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(Long-Baseline) Interferometric Measurements of Binary Stars

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Outline

- Introduction:
  - Why study binary stars (with an interferometer)…
  - What kinds of binary star measurements are interesting
  - What kinds of binary stars are best suited to interferometry
- History of Interferometric Binary Star Measurements:
  - Classical imaging
  - Speckle
  - Long-baseline interferometry
- How Do Interferometers Measure Binary Stars
  - Visibility model
  - Interpretation
- Case Study: HD 195987
  - Why is the system interesting
  - Measurements & integrated orbit modeling
- Future Directions

Why Study Binary Stars?

Don't try to teach a pig to sing…it doesn't work, and it annoys the pig!

- Multiplicity (binary) is a pervasive phenomenon
  - Multiplicity's role in the star formation process
    - Most stars form in multiple associations
  - Multiplicity's role in the field
    - Two out of three solar-like stars have a stellar companion (DM91)
  - Multiplicity's role in stellar evolution
    - The cornucopia of interacting binary stars
- Binary star interactions are SIMPLE, allowing insight into the properties of the components
  - Mass (through physical orbit)
  - Radius
  - Luminosity (through photometry, physical & angular orbit)

The Lexicon of Binary Stars

- Eclipsing Binaries
  - Systems aligned so that components occlude each other (constrains inclination)
  - (By phase-space arguments) highly likely to be close => short-period
- Spectroscopic Binaries
  - Systems whose kinematics and component properties yield detectable component radial velocity variations
  - SB1 – single-lined binaries
  - SB2 – double-lined binaries
  - Most (almost all) eclipsing binaries are spectroscopic binaries
    - Combination directly yields masses, radii
- Visual Binaries
  - Systems whose components can be resolved into two distinct sources…
    - …Allowing astrometry
    - Motion in time yields orientation of orbit (inclination)
    - Combined with SB2 => masses, distance (luminosity)

What Kinds of Binary Information is Interesting?

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- Multiplicity statistics
- Orbit characteristics statistics

  as remnants of the formation process
- Component properties
  - Mass, Radius, Luminosity (the "big" three)
  - Abundance

    as constraints on stellar astrophysics & measure of system age
  - Rotation

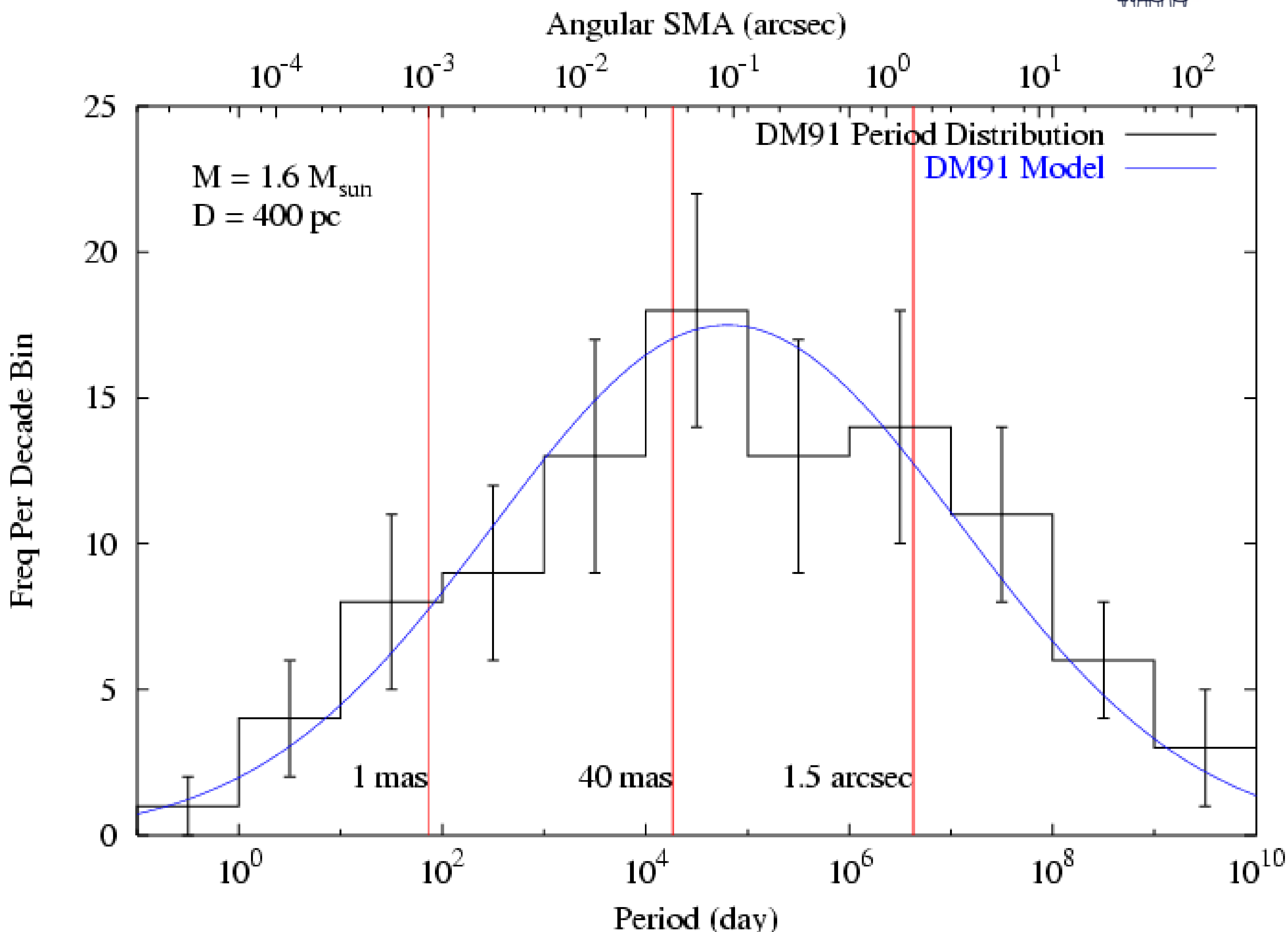
    as markers of tidal interaction & internal convective structure
- Distance ("orbital parallax")

  for direct & indirect luminosity calibration

What Kinds of Binary Measurements are Interesting?

- Photometry
  - Detection and measurements of binary eclipses
  - Marker of stellar rotation period
  - System and/or component luminosity
- "Imaging"
  - Inference of association
  - Astrometry
    - "Absolute" (relative to some "quasi-inertial" fiducials)
    - "Relative" (two components relative to each other)
- Spectroscopy
  - Astrophysics of components
  - "Velocimetry" – gauging the line-of-sight motions of components

What Binaries are Suitable for



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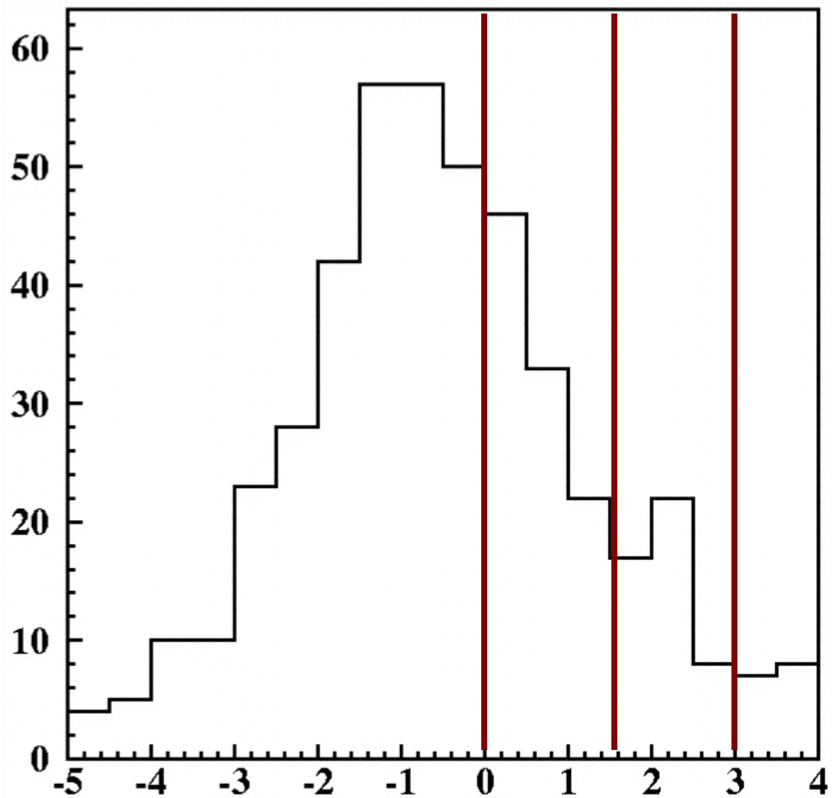
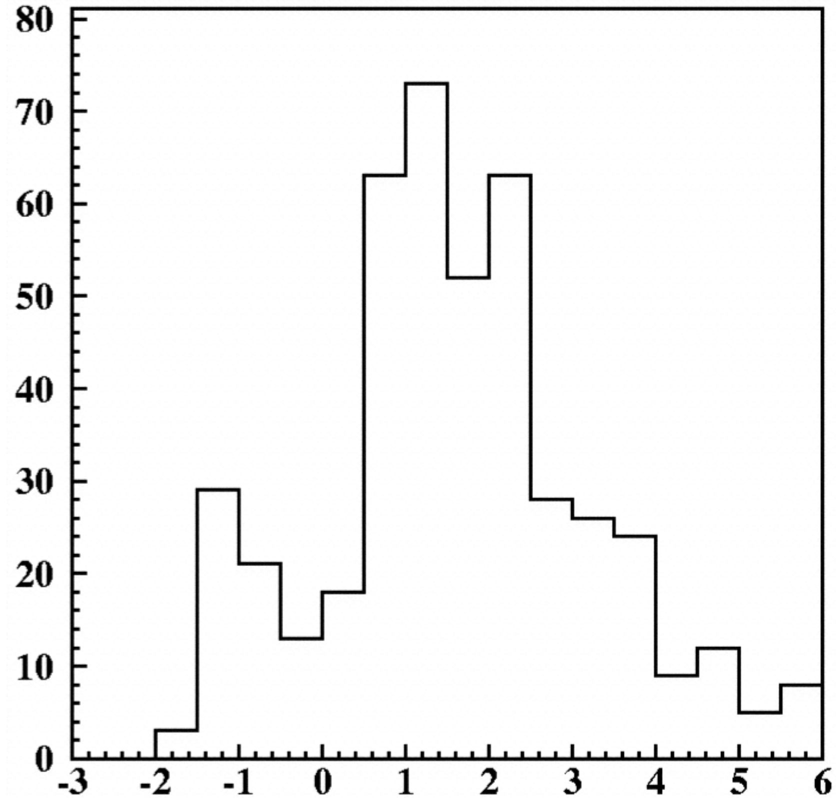
Known Spectroscopic Binary Distributions

From Taylor, Harvin, and McAlister 2003



Log Greater Nodal Sep (mas)



Log Period (d)

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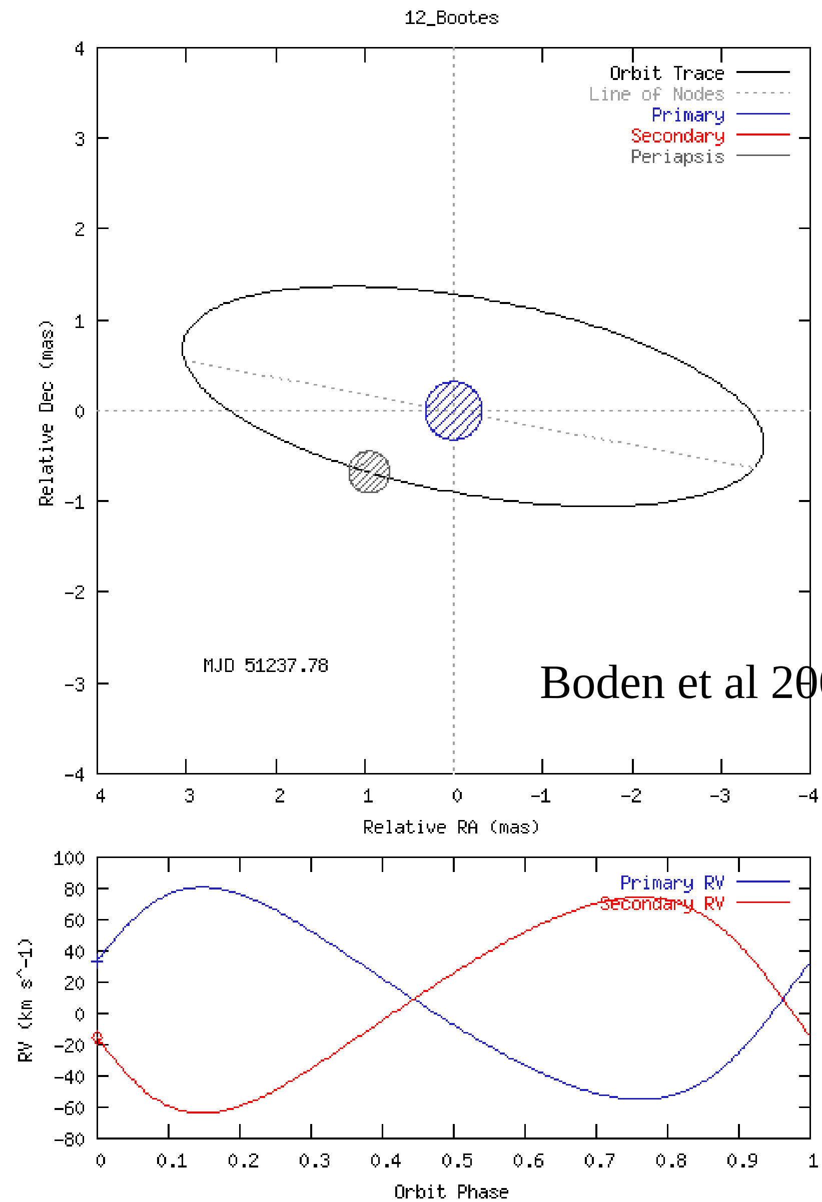
"The Deal" with Binary Star Studies

- In (essentially) all cases, observational objective is to determine "physical orbit" (physical dimensions, orientation), this provides component masses
- Eclipsing systems provide that with spectroscopy ("spectroscopic orbit") & photometry (inclination)
- Non-eclipsing systems require integrating the "visual orbit" to determine system orientation
- Ratio of physical and angular scales (e.g. semi-major axis) yields system distance (duh)



Boden et al 2000

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- Why?

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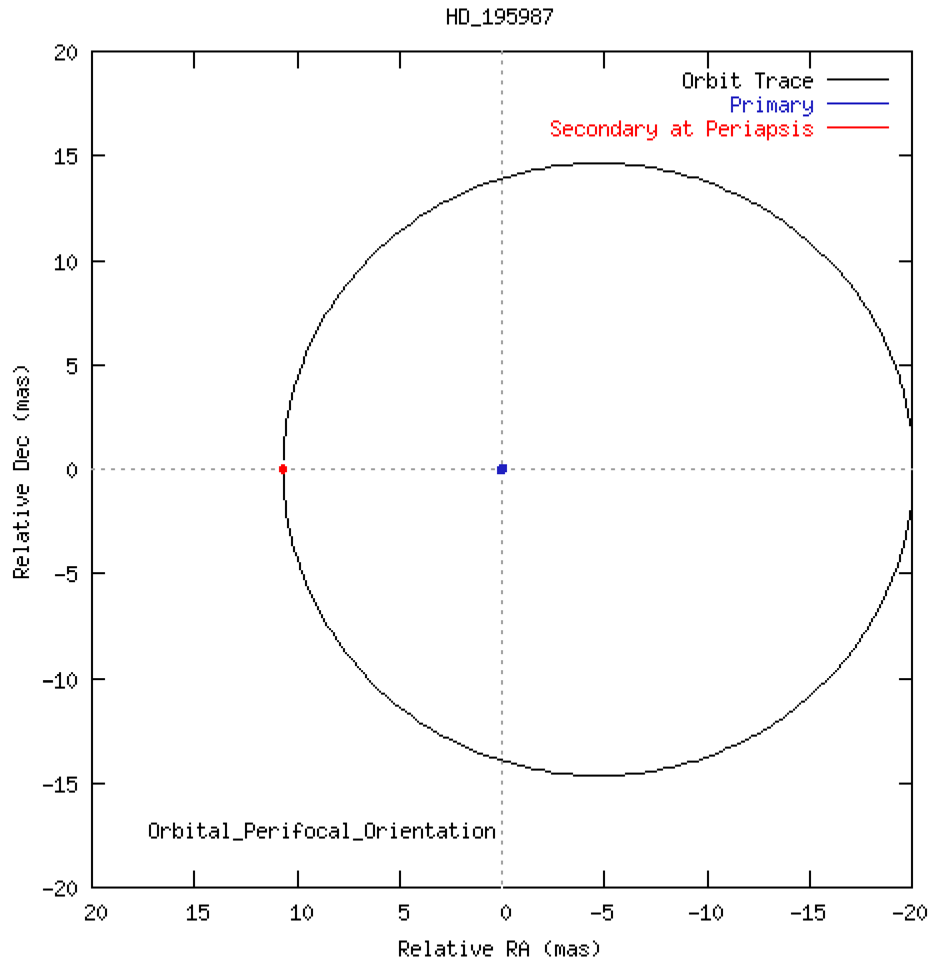
Describing Binary Systems

- (By definition) binary systems have *Primary* (A) and *Secondary* (B) components
- We describe binary kinematics with *orbital elements*
  - Four elements (a, e, P, T_0) describe motion in the orbital plane
  - Three elements (Euler angles, i, Ω, ω) define orbital plane orientation
  - Three elements (K_A, K_B, γ) describe rates projected onto the line-of-sight
- Additional parameters may describe component properties
  - Diameters (θ_A, θ_B)
  - Intensity ratio ($r = B / A$)



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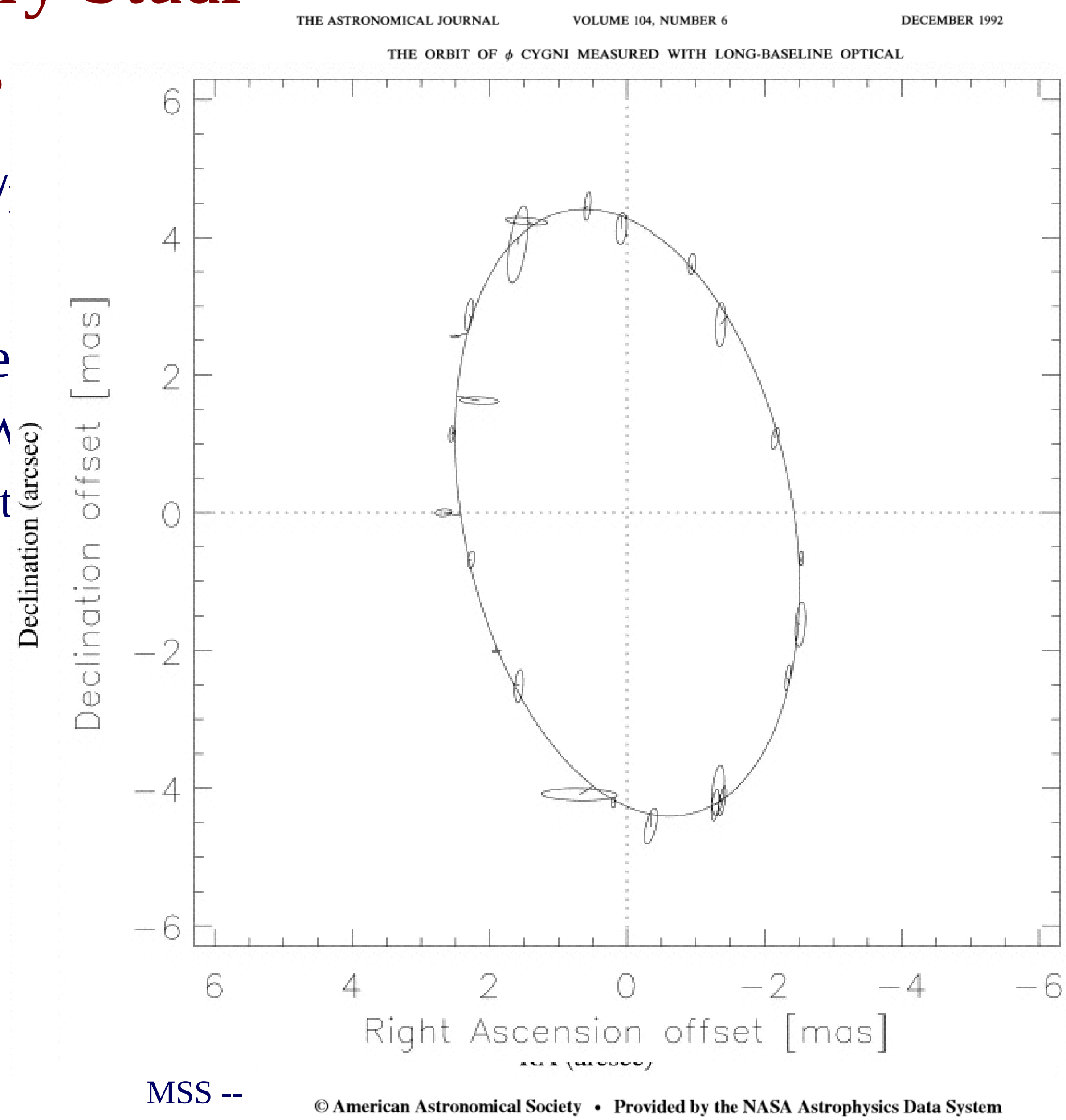
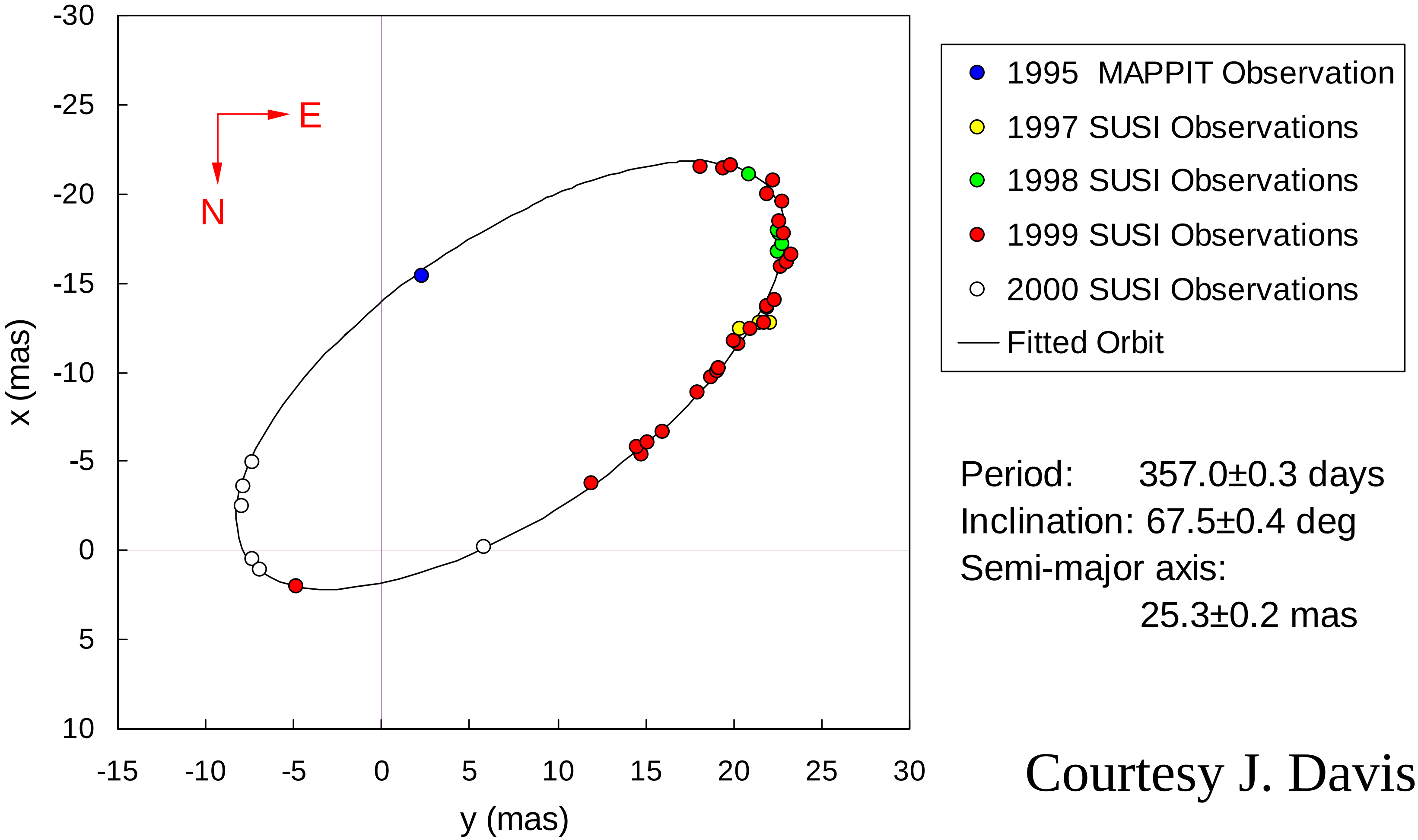
Historical Binary Studi
Interferometers

- Classical imaging/
- Speckle
- Long-baseline inte
  - Capella with Mt W
  - α Vir with intensit
  - Mark III
  - HST FGS
  - NPOI
  - PTI
  - SUSY



The orbit of β Centauri determined from SUSI observations



Period: 357.0±0.3 days
Inclination: 67.5±0.4 deg
Semi-major axis:
25.3±0.2 mas

Courtesy J. Davis

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Admonitions From P. Tuthill

- Imaging may well be the "Holy Grail", but the distinction between imaging and modeling is sometimes unclear
- In all cases, you want to make optimal use of your data
- Usually this means working "as close to your data" as possible

Long-Baseline Interferometry Observables

- (L-B) Interferometers provide visual (i.e. astrometric) information on binary stars
- Interferometric visibility as proxy for relative component astrometry

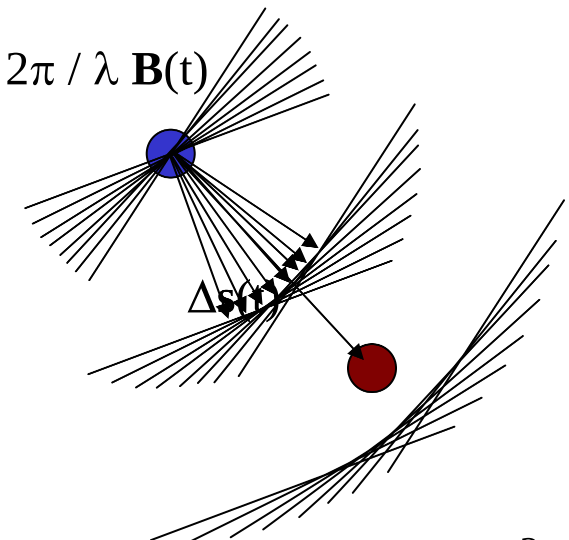
$$V_{binary} = \frac{P_A V_A + P_B V_B}{P_A + P_B} = e^{-2\pi i(u\alpha_1 + v\beta_1)} \frac{|V_A| + r|V_B| e^{-2\pi i(u\Delta\alpha + v\Delta\beta)}}{1+r}$$

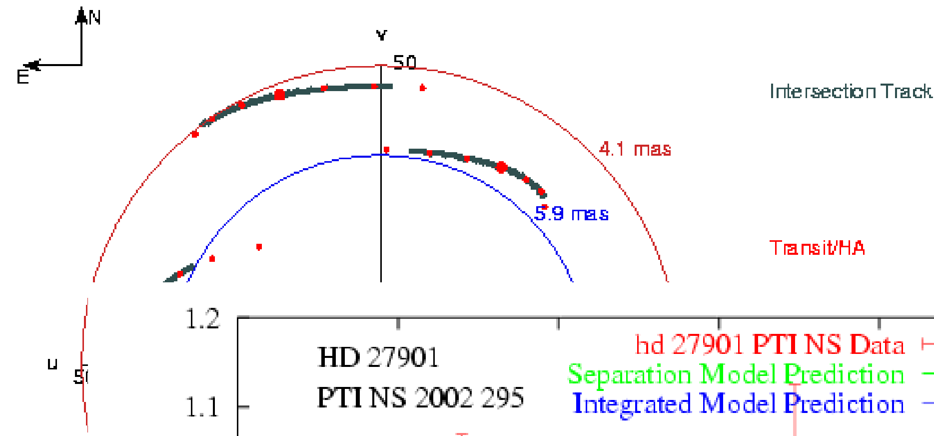
$$V_{binary}^2 = V_{binary}^* V_{binary} = \frac{|V_A|^2 + r^2 |V_B|^2 + 2r|V_A||V_B| \cos(2\pi(u\Delta\alpha + v\Delta\beta))}{(1+r)^2}$$

$$= \frac{|V_A|^2 + r^2 |V_B|^2 + 2r|V_A||V_B| \cos(\frac{2\pi}{\lambda} B \bullet \Delta s)}{(1+r)^2}$$

Δs – relative separation r – relative intensity ***B*** – baseline

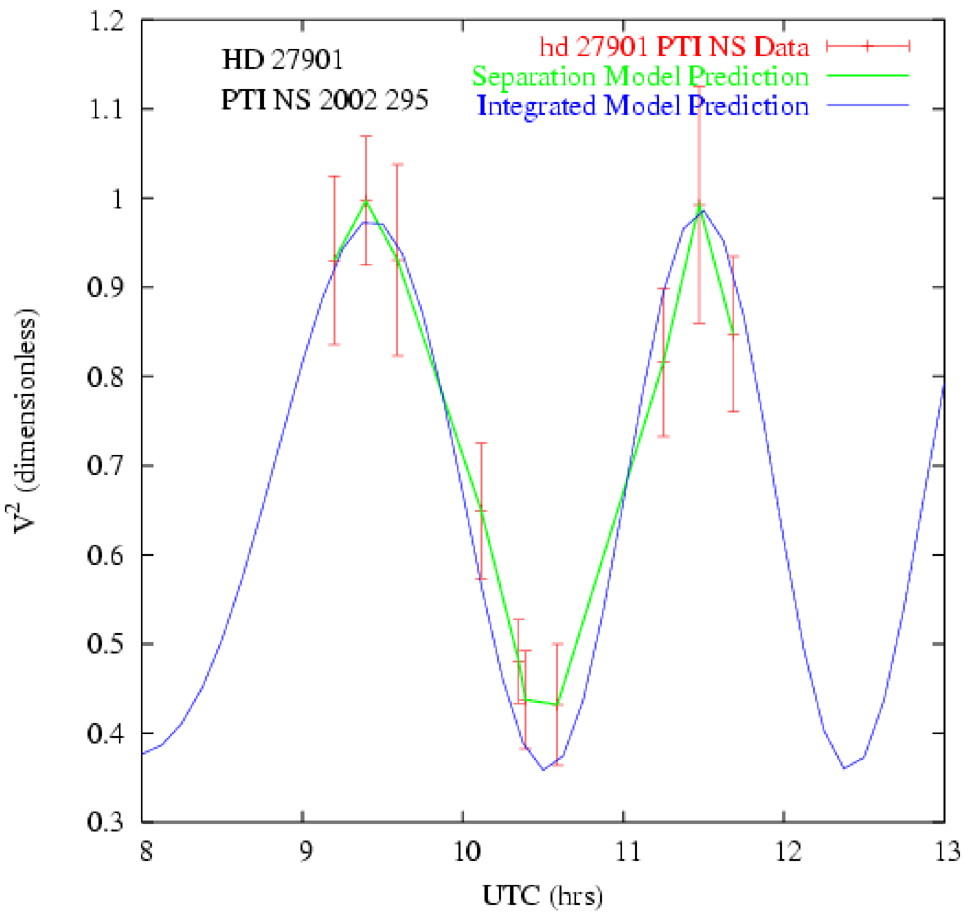
Separation Vector Modeling



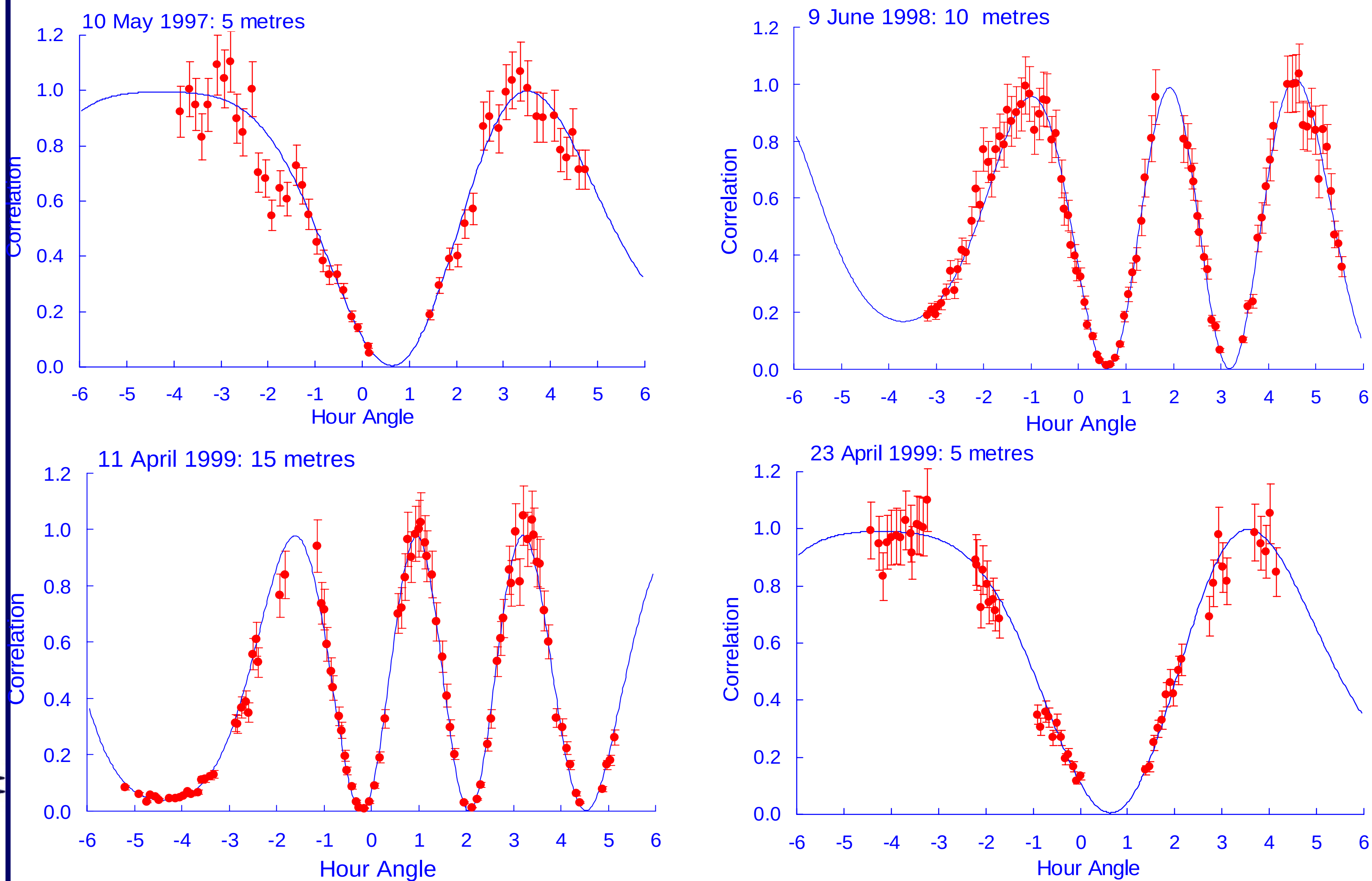


$$V_{binary}^2 = \frac{|V_A|^2 + r^2|V_B|^2 + 2r|V_A||V_B|\cos(\frac{2\pi}{\lambda}B\bullet\Delta s)}{(1+r)^2}$$

- Projected baseline motion (earth rotation) varies relative geometry
- This geometry variation allows (straightforward!) estimation of binary separation



Examples of SUSI Observations of β Centauri



Courtesy J. Davis

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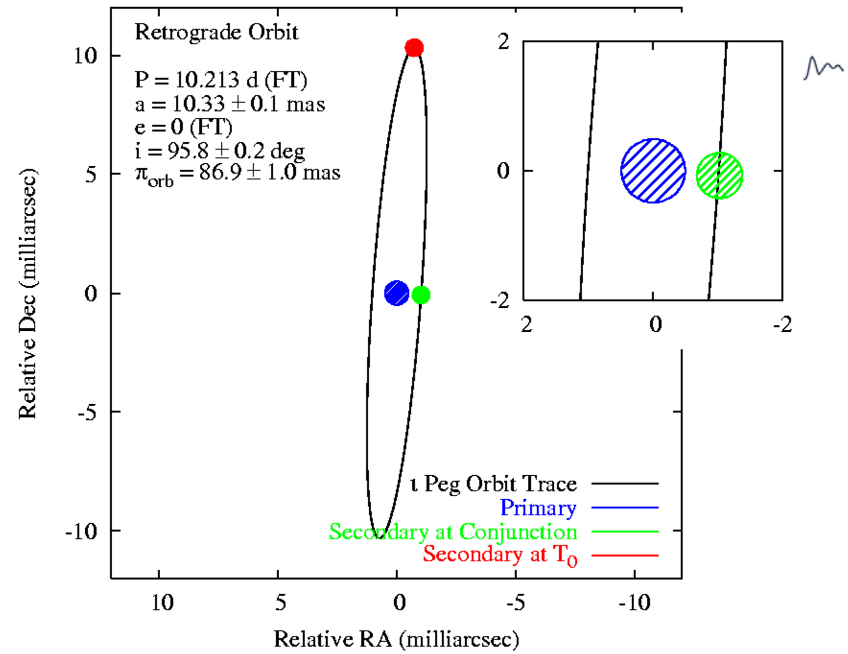
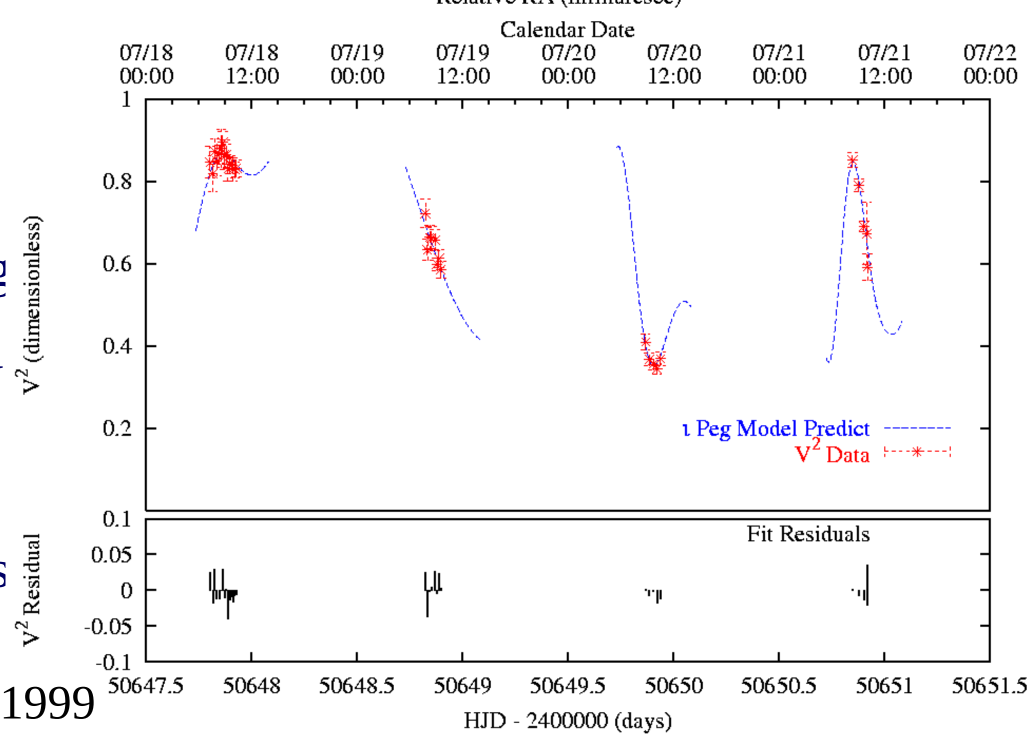
Integrated Modeling I

- Separation vector modeling works in many cases, but breaks down when:
  - System is marginally resolved, providing little visibility evolution on a given night
  - Few data points are available on given night
  - System moves appreciably during night
- Solution: integrated modeling – estimating orbit directly from visibilities (just like RV Orbit modeling)
- This is what (essentially) everyone in the business does





7-10 July 2003

Boden et al 1999

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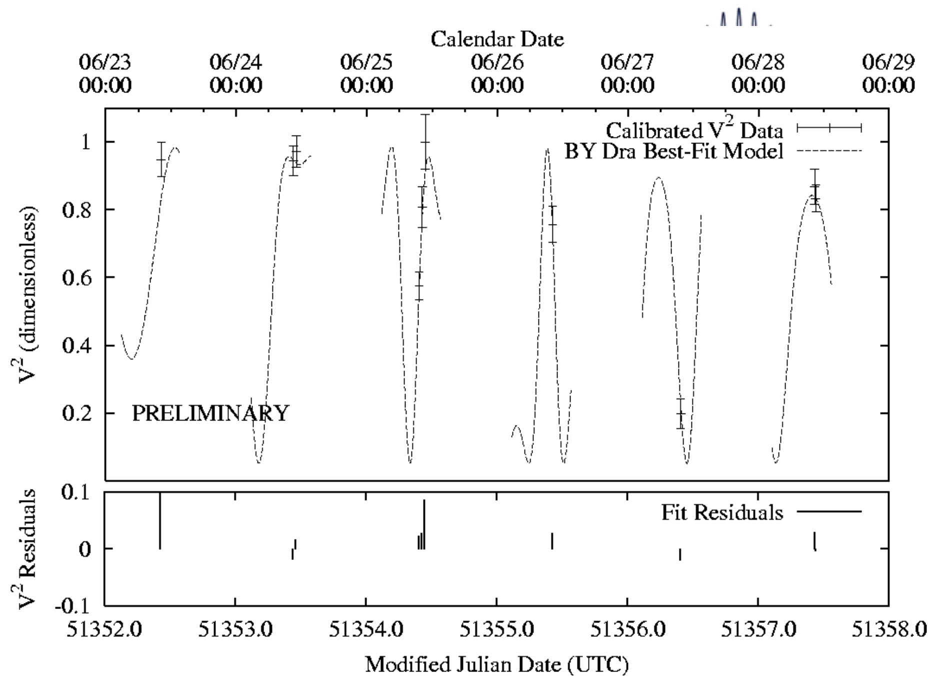
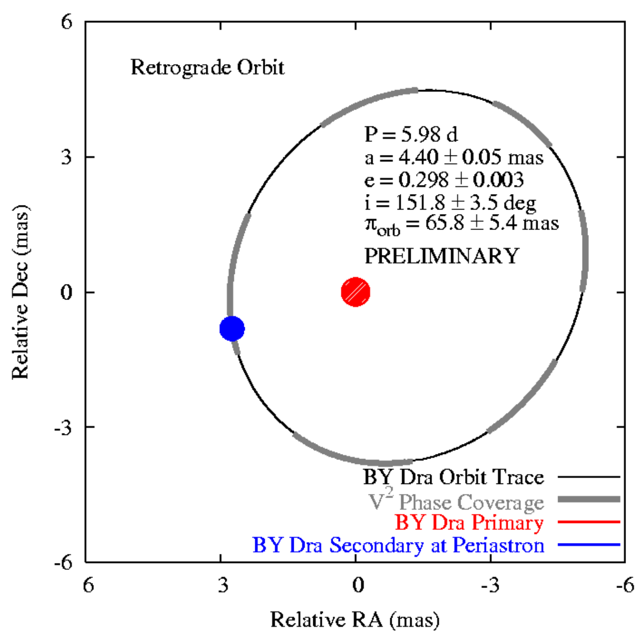
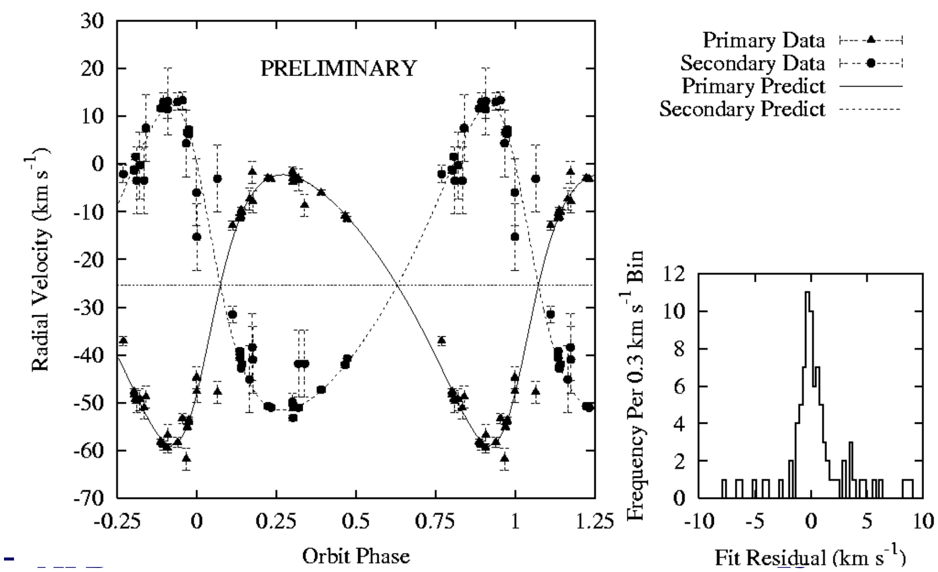
Integrated Modeling II

- While you’re at it, you might as well also directly integrate with RV measurements



Boden & Lane 2000





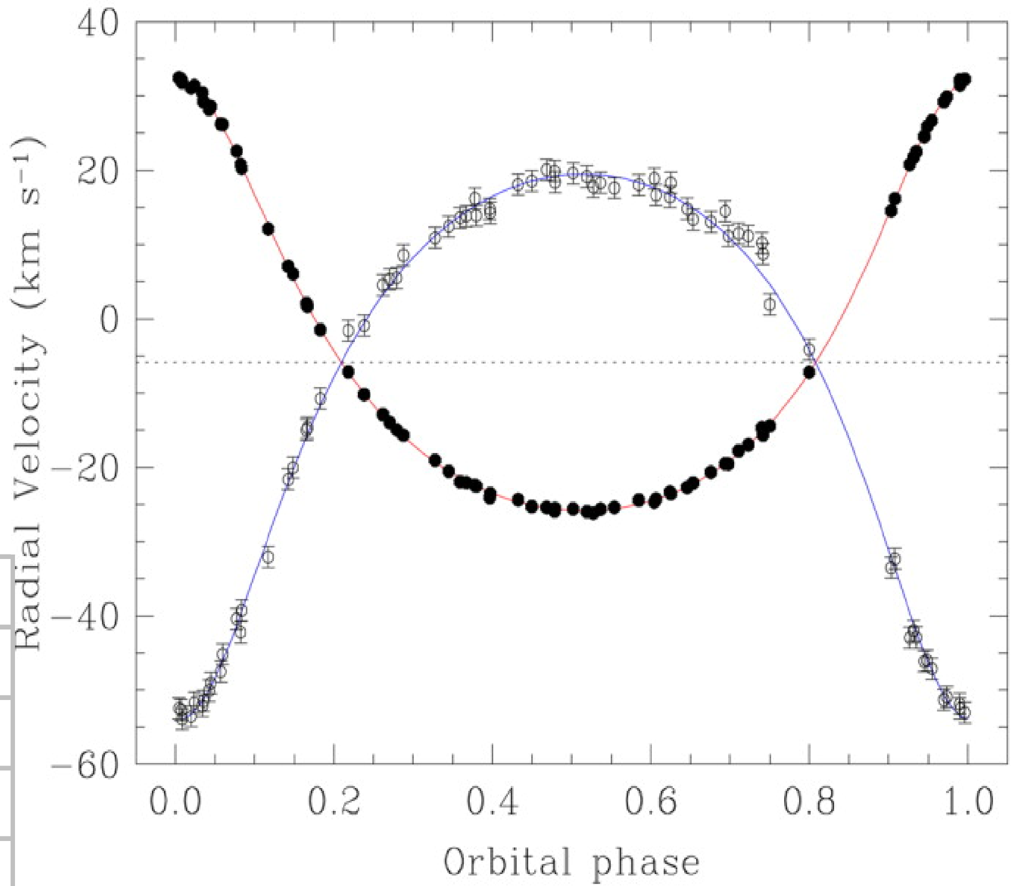
Case Study: HD 195987

- HD 195987 is a modestly low-metallicity ([Fe/H] ~ -0.5) double-lined spectroscopic binary (SB2)
- (Essentially) no eclipsing system constraints for metal-poor stellar models
- RV Orbit determine as part of Carney-Latham high-proper-motion survey
- Long-term velocity monitoring CfA
- Visibility orbit from PTI circa 1999
- Integrated orbit solution (Torres et al 2002)
- First (precision) O/IR interferometric solution for “metallicly-challenged” system

HD 195987 RV Orbit

- Modest eccentricity (*e*~0.3) double-lined orbit
- 0.1 contrast ratio in the visible – TODCOR extraction of RV lines
- 73 double-lined measurements

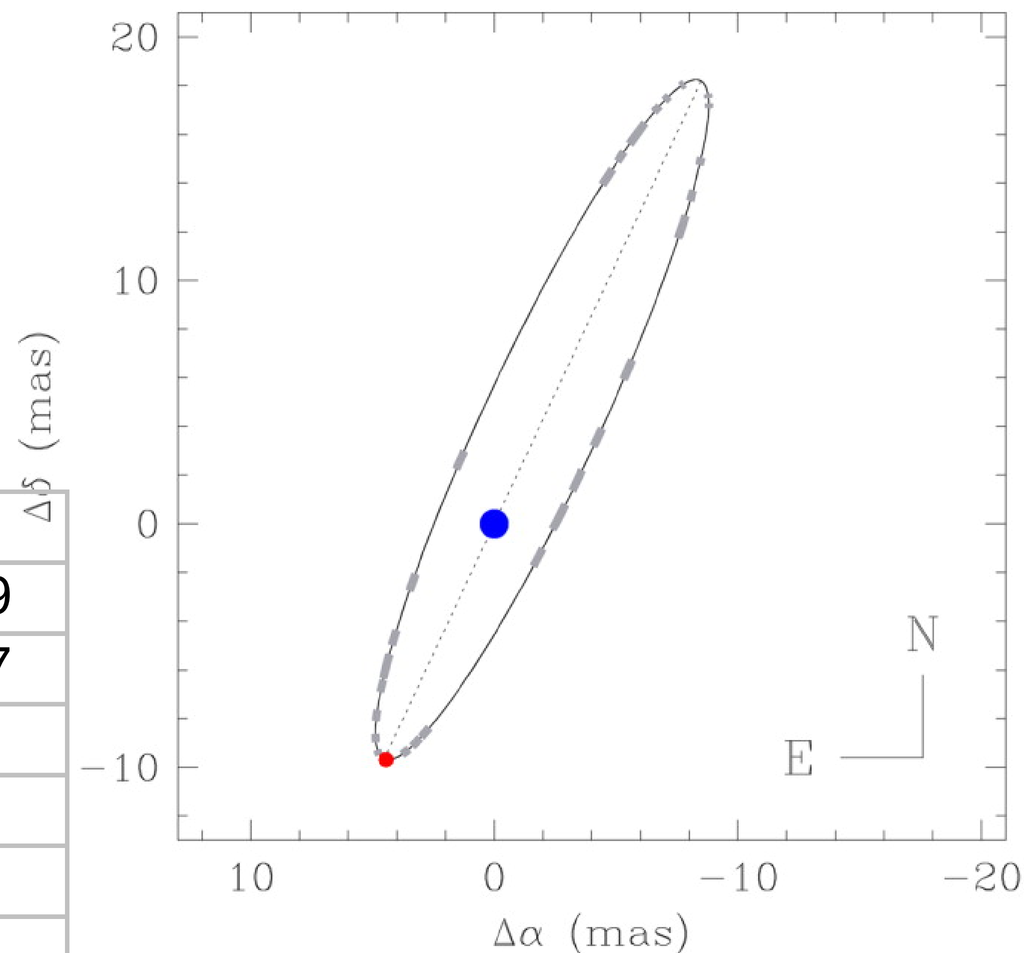
T0 (d)	49404.825 ± 0.045
e	0.3103 ± 0.0018
γ	-5.867 ± 0.038
KA	28.944 ± 0.046
KB	36.73 ± 0.21
ω	357.03 ± 0.35



HD 195987 Visual Orbit

- a” ~ 15 mas; easily resolvable with PTI
- K-band operation facilitates measurement of secondary (r ~ 0.38)

P (d)	57.3298 ± 0.0035
T0	51354.000 ± 0.069
e	0.30740 ± 0.00067
a	15.368 ± 0.028
i	99.379 ± 0.088
Ω	335.061 ± 0.082
ω	358.89 ± 0.53

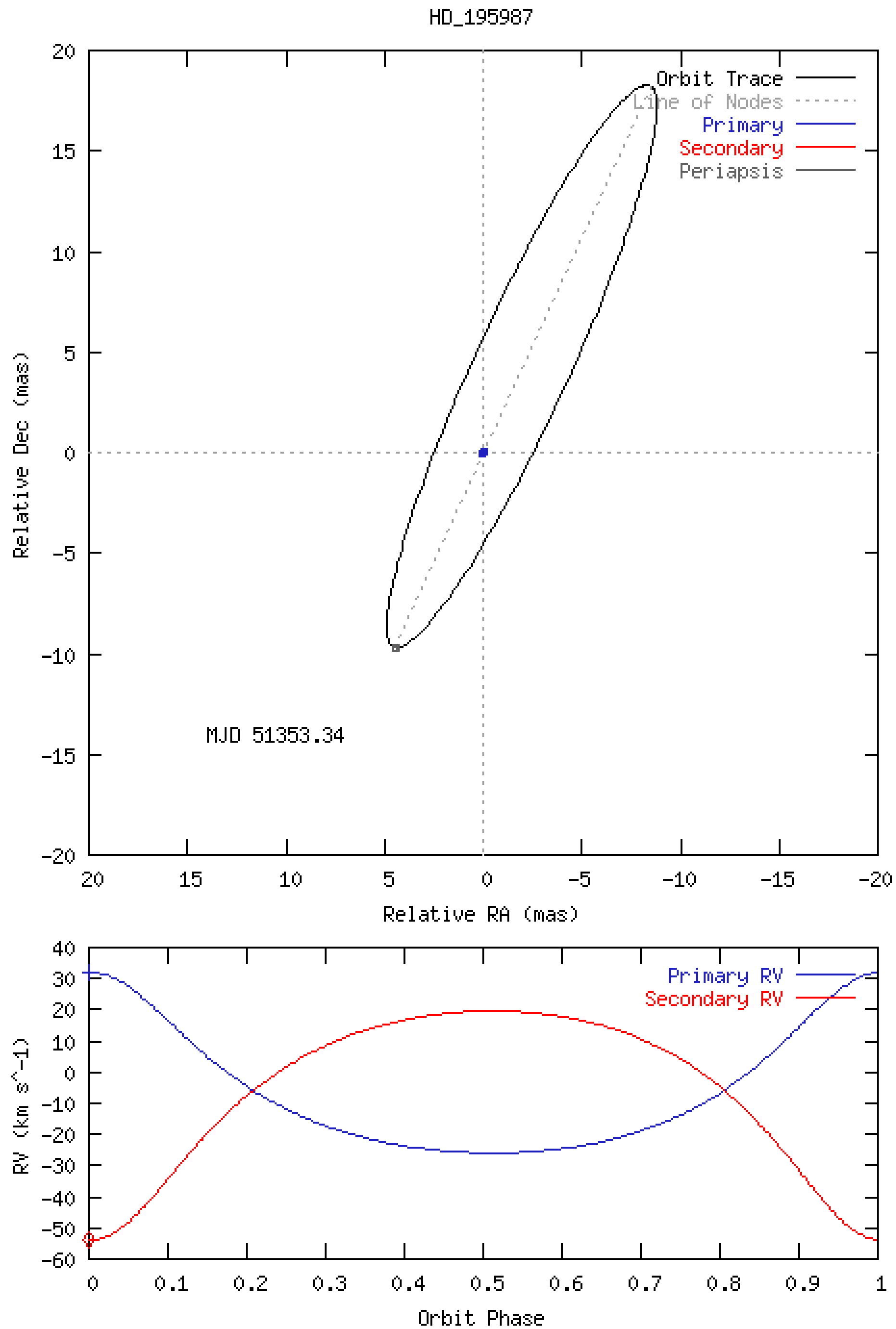


Components rendered 3x actual size

HD 195987 Physical Orbit

- Simultaneous solution to both RV and PTI visibility data
- Complementary information about "mutual" elements (P, T_0, *e*, ω)

P	57.32178 ± 0.00029
T0	51353.813 ± 0.038
γ	-5.841 ± 0.037
KA	28.929 ± 0.046
KB	36.72 ± 0.21
a	15.378 ± 0.027
e	0.30626 ± 0.00057
i	99.364 ± 0.080
Ω	334.960 ± 0.070
ω	357.40 ± 0.29



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HD 195987 System Parameters

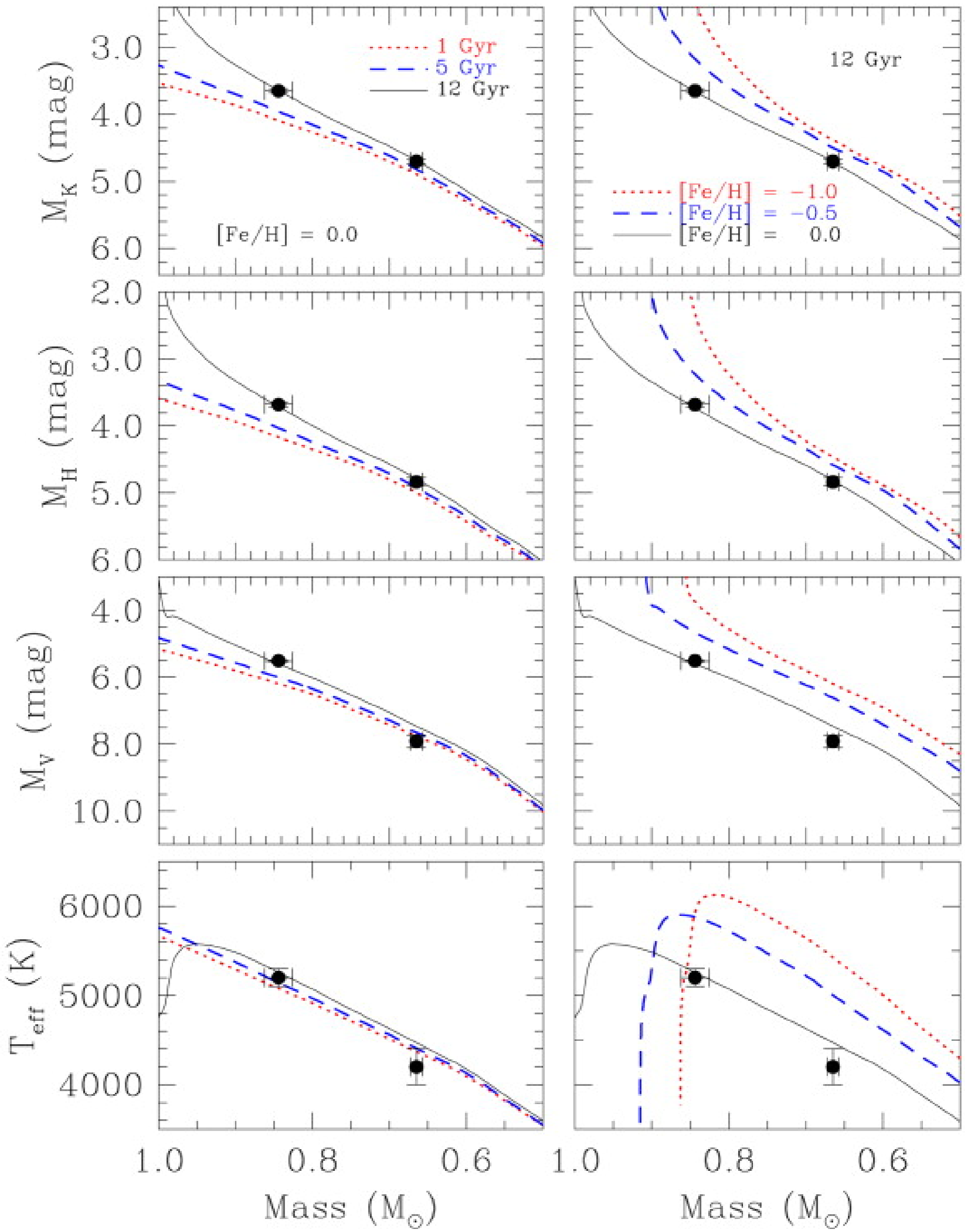
2% Primary Mass, 1% Secondary Mass

Parameter	Primary	Secondary
Mass (M)..	0.844 ± 0.018	0.6650 ± 0.0079
Teff (K)...	5200 ± 100	4200 ± 200
oPlx (mas)	46.08 ± 0.27	
Dist (pc)...	21.70 ± 0.13	
MV (mag).	5.511 ± 0.028	7.91 ± 0.19
MH (mag)	3.679 ± 0.037	4.835 ± 0.059
MK (mag)	3.646 ± 0.033	4.702 ± 0.034
V-K (mag)	1.865 ± 0.039	3.21 ± 0.19

Factor of two better than Hipparcos

Stellar Model Comparisons

- Having determined component parameters, it's time to test stellar models!
- No single set of models do a perfect job of predicting HD195987 component parameters
- This is how an observationalist defines progress…



Future Directions

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- We've been doing this binary thing for a while, what is there left to do?
  - Component parameters for stars that are not well covered by eclipsing systems
    - Subgiant & Giant stars
    - Pre-main sequence stars
    - Metal-poor & metal-rich stars
  - Systems where there's "extra" physics
    - Tidal interaction & angular momentum evolution
    - Interacting systems
    - Higher-order (hierarchical) systems
  - Systems where there is science beyond/in addition to the component properties
    - e.g. Cluster distances and ages

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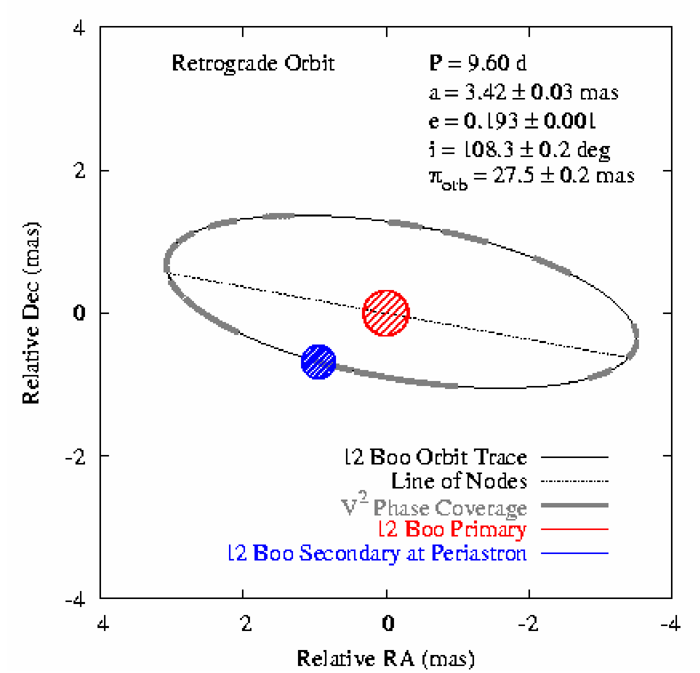
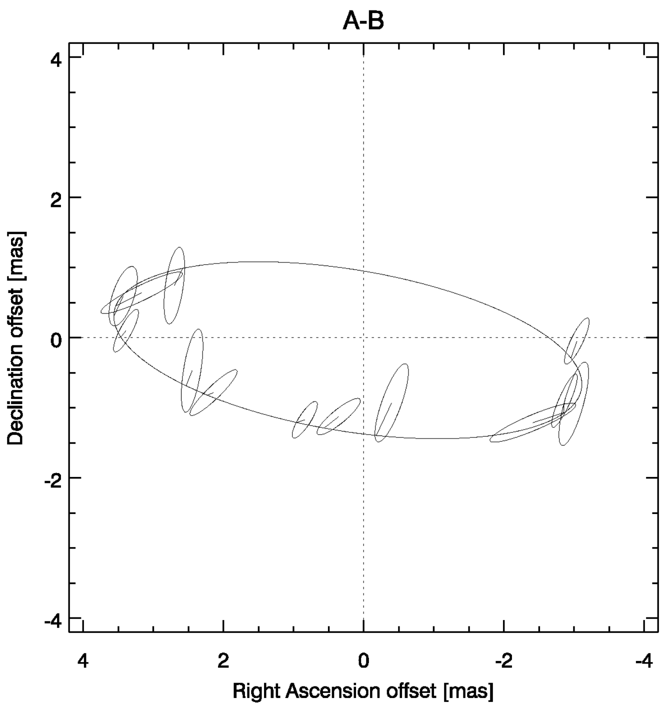
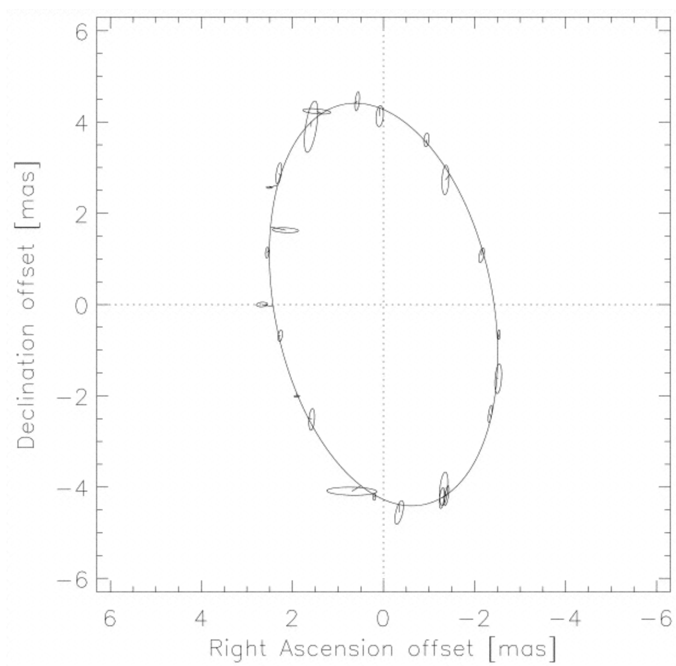
Evolved Stars

- Surprisingly few high-precision tests exist of stars off the main sequence…
  - 12 Boo
  - Omi Leo
- But some more are on the way…







Short Period Systems:

Tidal Interactions

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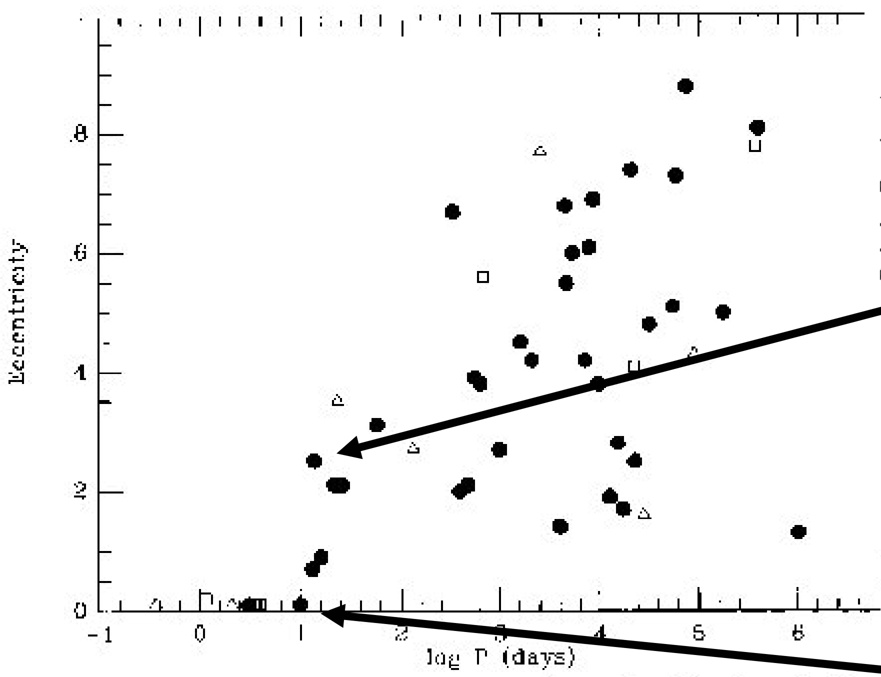
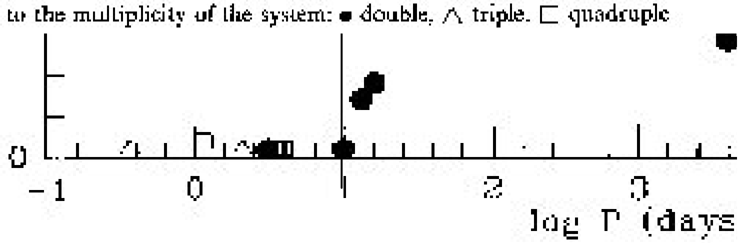


Fig. 5. Diagram eccentricity versus period for the complete nearby G-dwarf sample. Note the strong circularization effect due to tidal stresses for short periods binaries. The symbols are according to the multiplicity of the system: ● double, △ triple, □ quadruple



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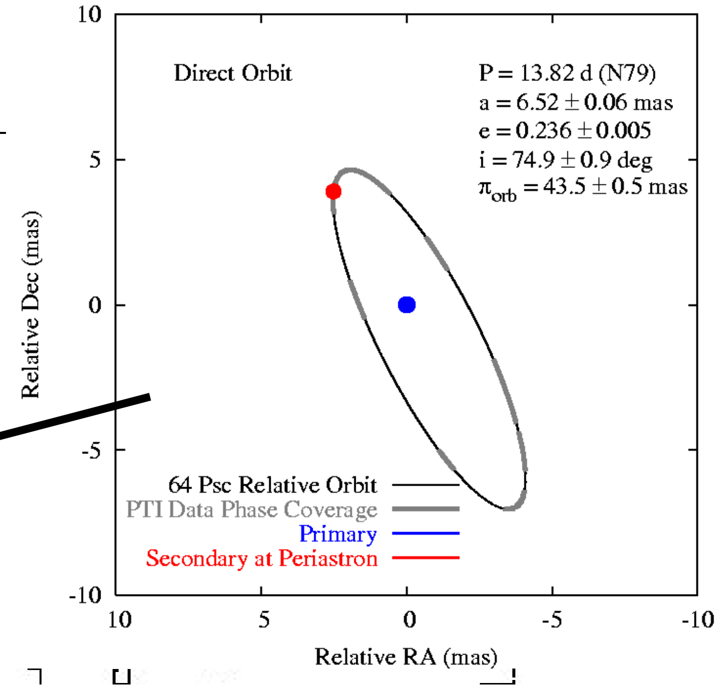

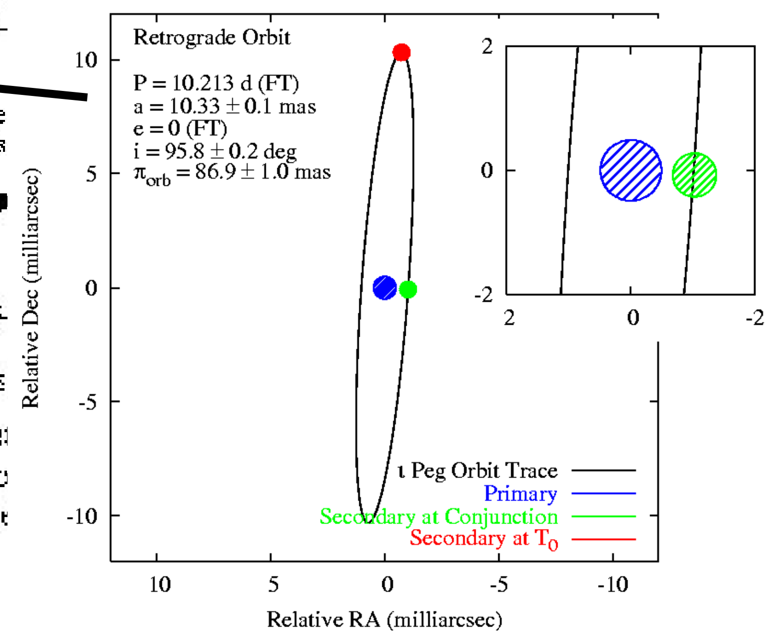

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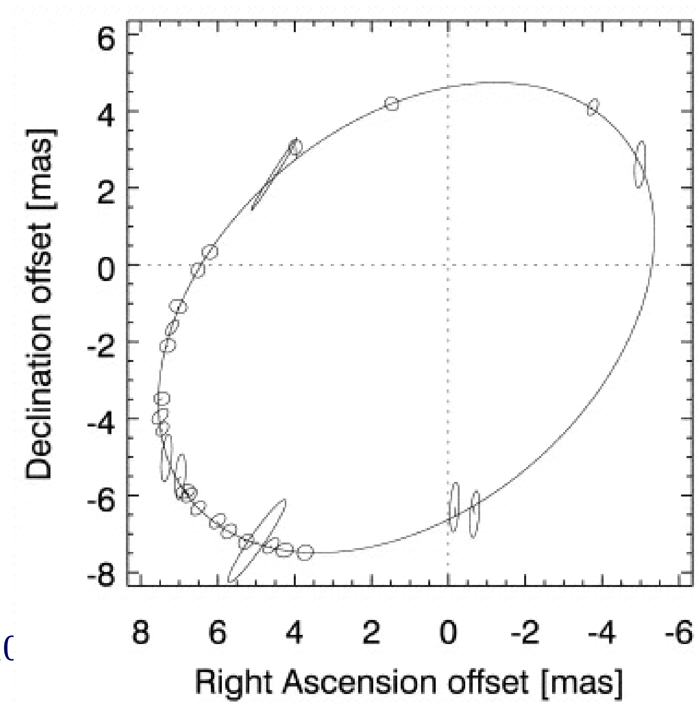
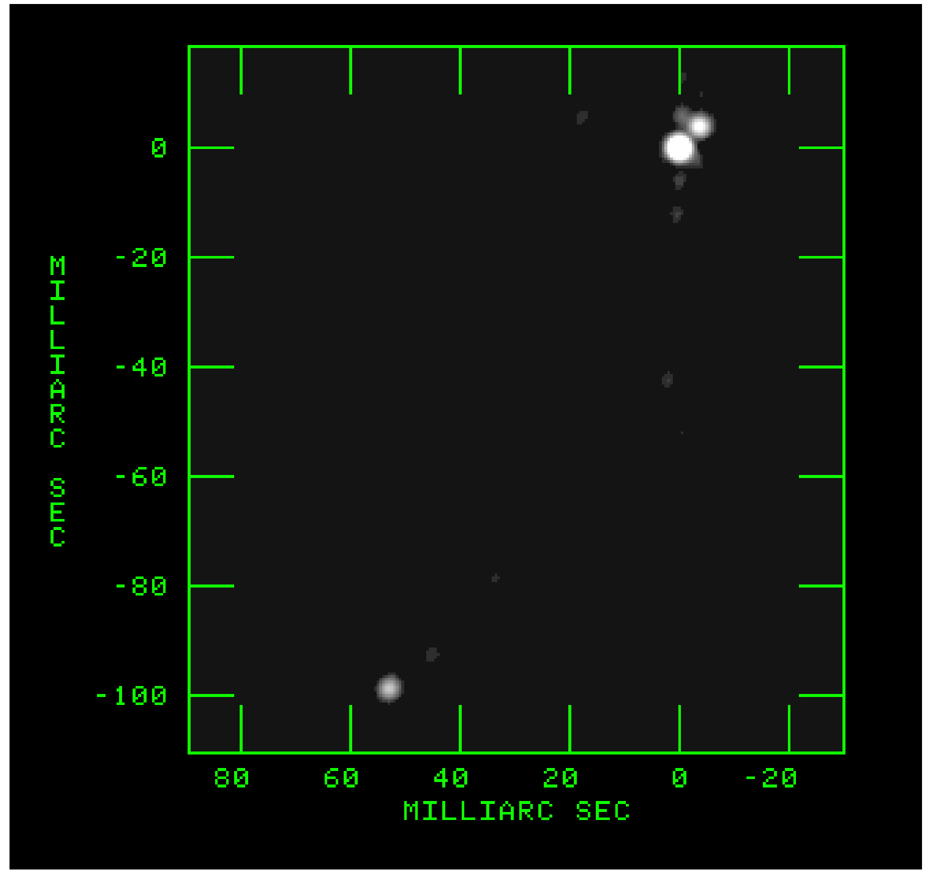
Hierarchical Systems

- η Vir was a known triple system recently done by NPOI (Hummel et al 2003)
- Non-coplanarity of outer and inner orbits established (diff 5.1 +/- 1.0 deg)





The Triple System η Vir
Hummel et al 2003

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Summary (what to take away…)

- Binaries are important systems to study
  - "The hydrogen atoms of stellar astrophysics" argument
- LB Interferometers have an important role to play in binary star studies:
  - Making "visual" binaries out of "spectroscopic" ones
  - Resolving more distant systems
  - "Competitive" accuracy with eclipsing systems
  - Providing angular scale (distance!) for eclipsing systems
  - Providing additional component diversity beyond eclipsing systems
- LB Interferometers can also provide new windows into physics beyond component parameters
  - Tidal interactions
  - "Yardsticks and chronometers"
- All interferometers should study binary stars
  - (…to the exclusion of *all* other science…)
- Enjoy BC…