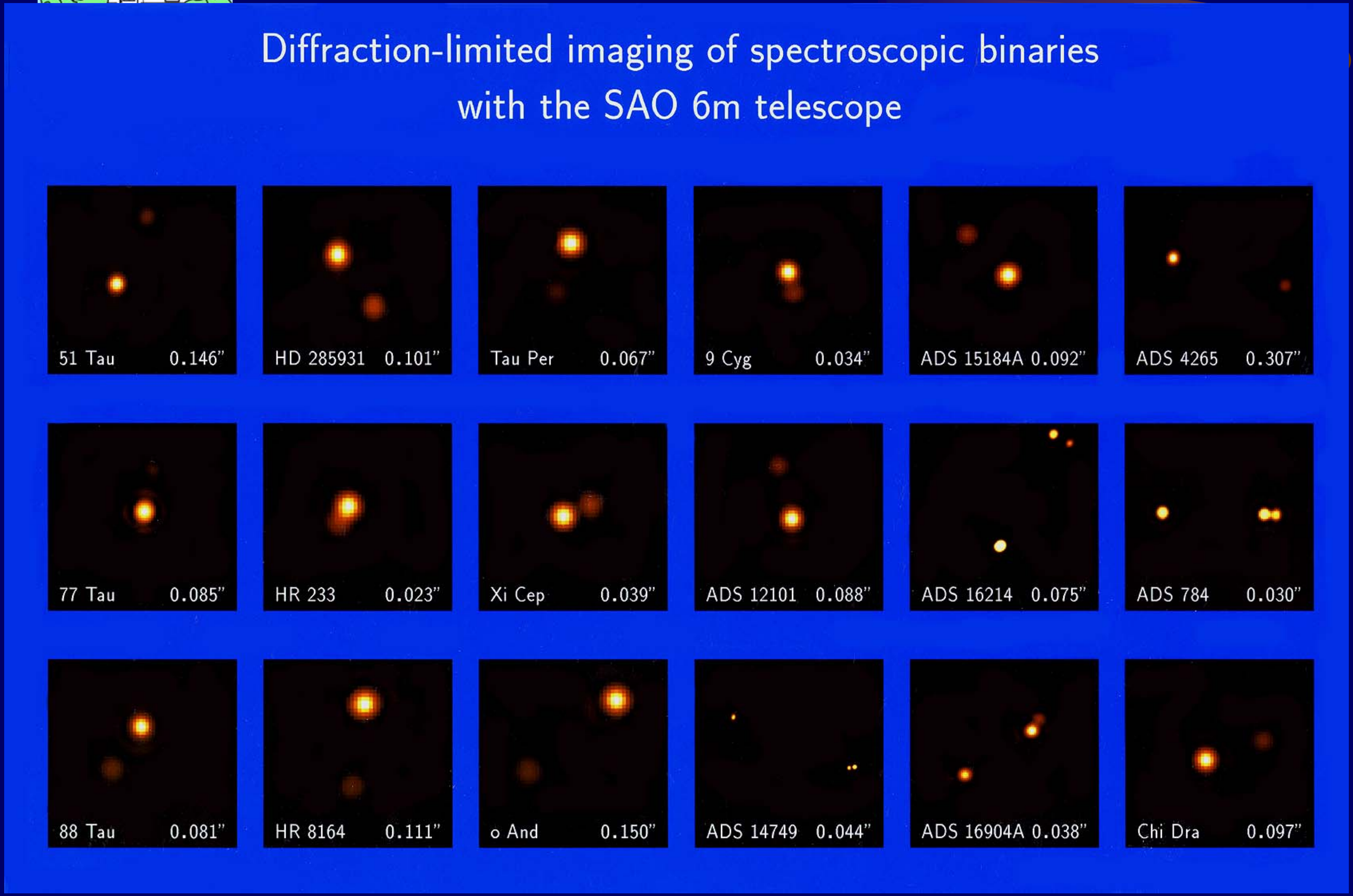
γ Per, Observed Jan 2001
with KPNO 4m,
P = 14.6y, ρ = 0.23"





NEW!!! WSI 28 =
HIP 40001, ρ = 0.27"

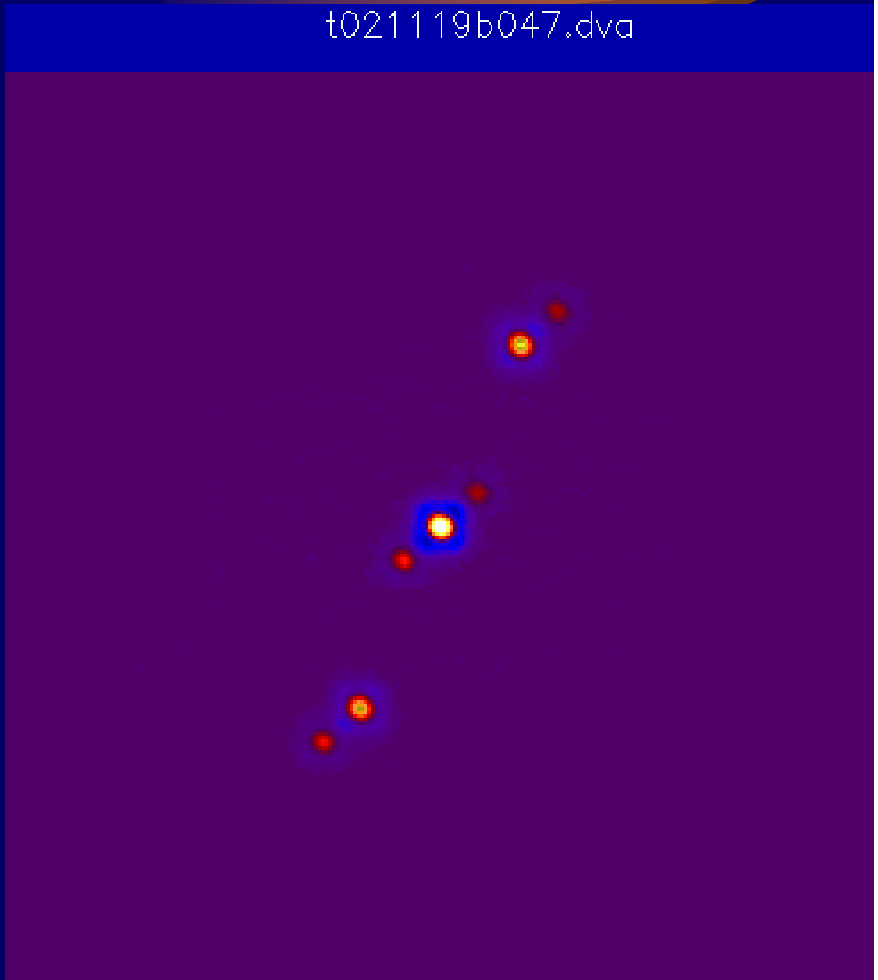
Reconstructed images of multiple stars



Triple

- STF 484GH & GI
- Discovered by F.G.W. Struve
- Pulkova Observatory, 1830
  - Sep = 5.6 & 22.5 arcsecs
  - V_G = 10.0
  - V_H = 10.5
  - V_I = 10.0

This observation obtained 11/18/02 with USNO speckle camera and 26” telescope



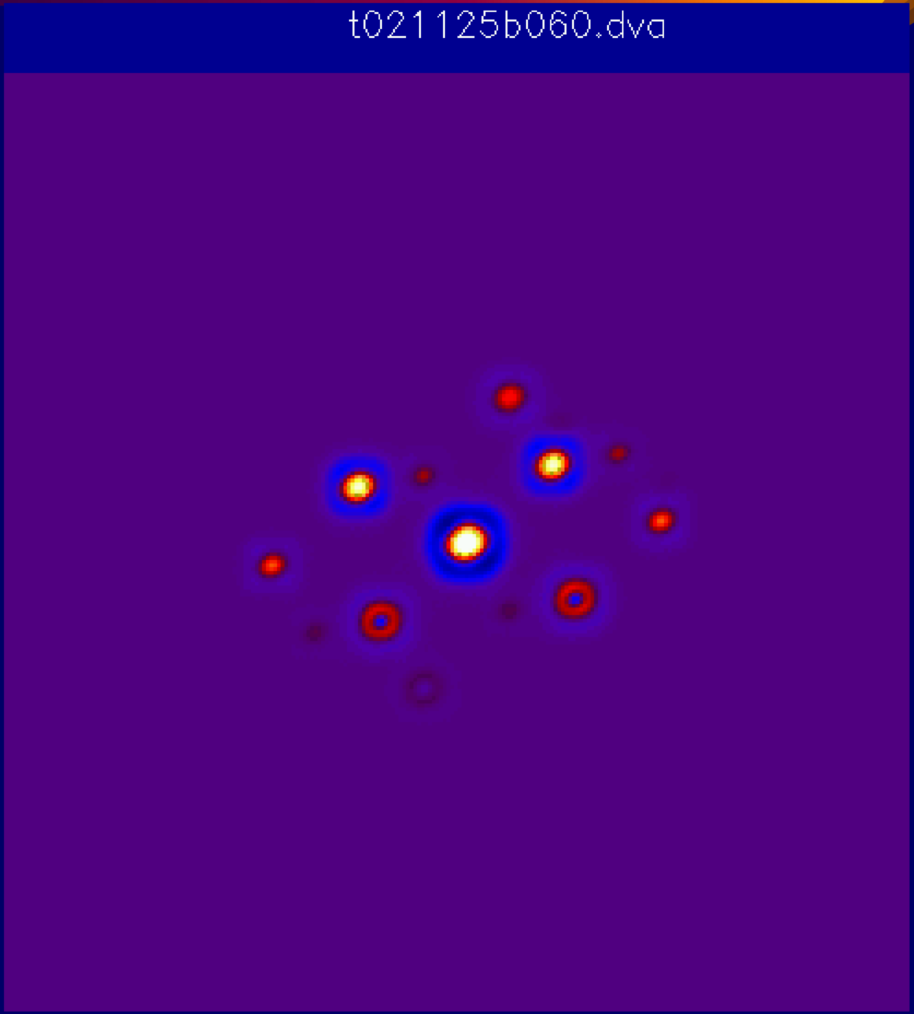
Quadruple

- **The Trapezium**

(actually <u>five</u> components visible)

separations from five
To twenty-one arcsecs

Visible magnitudes
from 5 to 11th



Still more…

Resolution limit defined by Rayleigh criterion (= 1.22 λ/D)

- → 30 mas for 4-meter telescope in *V*
- IR more forgiving in coherence length and time (but Rayleigh limit for 10-meter telescope in *K* much larger than 4-meter in *V*!)

Only 30 mas? Why bother?

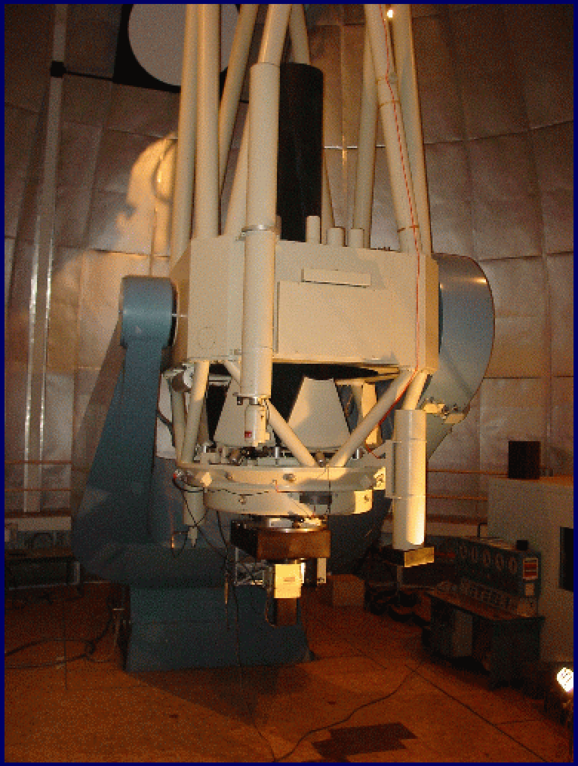
Speckle – the disadvantages

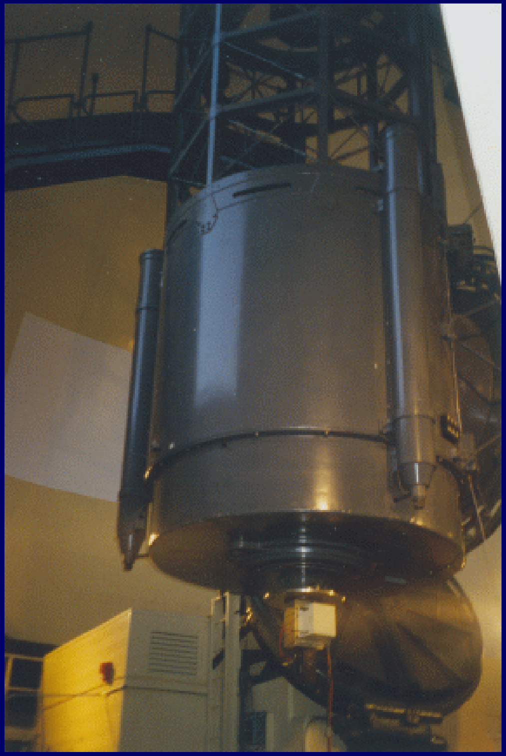
- **Resolution limit**: no single aperture technique can compete with multiple-aperture instruments!
- **Object complexity**: need simple structures (pairs of point sources) No nebulae, galaxies, planetary surfaces
- **Magnitude limits**: Δm limited to 3 or 4 at best. Magnitude limit bright compared to CCD imaging, etc. (to 12 or 13 in DC, sometimes a bit fainter)
- **Precise differential photometry**: difficult

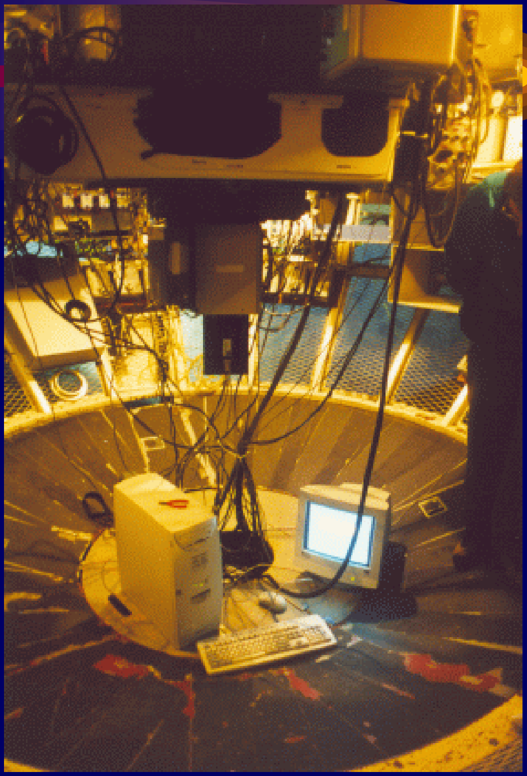
Speckle – the advantages

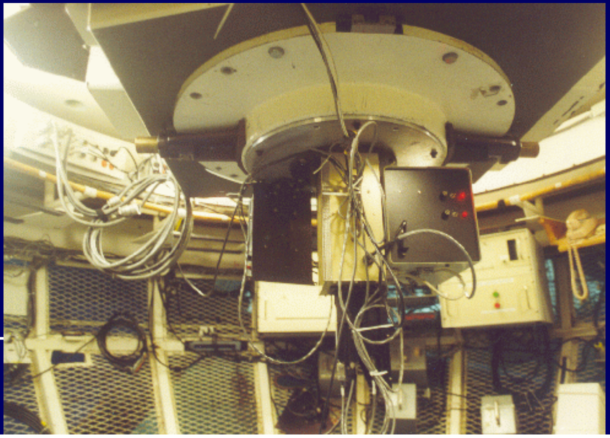
- **It's cheap!** 2 or 3 orders of magnitude less than array. "Poor man's AO" justifiable on small telescope, bright site
- **It's transportable!** Observe both hemispheres
- **It's easy!** 1 or 2 person operation to install and operate. Data reduced in real time
- **It's fast!** 1 or 2 minutes per observation. 150-200 objects per night common
- **Magnitude limit** still MUCH better than array!
- **It's accurate** (~1 mas at 4-meter)

USNO Speckle Camera Travelog

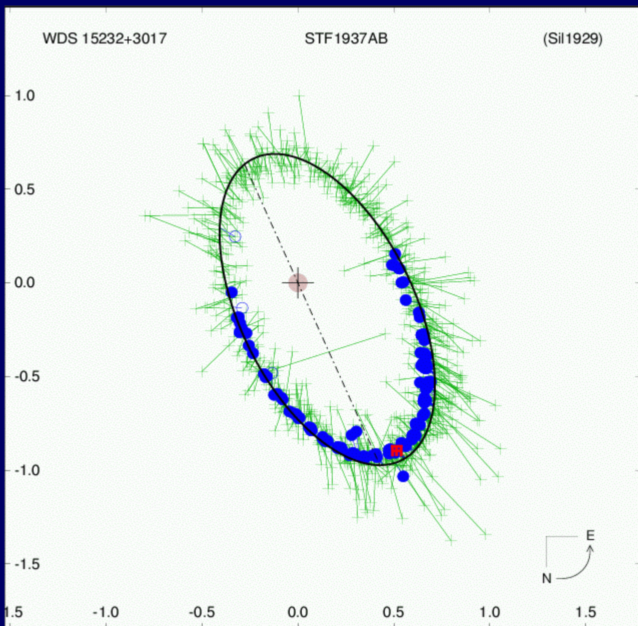


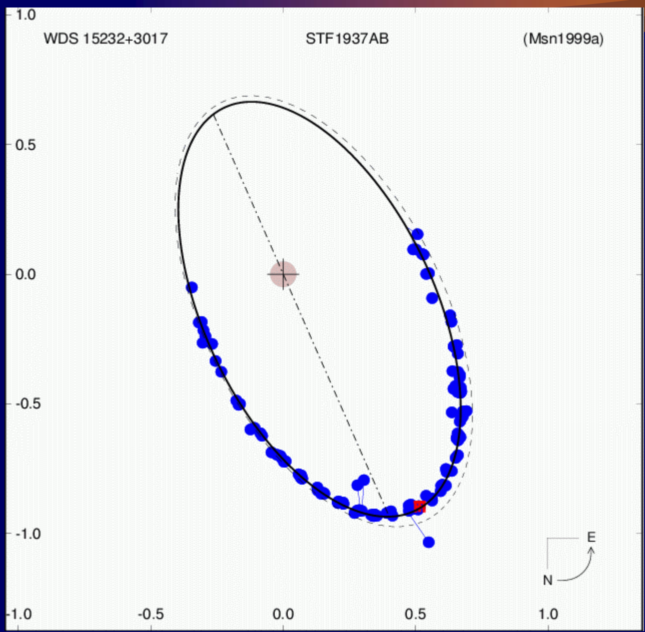






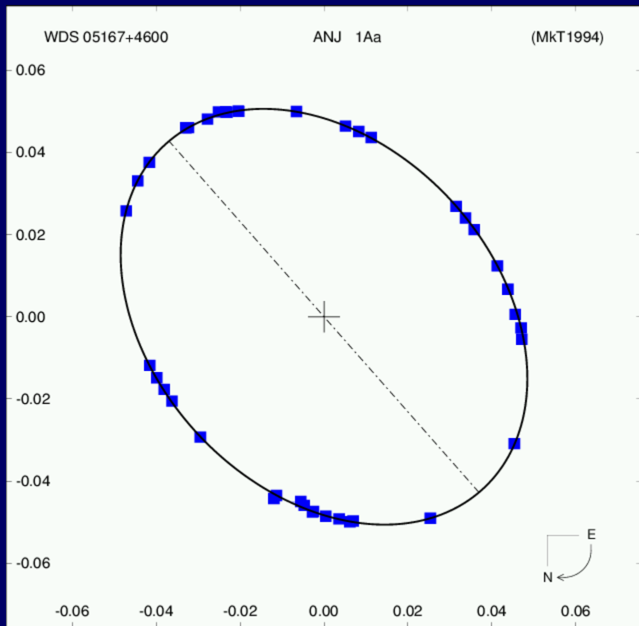
Orbital Precision

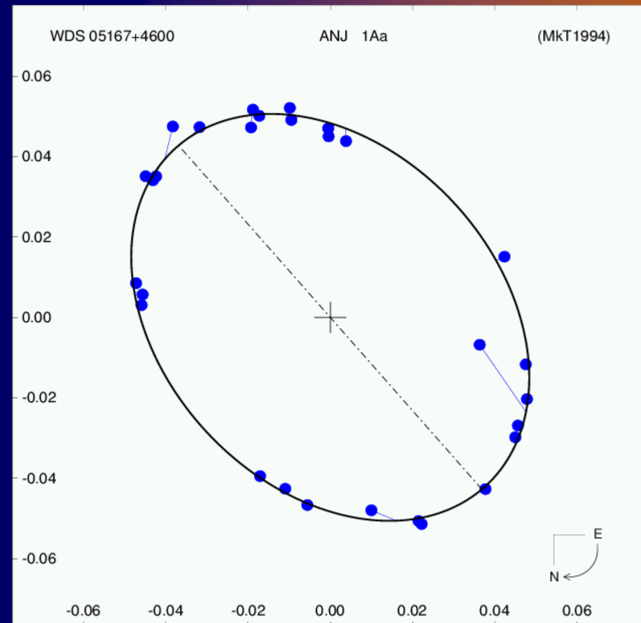




- The binary η CorBor is shown with all published data at left and only speckle data at right.
- The “string of pearls” appearance of the speckle data, coming from 20 different telescope/detector combinations is remarkably consistent.
- The new orbit changed the system mass by 14%.

Orbital Accuracy





- Capella, the "interferometrist's friend,'' is shown with data from the Mark III interferometer at left and speckle data at right. The orbit in both cases is based on the Mark III data.
- While the optical interferometry data is clearly better, the lack of systematic errors in the speckle data is a visual indication of the accuracy of the technique.

What Speckle Does Well

Mass is ***the*** fundamental quantity determining a star's luminosity, mass, etc.

Not a simple measured quantity, however – must measure its gravitational effect on another object →

Stellar masses require binary stars!

Orbits & Masses

- Kepler's 3rd: $P^2 = a^3 * (M_1 + M_2)$

  relative sizes of orbits → M_1, M_2

- One technique insufficient!

  visual orbits → *P, a'', i, etc.*

  spectroscopic orbits → P, $a \sin i$

  (or $a_1 \sin i$ and $a_2 \sin i$)

  visual + SB2 → P, a_1, a_2

  → M_1, M_2, distance

Orbits & Masses

The Problem:

Spectroscopic regime =

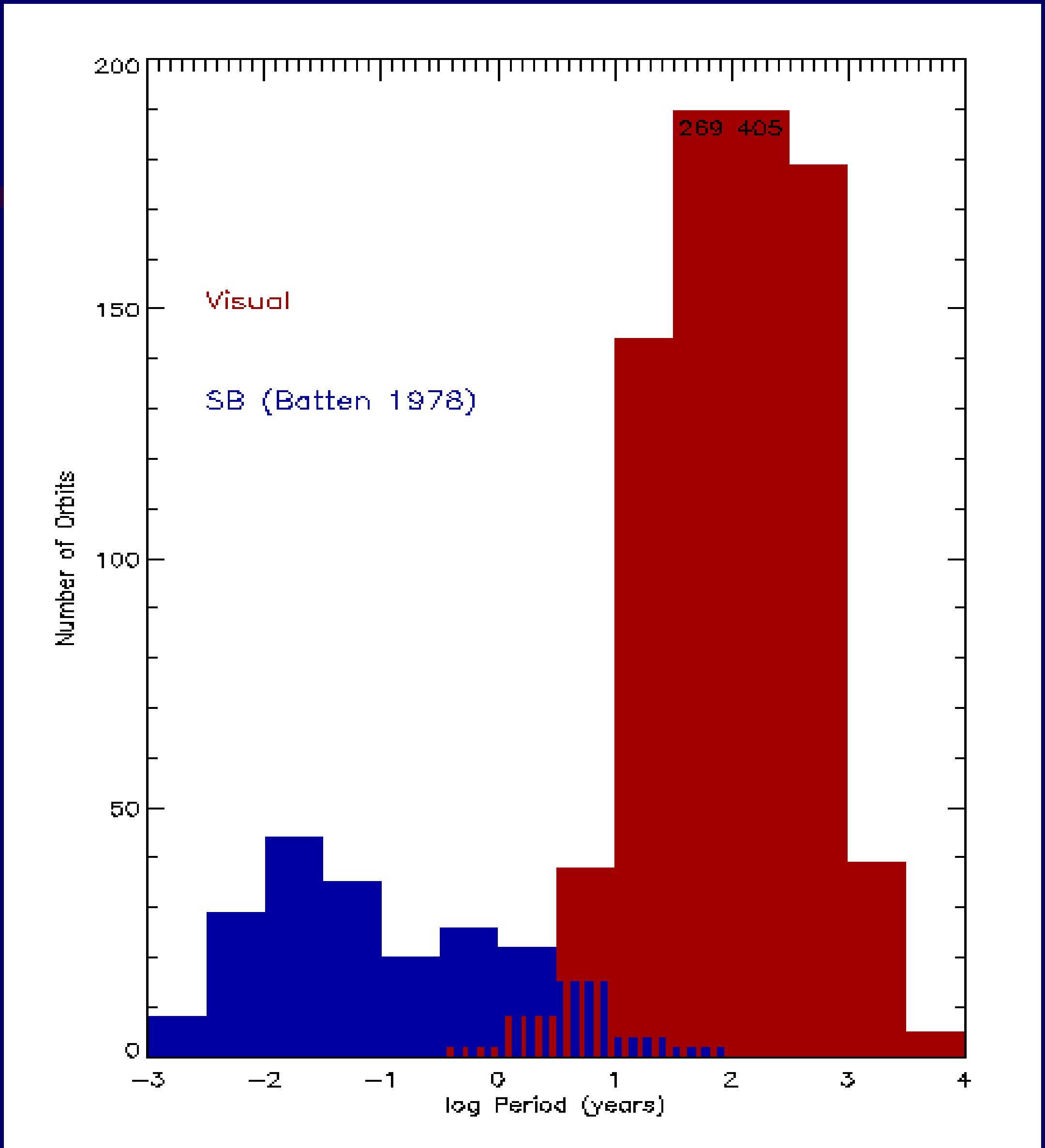
short periods, close separation

Visual regime =

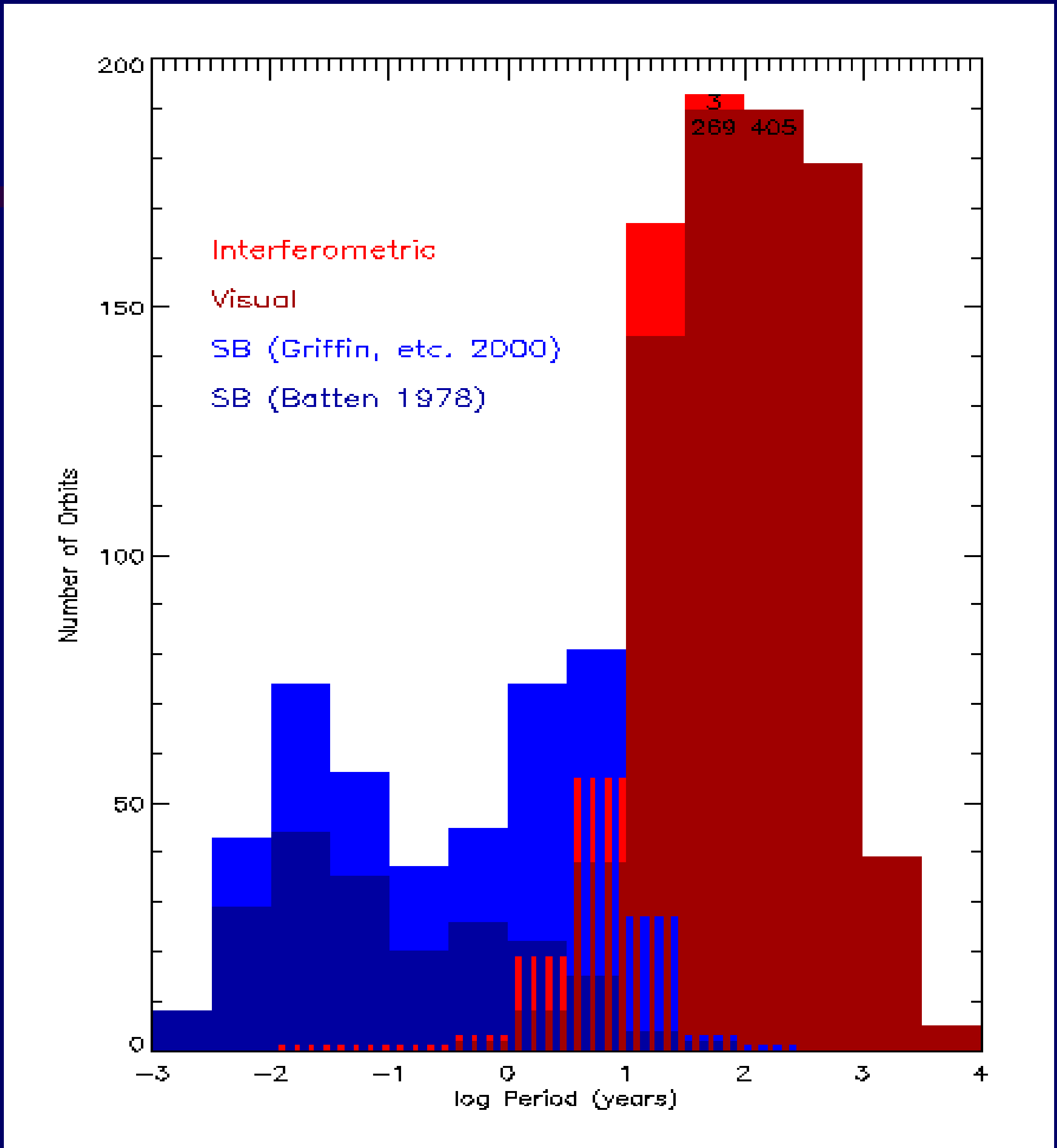
long periods, wide separations

Historically little overlap!

Spectroscopic versus Visual regimes (pre-interferometric)

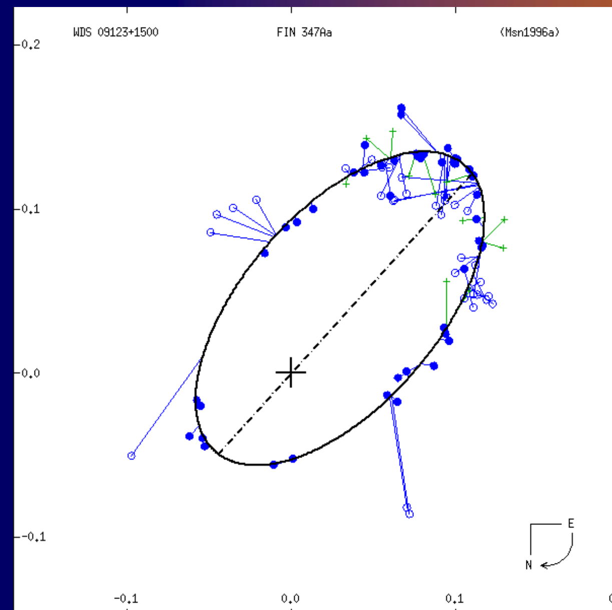


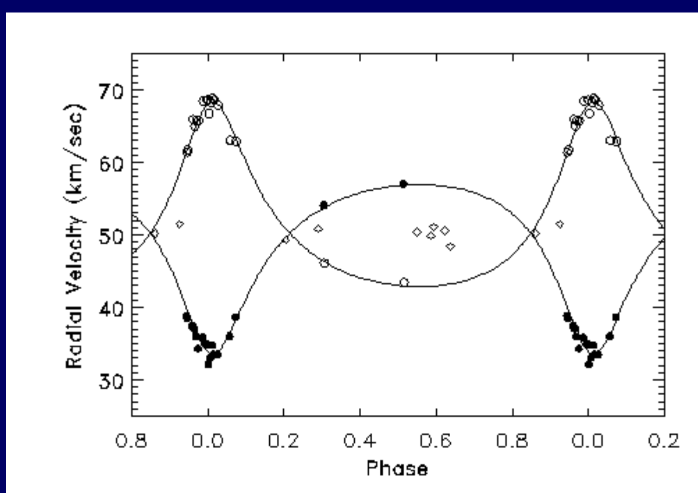
Spectroscopic versus Visual regimes (including interferometry and modern RVs)



Combined Solutions

Astrometric orbit plots of
FIN 347 (= 81 Cancri),
data 1959-2001,
P = 2.7yrs., 14 rev.

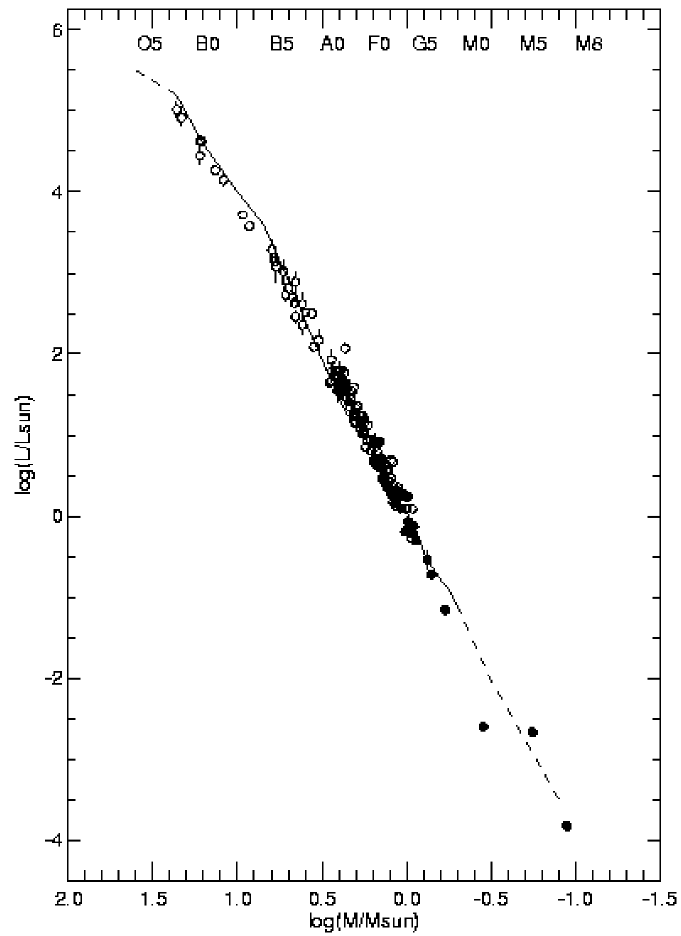




Spectroscopic orbit plot of 81 Cancri
from Griffin & Griffin
(*The Observatory* **102**, 217) 1982.

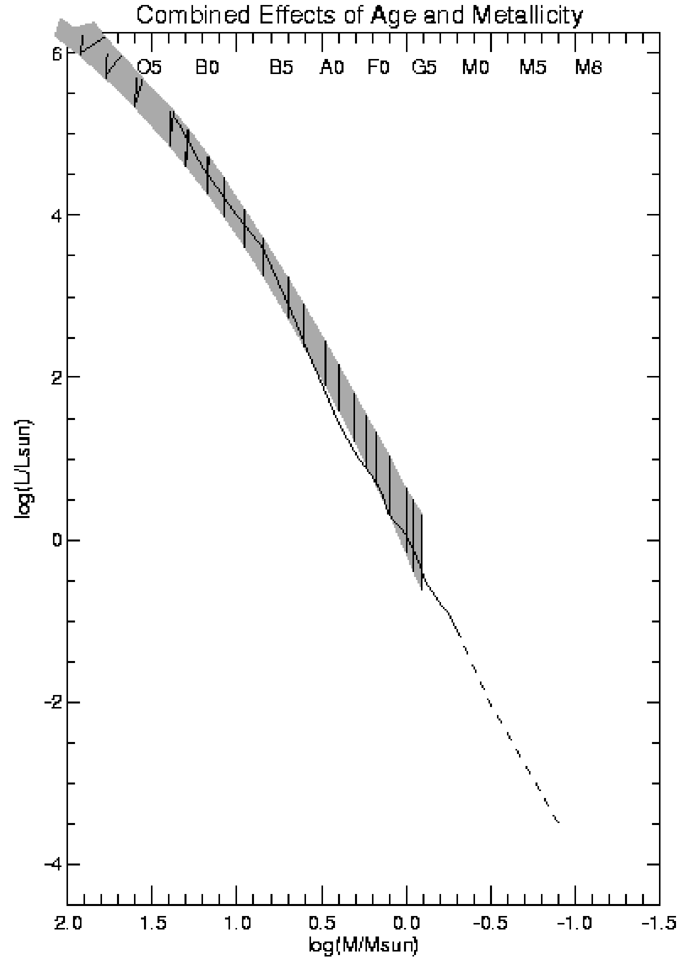
Why more masses?
M/L relation not
badly defined, right?

M/L is not a line!
Other effects
(evolution, metallicity)
To consider.

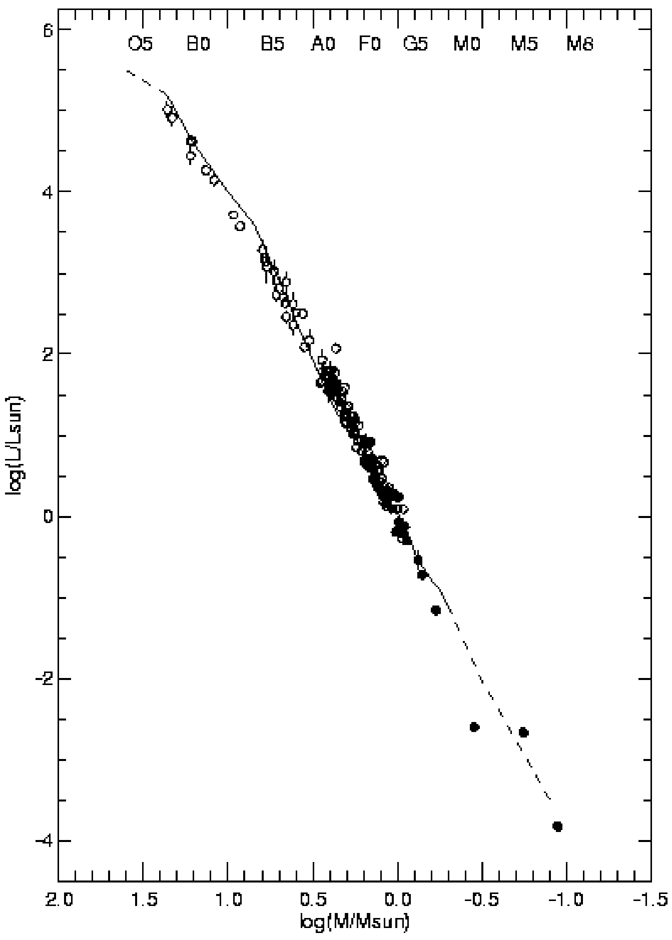


Theoretical changes for 0.001-0.020 in Z, 0.8 – 120 Msun ZAMS to turnoff

Andersen: Errors <2% in mass, 1% in radius, 2% in T, 25% in Z needed

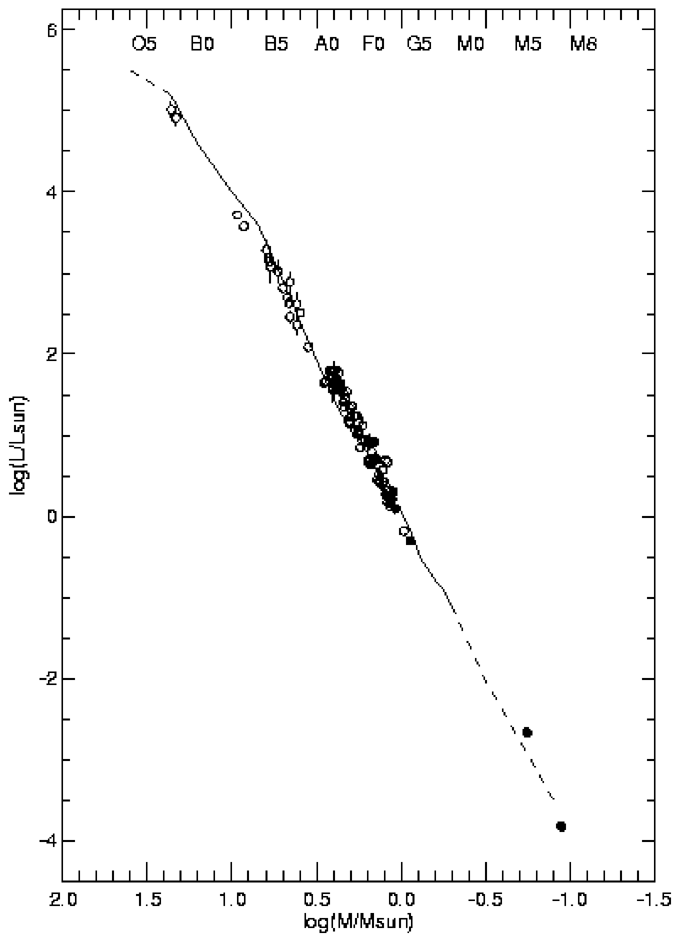


Masses good to 5% or better.



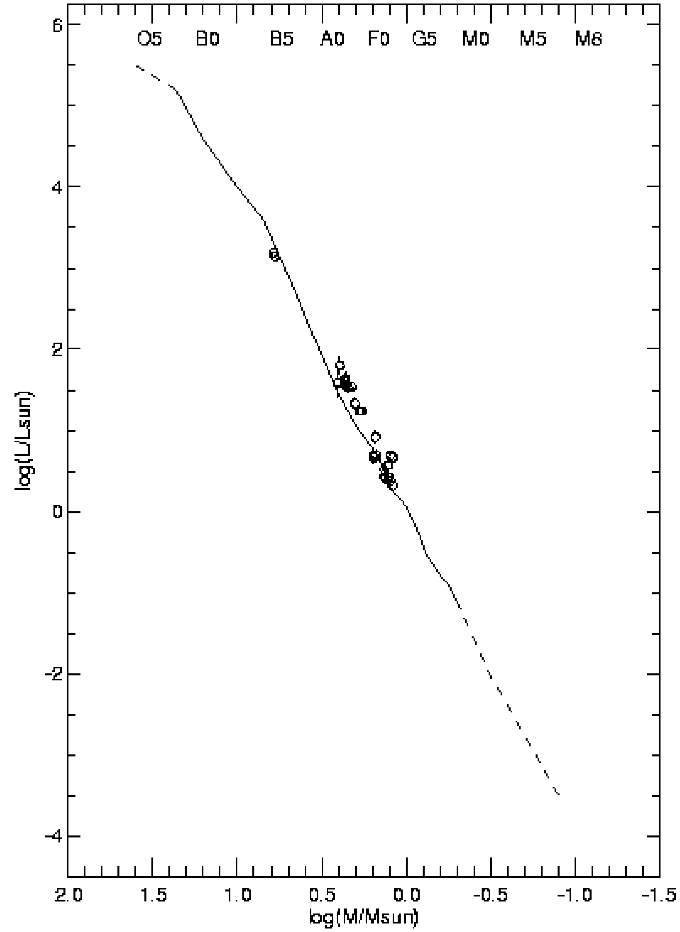
Masses good to

2% or better



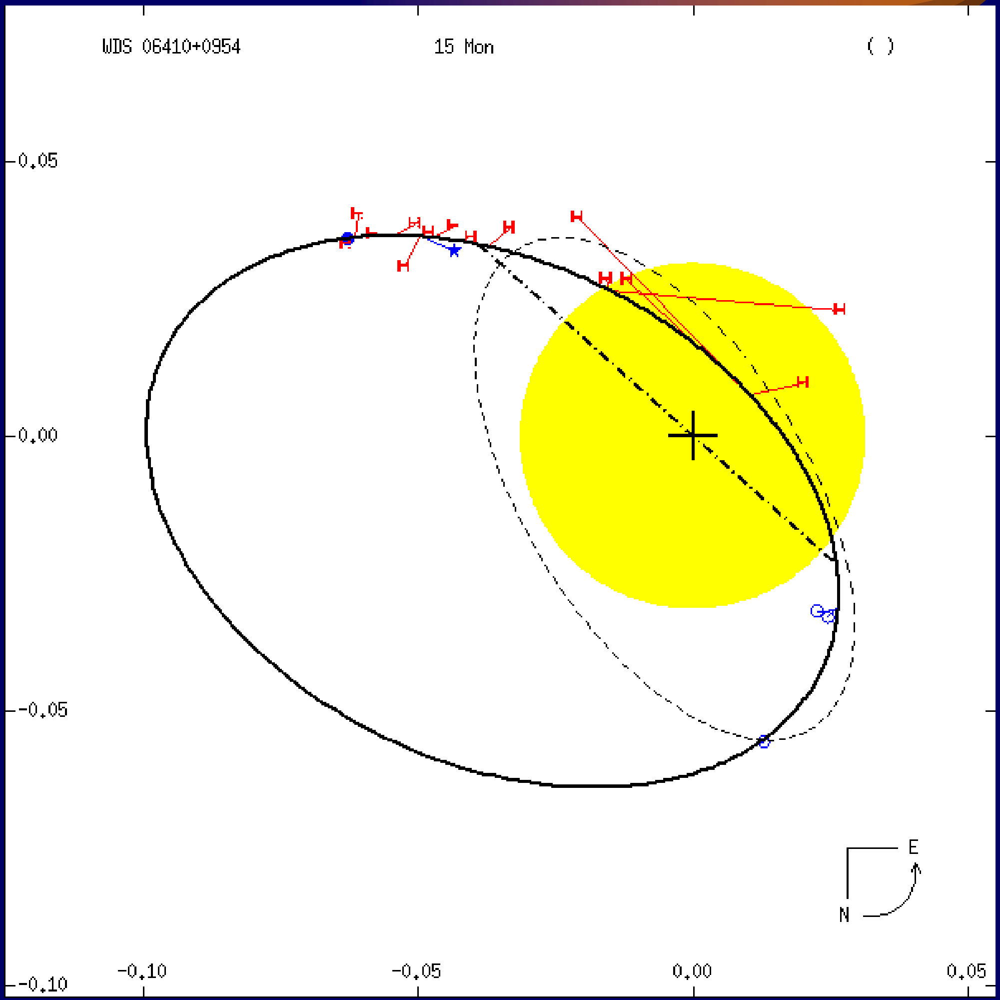
Masses good to 1% or better.

Situation somewhat better than this now, but *many* more still needed!

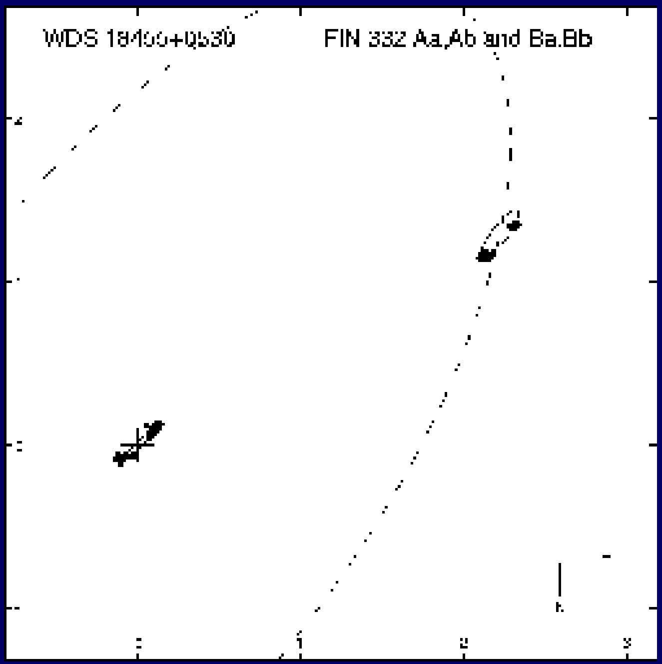


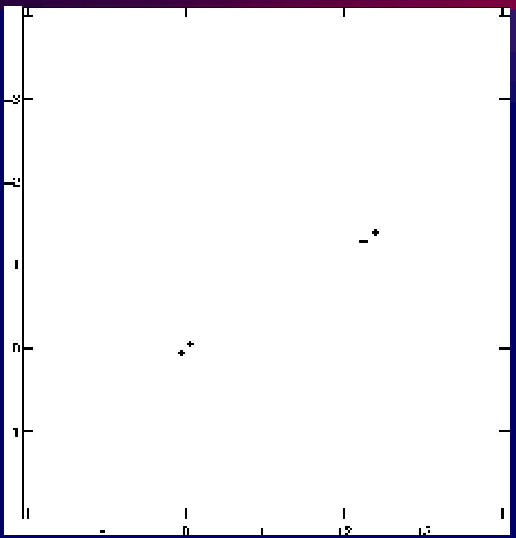
Other Orbits: 15 Mon

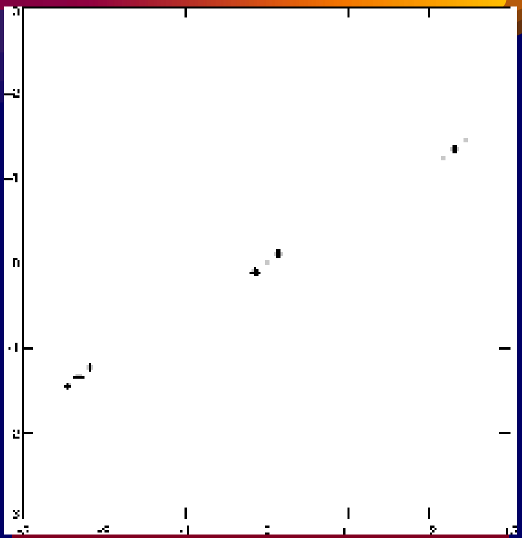
The NPOI measure is a filled circle. Speckle measures are blue open circles (CHARA) or stars (USNO). HST-FGS measures are red H. Dashed line is the orbit of Gies *et al.* (1997). HST measures were of lower quality in 1996-7 when FGS3 was in use. All subsequent data taken with FGS1r. 2004 FGS1r, Δm_v = 1.2.

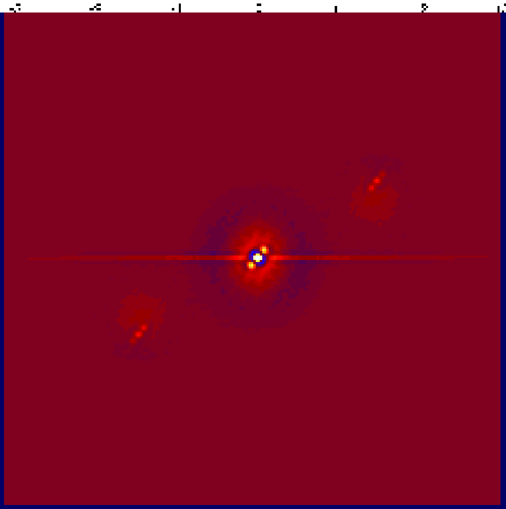


Tweedlee & Tweedledum







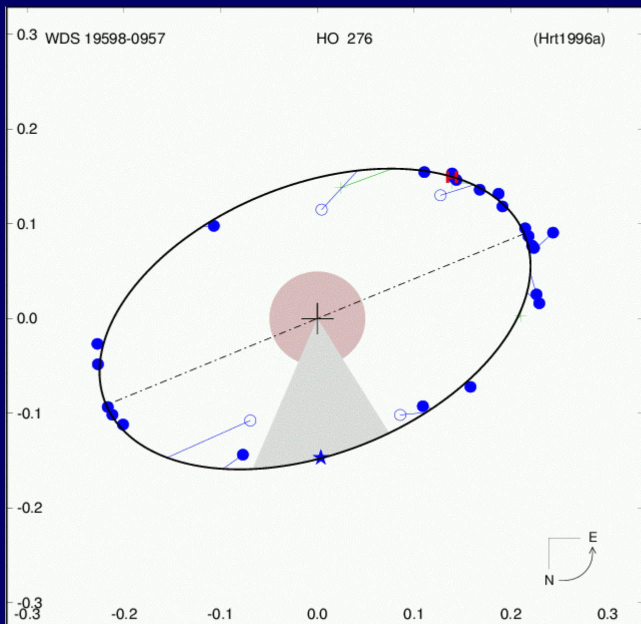


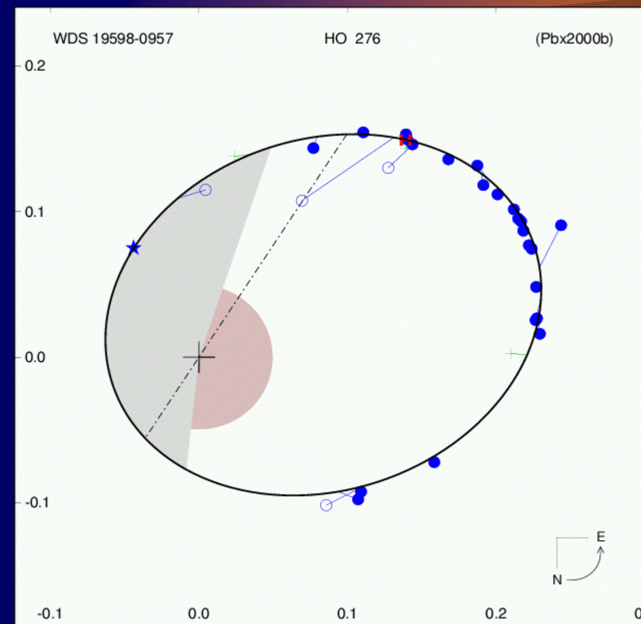
A real mess!

The confusing interferometric system

Finsen 332

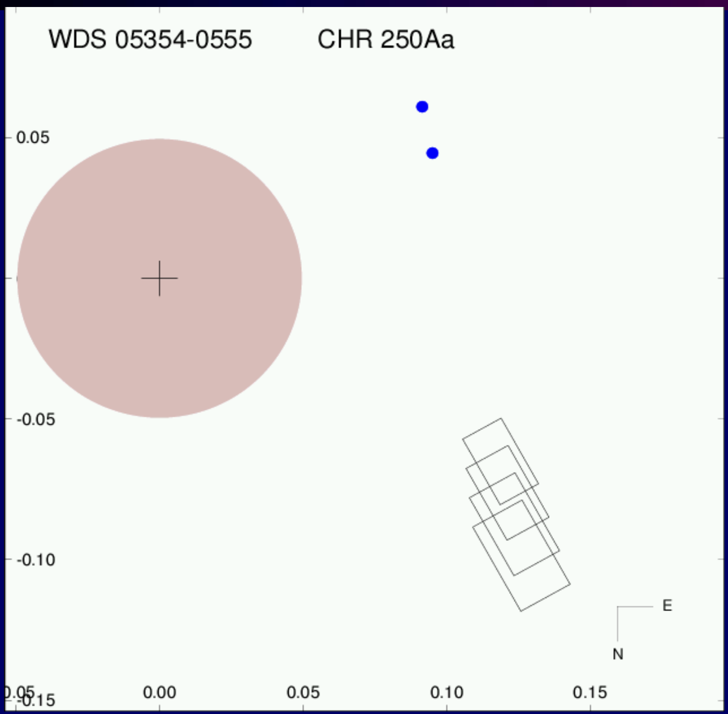
Quadrant Ambiguity Pairs

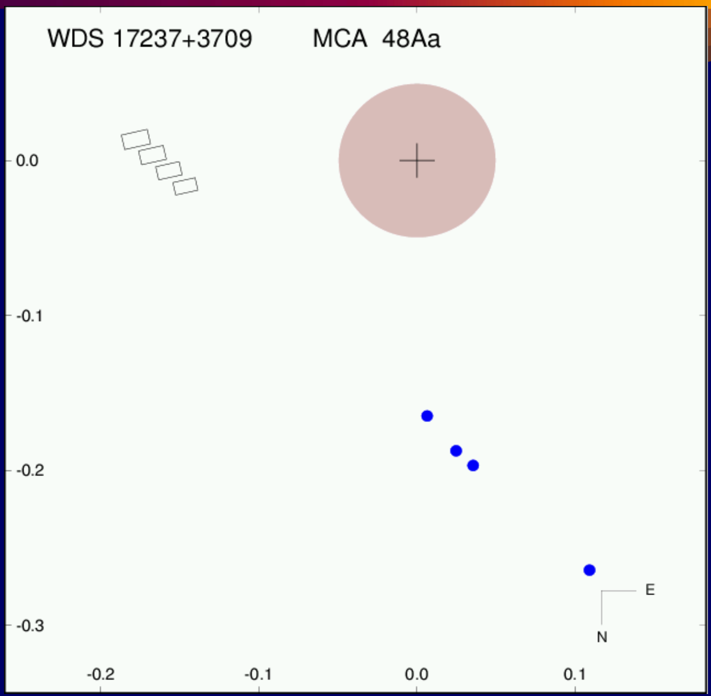




- Two possible solutions of a “quadrant ambiguity” system. Both orbits are quite good and show very small residuals, however over the period 2006.5-2007.5 (2007.0 indicated with a star), these two orbits have very different predictions.

Determining Physicality





- Despite their close angular separation, the true nature - physical or optical – of these pairs is unknown.
- Due to the accuracy and precision of speckle interferometry, this can be determined with one more resolution. Boxes indicate where the secondary should be in 2006-2009, assuming the motion is linear.

What Speckle Does Well

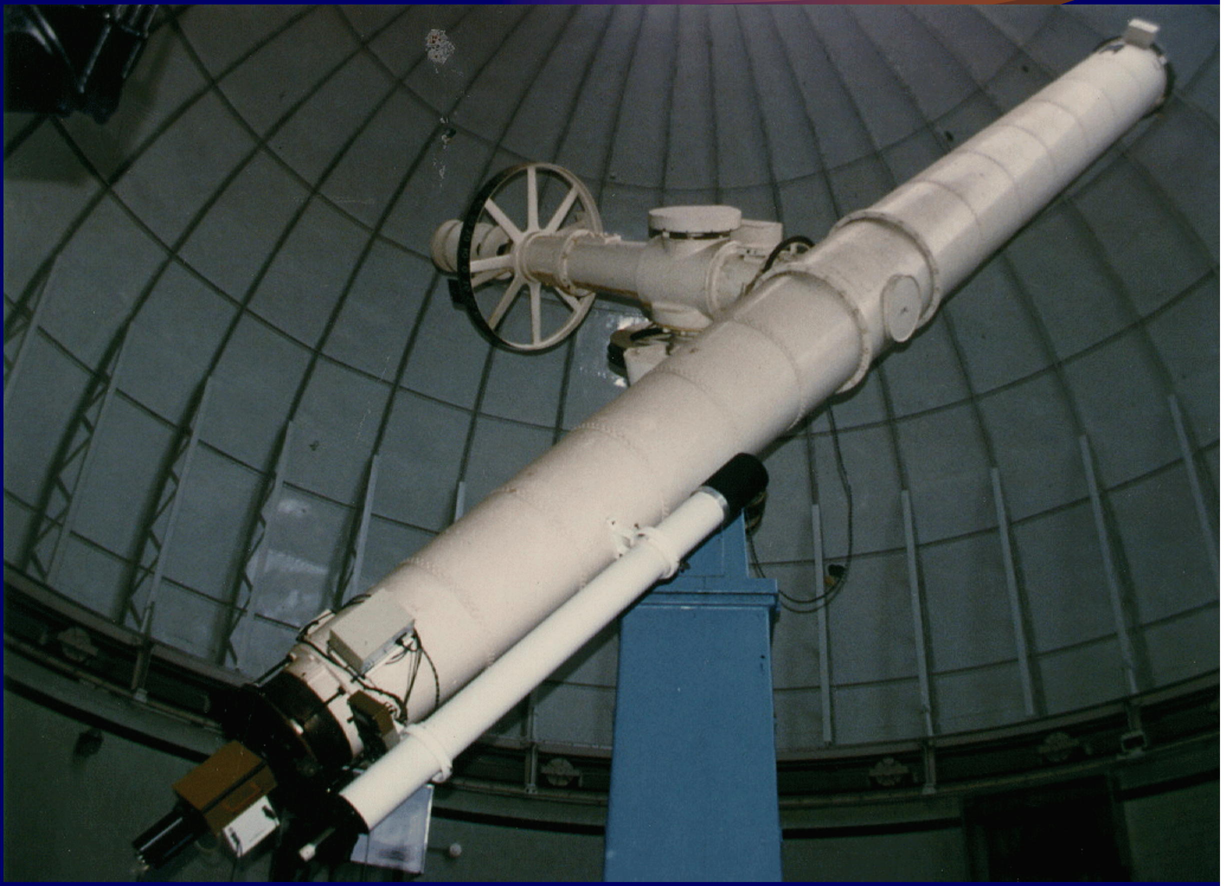
Confirming duplicity of discoveries from other techniques (occultations, space-based); followup measures

Example: many Hipparcos and Tycho pairs confirmed using 26inch Clark refractor and USNO speckle camera

70% of Hip/Tyc binaries observable *(much more cheaply!)* by 4-meter speckle

USNO Speckle Camera

- The 26-inch Clark Refractor and USNO speckle camera

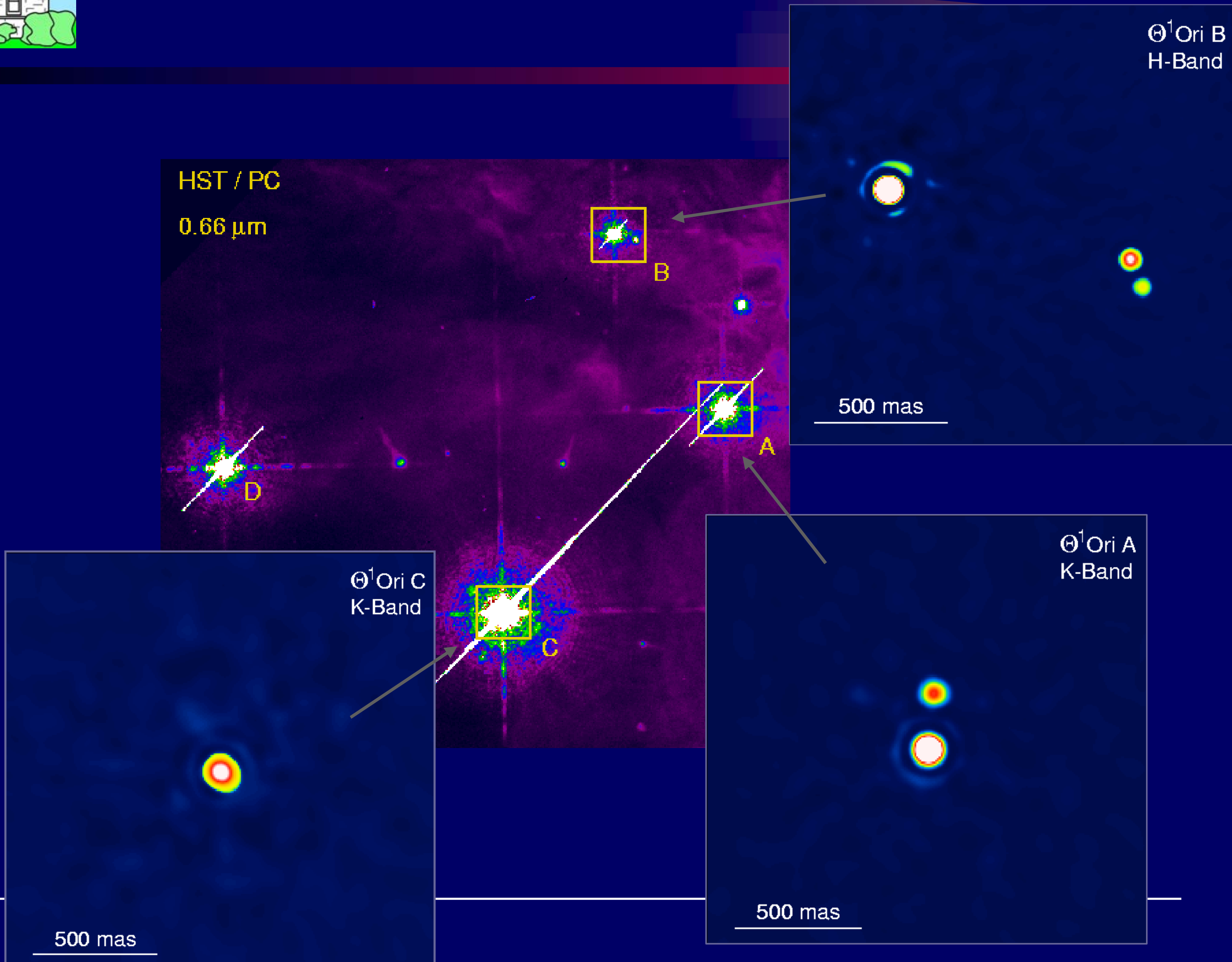


What Speckle Does Well

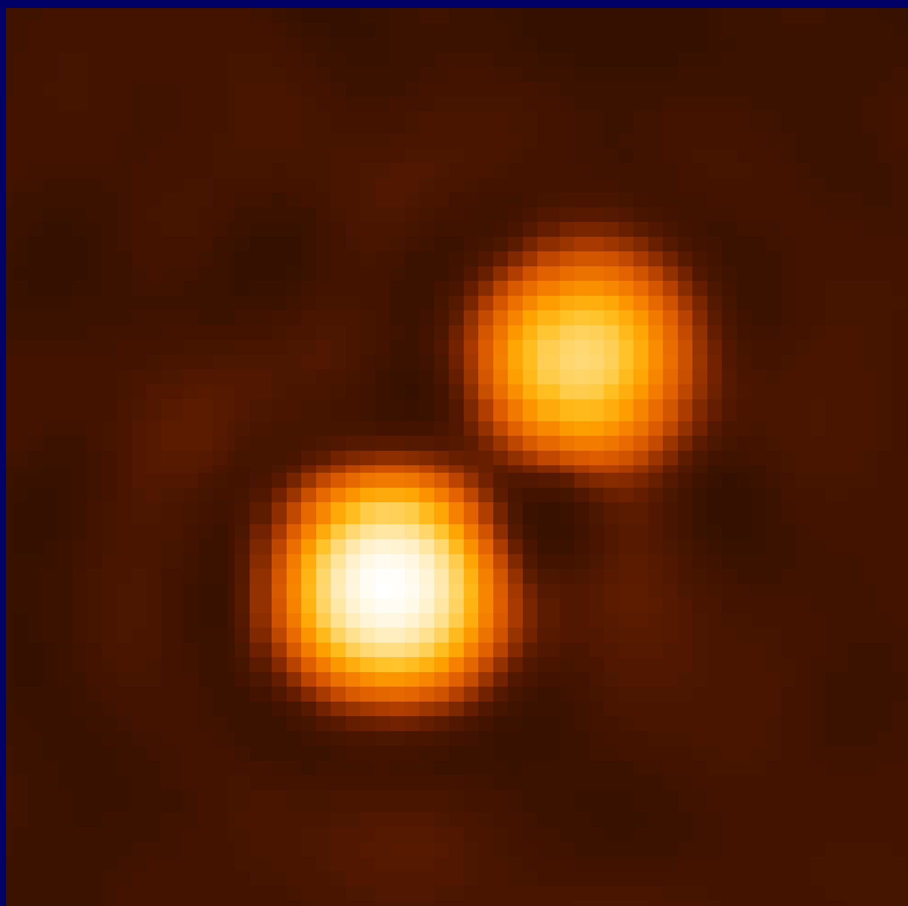
Duplicity surveys – examples include:

- Groups sorted by proximity or coeval nature (e.g., visual and IR surveys of Hyades, Pleiades, pre-MS complexes)
- Stars of given spectral class (white dwarfs, Be and O stars, Wolf-Rayets, G dwarfs, MLT dwarfs)
- Stars with certain kinematic characteristics (high-velocity stars)
- Stars sorted by other characteristics (bright stars)

Young massive stars in Orion Trapezium



Young multiple brown dwarf system GL569B



6 m telescope

March 2001, J-band

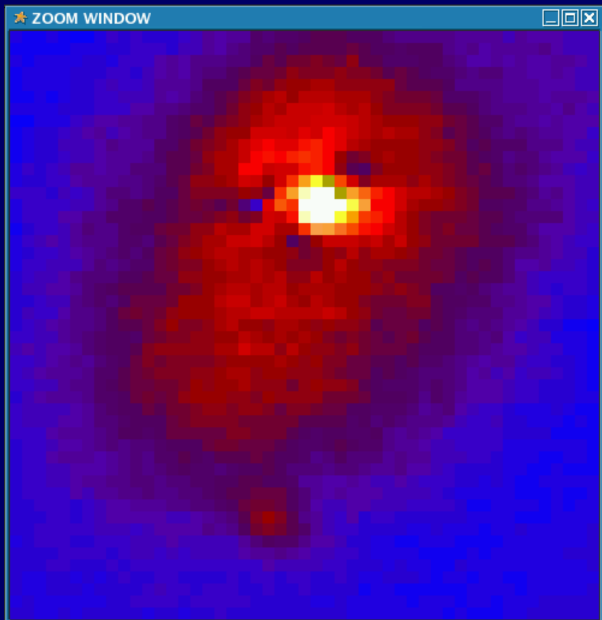
Sep. 89.9 mas
(about 1 AU)

Orb. period 3.5 yr

Mass sum 0.115 Mo

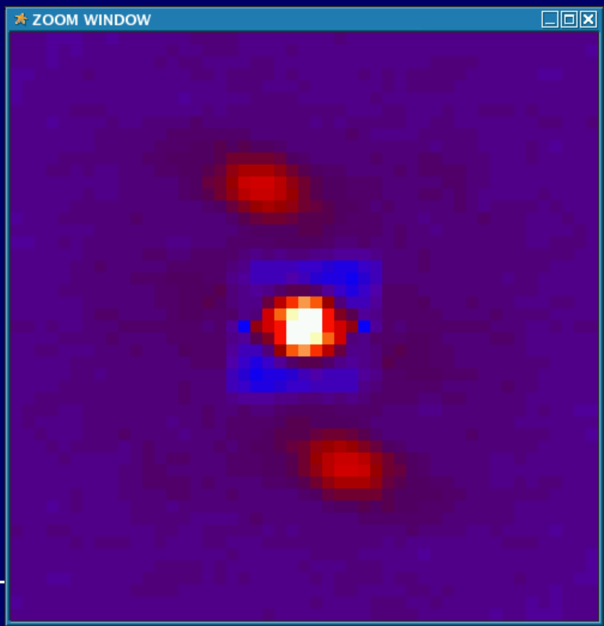
(Kenworthy et al. 2001)

WR 146 & 147



WR 147 confirmed Summer 2001 at KPNO 4-m with USNO speckle camera. Noisy quality of image due to largish Δm (2.2) and faintness of secondary (V = 17.2).

WR 146 also confirmed in Summer 2001. Much closer (150 mas instead of 600), but secondary brighter (V = 16.4) and Δm much smaller (0.2).



Duplicity Evolution?

Survey results may have important implications for stellar evolution and galaxy dynamics

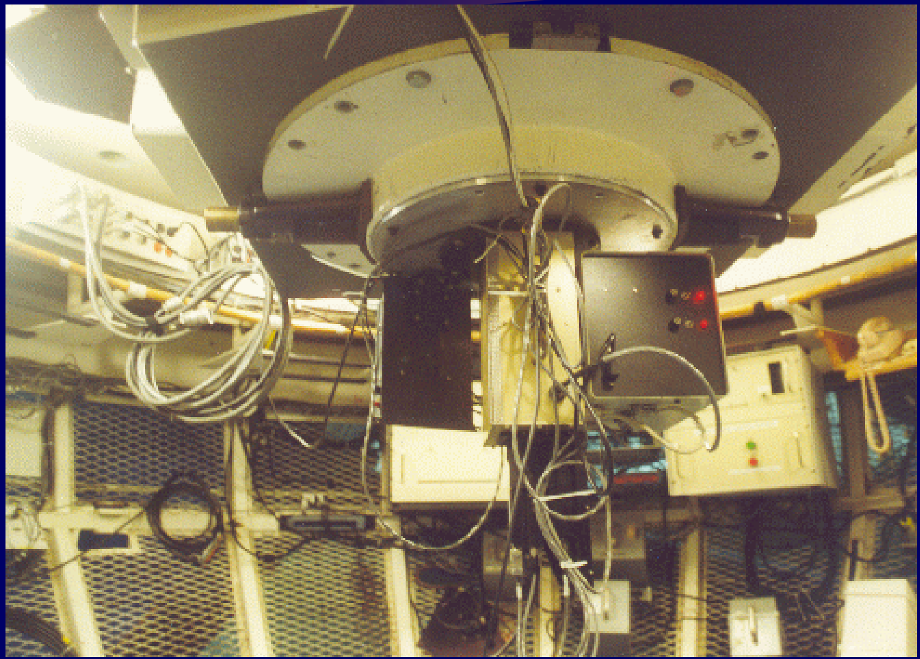
- O stars: lower binary frequency in clusters and associations than in field
- Pre-MS duplicity rates twice that of older solar-neighborhood stars (Hyades somewhere in between)

Do cluster binary-binary interactions eject stars?

When do these disruptions occur?

Nearby G-dwarf Grid Stars

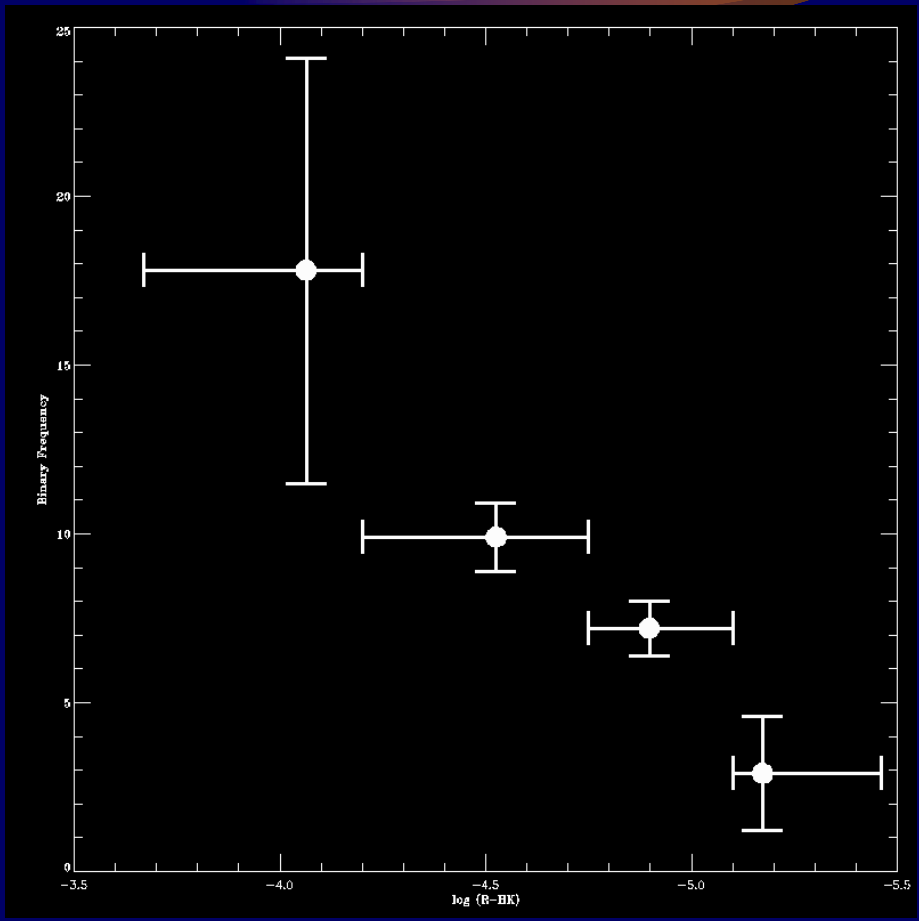
- G-dwarfs: 0.5 <B-V< 1.0
- Nearby: less than 50pc
- Number: 3589
- Purpose: USNO's suggested grid star catalog for SIM
- Approx. 16% checked before 2001
- All but 200 observed during four 2001 KPNO 4-m and CTIO 4-m observing runs using USNO speckle camera



Speckle Camera on the KPNO 4m

Chromospheric Activity & Multiplicity

- In a survey of ~200 G dwarf stars, broadly characterized as active (young) or inactive (old) a statistically significant difference was found.
- Based on a larger sample of ~3000 G dwarf stars observed in 2001, very active stars have a multiplicity fraction of 17.8%, active stars 9.9%, inactive stars 7.2%, very inactive stars 2.9%.



Publications:

- *A Multiplicity Survey of Chromospherically Active and Inactive Stars*, (AJ, **116,** 2975, 1998)
- *Evidence for the Destruction of Binary Stars with Age (in progress)*

Non-Duplicity Surveys

- Variability mimicked by duplicity
- PSF distortions for AO, etc.
- Exoplanet or pole-on binary?
- Contamination of reference frames by “vermin”
- Satellite time wasted observing double guide or target stars

Other Projects

- Globular cluster proper motions
- Submotions from unresolved companions
- Asteroid duplicity
- Mutual events of Galilean satellites

Closing Stats

62,000 published interferometric observations

- 52,000 (84%) of these from speckle
    - 50,000 (97%) of these visible
        - 42,000 (83%) of these from CHARA or USNO programs

Competition is Good!

Acknowledgments

Portions of this talk adapted from chapter on speckle interferometry by Mason & Hartkopf for the book ***The Future of Small Telescopes in the Age of Big Glass***, Terry Oswalt, ed.

Slides from 6-meter telescope courtesy Yuri Balega.

2005 4-m Speckle Observing Proposals

- Bright O & WR stars
- Fainter O stars
- O close orbit stars
- Hyades & Pleiades
- Torres specials
- White dwarfs
- Red dwarfs
- Coplanarity multiples

Regions indicate late March (CTIO) and mid-November (KPNO) 4-m runs