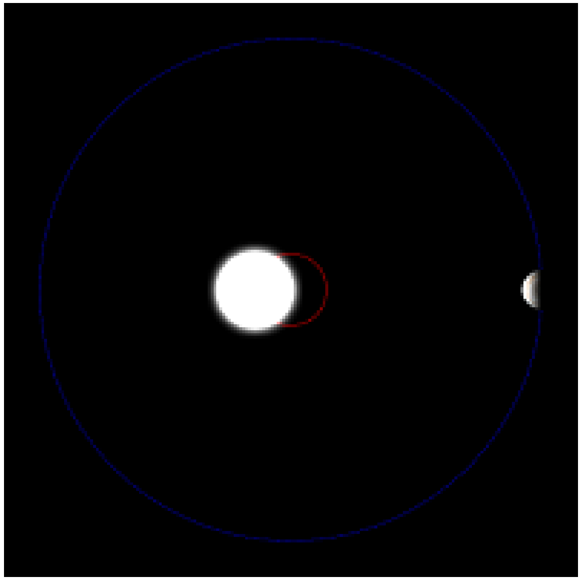
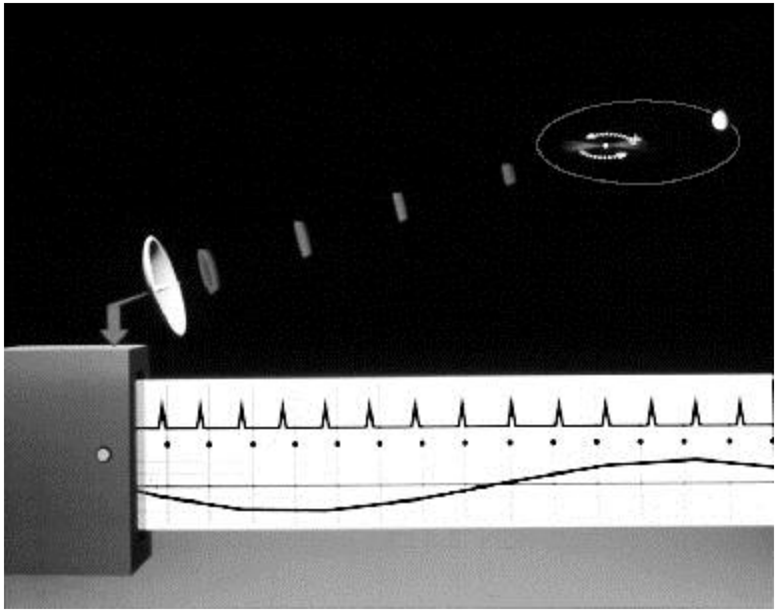
Detection of Exoplanets by:

I. Astrometry:



II. Timing Method:



Angles & Coordinates:

- 1 full circle = 360 degrees
- 1 degree = 60 arcminutes
- 1 arcminute = 60 arcseconds

~ 1 inch @ 100 yards
(2.908 cm at 100 meters)

1 milliarcsec (mas) = 0.001 arcsec

1 microarcsec (μas) = 0.000001 arcsec

Astronomical coordinates on sky:

E-W: Right Ascension (RA) in *h:m:s* (0-24h)

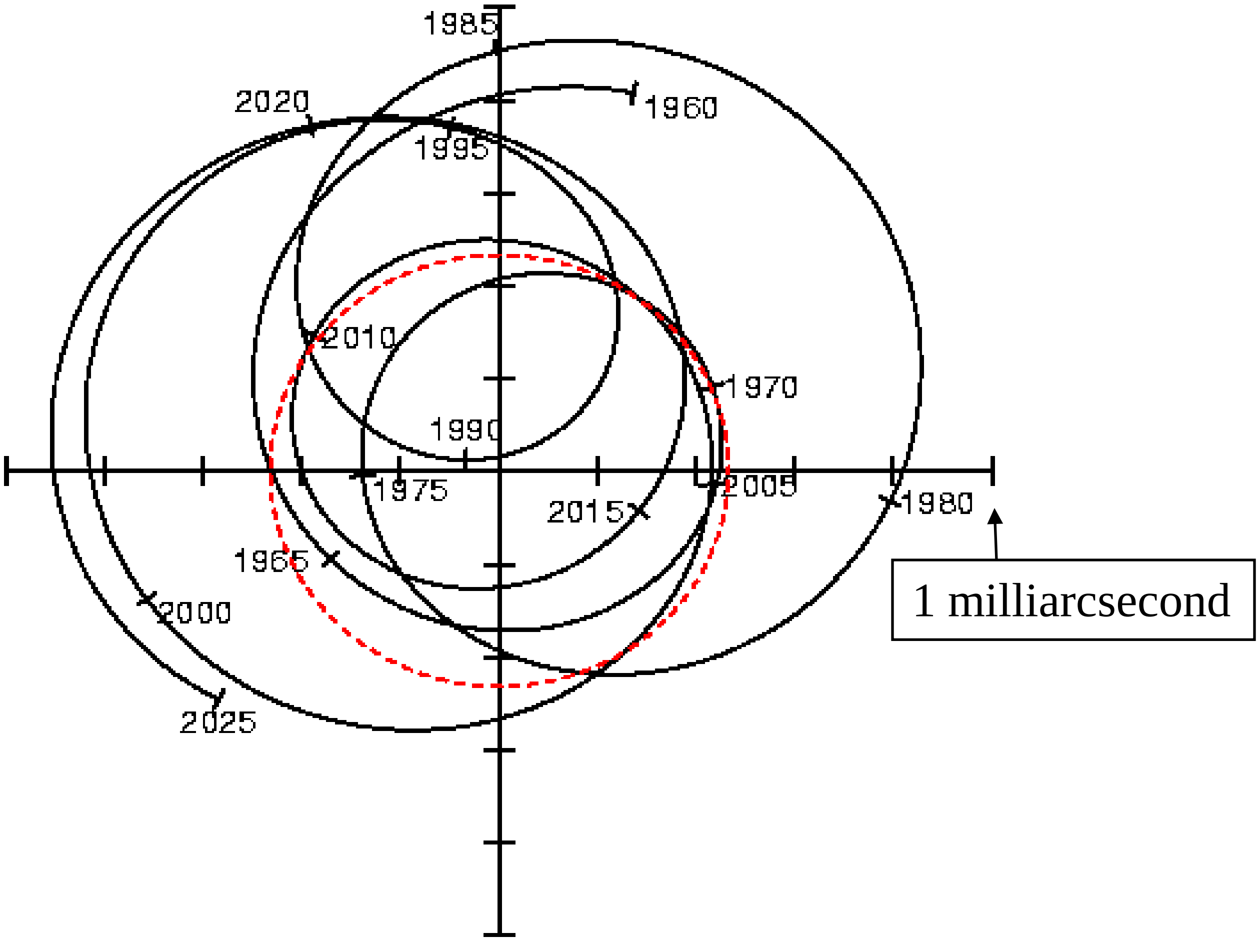
N-S: Declination (DEC) in deg:arcm:arcs (-90 - +90)

Stellar Motion

There are 4 types of stellar „motion“ that astrometry can measure:

1. Parallax (distance): the motion of stars caused by viewing them from different parts of the Earth‘s orbit
2. Proper motion: the true motion of stars through space
3. **Motion due to the presence of companion**
4. „Fake“ motion due to other physical phenomena

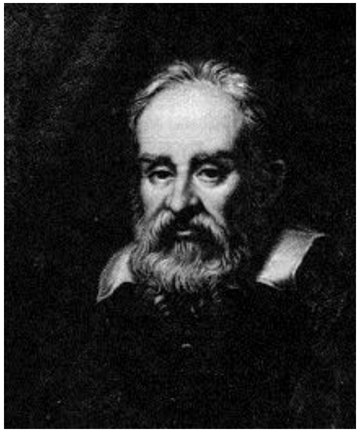
Our solar system from 32 light years (10 pcs)



Brief History

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

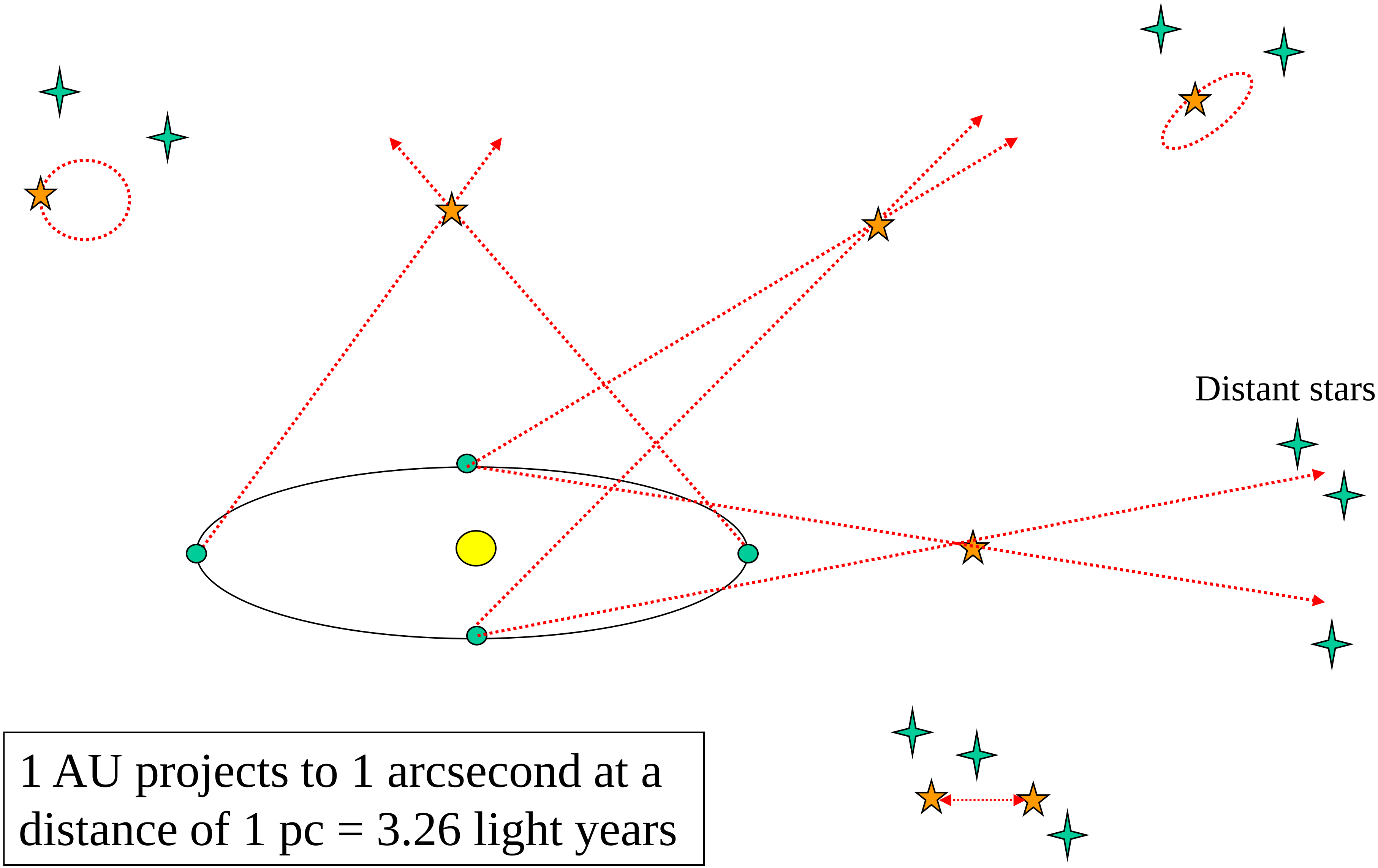
- It is one of the oldest subfields of the astronomy dating back at least to Hipparchus (130 B.C.), who combined the arithmetical astronomy of the Babylonians with the geometrical approach of the Greeks to develop a model for solar and lunar motions. He also invented the brightness scale used to this day.



- Galileo was the first to try measure distance to stars using a 2.5 cm telescope. (He of course failed.)

- 1838 first stellar parallax (distance) was measured independently by Bessel (heliometer), Struve (filar micrometer), and Henderson (meridian circle).

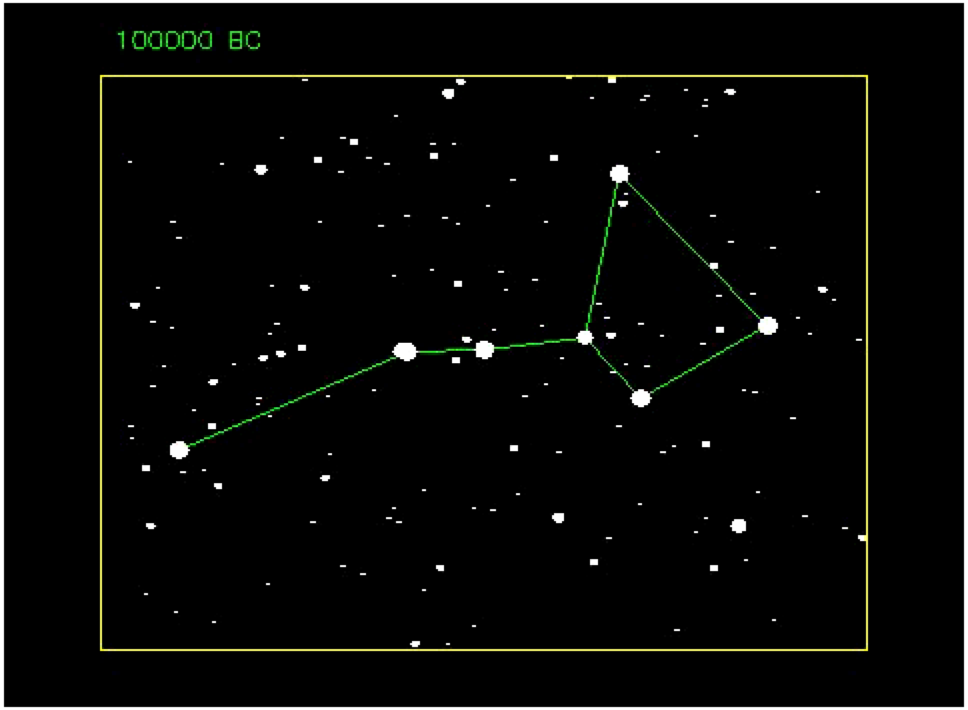
Astrometry: Parallax



1 AU projects to 1 arcsecond at a distance of 1 pc = 3.26 light years

Astrometry: Proper motion

Discovered by Halley who noticed that Sirius, Arcturus, and Aldebaran were over ½ degree away from the positions Hipparchus measured 1850 years earlier



Astrometry: Proper motion

Barnard is the star with the highest proper motion (~10 arcseconds per year)

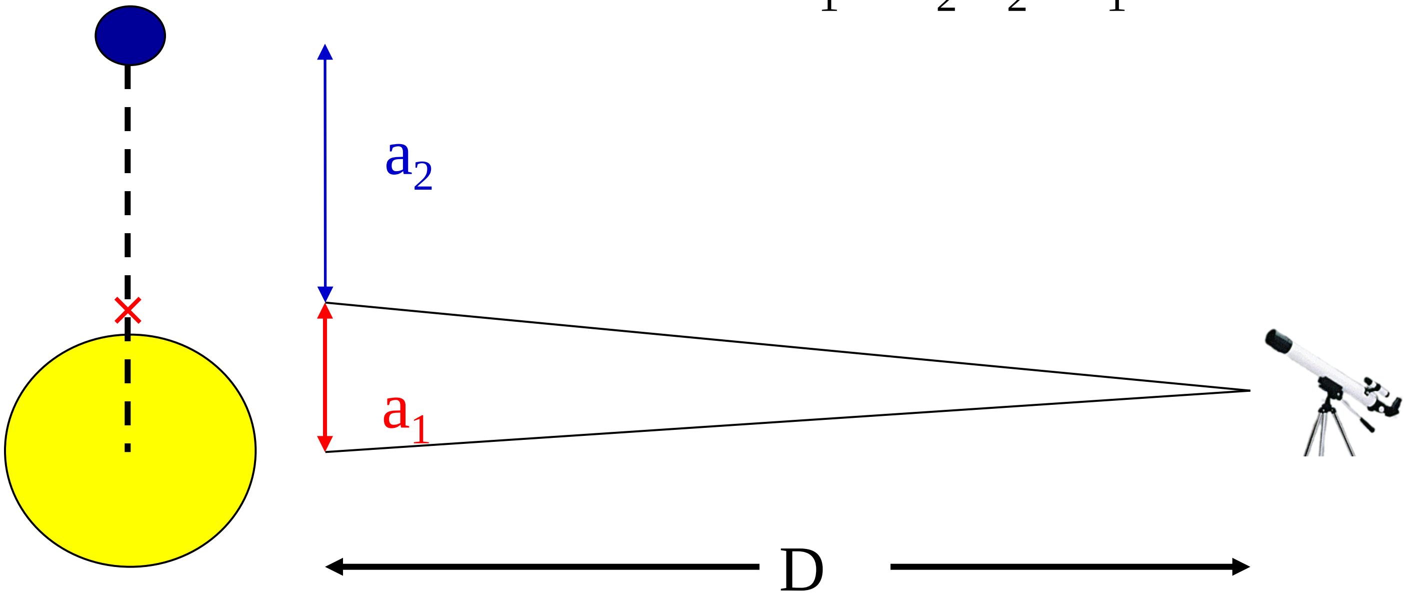
Barnard‘s star in 1950

Barnard‘s star in 1997

Astrometry: Orbital Motion

$$a_1 m_1 = a_2 m_2$$

$$a_1 = a_2 m_2 / m_1$$



To convert to an angular displacement you have to divide by the distance, D

Astrometry: Orbital Motion

The astrometric signal is given by:

$$\theta = \frac{m}{M} \frac{a}{D}$$

This is in radians. More useful units are arcseconds (1 radian = 206369 arcseconds) or milliarcseconds (0.001 arcseconds) = mas

m = mass of planet

M = mass of star

a = orbital radius

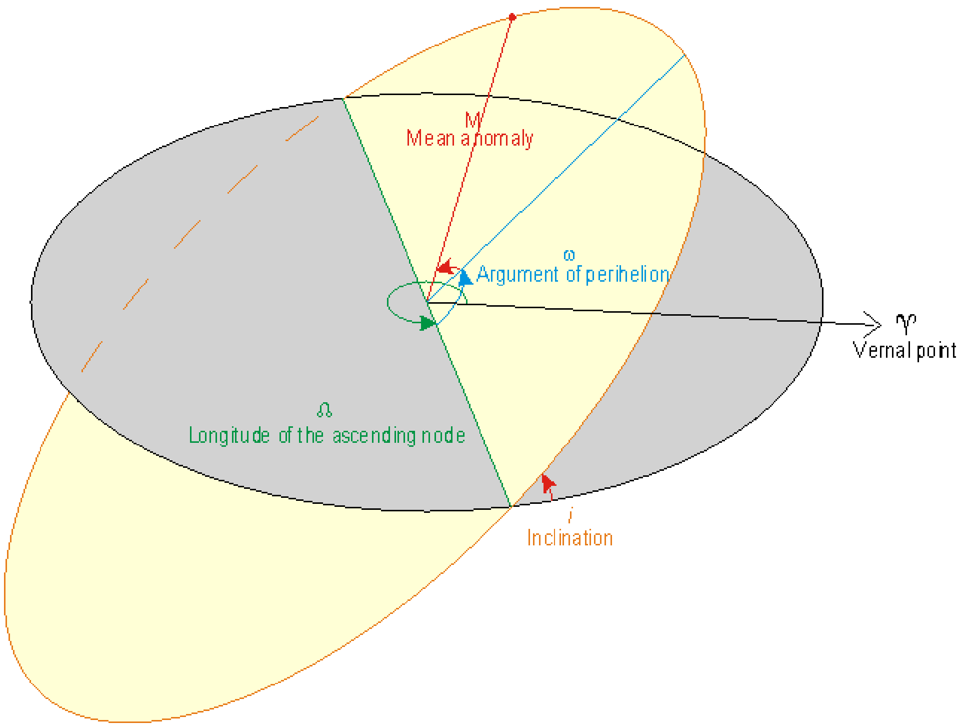
D = distance of star

$$\theta = \frac{m}{M^{2/3}} \frac{P^{2/3}}{D}$$

Note: astrometry is sensitive to companions of **nearby stars** with large orbital distances

Radial velocity measurements are distance independent, but sensitive to companions with small orbital distances

Astrometry: Orbital Motion



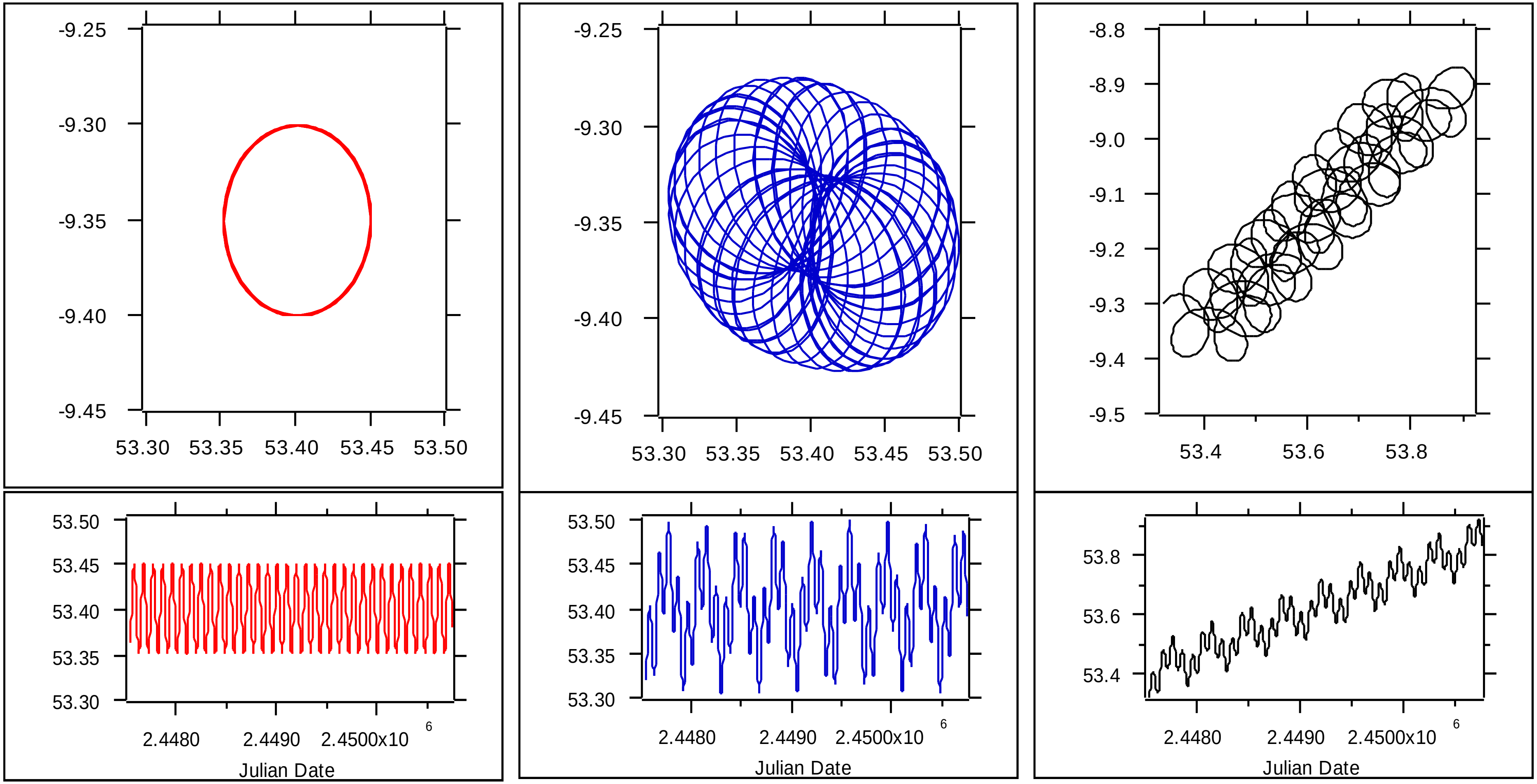
With radial velocity measurements and astrometry one can solve for all orbital elements (including *i*)

=> true mass of companion!!!

So we find our astrometric orbit

But the parallax can disguise it

And the proper motion can slinky it



Astrometric Detections of Exoplanets

The Challenge:

for a star at a distance of 10 parsecs (=32.6 light years):

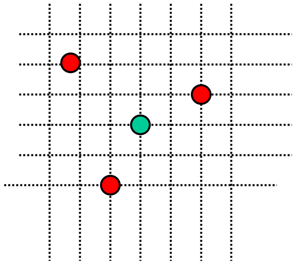
Source	Displacment (μas)
Jupiter at 1 AU	100
Jupiter at 5 AU	500
Jupiter at 0.05 AU	5
Neptune at 1 AU	6
Earth at 1 AU	0.33
Parallax	100000
Proper motion (/yr)	500000

The Observable Model

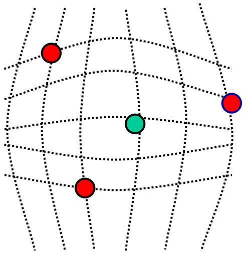
Must take into account:

1. Location and motion of target
2. Instrumental motion and changes
3. Orbital parameters
4. Physical effects that modify the position of the stars

The Importance of Reference stars

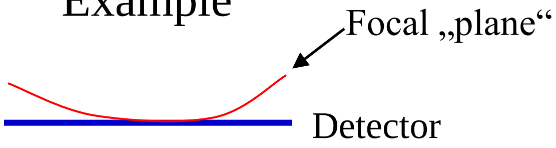


Perfect instrument



Perfect instrument at a later time

Example

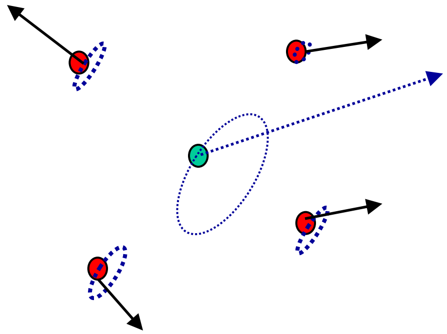


Reference stars:

1. Define the „plate scale“
2. Monitor changes in the plate scale (instrumental effects)
3. Give additional measures of your target

Typical plate scale on a 4m telescope (Focal ratio = 13) = 3.82 arcsecs/mm = 0.05 arcsec/pixel (15 µm) = 57mas/pixel. The displacement of a star at 10 parsecs with a Jupiter-like planet would make a displacement of 1/100 of a pixel (0.00015 mm)

Good Reference stars can be difficult to find:

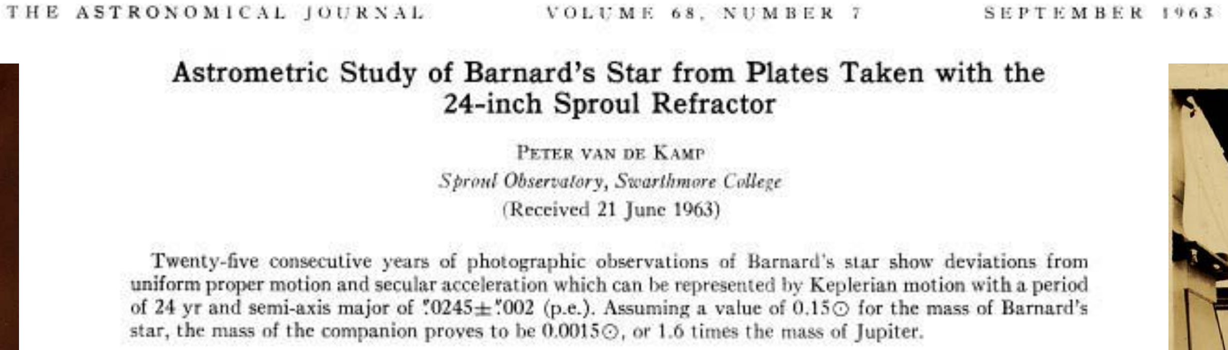


1. They can have their own (and different) parallax
2. They can have their own (and different) proper motion
3. They can have their own companions (stellar and planetary)
4. They can have starspots, pulsations, etc (as well as the target)

Astrometric detections: attempts and failures

To date **no** extrasolar planet has been discovered with the astrometric method, although there have been several false detections

Barnard´s star



THE ASTRONOMICAL JOURNAL VOLUME 68, NUMBER 7 SEPTEMBER 1963

Astrometric Study of Barnard's Star from Plates Taken with the 24-inch Sproul Refractor

PETER VAN DE KAMP
Sproul Observatory, Swarthmore College

(Received 21 June 1963)

Twenty-five consecutive years of photographic observations of Barnard's star show deviations from uniform proper motion and secular acceleration which can be represented by Keplerian motion with a period of 24 yr and semi-axis major of $\overset{''}{.}0245 \pm \overset{''}{.}002$ (p.e.). Assuming a value of $0.15\odot$ for the mass of Barnard's star, the mass of the companion proves to be $0.0015\odot$, or 1.6 times the mass of Jupiter.

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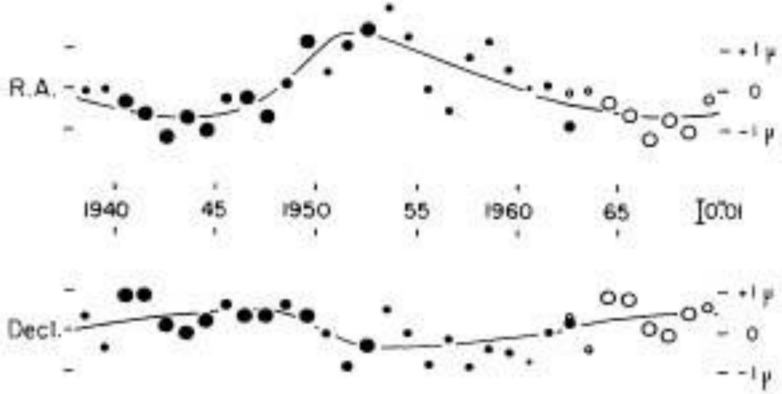


FIG. 5. Barnard's star—yearly means, averaging 96 plates and weight 64. Time displacement curves for $P=24$ yr, $e=0.6$, $T=1950$. Circles are early means transferred 24 yr forward. The scale of the displacements is shown both in terms of 0″.01 and of 1μ (.001 mm) on the Sproul plates.

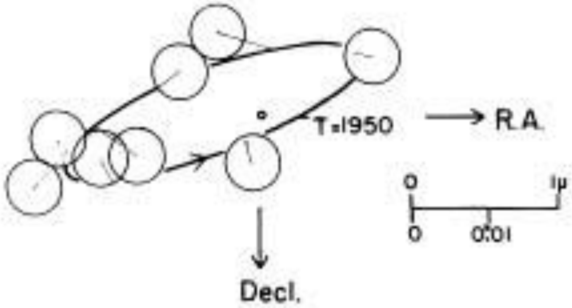


FIG. 7. Barnard's star—apparent orbit. Eight normal points of average weight 203. ○ center of mass. Radii of circles indicate probable errors. $\alpha = 1.30\mu = 0''.0245$, $i = \pm 77°$.

on the assumption that the observed data contain no perturbation but are ascribed to errors of observations:

p.e. ignoring allowing for

Alternate Dynamical Analysis of Barnard's Star

PETER VAN DE KAMP

Sproul Observatory, Swarthmore College, Swarthmore, Pennsylvania

(Received 12 May 1969)

An alternate dynamical analysis of Barnard's star's motion over the interval 1938–1968 yields two companions in co-revolving, approximately coplanar, circular orbits with periods of 26 and 12 years, and masses of 1.1 and 0.8 times Jupiter, respectively.

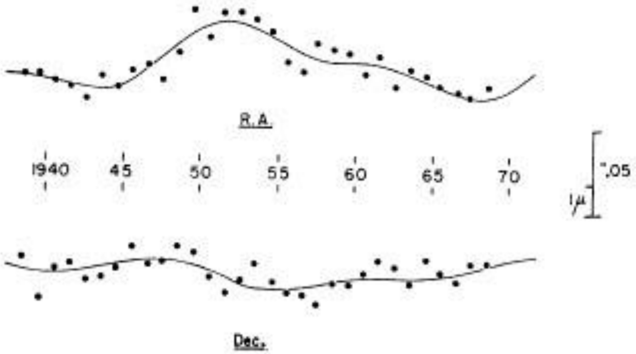


FIG. 1. Barnard's star: Yearly means, averaging 102 plates and weight 69; time-displacement curves resulting from two circular orbits with $P=26$ years and $P=12$ years.

perturbations have probable errors of [illegible] $=\pm 0''.0011$. The (calculated) apparent orbits of the two perturbations are illustrated in Fig. 3.

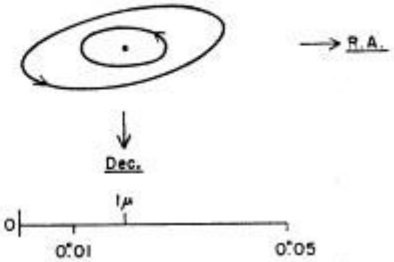


FIG. 3. Barnard's star: Apparent orbits of the two perturbations with circular orbits, and $P=26$ years and $P=12$ years.

THE ASTRONOMICAL JOURNAL VOLUME 78, NUMBER 8 OCTOBER 1973

An unsuccessful search for a planetary companion of Barnard's star*
(BD + 4°3561)

George Gatewood
Allegheny Observatory, University of Pittsburgh, Pittsburgh, Pennsylvania

Heinrich Eichhorn
Department of Astronomy, University of South Florida, Tampa, Florida

(Received 8 February 1973; revised 30 April 1973)

The parallax, proper motion, and acceleration in position of Barnard's Star have been determined from 241 Allegheny and Van Vleck Observatory photographic plates. The measurements were reduced by means of a variant of a rigorous overlap type method previously proposed by one of us. (Eichhorn 1960). Despite relatively small rms errors, several test failed to confirm van de Kamp's published orbit. The weighting system was carefully studied from the adjustment residuals. In essence, the weight of a Thaw or Van Vleck plate is proportional to the number of exposures.

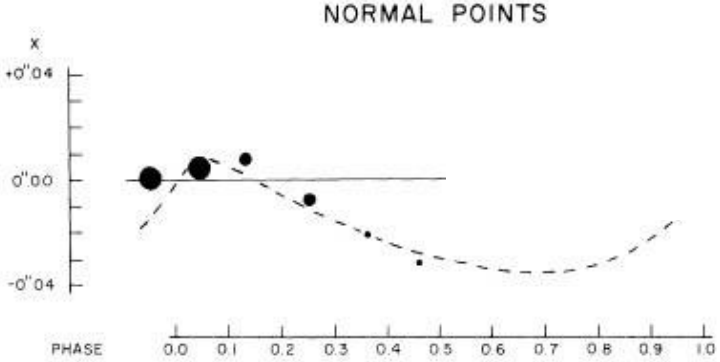


FIG. 1. Normal points.

New cell in lens installed

Lens re-aligned

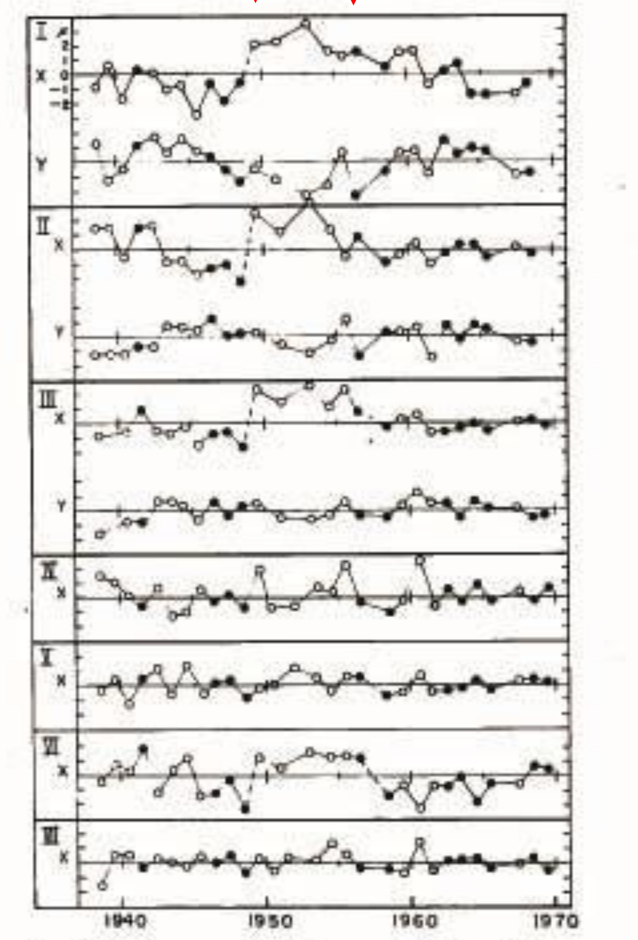
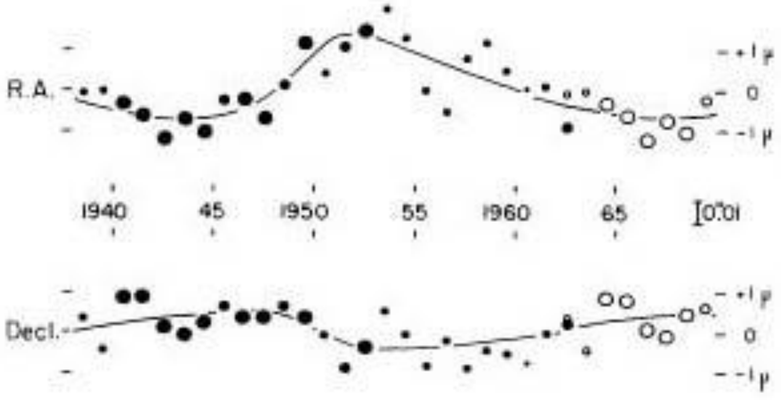


FIG. 1. Yearly mean residuals from several solutions. The source of each residual series is given in Table III and in the text. The weights of the points vary greatly. Points with weight less than 10 are shown as *open circles* ○, and points of weight 10 or greater are shown as *filled circles* ●. A few years of very low weight were combined into single points. The vertical scale is in microns; one μ=0″.01887 for the Sproul refractor.

Hershey 1973

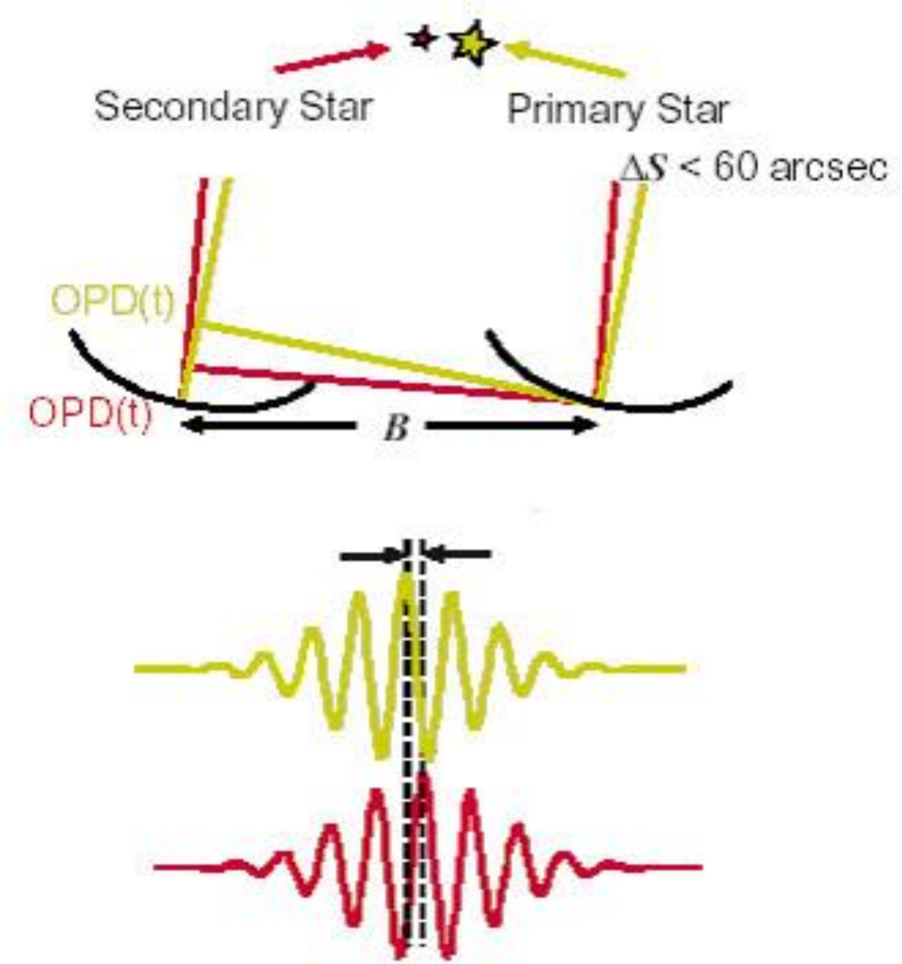


Van de Kamp detection was most likely an instrumental effect

Real Astrometric Detections with the Hubble Telescope Fine Guidance Sensors

S82E5937 1997:02:19 07:06:57

HST uses „Narrow Angle Interferometry“!



G. Fritz Benedict
(McD Obs.)

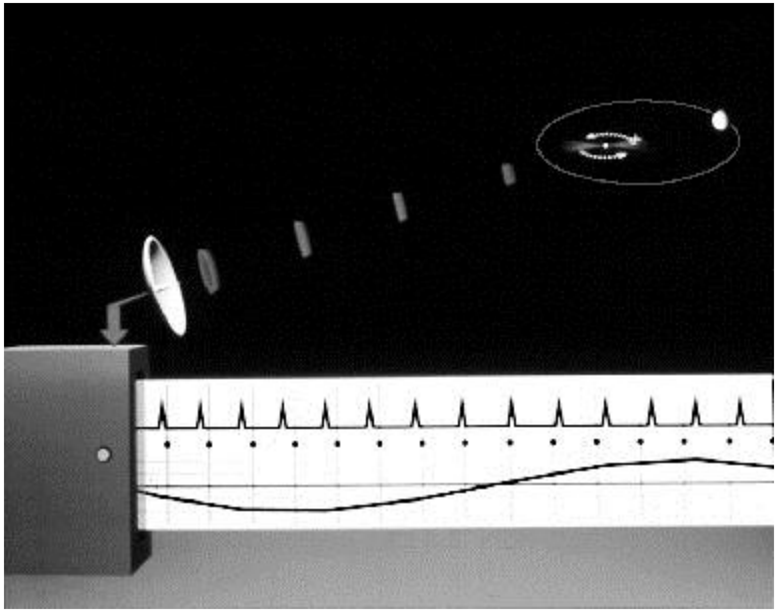
HST is achieving astrometric precision of **0.1–1 mas !**

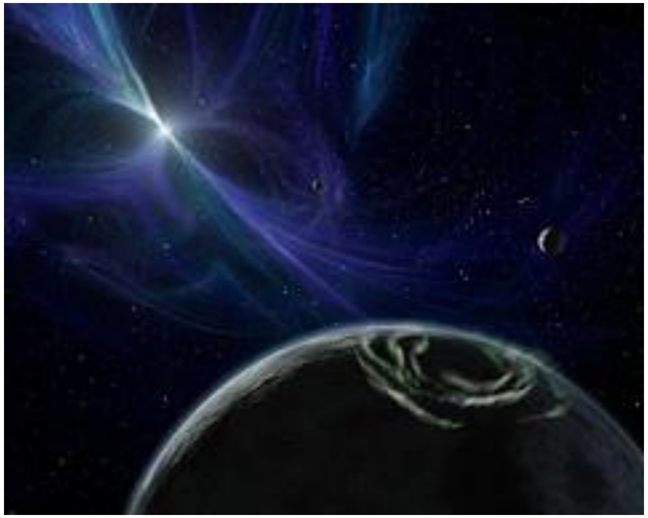
Comparison between Radial Velocity Measurements and Astrometry.

Astrometry and radial velocity measurements are fundamentally the same: you are trying to measure a displacement on a detector

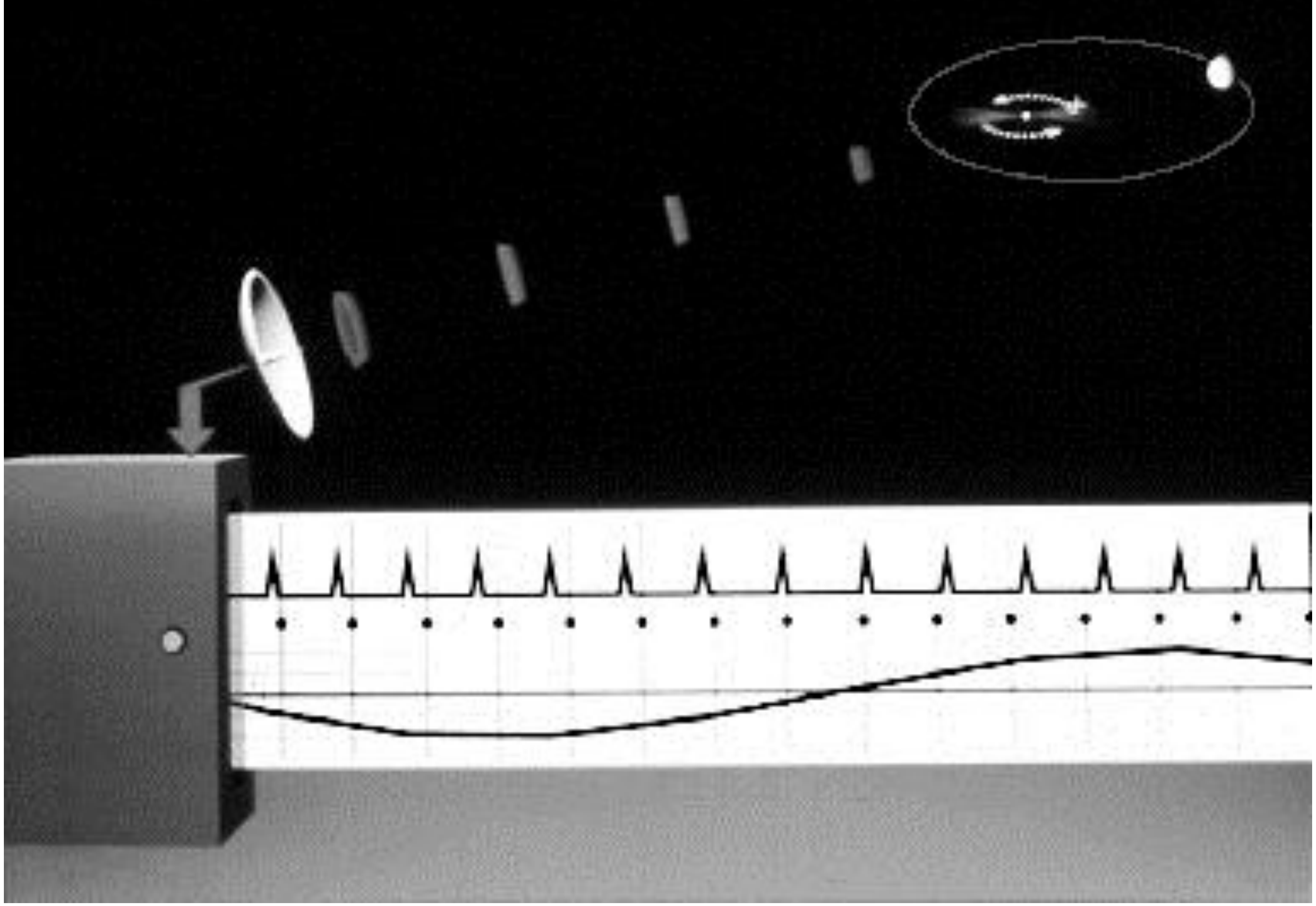
Radial Velocity	**Astrometry**
1. Measure a displacement of a spectral line on a detector	1. Measure a displacement of a stellar image on a detector
2. Thousands of spectral lines (decrease error by $\sqrt{N_{\text{lines}}}$)	2. One stellar image
3. Hundreds of reference lines (Th-Ar or Iodine) to define „plate solution“ (wavelength solution)	3. 1-10 reference stars to define plate solution
4. Reference lines are stable	4. Reference stars move!

II. The Timing Method





The Technique:



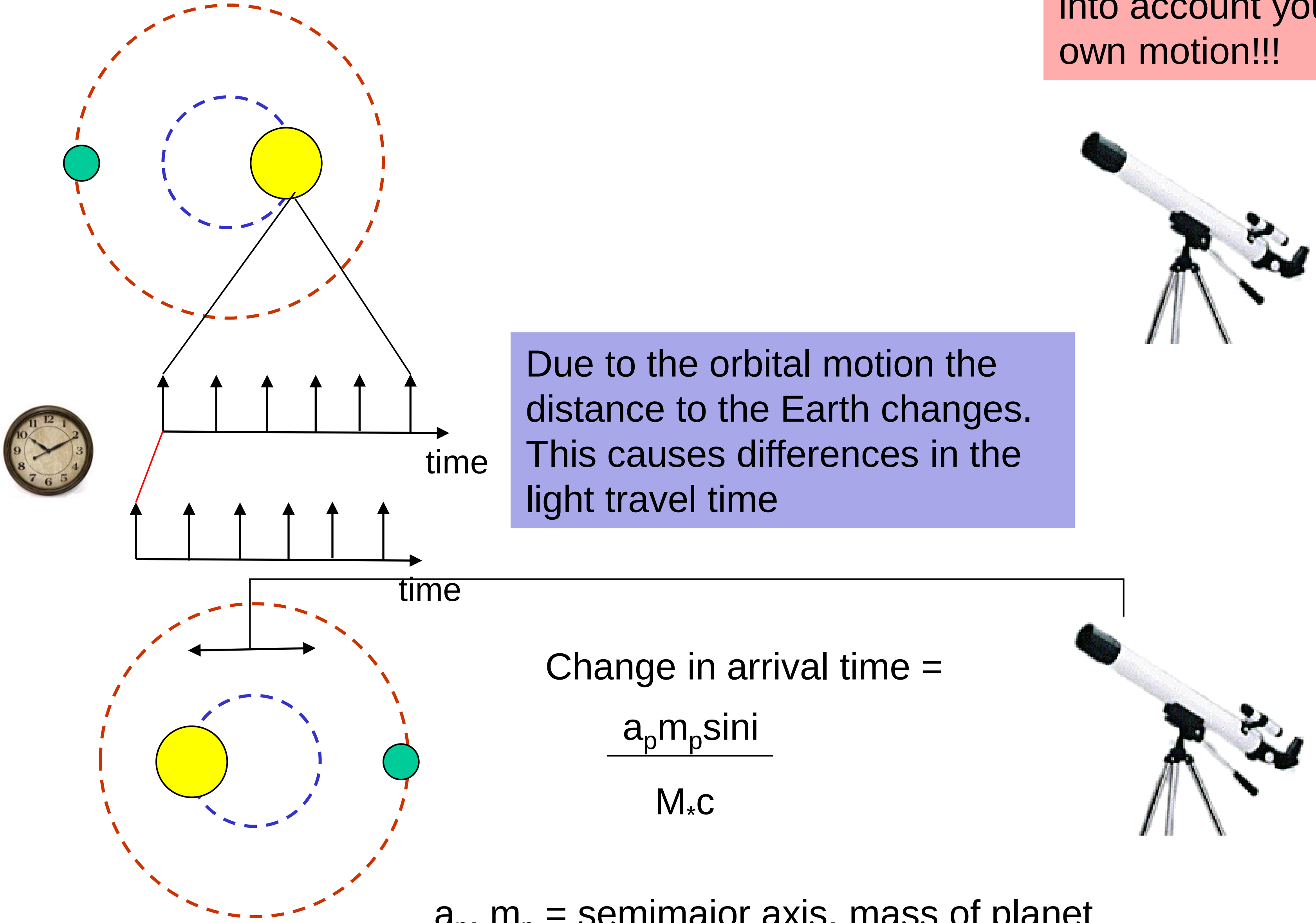
If you have a very stable “clock” that sends a signal with a constant pulse rate and the capability to measure the time of arrival (TOA) of the signal with very high precision

⇒Search for systematic deviations in the TOAs that indicate

different light travel times due to orbital motion

Timing Variations:

Don’t forget to take into account your own motion!!!



Due to the orbital motion the distance to the Earth changes. This causes differences in the light travel time

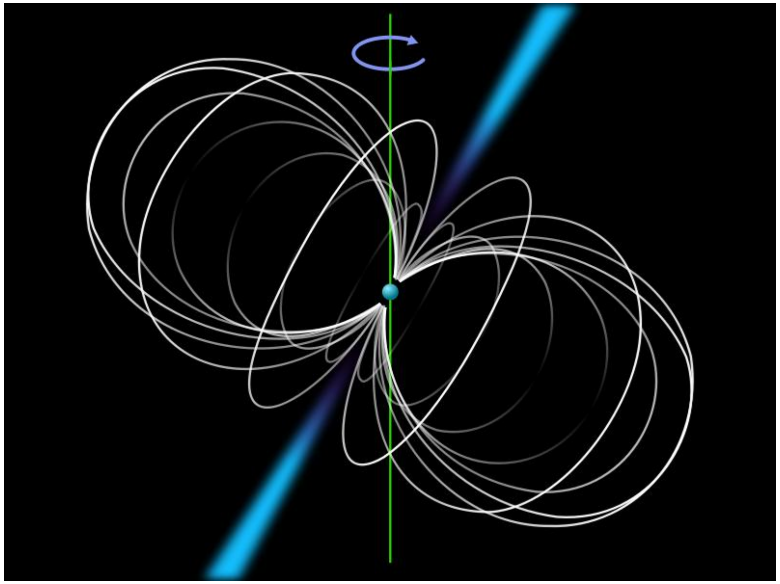
Change in arrival time =

$$\frac{a_p m_p \sin i}{M_* c}$$

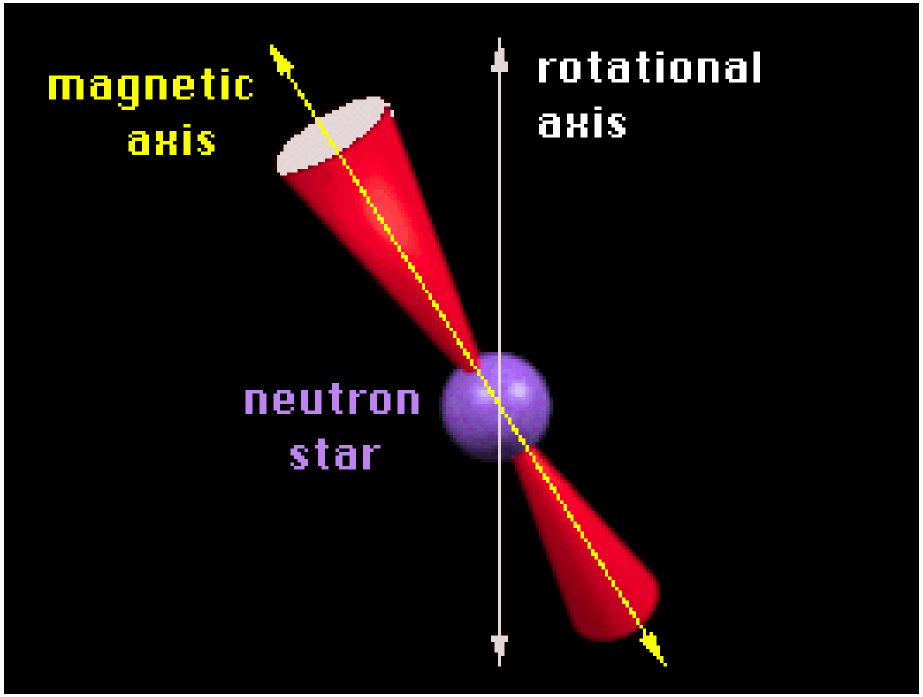
a_p, m_p = semimajor axis, mass of planet

A Pulsar: a very stable astronomical clock!

radiation



Strong magnetic field

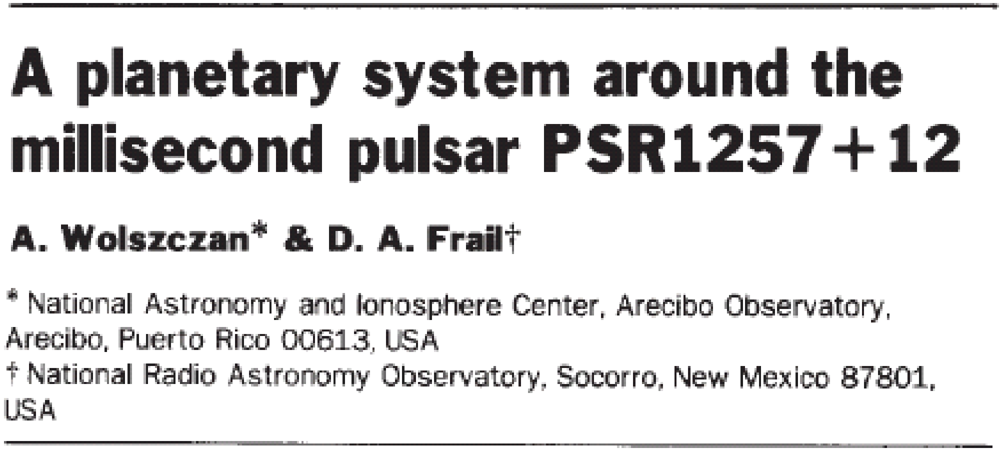


Acts like a cosmic lighthouse

Rotation periods of pulsars < 10 second

The fastest rotators are millisecond pulsars:
PSR1257+12: P = 0.00621853193177 +/- 0.00000000000001 s

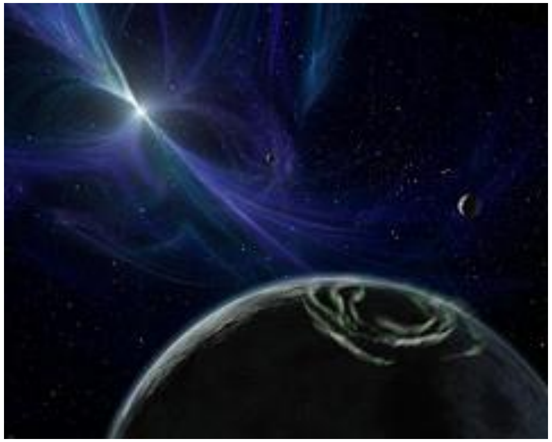
The (Really) First Exoplanets: in 1992



A planetary system around the millisecond pulsar PSR1257+12

A. Wolszczan* & D. A. Frail†

* National Astronomy and Ionosphere Center, Arecibo Observatory, Arecibo, Puerto Rico 00613, USA
† National Radio Astronomy Observatory, Socorro, New Mexico 87801, USA



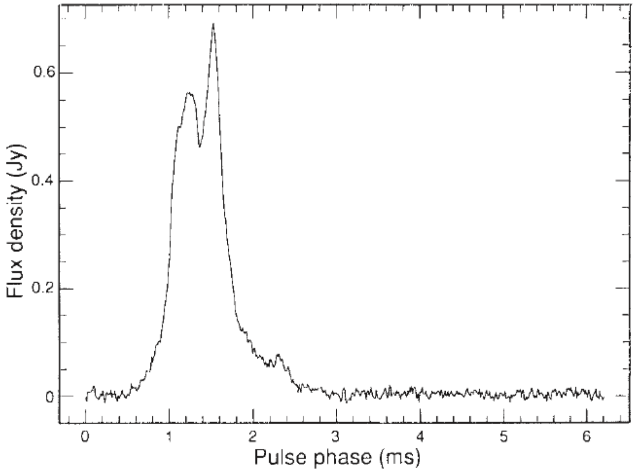


FIG. 1. The average pulse profile of PSR1257+12 at 430 MHz. The effective time resolution is ~12 μs.

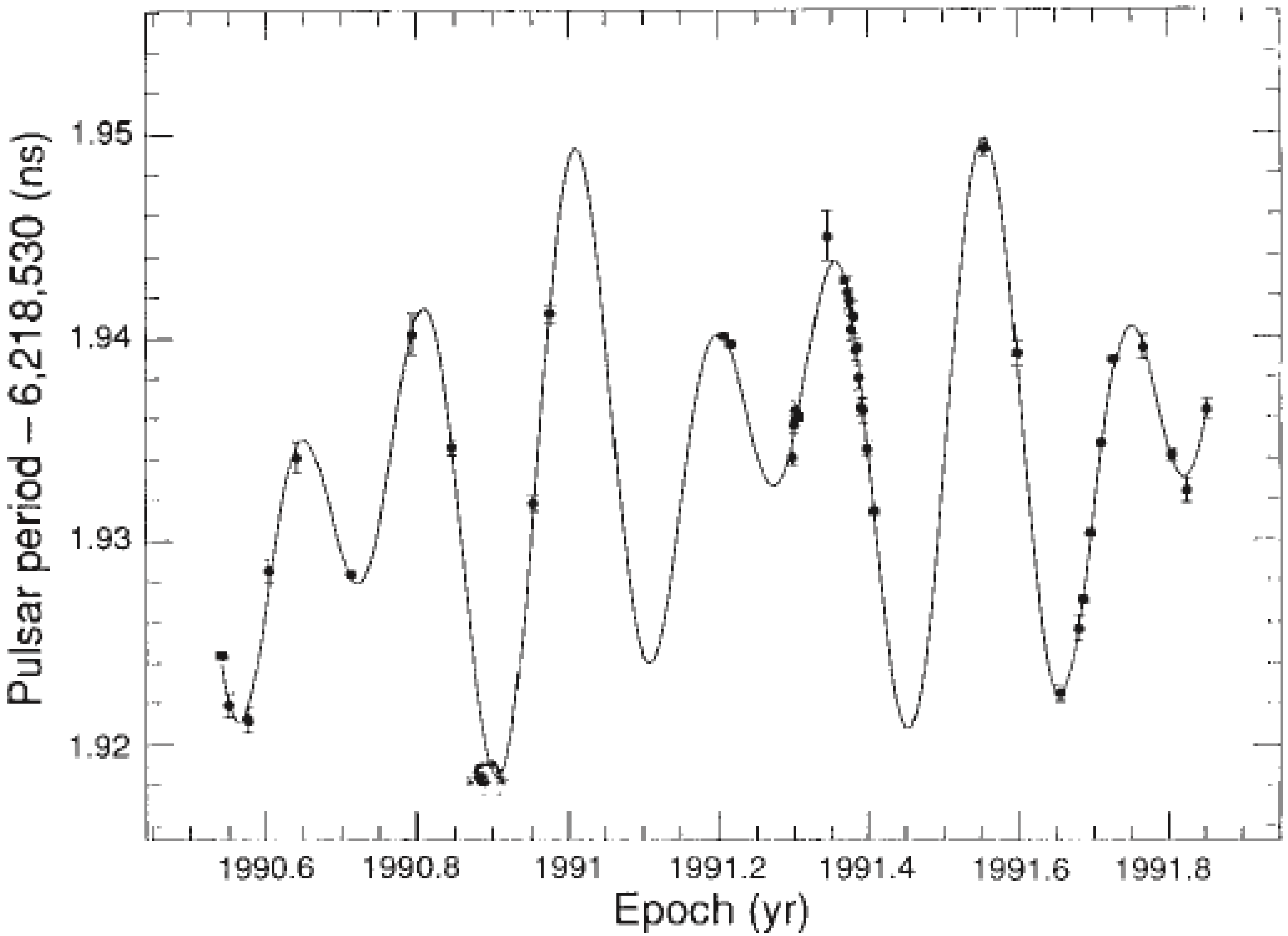


FIG. 3 Period variations of PSR1257+12. Each period measurement is based on observations made on at least two consecutive days. The solid line denotes changes in period predicted by a two-planet model of the 1257+12 system.

Other applications of the timing method:

- Stably pulsating white dwarfs (P~200s)
- Pulsating sdB stars (P~500s)
- Eclipse timing
- Transit time variations

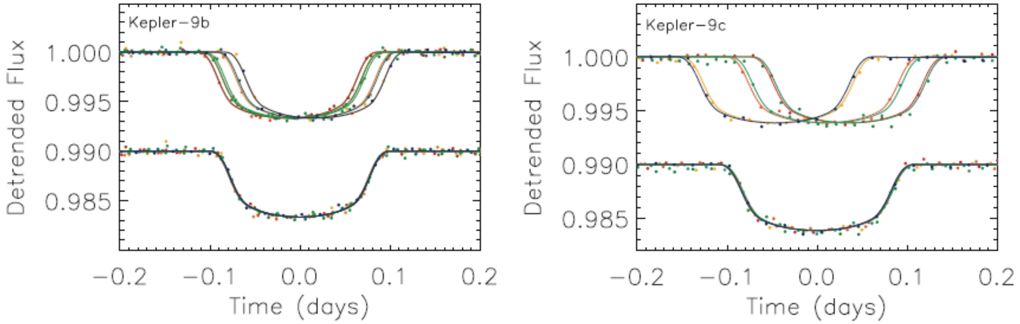
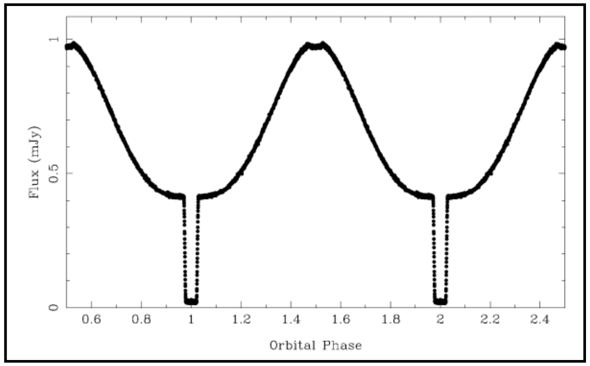


Fig. 5. Light curves for Kepler-9b (**left**) and Kepler-9c (**right**). In each panel, the top curve shows the detrended Kepler photometry (points, colored by transit epoch) folded with the best-fit period. Significant displacements are due to the large TTVs caused by gravitational interactions between the planets, as described in the text. The bottom curve in each panel (displaced downward for clarity) shows the transits shifted to a common center using the measured transit times (SOM), giving depths of ~7 millimagnitudes and durations of ~4.5 hours. Also shown are solid lines (also colored by transit epoch) from the full numerical-photometric model, folded or shifted in the same way as the data.

Kepler-9 transits



NN Ser eclipses

Timing Method Summary:

- First successful detection technique!
- Requires a suitable target (clock)
- Lack of large sample => not efficient
- In best case (very short periods) is sensitive to Earth-mass planets