Transit photometry

OUTLINE:

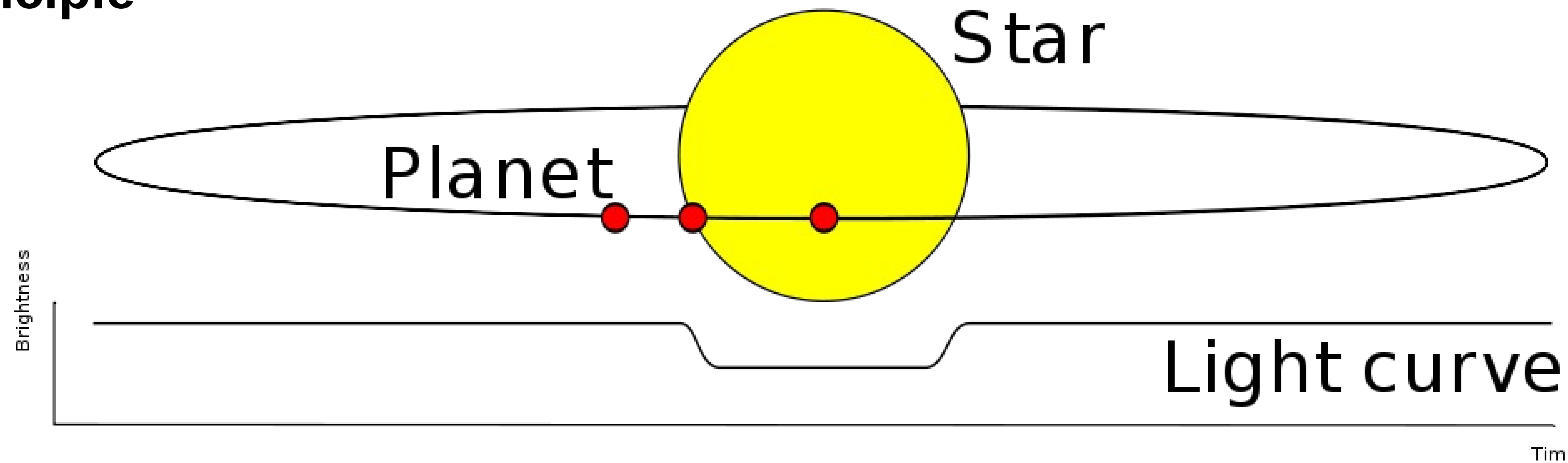
Signal amplitude and statistics

What can be measured ?

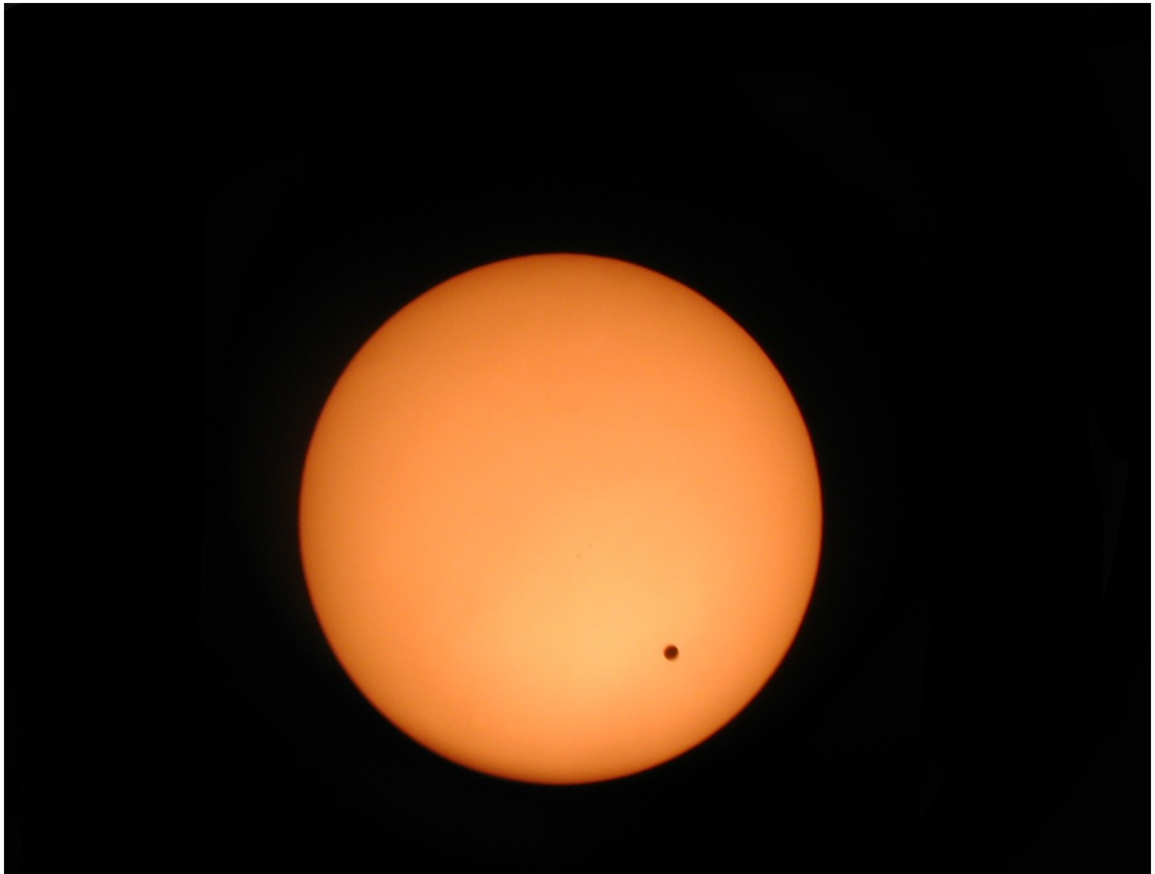
Transit timing variations

Measurement requirements

Principle



2004 transit of Venus

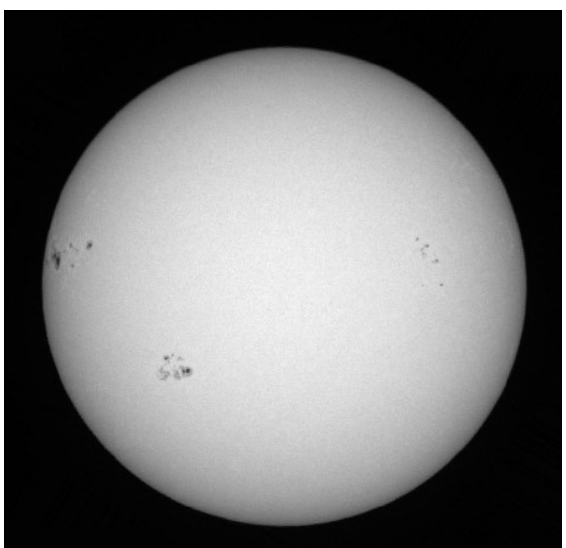


Transit depth

Transit depth = $(R_{planet} / R_{star})^2$

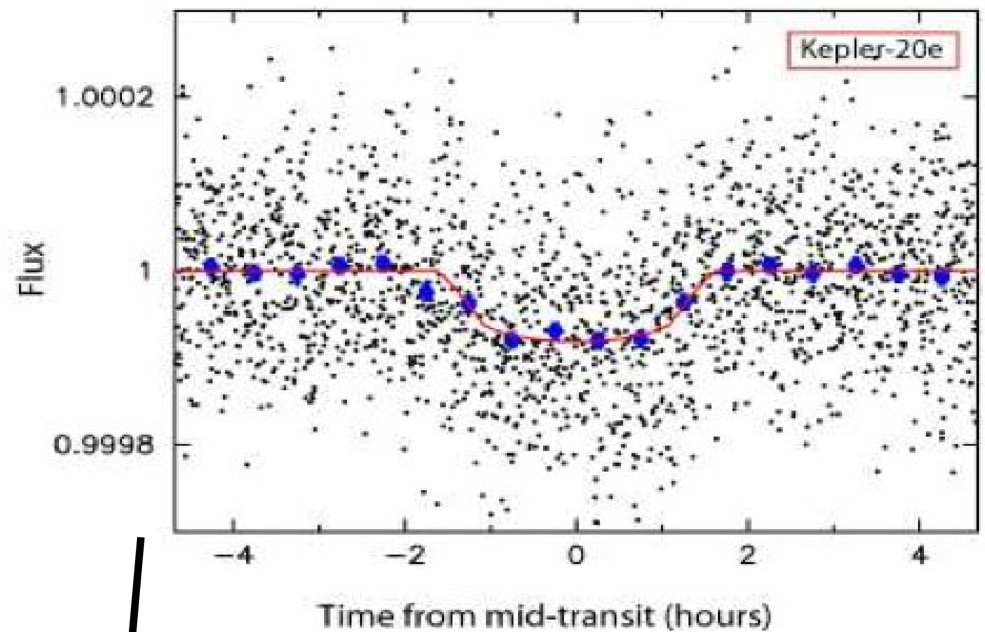
Earth radius = 6,371 km
Jupiter radius = 69,911 km
Sun radius = 696,000 km

→ Amplitude = 8e-5 (Earth)
→ Amplitude = 1% (Jupiter)



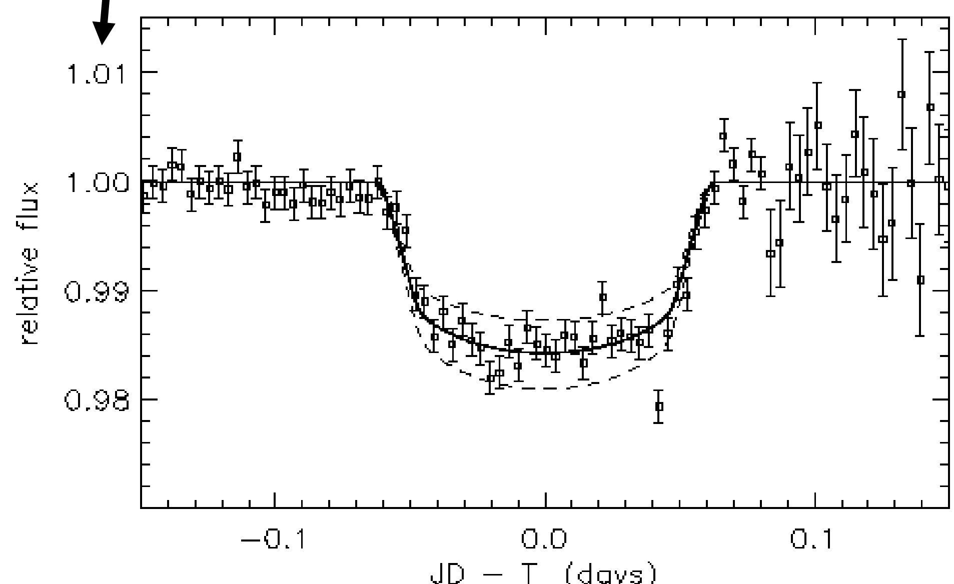
Note that transit is deeper at mid-transit (limb darkening)

Kepler 20e: transit depth = 0.008 %
(similar to Earth transit depth)



~100x factor in scale

HD 209458: 1.7% deep transit



Probability, period and duration

Assuming that planet size << star size:

Probability of transit ~ R_{star}/a_{planet}

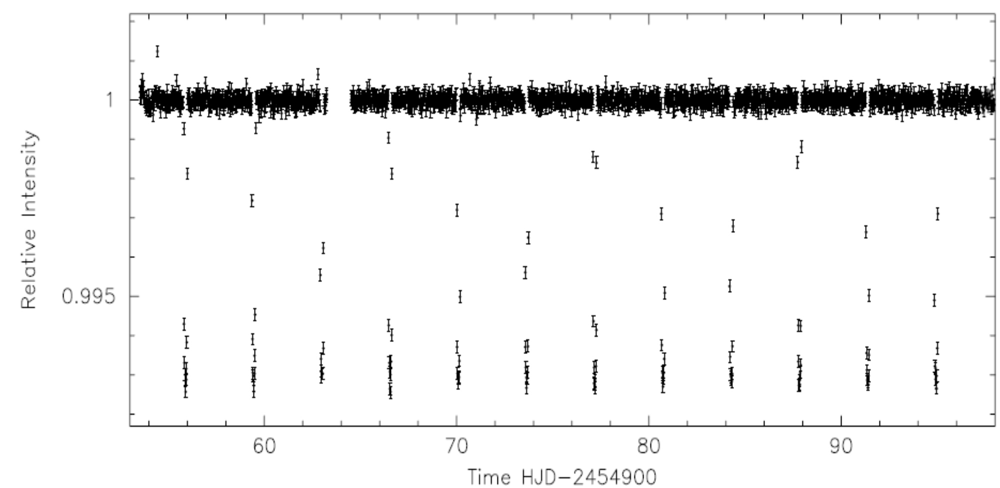
Earth distance to Sun = 150e6 km
Sun radius = 696,000 km

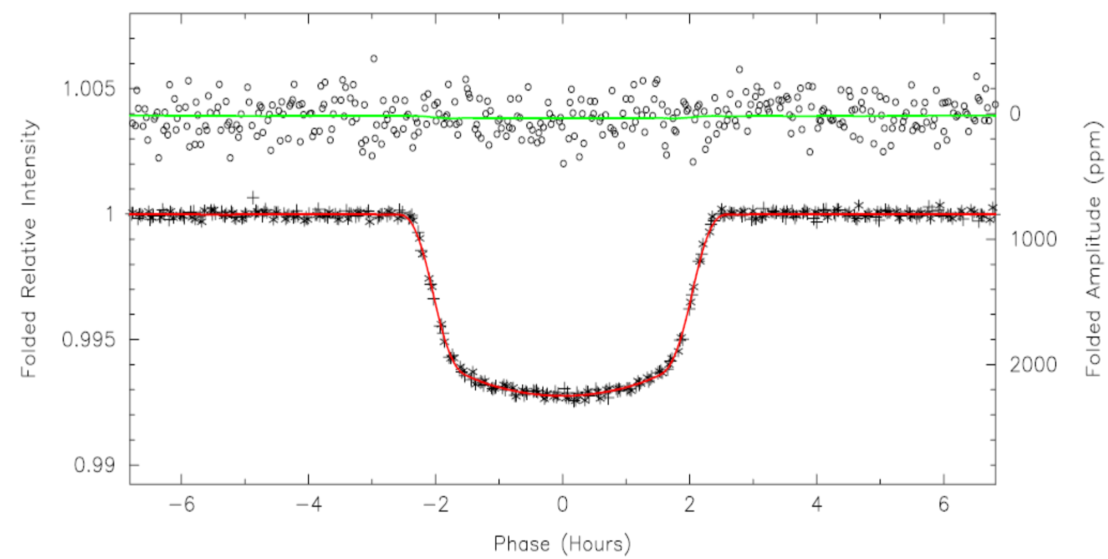
→ Probability = 0.5% (Earth)
→ Probability = 0.1% (Jupiter)

Large # of stars need to be surveyed for discovery

Period = orbital period = $2\pi (a^3/GM)^{1/2}$

Duration = $[2R_{star} / (2\pi a_{planet})] \times$ Period





Kepler 5 light curve
Period = 3.5 day
0.7% transit depth

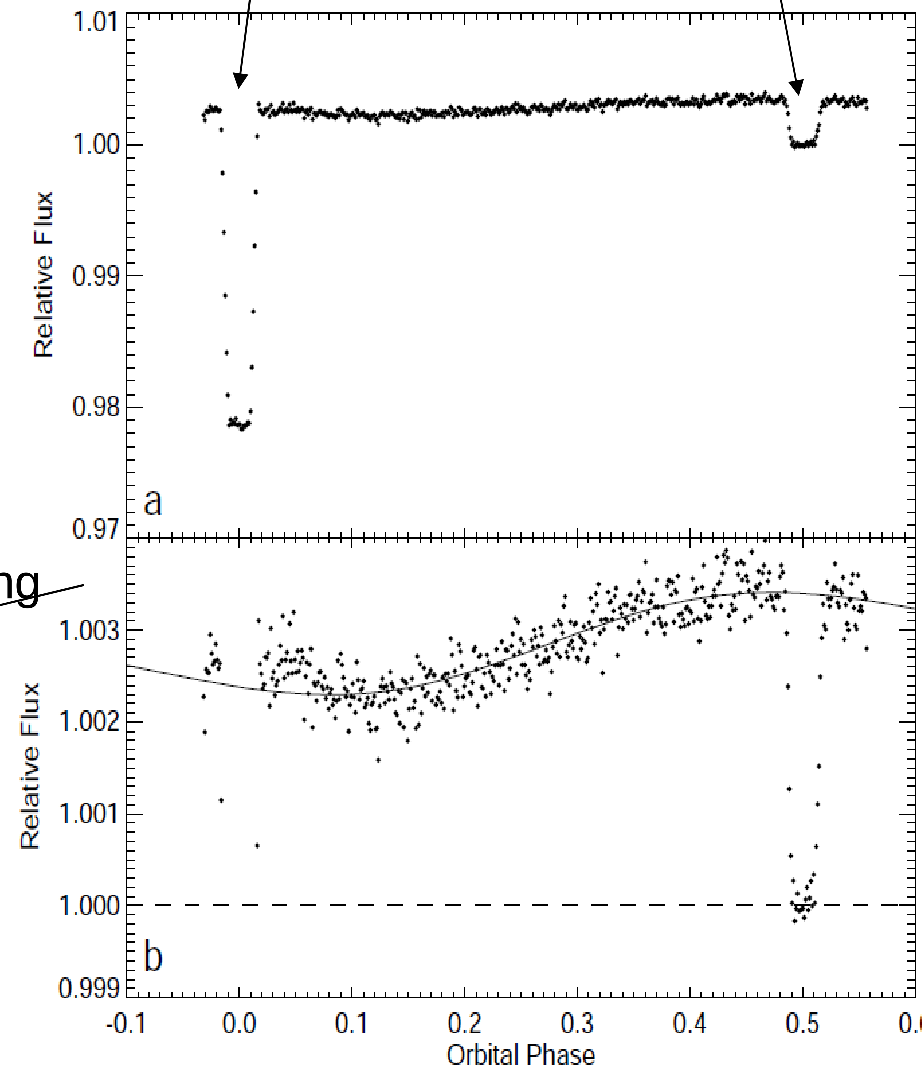
Secondary transits and planet phase modulation

Planet occulted by star → secondary transit

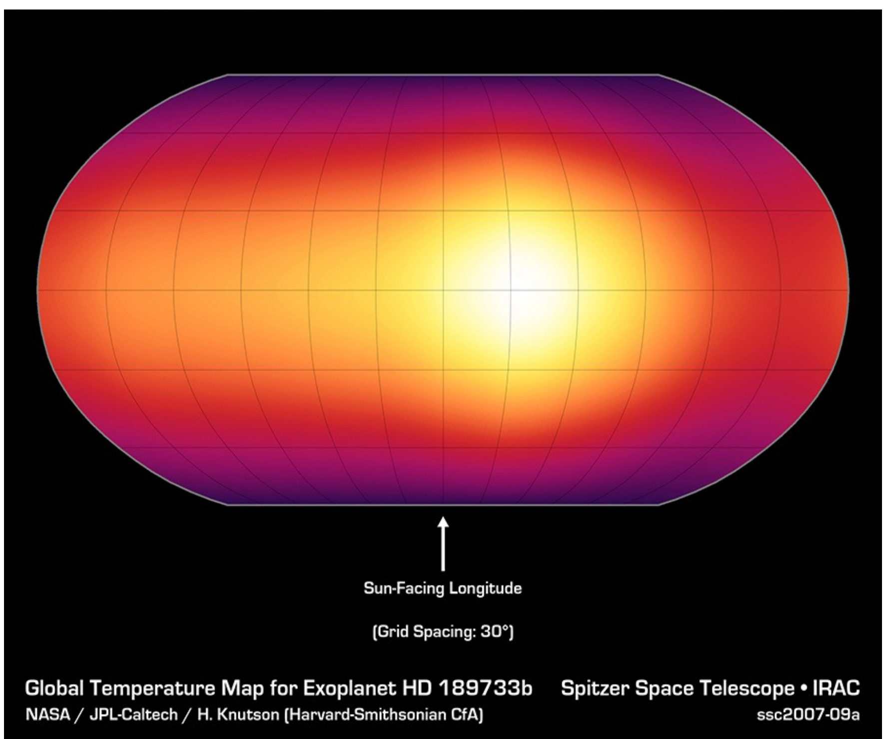
Planet phase changes total measured flux

secondary transit

primary transit



phase mapping



HD 189733
Knutson et al. 2007

Transit timing variations

Planet – planet interactions can be measured in planetary systems
→ this technique can be used to identify new planets

1846: Neptune discovered thanks to predictions by Le Verrier from otherwise unexplained perturbations of Uranus' orbit

Single planet: transit is periodic, variations in the time interval between 2 consective transits are extremely small (and mostly secular)
Multiple planets: non-periodicity of transits

Monitoring transit timing variations (TTV) can :

(1) Reveal new planets

Example: Kepler 19c identified from 5mn TTV of Kepler 19b

(2) Allow mass measurement of already known planets

Example: Kepler 11 system (6 planets), see next slide

Transit timing variations

Kepler 11 system
(Lissauer et al. 2011)

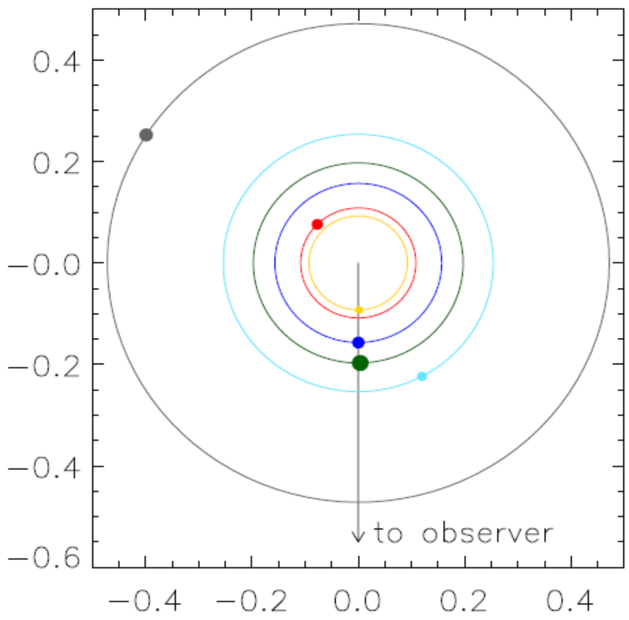


Fig. S12.— Planetary configuration during the triple transit seen at BJD 2,455,435.2. The radii of the points are scaled to the radius of each planet. Orbits are also to scale with one another, but planetary radii are exaggerated relative to orbital ones for clarity. Planetary colors match Figures 1 and 2 in the main text.

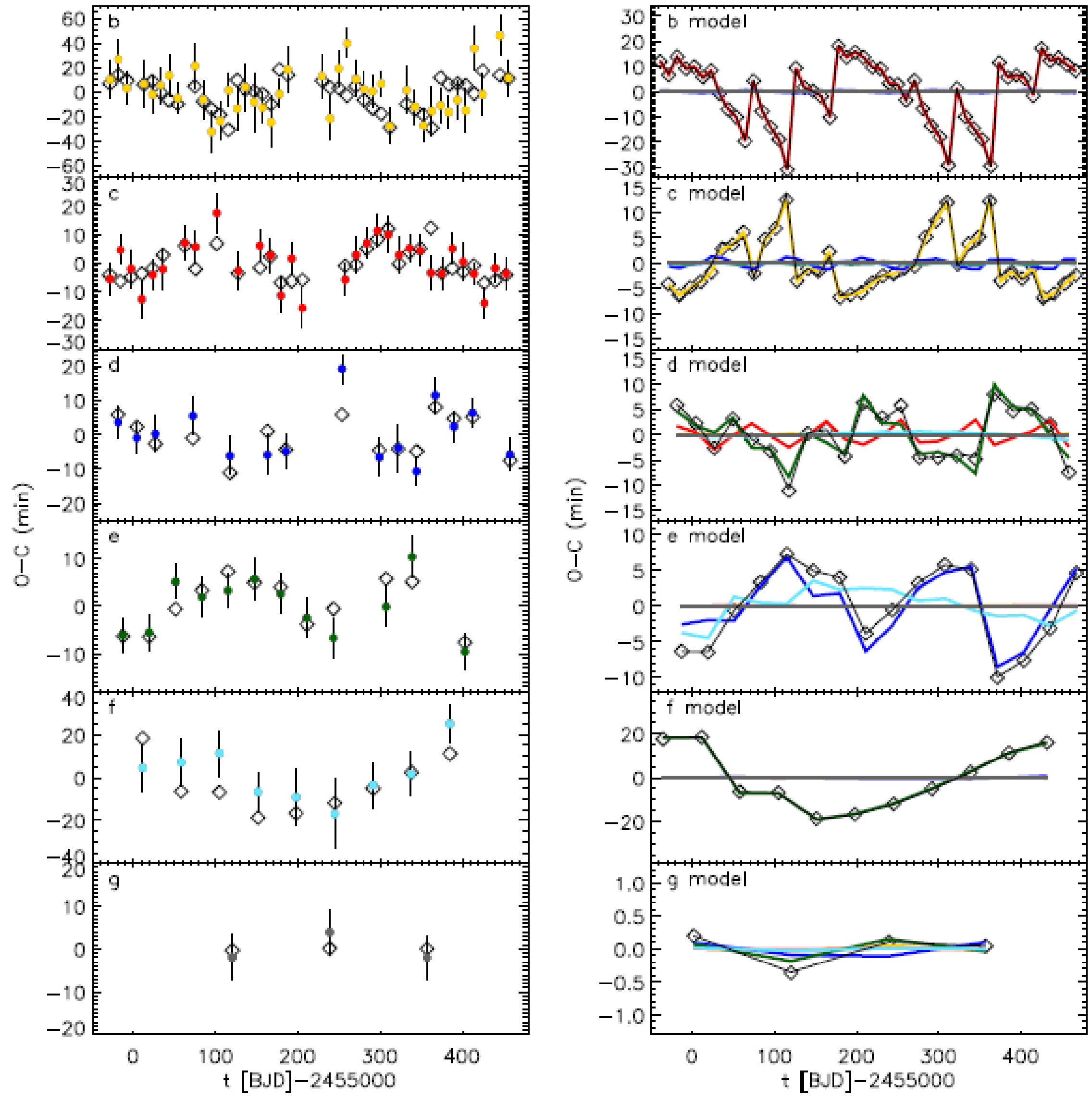
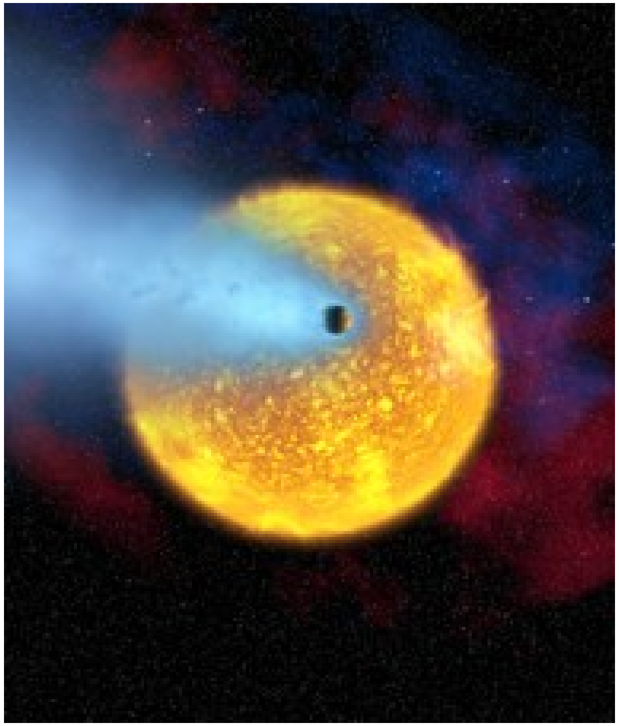


Fig. S6a.— Left side: Observed (O) mid-times of planetary transits minus a Calculated (C) linear ephemeris, plotted as dots with error bars; colors correspond to Figures 1–3 in the main text. Numerical integration dynamical model, the Circular Fit of Table S4, is given by the open diamonds. Right side: Contributions of individual planets to these variations. Total variations from saw ix-planet integrations are given as diamonds (same values but different scale than left side), and contributions from every other planet is shown by a line with color corresponding to the perturbing planet, determined by two-planet integrations. The solid black line is the sum of these integrations, which matches nearly identically with the diamonds; thus we conclude the perturbations from different planets add up very linearly.

Transit spectroscopy

Measure planet radius as a function of wavelength
→ atmosphere composition can be probed near and above the altitude at which atmosphere becomes opaque

Example:
HD 209458b's extended Sodium atmosphere
(HST)



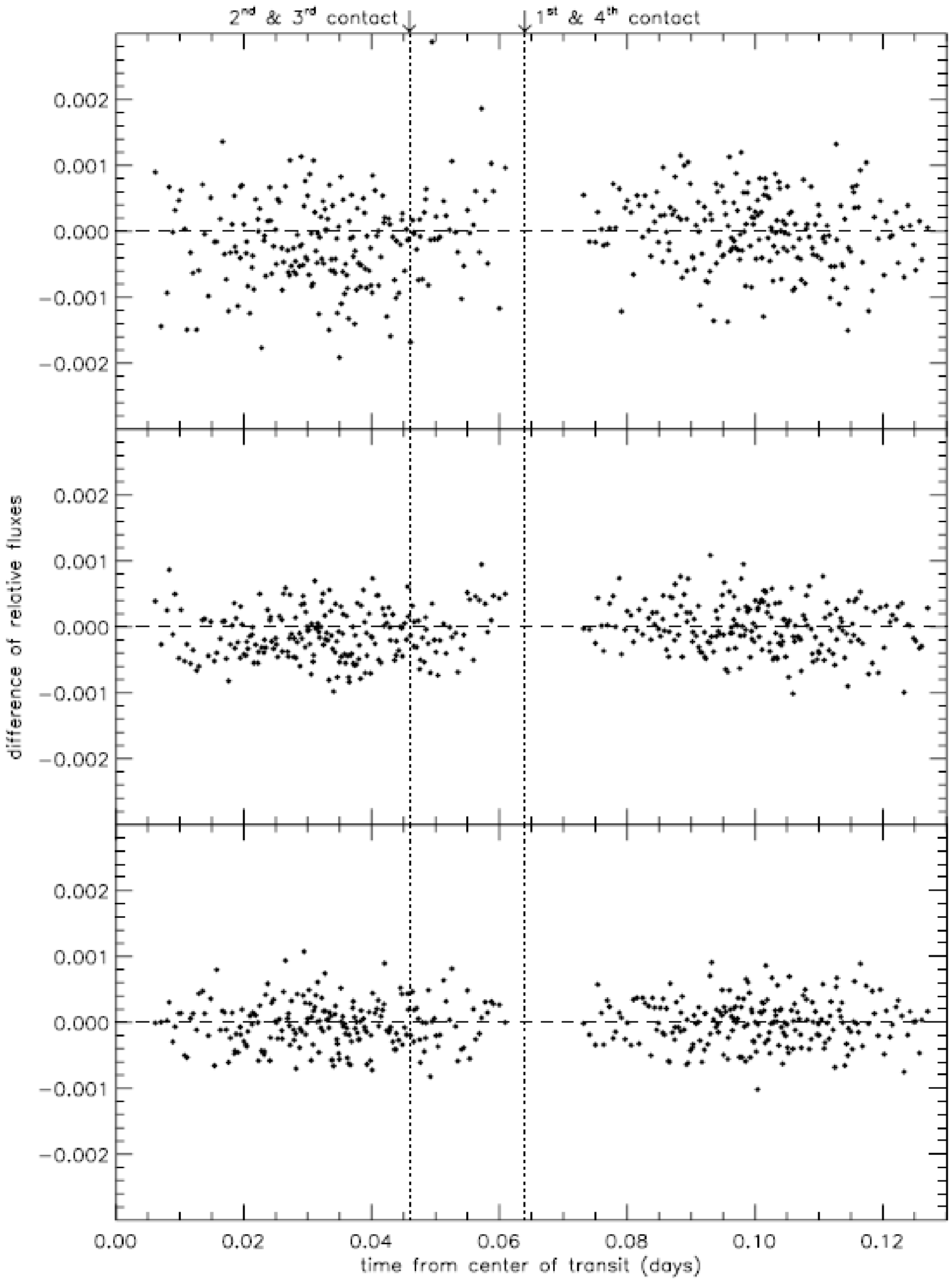


FIG. 2.—Unbinned time series n_{Na} (*top*), m_{Na} (*middle*), and w_{Na} (*bottom*) as a function of absolute time from the center of transit. The means of the in-transit values of n_{Na} and m_{Na} are both significantly offset below 0.

Charbonneau et al. 2002

Transit spectroscopy

GJ 1214b planet (6.5 Mearth)
(Bean et al. 2011)

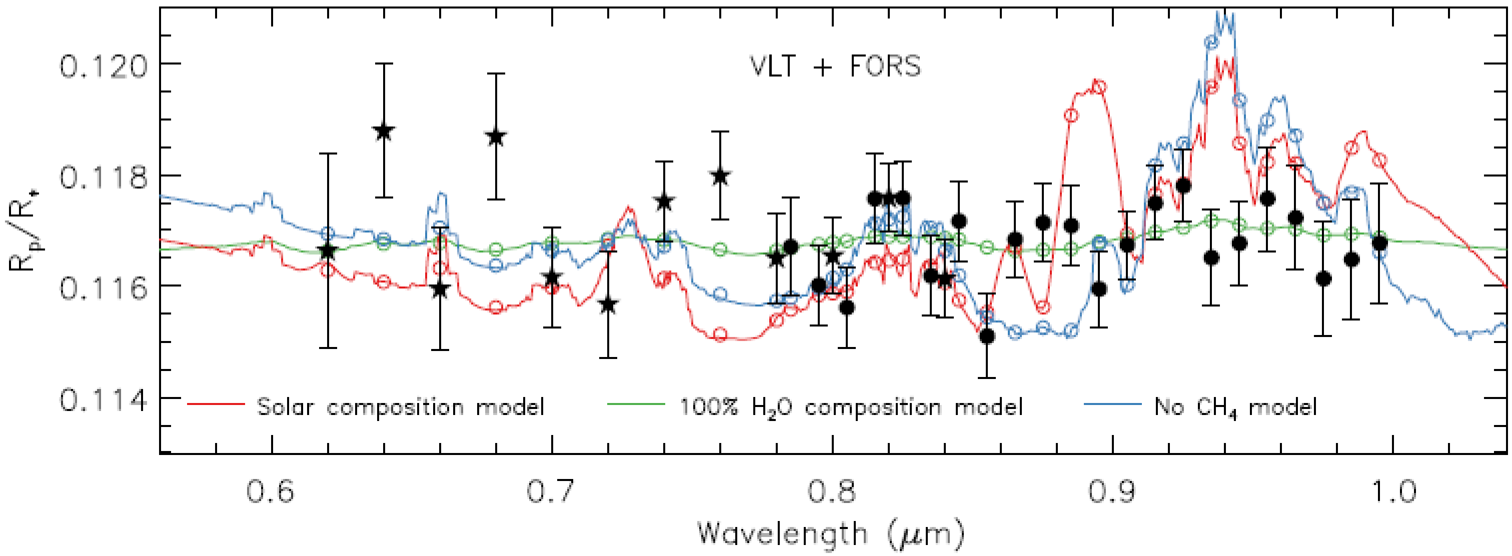


FIG. 12.— The derived transmission spectrum of GJ 1214b from the FORS blue data (filled stars) and FORS red data (filled circles) spectroscopy compared to theoretical models (lines). The FORS blue were adjusted downward by 0.0007 to match the red data in the region where the data sets overlap. The models were binned over the bandpasses of the measurements (open circles) and scaled to give the best fit to the data. All calculations were done with high-resolution models; the models shown are smoothed for clarity.

Transit spectroscopy may be possible in IR with JWST for large rocky planets in HZ of nearby M dwarfs

Rossiter-McLaughlin effect

Radial velocity measurement during transit
As planet moves across stellar disk, average radial velocity changes due to stellar rotation
Sun rotation ~ 2 km/s → one side of the Sun is + 2 km/s, other side is – 2 km/s
1% transit depth can create ~ 0.01 x 2 km/s = 20 m/s modulation

Geometry is important (impact parameter, alignment between stellar rotation spin vector and transit trajectory on disk)

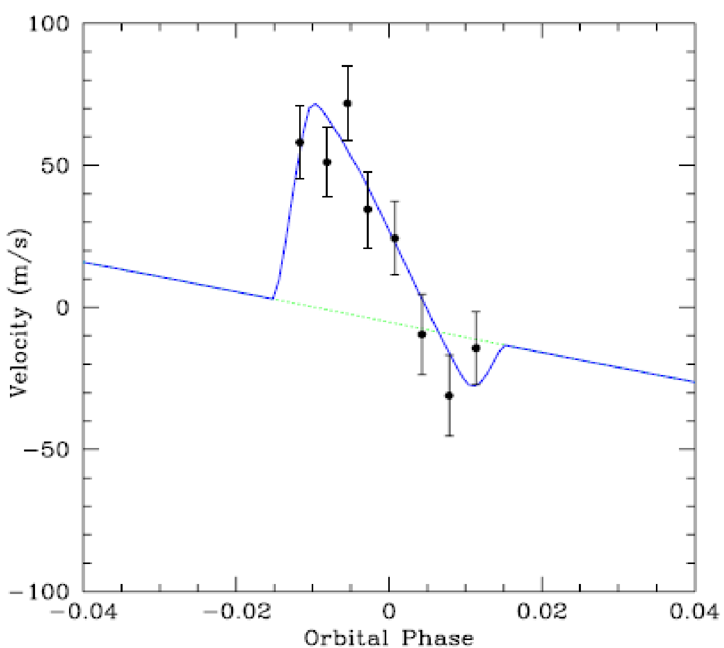


Figure 7. R-M effect for Kepler-8. The observed RVs obtained with HIRES on the Keck 1 telescope are plotted together with the predicted velocities from the best-fit model of the R-M effect. The high velocities near ingress and low velocities near egress imply a prograde orbit. The asymmetry in the model curve indicates a projected tilt of the orbit relative to the star's equator, as well as a transit with a large impact parameter on the star. The errors presented here in the RVs measured during transit are smaller than the errors in the other RV measurements due to the fact that a long slit was used, allowing for better sky subtraction, and also because the RV jitter was smaller during the 3 hr of the transit.

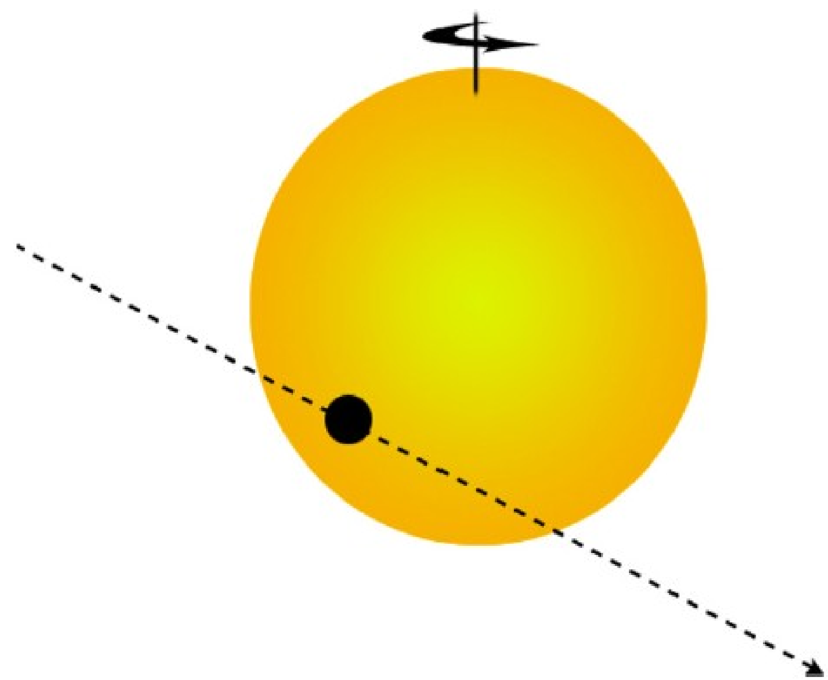


Figure 8. Sketch of the transit geometry for Kepler-8. The *Kepler* photometry and R-M measurements set the impact parameter, $b = 0.724 \pm 0.020$, and the angle projected on the sky between the star's spin axis and the normal to the orbital plane, $\lambda = -27^\circ$, indicating a prograde orbit with a moderate inclination.

Kepler 8b RM effect measurement (Jenkins et al. 2010)

What can be measured with transits ?

Orbital Period → distance from star

Orbit is (nearly) edge on → planet mass with radial velocity, if possible

Transit Depth → planet radius

planet density
internal structure

Transit Depth as a function of lambda → atmosphere

Transit timing variations → dynamical masses

RM effect → alignment between stellar spin vector and planet orbit

Transit surveys are great for measuring statistical occurrence of planets
how many Earth-like planets ? Around which stars ?

Requirements on optical system / camera

Ultra high precision photometry (less than 1%, ideally few ppm)
→ space is preferable
→ large aperture to reduce scintillation and photon noise
→ very good scheme to remove systematics, calibrate errors
→ high stability

For surveys aimed at detecting new planets: Large field of view + good sensitivity + good time coverage
→ground-based: multiple units geographically spread to increase time coverage
→ high etendue (product of collecting area x field of view)

Examples will be covered in next lecture:

ground-based surveys
Kepler optical design
TESS