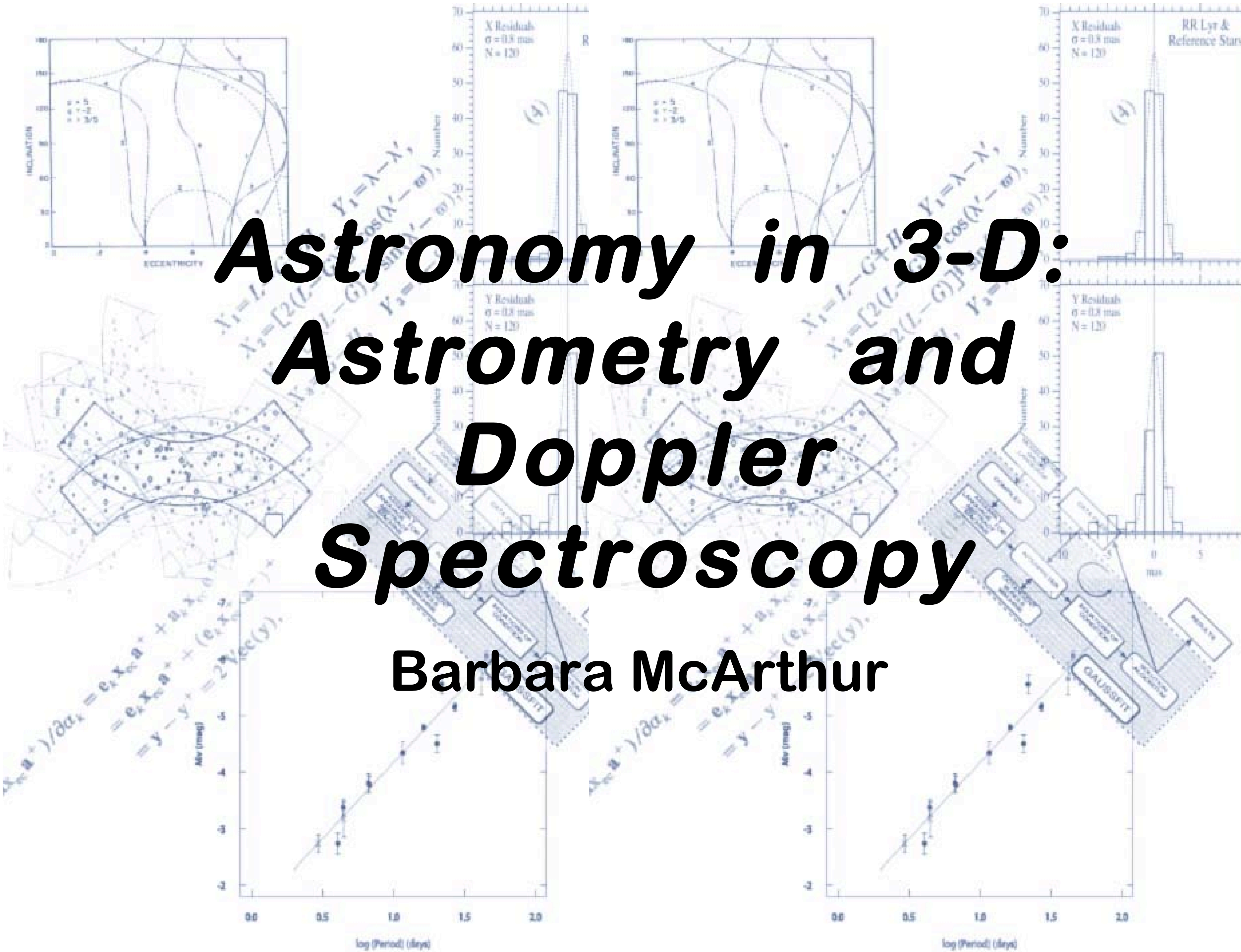


Astronomy in 3-D: Astrometry and Doppler Spectroscopy

Barbara McArthur

And a cast of many coauthors (special, famous and infamous):

G. Fritz Benedict

Otto G. Franz
Todd J. Henry
I. V. Strateva
Phillip Ianna
Ed Nelan
William Van Altena
Paul D. Hemenway
Darrell Story
Art J. Bradley
Theirry Forveille
R. Paul Butler
Geoffrey Marcy
C. Perrier
Michael Endl
Debra A. Fischer
Diedre Queloz
Thomas E. Harrison

Larry H. Wasserman
T. Takato
James L. Crawford
D. W. McCarthy
William H. Jefferys
Pete J. Shelus
Ray L. Duncombe
Art L. Whipple
Larry W. Fredrick
Xavier Delfosse
William Spiesman
B. Goldman
Michel Mayor
William D. Cochran
Dominique Naef
Stephane Udry T

The usual suspects

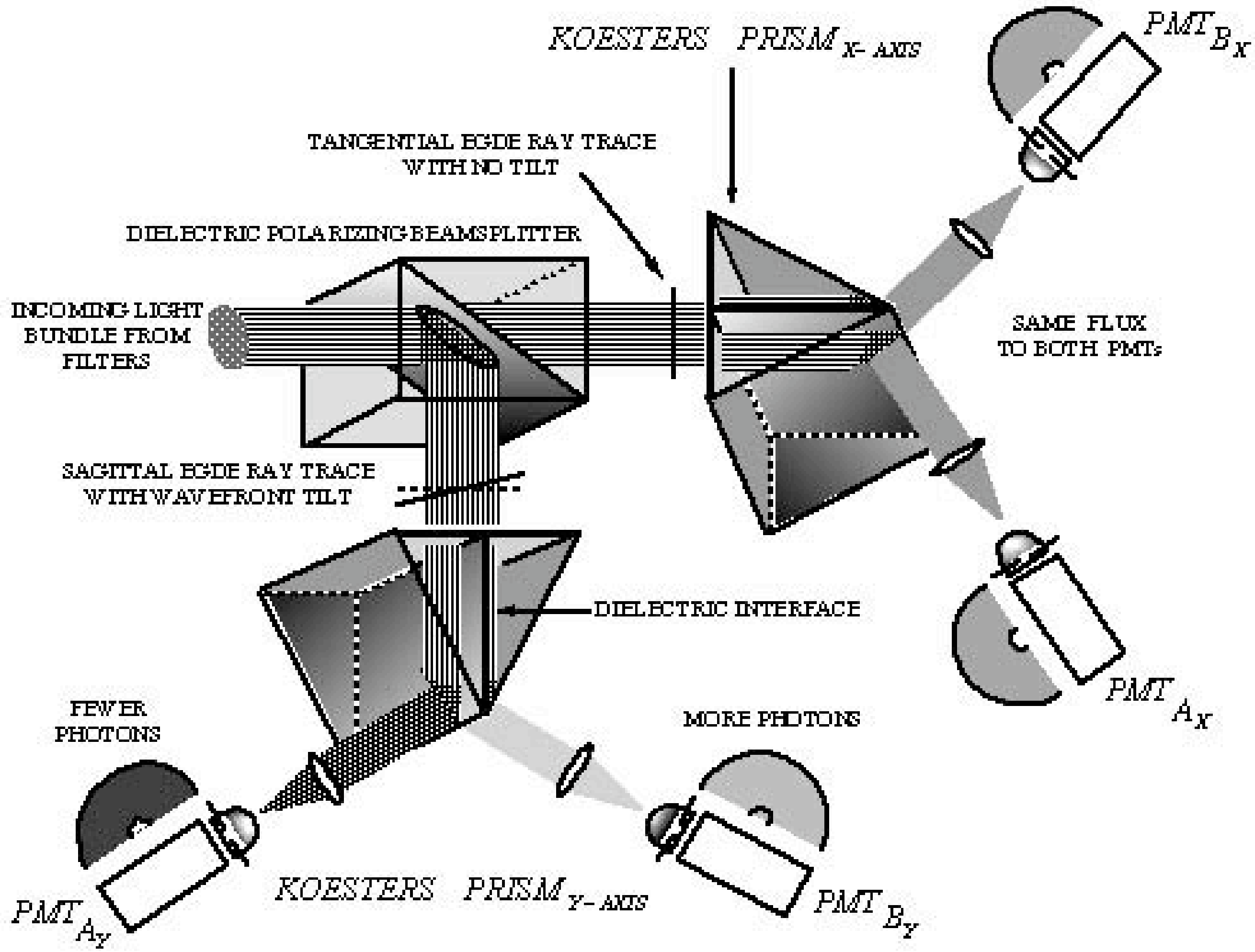
What is astrometry ?

***astrometry** - the branch of astronomy that deals with the measurement of the position and motion of celestial bodies*

It is one of the oldest subfields of the astronomy dating back at least to Hipparchus (130 B.C.), who combined the arithmetical astronomy of the Babylonians with the geometrical approach of the Greeks to develop a model for solar and lunar motions. Modern astrometry was founded by Friedrich Bessel with his *Fundamenta astronomiae*, which gave the mean position of around 3000 stars. Astrometry is also fundamental for fields like celestial mechanics, stellar dynamics and galactic astronomy. Astrometric applications led to the development of spherical geometry.

What is astrometry with the Hubble Space Telescope?

The Fine Guidance Sensors aboard HST are the only readily available white-light interferometers in space. The interfering element is called a Koester’s prism. Each FGS contains two, one each for the x and y axes, as shown in the following optical diagram.



The dual-axis Koester's prism configuration for FGS 3, with wavefront tilt in the y-axis

How do we determine orbits with astrometric measurements?

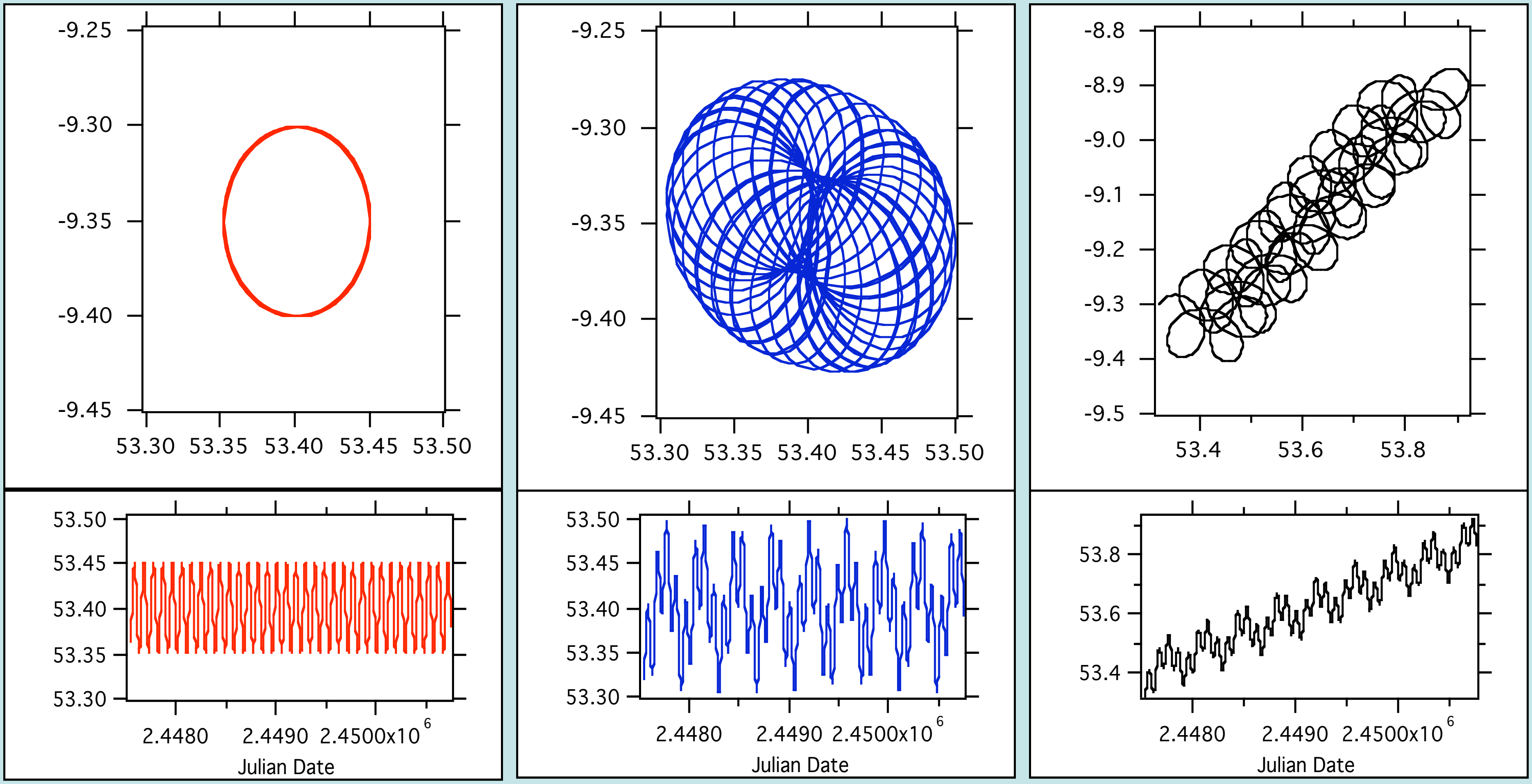
We measure a star in a reference frame over time. We correct the positions for many instrumental effects, then we are left to derive the motions of the star.

As a planet tugs on a star with its gravitational pull, it causes the star to **wobble** in its path across the sky. By making careful, precise measurements of the star's position in the sky, we can detect wobble. But this tugging is not the only motion of the star….

So we find our astrometric orbit

But the parallax can disguise it

And the proper motion can slinky it



What is Doppler Spectroscopy?

As a planet orbits a star, it periodically pulls the star closer to and farther away from Earth (our observation point). This motion has an effect on the spectrum of light coming from the star. As the star moves toward the Earth, the light waves coming from it are compressed and shifted toward the blue (shorter-wavelength) end of the spectrum. As the star moves away from us, the light waves are stretched out toward the red (longer-wavelength) end of the spectrum. These shifts in the spectrum of light coming from the star are called **Doppler shifts**. By making measurements of the star's spectrum over time, we can detect shifts that would indicate the presence of a planet.

Astrometry works best when the star has a relatively low mass and the planet isn't too close to the star. In these cases, the star makes the greatest excursion across the sky and is easiest to detect. Think teeter-totter.

Doppler Spectroscopy has worked best detecting close-in short period planets.

Why combine astrometry with doppler spectroscopy?

More bang for the buck! We can enhance limited amounts of HST astrometry with relatively ‘cheap’ ground-based doppler spectroscopy.
And with a queue-scheduled instrument like the Hobby-Eberly High-Resolution spectroscope we can intensely monitor an object more efficiently than anyone else.
AND more importantly
The accuracy of our result is improved by the constraint that astromery and radial velocities should describe the same physical system.

Why combine doppler spectroscopy with astrometry?

Without astrometry providing an inclination, any mass determined with doppler spectroscopy is only a minimum mass. We need astrometry to determine the actual mass.

So - how do we do this?

- Using GaussFit, (thanks Bill), we do a simultaneous solution incorporating both astrometry and radial velocities from doppler spectroscopy

- Solve for these orbital elements with astrometry and RV:

  P - period

  T - epoch of periastron

  ω - longitude of periastron passage

  e -eccentricity

- Solve for these with astrometry

  α - semiaxis major

  i - orbital inclination

  Ω - position angle of ascending node

  μ - proper motion

  π - parallax

- Solve for these with radial velocity

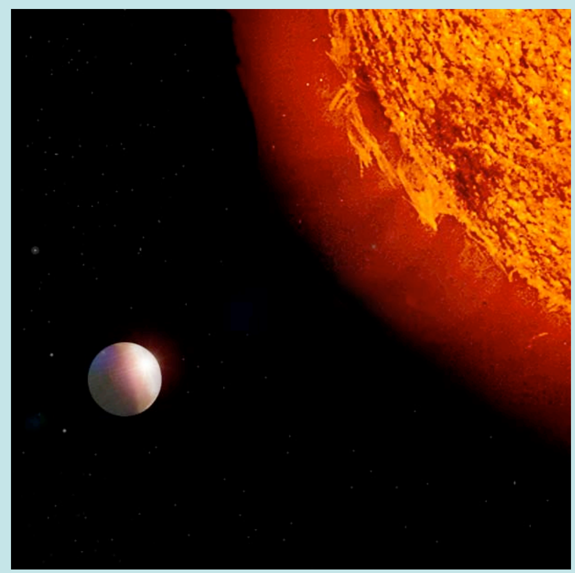
  γ - offset

  K - semi-amplitude

- We apply a (Pourbaix & Jorrisen 2000) constraint

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

And what have we done so far?



THE ASTRONOMICAL JOURNAL, 121:1607-1613, 2001 March

PRECISE MASSES FOR WOLF 1062 AB FROM *HUBBLE SPACE TELESCOPE* INTERFEROMETRIC ASTROMETRY AND McDONALD OBSERVATORY RADIAL VELOCITIES

[1] G. F. BENEDICT,[2] B. E. MCARTHUR,[2] O. G. FRANZ,[3] L. H. WASSERMAN,[3] T. J. HENRY,[4] T. TAKATO,[7] I. V. STRATEVA,[14] J. L. CRAWFORD,[15] P. A. IANNA,[13] D. W. MCCARTHY,[5] E. NELAN,[6] W. H. JEFFERYS,[7] W. VAN ALTENA,[8] P. J. SHELUS,[2] P. D. HEMENWAY,[9] R. L. DUNCOMBE,[10] D. STORY,[11] A. L. WHIPPLE,[11] A. J. BRADLEY,[12] AND L. W. FREDRICK[13]

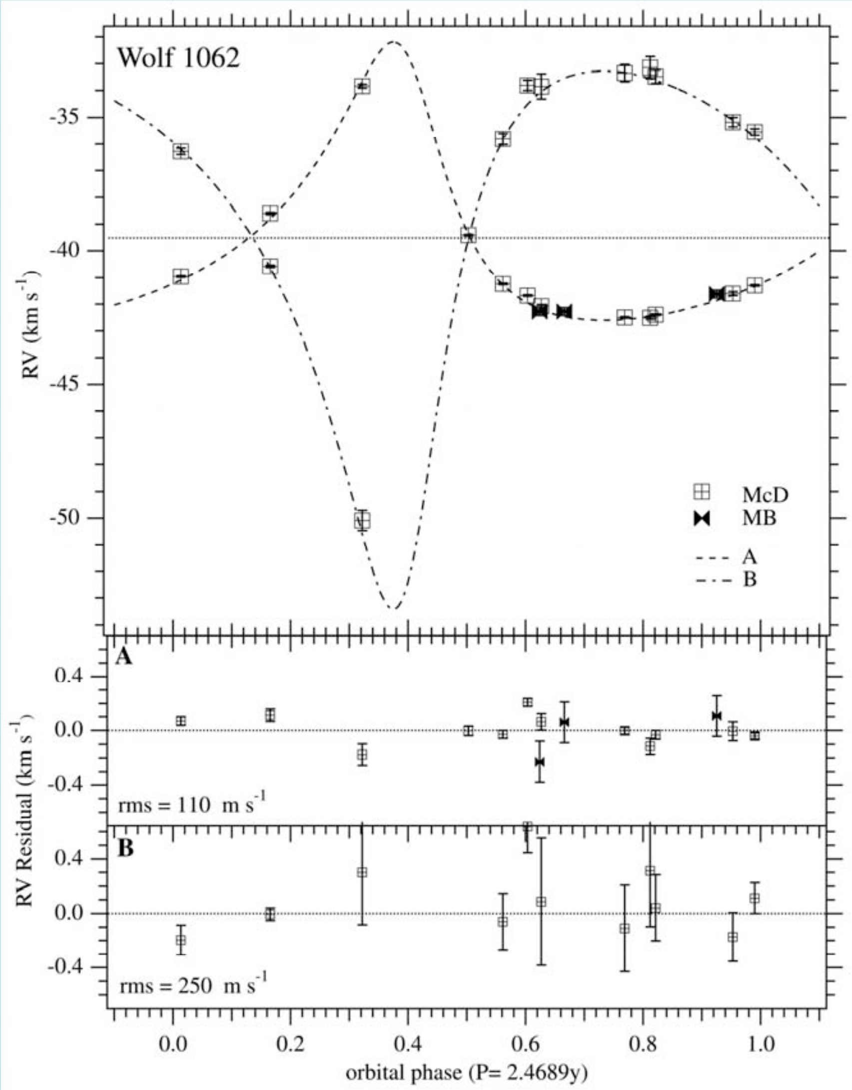
Received 2000 August 28; accepted 2000 December 1

ABSTRACT

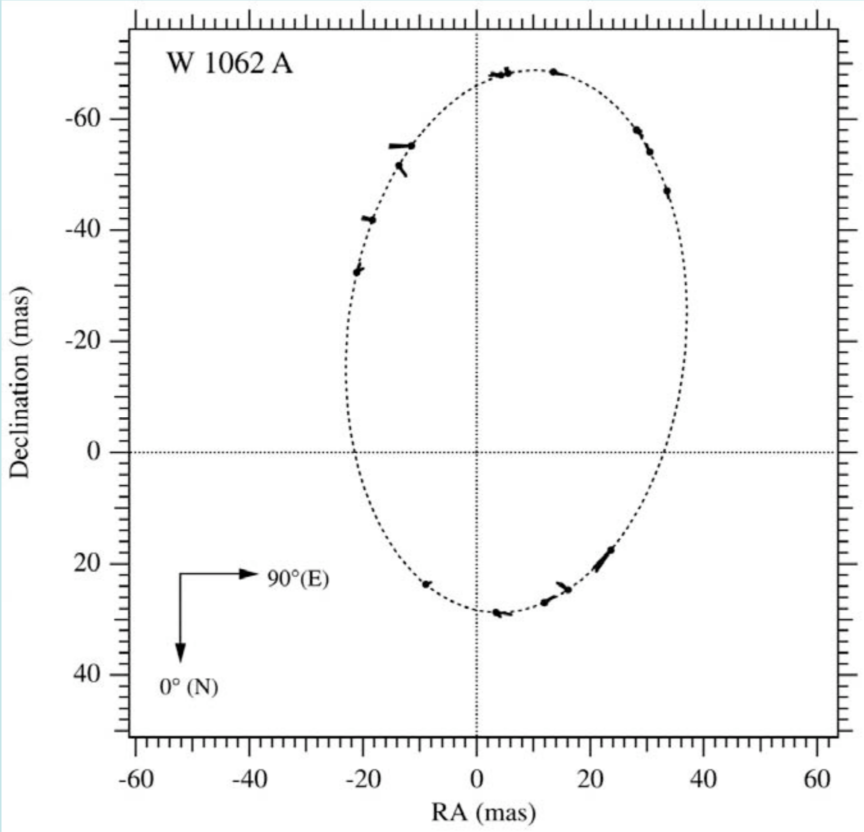
We present an analysis of astrometric data from Fine Guidance Sensor 3 (FGS 3), a white-light interferometer on *HST*, and of radial velocity data from two ground-based campaigns. We model the astrometric and radial velocity measurements simultaneously to obtain parallax, proper motion, and component masses for Wolf 1062 (Gl 748; M3.5 V). To derive the mass fraction, we relate FGS 3 fringe scanning observations of the science target to a reference frame provided by fringe tracking observations of a surrounding star field. We obtain an absolute parallax (abs = 98.0 ± 0.4 mas) yielding *MA* = 0.379 ± 0.005 *M* and *MB* = 0.192 ± 0.003 *M*, high-quality component masses with errors of only 1.5%.

Wolf 1062 - Orbits and RV

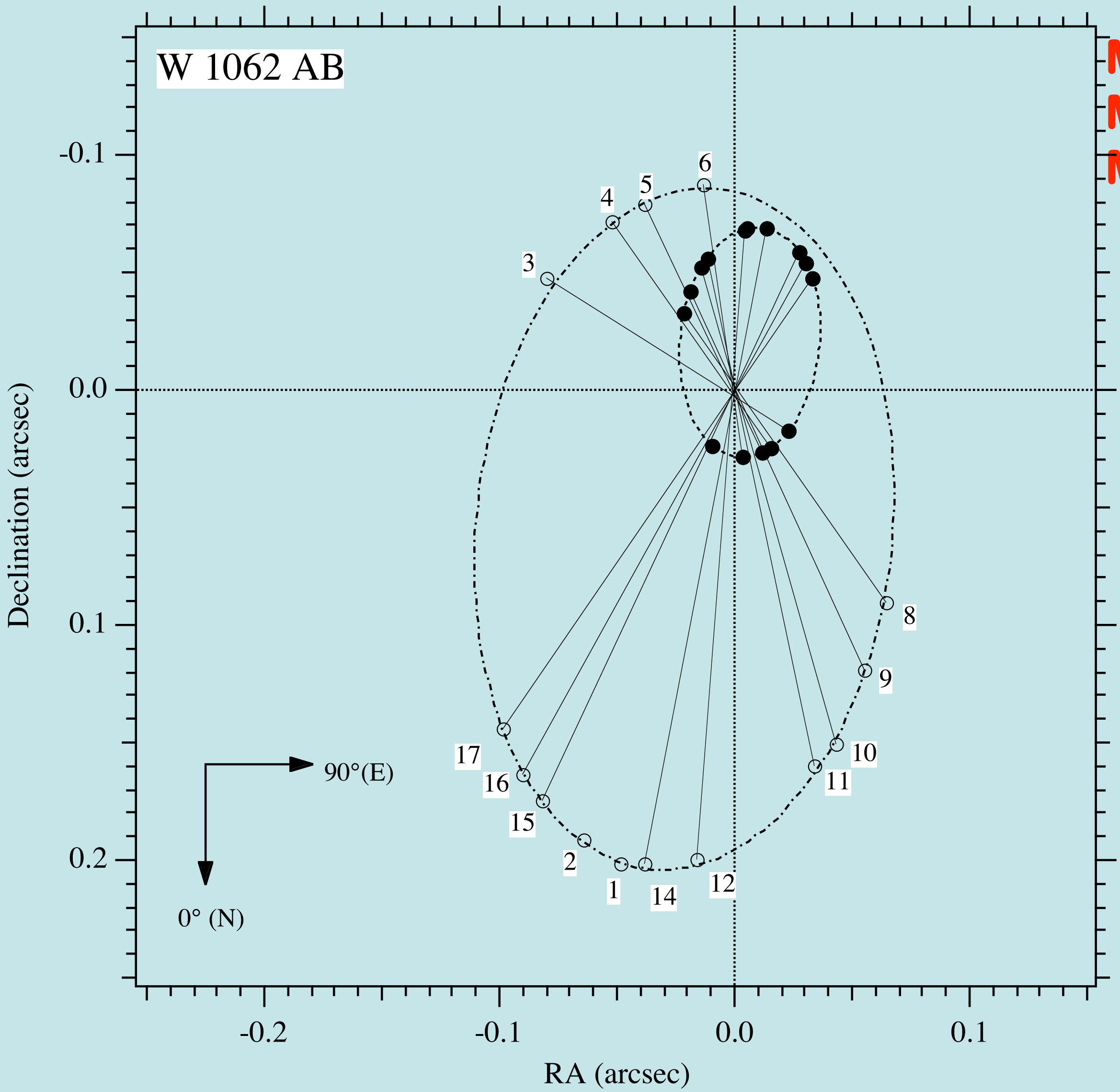
RV RMS Residual ~ BIG m s^{-1}



AST RMS Residual ~ 1 mas



Fossil Astronomy at its Finest - 1.5% Masses



M_{Tot} =0.568 ± 0.008M_O

M_A =0.381 ± 0.006M_O

M_B =0.187 ± 0.003M_O

π_{abs} = 98.1 ± 0.4 mas

The Astrophysical Journal, 581:L115-L118, 2002 December 20

A Mass for the Extrasolar Planet Gliese 876b Determined from *Hubble Space Telescope* Fine Guidance Sensor 3 Astrometry and High-Precision Radial Velocities

1 G. F. Benedict ,2 B. E. McArthur ,2 T. Forveille ,3,4 X. Delfosse ,4 E. Nelan ,5 R. P. Butler ,6 W. Spiesman ,2 G. Marcy ,7 B. Goldman ,8 C. Perrier ,4 W. H. Jefferys ,9 and M. Mayor 10

Received 2002 September 24; accepted 2002 November 11; published 2002 November 25

ABSTRACT

We report the first astrometrically determined mass of an extrasolar planet, a companion previously detected by Doppler spectroscopy. Radial velocities first provided an ephemeris with which to schedule a significant fraction of the *Hubble Space Telescope* (*HST*) observations near companion peri- and apastron. The astrometry residuals at these orbital phases exhibit a systematic deviation consistent with a perturbation due to a planetary mass companion. Combining *HST* astrometry with radial velocities, we solve for the proper motion, parallax, perturbation size, inclination, and position angle of the line of nodes, while constraining period, velocity amplitude, longitude of periastron, and eccentricity to values determined from radial velocities. We find a perturbation semimajor axis and inclination, = 0.25 ± 0.06 mas, *i* = 84 ± 6, and Gl 876 absolute parallax, abs = 214.6 ± 0.2 mas. Assuming that the mass of the primary star is *M** = 0.32 *M*, we find the mass of the planet, Gl 876b, *Mb* = 1.89 ± 0.34 *M*Jup.

The Results:

TABLE 4

ASTROMETRY OF Gl 876

Parameter	Value
HST study duration	1.8 yr
Number of observation sets	27
Reference stars ⟨*V*⟩	13.6
HST absolute parallax[a]	214.6 ± 0.2 mas
Hipparcos absolute parallax	212.7 ± 2.1 mas
YPC95 absolute parallax	211.9 ± 5.4 mas
HST relative proper motion[a]	1168.3 ± 1.2 mas yr^{-1}
In position angle	125°.3 ± 0°.1
Hipparcos proper motion	1174.2 ± 5.4 mas yr^{-1}
In position angle	125°.1 ± 0°.6
YPC95 proper motion	1143 mas yr^{-1}
In position angle	123°.5

[a] Values come from modeling RV and astrometry simultaneously (§ 4).

TABLE 5

ORBITAL ELEMENTS OF PERTURBATION DUE TO Gl 876b

Parameter	Value
α	0.25 ± 0.06 mas
α	0.0012 ± 0.0003 AU
i	84° ± 6°
P[a]	61.02 ± 0.03 days
T_0 (JD)[a]	2,450,107.87 ± 1.9
e[a]	0.10 ± 0.02
Ω	25° ± 4°
ω[a]	338°.96 ± 0°.36
K_1[a]	0.210 ± 0.005 km s^{-1}
M_*	0.32 ± 0.05 $M_\odot$
M_b	1.89 ± 0.34 M_{Jup}
M_b	1.9 ± 0.5 M_{Jup}[b]

[a] Constrained to values determined from RV measurements.

[b] Error includes M_* uncertainty.

The mass of Gl876B

- The more massive companion to Gl 876 (Gl 876b) has a mass $M_b = 1.89 \pm 0.34 M_{Jup}$ and an orbital inclination $i = 84° \pm 6°$.
- Assuming coplanarity, the inner companion (Gl 876c) has a mass $M_c = 0.56 M_{Jup}$

The Astrophysical Journal, 614:L81-L84, 2004 October 10

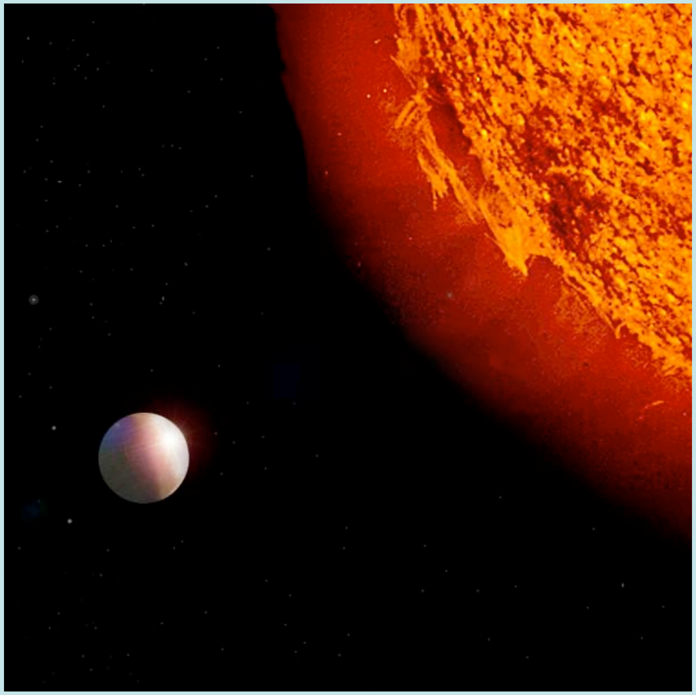
Detection of a Neptune-Mass Planet in the ρ1 Cancri System Using the Hobby-Eberly Telescope

Barbara E. McArthur ,[1] Michael Endl ,[1] William D. Cochran ,[1] G. Fritz Benedict ,[1] Debra A. Fischer ,[2] Geoffrey W. Marcy ,[2,3] R. Paul Butler ,[4] Dominique Naef ,[5,6] Michel Mayor ,[5] Diedre Queloz ,[5] Stephane Udry ,[5] and Thomas E. Harrison [7]

Received 2004 August 2; accepted 2004 September 1; published 2004 September 8

ABSTRACT

We report the detection of the lowest mass extrasolar planet yet found around a Sun-like star - a planet with an *M* sin *i* of only 14.21 ± 2.91 *M* in an extremely short period orbit (*P* = 2.808 days) around 1 Cancri, a planetary system that already has three known planets. Velocities taken from late 20032004 at McDonald Observatory with the Hobby-Eberly Telescope revealed this inner planet at 0.04 AU. We estimate an inclination of the outer planet 1 Cancri d, based on *Hubble Space Telescope* Fine Guidance Sensor measurements that suggest an inner planet of only 17.7 ± 5.57 *M*, if coplanarity is assumed for the system.



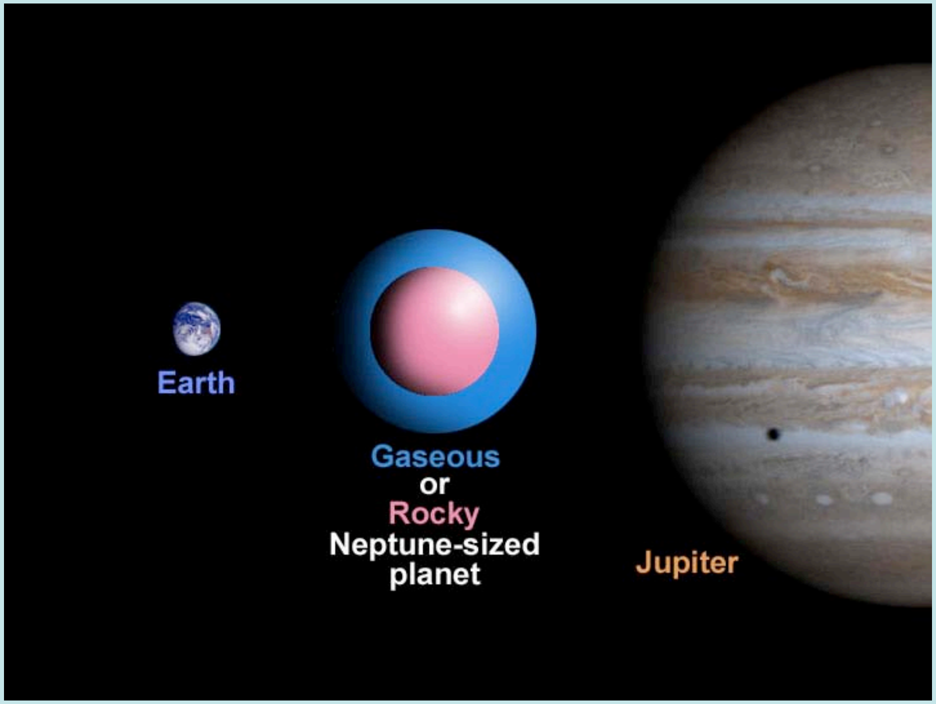
55 Cancri (ρ^1 Cancri = HD75732)

- G8V star, a bit ligher than the sun
- About 5 billion years old
- 41 light years away in the constellation Cancer
- A member of a double star system

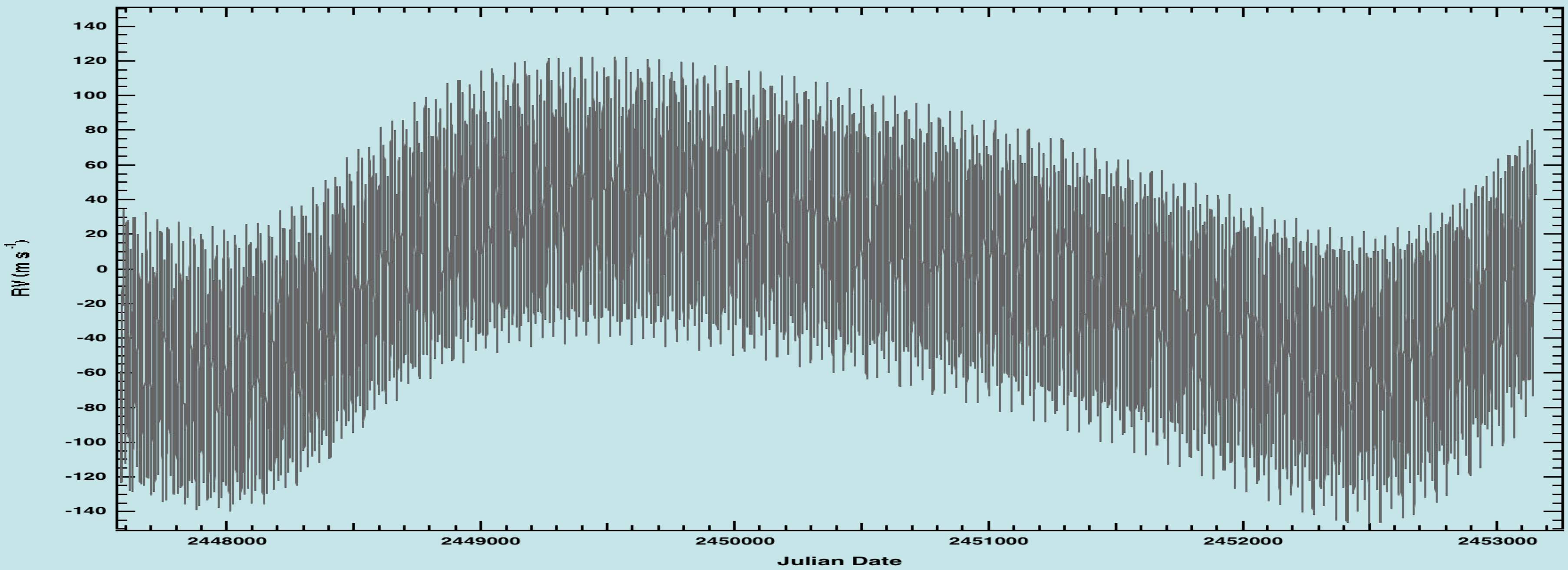
Serendipitous Discovery

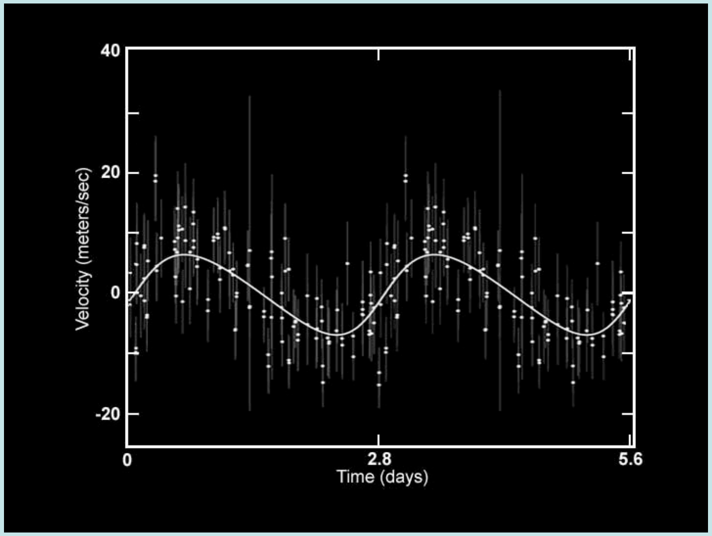
What we found . . .

The lowest M sin *i* planet in the first quadruple system.



What it looks like





The RV orbit of the quadruple planetary system

and 55 Cancri e

Just the Facts:

TABLE 2

QUAD-KEPLERIAN ORBITAL ELEMENTS OF ρ^1 CANCRI

Element	ρ^1 Cancri e	ρ^1 Cancri b	ρ^1 Cancri c	ρ^1 Cancri d
Orbital period P (days)	2.808 ± 0.002	14.67 ± 0.01	43.93 ± 0.25	4517.4 ± 77.8
Epoch of periastron T [a]	3295.31 ± 0.32	3021.08 ± 0.01	3028.63 ± 0.25	2837.69 ± 68.87
Eccentricity e	0.174 ± 0.127	0.0197 ± 0.012	0.44 ± 0.08	0.327 ± 0.28
ω (deg)	261.65 ± 41.14	131.49 ± 33.27	244.39 ± 10.65	234.73 ± 6.74
Velocity amplitude K (m s^{-1})	6.665 ± 0.81	67.365 ± 0.82	12.946 ± 0.86	49.786 ± 1.53
V_0 Lick (m s^{-1})	21.166 ± 1.31	...	...	...
V_0 ELODIE (m s^{-1})	2727.448 ± 2.42	...	...	...
V_0 HET (m s^{-1})	10.745 ± 0.59	...	...	...

[a] Add 2,450,000.0 to T.

TABLE 3

ρ^1 CANCRI: MASS LIMITS AND PARAMETERS

Parameter	ρ^1 Cancri e	ρ^1 Cancri b	ρ^1 Cancri c	ρ^1 Cancri d
a (AU)	0.038 ± 0.001	0.115 ± 0.003	0.240 ± 0.008	5.257 ± 0.208
$A \sin i$ (AU)	1.694E−6 ± 0.19E−6	9.080E−5 ± 0.12E−5	4 .695E−5 ± 0.14E−5	0.195E−1 ± 0.007E−1
Mass fraction ($M_\odot$)	8.225E−14 ± 2.33E−14	4.64E−10 ± 0.17E−10	7.151E−12 ± 0.54E−12	4.874E−08 ± 0.38E−8
$M \sin i$ (M_J)[a]	0.045 ± 0.01	0.784 ± 0.09	0.217 ± 0.04	3.912 ± 0.52
$M \sin i$ (M_N)[a]	0.824 ± 0.17	...	...	...
$M \sin i$ ($M_\oplus$)[a]	14.210 ± 2.95	...	...	...
M (M_J)[b,c]	0.056 ± 0.017	0.982 ± 0.19	0.272 ± 0.07	4.9 ± 1.1
M (M_J)[c,d]	0.053 ± 0.020	0.982 ± 0.26	0.244 ± 0.07	4.64 ± 1.3
M (M_N)[c,d]	1.031 ± 0.34	...	...	...
M ($M_\oplus$)[c,d]	17.770 ± 5.57	...	...	...

[a] Derived from radial velocity alone.
[b] Derived from radial velocity and astrometry, using $M \sin i/ \sin i$.
[c] Assuming coplanarity of the planetary system.
[d] Derived from radial velocity and astrometry, using $m2^3/(m1 + m2)^2 = a^3/P^2$.

Conclusions

I didn’t want to put everyone to sleep talking about the OFAD
But it’s been a great ride for me
And
I am so grateful that Bill Jefferys (and Fritz) took a chance and hired me those many years ago (after my early adventures in Molecular Biology)

I thank Bill so much for the tutelage and support he has given me taking me back to my first love of Math and the vision he has given me to look at what I see (observational data) and model it with Occum’s razor and Bayesian practices in mind.

Thanks Bill !