STEPS: Stellar Planet Survey

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Caltech

STEPS ground-based astrometry at Hale Telescope

- Started December, 1997. Now in 8th year.
- 30 nearby M-dwarf stars, V= 12-16.
- Search for > 1 MJ planets and brown dwarfs
- 4k x 4k CCD, 2 arcmin field
- Collaborators: Fritz Benedict (spectroscopy), James Lloyd (AO), Shri Kulkarni (AO), Todd Henry (HST)
- STEPS papers referenced on last page of this presentation
  - Discovery of M-dwarf and Brown Dwarf companions to M-dwarf stars.

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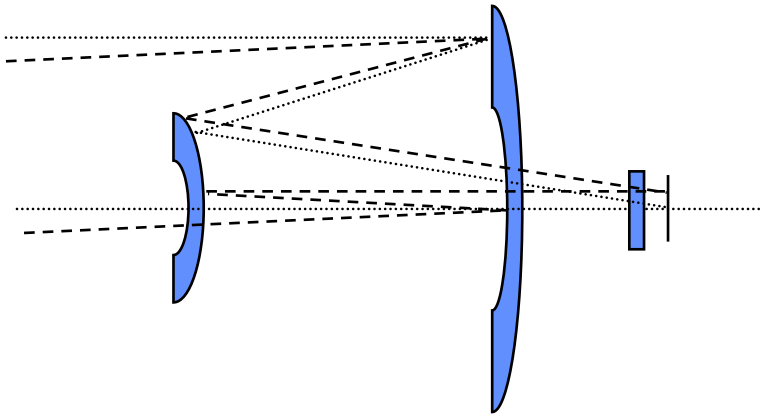
Instrument

- **4K Loral CCD**
- **LN2 Dewar**
- **SDSU (Leach) Electronics**
  - **4 amplifiers**
  - **Bin pixels 2x2**
  - **200 kpix read rate**
- **Binned pixel scale = 78 mas/pix**
- **Mounts at straight-Cass, f/16 on the Palomar 200 in. telescope.**
  - **Was also used at Keck II in 1998.**
- **Window is high quality lambda/30 p-v surfaces.**
  - **Focus term due to vacuum leads to plate scale magnification which is absorbed by the conformal model.**



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Targets

- Targets should not saturate detector too quickly
  - V>12
- Need reference stars
  - Gal. latitude < 30 deg.
- Need signal > 1 mas with M_J planet in 10 yr orbit
  - Nearby, low-mass
- Limited telescope time (~ 8 scheduled nights/yr)
- These criteria led to selection of 30 nearby M-dwarfs.
  - Earlier stars are too bright and their signals are too small.
  - Reference stars are typically V<19.5

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Why the Palomar 200 in. Telescope?

- **Large telescopes dramatically increase astrometric efficiency. (Lindegren 1980, Shao and Colavita 1992).**
  - **r.m.s. motion ~ $\theta/D^{2/3}$, θ = field, D = tel. diam.**
- **We typically achieve 300-500 micro-arcsec s.e.m. of target relative to reference frame in 20 1-minute exposures.**
- **Systematic error sources:**
  - **DCR: correct 10's of mas**
  - **Dust, window,**
  - **Electronics???**

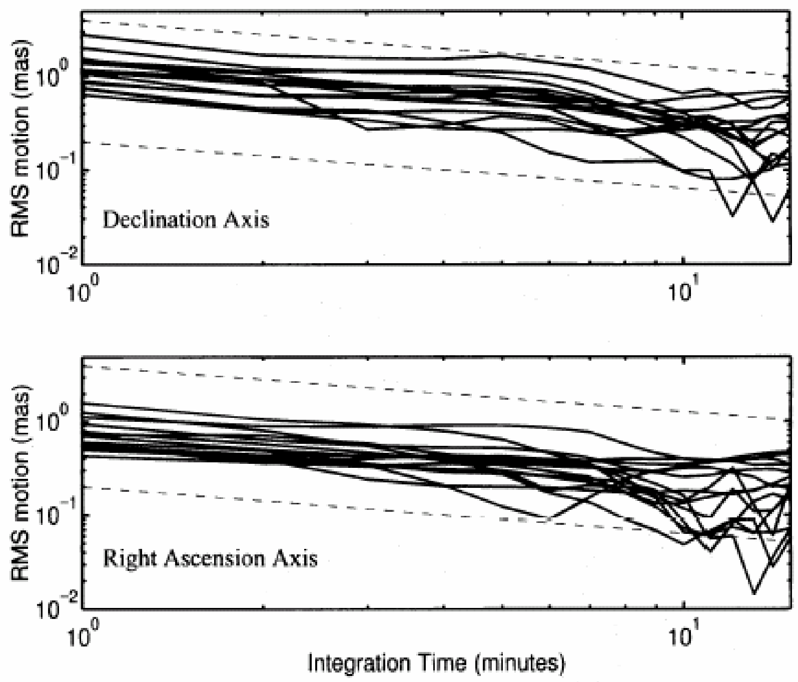

FIG. 2.—The square root of the Allan variance of the positional uncertainty of 15 stars in NGC 2420 observed with the Palomar 5 m. *Top*: Declination. *Bottom*: Right ascension.

Pravdo and Shaklan, 1996 ApJ 465, 264

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Observations

- Typically 20 1-minute exposures per field.
  - Standard error of mean < 1 mas
- Try to stay within 1 hr of meridian.
  - Minimize DCR
- Repoint from run-to-run to within a few arcsec.
  - Minimize impact of local CCD and window distortion
- Dither pointing in square pattern, 1 arcsec steps.
  - Reduce effect of hot pixels, local gradients….
- No fine guiding, no AO, just simple imaging.
  - PSF of all sources across the FOV are nearly identical
- Typically observe 2 or 3 consecutive nights.
  - Helps distinguish systematic vs. stochastic noise
- Compute nightly statistic: mean position and standard error of the mean relative to reference frame.

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Data Processing Sequence

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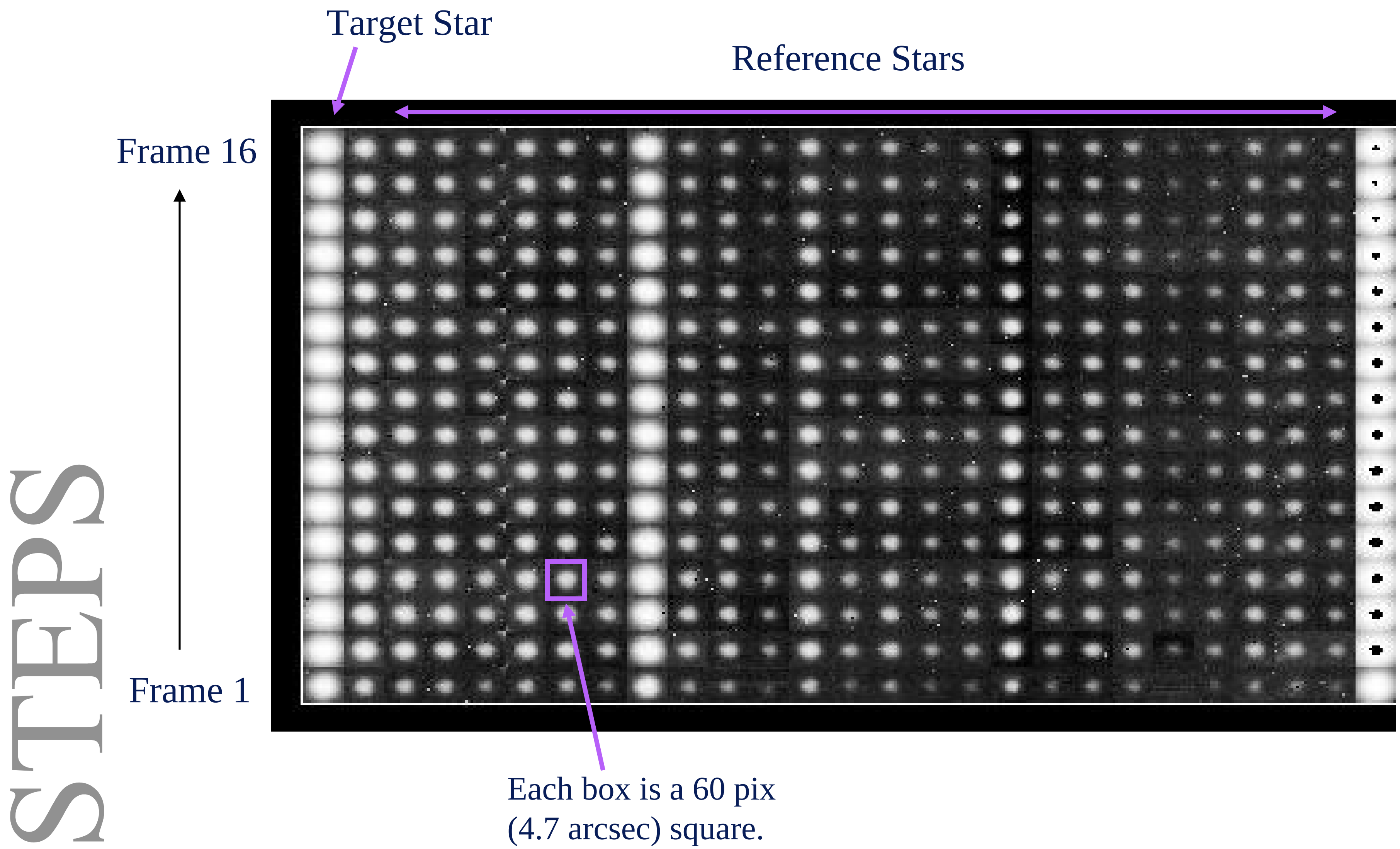
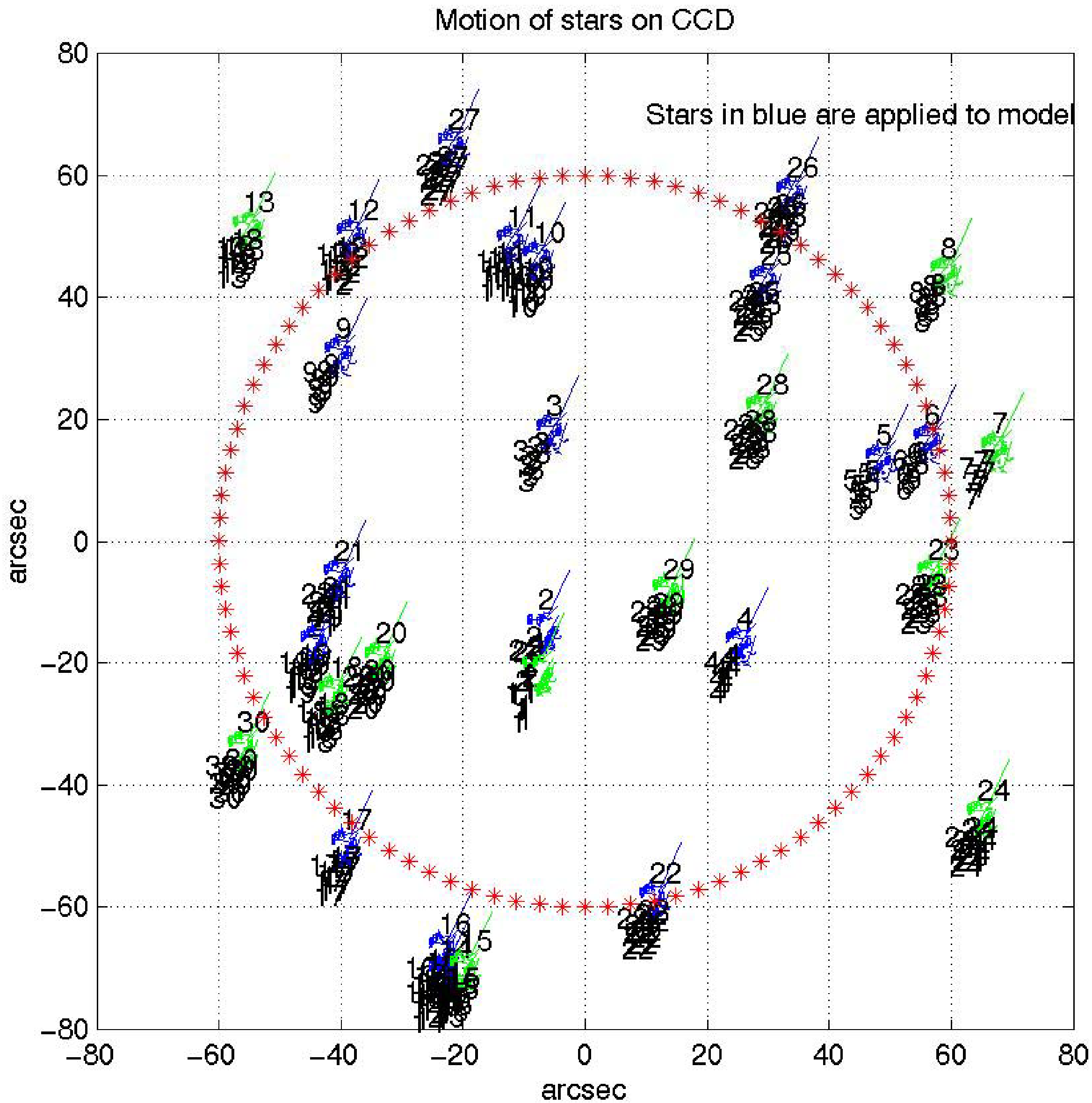
- Observe 20-30 1-minute exposures
- Compress and transfer data to JPL
- Extract stars
- Compute high-precision centroids
- Correct DCR
- Select reference stars and remove bad frames

- Compute Conformal Transformations
- Compute relative Target Star position

- Fit relative proper motion and parallax
- Analyze residuals for presence of planet

Stars extracted from one night, one field




Motion of stars on CCD
Stars in blue are applied to model
arcsec
arcsec

Centroid Pre-processing

- **Step 1: Flatfield image**
  - Fit quadratic function in each of the 4 quadrants.
- **Step 2: Find stars, center in 60 pixel (4.7 arcsec) box**
  - Center the star in the box using a standard centroid
  - (This is not the high precision centroid.)
- **Step 3: Remove horizontal artifacts**
  - Occasionally we see noise pick-up during readout, appears as aperiodic horizontal offset.
- **Step 4: Median filter images**
  - Use 7-pixel wide median filter line by line in x (Dec) then in y (RA).
  - Removes hot-pixels, cosmic rays

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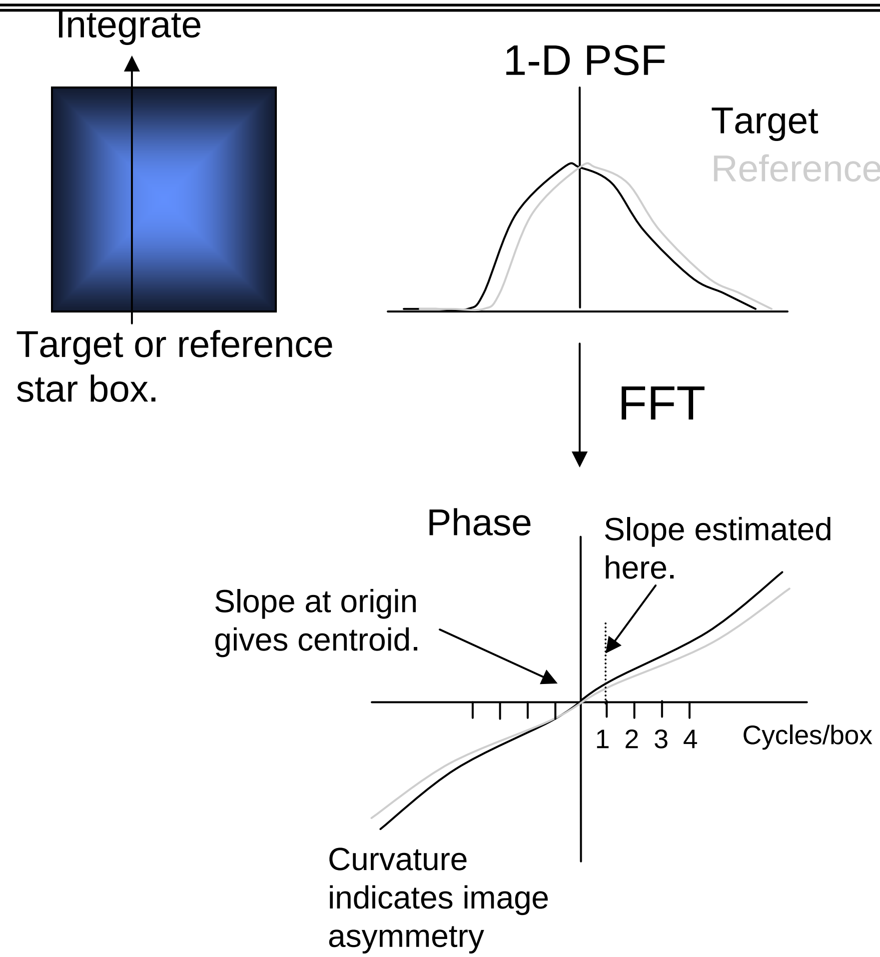
STEPS Cross-Correlation Centroiding

- ***Step 1*: Integrate images in 1-dimension.**
  - **We will compute x and y centroids in separate steps. We do not do joint (x,y) estimation.**
- ***Step 2*: Compute FFT of 1-D image.**
- ***Step 3*: Estimate slope at origin using 1st point (1 cycle per box) of FFT.**
- ***STEP 4*: Compare slope to that of target star.**
  - **Slope difference yields relative centroid position.**
- ***NOTE 1*: Slope at origin of FFT is mathematically identical to the centroid.**
  - **Our first frequency value is an approximation to the slope.**
- ***NOTE 2*: Constant background bias gives delta-function at origin, but does not change slope.**



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Advantages of Cross-Correlation approach

- **Insensitive to background bias**
  - **Constant background does not need to be estimated and does not affect position measurement.**
- **Good SNR**
  - **Most of the energy is in the first spatial frequency.**
  - **High frequencies can be used and weighted by the FFT amplitude function.**
    - **We currently do not use these points**
- **No separate matched-filtering function to compute**
  - **The target star is the image template**
- **No resampling required**
  - **Image is already sampled well above Nyquist.**
- **Fast**
  - **1-D 60 point FFT**

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STEPS Conformal Model

- **We generally use a 6-term model:**

$$\mathrm{RA} = a * \mathrm{RA} + b * \mathrm{Dec} + c$$

$$\mathrm{Dec} = d * \mathrm{RA} + e * \mathrm{Dec} + f$$

- **This requires a minimum of 3 reference stars.**
- **Allows different magnification in two axes**
- **Cross term (RA*Dec) is needed for ‘keystone’ caused by CCD tilt, system misalignment.**
  - **Expected to be negligible, ~ 150 uas peak at edge of 1 arcminute radius for 200 um of CCD tilt.**
  - **Also should be very stable because CCD is hard-mounted.**
- **Performance is only slightly better than simple rotation/translation model.**

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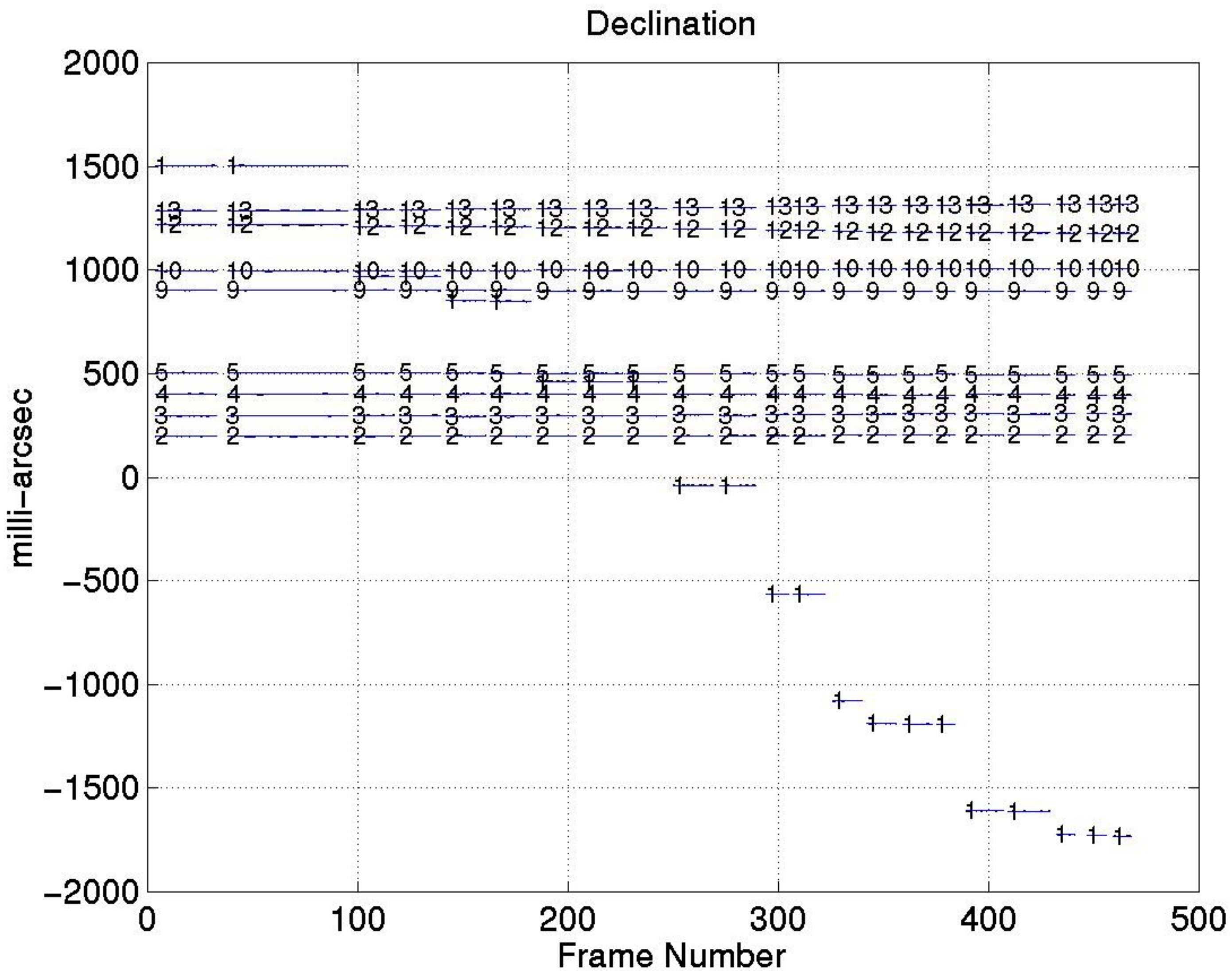
Frame-by-Frame Astrometry



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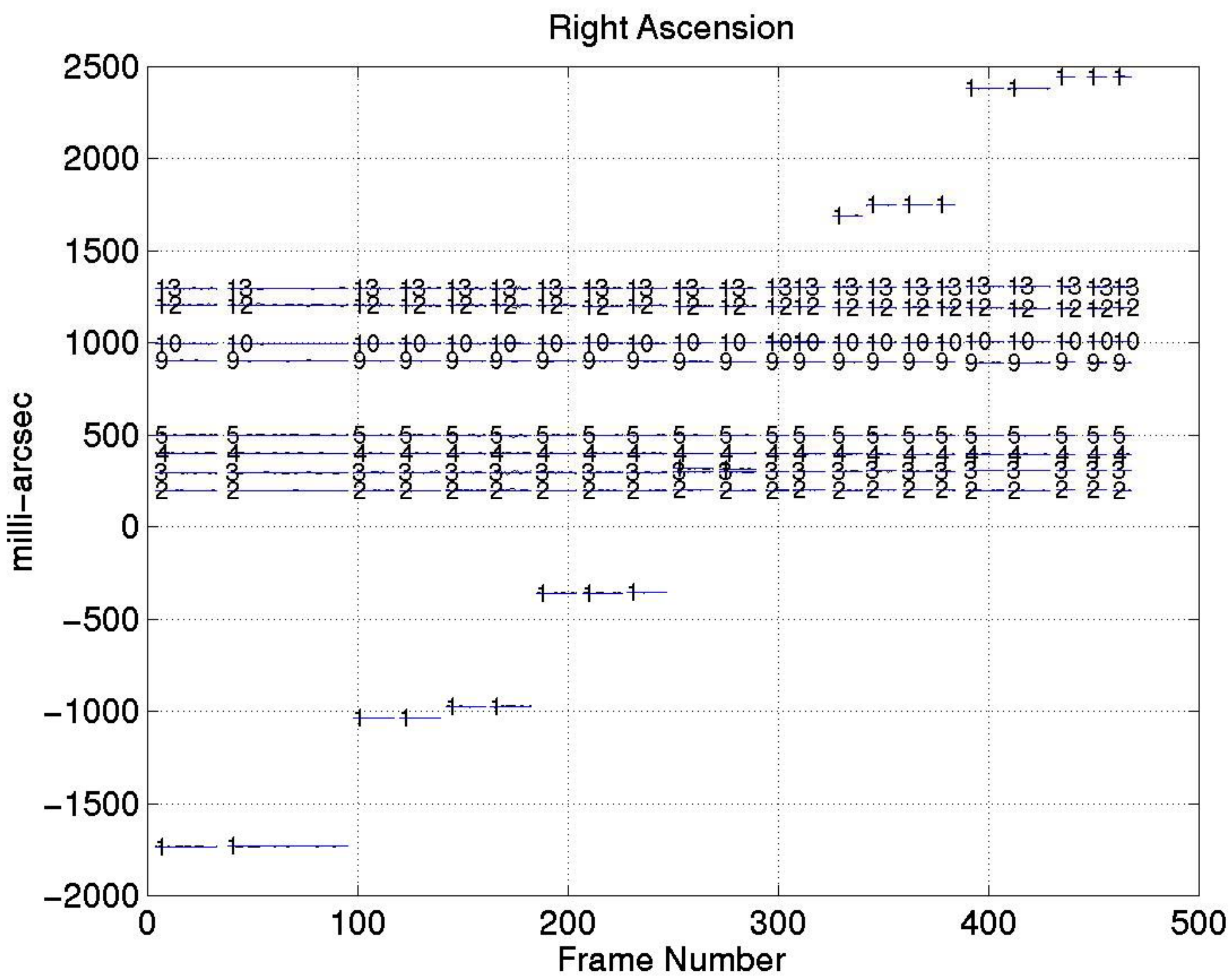
Frame-by-Frame Astrometry



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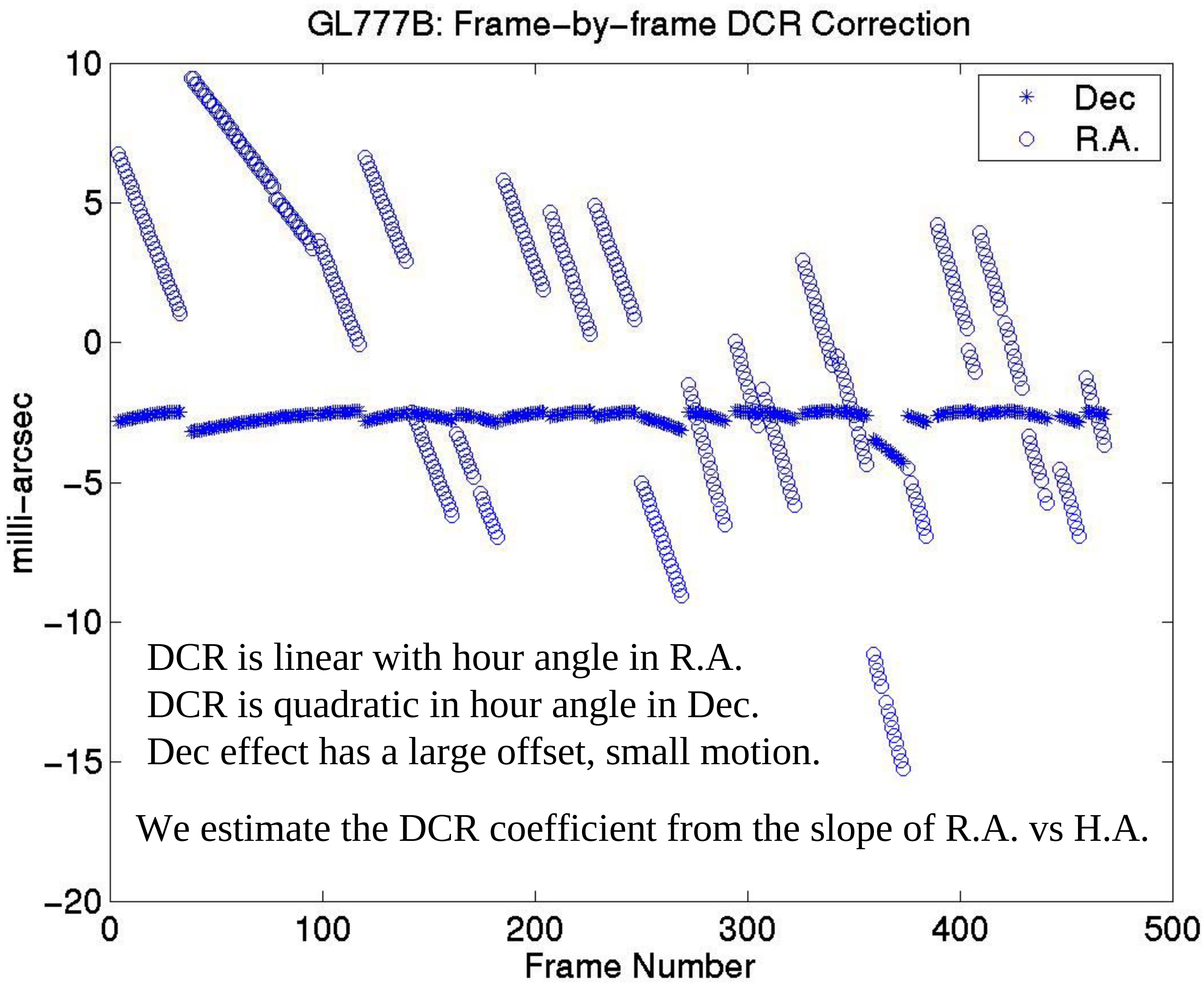
Differential Chromatic Refraction



DCR is linear with hour angle in R.A.
DCR is quadratic in hour angle in Dec.
Dec effect has a large offset, small motion.

We estimate the DCR coefficient from the slope of R.A. vs H.A.

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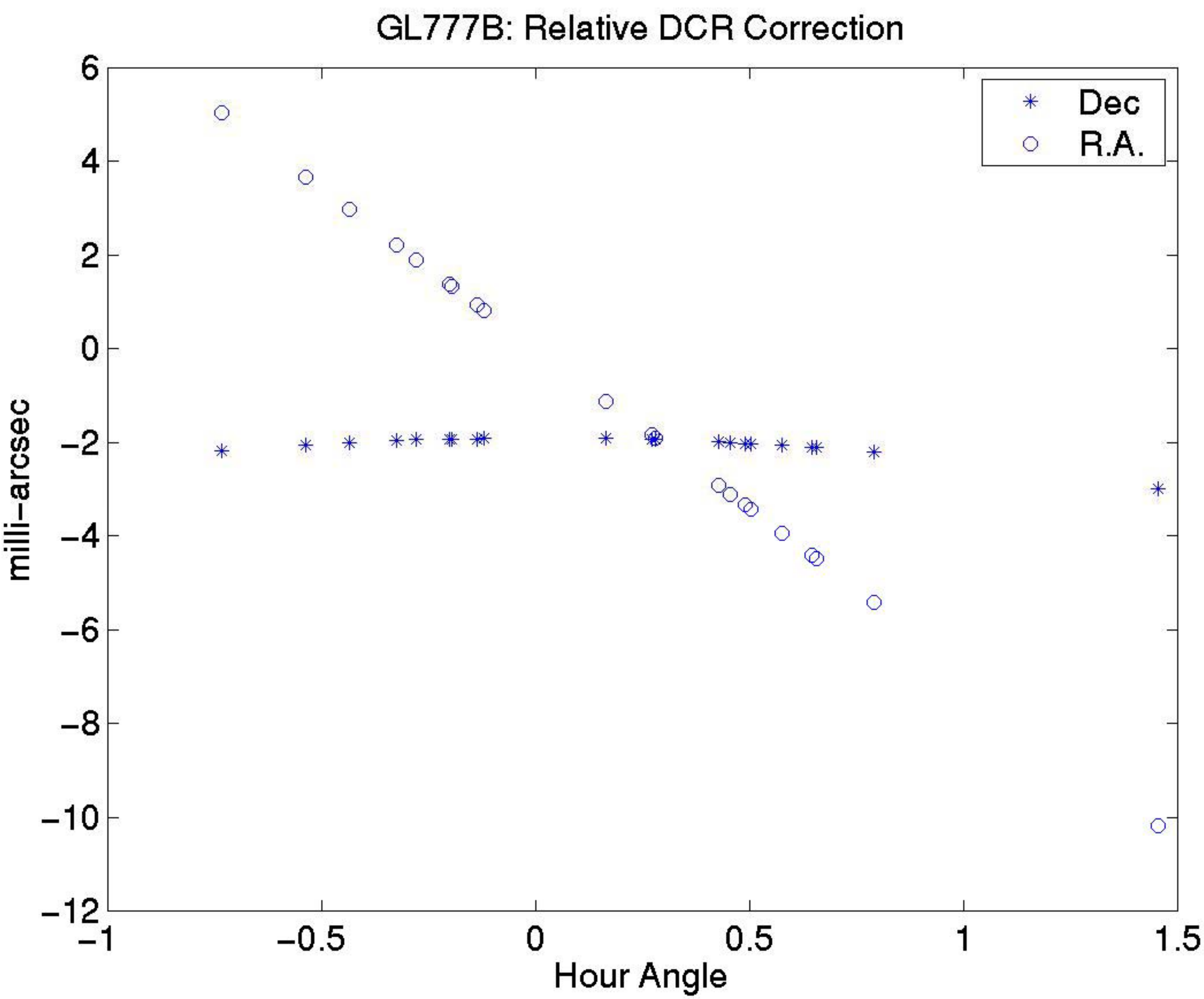
Relative DCR Correction vs. Hour Angle



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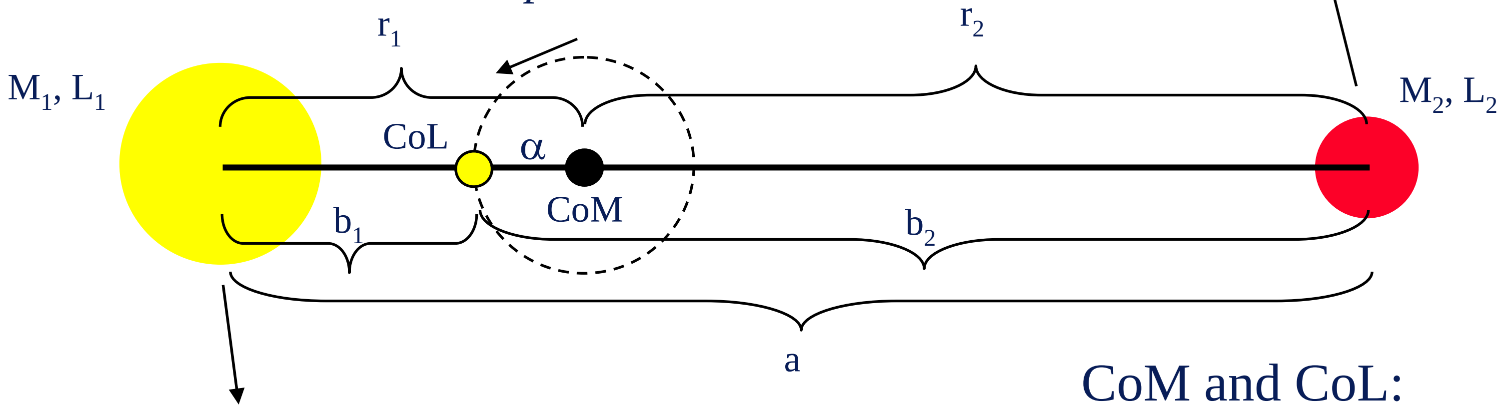
Motion of Center of Light about Center of Mass: Photocentric Orbit

For unresolved systems (< 1 arcsec separation), STEPS observes the motion of the COL about the COM.
This is called the *photocentric motion*.



$f = M_2 / M_{tot}$ (fractional mass)

$\beta = L_2 / L_{tot}$ (fractional light)

CoM and CoL:

r1 = a*M2/MT = a*f

b1 = a*L2/LT= a*β

STEPS Measures:

α=CoL – CoM = r1 – b1 = a*(f-β)

α/a = ratio of photocentric to Keplerian orbit= f - β

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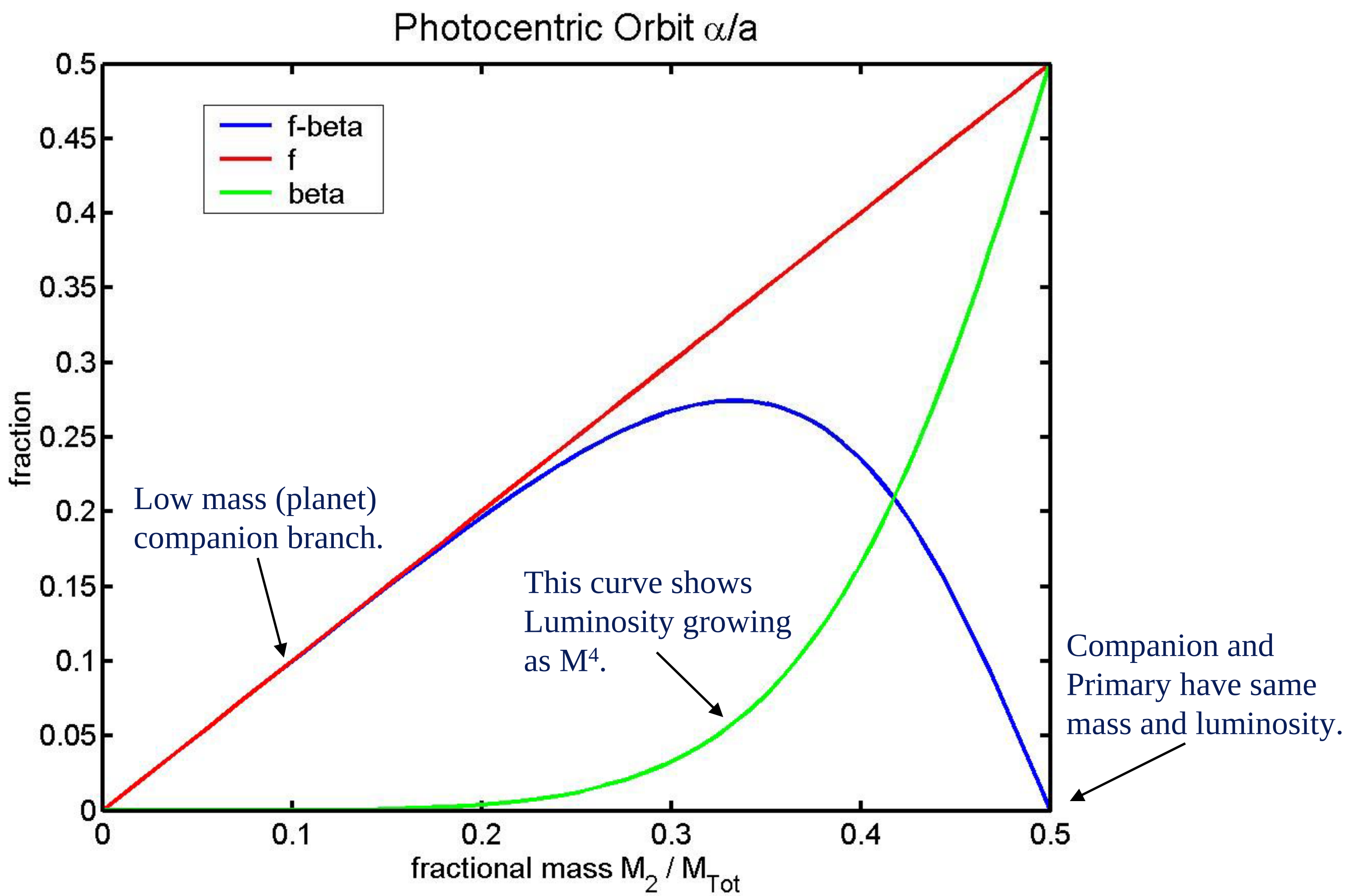
Photocentric Motion vs. Fractional Mass



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How to determine companion mass

STEPS determines orbital parameters (P, ecc, incl, epoch, orientation) and photocentric motion α.

A high-resolution image determines the flux ratio (β). It also determines scale (a) when a companion is visible.

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Case 1: no light from companion ($\beta = 0$)

STEPS constrains $c=f^3*M_{tot}$

↓

Mass-Luminosity Relationship provides M_1

↓

M_2 is determined from $M_{tot} = M_1+M_2$ and c

Case 2: Image detects a companion

STEPS constrains $c=f^3*M_{tot}$

↓

Image determines scale (a) and flux ratio (β).

↓

Mass ratio is determined from $f = \alpha/a + \beta$

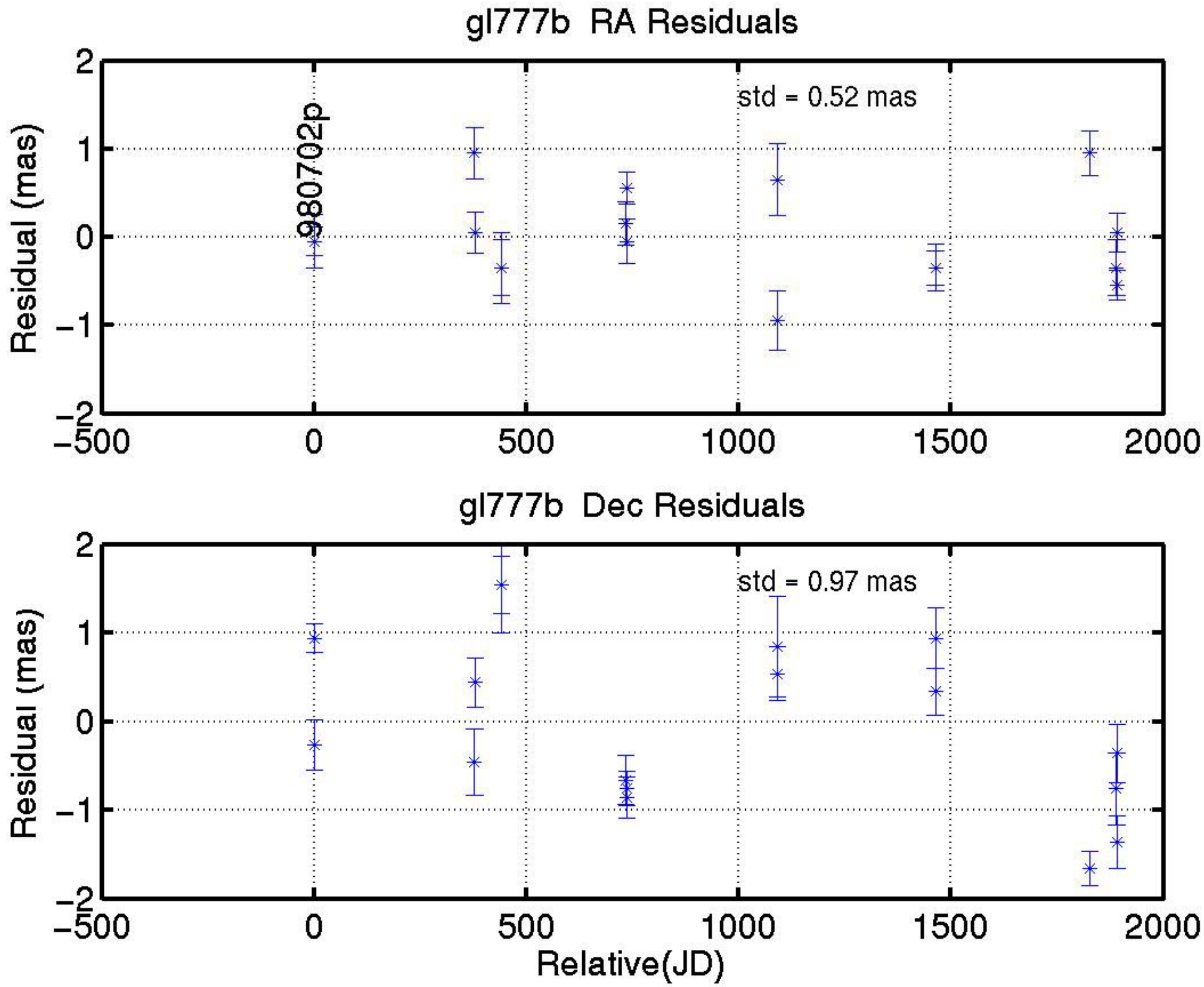
↓

M_{tot} is determined from Kepler $M = a^3/P^2$

GJ 777B

Residuals after fitting PM and Parallax

20.1 hr, +29.9°
V=14.4
Spec M4.5
Parallax 61 mas
Note: primary is
G6IV, > 3 arcmin



σ_{RA} = 0.52 mas
σ_{Dec}= 0.97 mas

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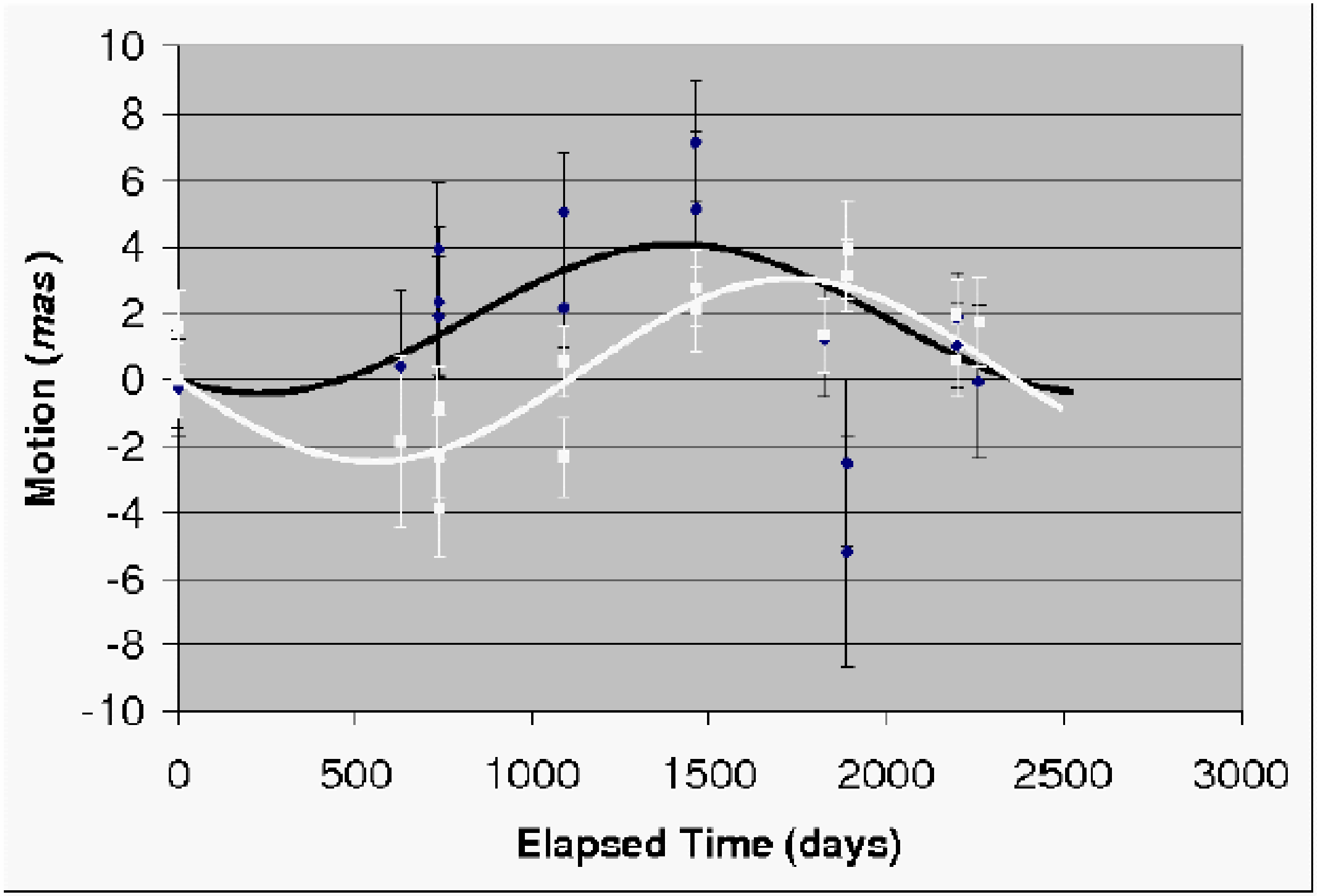
GJ 1210

One possible orbit plotted with the data



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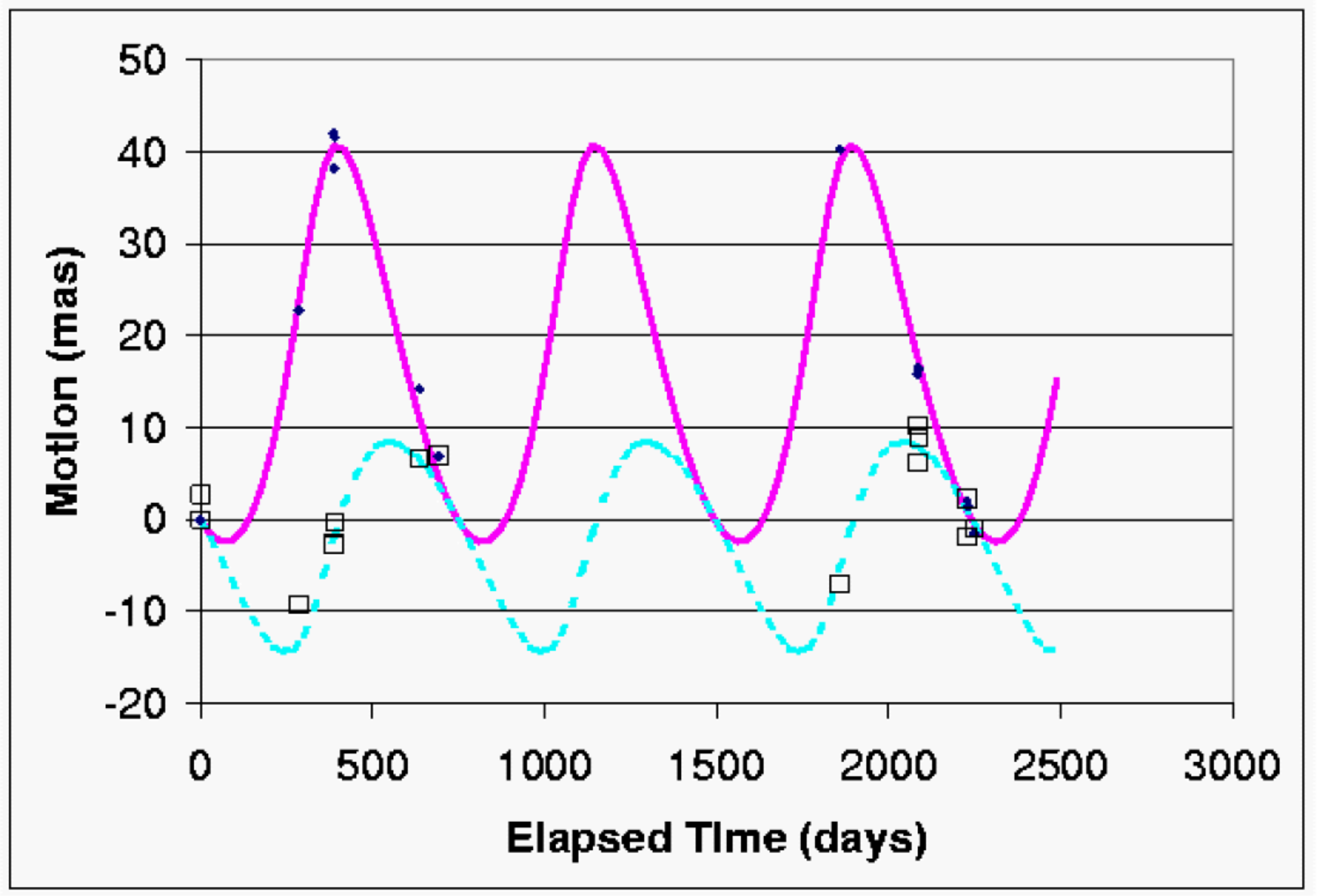
GJ 164
One possible orbit plotted with data



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High-Resolution Imaging of STEPS Targets

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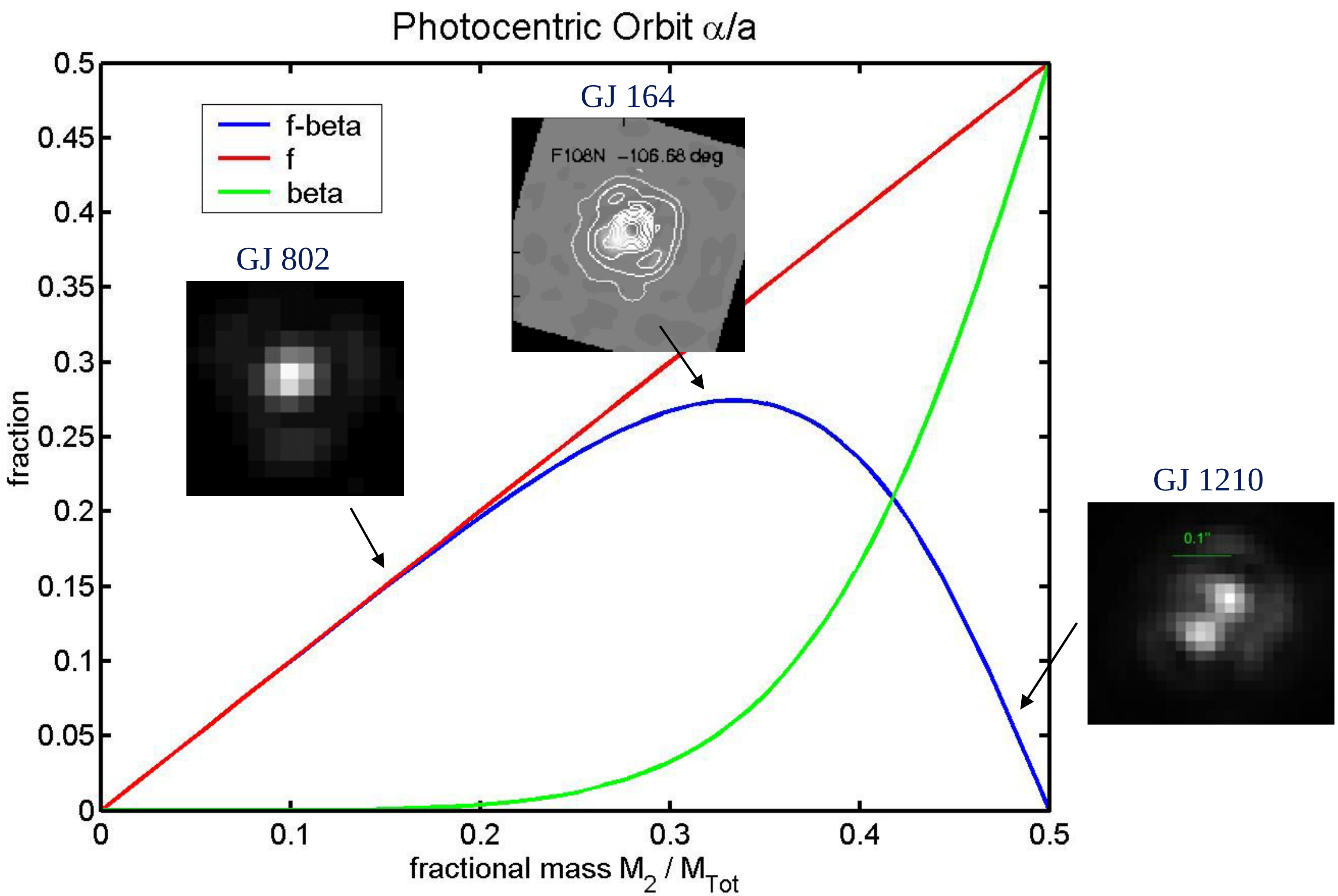
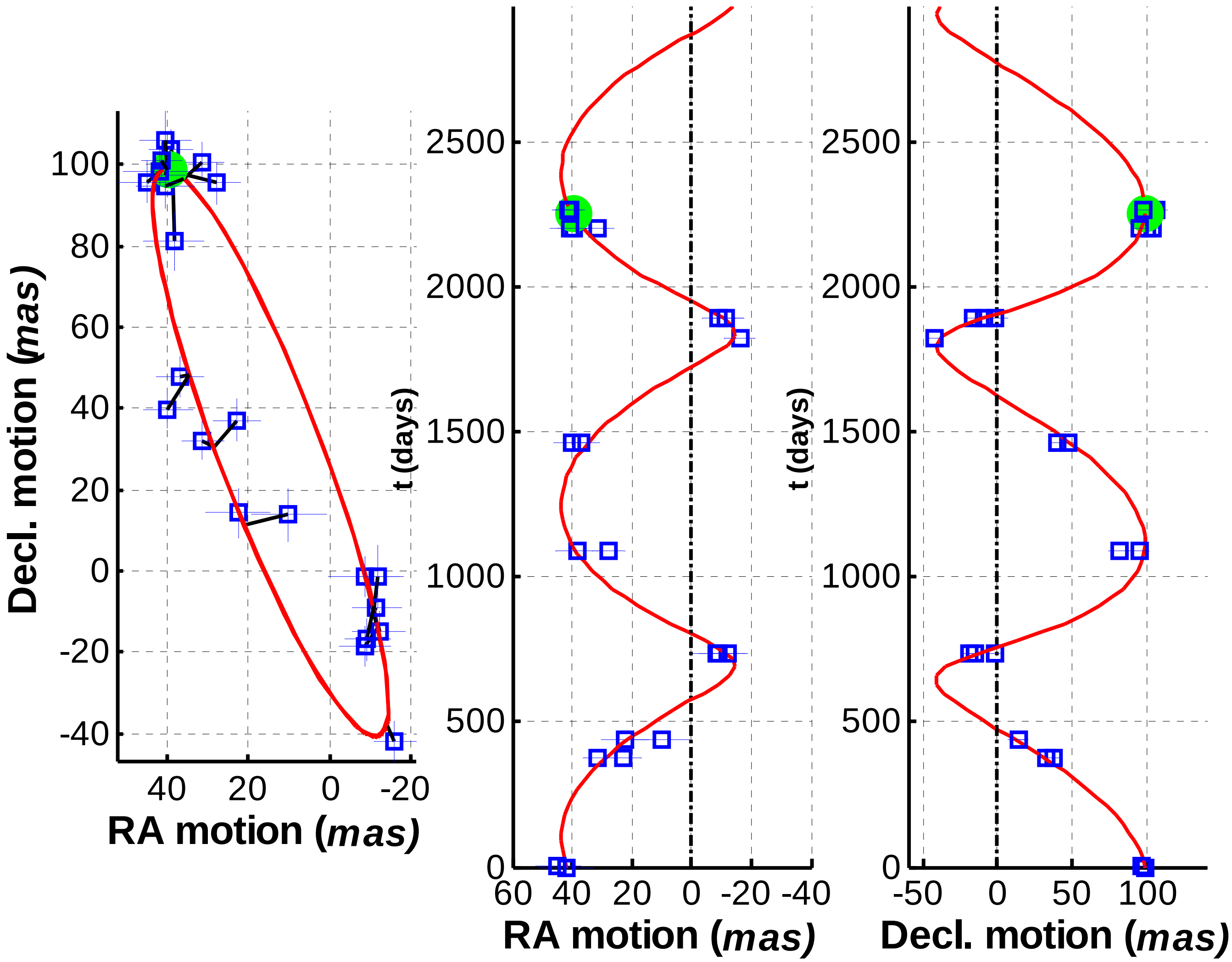


GJ 802
One possible orbit plotted with data, Keplerian frame



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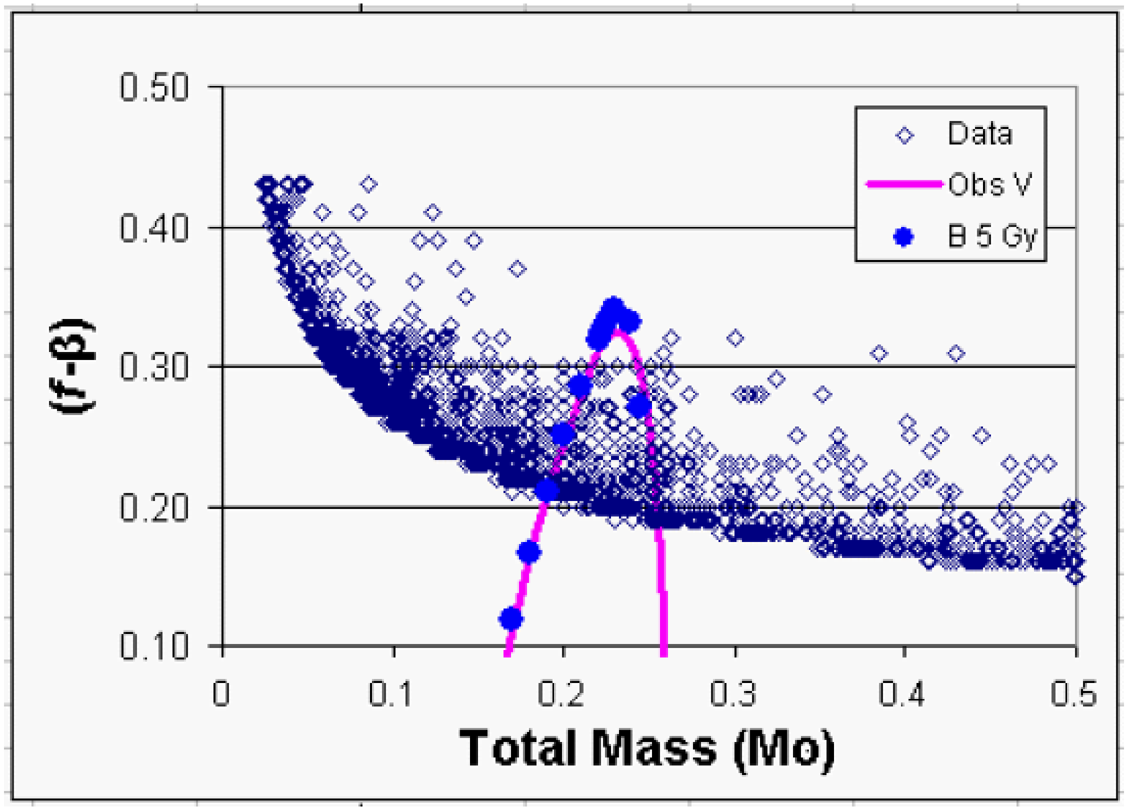
GJ 802 Photocentric Orbit vs. Mass



The points show the results of ~11,000 Monte Carlo trials for the GJ 802 orbit. We plot (*f*-β) vs. M_{tot} for all models falling within the one-sigma confidence limits. Superimposed on the data are the composite MLR curve in the *V*-band based upon observations (Henry et al. 1999) and the MLR points from the model of Baraffe et al. (2003).

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GJ 802b Mass vs. Eccentricity

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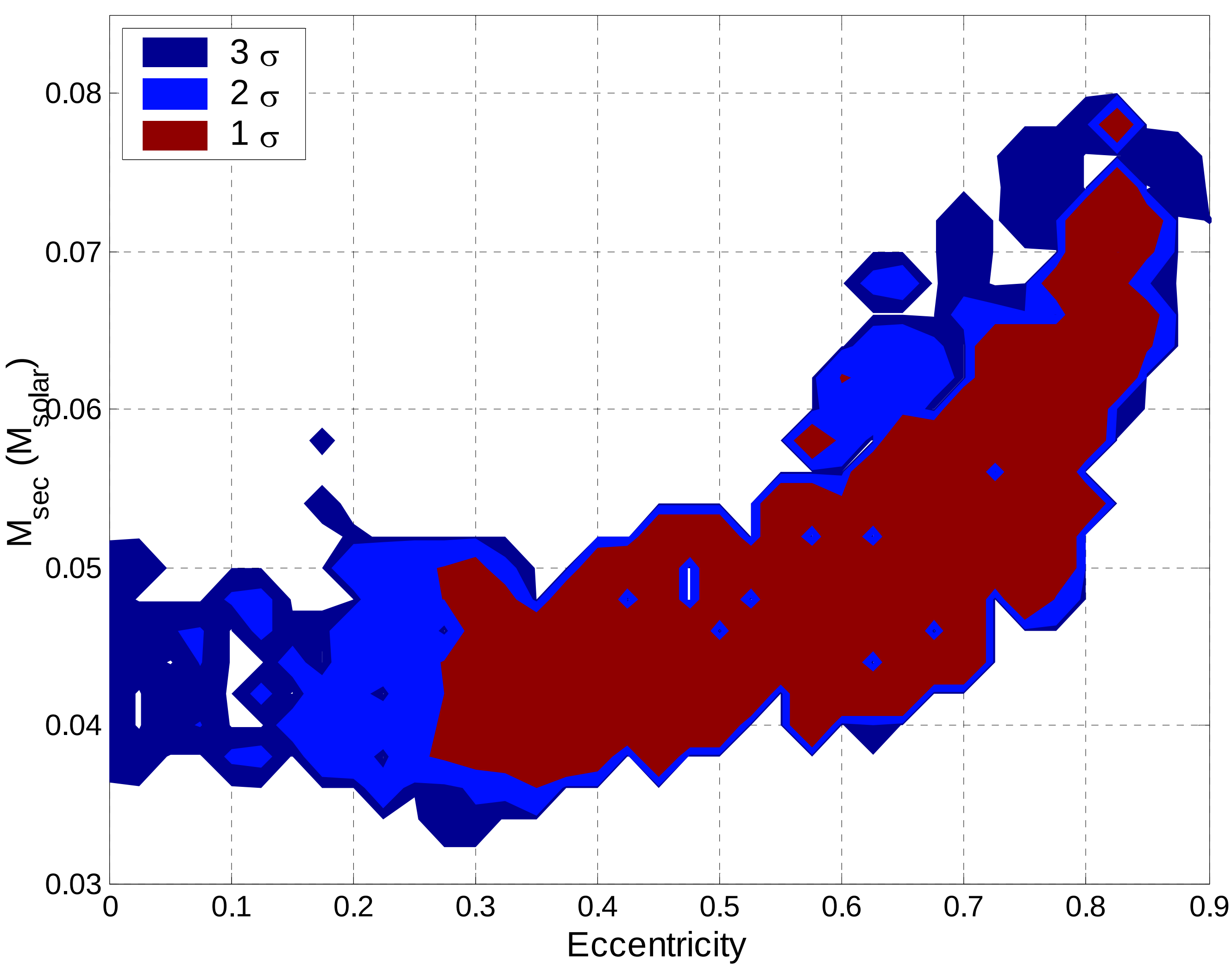

GJ 802 Results

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Table 1. GJ 802 Known Properties

RA (2000)[a]	20 43 19.41
Dec (2000)[a]	+55 20 52.0
V[b]	14.69
J[c]	9.563 ± 0.023
H[c]	9.058 ± 0.019
K[c]	8.753 ± 0.013
Type	dM5e
Parallax[d] (*mas*)	63 ± 5.5
Proper Motion[e] (*mas* y^{-1})	1915 ± 13
Position Angle[e] (deg)	27.6 ± 0.6

Table 2. STEPS Astrometric Measurements[a] of GJ 802

Relative Parallax (*mas*)	61 ± 2
Proper Motion (*mas* y^{-1})	1933 ± 1
Position Angle (deg)	27.0 ± 0.1
Period (y)	3.14 ± 0.03
Total Mass ($M_\odot$)	0.215 ± 0.045
Semi-Major Axis (AU)	1.28 ± 0.10
Eccentricity, *e*	0.56 ± 0.30
Inclination (deg)	80.5 ± 1.5
Lon. Asc. Node[b] (deg)	17.5 ± 3.5
Primary Mass, M_{pri} ($M_\odot$)	0.160 ± 0.03
Secondary Mass, M_{sec} ($M_\odot$)	0.057 ± 0.021

STEPS progress through December, 2004

Target	Type	M-Dwarf Companion	BD Companion	Clear Signal	Flatline	TBD		AO Signal	AO Null
1	M5					x			
2	M5				x				
3	M4			x					
4	M4					x			x
5	M3.5					x			
6	M3	x					Unpub	x	
7	M4.5	x					GJ 164	x	
8	M5					x			
9	M4.5					x			
10	M5			x					
11	M3.5	x					Unpub	x	
12	M5			x					
13	M4					x			
14	M5					x			
15	M5					x			
16	>M6					x			
17	M4					x			
18	M3					x			
19	M3					x			
20	M5	x					GJ 1210	x	
21	M5					x			
22	M8					x			
23	M5.5				x				
24	M4.5				x				
25	M5				x				
26	M5		x				GJ 802		x
27	M4				x				
28	M4.5					x			x
29	M5			x					x

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STEPS Future

- Continued observation at Palomar 200 in.
  - We are in our 8th year, and have the sensitivity to detect Jupiter mass objects in 10-yr orbits around several stars.
- RV and imaging collaborations
  - Flux ratios for MLR
  - Velocities for improved orbits
- Astrometric collaborations
  - Overlapping target lists to confirm discoveries, improve orbital fits, help distinguish systematic errors from real motions.
- Investigate new HAWAII-2RG detectors: higher dynamic range possible

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STEPS Papers

- “Astrometric Discovery of GJ802b: In the Brown Dwarf Oasis?” Pravdo, Shaklan, Lloyd, Accepted ApJ (2005).
- “Discovering M-dwarf Companions with STEPS,” Pravdo, Shaklan, Lloyd, Benedict, ASP Conf. Series, Astrometry in the Age of the Next Generation of Large Telescopes (Flagstaff, 2005).
- “Astrometric Discovery of GJ164B,” Pravdo, Shaklan, Henry, Benedict, ApJ 617, 1323-1329 (2004).
- “Stellar Planet Survey,” Pravdo & Shaklan, Scientific Frontiers in Research on Extrasolar Planets, ASP Conference Series, Vol 294, 107-110 (2003).
- “Astrometric Detection of Extrasolar Planets: Results of a Feasibility Study with the Palomar 5 Meter Telescope,” Pravdo & ApJ 465, 264-Astrophysical Journal v.465, p.264-277 (1996)
- “High-precision measurement of pixel positions in a charge-coupled device,” Shaklan, Pravdo, Sharmon, Appl. Opt. 34, 6672-6681 (1995).

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