PHASES

The Palomar High-precision Astrometric Search for Exoplanet Systems

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Reference Fields

- Wide-angle (Global) Astrometry
  - Absolute Positions of Stars on Sky
  - Limited by Atmosphere or Size of Satellite
  - Precisions $\approx$ few mas
  - 2012: SIM, precisions 4 μas
- Narrow-Angle Astrometry
  - Separations $\approx$ 10-30 arcsec
  - Target and Reference may be physically related. Unimportant for few-year timescale phenomena.
  - Precisions$\approx$ 20-100 μas.
- Sub-Arcsecond Astrometry
  - Target and Reference physically related Orbital motion can be significant.
  - Precision measured relative to separation.

Dualstar Advantages

- Unbiased Estimators
- Differential Measurements
- Apply Full Angular Resolution of Interferometer to Larger Field Of View
  (Not limited to Interferometric Field-of-View/Coherence Length/Fringe Packet Size)
- Observable Insensitive to Effective Bandpass/Fringe Packet Shape to high order
- Calibration tied to stability of metrology laser, rather than other astrophysical sources of potentially unknown nature.

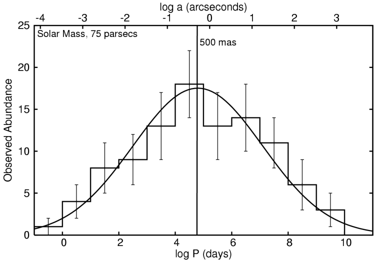
Dualstar Experiment

At Mark III (Colavita, 1994) and PTI (Shao et al, 1999).

- Differential astrometry on 8-50 arcsec separation pairs
- Starlight separated at telescopes
- Bright star $K \sim 4.5$
- Finite Fringe Lock Lengths: Faint star $K \sim 7$
- $\sim 100\mu$as repeatability over weeks to months
- 1 Target in PTI sky: 61 Cyg
- 16 Cyg (with exoplanet!): A few degrees too far north!
- Complex, Occasional Metrology Alignment Drops/Realignments

PHASES Modification: Motivations

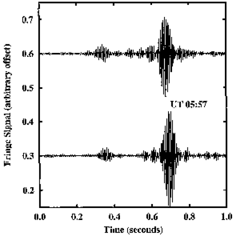
- **Need a Bright Reference Star Nearby:**
  Much more likely if you target physically associated binaries.
- **Need More Science Targets:** For bright stars, distribution of binaries peaks at $\sim$ few 100 mas.



(Measurements from Duquennoy & Mayor 1991)

- **Need a Simpler Instrumental Setup:**
  Telescopes cannot resolve subarcsecond binaries; split light later.

PHASES Modification: Timeline



(Dyck, Benson, and Schloerb, 1995.)

- Began 2002, (built on many years of dualstar development)
- Routine operations late 2003
- Technique published 2004 (Lane & Muterspaugh, ApJ)
- First Science 2005 (Muterspaugh et al., AJ)

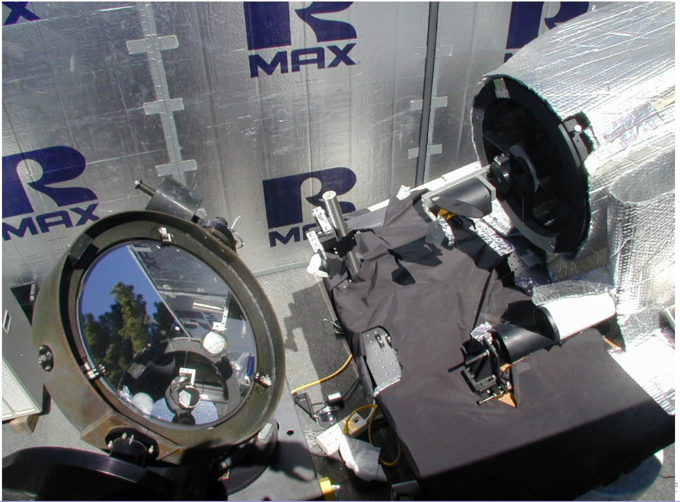
PHASES Modification: New Challenges

- Star and Reference light mixed
- New observable, not as clean; new data pipeline and algorithm
- New systematics
- Automation and reliability to enable frequent observing

The Palomar Testbed Interferometer

Light Collectors

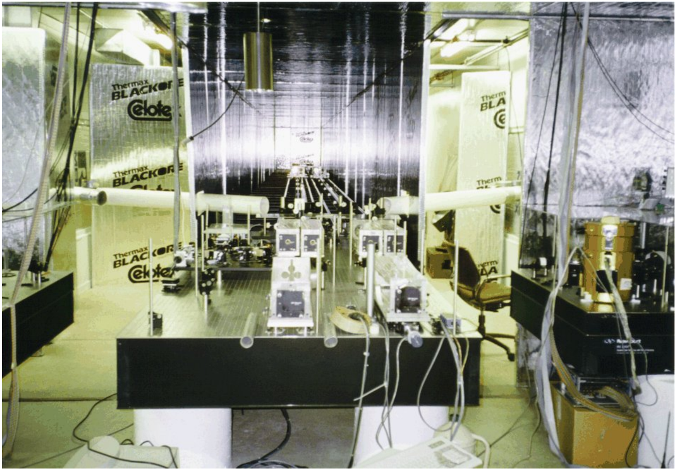
Light Collectors



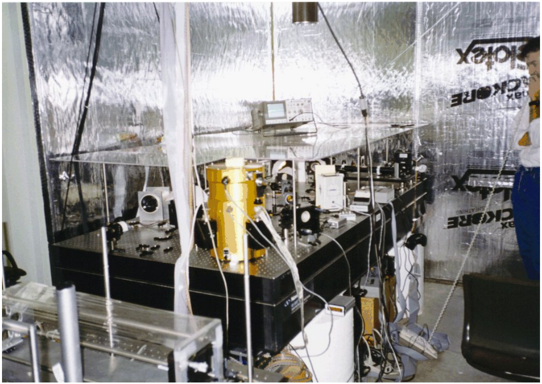
Light Pipes

National Geographic 2004 "Pictures of the Year"

Delay Lines

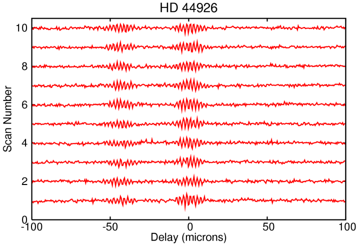


Beam Combiners



Control

PHASES Data and Reduction



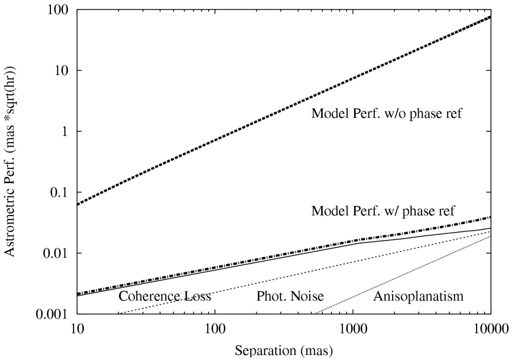
- Fringe fitting: highly oscillatory PDF—processor intensive.
- Fringe Packet Fitting: χ^2 vs. Separation
- Convert Delay Separation to Sky Separation via Baseline
- Sum Oscillatory χ^2 on grid of RA, Dec, Incoherently
- Global minimum: coadd χ^2 over many scans
- Non-global minuma blurred by earth rotation.

Useful Tools

- NOVAS/NOVAS-C: Naval Observatory Vector Astrometry Subroutines
  Kaplan and Bangert
  Time Required To Learn: 1 Long, Miserable, Focused Weekend
- MPI/MPICH: Multiprocessing interface with simple inter-process communications.
  Time Required To Learn: 1 Cloudy Winter Night, Isolated at the Observatory

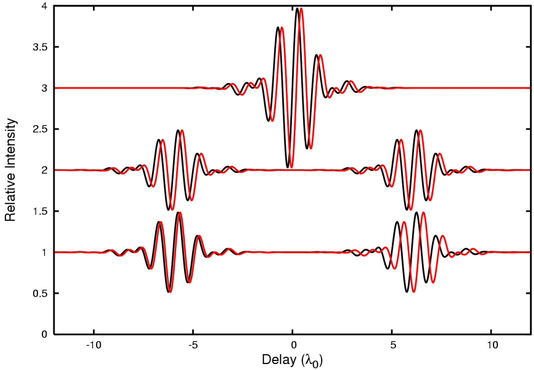
Differential Astrometry: Theoretical Precision

$$\delta D = \delta\vec{s}\cdot\vec{B} - \delta d - \delta a$$



- Baseline $\vec{B}$ measured by wide-angle astrometry.
- Internal delay d measured by laser interferometer.
- $\delta a(t, \vec{s})$ nonzero due to two terms:
  1. Anisoplanatism: $\delta\vec{s} > 30$ arcsec.
  2. Coherence Loss: Temporal turbulence variations.

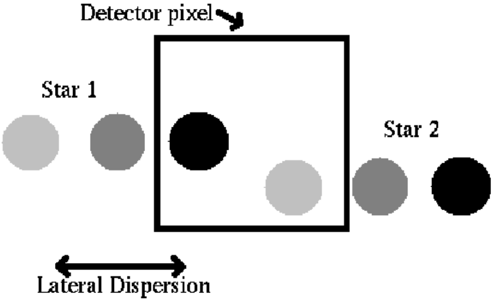
Differential Dispersion



Order of Magnitude: 30 μas

Use vacuum delay lines or a dispersion compensator!

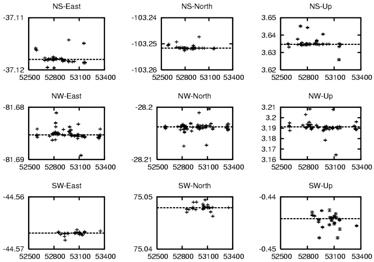
Differential Dispersion



Order of Magnitude: 30 μas

Again, Use vacuum delay lines or a dispersion compensator!

Baseline Errors



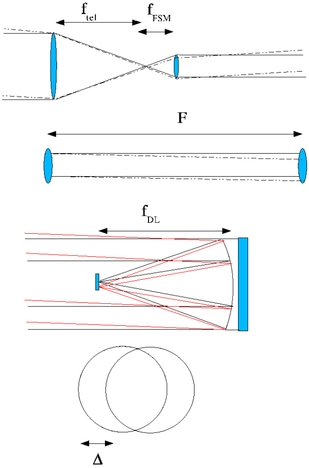
$$\overrightarrow{B} \cdot \overrightarrow{\Delta S} = \left(\overrightarrow{B} + \overrightarrow{\sigma_B}\right) \cdot \left(\overrightarrow{\Delta S} + \overrightarrow{\sigma_{\Delta S}}\right)$$

$$\frac{\sigma_{\delta S}}{\delta S} = -\frac{\sigma_{Bx}\cos\phi + \sigma_{By}\sin\phi + \sigma_{Bz}\tan z}{|B|}.$$

$B = 100$m, $z < 45$ deg, $\sigma_B \sim 2$mm, $\delta S \sim 0.5$as: 10 μas.

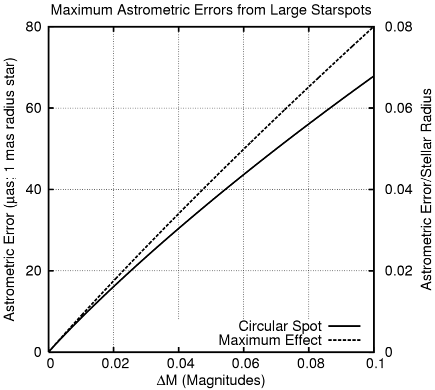
Order of Magnitude: < 10 μas

Beam Walk



Order of Magnitude: 0.5 μas

Starspots and Granulation

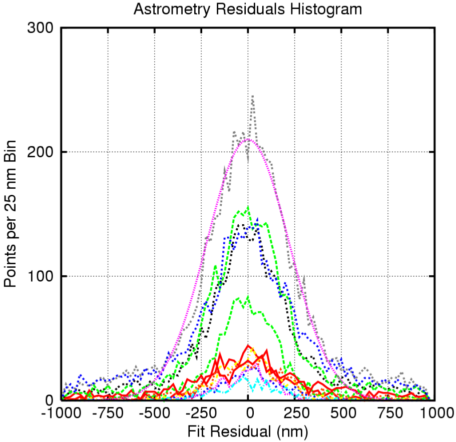


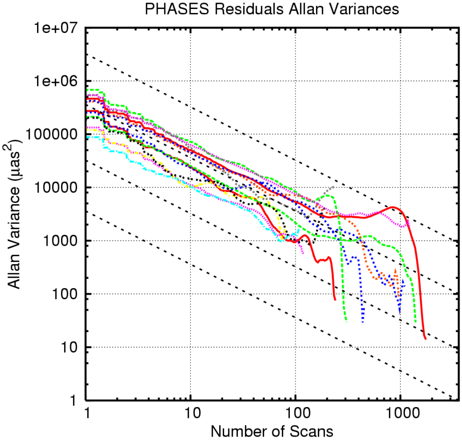
Order of Magnitude: $< 8\ \mu$as, $< 3\ \mu$as

Other Errors

- Fringe Template (1 μas)
- Scan Rate (1 μas)
  $\Delta s \approx 500\,\mathrm{mas} \times \cos(2\pi t/\mathrm{day})$
  Take first derivative, convert sky angle to delay: 20 nm/sec = 5 nm/scan = 10 μas, but cancels by 10$\times$.
  Second order (curvature) at nano-as level.
- Global Astrometry ($<$ 1 μas)

Differential Delay Residuals

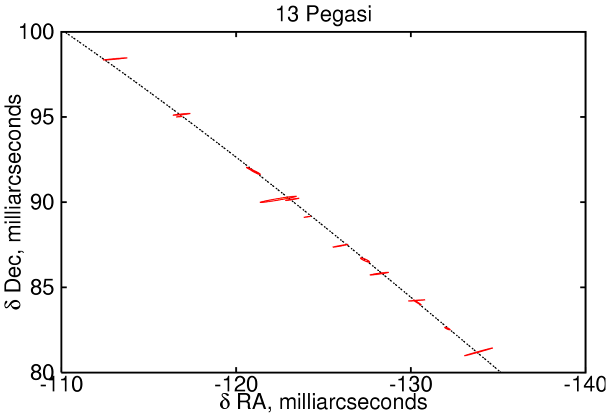




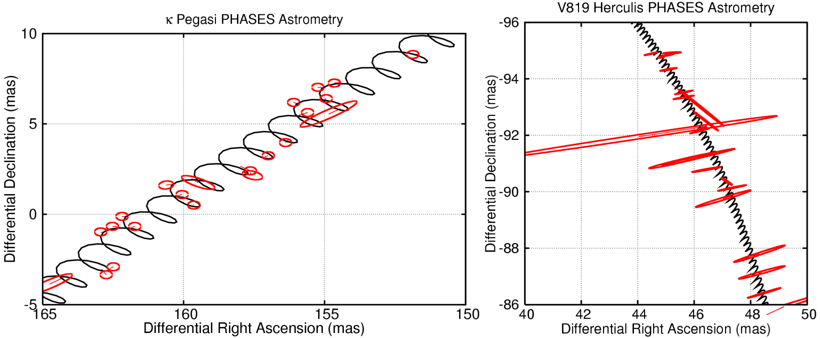
13 Pegasi

F2IV
33 pc, P=29y

- Median minor axis error: 12.8 μas
- Average relative precision: $\frac{13}{155000} = 8 \times 10^{-5}$
- Slope consistent with speckle orbit.

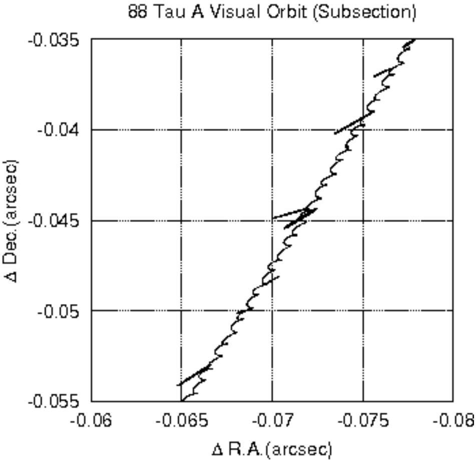


Triple Stars: Results



- κ Peg
  - P_o =11.6 yr, P_i = 5.97 d
  - $\Phi = 43.4 \pm 3.9$ deg
- V819 Her
  - P_o =5.5 yr, P_i = 2.23 d
  - $\Phi = 26.3 \pm 1.5$ deg

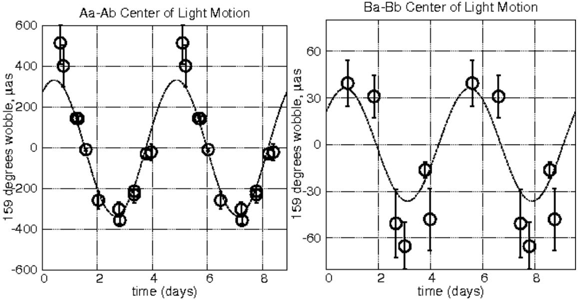
Quadruple Stars: 88 Tau A



- $P_o = 18$ yr,
  $P_i = 3.57$ d,
  $P_i = 7.89$ d
- $\Phi = 143.3 \pm 2.5$ deg,
  $\Phi = 82.0 \pm 3.3$ deg

Lane et al. 2007

Quadruple Stars: μ Ori



μ Ori

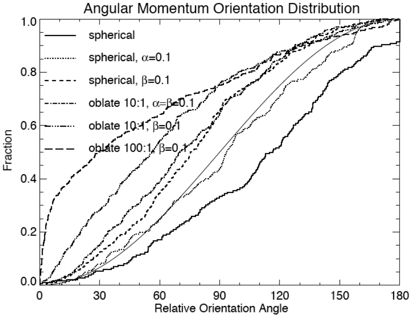
- $P_o = 18.7$ yr, $P_i = 4.45$ d, $P_i = 4.78$ d
- $\Phi = 136.7 \pm 8.3$ deg,
  $\Phi = 91.2 \pm 3.6$ deg

Muterspaugh et al. 2008

Triple System Structure: Theory I

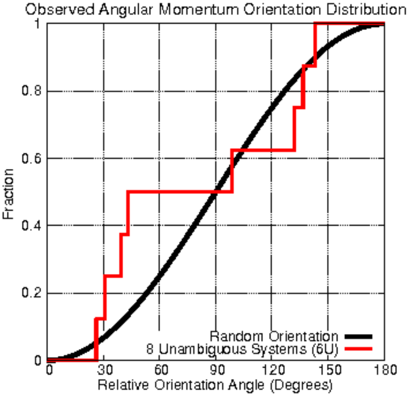
Sterzik & Tokovinin 2002

- Mutual Inclinations are key Observable
- Distribution if random orbits: $(1 - \cos\Phi)/2$
- More coplanar: fingerprint of structure in molecular cloud



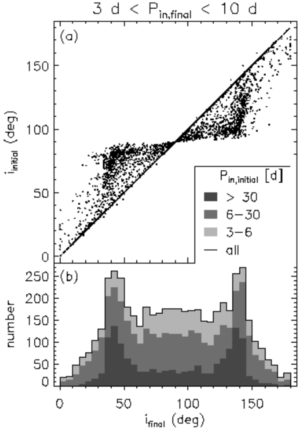
Random Coplanarity?

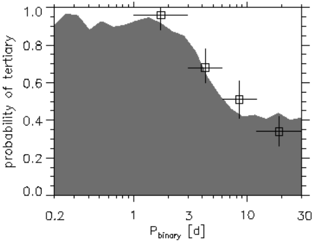
Sterzik & Tokovinin 2002: Mutual Inclination Distribution and Formation



Triple System Structure: Theory II

Fabrycky & Tremaine 2007





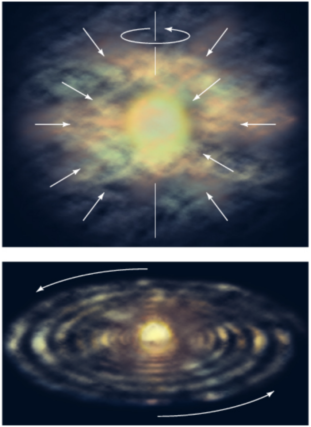
- Kozai Cycles with Tidal Friction
- Prediction: All short period binaries (< 10 days) have outer companions.
- Prediction: Spikes in Mutual Inclination distribution near 40, 140 degrees.
- Prediction: Planet Orbit/Star Spin Vectors Misaligned .

Spikes in Distribution?

Fabrycky & Tremaine, 2007 Predictions:

- Spikes Near 40, 140 degrees?
  - 5 systems outside 3-10 day range:
    V819 Her, Algol, η Vir, ξ UMa, ϵ Hya ABC
  - 0 systems in 3-10 day but outside 40-140 deg
  - 2 systems in 3-10 day and between 40 and 140 deg:
    μ Ori AB-BaBb, 88 Tau AaAb-Ab1Ab2
  - 3 systems in 3-10 day and near 40 and 140 deg:
    μ Ori AB-AaAb, 88 Tau AaAb-Aa1Aa2, κ Peg
- All Short Period Binaries are in Triples?
  - Tokovinin 2006
  - Deep AO Imaging, pushing visible identification to cross with RV sensitivity.
  - Results Consistent with All in Triples

Extrasolar Planets: Motivation



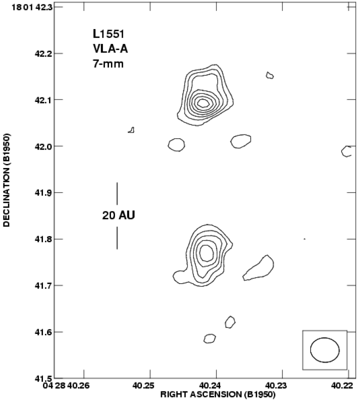


Image from Rodriguez et al., 1998

Planets In Binaries

Object	a_b (AU)	e	M_1/M_2	R_t (AU)	Refs
HD 188753	12.3	0.50	1.06/1.63	1.3	1
γ Cephei	18.5	0.36	1.59/0.34	3.6	2
GJ 86	$\sim$20		0.7/1.0	$\sim$5	3
HD 41004	$\sim$20		0.7/0.4	$\sim$6	4
HD 196885	$\sim$25		1.3/0.6	$\sim$7	5

(1) Konacki 2005

(2) Campbell et al. 1988, Hatzes et al. 2003

(3) Queloz et al. 2000, Mugrauer & Neuhauser 2005, Lagrange et al. 2006

(4) Zucker et al. 2004

(5) Chauvin et al. 2006

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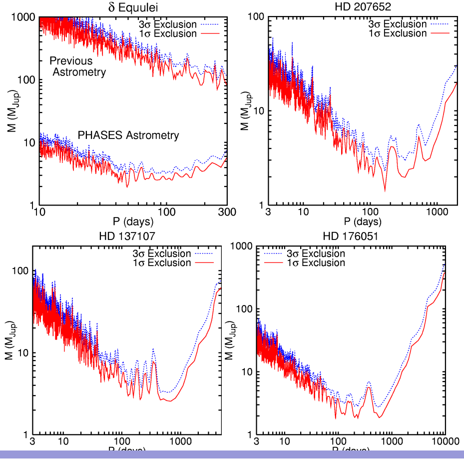
Palomar High-precision Astrometric Search for Exoplanet Systems



Recommendations

- Begin With A Reliable, Well Engineered Base System:
  V^2 mode should be 99% reliable before adding extra complexity.
- Automate it, procedurize:
  Necessary for reliability required for time-variable phenomena.
- Don't Push the Threshold of Reference Star Faintness
- Collaborate with RV