Turning Companions into Planets - HST Astrometry of Exoplanet Candidates

G. F. Benedict & B. E. McArthur

With help from

G. Gatewood, A. Hatzes, W. Cochran, T. Forveille,

G. Marcy, M. Endl

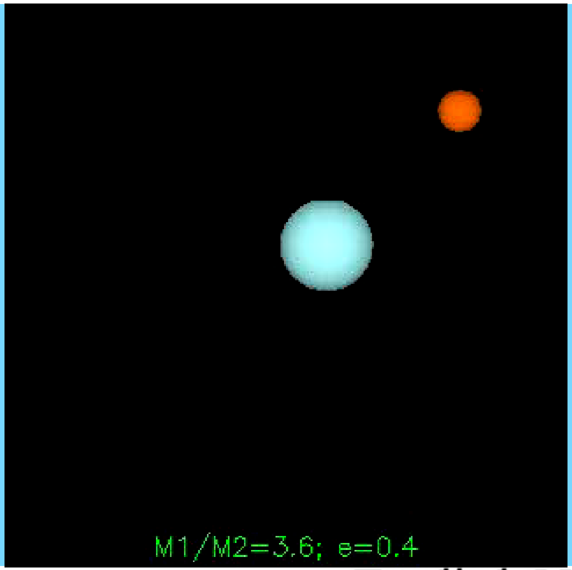
P. Butler, M. Mayor, G. Walker, T. Harrison, and B. Campbell

HST/FGS Exoplanet Host Star Astrometry
Outline

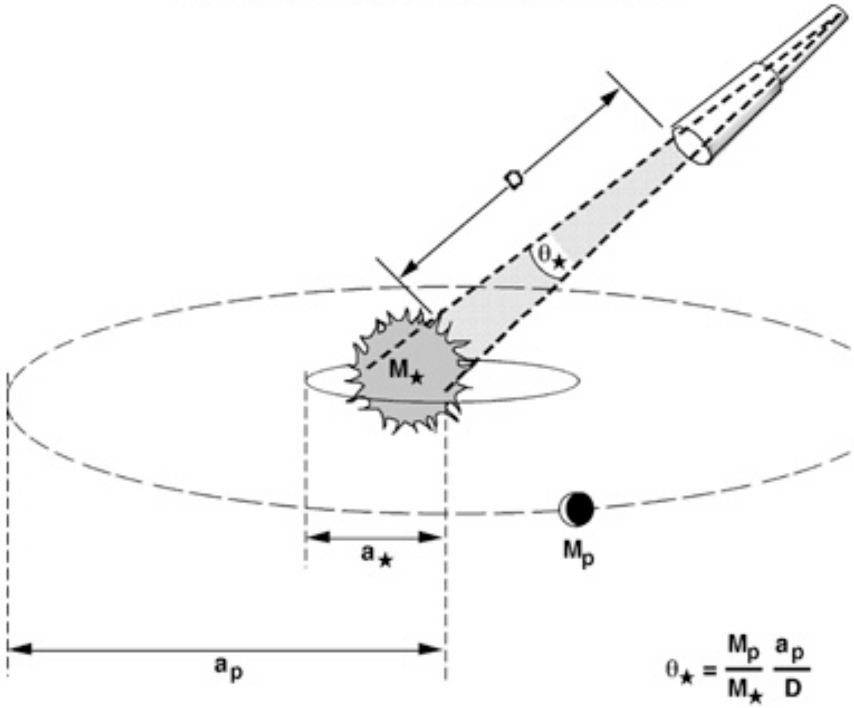
- What astrometry brings to the party
- Which targets to attack?
- What we have done (exoplanet masses for
  - Gl 876b, c
  - 55 Cnc b, c, d, e
  - ε Eri b
- Future work

Recommended

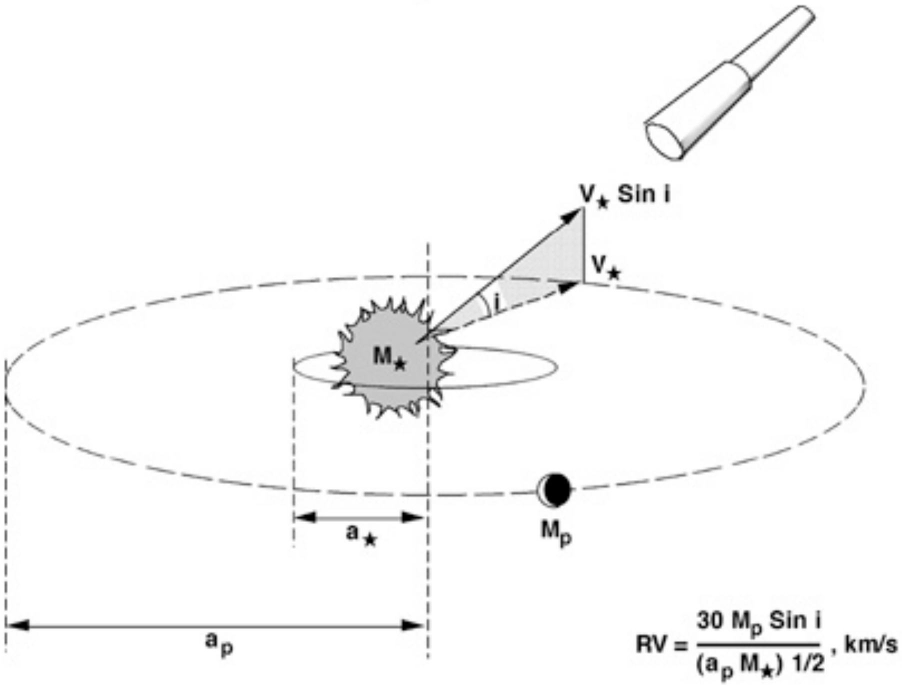
Sozzetti, A. 2005.
"Astrometric Methods and Instrumentation to Identify and Characterize Extrasolar Planets: A Review."
ArXiv Astrophysics e-prints arXiv:astro-ph/0507115.

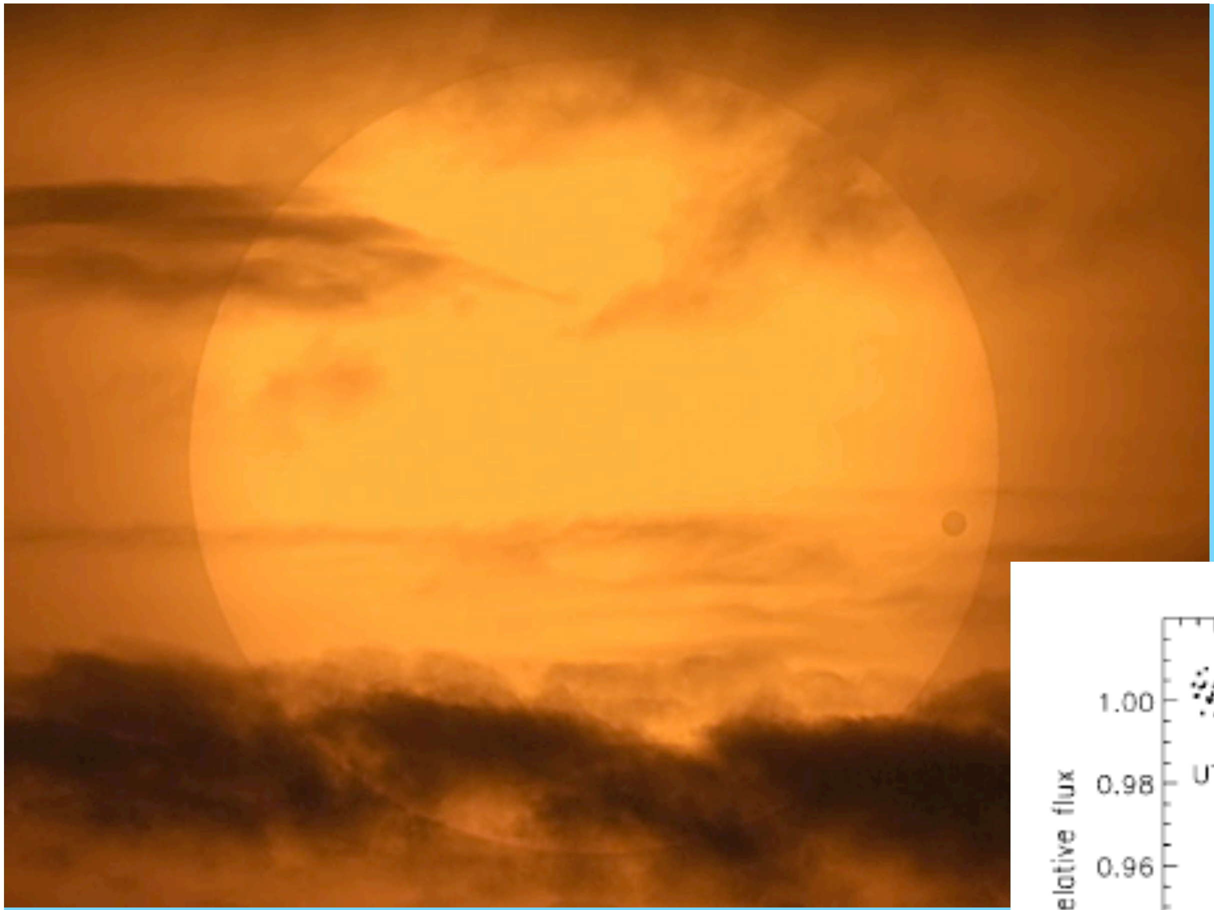


Astrometric Method



Radial Velocity Method





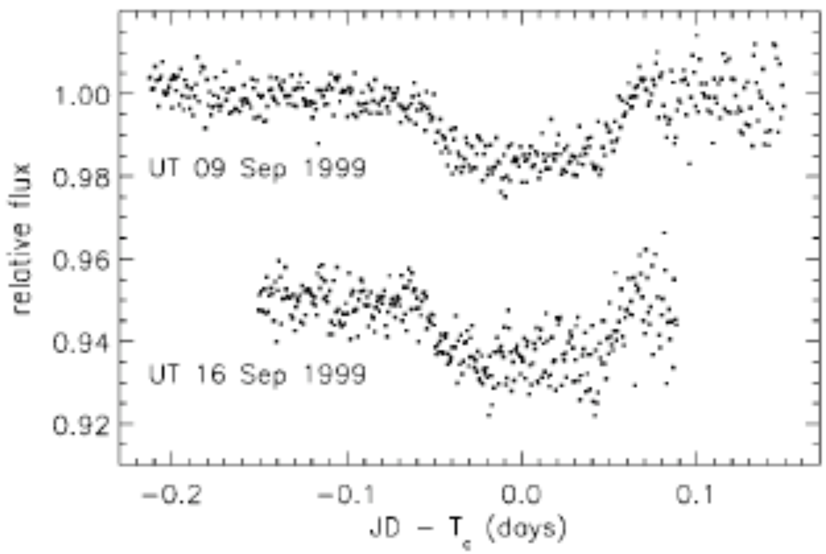


FIG. 1.—Shown are the photometric time series, corrected for gray and color-dependent extinction, for 1999 September 9 and 16 plotted as a function of time from T_c. The rms of the time series at the beginning of the night on September 9 is roughly 4 mmag. The increased scatter in the September 16 data relative to the September 9 data is due to the shorter exposure times. The data from September 16 are offset by −0.05 relative to those from September 9.

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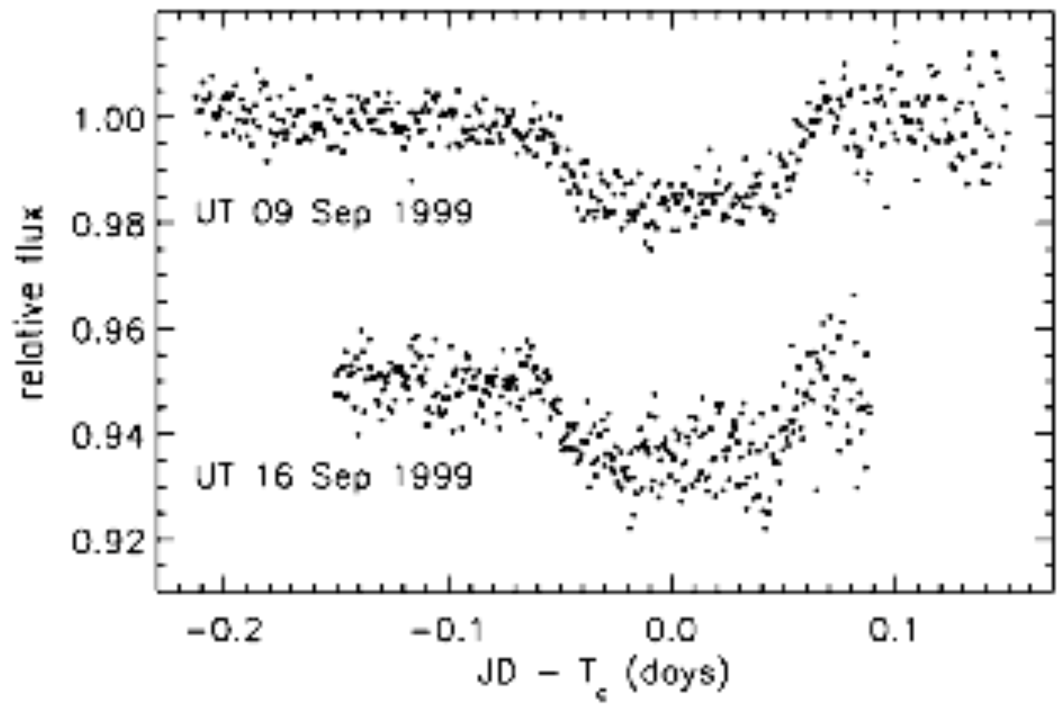
Eclipsed light and HD 209458

- P = 3.52 DAYS
- R = 1.27R_{Jup}

Planet mass is unknown and depends on density (gas giant or rocky/metallic?)



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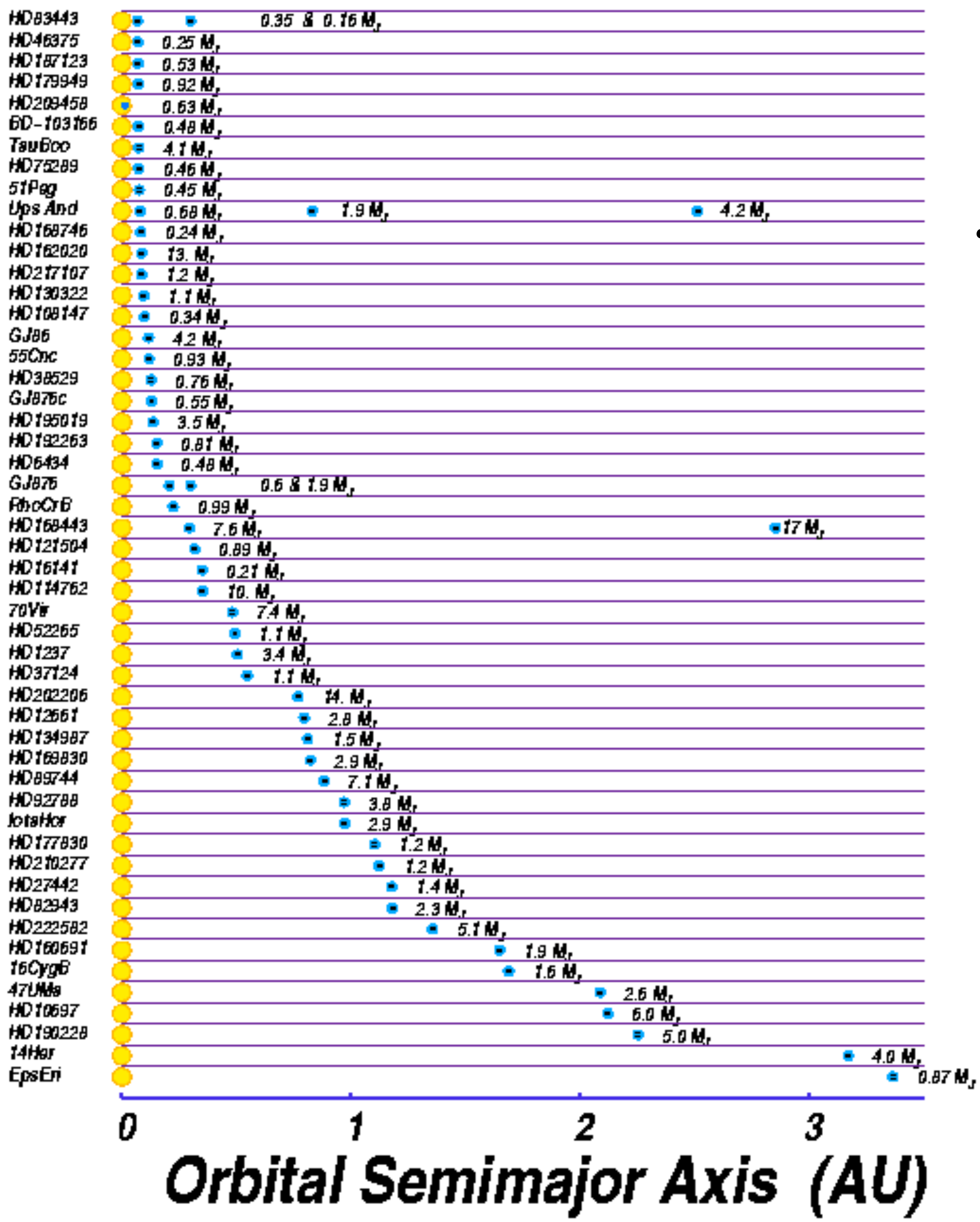
Possible planets found by Radial Velocities

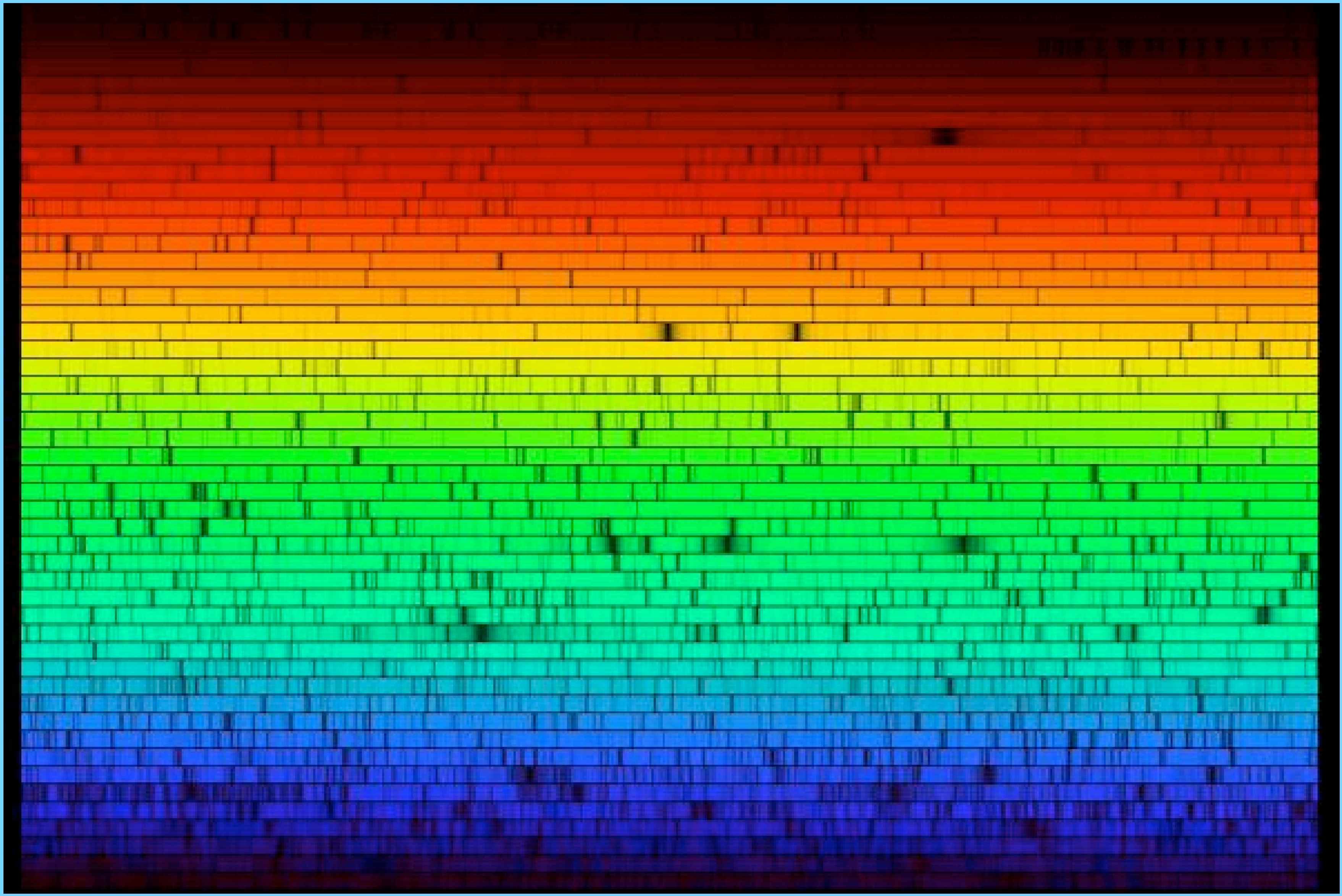


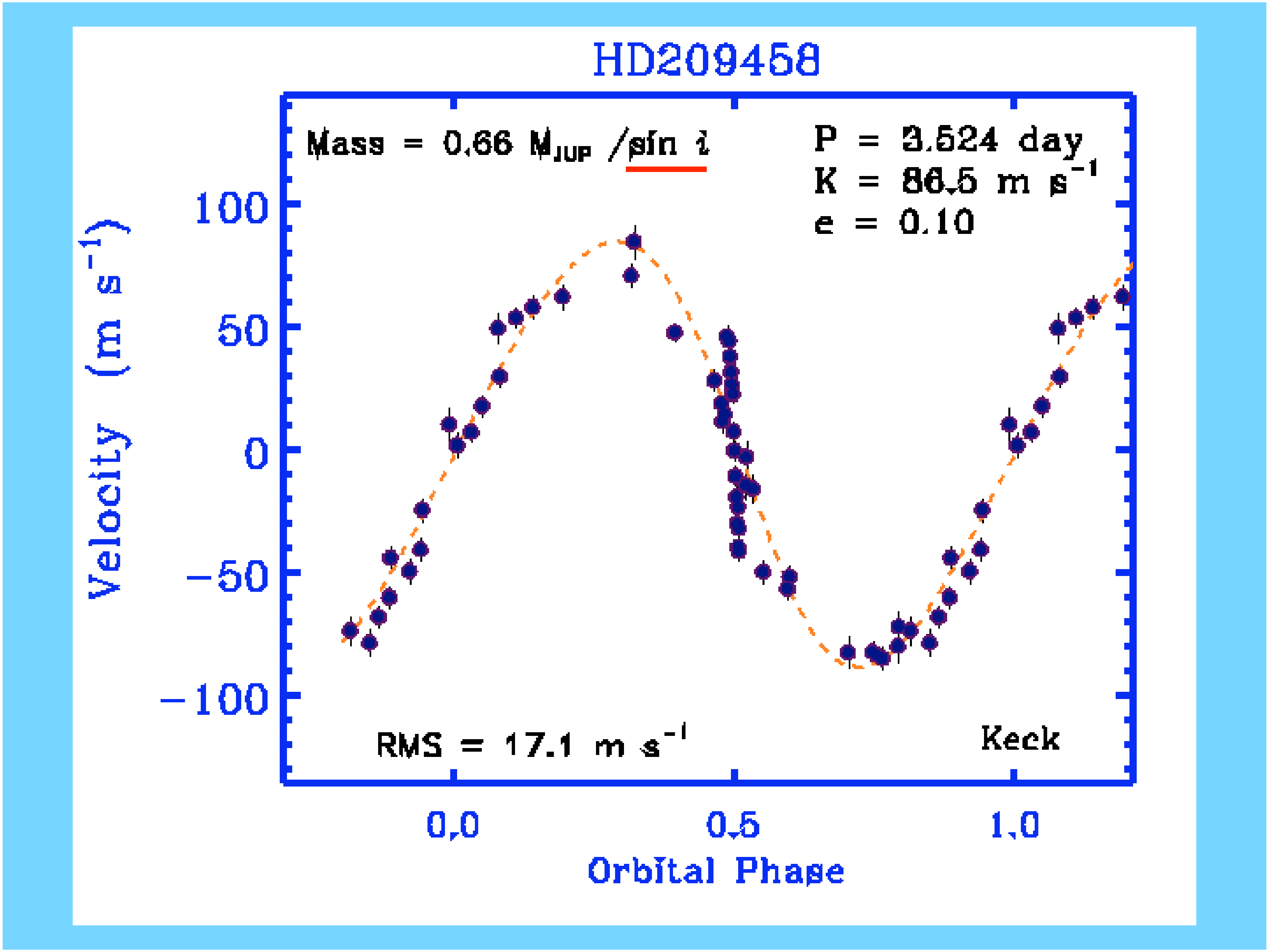
By what?

The Doppler Effect

http://exoplanets.org/index.html

CtoP - 7 GFB

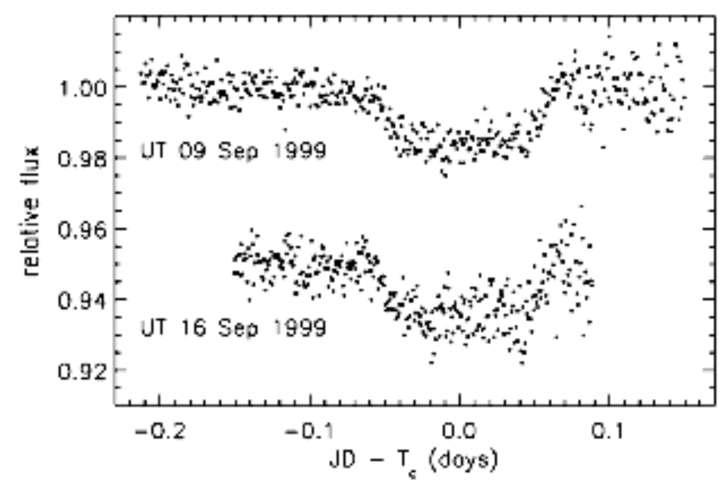




HD209458
Mass = 0.66 M_JUP /sin i
P = 3.524 day
K = 86.5 m s^-1
e = 0.10
RMS = 17.1 m s^-1
Keck
Velocity (m s^-1)
100
50
0
−50
−100
0.0
0.5
1.0
Orbital Phase

Eclipsed light and HD 209458

- P = 3.52 DAYS
- R = $1.27 R_{Jup}$
- $\mathcal{M} \sim 0.63 \mathcal{M}_{Jup}$



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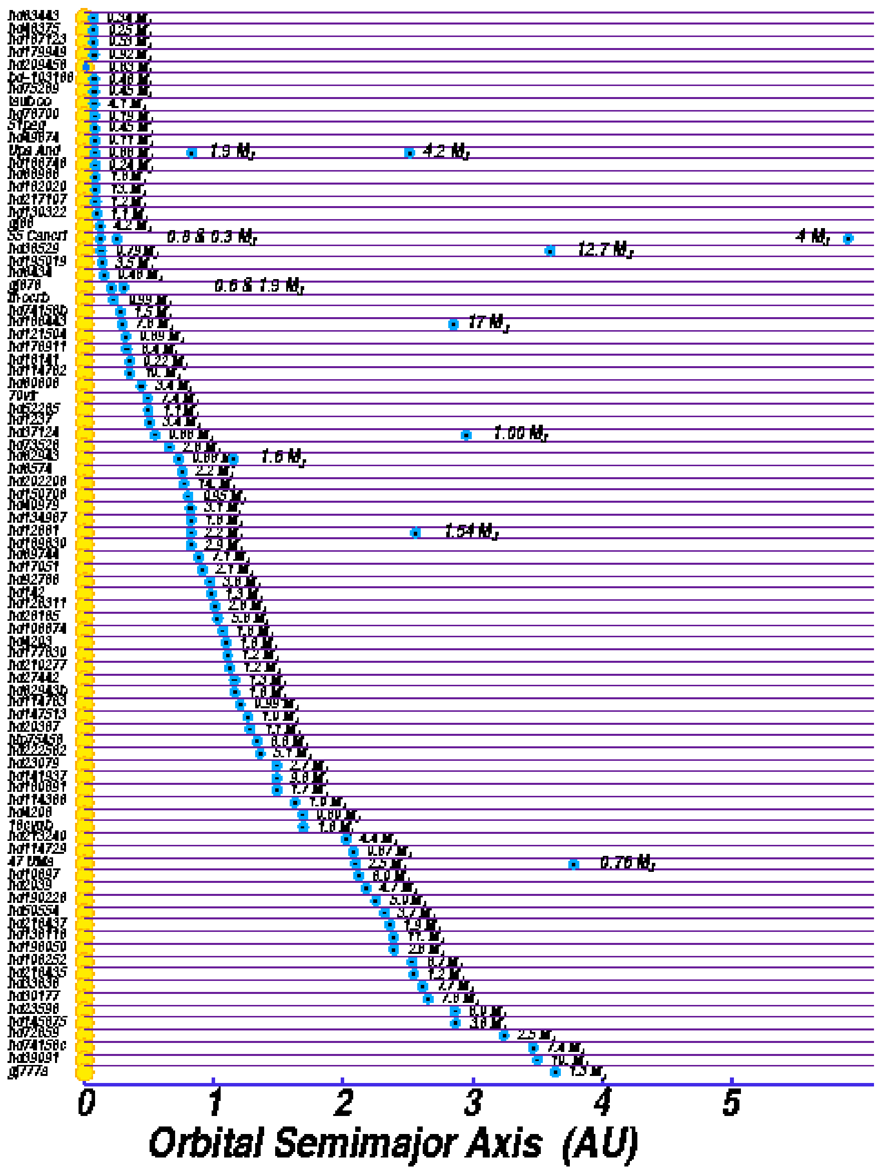
We know mass because we know the inclination (i ~90° from eclipse)

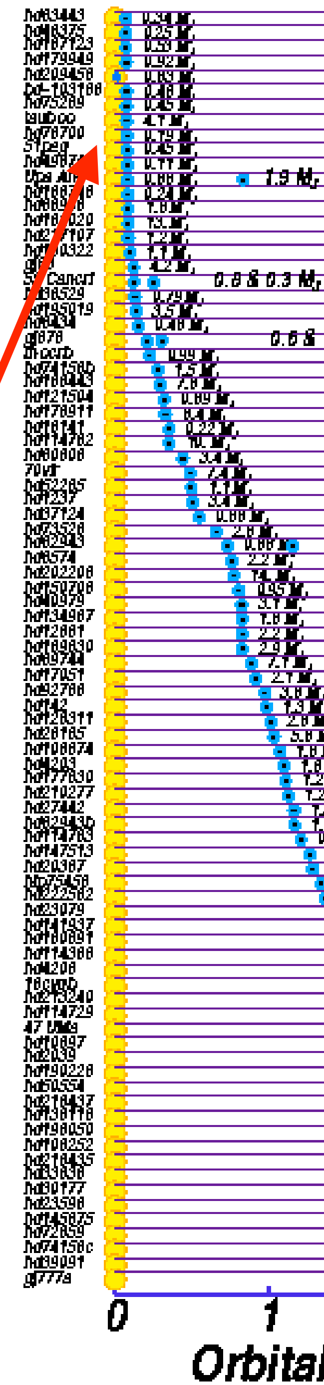


Other than multiple planet systems, these are not planets until either transits or astrometry provide orbit inclination

http://exoplanets.org/index.html

The Questions

1. Do extrasolar planets exist?
2. How do we find them?
3. How far away from their parent s these planets?
4. **Why was this a huge surprise?**
5. How massive are these planets?
6. Do extrasolar planetary systems (to our solar system) exist?



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Gas giants close to their host stars should not have been a huge surprise.

Goldreich and Tremaine (1980) predicted migration in the context of planetary rings.

W. Ward (1986) predicted that most planetary migrations, in the presence of a nebular disk, would be inward.

Motivation

Planet type depends upon mass. As for stars, mass critically determines most of the instantaneous characteristics and future evolution of a planet. Our present instruments and techniques can distinguish between brown dwarfs, gas giants, and rocky-cored Neptunes.


S82E5937 1997:02:19 07:06:57

The Goal of HST Astrometry

- establish the semi-major axis size (thus, the inclination) of the perturbation to determine the **mass** of the perturbing object

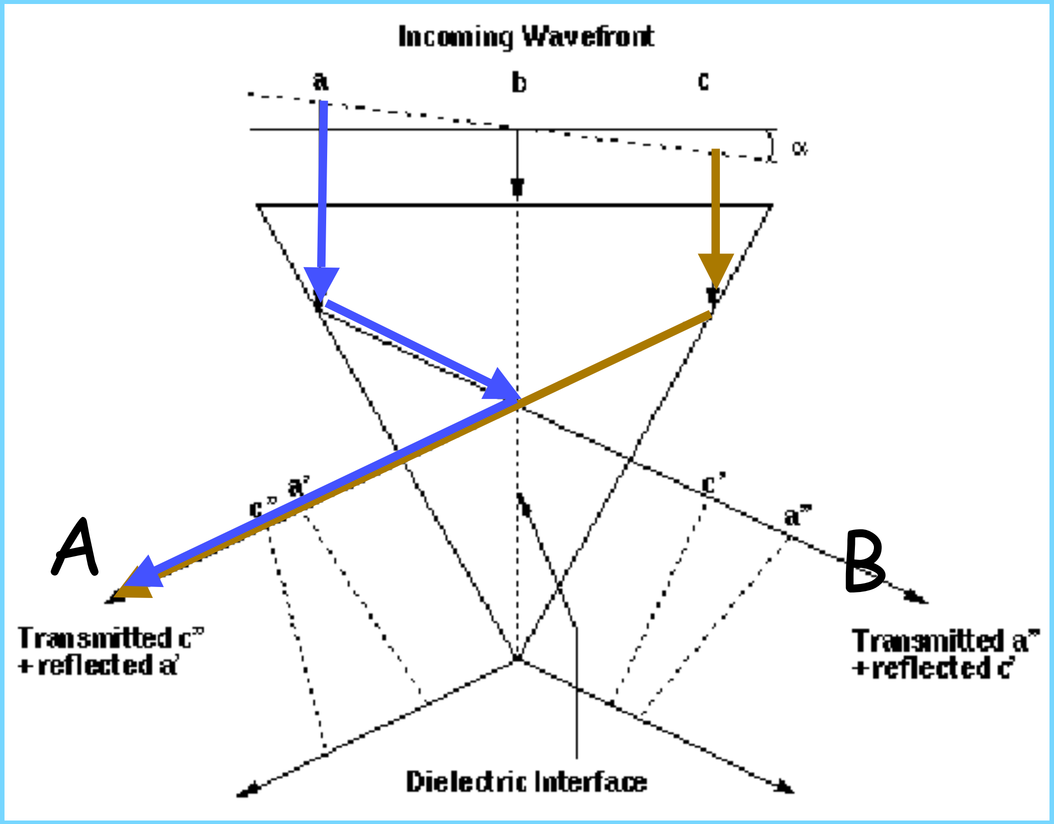
The Tools

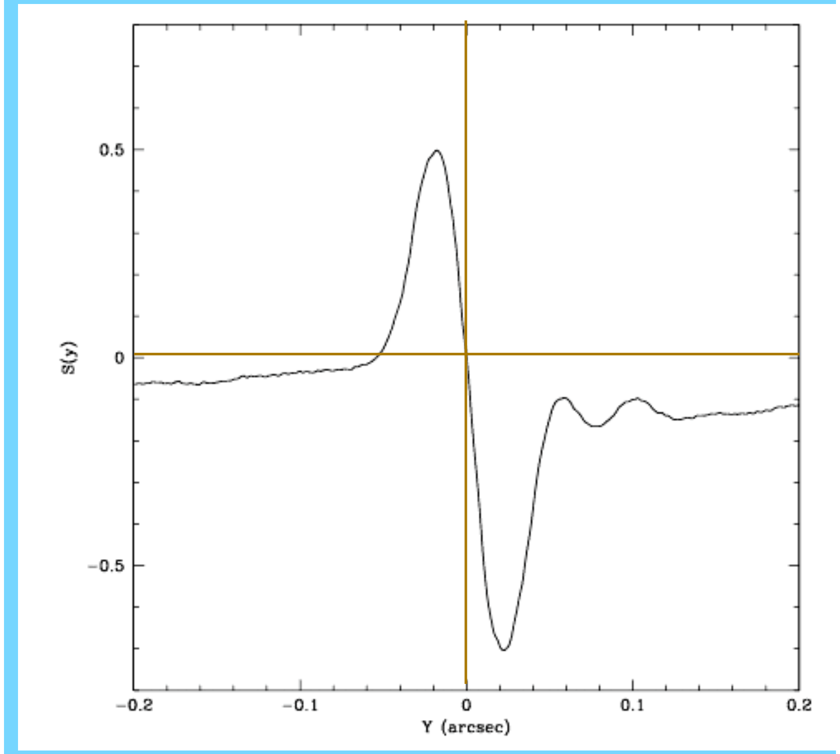
- small field relative astrometry using Fine Guidance Sensor 1r (FGS 1r) on Hubble Space Telescope
- ground-based, high-precision radial velocities from multiple sources

Our methodology is briefly outlined in Benedict et al. (2002, ApJL, **581**, 115) where we estimated the mass of Gl 876b

Space Astrometry with an Interferometer on Hubble Space Telescope

The Koester's Prism - the Interferometric Heart of an FGS





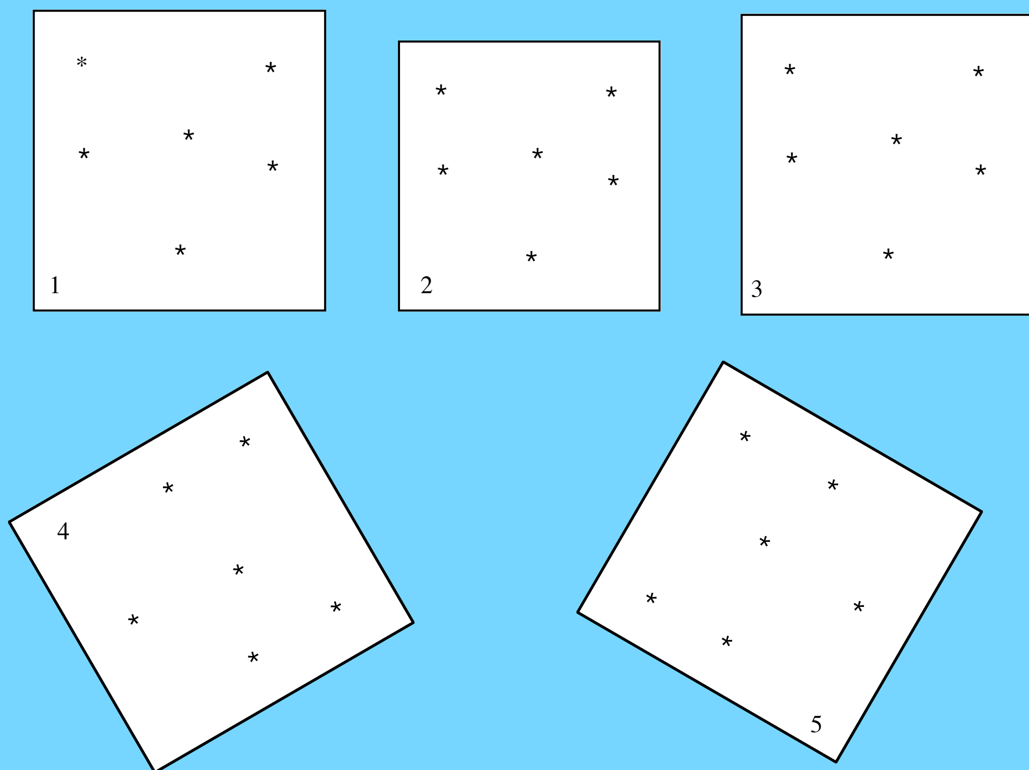
$$S = (A-B)/(A+B)$$

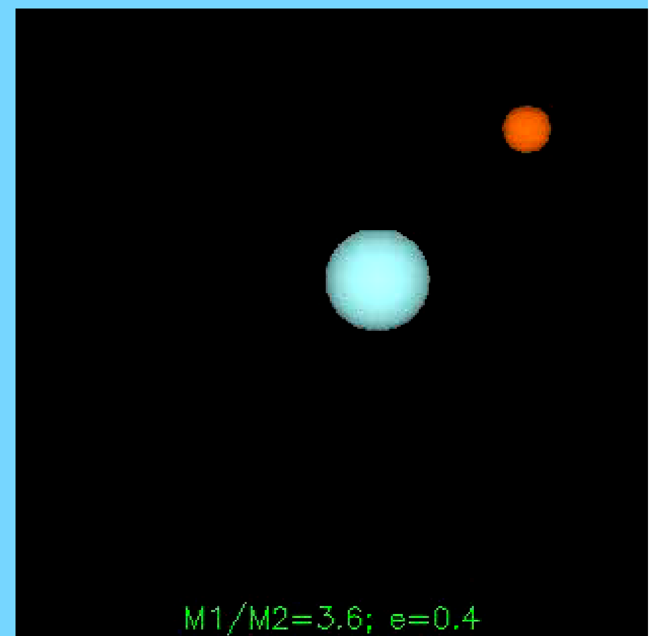
Astrometry, a simple example

5 "plates"

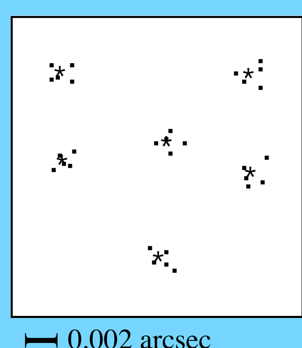
different scales

different orientations





Result of Overlap Solution to Plate #1

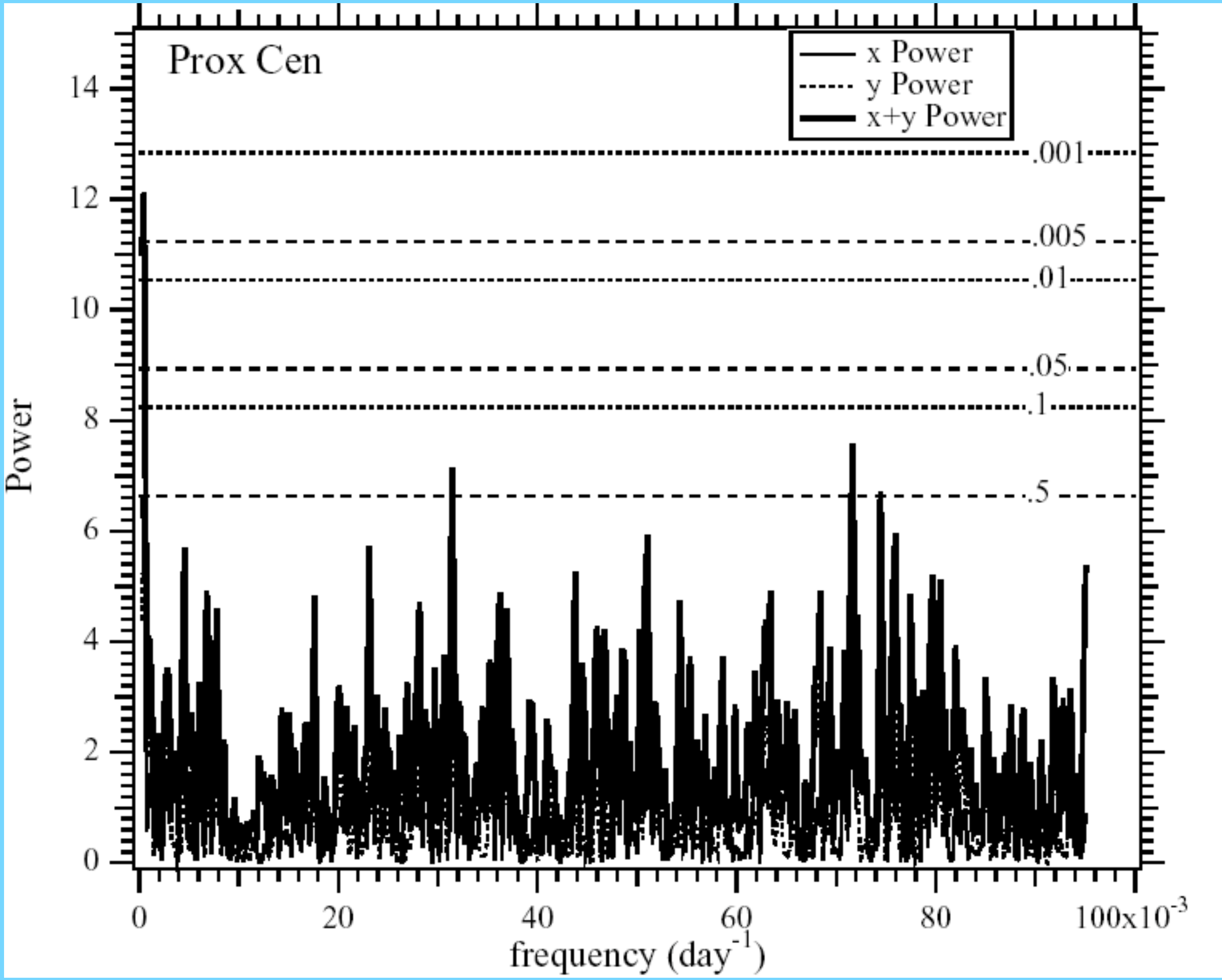


Precision = standard deviation of the distribution of residuals (▪) from the model-derived positions (*)

HST Astrometry Extrasolar Planetary Mass Targets

Star	d(pc)	Sp. T.	Status
Proxima Cen	1.3	M5 Ve	Upper Limits
Barnard's Star	1.8	M4 Ve	Upper Limits
Gl 876	**4.7**	**M4V**	**masses**
ρ^1 = 55 Cnc	**12.5**	**G8V**	**masses**
ε Eri	3.2	K2V	preliminary
υ And	13.5	F8V	in progress

Proxima Cen Periodogram



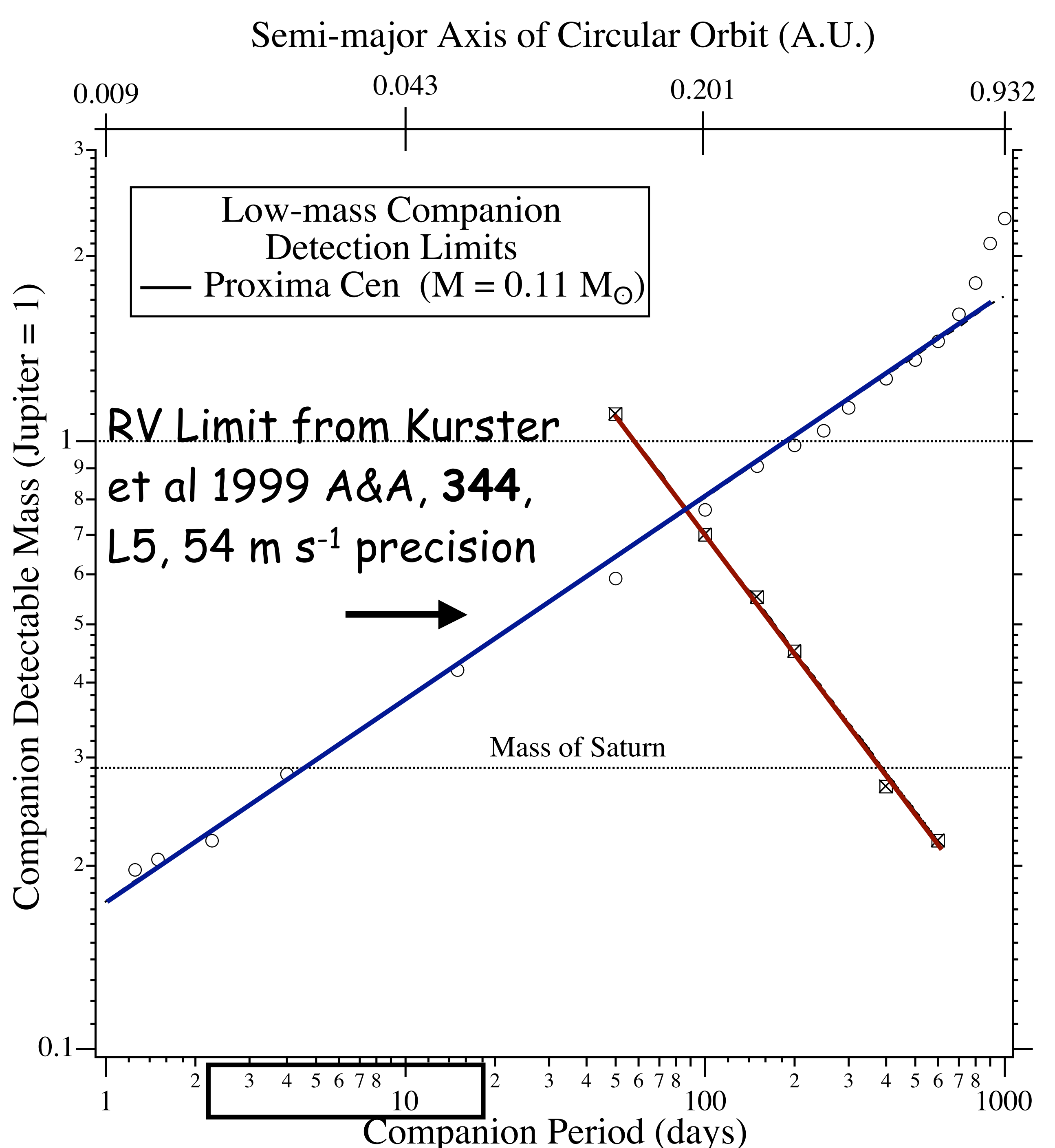
59 epochs

Over 5.5y

30 m < Δt < 1 yr

Benedict et al. 1999, AJ, **118**, 1086

Astrometry limit from Monte-Carlo analysis: 3-σ detection of 1 mas perturbation



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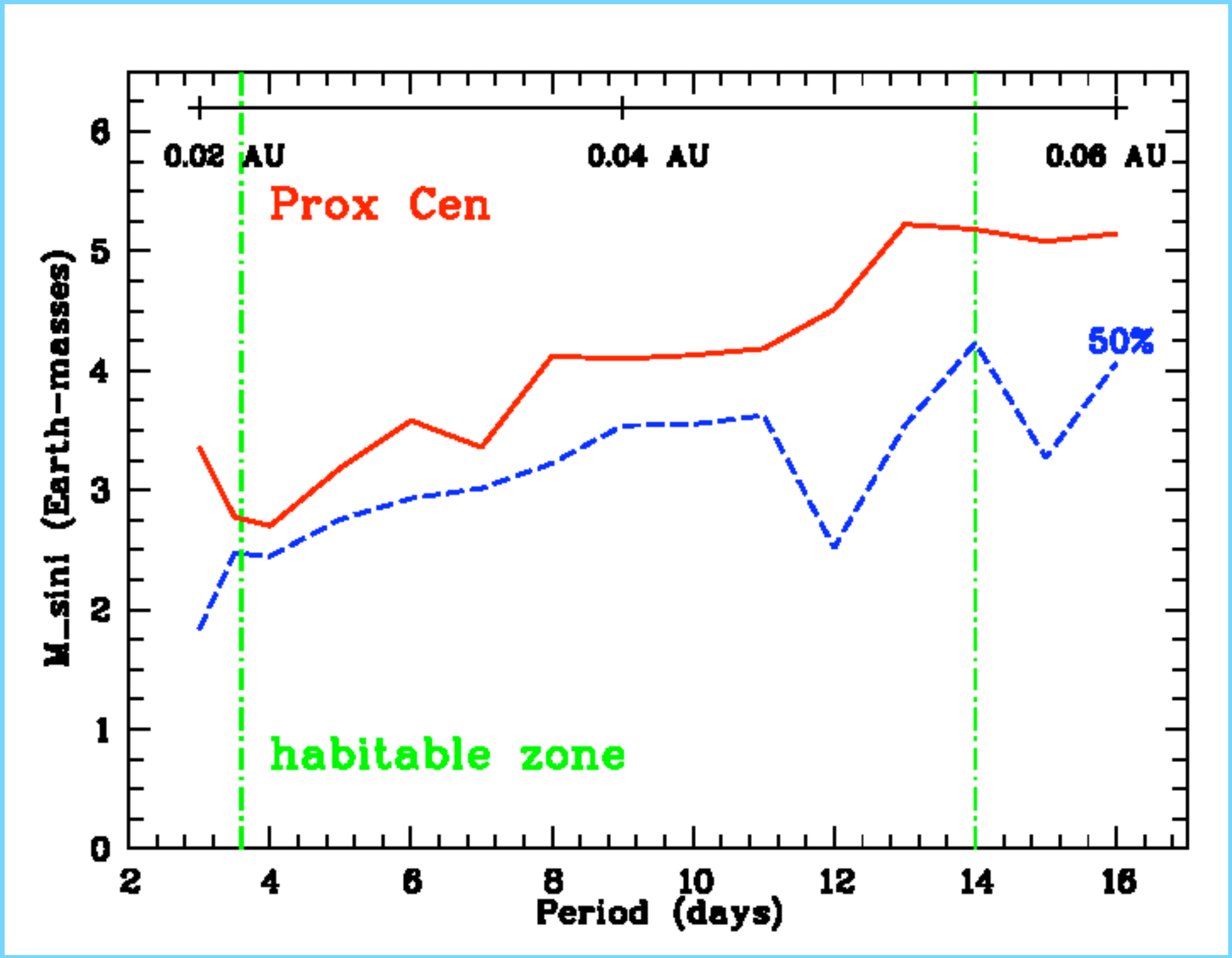

RV precision is now ~2.5 m s^{-1}

(Kürster & Endl, 2004, ASP, 321, 84)

Lemons to Lemonade

Rotation period of Proxima Cen from FGS millimag photometry

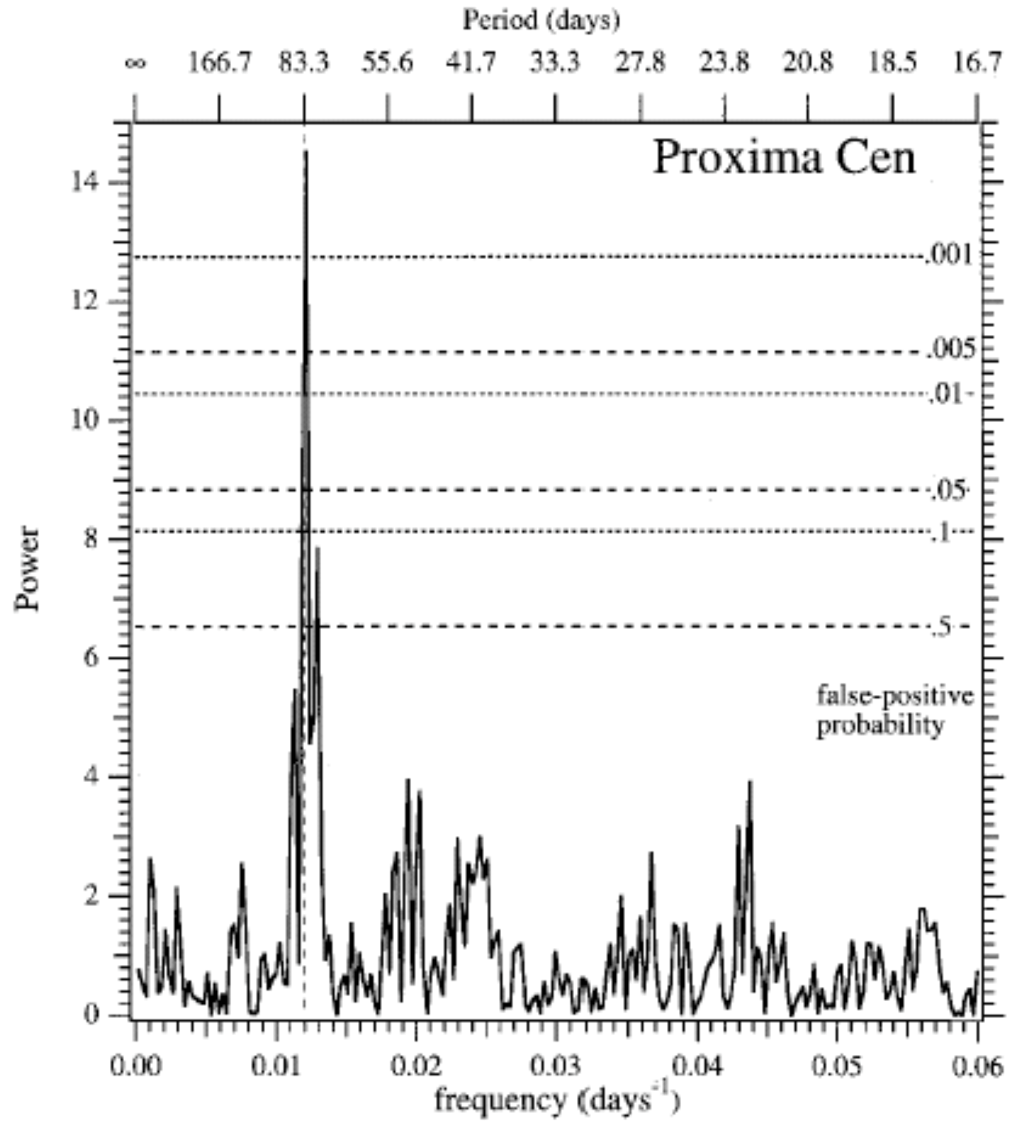

FIG. 11.—Periodogram from 71 normal points (average for each orbit) with flares removed, flat-fielded with eq. (2). The most significant peak is at $P \sim 83$ days, with less than a 0.1% false-positive probability.

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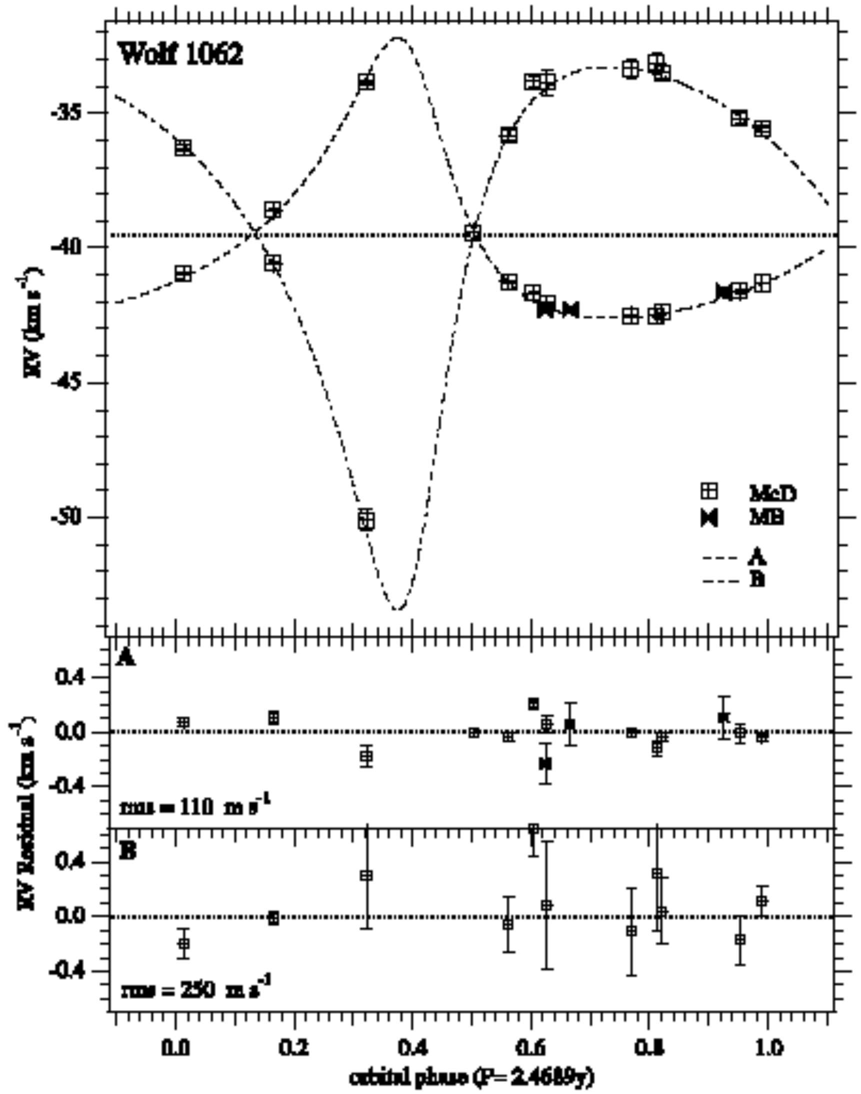

FIG. 4.—*Top*: radial velocity measurements from Marcy & Benitz (1989; MB) and the present study (McD), phased to the orbital period determined from a combined solution including astrometry and radial velocity. The lines are velocities predicted from the orbital parameters derived in the combined solution. *Middle* and *bottom*: radial velocity residuals from the combined solution for component A and B, respectively. The error bars on the residuals are the original measurement errors (1 σ).

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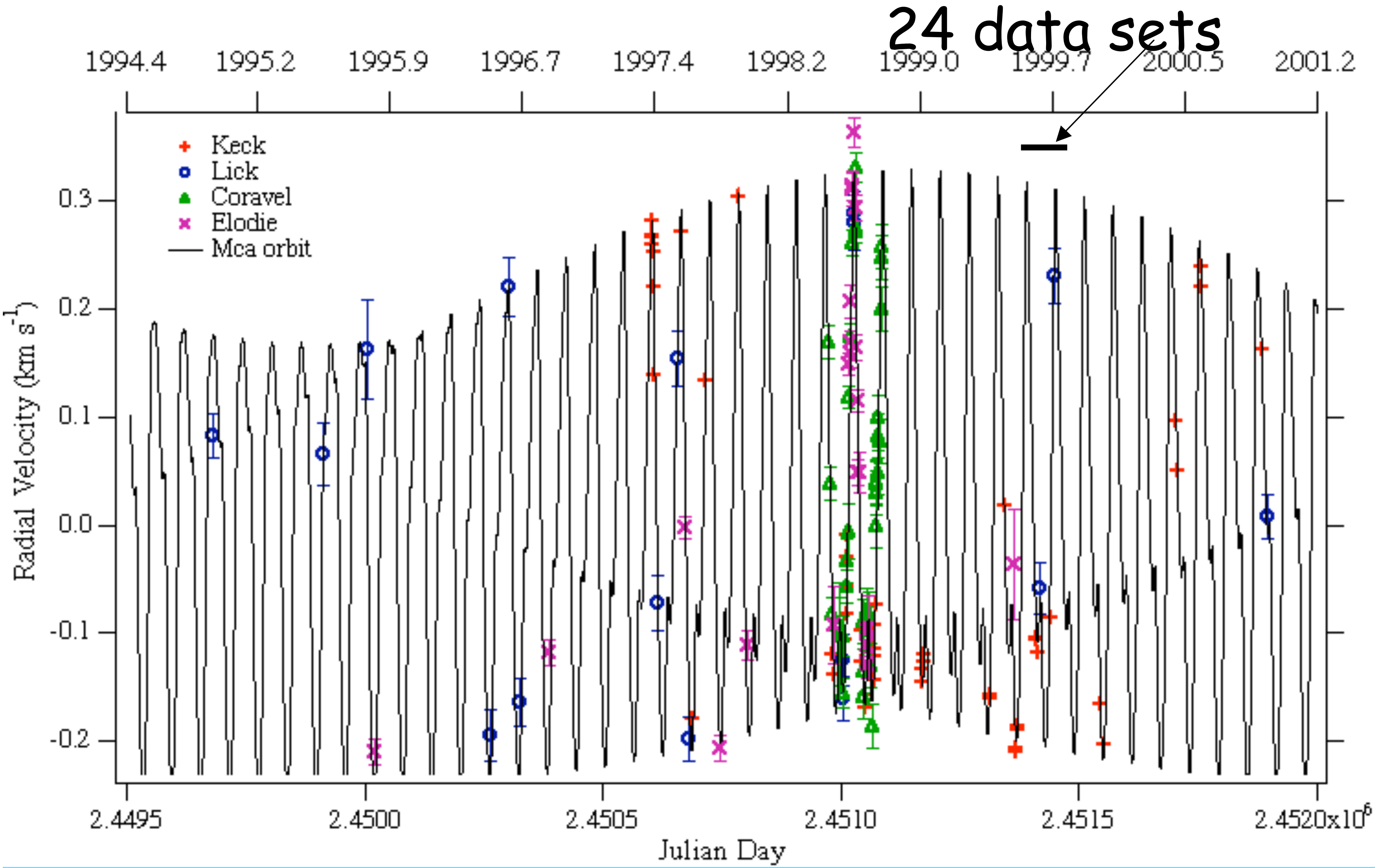
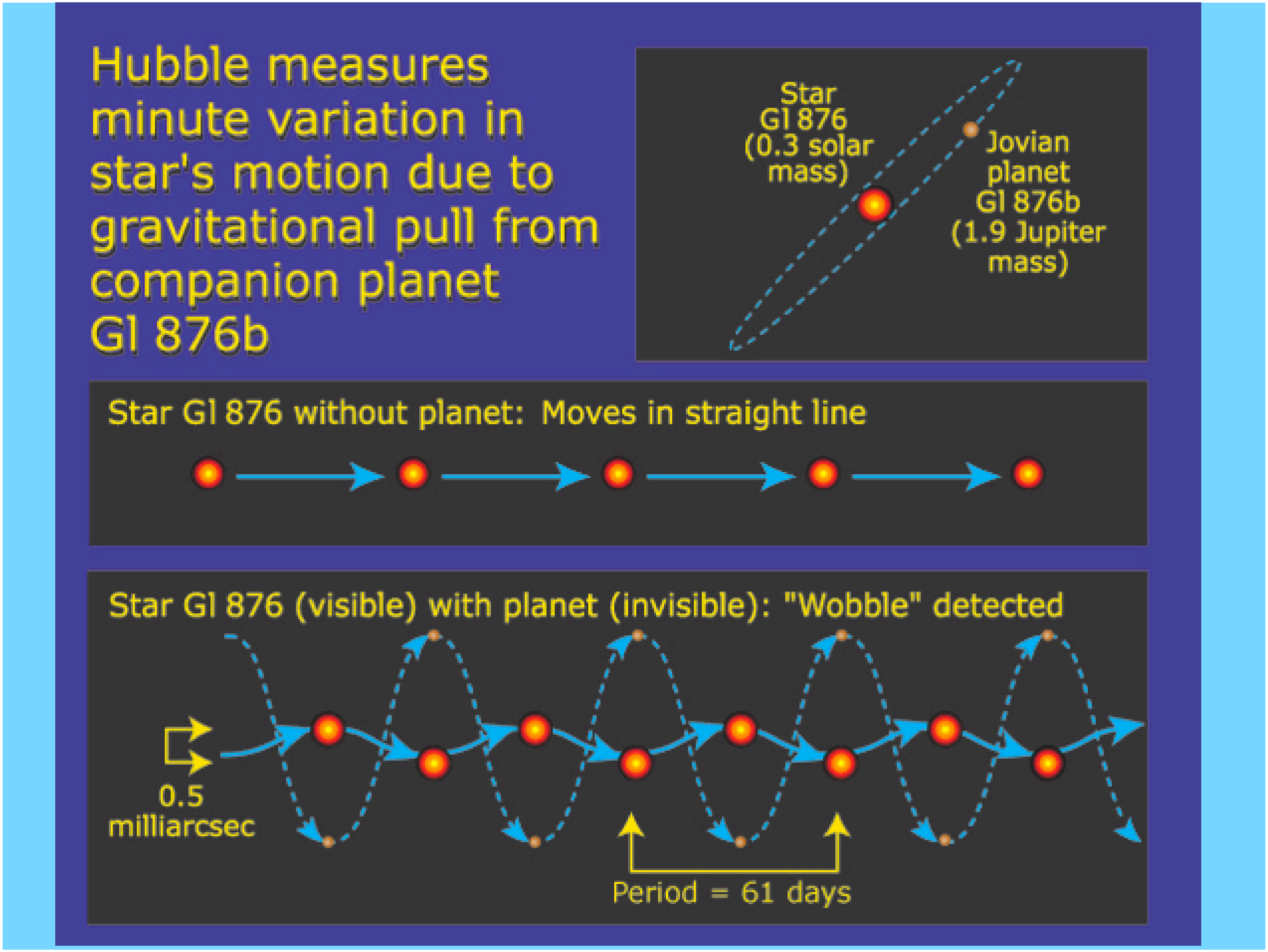
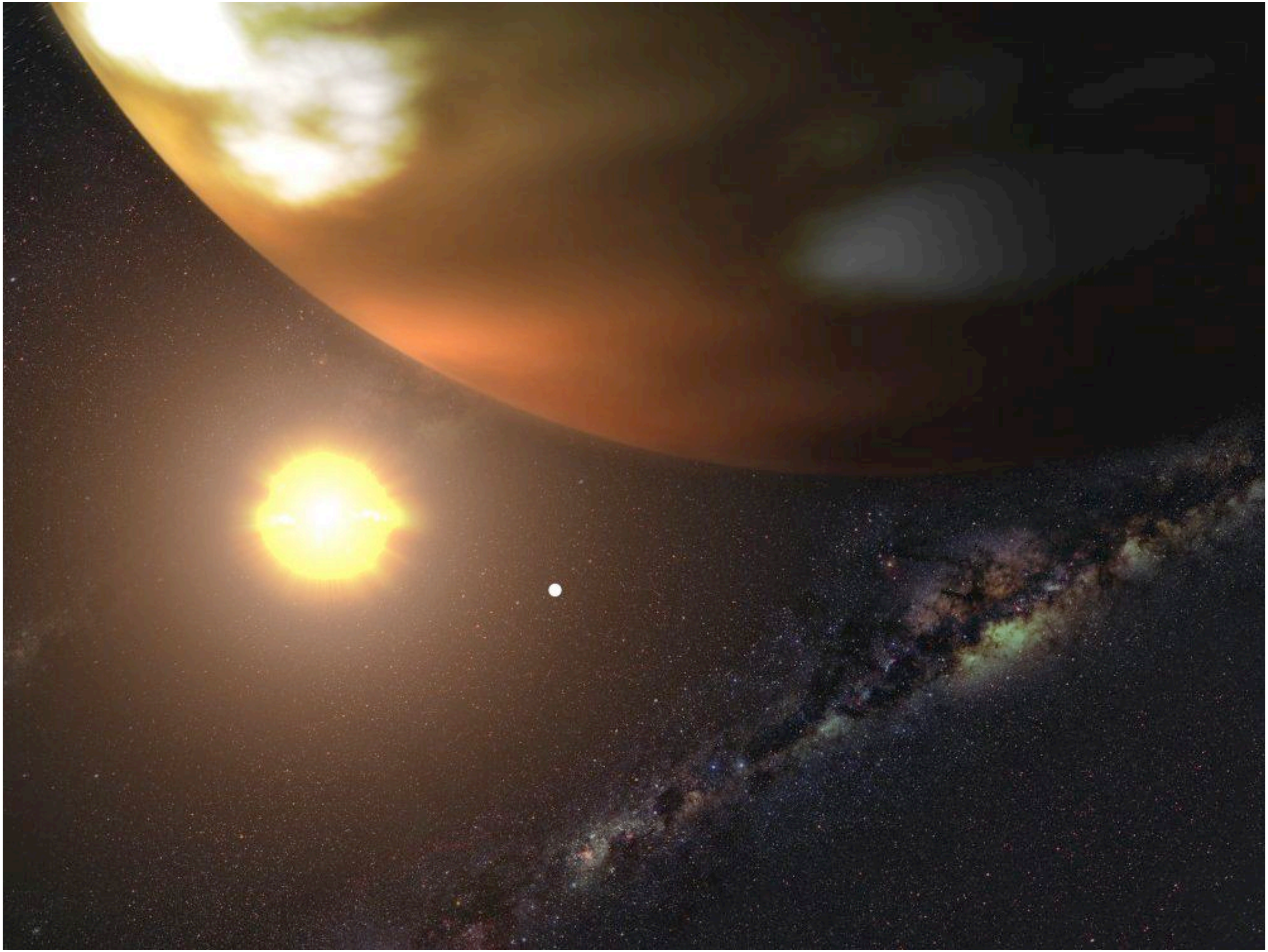


GJ 876 radial velocities


Hubble measures minute variation in star's motion due to gravitational pull from companion planet Gl 876b
Star Gl 876 (0.3 solar mass)
Jovian planet Gl 876b (1.9 Jupiter mass)
Star Gl 876 without planet: Moves in straight line
Star Gl 876 (visible) with planet (invisible): "Wobble" detected
0.5 milliarcsec
Period = 61 days

Gl 876 and Gl 876b from a hypothetical moon orbiting Gl 876b

Artist's rendition courtesy of Lynette Cook (http://extrasolar.spaceart.org/)



GJ 876

We have determined relatively precise extrasolar planetary **masses** (not msini !!). We get the mass of component c by invoking coplanarity.

Gl 876, M4V $\mathcal{M}_b = 1.89 \pm 0.34 \mathcal{M}_{Jup}$

$$\mathcal{M}_c = 0.56 \pm 0.10 \mathcal{M}_{Jup}$$

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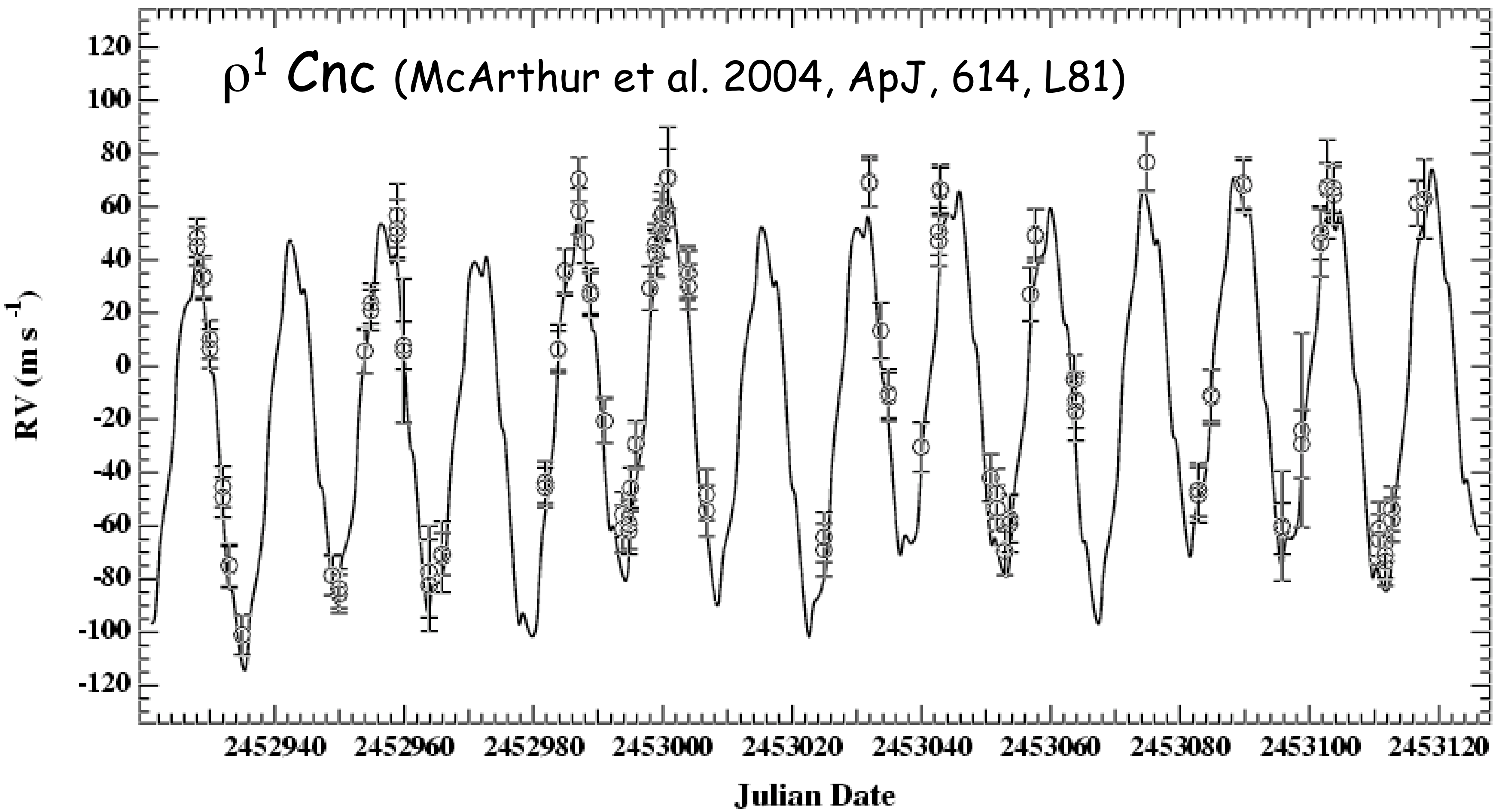
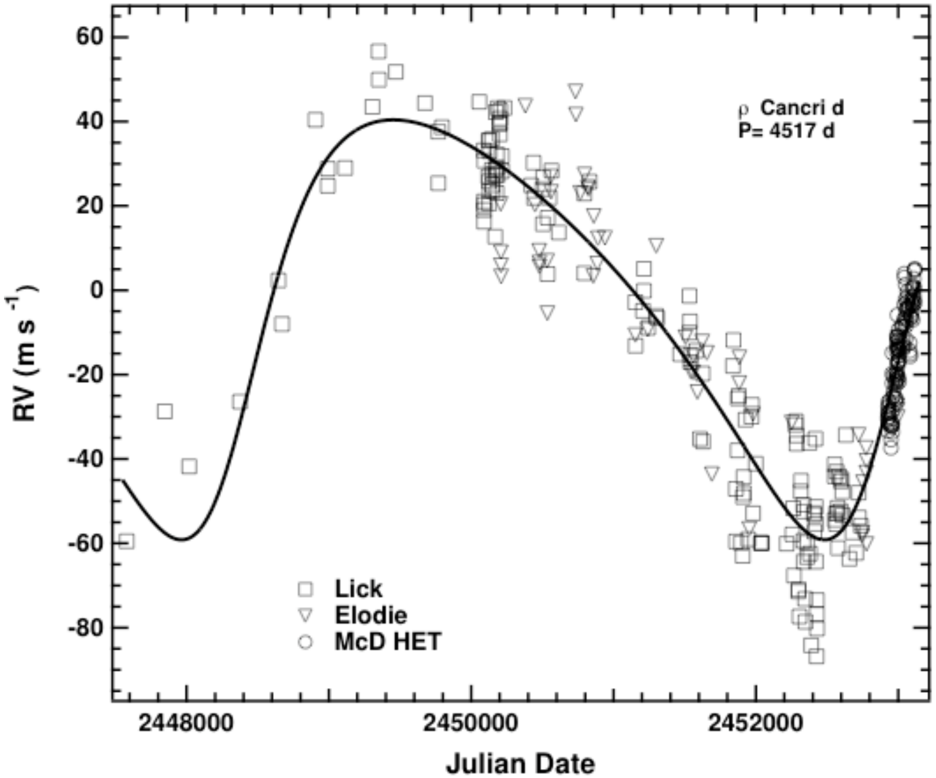


The Approach: use ground-based radial velocities to determine **P**, period; **e**, eccentricity; ω, longitude of periastron passage; **T**, time of periastron passage; $\mathbf{K_1}$, RV amplitude



ρ^1 Cnc d = 55 Cnc d

Perturbation due to component d,

P = 4517 days

α = 1.9 ± 0.4 mas

i = 53° ± 7°

$m_d \sin i = 3.9 \pm 0.5 m_J$

$m_d = 4.9 \pm 1.1 m_J$

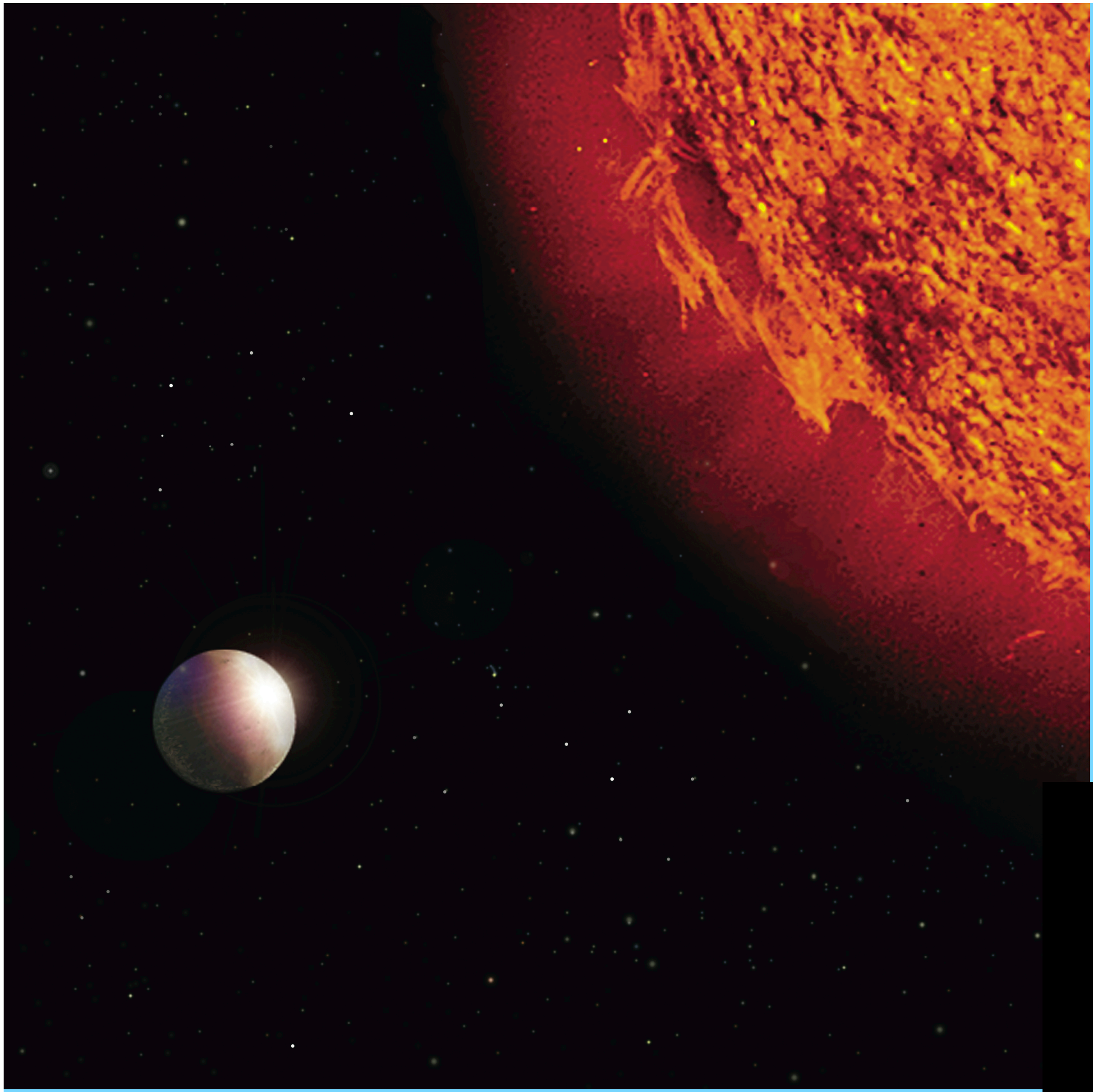
Combining HST astrometry and ground-based RV

McArthur et al. 2004 ApJL, 614, L81

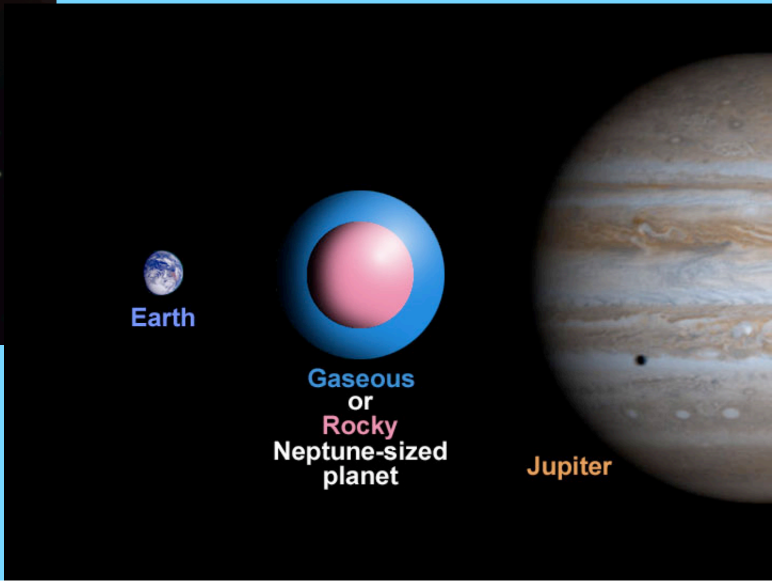
The 55 Cnc (= ρ^1 Cnc) planetary system, from outer- to inner-most

ID	r(AU)	$\mathcal{M}$ ($\mathcal{M}_{Jup}$)	
d	5.26	4.9 ± 1.1	
c	0.24	0.27 ± 0.07	
b	0.12	0.98 ±0.19	
e	0.04	0.06 ± 0.02	**= (17.8 ± 5.6$\mathcal{M}_\oplus$) a Neptune!!**

Where we have invoked coplanarity for c, b, and e



To find planet e, HET access and cadence essential



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Our Approach

Use FGS astrometry to determine

- α, semi-major axis of perturbation
- i, orbit inclination
- Ω, position angle of ascending node
- π, parallax of system
- μ, proper motion of system

Use lower-precision ground-based astrometry to extend the time baseline to better define the proper motion and, eventually the perturbation

- ε ERI, 1989 - present

Our Approach, continued

Simultaneous solution incorporating both astrometry and radial velocities

- Constrain all plate constants to those determined from astrometry-only
- Constrain K, e, P, ω to values determined only from radial velocities
- Invoke (Pourbaix & Jorrisen 2000) constraint

$$\frac{\alpha_A \sin i}{\pi_{abs}} = \frac{P K_1 sqrt(1-e^2)}{2\pi \times 4.705}$$

- Solve for α, i, μ and π

• ε Eri age < 1 Byr (Di Folco et al. 2004, A&A 426, 601)

• ε Eri has an associated dust disk (Greaves et al. 2005, ApJ 619, L187)

• Dust disk inclination ~30°

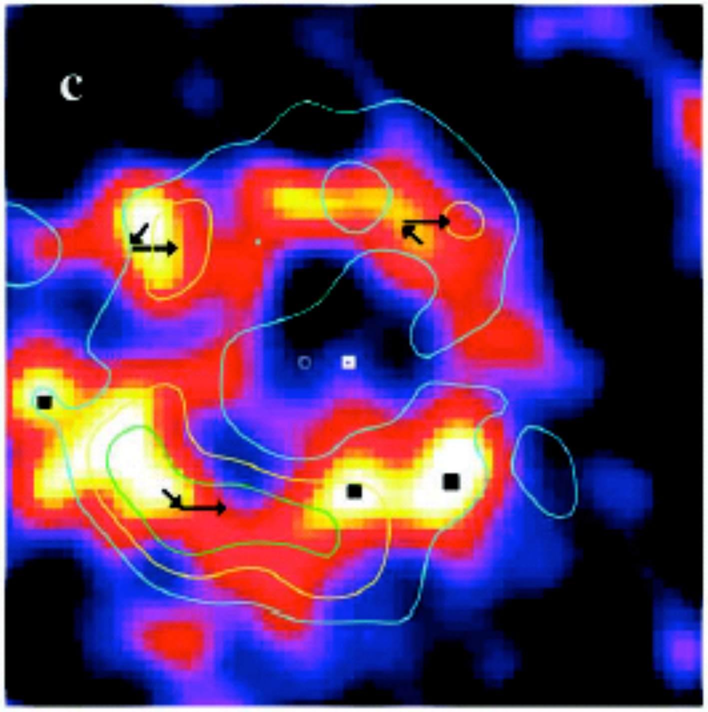
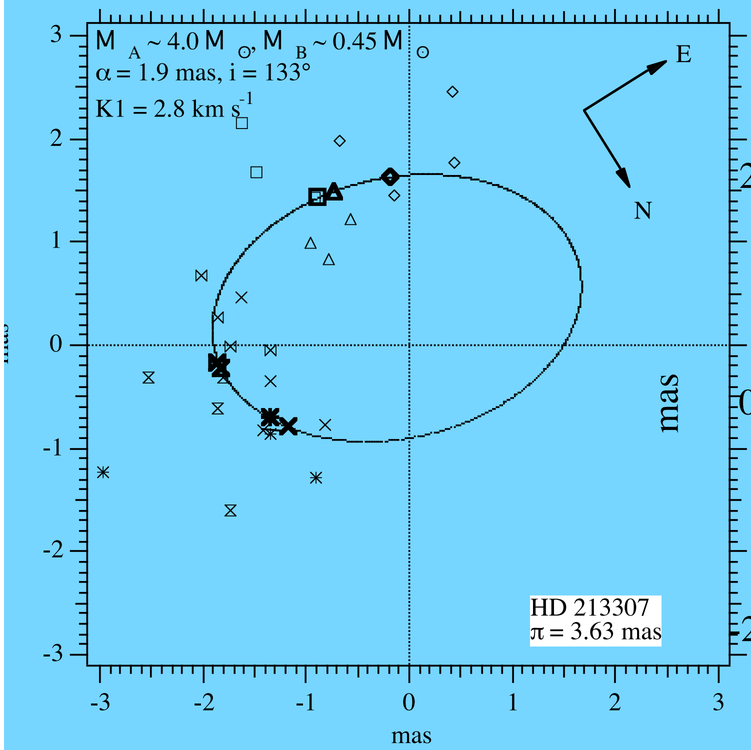
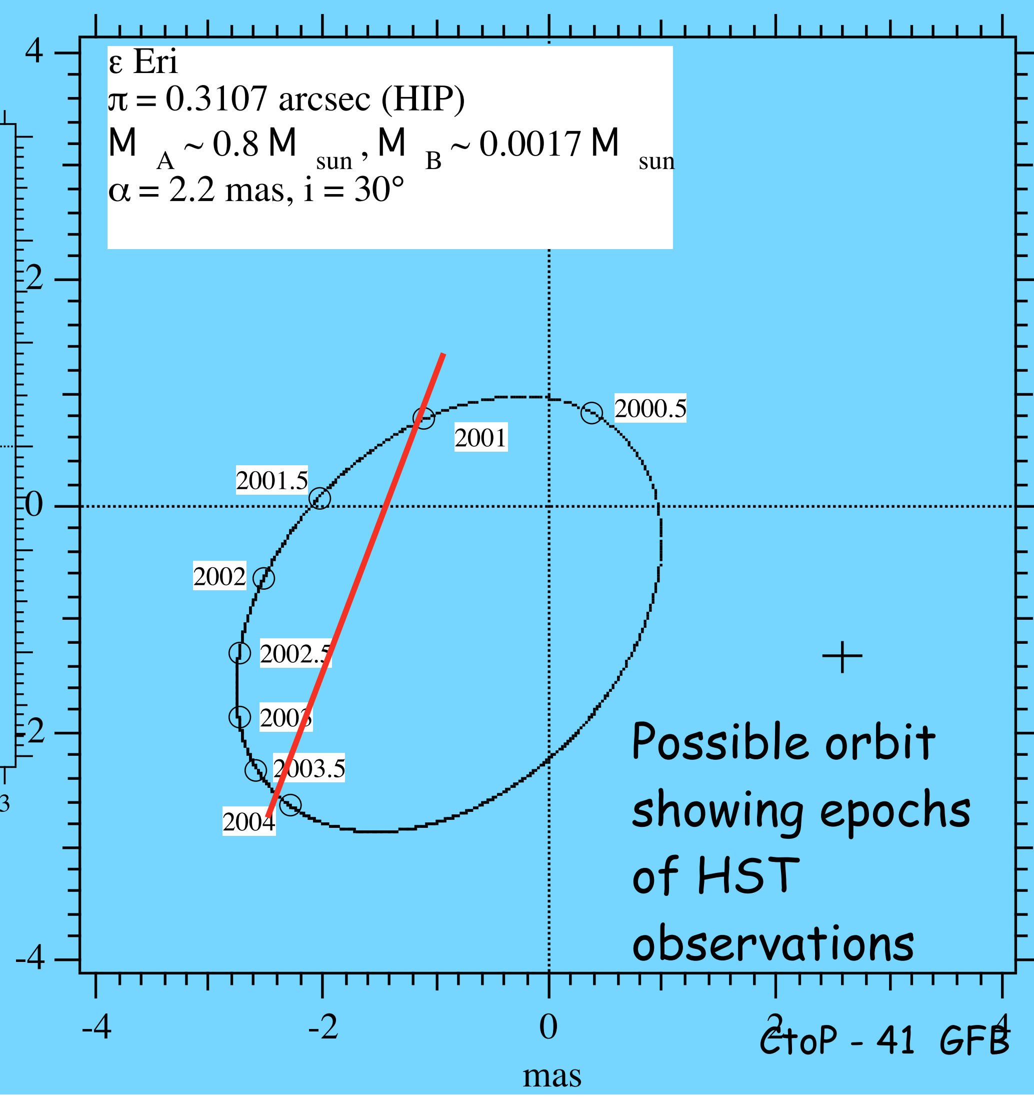


FIG. 1.—Results for the ε Eri dust disk. (*a*) Entire 850 μm data set, showing 1″ pixels in a 70″ field in R.A., decl. coordinates (north is up, east is left) centered about the star (*white square*, epoch 2002.8). Flux scale is linear from 0 to 5.4 mJy beam^{-1} (90% of the peak); contours are 5, 8, and 11 σ, where 1 σ is 0.5 mJy beam^{-1}. (*b*) Entire 450 μm image, showing flux from 0 to 20 mJy beam^{-1} (90% of peak), overlaid with the 850 μm contours from (*a*). (*c*) 850 μm data from 1997/8 (color scale) with superposed 30%, 50%, and 70% contours from the 2000–2002 data, in a fixed coordinate frame. The unfilled white square shows the star's position backtracked by 4.5 yr for demonstration purposes. Black squares are suggested background features, and black arrows are motion associated with the disk (see text).

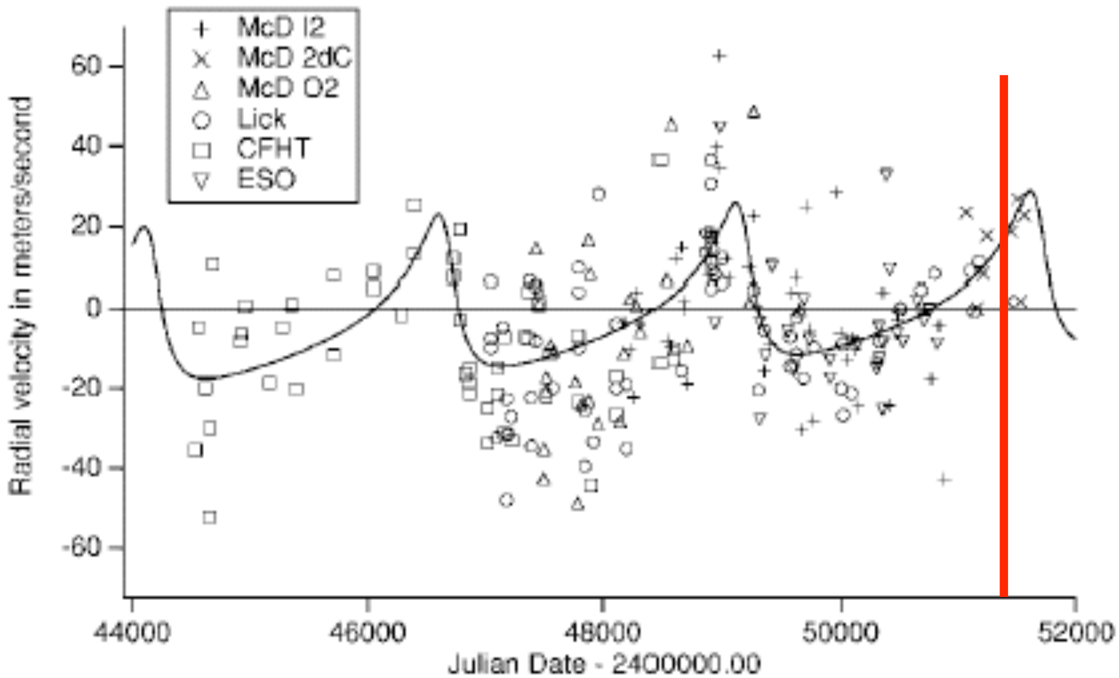
One might expect the planet orbital plane and the dust disk to be coplanar.

HST Astrometry of the extrasolar planet of ε Eridani





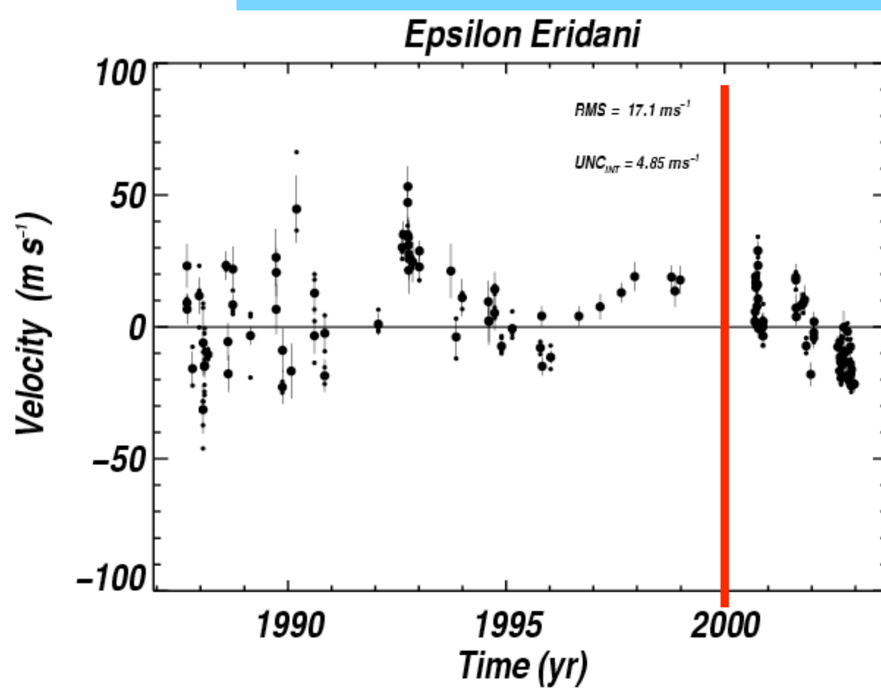
Possible orbit showing epochs of HST observations



Hatzes et al. 2000, ApJL, 544, L148

California-Carnegie web site

ε Eri is a chromospherically active star producing ΔV unrelated to companions



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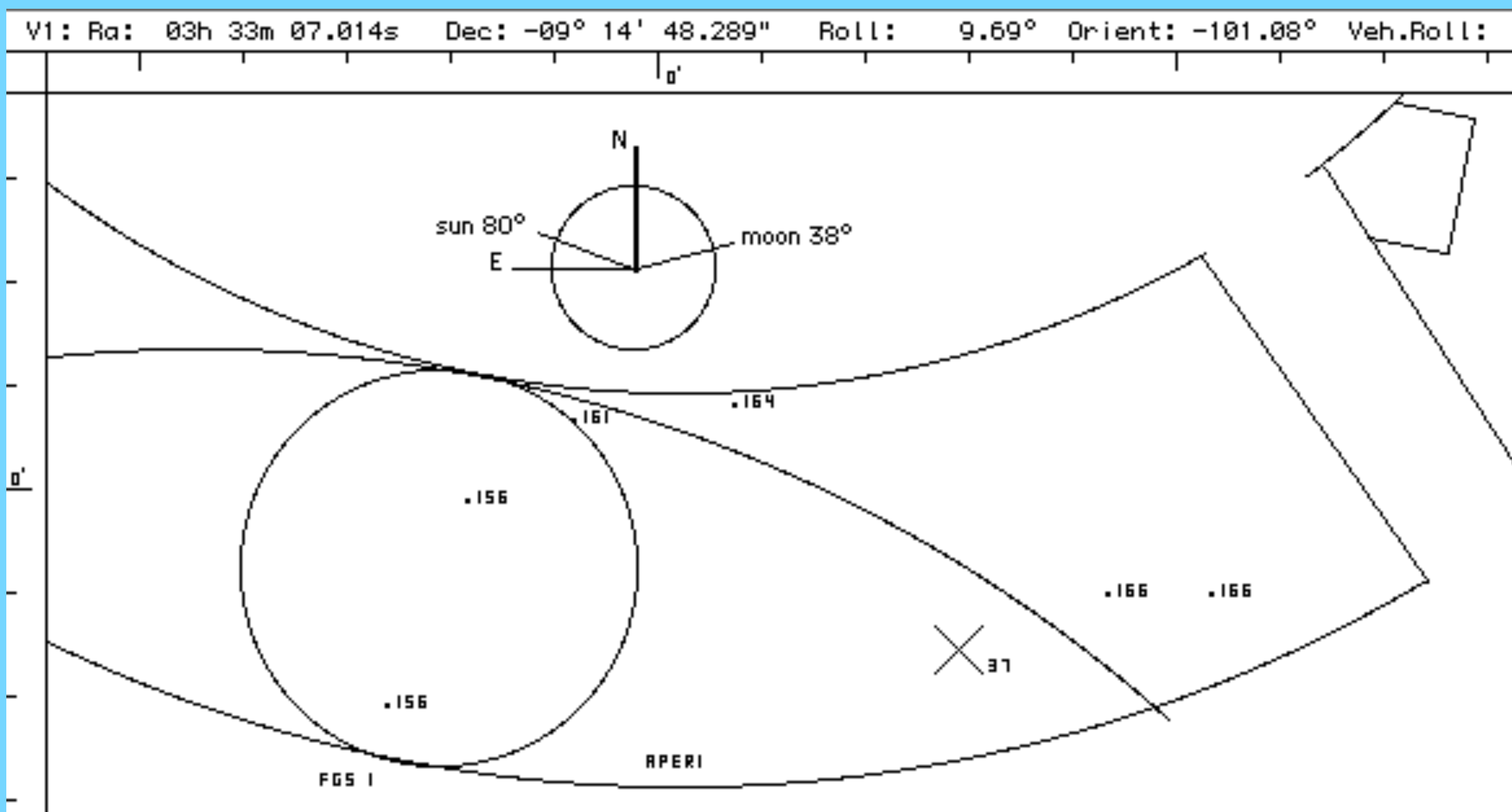
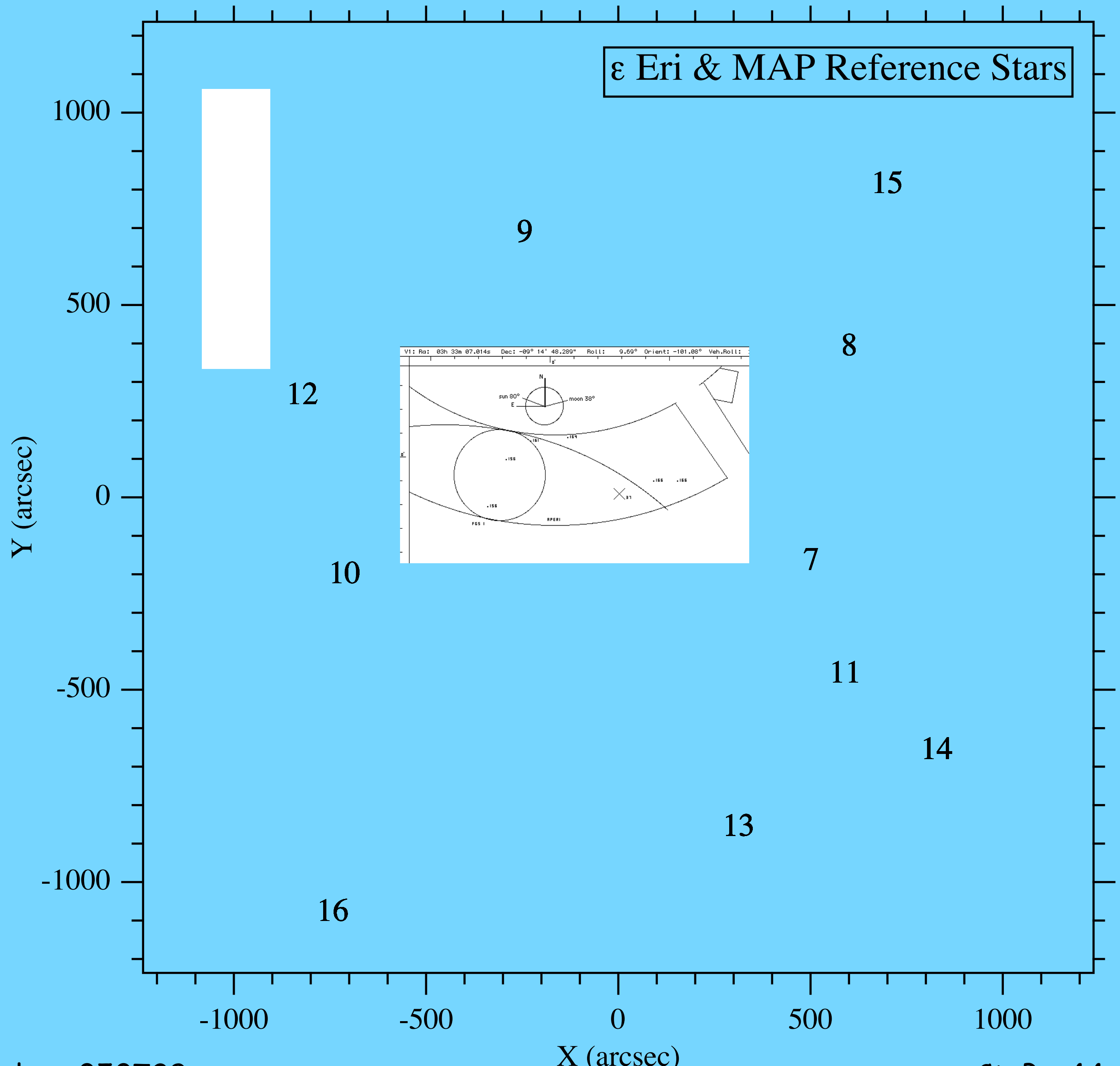
Also

ε Eri FGS astrometry afflicted with poor distribution of, and very faint, reference stars



The FGS has a dynamic range > 13 magnitudes.



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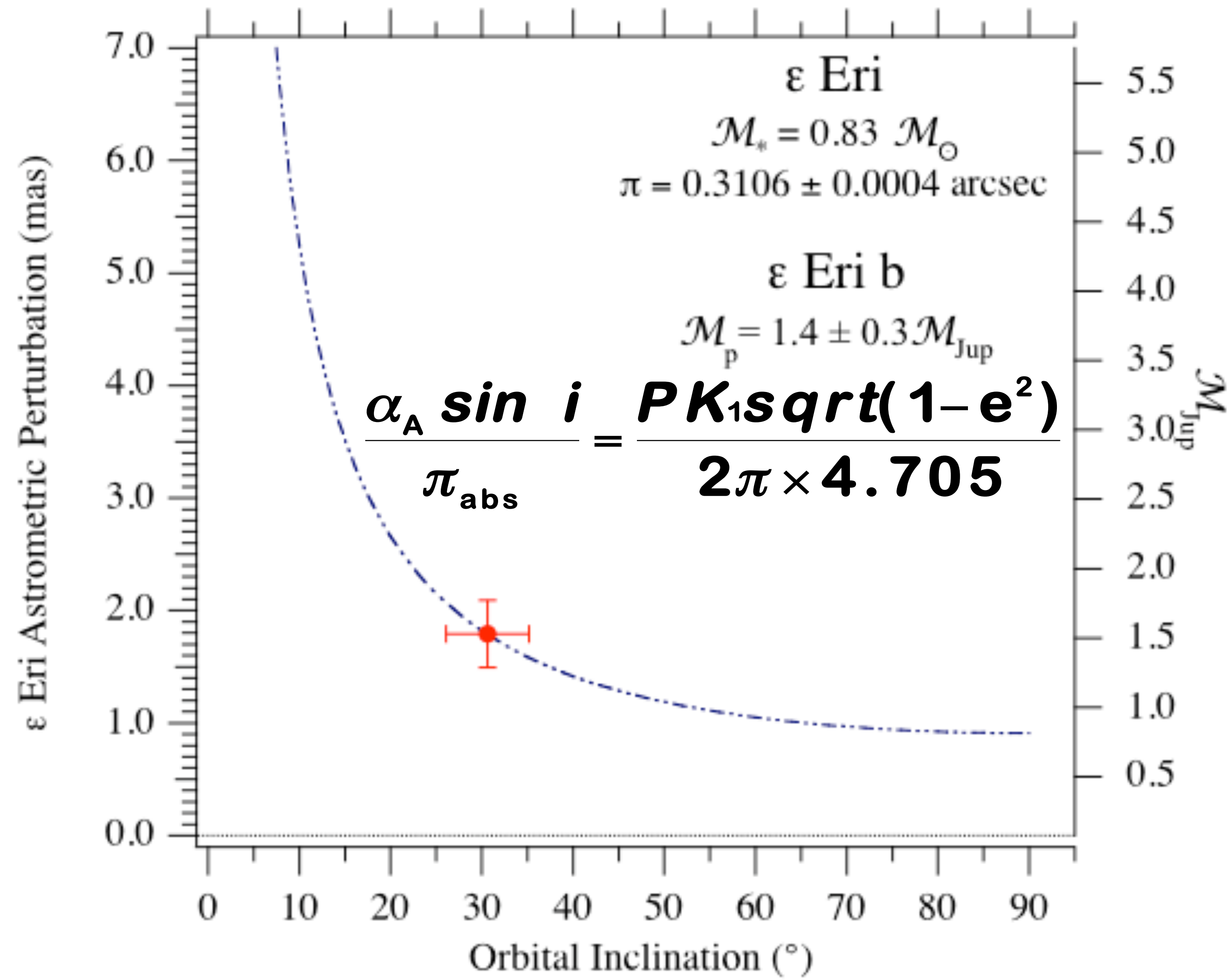


$$\frac{\alpha_A \sin i}{\pi_{abs}} = \frac{P K_1 sqrt(1 - e^2)}{2\pi \times 4.705}$$

The point cannot stray far from the curve because the errors on rhs are relatively small. The curve is a quasi-Bayesian prior.

DPS Pasadena Meeting 2000, 23-27 October 2000
Session 32. Extra-Solar Planets Posters

[32.01] The Actual Mass of the Object Orbiting Epsilon Eridani - G. Gatewood (UPitt,AO)

12 years, 112 observations, 15 mas per observation precision (HST was 3 years, 50 observations, 1 mas per observation precision)

$$\alpha = 1.51 \pm 0.44 \text{ mas}$$

We get $\alpha = 1.8 \pm 0.39$ mas

Weighted average $\alpha = 1.67 \pm 0.29$ mas

$$\mathcal{M}_b = 1.5\mathcal{M}_{Jup} \pm 0.2\mathcal{M}_{Jup}$$

Stay Tuned For

ε Eri - a simultaneous solution incorporating Gatewood ground-based astrometry (including this has preliminarily reduced the error on proper motion by 25%). It may reduce the final mass uncertainty. Or ...

υ And - determination of the inclination of component d will yield masses for b,c, and d.

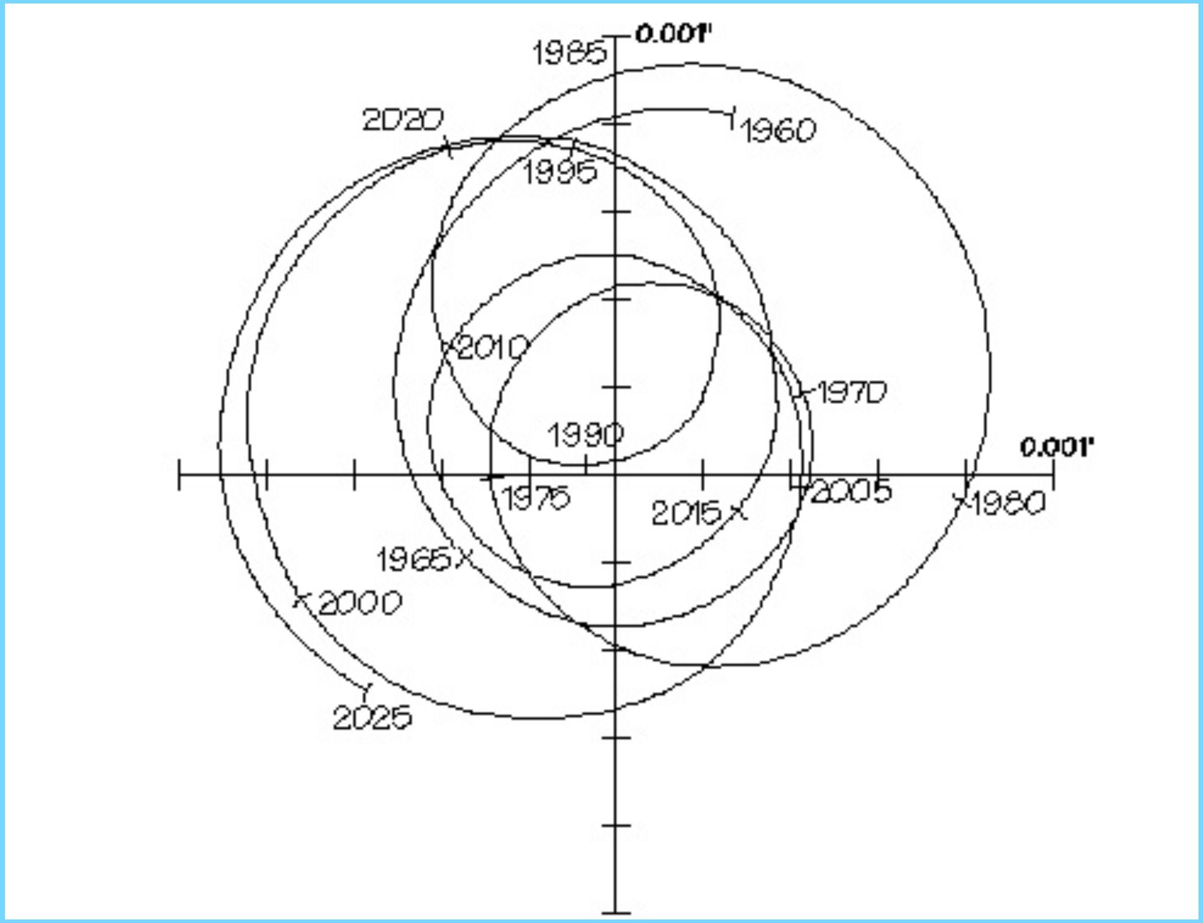
The Near-term Future

Table 3 - Future HST Targets							
Companion	$\mathcal{M}_*$ ($\mathcal{M}_\odot$)	Sp.T.	d(pc)	ecc	$\mathcal{M}$ sini ($\mathcal{M}_{Jup}$)	αsini (mas)	P(d)
HD 47536 b	1.1	K1 III	12.1	0.2	7	0.8	712
HD 136118 b	1.21	F9 V	52.3	0.36	11.8	0.4	1209
HD 168443 c	1.05	G6 IV	37.9	0.2	17.4	1.3	1739
HD 145675 b	1.00	K0 V	18.1	0.38	4.9	0.8	1796
HD 38529 c	1.45	G4 IV	42.4	0.33	13.1	0.8	2207
HD 33636 b	1.02	G0 V	28.7	0.53	9.4	1.1	2447

Cycle 14, 15.

Planetary masses by March 2007.

Watching our Solar System from 30 light years away



To detect the wobble due to earthlike planets we need to measure angles 1000 times smaller than with Hubble Space Telescope.

The Future

Space Interferometry Mission

Several ExP Key Projects

Testing coplanarity

Earth-mass companions