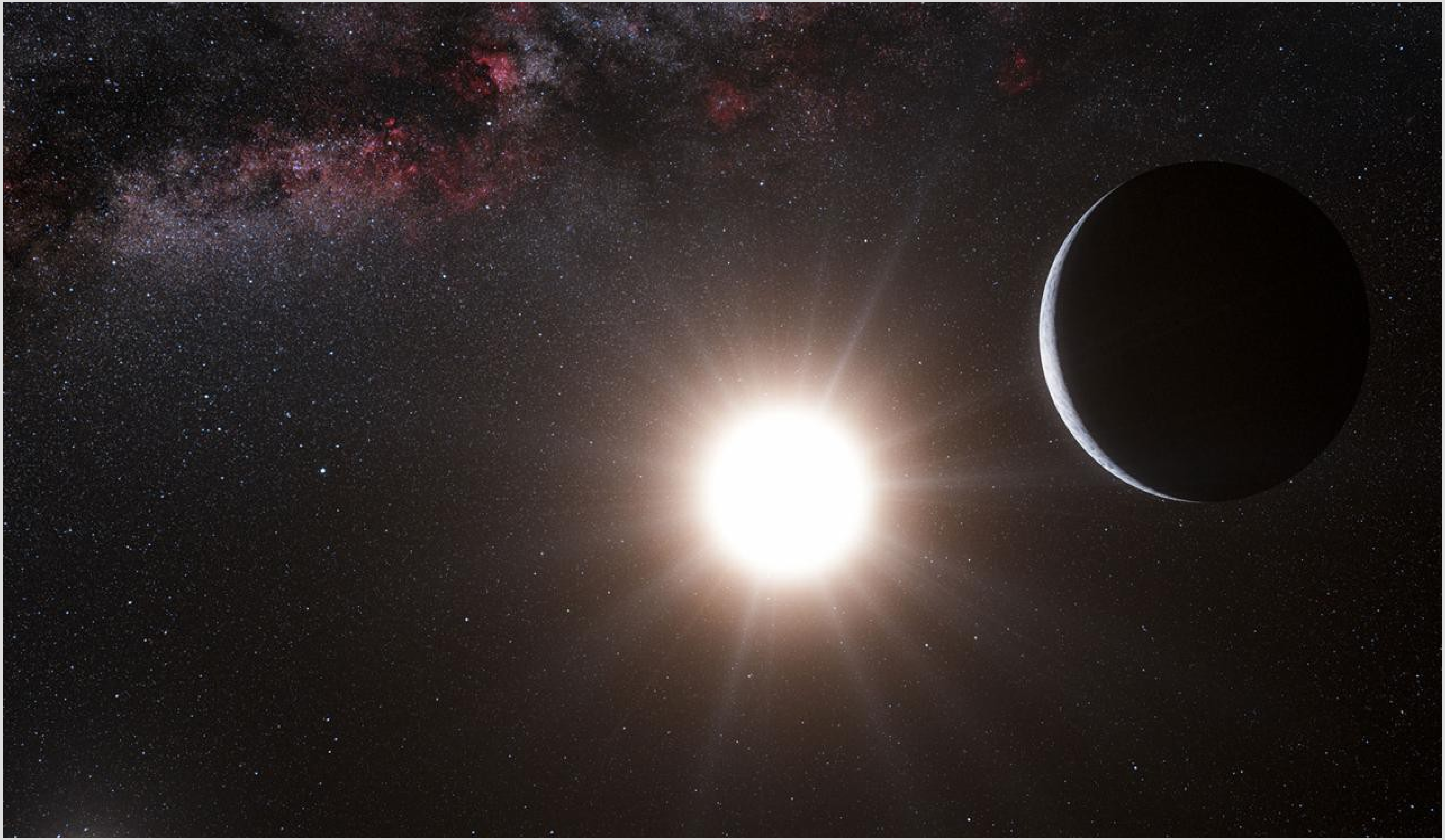
ASTR 407/507

Exoplanetary Detection Techniques



Exoplanet detection

- This is a subject that had a long history, full of 'what turned out to be incorrect' claims.
- It is technically very challenging to detect planets around other stars.

Three main techniques currently

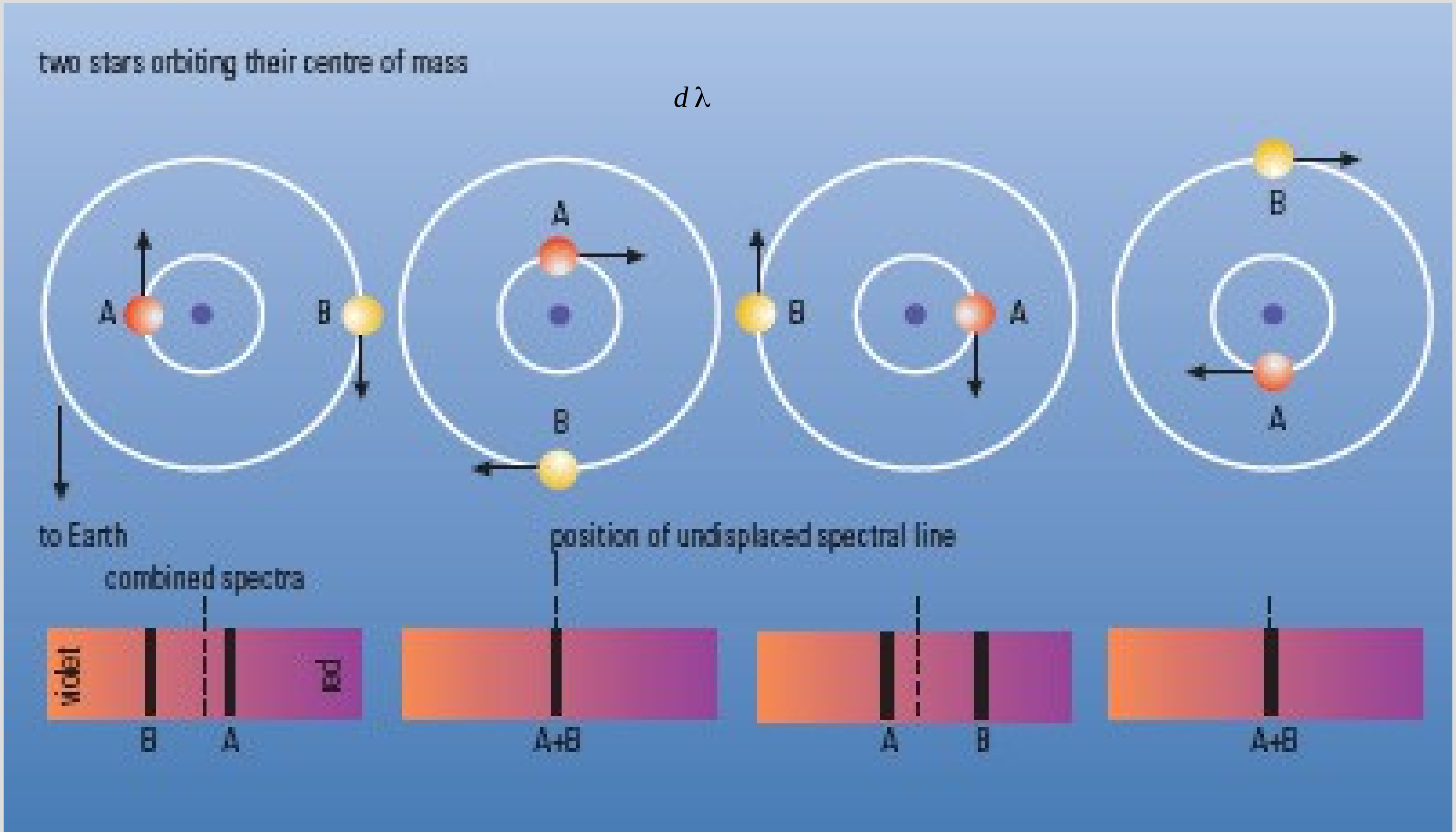
1) Radial velocity (spectral) method on parent star
2) Transit method
3) Direct imaging method

There are also some known via other techniques

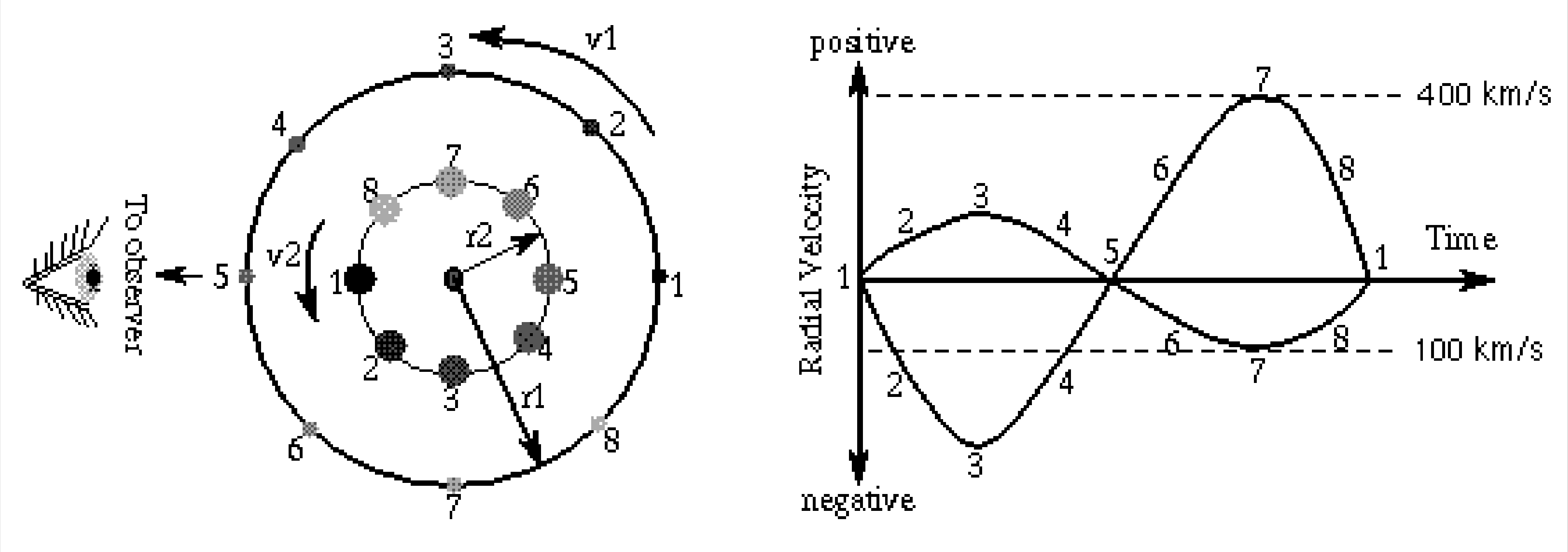
4) Pulsar timing
5) Gravitational microlensing

Absorption Lines in Stellar Binaries

- Unresolved stellar binary star systems are studied by using the shifting stellar lines in a spectrum. One gets the radial component of v by observing $\Delta\lambda$
- Doppler effect gives $v = c\,(\Delta\lambda/\lambda)$, v is velocity *away*

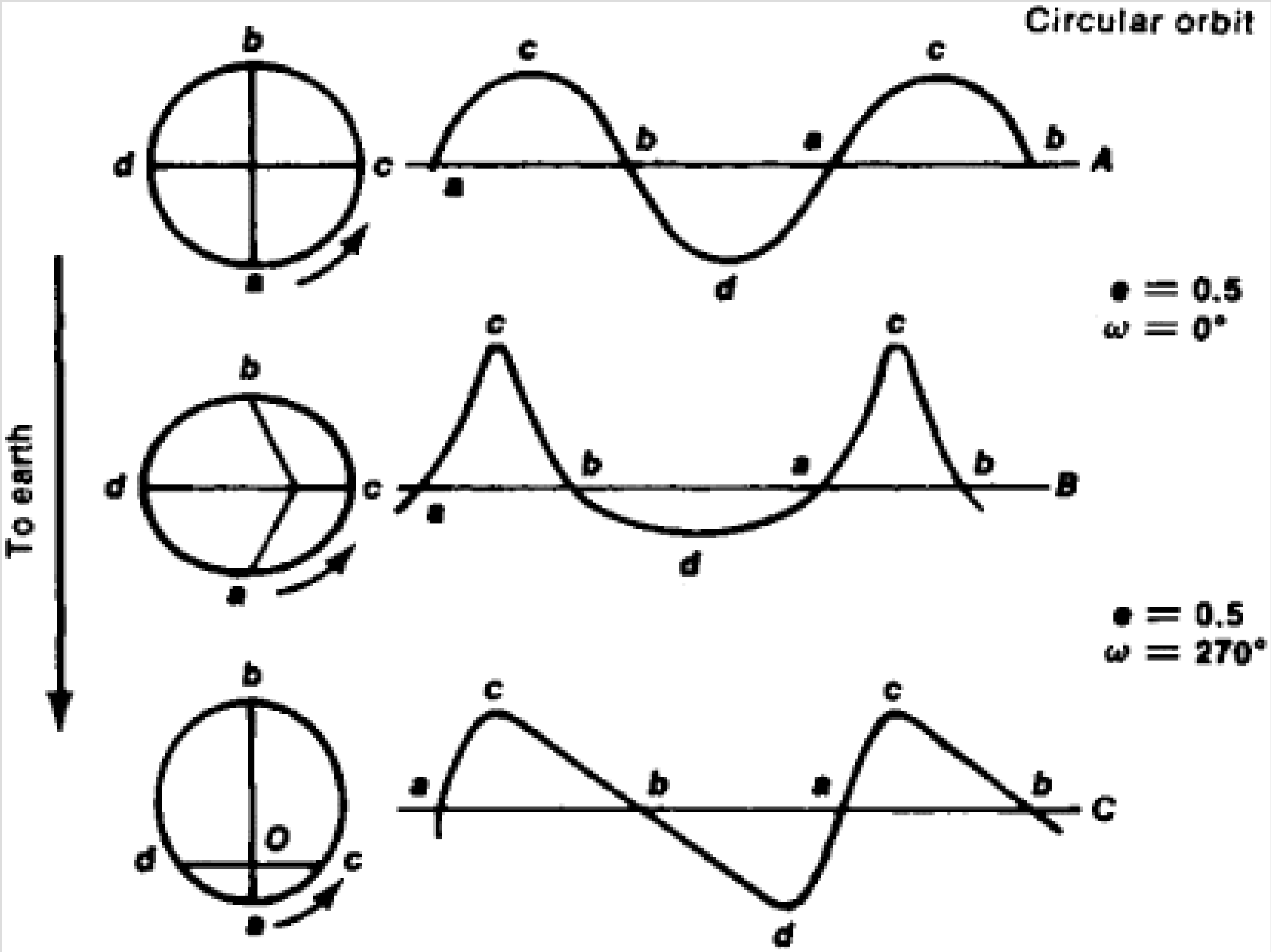


The Doppler effect allows the measurement of the radial velocity



- Here an example where you see spectral lines from both stars
- They usually have different amplitudes (b/c different masses)
- Note radial *v* in this plot above is relative to that of the center of mass
  - (that is, the long term average of both signals)
  - (center of mass could be moving towards or away from observer)

The shape of the RV curve is a sine wave for circular orbits, but distorts for elliptical orbits



Allows measurement of orbital '*e*' (same for both stars) and orientation of periastron relative to the observer's line of sight

Exoplanetary RV detection

- Unlike a stellar binary, the exoplanet member of the 'binary' emits negligible light.
- Thus the entire system's signal consists of a spectrum with a single absorption line that varies.
- The repeating nature of this pattern tells you something is tugging on the star.
- The repeating time signal of stellar wavelength then lets one measure the radial component of the stellar velocity (K, see next slide)

Star's velocity amplitude K due to the presence of unseen planet

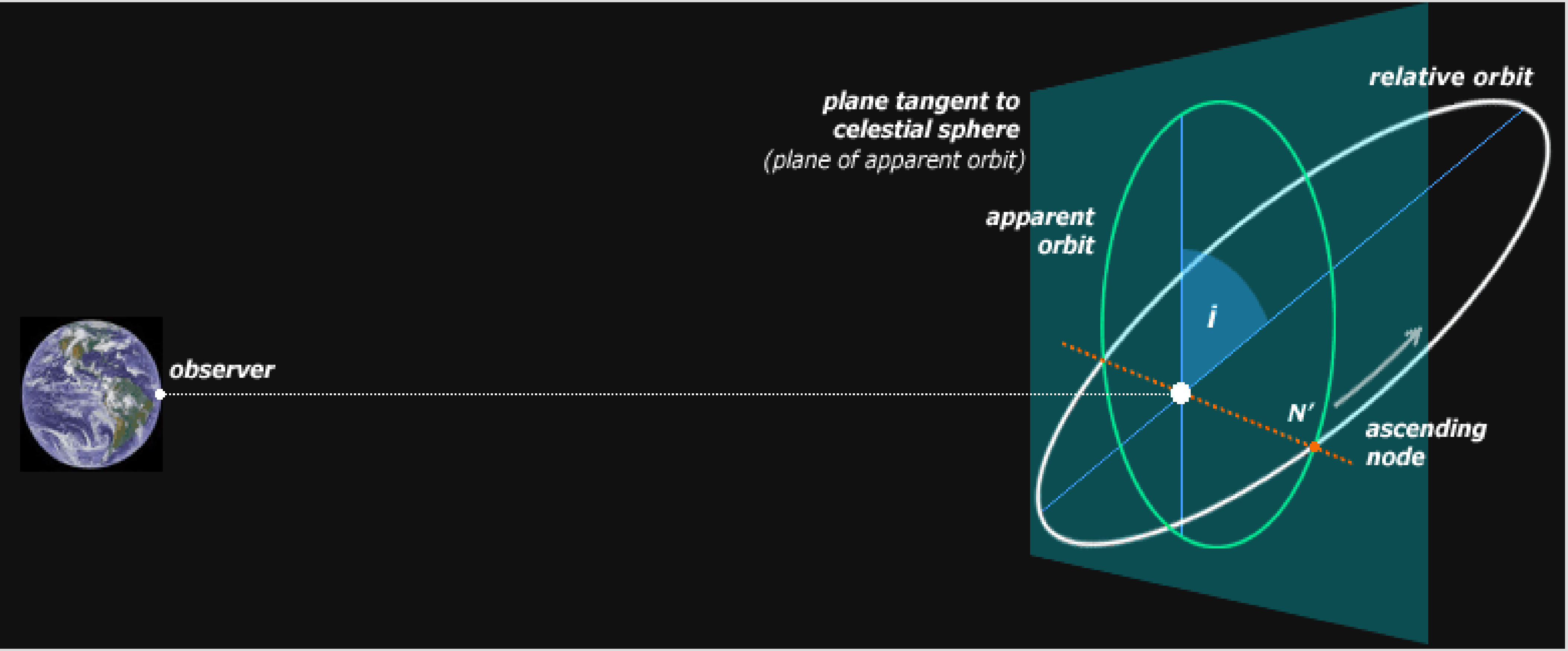
$$K = \left(\frac{2\pi G}{P_{\rm orb}}\right)^{1/3} \frac{M_{\rm p} \sin i}{(M_\star + M_{\rm p})^{2/3}} \frac{1}{\sqrt{1-e^2}}.$$

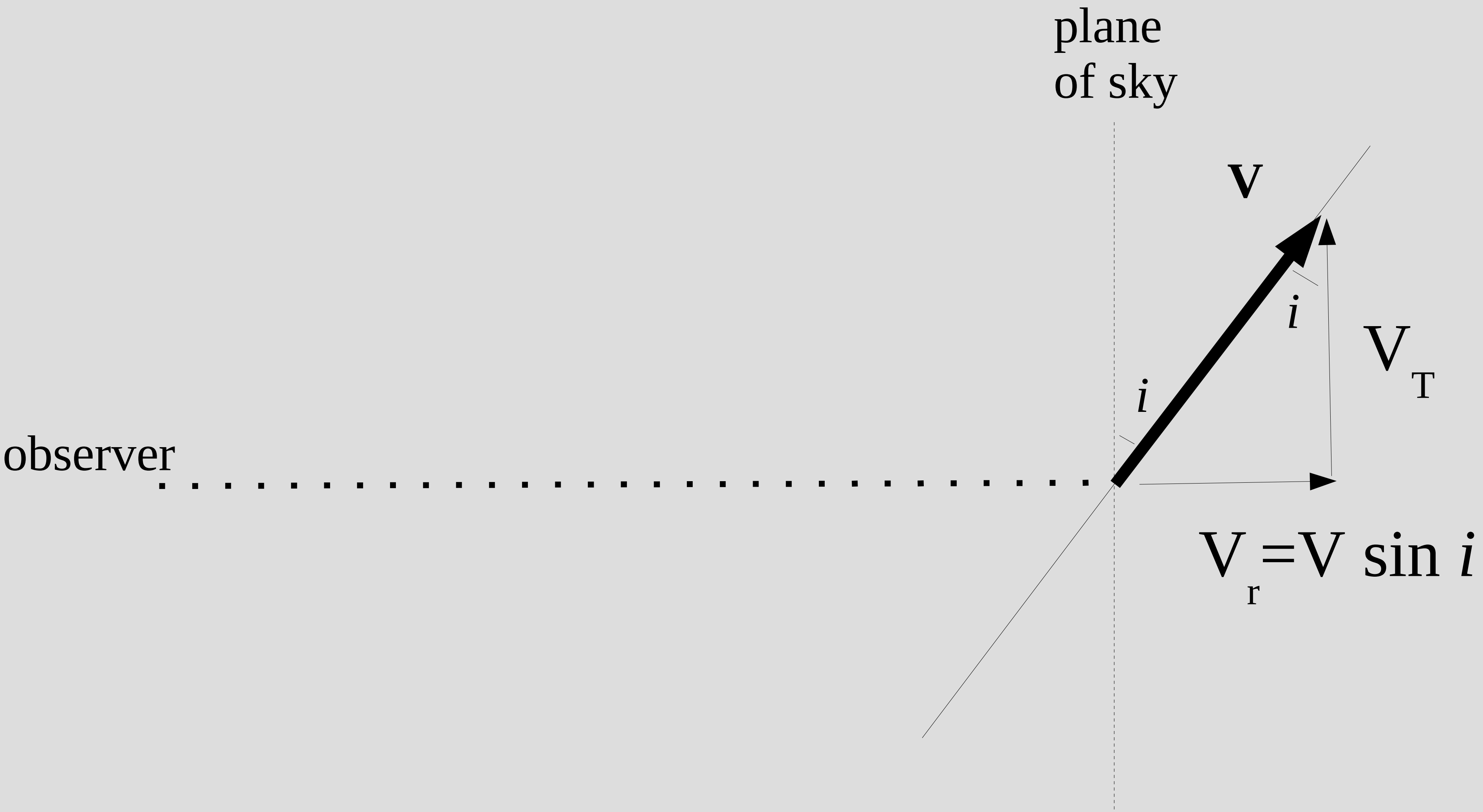
If the planet's mass is small, then measurement of stellar velocity amplitude K, orbital period, and eccentricity (from shape of RV curve) gives, if the star's mass can be estimated from its spectrum: $M_p \sin i$

There is an uncertainty due to the unknown projection effect to the radial direction (line of sight to the system).

The effect of inclination

- The Doppler effect only sees the component of radial velocity of 'away or towards' the observer
- So, i measures inclination angle of the orbital plane from the 'plane of the sky'. An edge-on orbit has i=90 degrees.
- If i=0, all motion in plane of sky, and Doppler effect goes away





only MEASURE V sin *i* *of star*

Can derive : Kepler's 3rd law for velocity components:

This side measurable

$$(m_A + m_B)\sin^3 i \;=\; \boxed{\frac{P}{2\pi G}\left(V_A \sin i + V_B \sin i\right)^3}$$

For exoplanet B, $m_B \ll m_A$ and $V_A \ll V_B$ (center of mass relations)

Mass ambiguity

- So one only measures $(m_A + m_B) \sin^3 i = f$
- So the total system mass is

$$m_A + m_B = \frac{f}{\sin^3 i} \geqslant f$$

- And thus one obtains a *lower limit* to the mass, needed to produce the observed radial velocity
- If the system is *more inclined*, then to maintain the same observed radial velocities, it has to have *more mass,* so that the speeds rise to keep the line-of-sight radial component the same

Stellar radial velocity method

- Assume there is a Jupiter-mass planet (10^{-3} the mass of the Sun) in an orbit around a 1-solar mass star, with orbital a=4 au.
- Assume we see the planet's orbit 'edge on' (i=90 deg)
- The star+planet is like a binary star, but we only see the light from the star.

(a) How fast is the planet moving (km/s) in its orbit?

(b) How fast is the *star* moving (km/s) in its orbit around the center of mass?

Stellar radial velocity method

- Assume there is a Jupiter-mass planet (10^{-3} the mass of the Sun) in an orbit around a 1-solar mass star, with orbital a=4 au.
- V_p = (30 km/s)/sqrt(a) and $V_s = (m_p/m_S)\ V_p$
- **Planet speed~15 km/s, star ~15 m/s**

(c) What will be the period of the star's Doppler shift pattern for its spectral lines?

(d) What will be the wavelength shift for a visible line (say with 'rest' wavelength of 500 nm)?

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(d) What will be the wavelength shift for a visible line?

$$\Delta\lambda = \lambda\frac{v}{c} = (500\,nm)\frac{15\,m/s}{3\,x\,10^{8}\,m/s} = 25\,x\,10^{-6}\,nm \sim 3\,x\,10^{-5}\,nm$$

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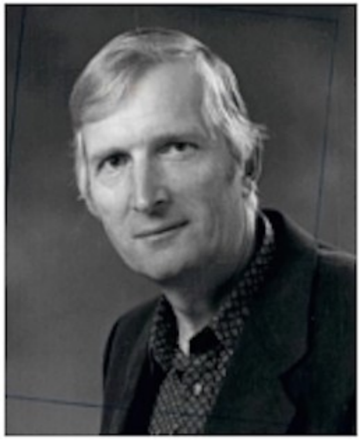
Well THAT looks hard...

Campbell & Walker: Hydrogen Fluoride cell:



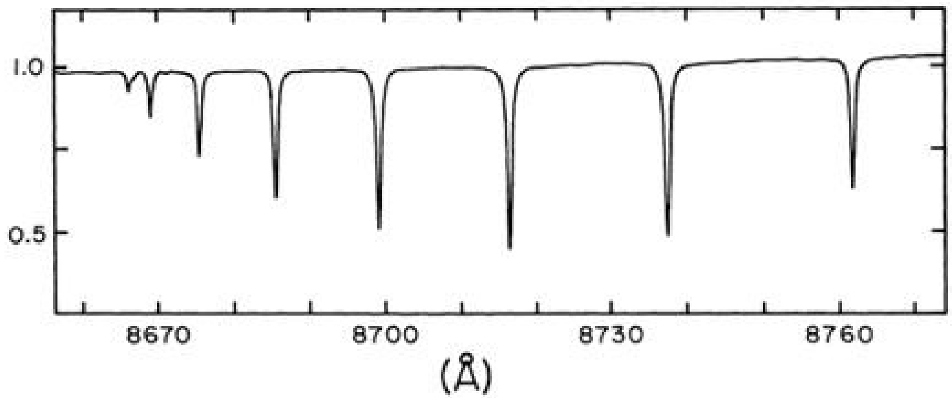


FIG. 1—Absorption spectrum of hydrogen fluoride 3–0 band *R* branch.

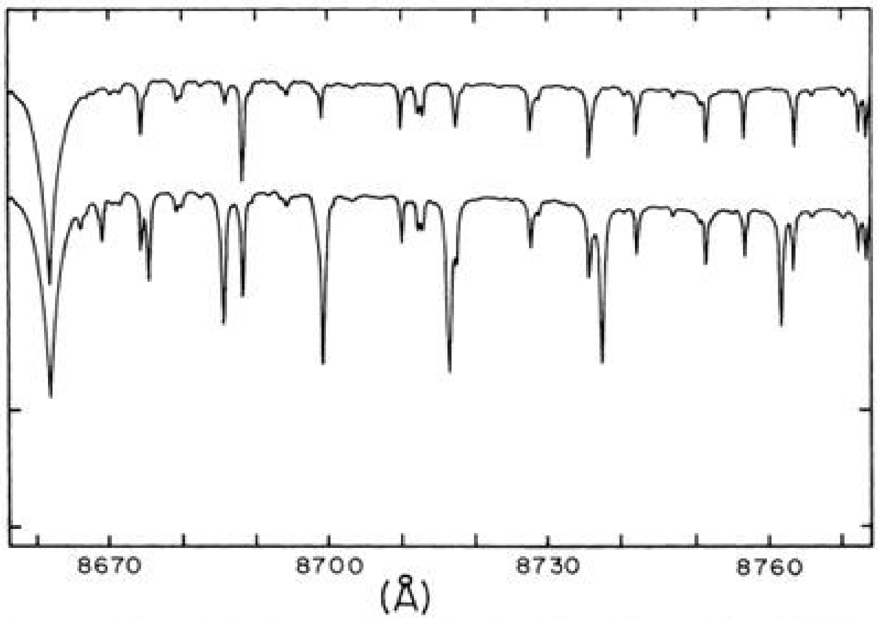


FIG. 3—Solar spectra with (*lower*) and without (*upper*) the hydrogen fluoride lines. The strong line at left is Ca II λ8662.

Geo Physics and Astronomy

- Use a gas cell (HF) in the beam to serve as a reference to finely measur the wavelength centers of *many* spectral lines

Demonstrated radial velocity precision of 13 m s^{-1} in 1980!

Signal of jovian planets around other stars

Expected signal was thus :

- Stellar radial velocity ~10 m/s
- Need to, by luck or by doing a large number of target stars, find one where planetary orbit is roughly edge on
- Planetary periods (and thus period of stellar RV cycle) of roughly 1-2 decades
  - This is going to take a while. People started doing big observational campaigns in the early 1990s, expecting to work a long time before seeing the slow variations...

The BIG surprise

article

Nature **378**, 355 - 359 (23 November 1995); doi:10.1038/378355a0

A Jupiter-mass companion to a solar-type star

MICHEL MAYOR & DIDIER QUELOZ

Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.

Nature paper announcing the discovery of a planet orbiting 51 Pegasi

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Orbital period is ~4 days !

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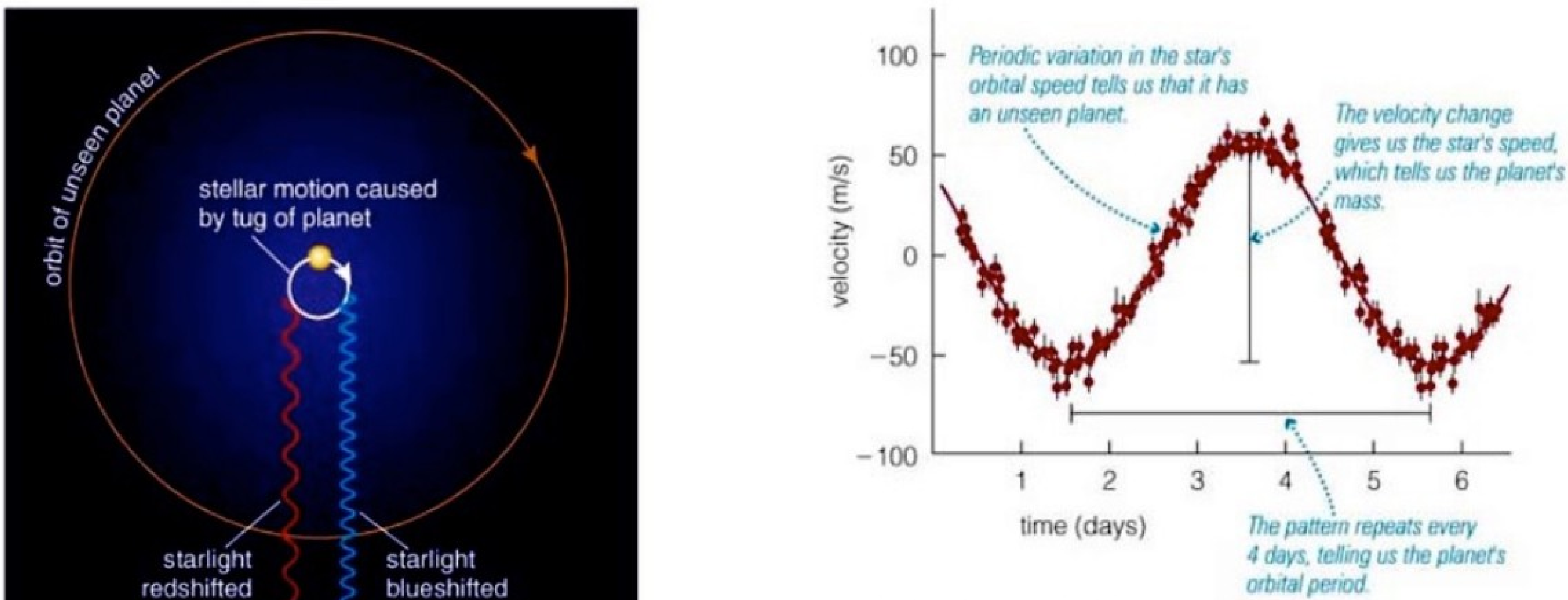
Discovery of the first exoplanets

Radial Velocity signal



a Doppler shifts allow us to detect the slight motion of a star caused by an orbiting planet.

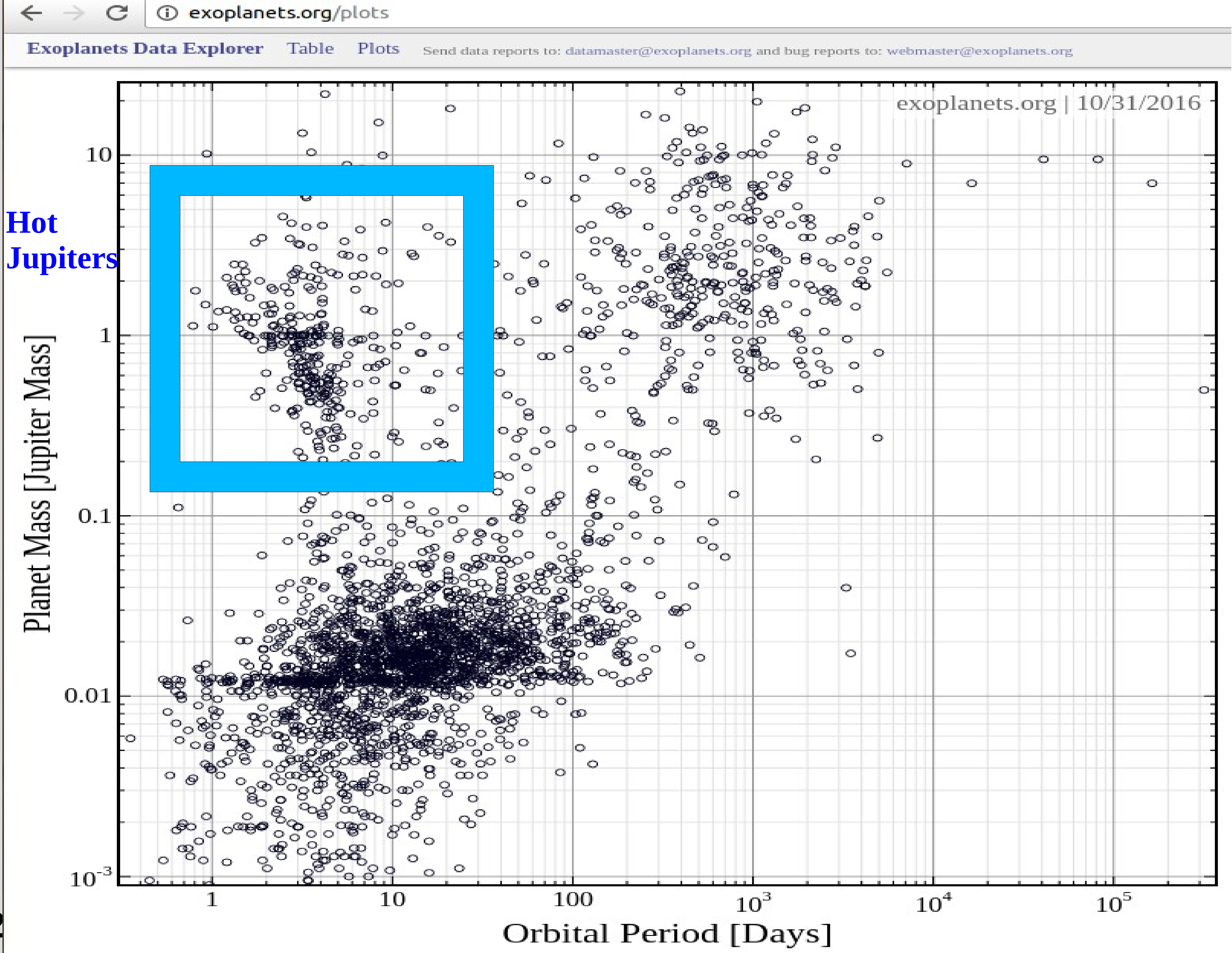
b A periodic Doppler shift in the spectrum of the star 51 Pegasi shows the presence of a large planet with an orbital period of about 4 days. Dots are actual data points; bars through dots represent measurement uncertainty.

Data showing the periodic Doppler shift produced by the planetary companion to the star 51 Pegasi.

The orbital period of the planet is only ~ 4 days! So, it must be orbiting very close to the star (by Kepler's third law).

This was a *big* surprise

- There are jovian mass planets in orbits around stars, but closer than the distance at which Mercury orbits the Sun
- These objects are called 'hot Jupiters' because their equilibrium temperatures will be high.
- Many (but not all) astronomers believe that these planets formed further out away from the star (past the snow line) but then migrated in to their current position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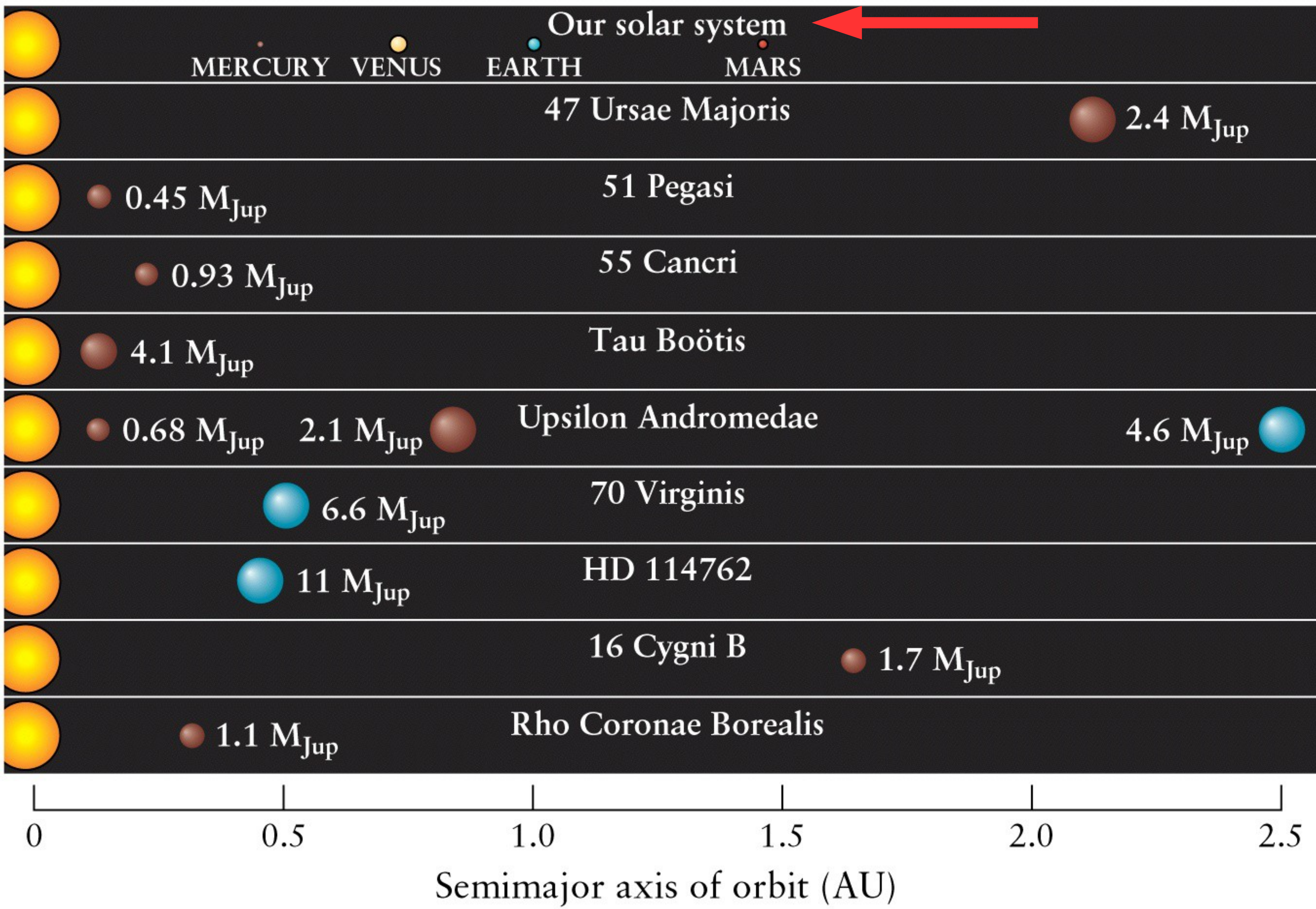
Hot Jupiters
Planet Mass [Jupiter Mass]
10
1
0.1
0.01
10^{-3}
1
10
100
10^3
10^4
10^5
Orbital Period [Days]

The first few RV systems

Whoa! 0.5-5 Jupiter-mass planets only 0.1 – 2.0 AU from their star.



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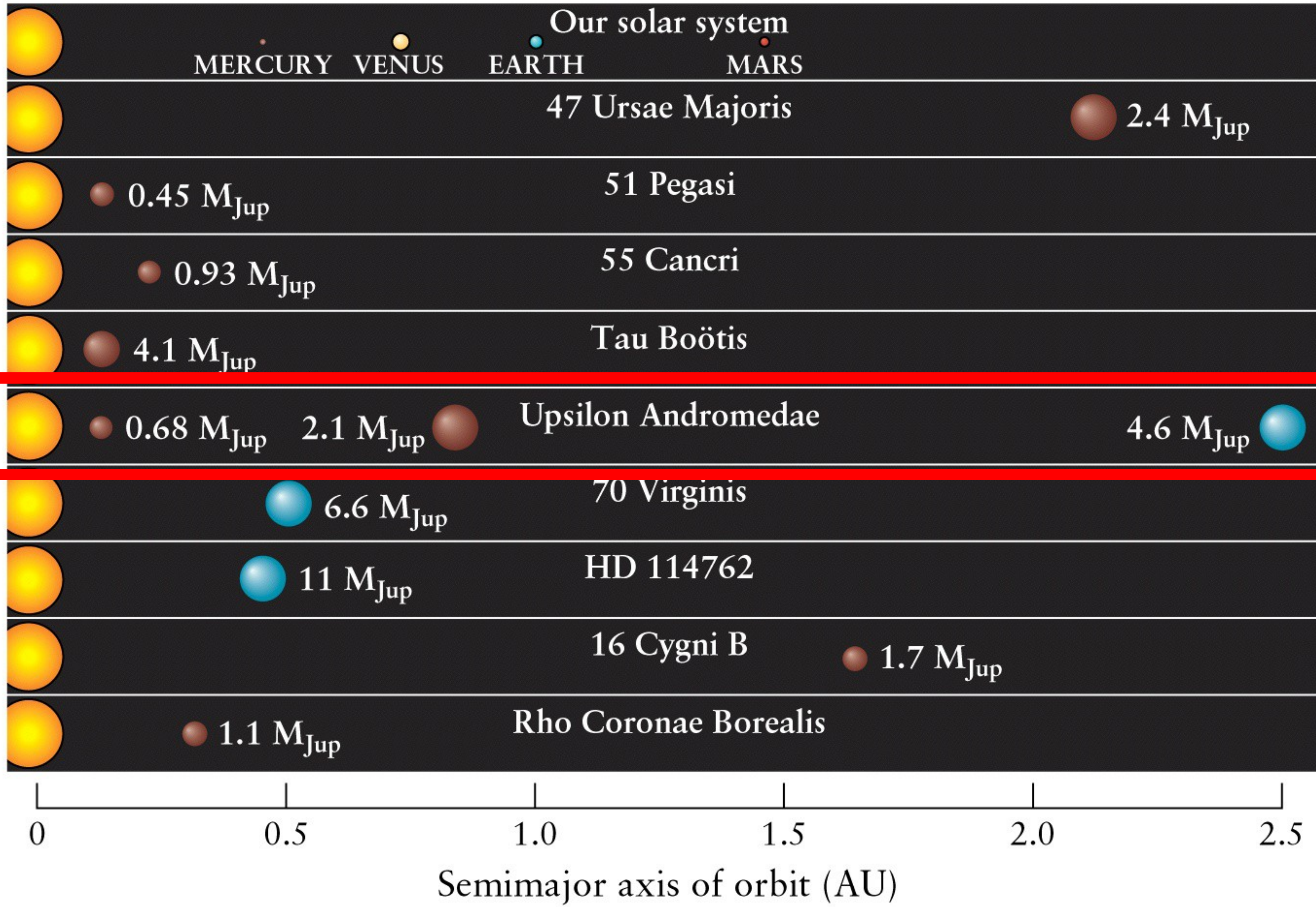

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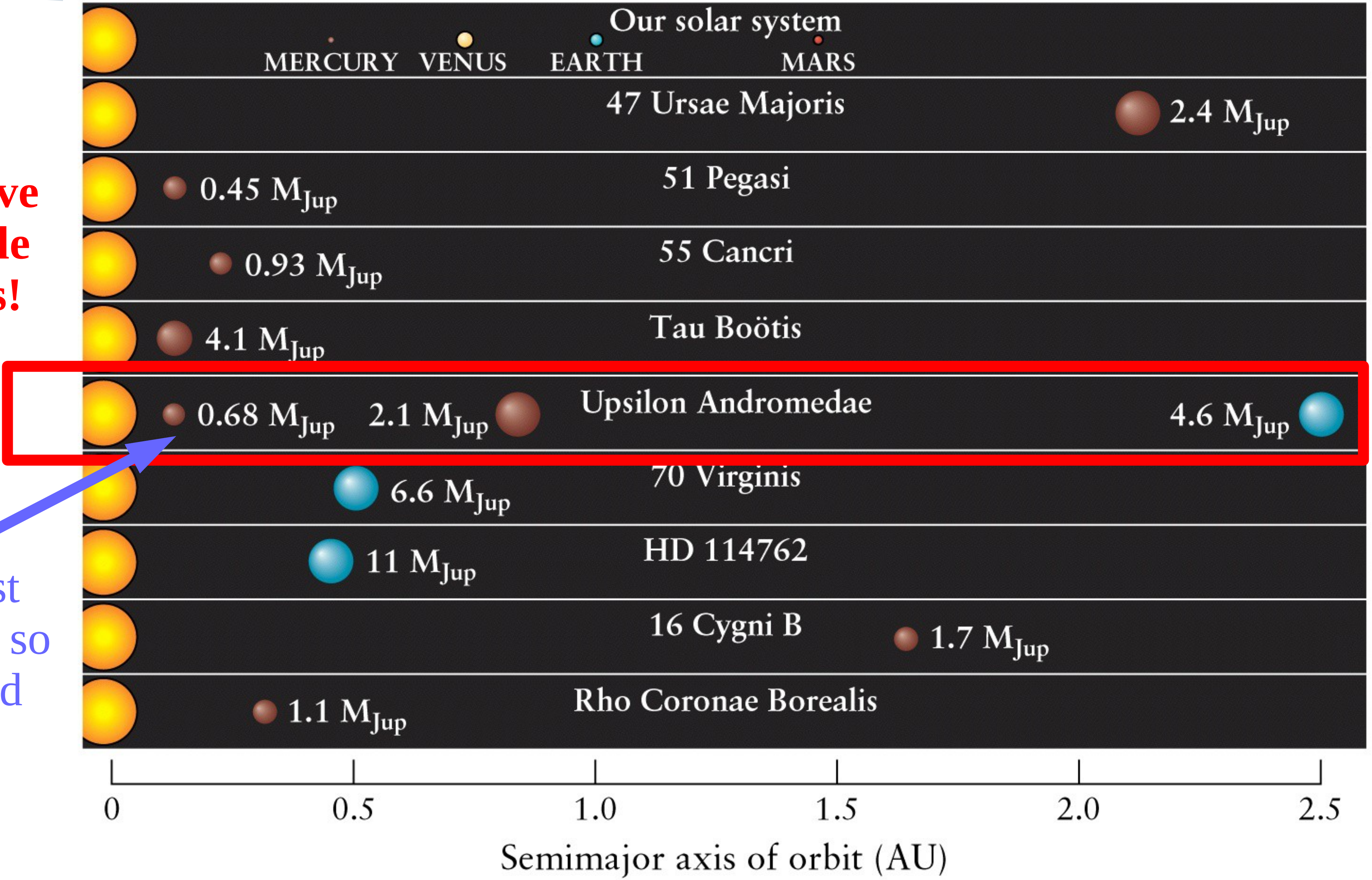
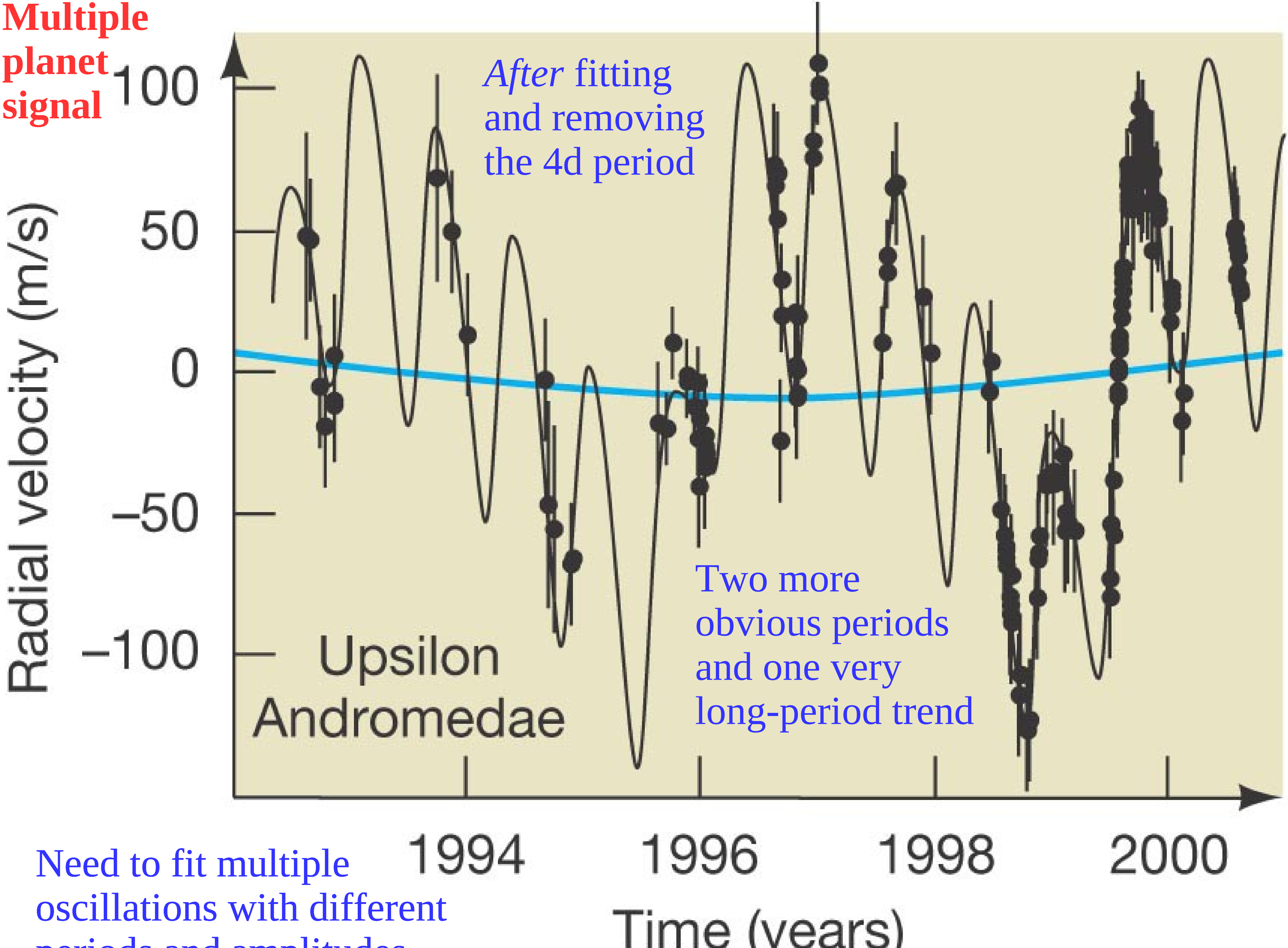


Shortest period, so detected first

Multiple planet signal



Need to fit multiple oscillations with different periods and amplitudes

Directly imaging planets

- Why doesn't one just take a picture??

- Perhaps it is angular separation. Ground based telescopes have trouble separating object if they are closer in angular separation than ~0.5”
  – Suppose one was an astronomer on a planet in the Alpha Centauri system, 1.3 pc from the Sun, looking back at the Sun-Jupiter system.
  – What is the angular separation of Jupiter when Jupiter is as far away as possible (in an angular sense) from the Sun? : **About 4”.**

Directly imaging planets

- So, the problem is NOT angular separation, when it comes to looking for planets within ~10 pc from the Sun
- The problem is CONTRAST.
  - One is looking for a faint object near a bright one (the star).
  - Analogy is to see a firefly near a streetlamp; the light of the firefly is easy to see in the dark, but hard when there is lots of nearby light
- There are several techniques used to block or cancel out the light of the star (or at least greatly reduce the scattered light/contamination).

Reflected light

- What is the ratio of reflected optical light from Jupiter to that of the Sun? Take A_jup=0.5, R_jup=70,000 km, a_jup=5.2 au
    - This is a few parts in a billion.

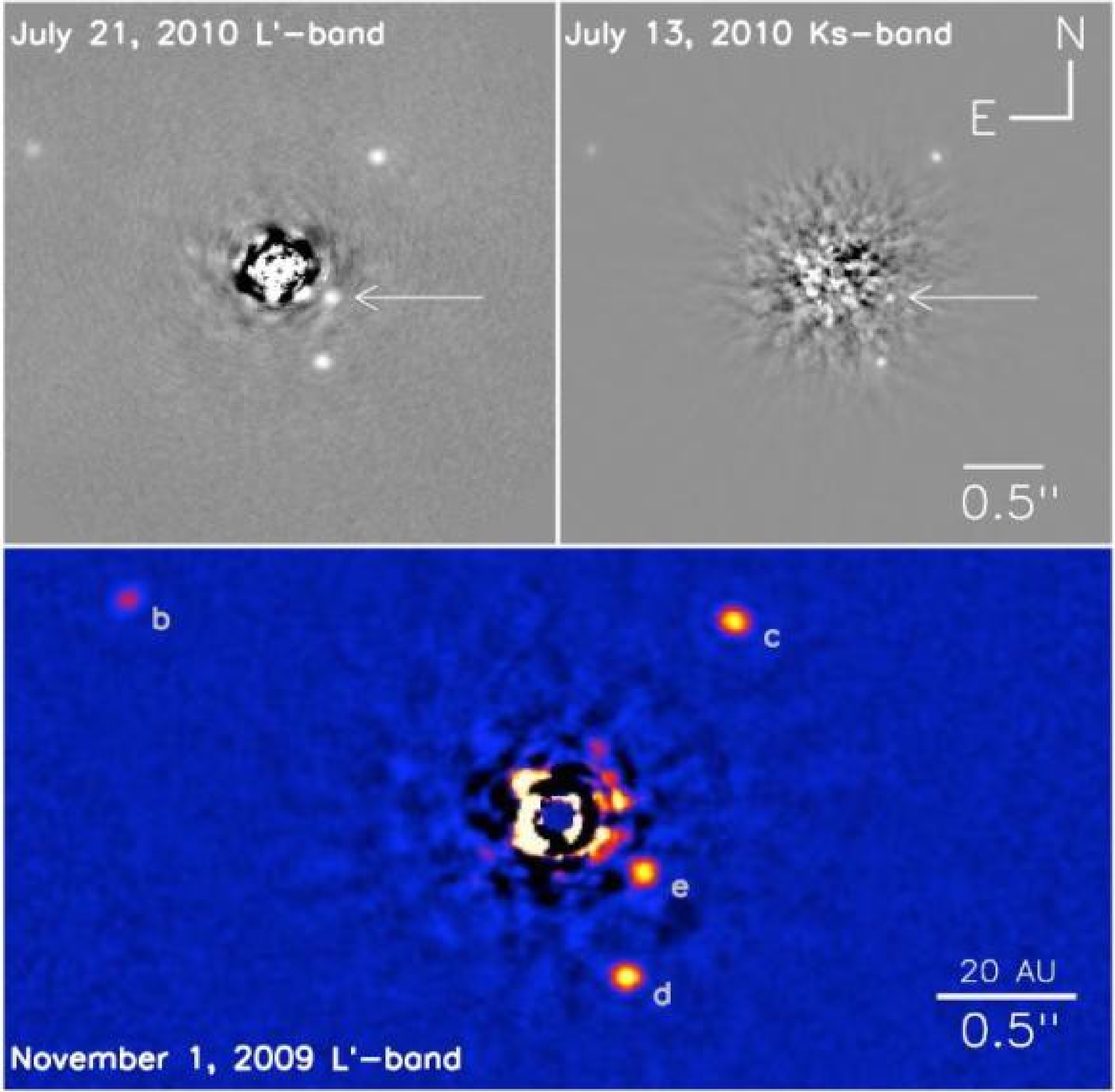
Thermal planetary light

- What about the THERMAL planetary light?
- Turns out contrast is better in the IR, by several orders of magnitude, so most direct imaging projects use the near-infrared atmospheric windows.

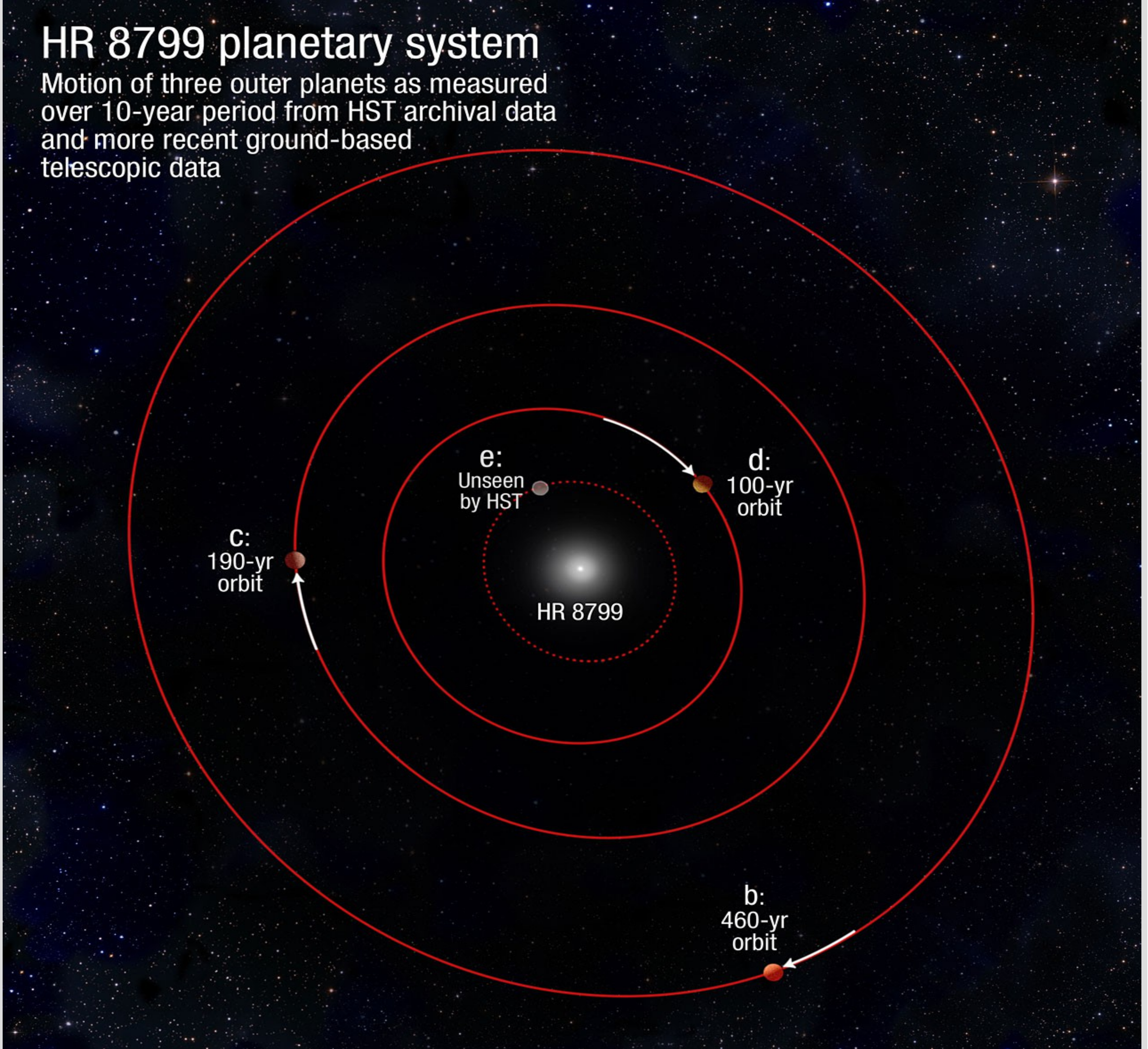
HR 8799

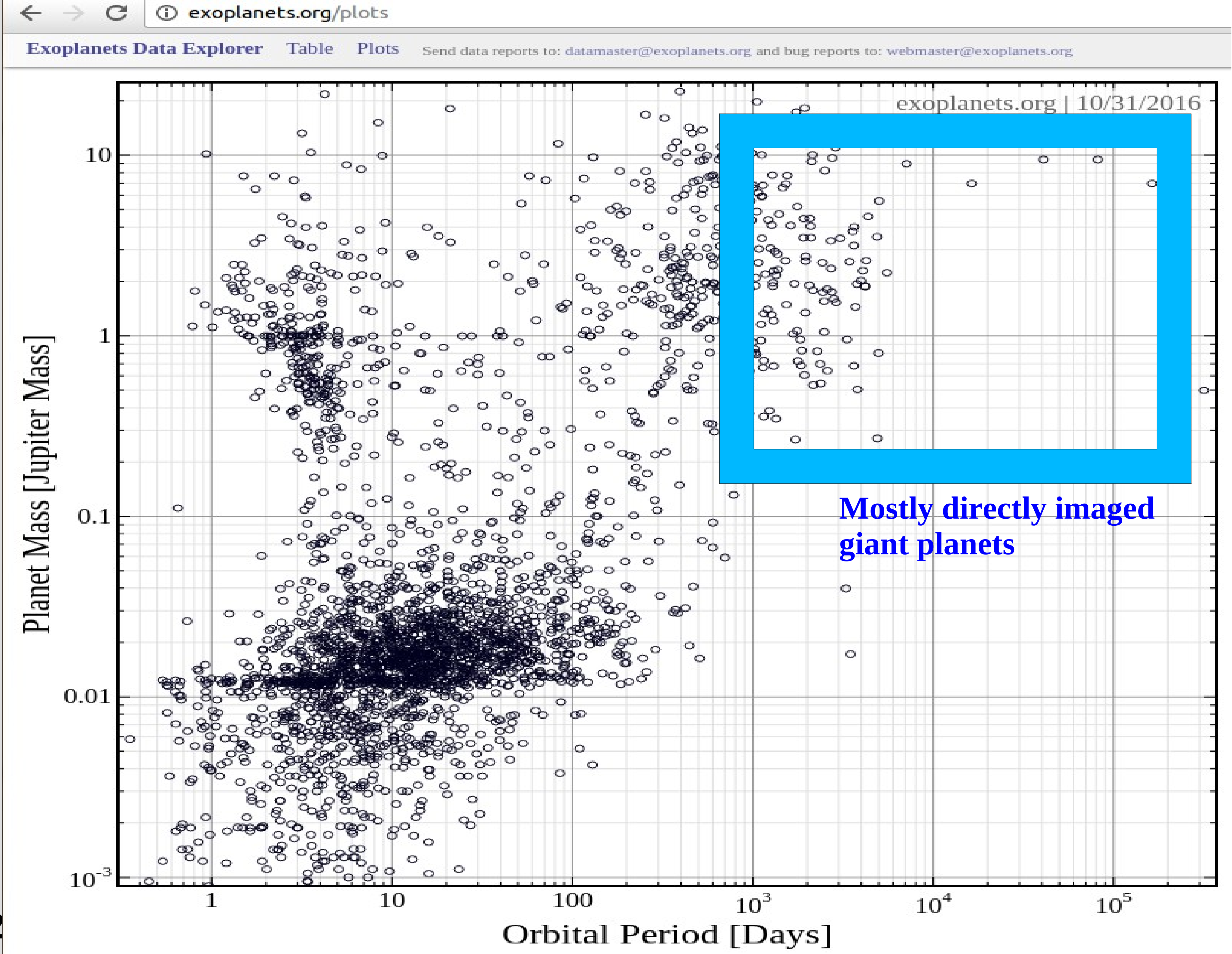
4 planets around a star 40pc away

Imaging is in the near infrared



Note : This image rotated relative to the image shown on the previous slide

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Planet Mass [Jupiter Mass]
10
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0.1
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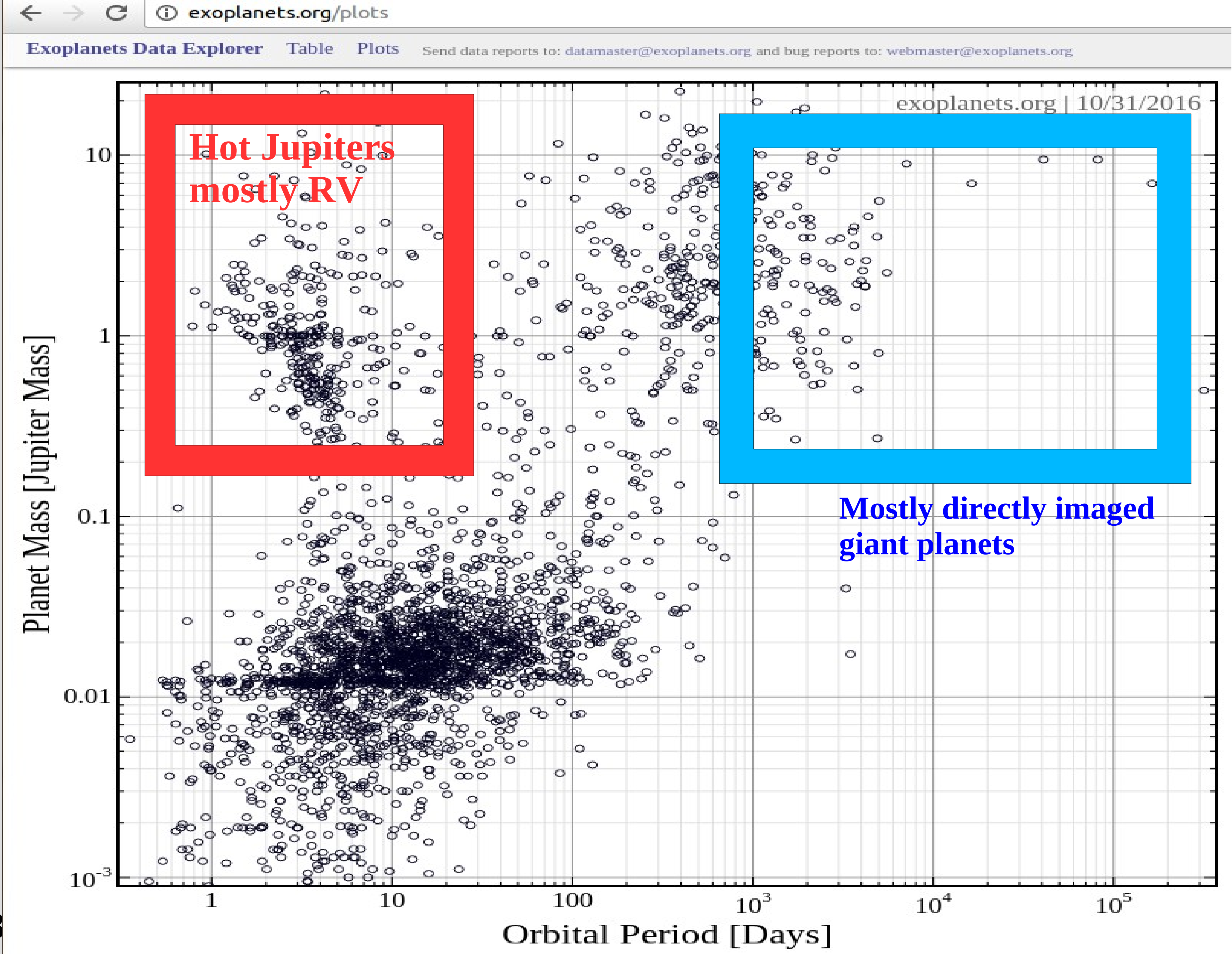
1
10
100
10^3
10^4
10^5
Orbital Period [Days]
Mostly directly imaged giant planets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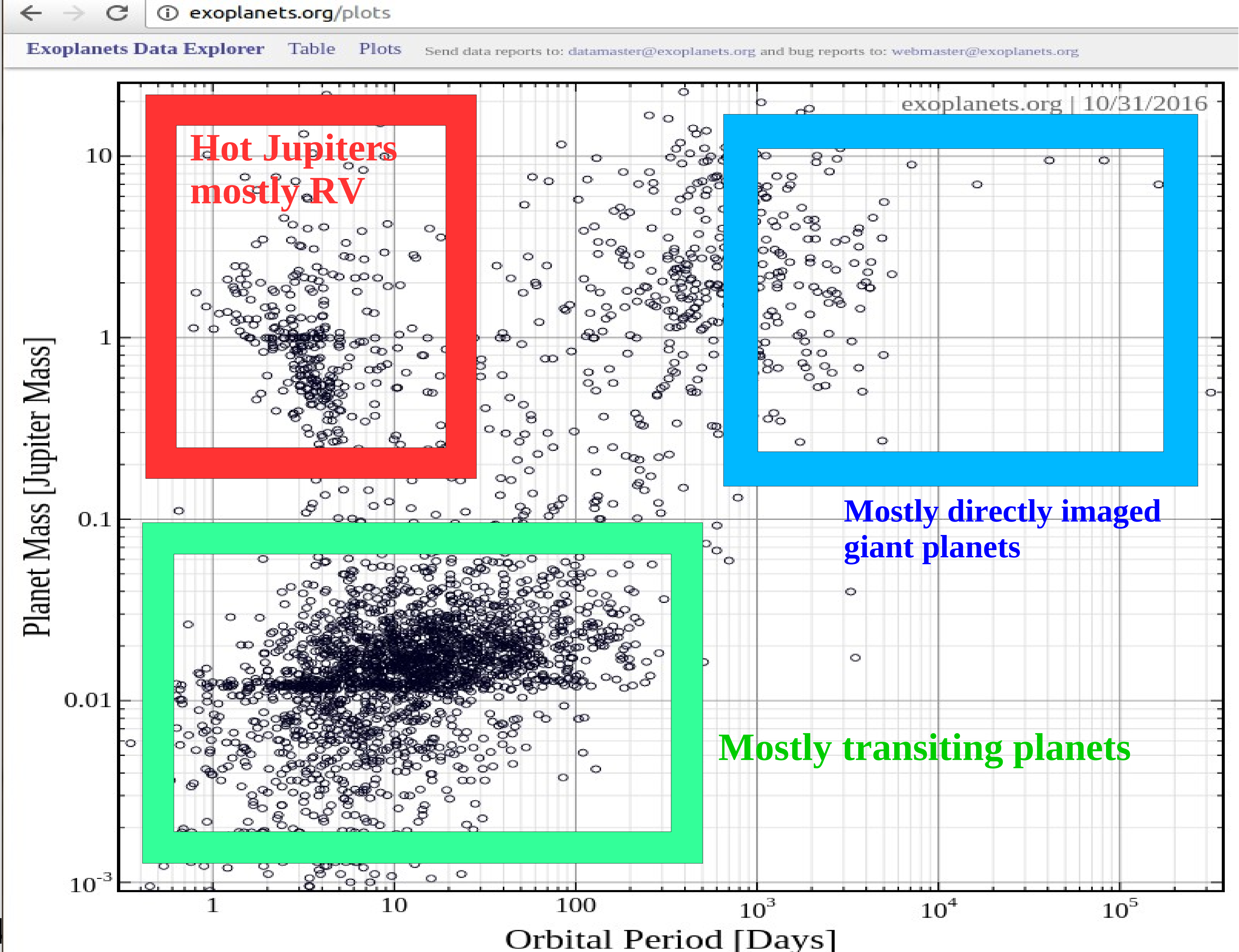
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Hot Jupiters
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10
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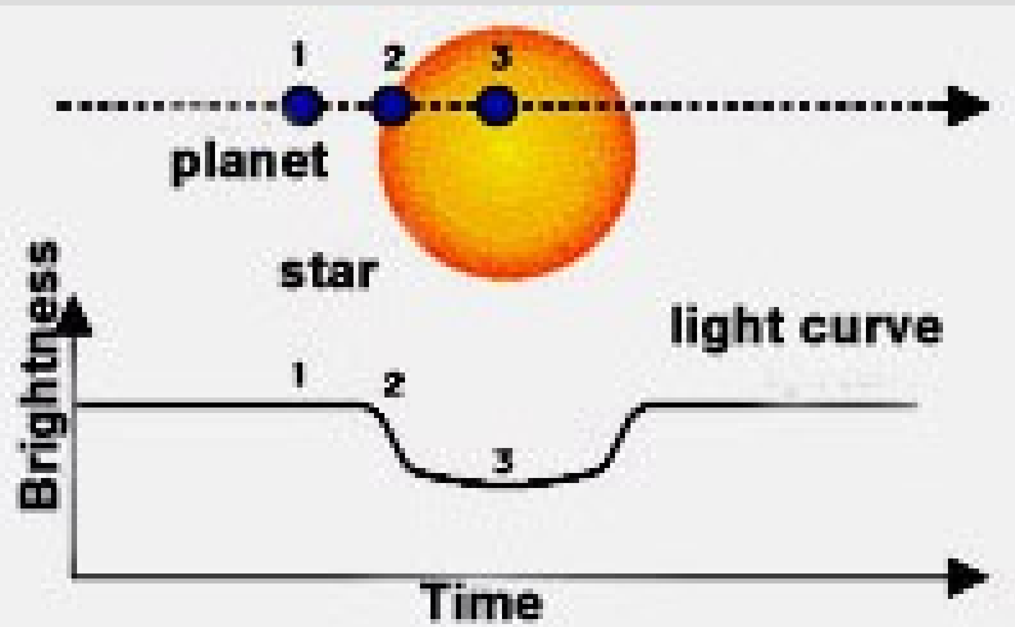
The transit method

- If an edge-on orbit results in the planet crossing in front of the line of sight to the star, it simply blocks the star's light from that portion of the surface.
- The fractional drop in the star's arriving flux/luminosity is just the fraction of the stellar disk blocked

$$\frac{\Delta L}{L} = \frac{\pi R_p^2}{\pi R_s^2} = \left(\frac{R_p}{R_s}\right)^2$$

- Usually the star's spectrum allows a decent estimate of its radius, and thus measured $\Delta L / L$ gives R_p.
- There are complexities related to stars having non-uniform surface brightness (limb darkening)

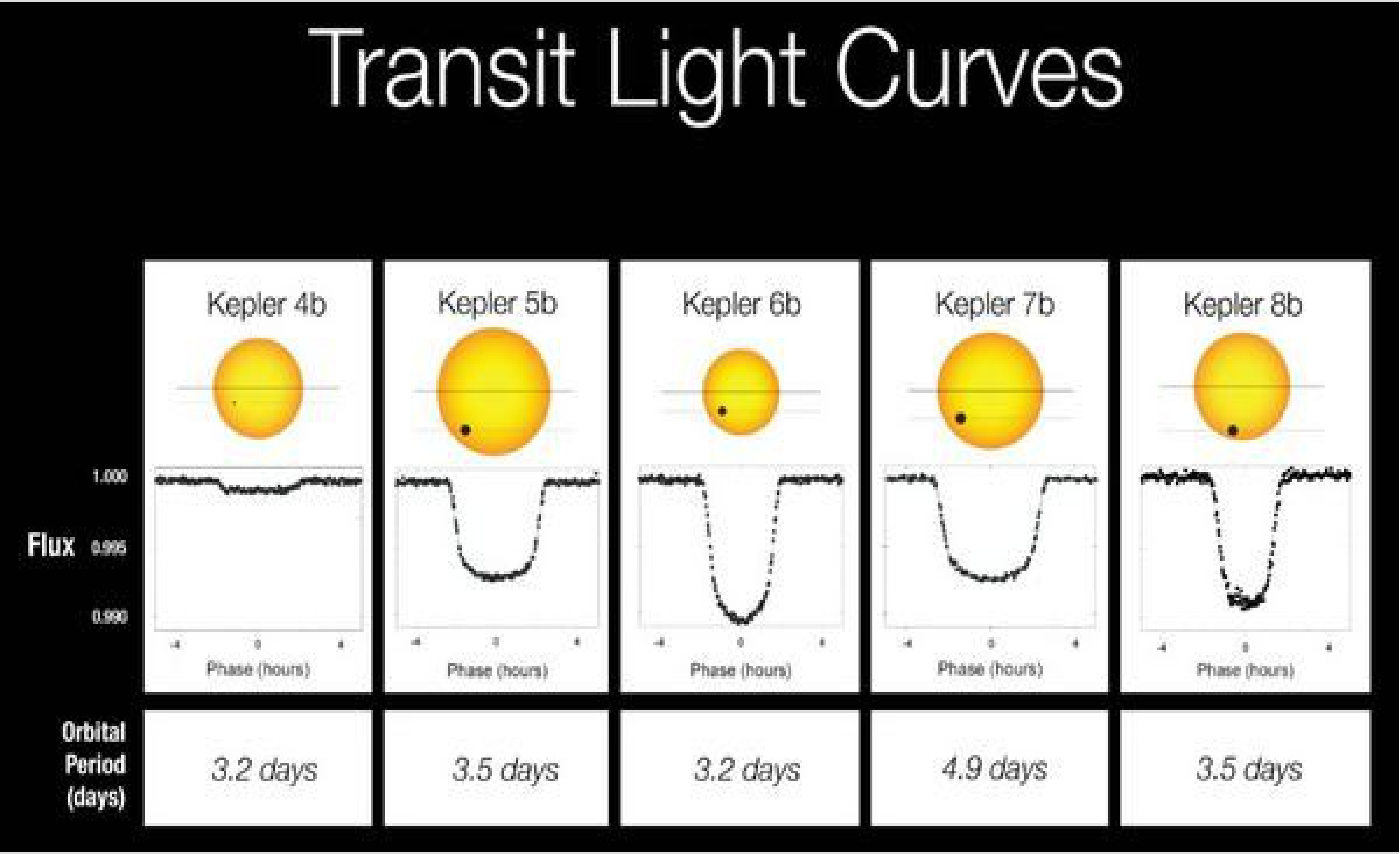
You can see the dimming of the star



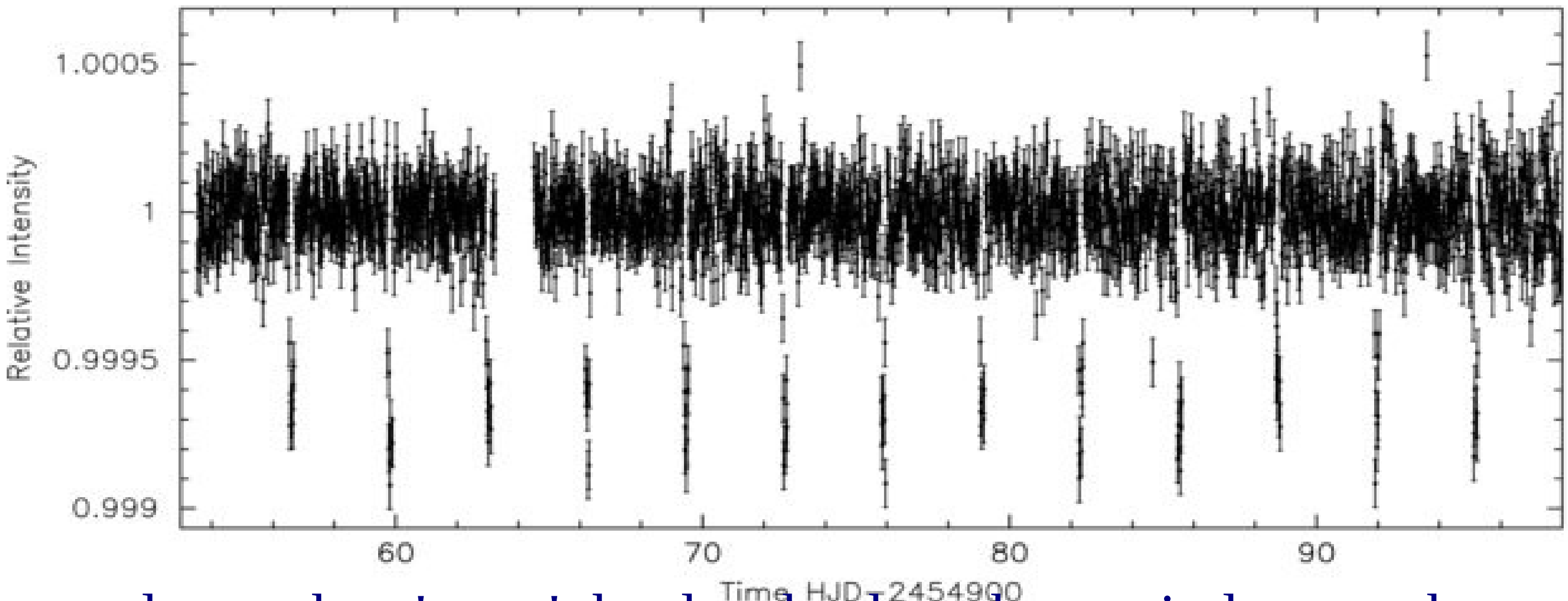
When planet passes in front of the star, it blocks some of the light of the star.

(Just the geometrical fraction of the disk that it blocks, which can be around a percent).

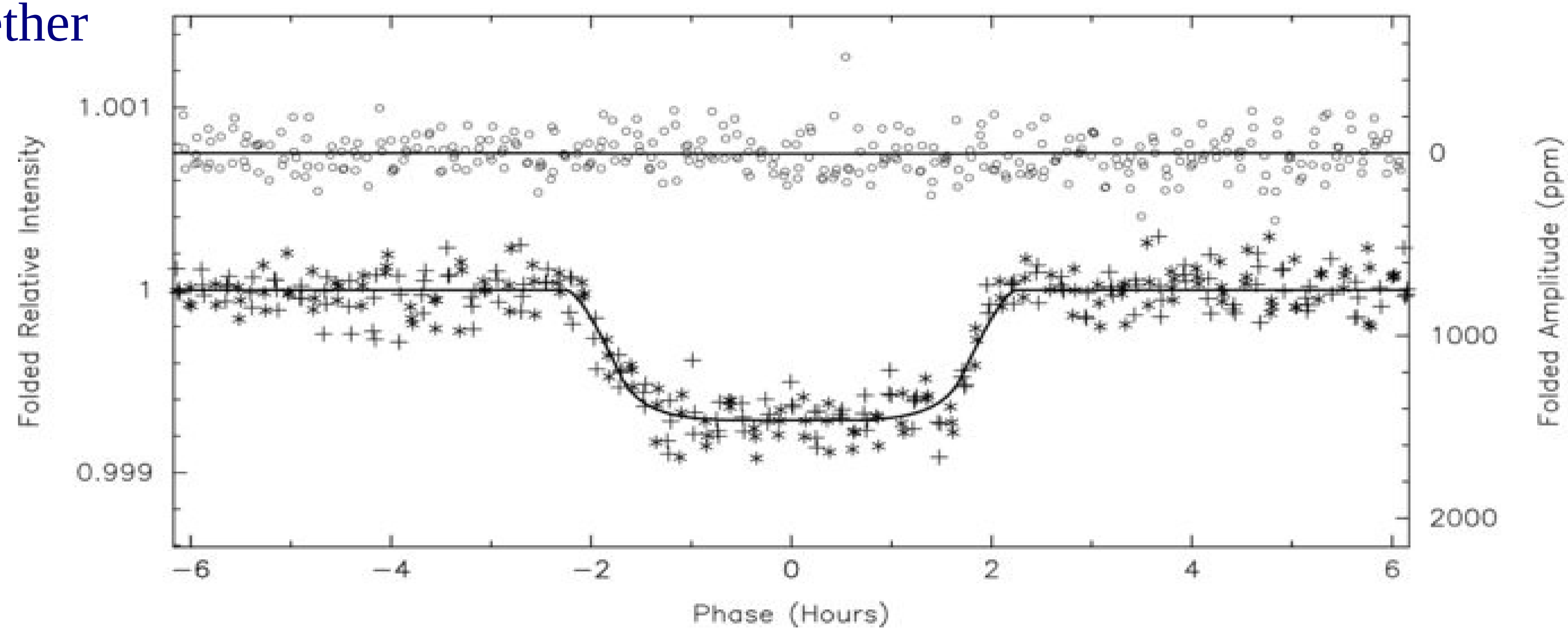
Using points labeled at left, $(L_1 - L_3)/L_1$

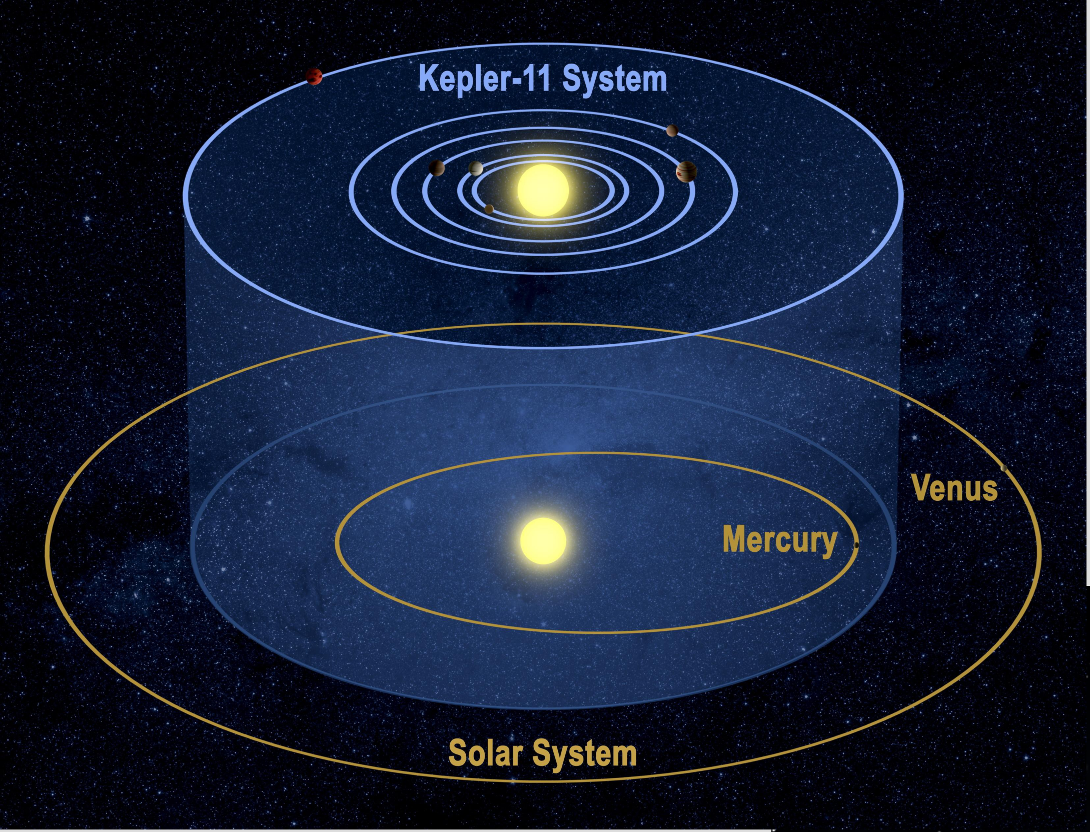

Transit Light Curves
Kepler 4b
Kepler 5b
Kepler 6b
Kepler 7b
Kepler 8b
1.000
Flux
0.995
0.990
Phase (hours)
Orbital Period (days)
3.2 days
3.5 days
3.2 days
4.9 days
3.5 days

If it's a planet, it REPEATS

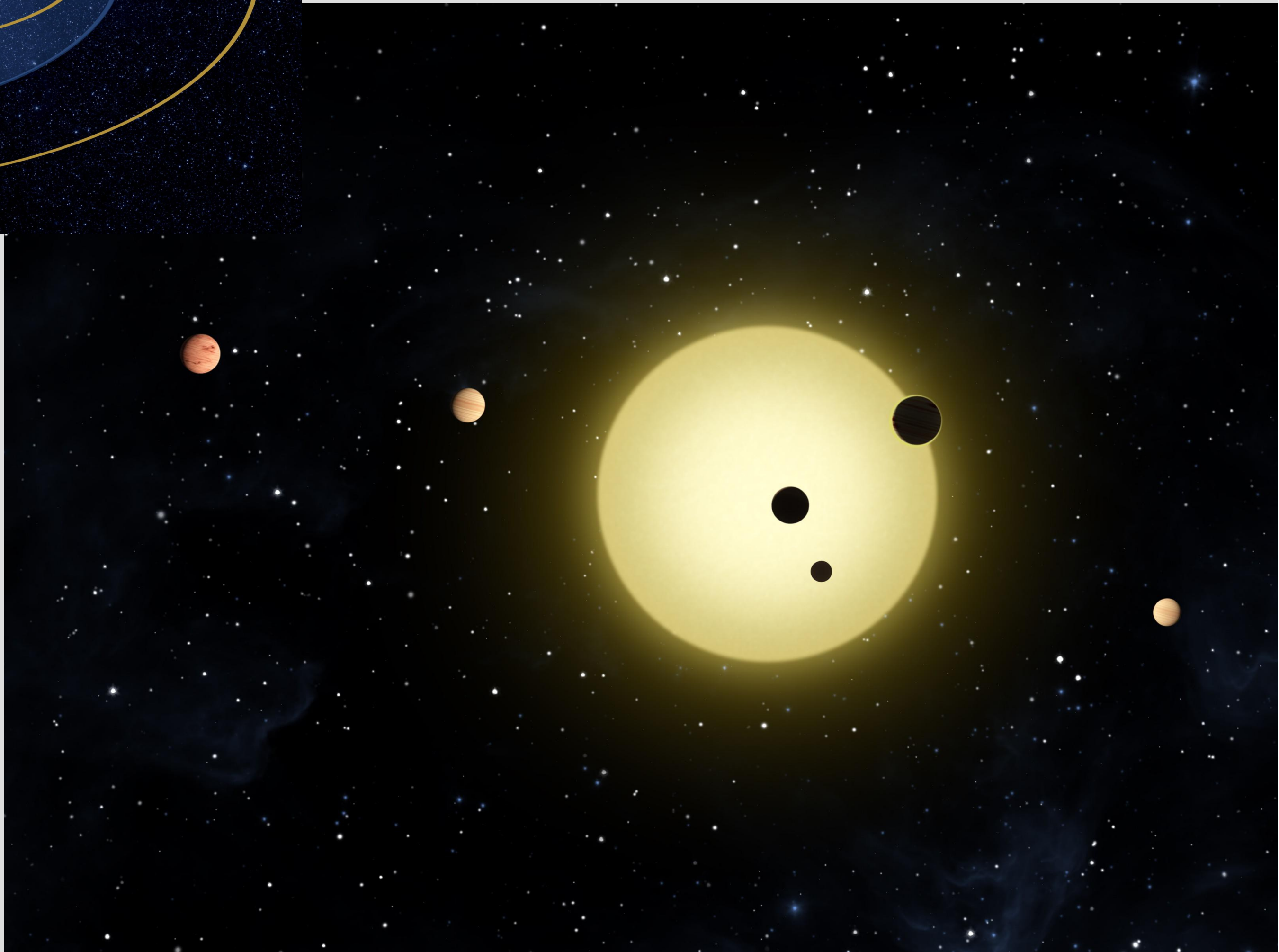


Once detected, you then 'wrap' the data back at that period to put them all together





One specific example: the Kepler-11 system



The Kepler-11 system (6 planets)

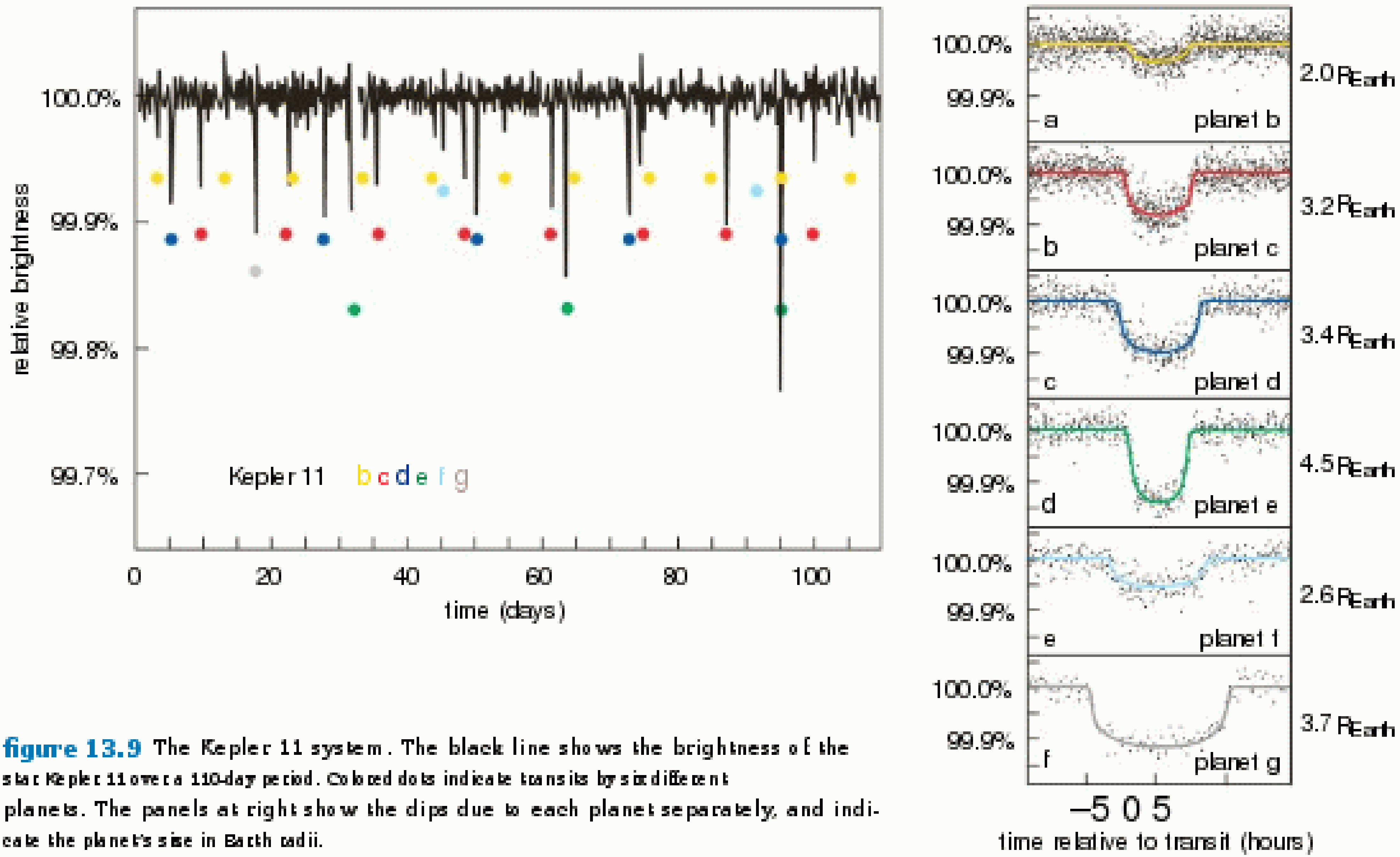
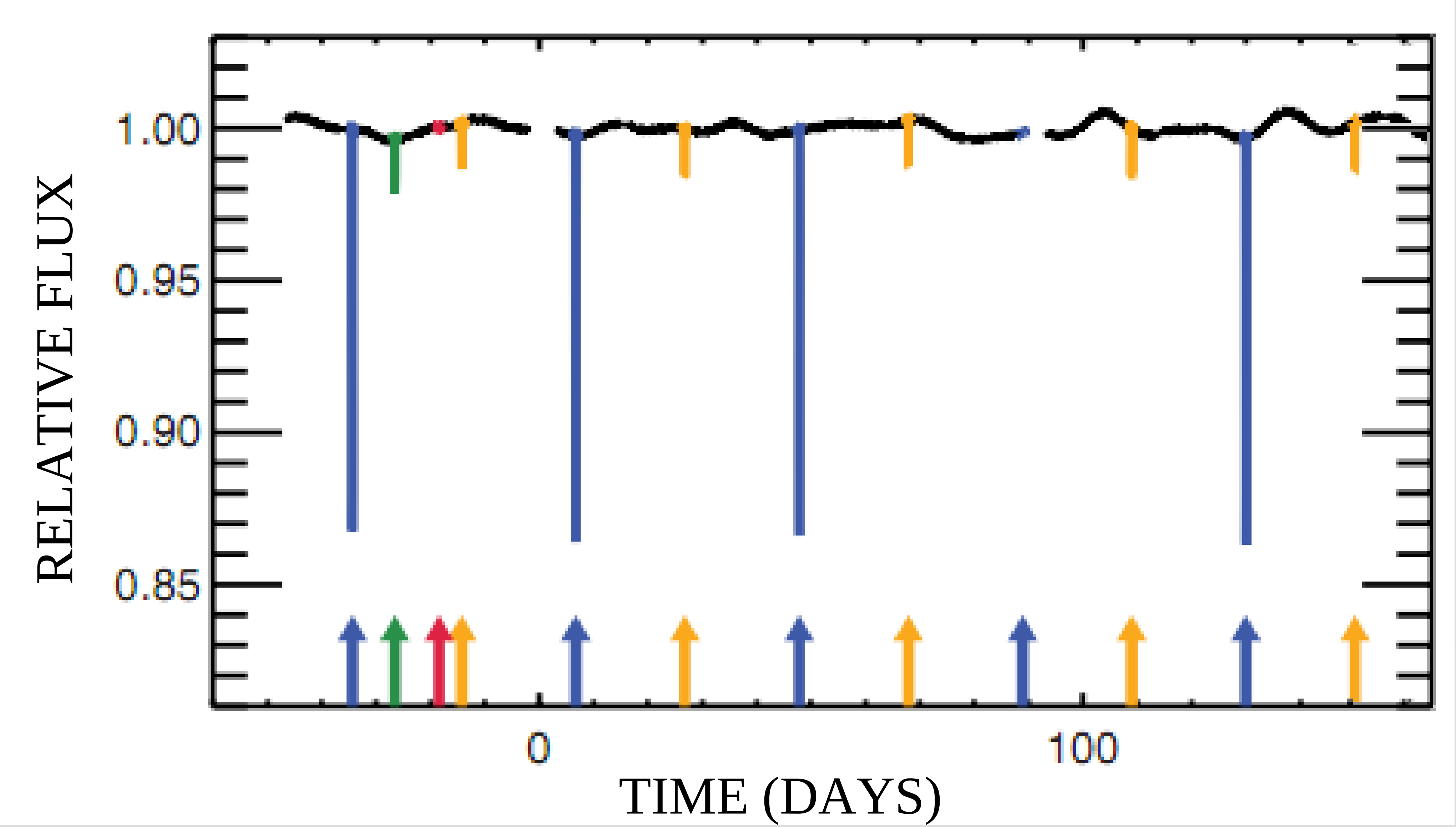


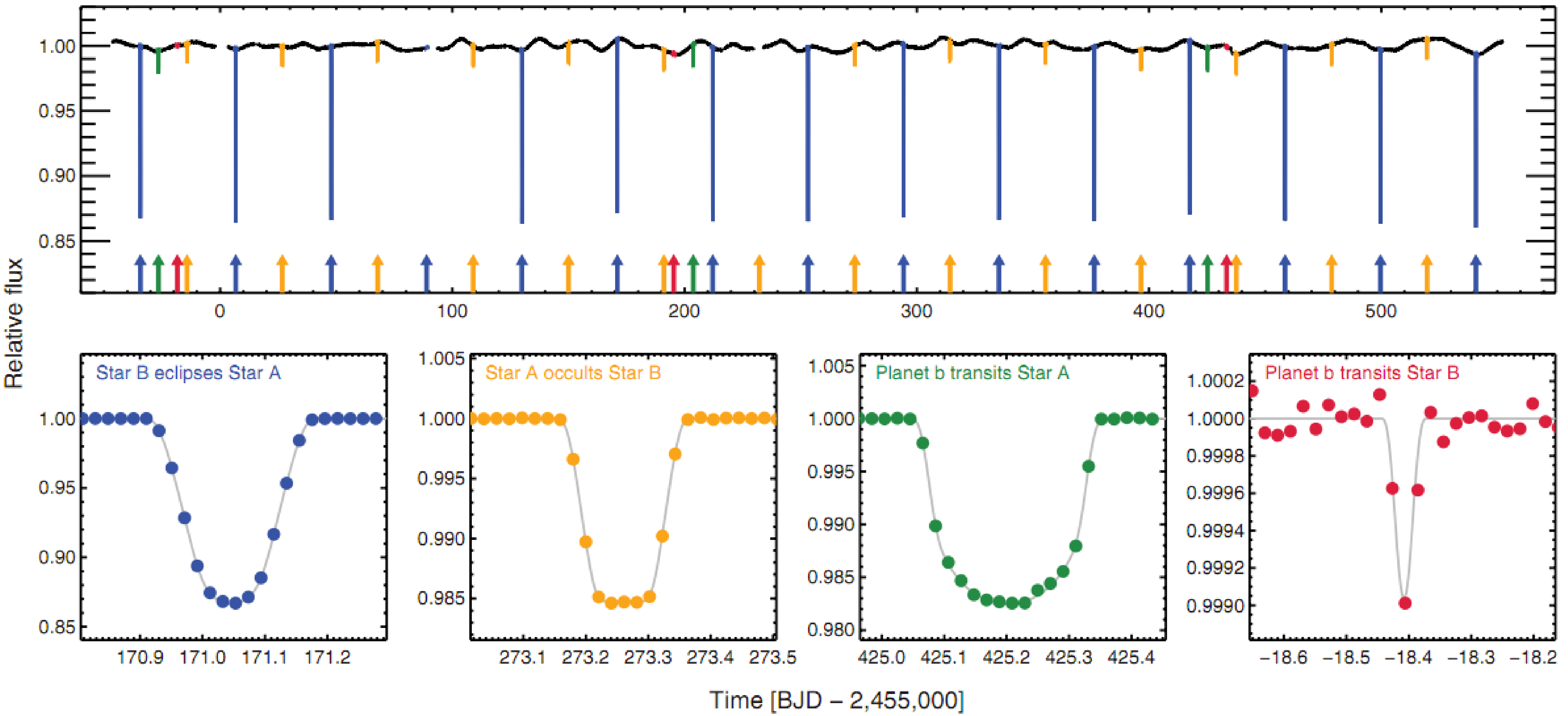
figure 13.9 The Kepler 11 system. The black line shows the brightness of the star Kepler 11 over a 110-day period. Colored dots indicate transits by six different planets. The panels at right show the dips due to each planet separately, and indicate the planet's size in Earth radii.

Circumbinary Planets



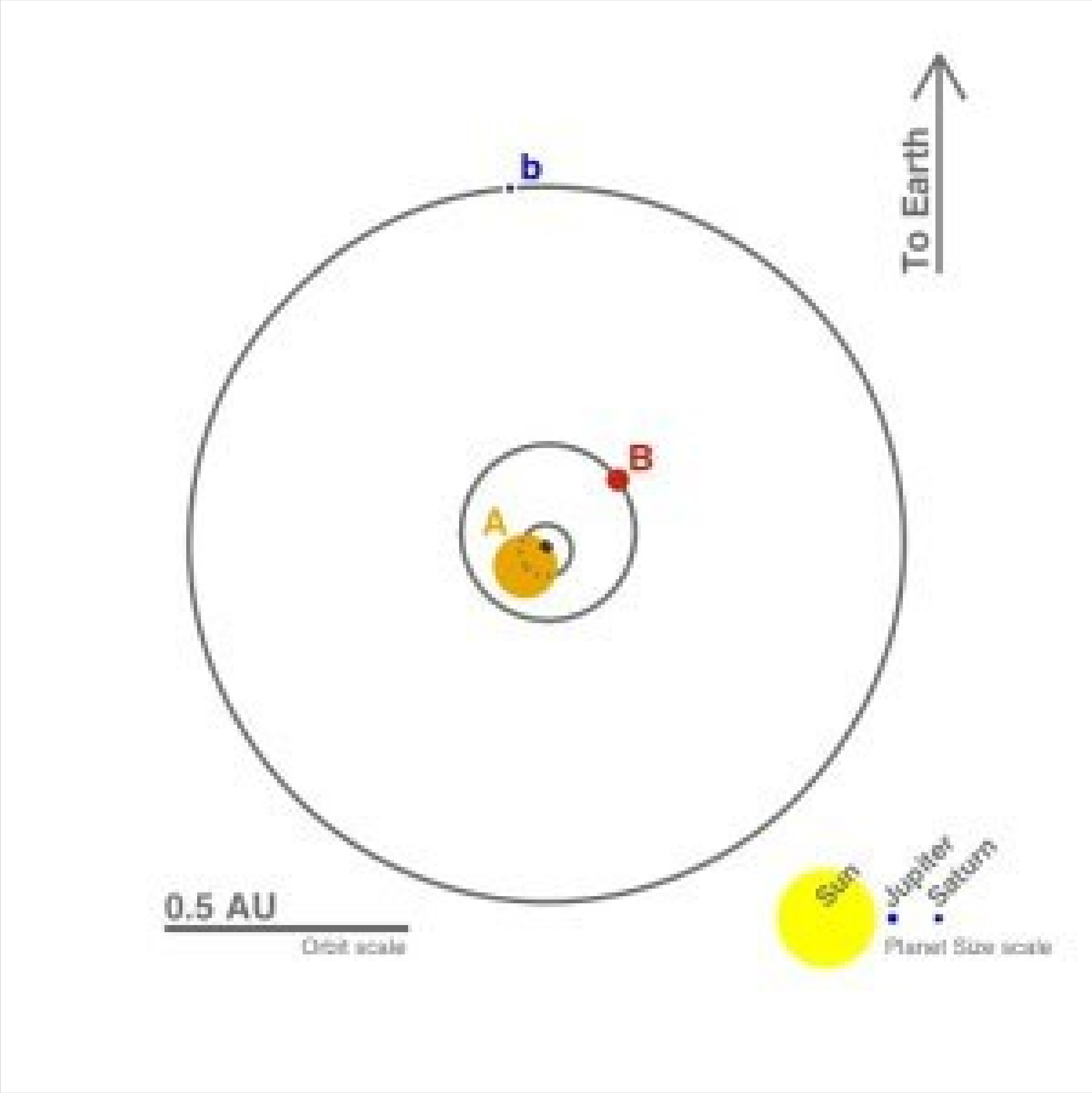
KEPLER-16

Circumbinary Planets



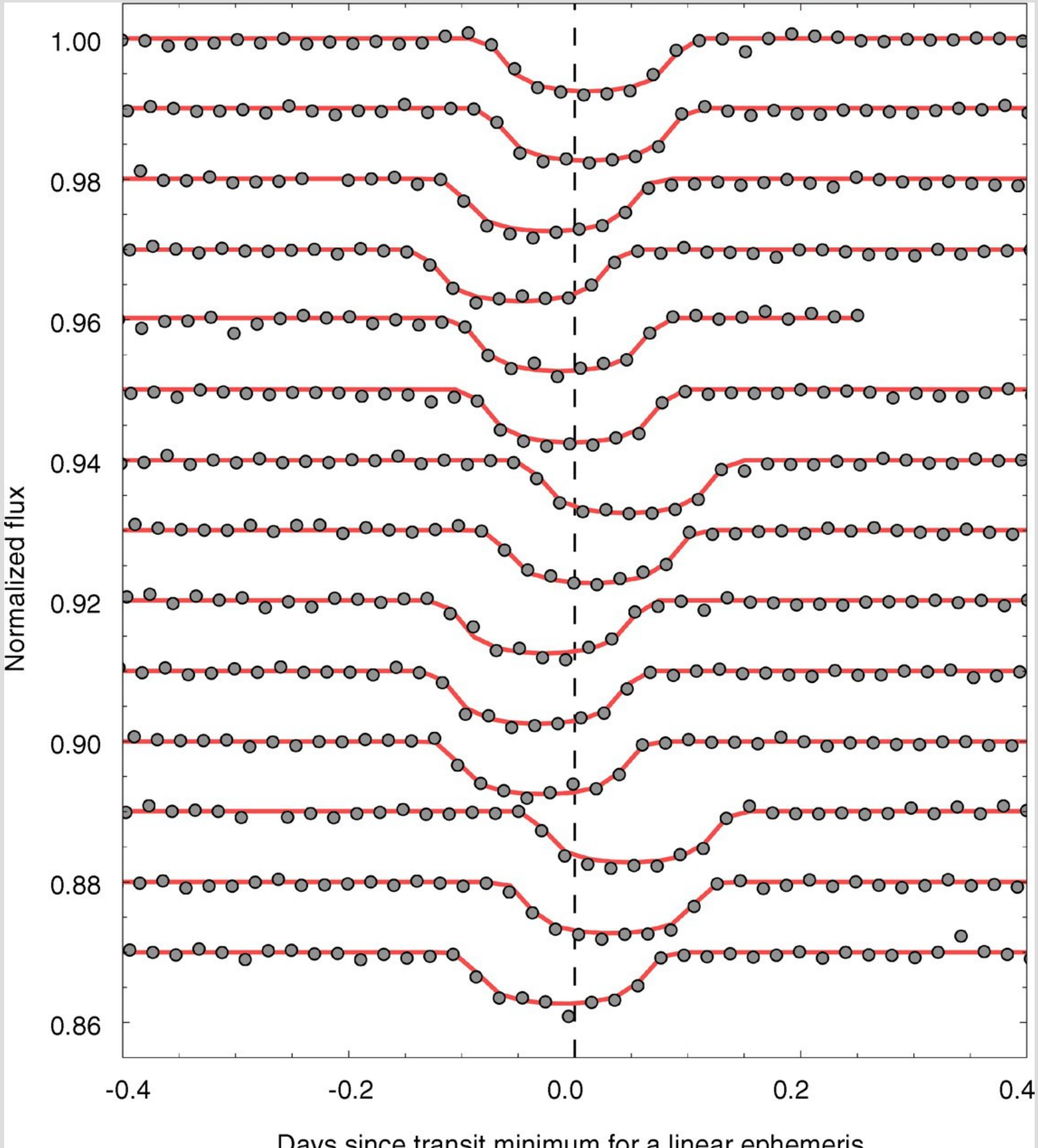
KEPLER-16

Circumbinary Planets



KEPLER-16

Transit Timing Variations



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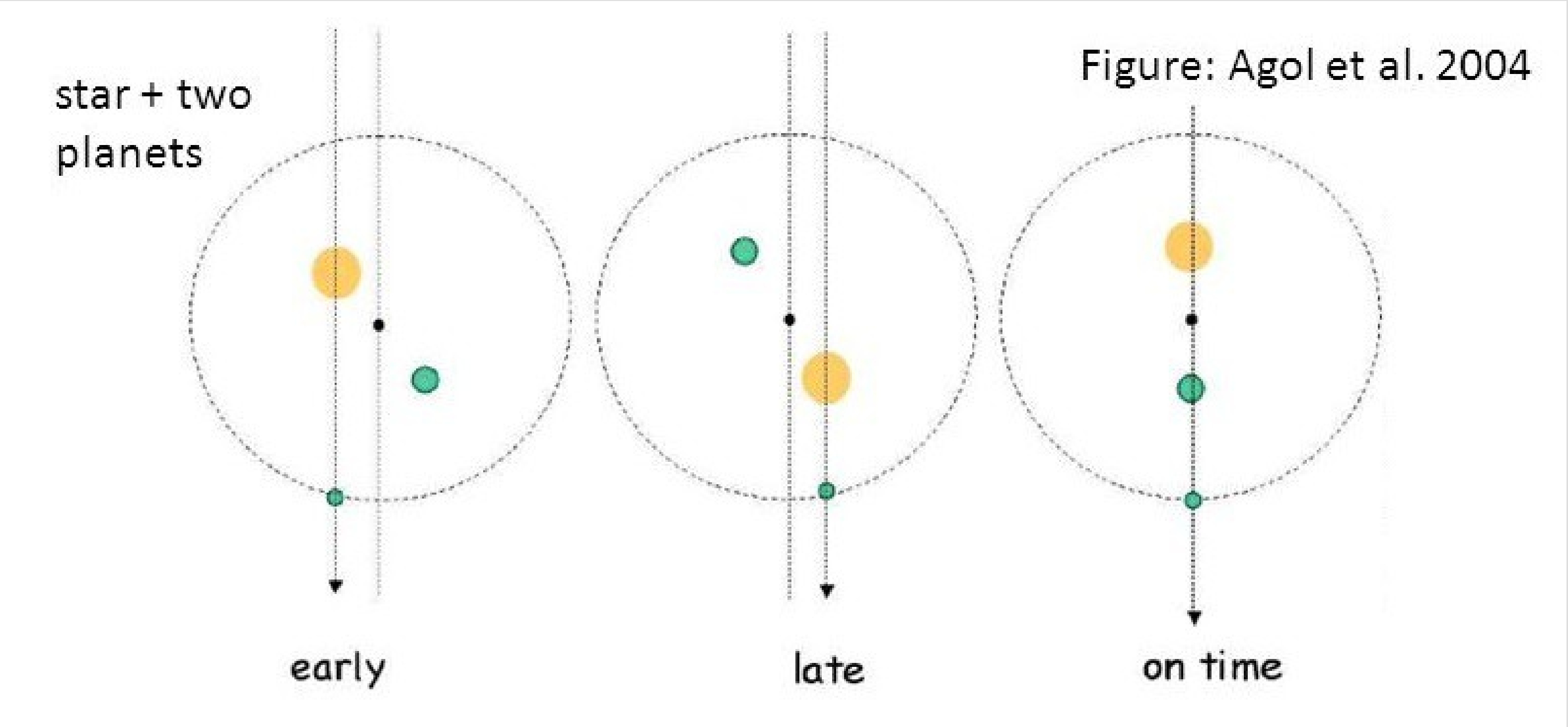


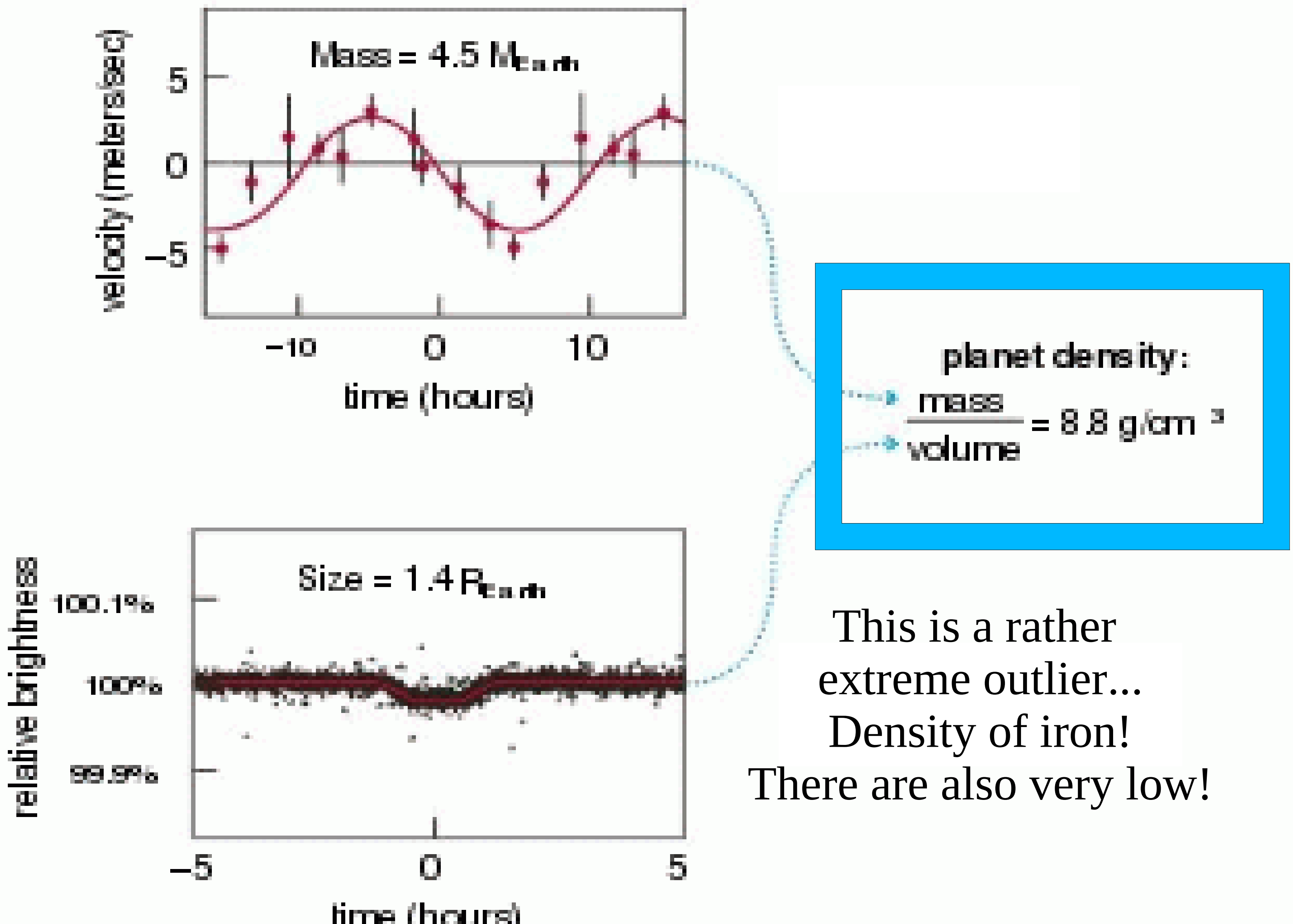
shift in location of center of mass
causes change in transit time

How can we learn more about the properties of these planets?

- What kind of things would we like to know about the planets?
  - Mass
  - Radius
  - Chemical composition

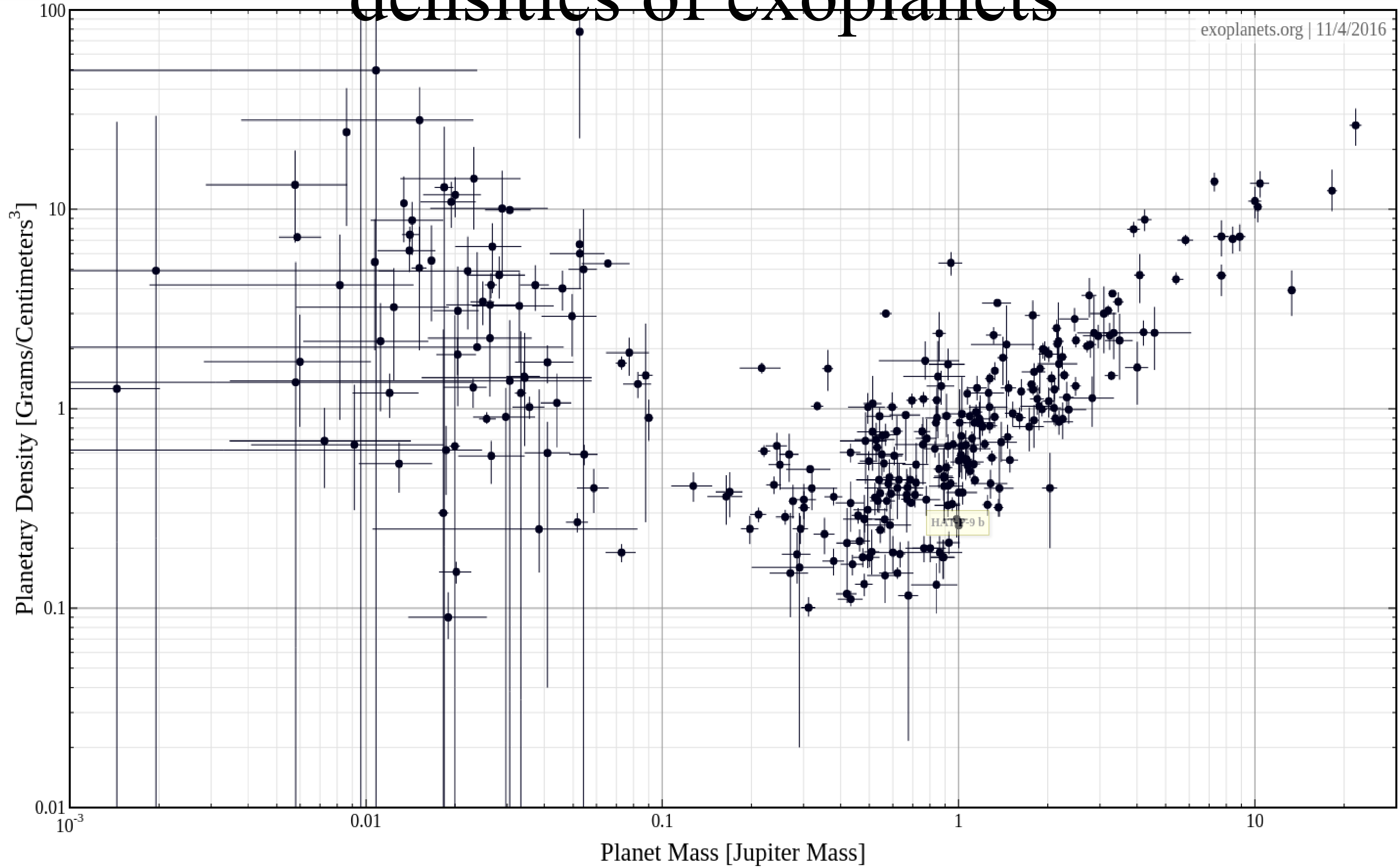
- Transits coupled with RV is the best, because
  - Transit ==> edge on
  - Thus sin(i)=1 and get planet mass
  - Transit depth this planetary radius

IF you can combine techniques



This is a rather extreme outlier… Density of iron! There are also very low!

Currently known estimated masses and densities of exoplanets



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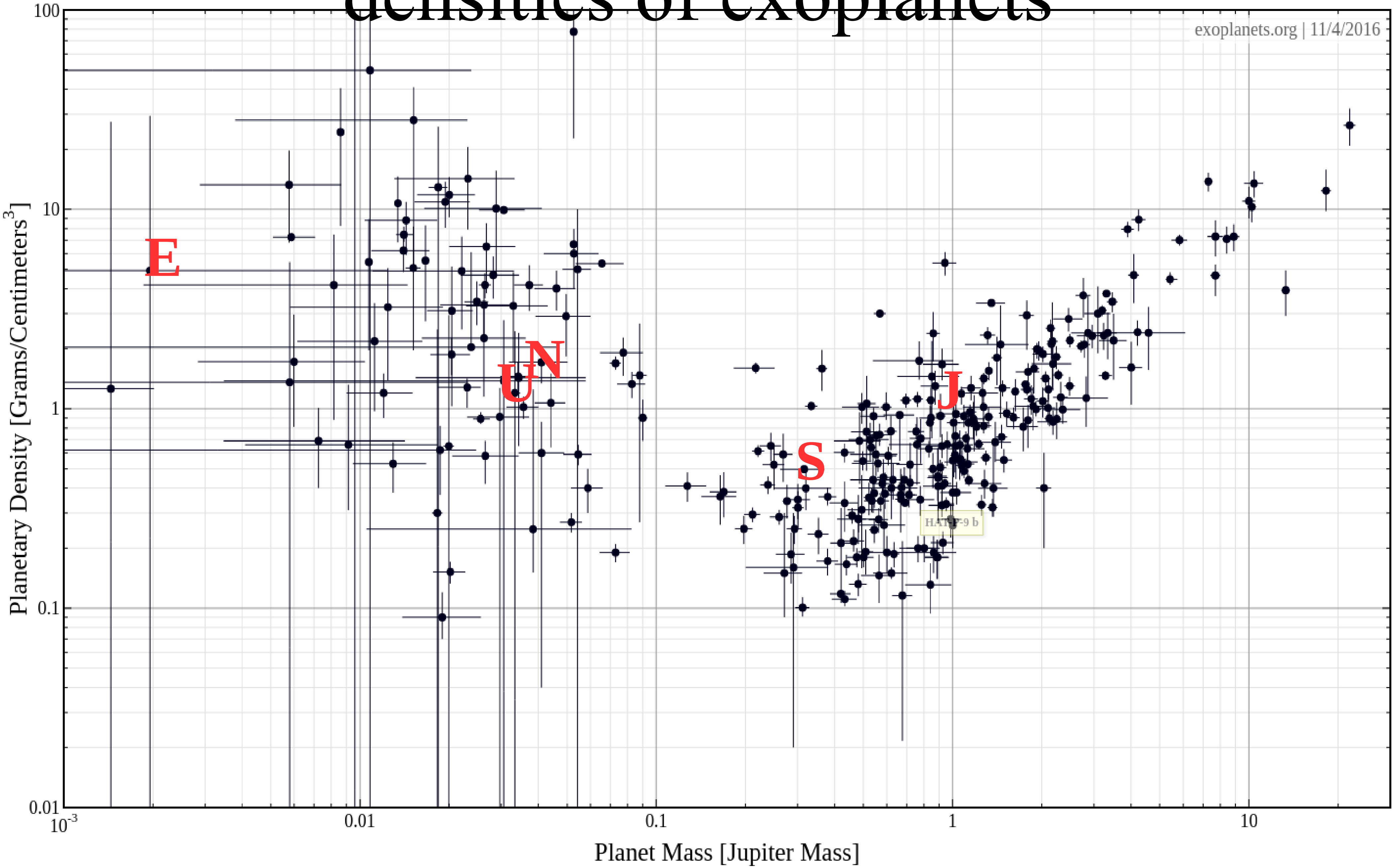
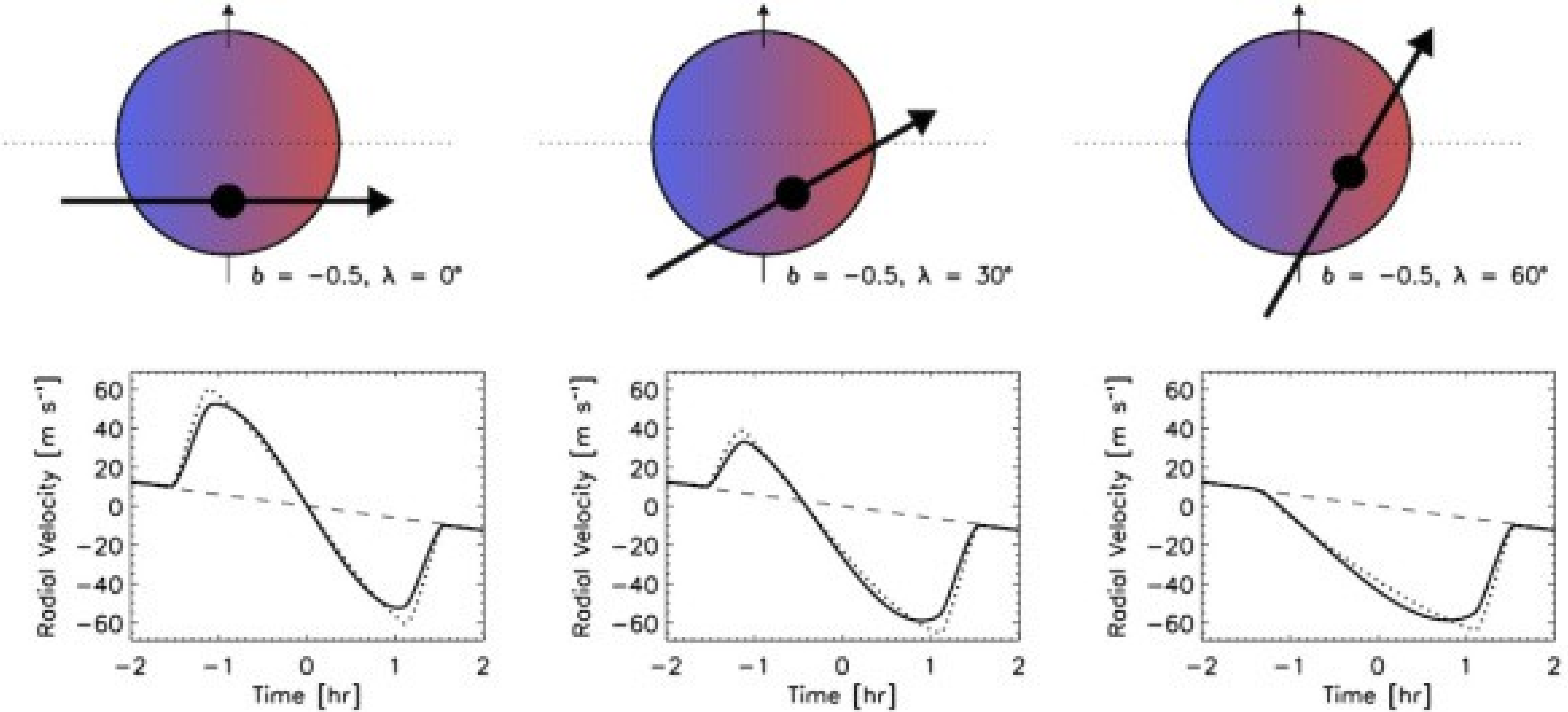
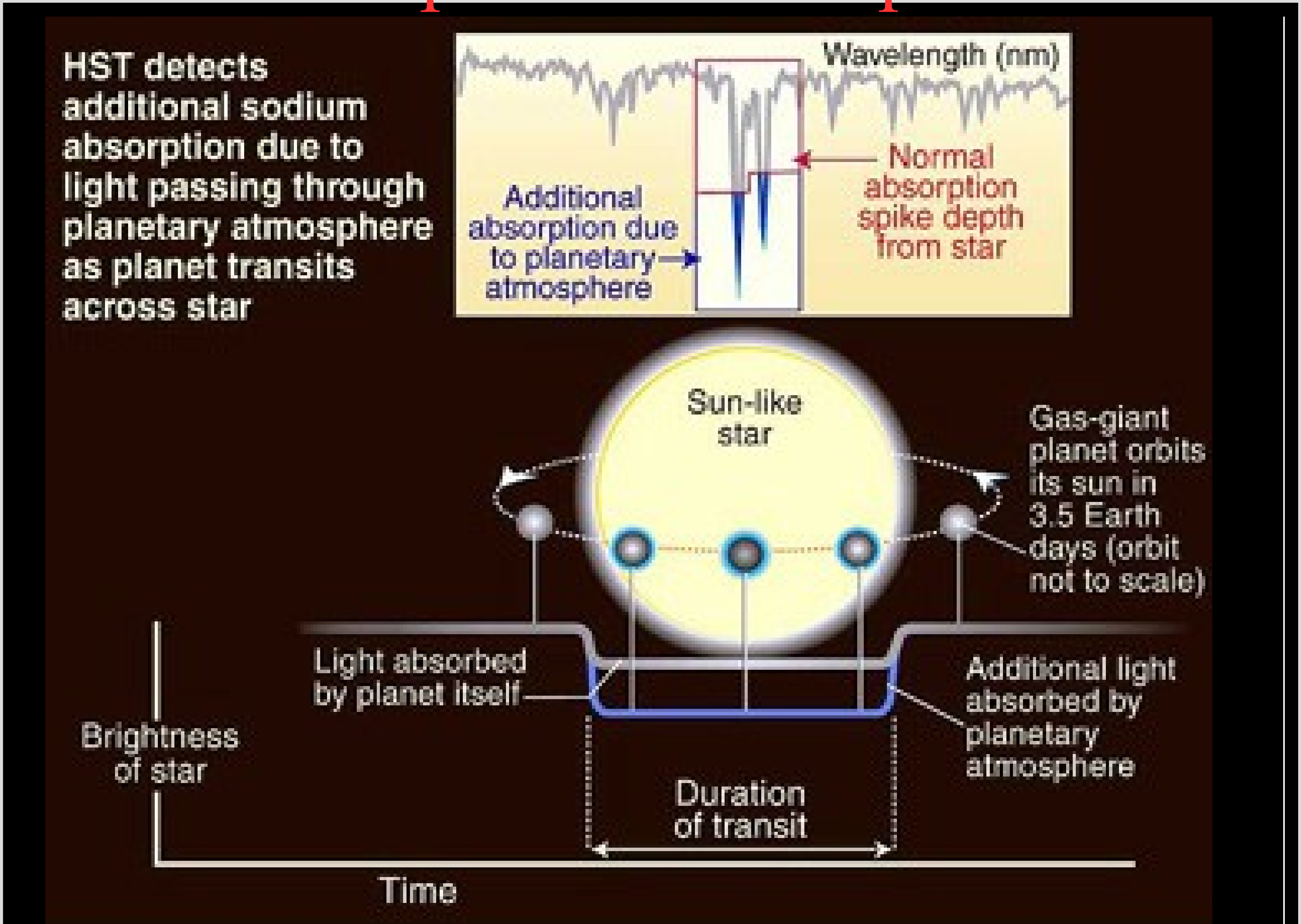


Very similar to the values for Earth, Uranus, Neptune, Saturn, Jupiter

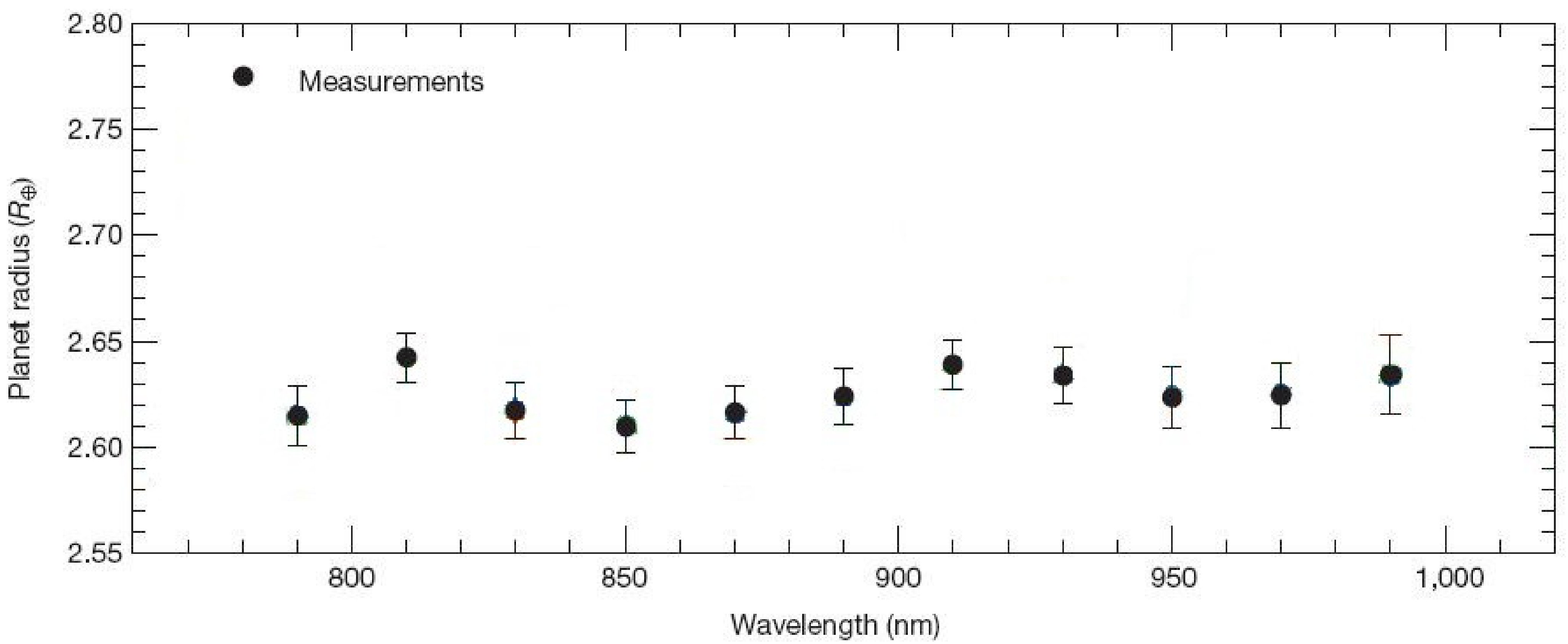
Rossiter-McLaughlin effect



Can even see absorption spectrum of the planet's atmosphere!



Transit spectroscopy



Transit spectroscopy