PHASES

The Palomar High-precision Astrometric Search for Exoplanet Systems

A Search for Planets in Binary Star Systems

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http://stuff.mit.edu/~matthew1/thesis/thesis.html

Planets In Binary Star Systems

57% of star systems are multiple

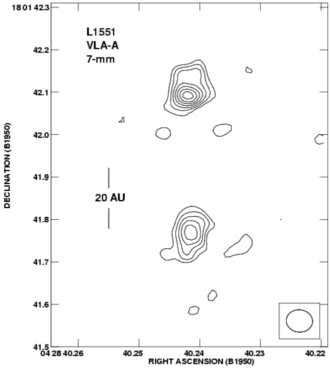
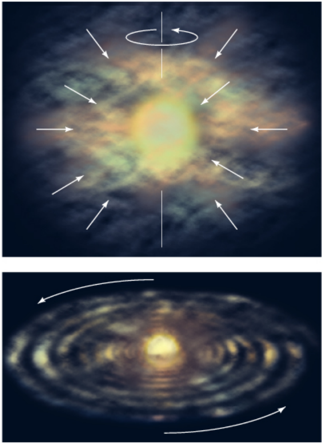


Image from Rodriguez et al., 1998

Close binaries complicate non-astrometric planet detection methods:

- Radial Velocity: Spectral "contamination".
- Stellar companions confuse photometric measurements.
- Light from stellar companions cannot be canceled by nulling and coronography, frustrating direct detection.

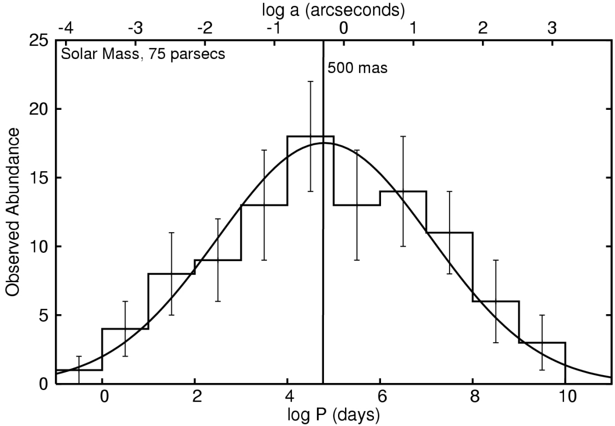
Planet Formation



Reference Fields

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

Binary Distribution

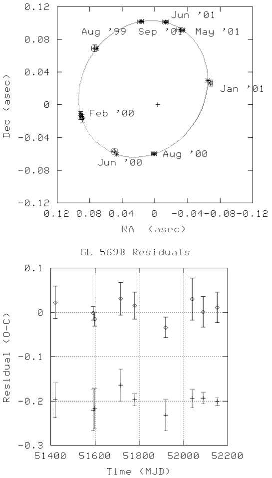


(Measurements from Duquennoy & Mayor 1991)

Required Precisions

- Stellar Astrophysics
  - Stellar Masses, Orbital Characteristics: 1% astrometry places constraints on current models.
  - Astrophysical Distance Scales: 1%.
- Detection of Additional Companions and Extrasolar Planets
  - Dynamically stable orbits at $\approx 20\%$ of binary separation. Relative effect on star: $\frac{\mathrm{M_J}}{\mathrm{M_\odot}} = 10^{-3}$
  - $1\mathrm{M_J}$ planet at critical orbit requires fractional precision $\approx 10^{-4}$.

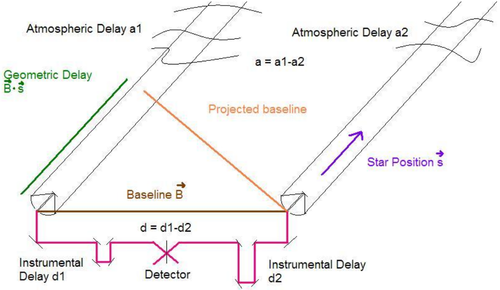
Single-Dish Astrometry

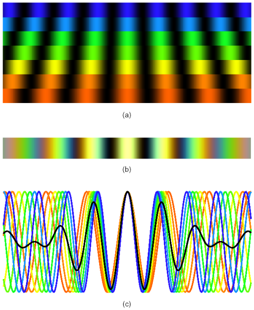


- Adaptive Optics, Speckle Interferometry
- System separation ≈ 100 mas.
- Astrometric Precision: ≈ 1 mas
- Precision limitations:
  - Atmosphere (Only negligible at small separations)
  - Pixel scale
  - Telescope size: Precision ∝ Diameter.

(Lane et al., 2001.)

Basic Interferometer



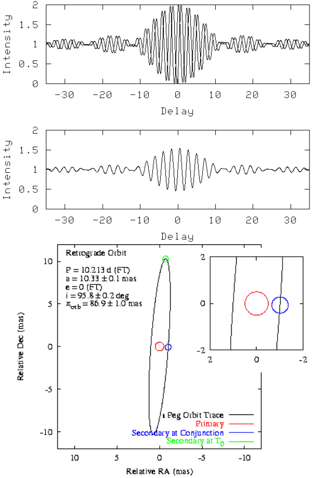


$$d = \vec{B} \cdot \vec{S} + \delta_a \left(\vec{S}, t \right) + c$$

$$I(x) = I_0 \left(1 + V \frac{\sin(\pi x / \Lambda)}{\pi x / \Lambda} \sin(2\pi x / \lambda) \right)$$

Image from Principles of Long Baseline Stellar Interferometry

Astrometry With Visibility Amplitudes

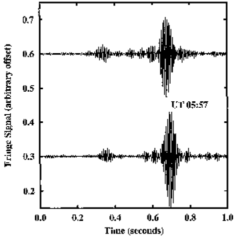


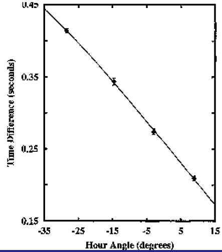
Fringe Amplitude determines separation.

- ι Peg: Parallax 1%, Axis 1%, Masses 1%.
- Precision: $\sigma_{V^2} \approx 1\%$.
  Integrated-optics: $\sigma_{V^2} \approx 0.1\%$.
- Limited field-of-view.
- Errors dominated by data calibration:
  - Visibility amplitudes are positive-biased data products.
  - Degeneracy between separation and starlight average wavelength.

(Boden et al., 1998.)

Over-Resolved Systems



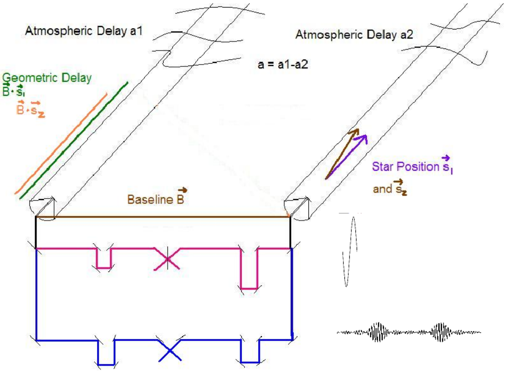


Measure each packet position separately.

- ζ Her: Fractional precision 3×10^{-3}.
- Atmosphere coherent on 10 ms timescale
- Observation of each star differs in time by 300 ms.
  Decoherence limits precision.
  Faster scanning limits sensitivity.
- Analysis traced "envelopes", discarded fringe phases. May bias results.

(Dyck, Benson, and Schloerb, 1995.)

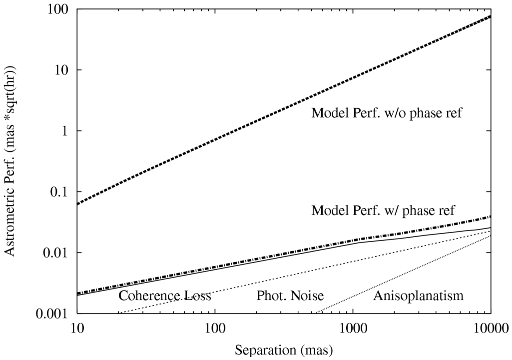
Phase-Referencing



- Fast tracking (10ms) determines a(t).
- Second detector stabilized, slowly scans the two stars.

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.

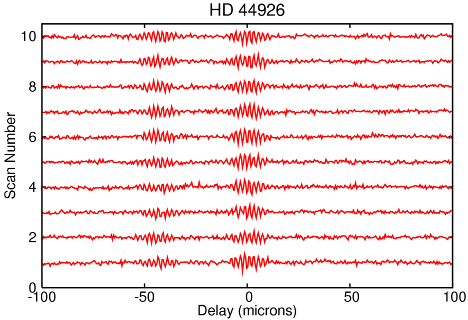
The Palomar Testbed Interferometer (PTI)

A.K.A. The Palomar 4,322 inch Telescope

The Palomar Testbed Interferometer (PTI)

National Geographic 2004 "Pictures of the Year"

PHASES Data and Reduction



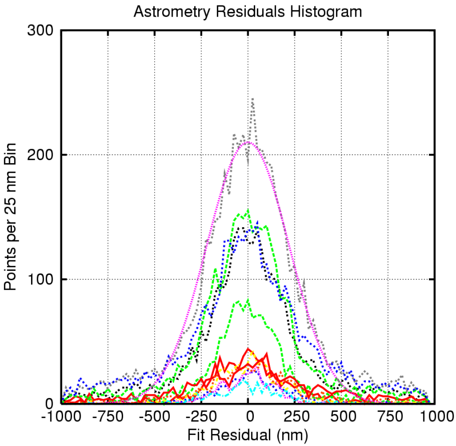
Fringe ambiguities in the presence of noise:

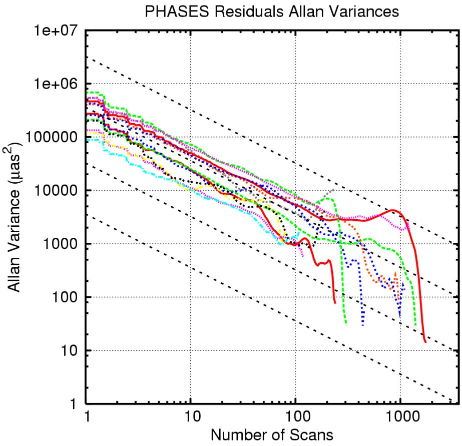
- Fringe fitting: highly oscillatory PDF—processor intensive.
- Incoherent averaging to determine correct local maxima.
- Incoherent averaging requires sub-wavelength stability.

Useful Tools

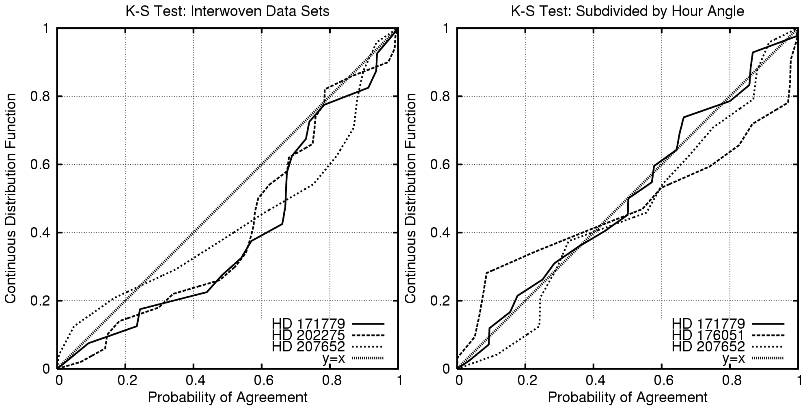
- NOVAS/NOVAS-C: Naval Observatory Vector Astrometry Subroutines
  Kaplan and Bangert
- MPI/MPICH: Multiprocessing interface with simple inter-process communications.

Differential Delay Residuals





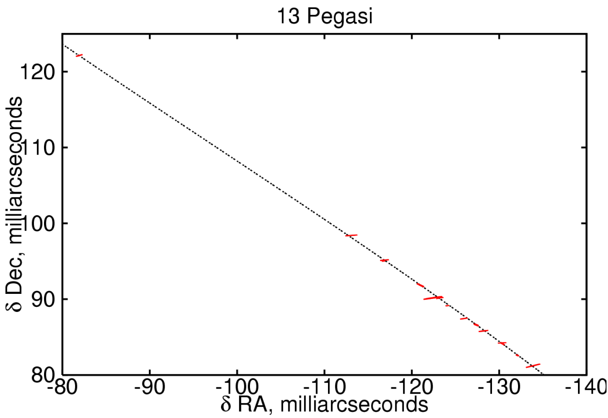
Intranight Repeatability



13 Pegasi

F2IV
33 pc, P=29y

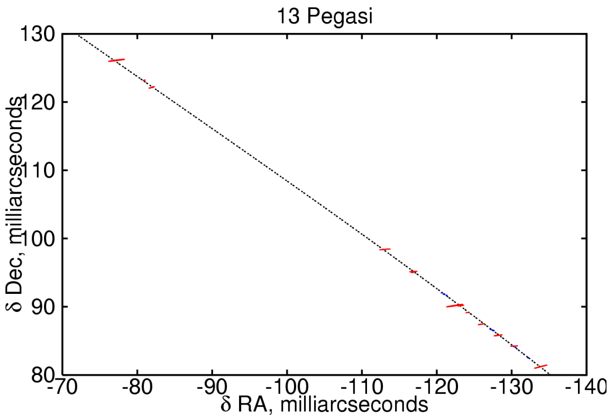
- Median minor axis error: 13.1 μas
- Average relative precision: $\frac{13}{160000} = 8 \times 10^{-5}$
- Slope consistent with speckle orbit.



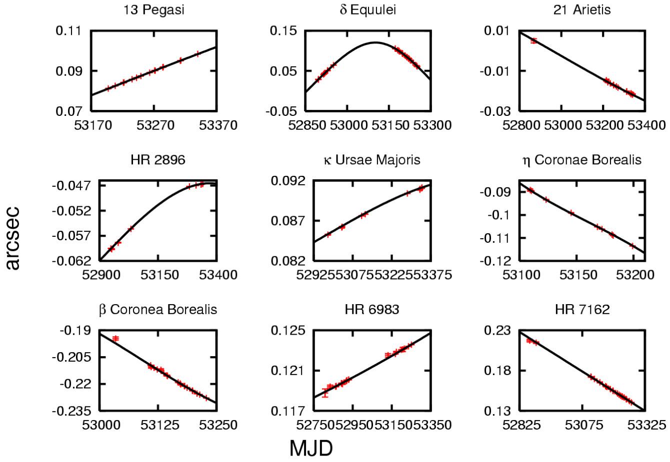
13 Pegasi

F2IV
33 pc, P=29y

- Median minor axis error: 16.4 μas
- Average relative precision: $\frac{16}{160000} = 10^{-4}$
- Slope consistent with speckle orbit.



Sample Results



δ Equulei

F7V+F7V

$P = 5.7058 \pm 0.0003$ years

$d = 18.39 \pm 0.05$ parsecs

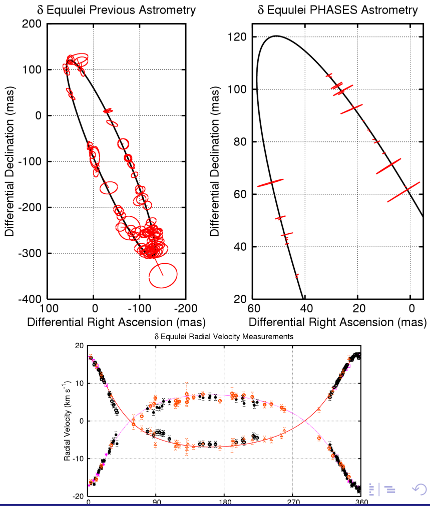
$V = 4.99,\ K = 3.27$

Each $1.19 \pm 0.01 \mathrm{M}_\odot$

Age 2.2 ± 0.6 Gyr

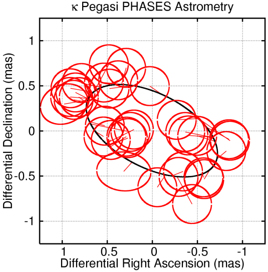
$$M_p \geq 11.5 \left(\frac{P}{\text{month}}\right)^{-\frac{2}{3}} \text{ Jupiter Masses}$$

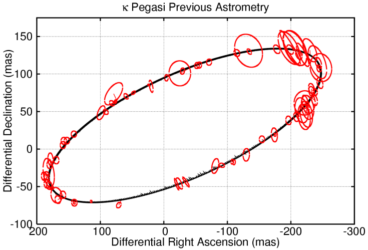
astro-ph/0507585

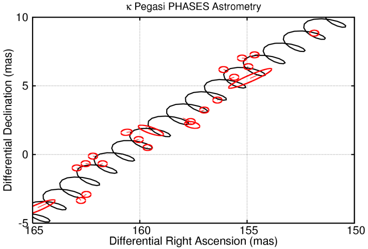


κ Pegasi

A: F5 IV, 1.54 $M_\odot$
Ba: F5 IV, 1.67 $M_\odot$
Bb: 0.82 $M_\odot$
A-B Period: 11.6 years
Ba-Bb Period: 5.97 days
Mutual Inclination: 43.8 degrees







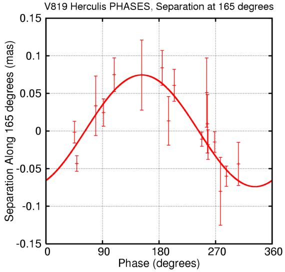
V819 Herculis

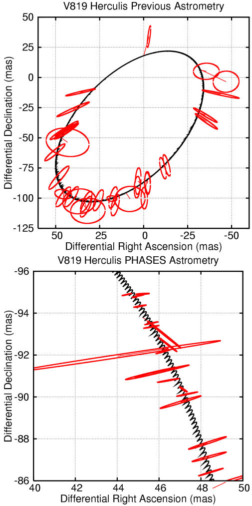
A-B Period: 5.5 years

Ba-Bb Period: 2.23 days

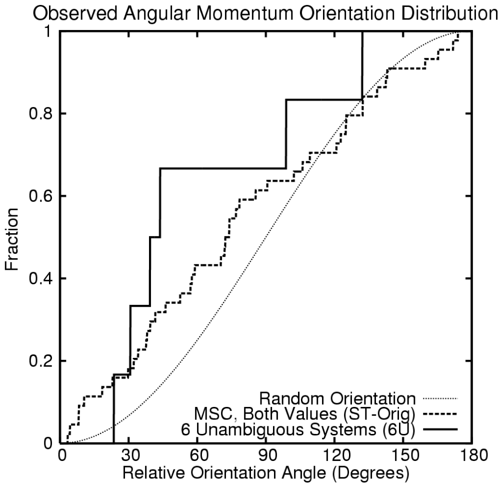
Ba-Bb shows eclipses

Mutual Inclination: 23.6 degrees





Mutual Inclinations

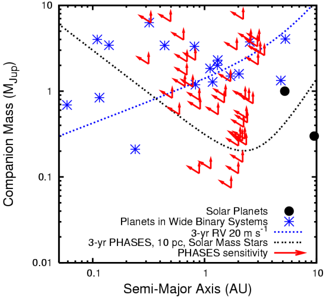


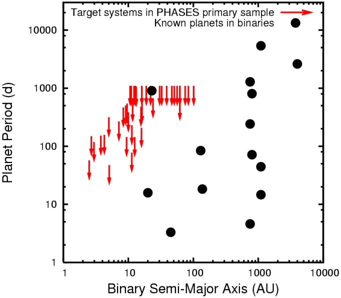
Future Work

$\approx$ 50 systems observable with *current* setup.

- Within view of PTI (dec $\approx +10$ to $+50$)
- $K < 4.5$
- Astrometry for $\Delta K < 1.5$. Direct detections at $\Delta K < 5$
- Separation less than 1 arcsecond
- Average $\mathrm{M_{pl,min}} = 0.7\mathrm{M_J}$.(3 $\sigma = 30\mu\mathrm{as}$)
- 36 systems: $\mathrm{M_{pl,min}} < 1\mathrm{M_J}$
- 17 systems: Maximum stable $\mathrm{P_{pl}} < 2\mathrm{y}$.

Conclusions





- Astrometry of sub-arcsecond binaries demonstrated at precisions $< 10^{-4}$.
- Astrometry detects faint companions to binary systems.
- A survey of sub-arcsecond binaries will search for planets around stars inaccessible to other methods.

Two Weeks Ago....

An extrasolar giant planet in a close triple-star system

Maciej Konacki[1]

Hot Jupiters are gas-giant planets orbiting with periods of 3–9 days around Sun-like stars. They are believed to form in a disk of gas and condensed matter at or beyond ~2.7 astronomical units (AU—the Sun–Earth distance) from their parent star[1,2]. At such distances, there exists a sufficient amount of solid material to produce a core capable of capturing enough gas to form a giant planet. Subsequently, they migrate inward to their present close

of planet formation in binary stellar systems is an impo and not only because the frequency of binaries among fiel than 1 Gyr is ~60% (ref. 14) and is even higher among sequence stars[15]. If we believe that the same basic processe formation of planets around single stars and componen

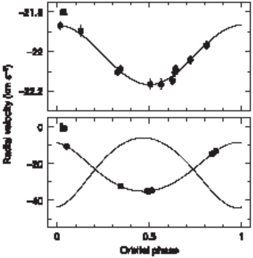
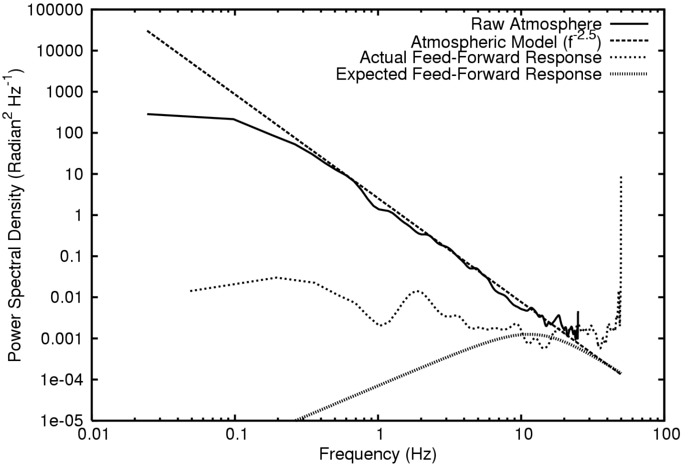


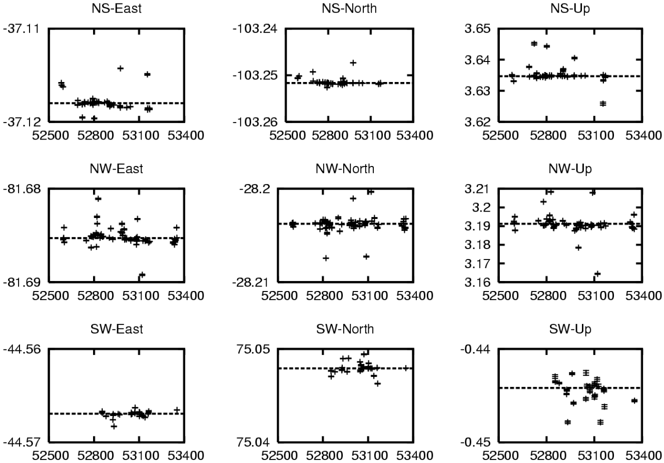
Figure 2 | Radial velocities as functions of orbital phase. Radial velocity (RV) of the primary (**a**) and the secondary (**b**) and their 1σ errors as a function of the orbital phase. The best-fit models are denoted with the solid

Phase Noise

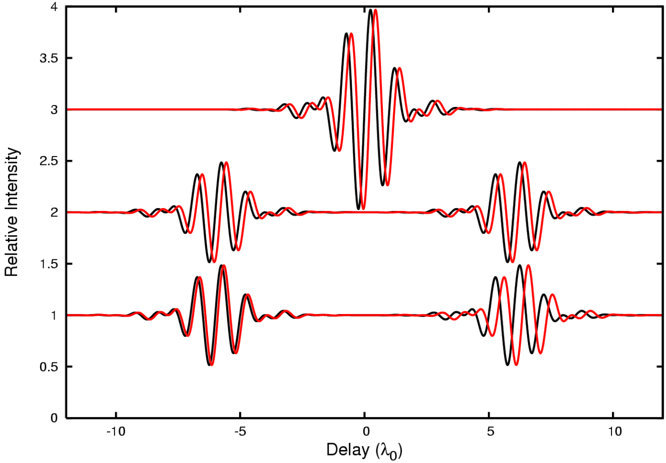


Raw Atmosphere
Atmospheric Model (f^-2.5)
Actual Feed-Forward Response
Expected Feed-Forward Response
Power Spectral Density (Radian^2 Hz^-1)
Frequency (Hz)
100000
10000
1000
100
10
1
0.1
0.01
0.001
1e-04
1e-05
0.01
0.1
1
10
100

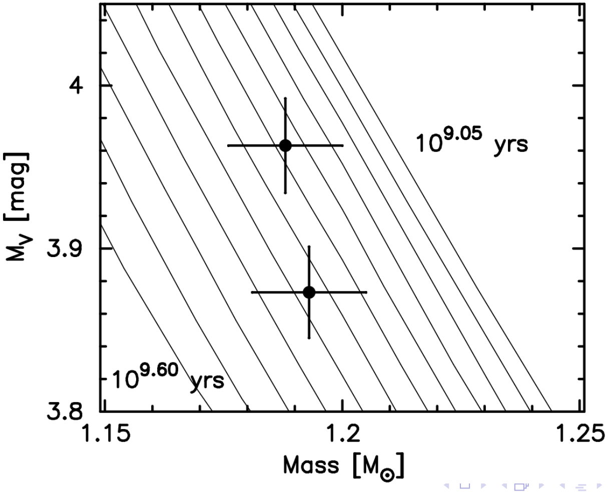
Baseline Stability



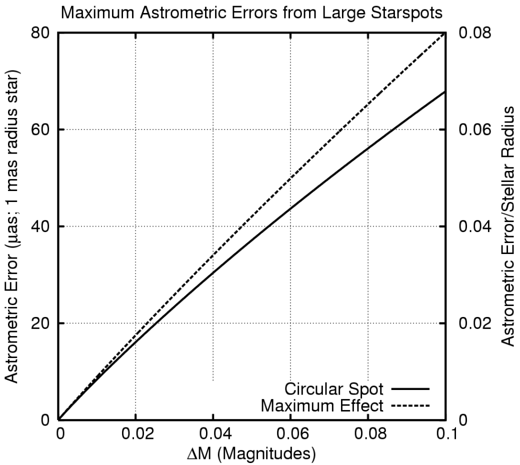
Differential Dispersion



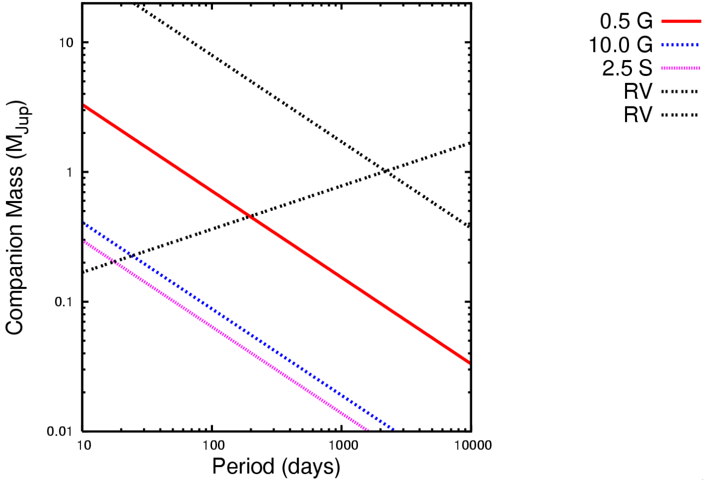
δ Equulei Isochrones



Starspots


Maximum Astrometric Errors from Large Starspots
80
60
40
20
0
0.08
0.06
0.04
0.02
0
0
0.02
0.04
0.06
0.08
0.1
ΔM (Magnitudes)
Astrometric Error (μas; 1 mas radius star)
Astrometric Error/Stellar Radius
Circular Spot
Maximum Effect

Circumbinary Planet Detection Sensitivity



Circumbinary Planet Microlensing Lightcurves