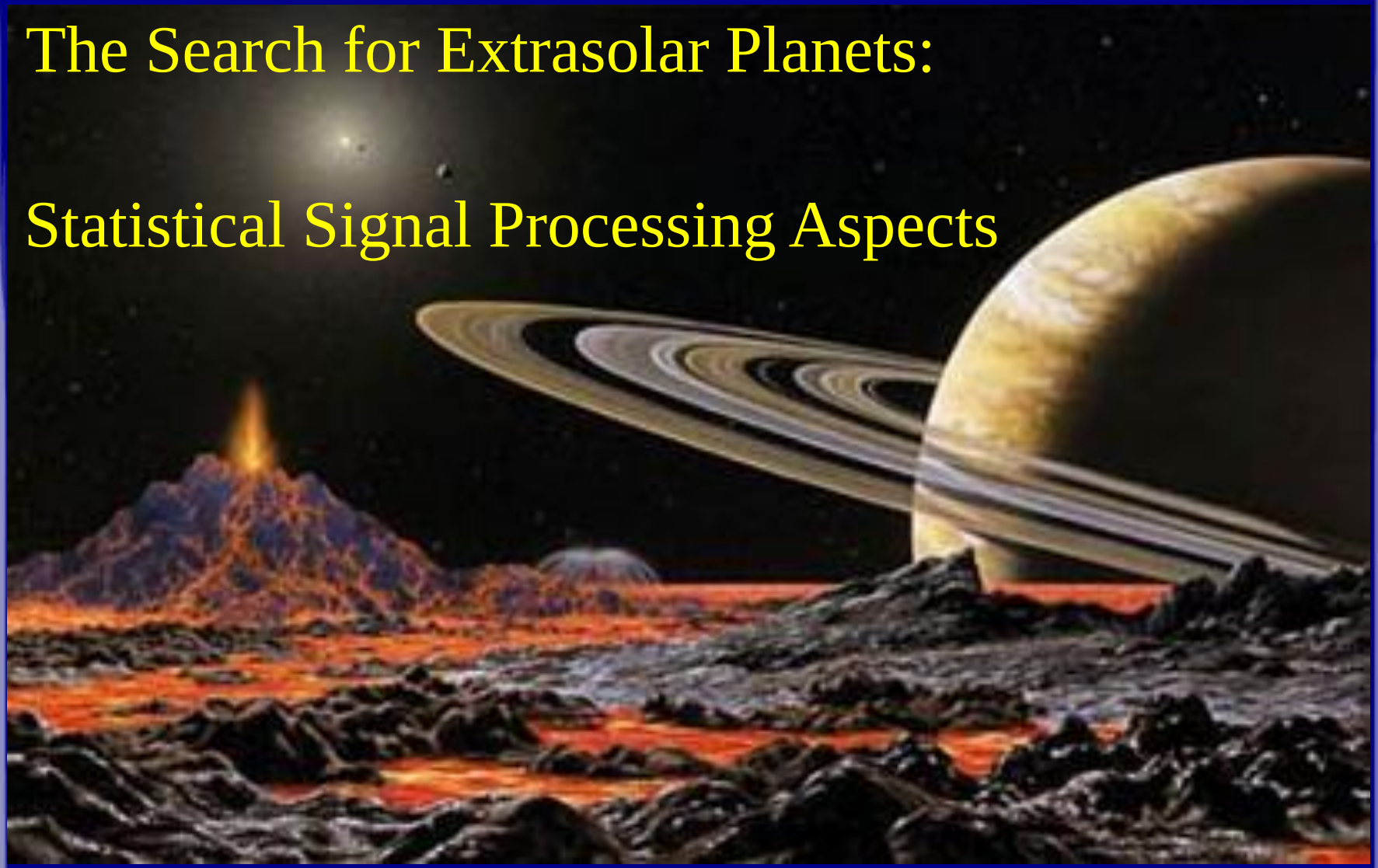
The Search for Extrasolar Planets:

Statistical Signal Processing Aspects



Shay Zucker, Dept. of Geophysics, TAU

Overview

- Preliminaries
- Extrasolar Planets
- Radial Velocities
- Transits
- Future prospects and challenges

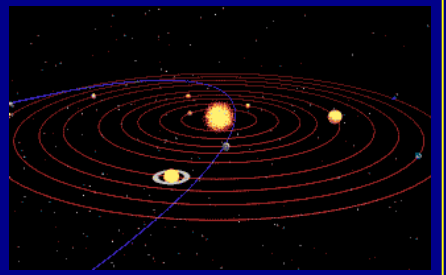
Basic Terminology

Star: large gaseous ball, emitting energy (thermonuclear fusion)

Planet: a much smaller ball, usually orbits a star

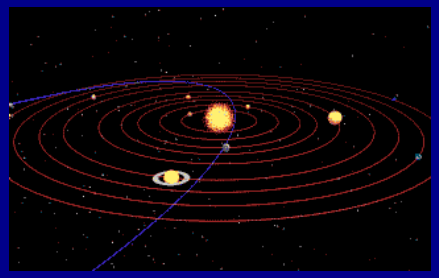
Our topic today: planets orbiting other stars, a.k.a. *extrasolar planets* a.k.a. *exoplanets*

The Solar System: the Sun, 8 planets, comets, asteroids etc.

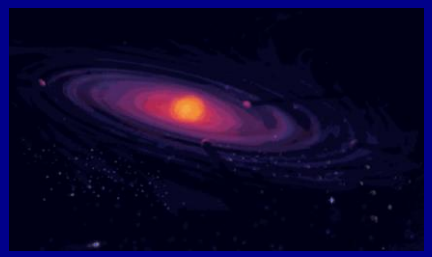


Galaxy: a system comprising ~10^{11} stars

Motivation



- The holy grail: Life
- Better understanding of the Solar System
- Better understanding of star formation
- Basic science



Is it that difficult?

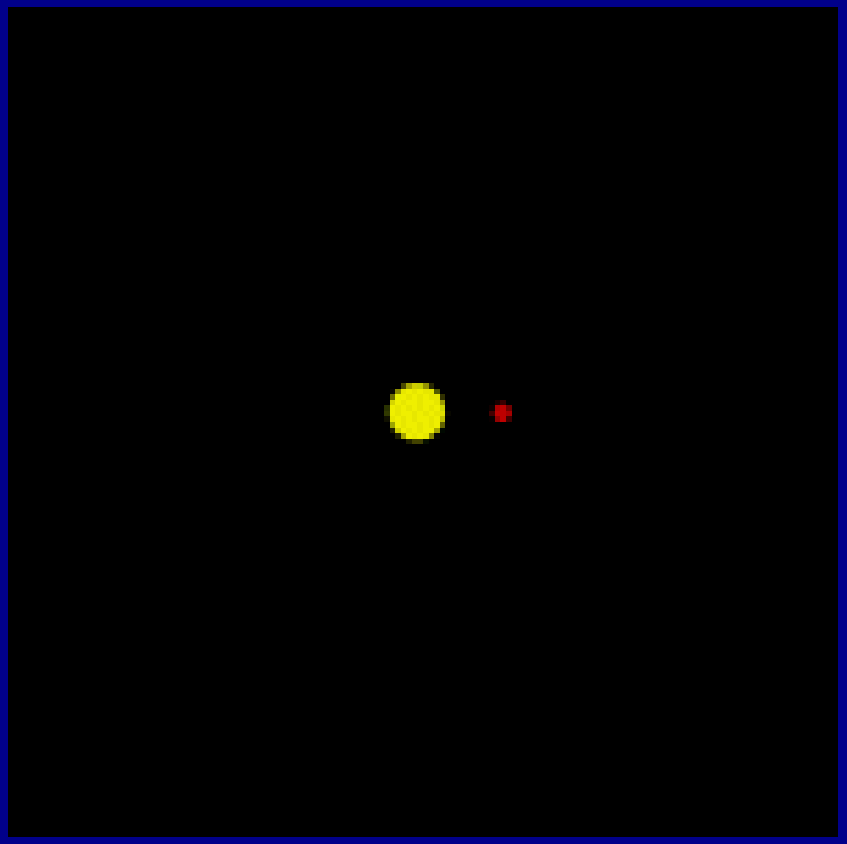
$$\frac{d_{01}}{d_{12}} \sim 10^5$$

d_{12}= 5 AU

d_{01}= 10 parsecs

$$\frac{L_{\text{sun}}}{L_{\text{Jup}}} \sim 10^8$$

Induced Stellar Motion ('Wobble')



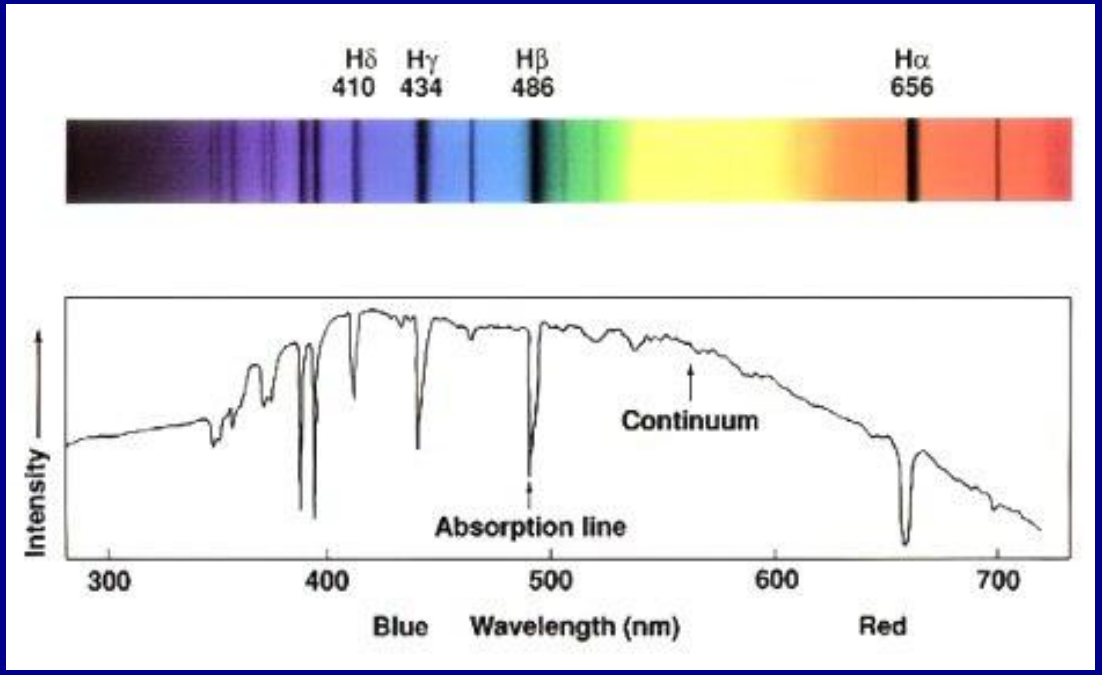
- Newton's 3rd law (attraction is mutual)
- Planet performs an elliptic motion
- Star should also
- Stellar motion on the celestial sphere is too small to detect.

Spectroscopy

Stellar spectrum

Spectroscopy

The stellar spectrum provides information about chemistry, temperature, rotation, stratification



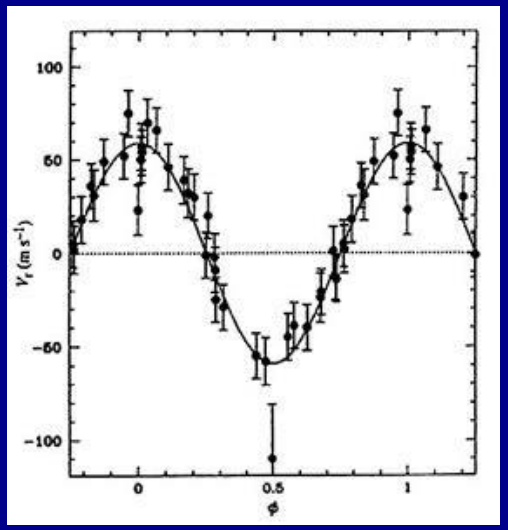
For exoplanets:
Doppler shift

⇓

Radial velocity

Detection by Radial Velocity (RV)

- Periodic variation may suggest a planet
- Mass can be inferred from period and amplitude
- First planet: Mayor & Queloz (1995)

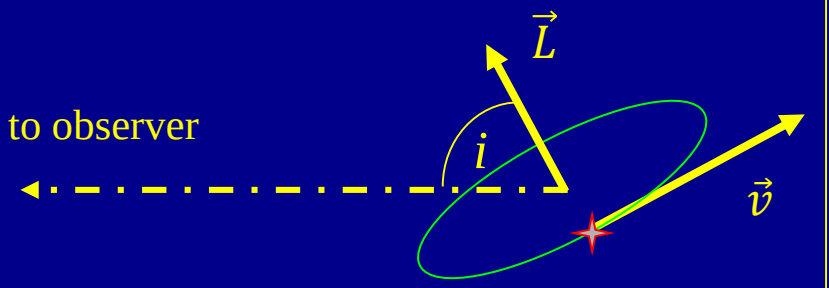


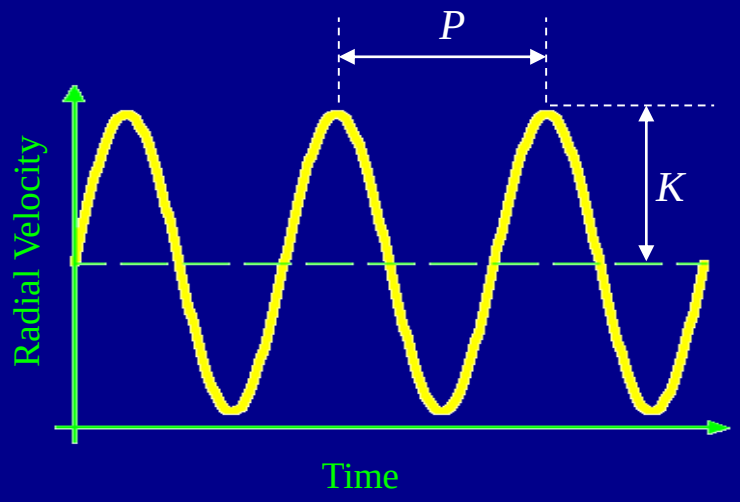
51 Peg b

$P = 4.23$ days

$M = 0.47\ M_{\mathrm{J}}$ (Jupite

RV signal (circular orbits)





$$K = \left(\frac{P}{1\,\mathrm{day}}\right)^{-1/3} \left(\frac{M_{\mathrm{star}}}{M_{\mathrm{sun}}}\right)^{-2/3} \left(\frac{M_{\mathrm{planet}} \sin i}{M_{\mathrm{Jup}}}\right) 203\ \mathrm{m\ s^{-1}}$$

RV signal (eccentric orbits)

P – period
T_0 – time of periastron
e – eccentricity
K – semi-amplitude
ω – argument of periastron
γ – RV of c.o.m.

$$K = \frac{2\pi a \sin i}{P\sqrt{1-e^2}}$$

Kepler Equation:

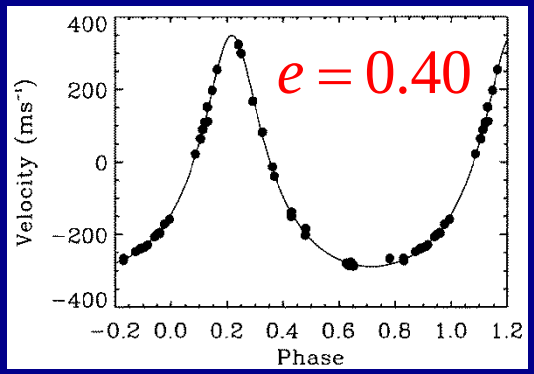
$$E - e \sin E = \frac{2\pi}{P}(t - T_0)$$

$$\tan\left(\frac{\theta}{2}\right) = \sqrt{\frac{1+e}{1-e}} \tan\left(\frac{E}{2}\right)$$

$$\mathrm{RV} = \mathrm{K} \cos(\theta + \omega) + Ke \cos$$

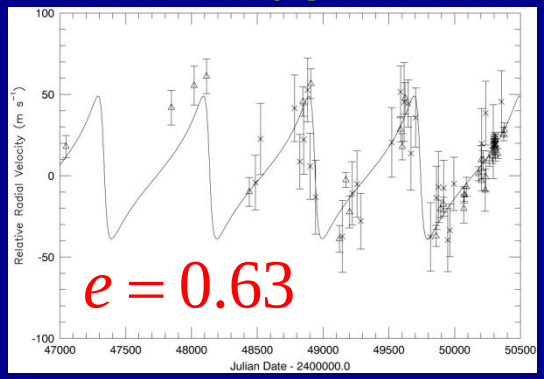
RV signal (eccentric orbits)

70 Vir



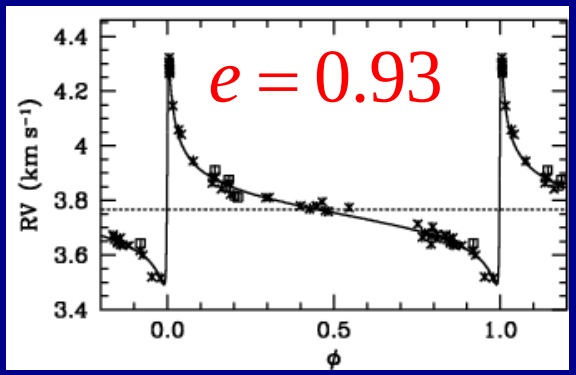
Marcy & Butler 1996

16 Cyg B

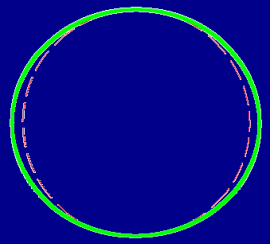


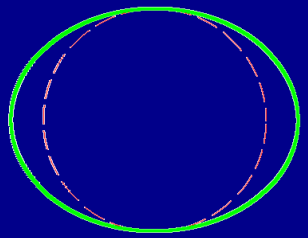
Cochran *et al.* 1997

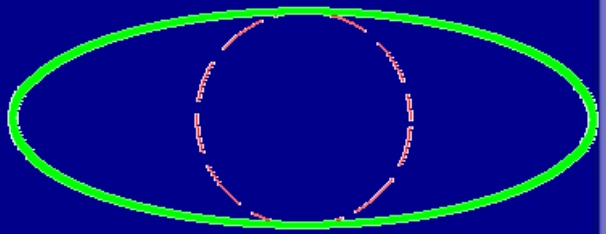
HD80606



Naef *et al.* 2001







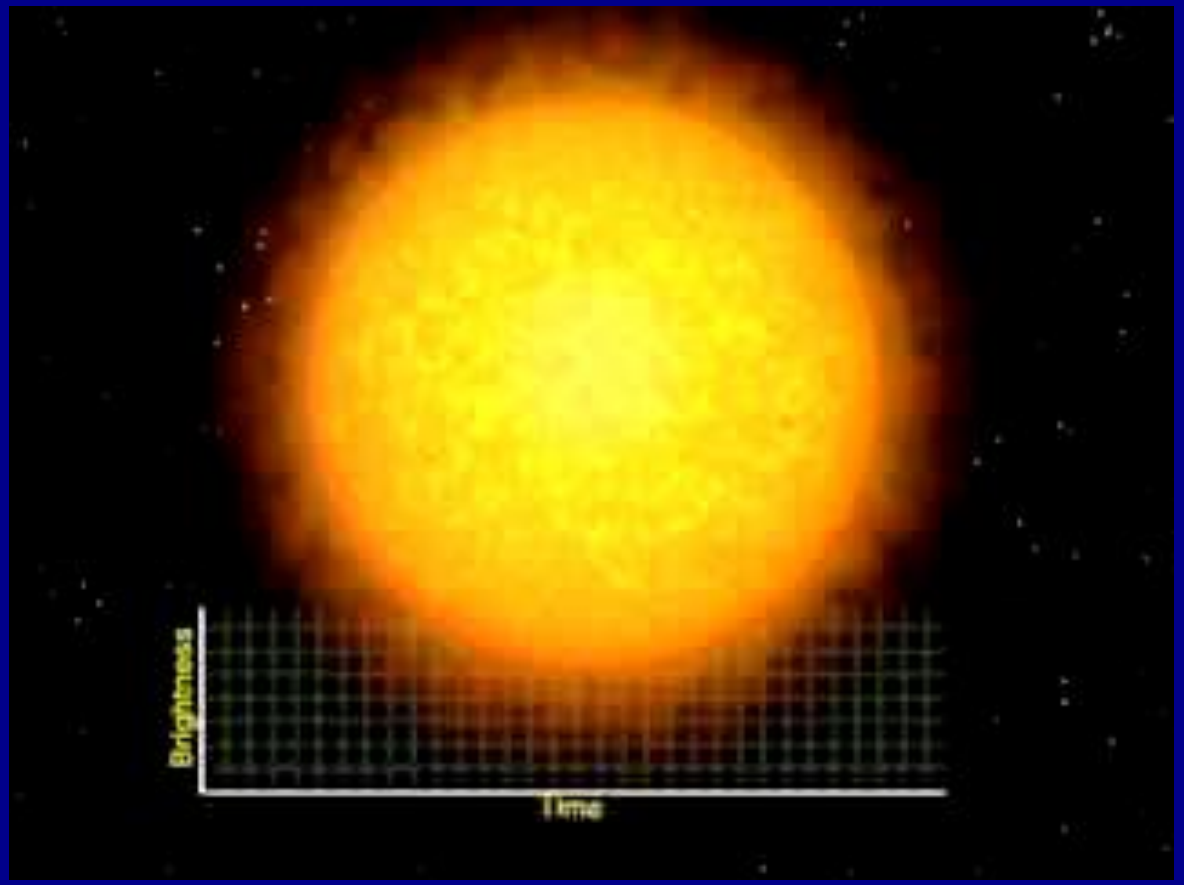
Idiosyncrasies of RV Time Series

- Sampling: sparse and irregular
  - Sampling times do tend to be at night
- Eccentricity introduces strong harmonics
- Multiple planets – more than one periodicity
- Stellar processes introduce colored noise
  - Quasi-periodicities as well

RV Analysis – Common Practices

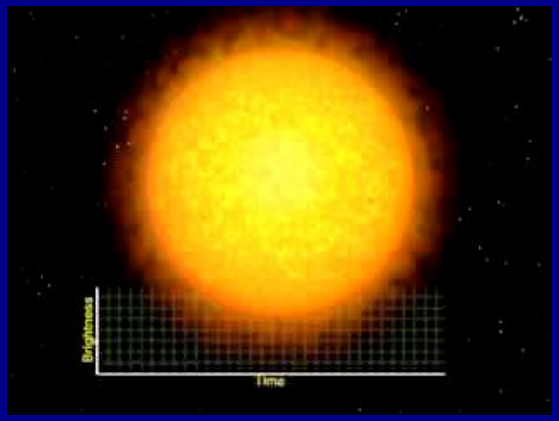
- Detection: Lomb-Scargle periodogram
  - My own recent contribution:
  - Phase Distance Correlation Periodogram
- Noise modelled as a Gaussian Process
- Extensive use of Bayesian inference (MCMC)

Photometry: Transits



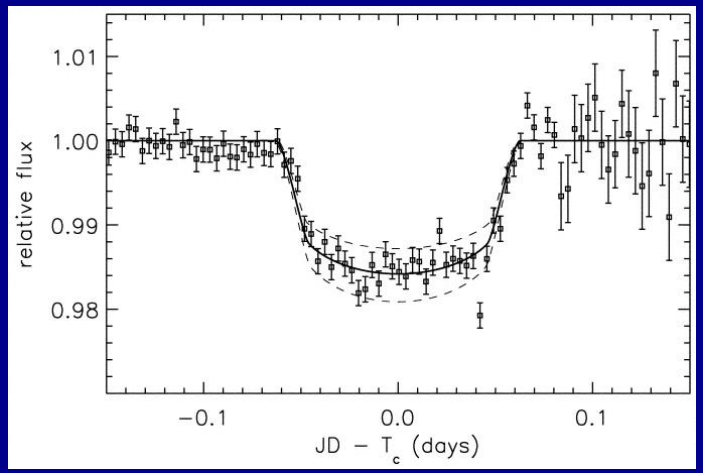
Photometry: Transits

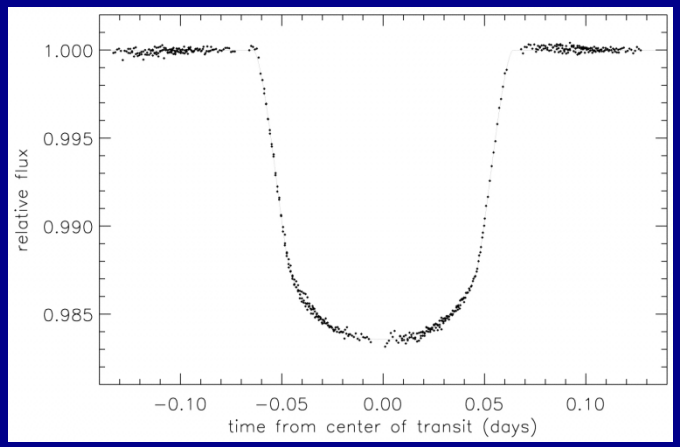
- Inclination should be ~90^0
- Not rare as one would think…



- Simultaneously monitor many stars (using CCD)
- Extract from the CCD the apparent stellar flux
  - Many interesting aspects of image processing
  - Calibration and pre-processing quite complex

Photometry: Transits



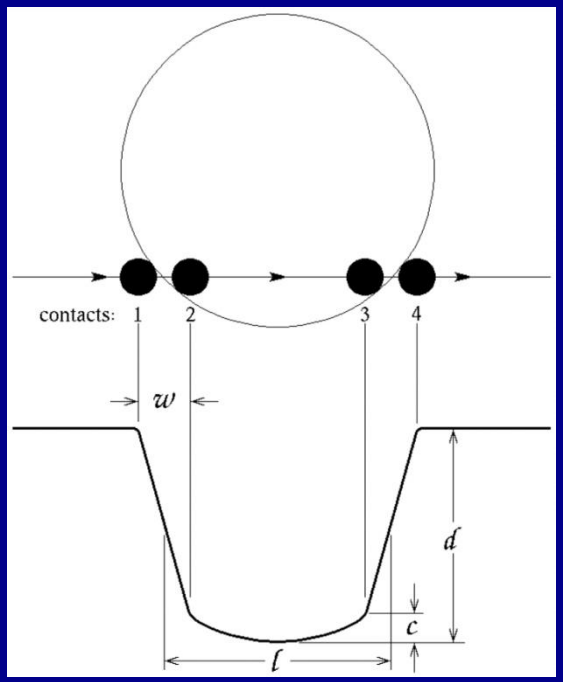


First known transiting planet:
HD 209458 b
Charbonneau et al. (2000)

$R_{\text{planet}} = 1.35 \pm 0.06\ R_{\text{Jup}}$

$\bar{\rho} = 0.35\ \text{g cm}^{-3}$

Anatomy of a Transit



$$d = \left(R_{\text{planet}}/R_{\text{star}}\right)^2$$

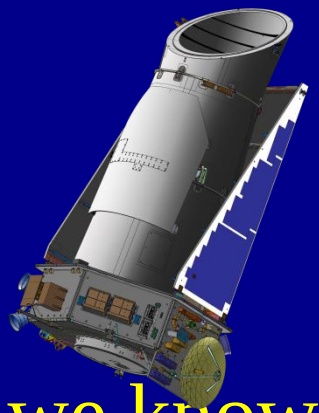
$$l \cong \frac{P}{\pi}\sqrt{\left(\frac{R_{\text{star}}}{a}\right)^2 - \cos^2 i}$$

Curvature at the bottom:
Stellar physics (‘limb darkening’)

The unique geometric situation of a transit allows performing many other kinds of observations

Photometry from Space

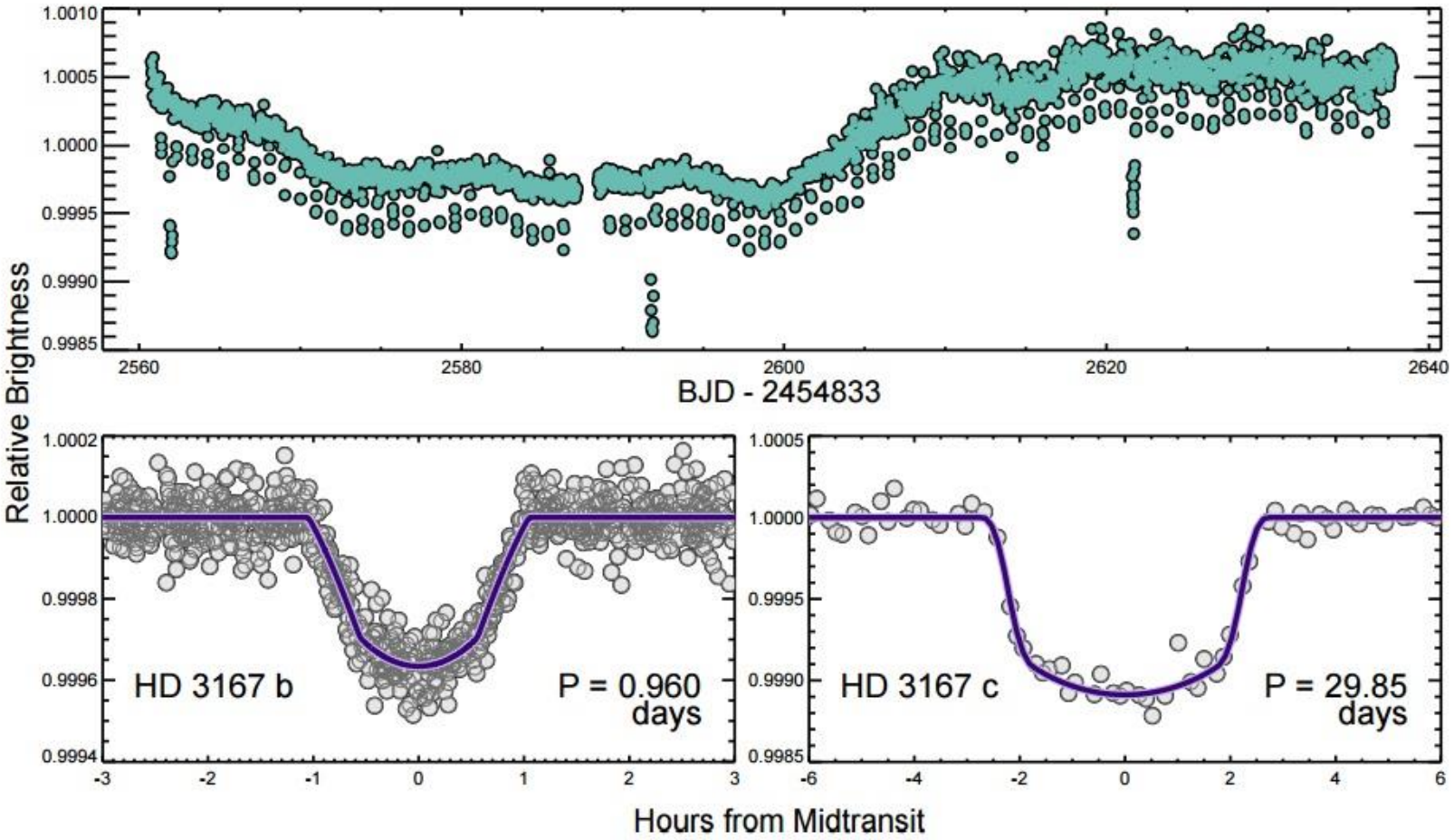
- Earth/Sun transit depth should be ~10^{-4}
- To maximize precision – we move to space
- Kepler space telescope
  - Unprecedented precision
  - Almost uniform sampling
  - Cadence ~30 min
- Provided most of the planets we know of
  - (~3500)



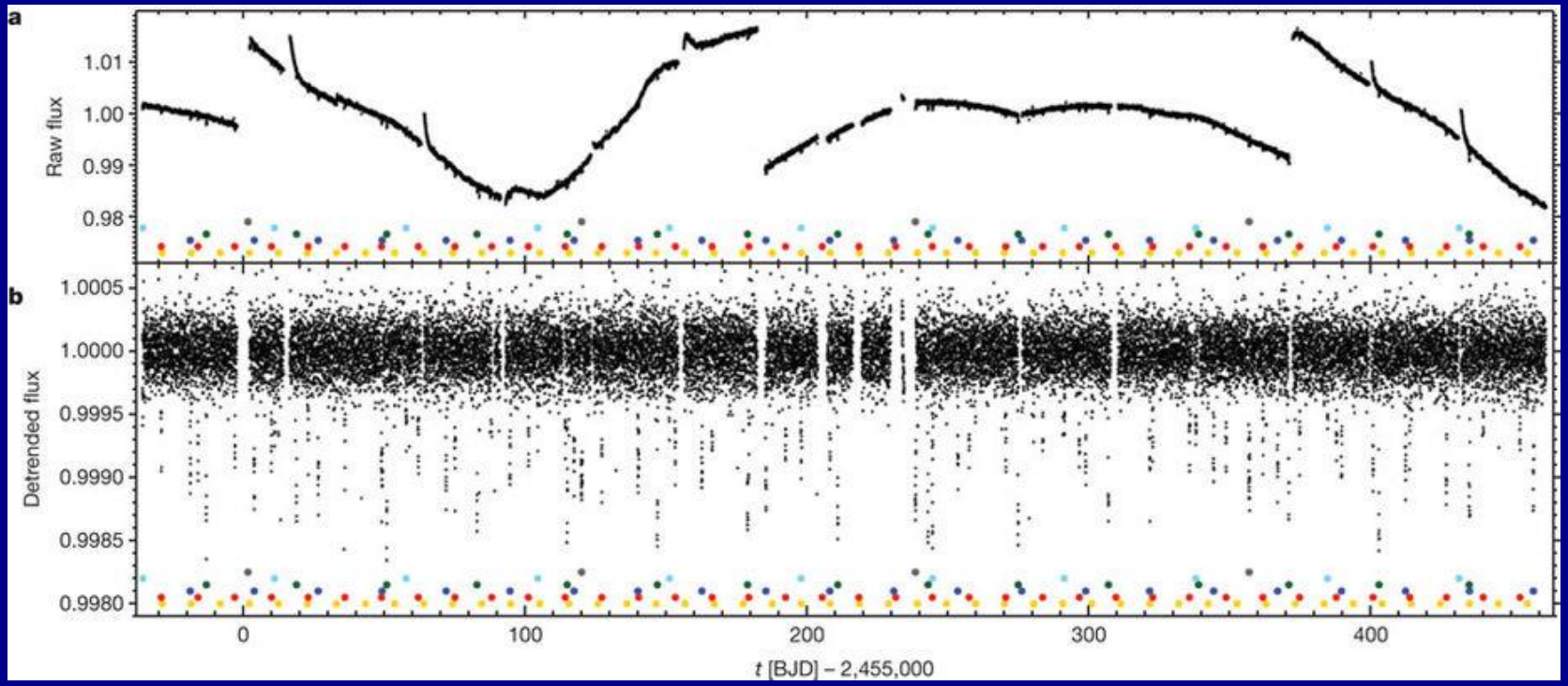
Transit Signal Idiosyncrasies

- Approximately a periodic pulse train
- Very low duty cycle:
  - Easy cases ~5%
  - Can get down to 0.01%
- Presence of additional planets can cause:
  - Additional transits with different period
  - Transit timing variations (TTV)
- Noise: colored noise + outliers + jumps
- Sampling: close to uniform but with gaps

Transit Signal Idiosyncrasies



Transit Signal Idiosyncrasies

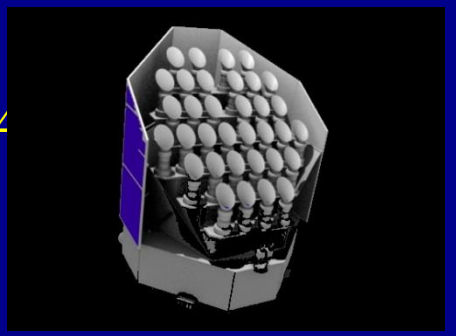


Transits – Common Practices

- Detection: the standard tool – BLS
  - (Box-Least Squares)
  - Kovács, Zucker & Mazeh (2002)
- Noise modelled as Gaussian Process
- Extensive use of Bayesian inference (MCMC)

Prospects and Challenges

- Challenge: Earth-like planets
  - Very shallow transits (depth ~10^{-4}
  - Long period (~1 year)
  - Implying very little information



- Instrumentation: PLATO (cadence 25s)
- Instrumentation: E-ELT
  - Direct imaging
  - Planet spectroscopy
    - (life?...)