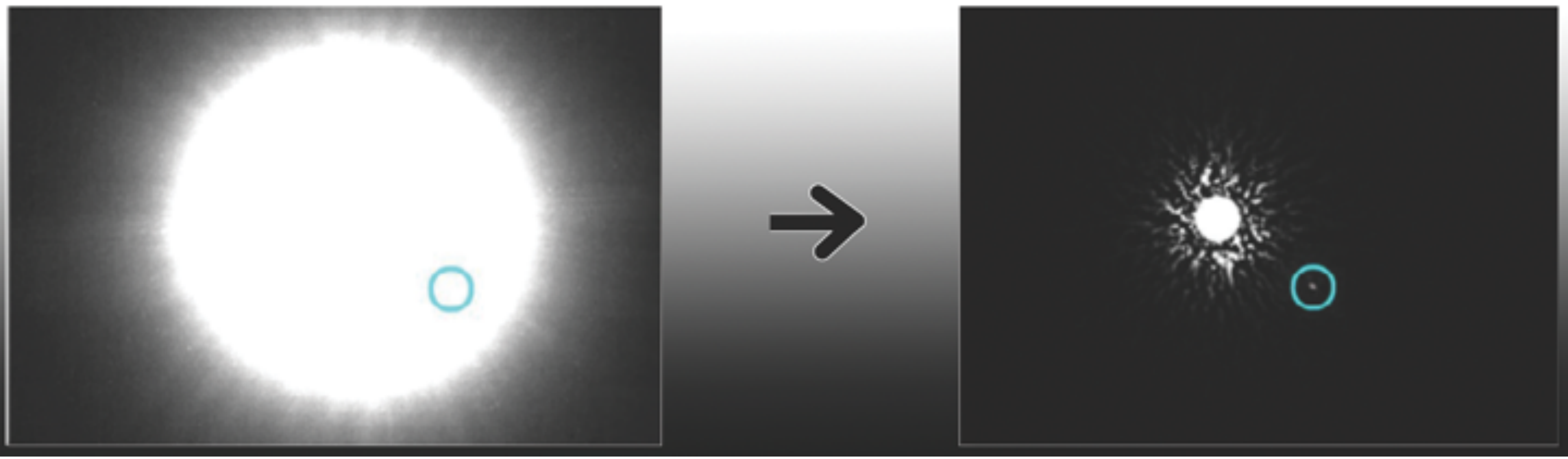
» How vast those Orbs must be, and how inconsiderable this Earth, the Theatre upon which all our mighty Designs, all our Navigations, and all our Wars are transacted, is when compared to them. A very fit consideration, and matter of Reflection, for those Kings and Princes who sacrifice the Lives of so many People, only to flatter their Ambition in being Masters of some pitiful corner of this small Spot.

» Christiaan Huygens, c. 1690

Why is it so challenging to learn about extrasolar planets?



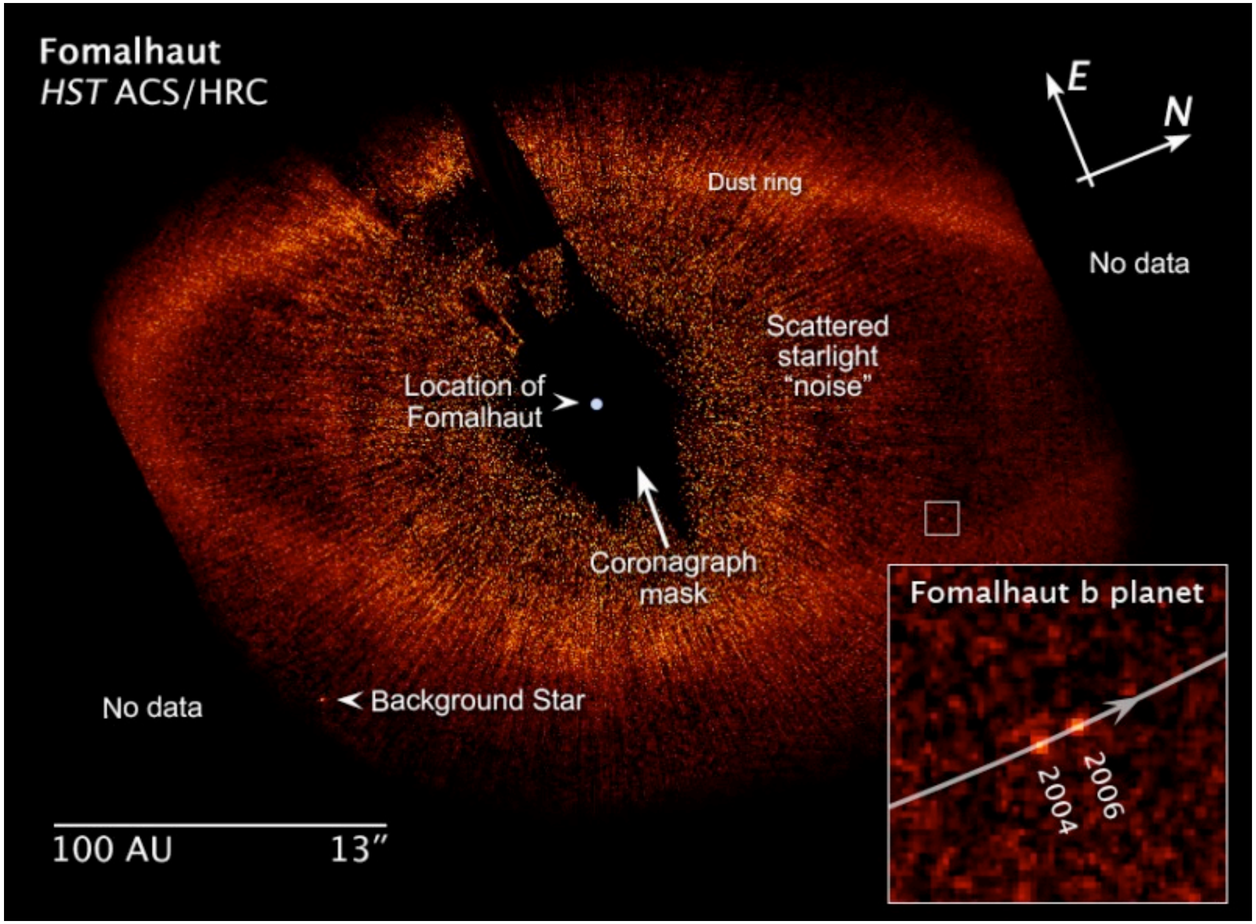
Brightness and Distance

- A Sun-like star is about a billion times brighter than the light reflected from its planets.
- Planets are close to their stars, relative to the distance from us to the star.
  - This is like being in San Francisco and trying to see a pinhead 15 meters from a grapefruit in Washington, D.C.

Planet Detection

- **Direct:** pictures or spectra of the planets themselves
- **Indirect:** measurements of stellar properties revealing the effects of orbiting planets

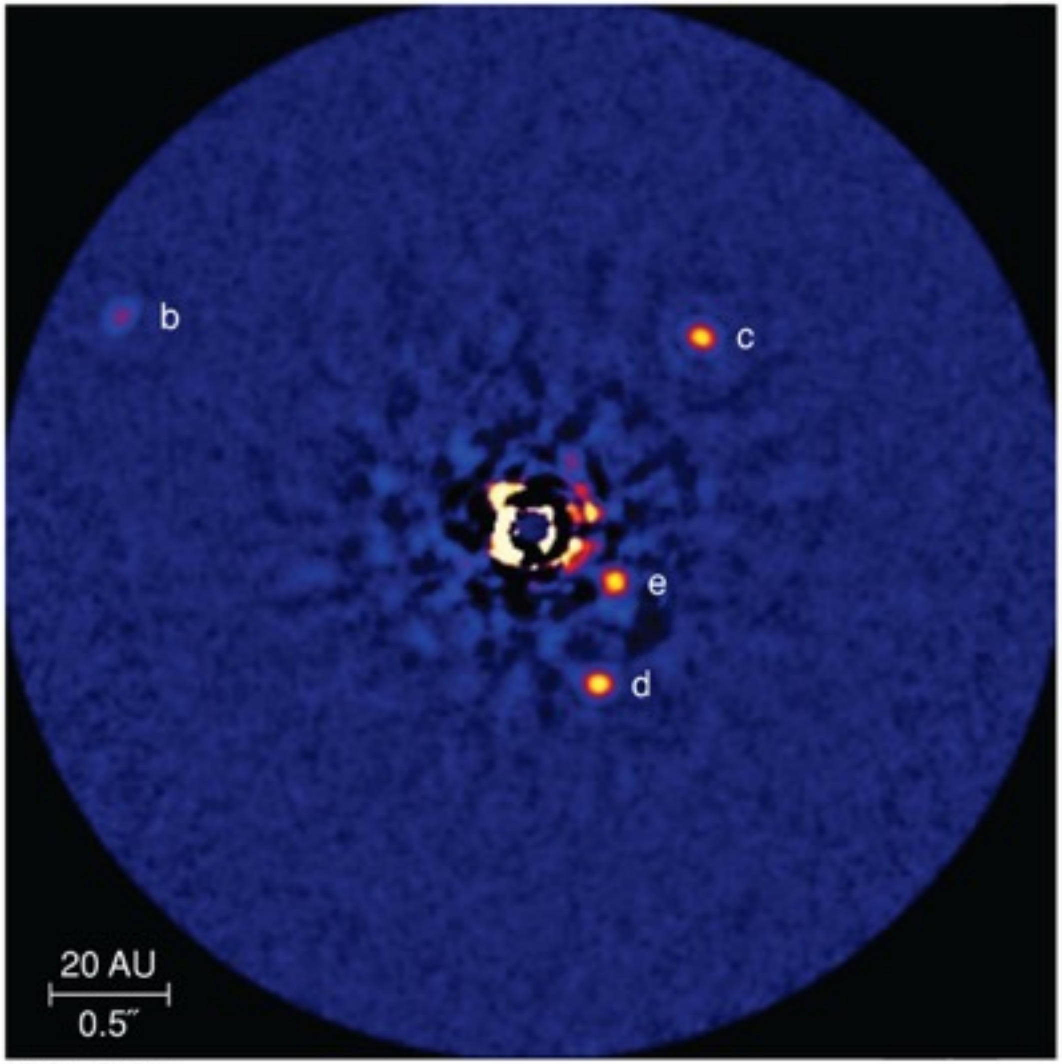
Direct Detection



- Special techniques like adaptive optics are helping to enable direct planet detection.

*Image Credit: NASA, ESA, P. Kalas, J. Graham, E. Chiang, and E. Kite (University of California, Berkeley), M. Clampin (NASA Goddard Space Flight Center, Greenbelt, Md.), M. Fitzgerald (Lawrence Livermore National Laboratory, Livermore, Calif.), and K. Stapelfeldt and J. Krist (NASA Jet Propulsion Laboratory, Pasadena, Calif.)

Direct Detection

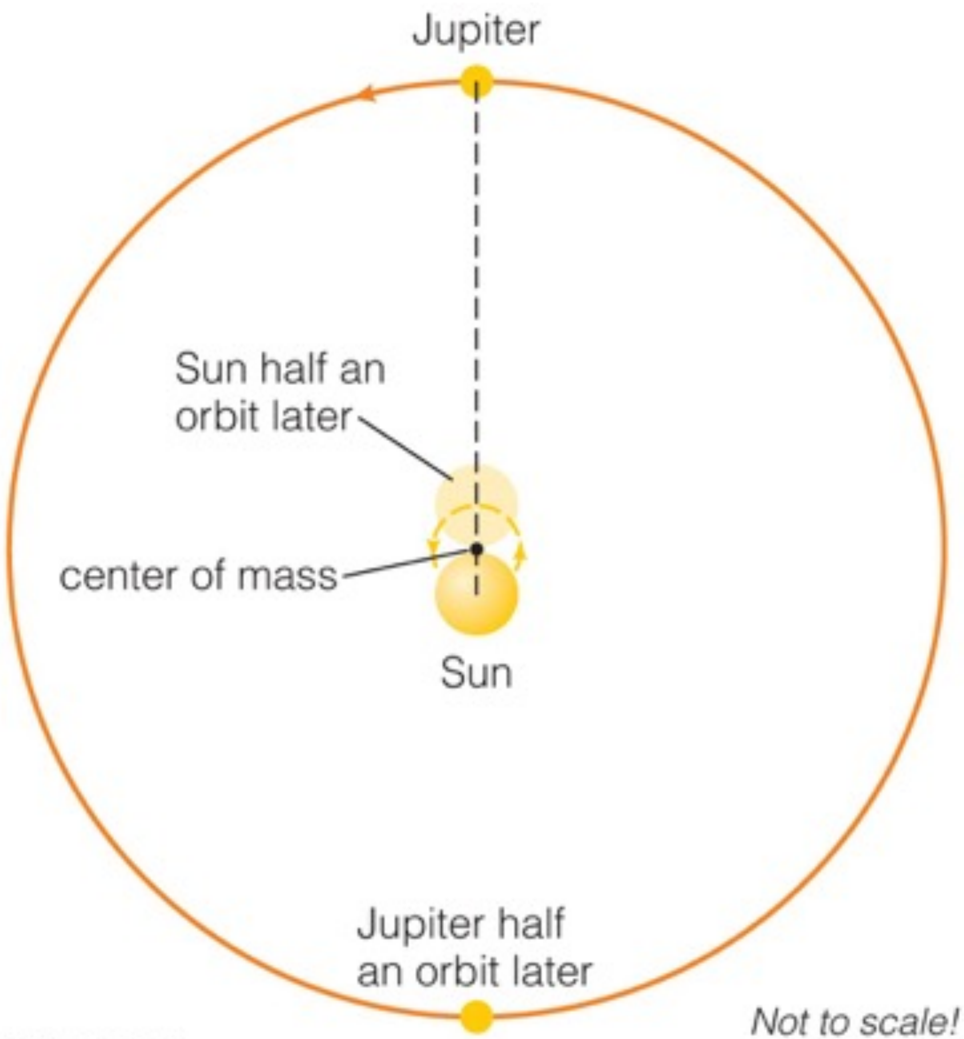


- Techniques that help block the bright light from stars are also helping us to find planets around them.

Indirect Detection

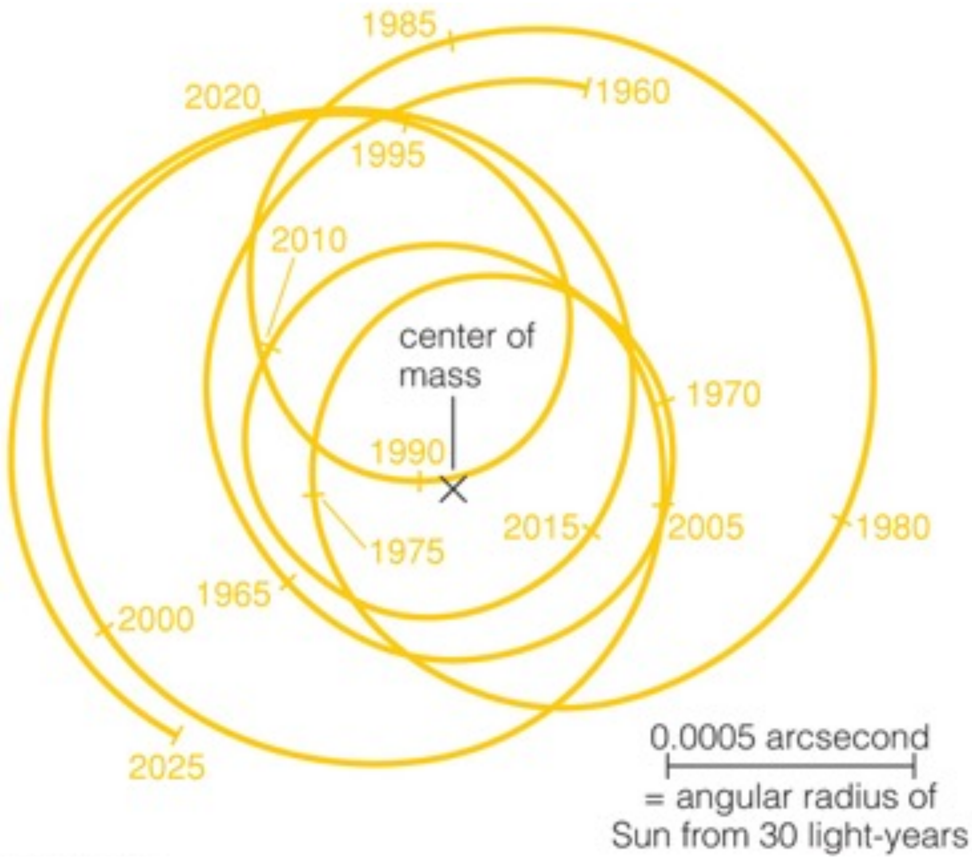
- **Doppler Technique:** observe red and blue Doppler shifts of the star's spectrum
- **Transit Method:** carefully observe dimming of star's light as a planet passes in front of it
- **Gravitational Microlensing:** light of distant star is enhanced by gravitational focusing whenever planet passes between us and distant star
- In none of these methods do you actually see the planet itself!!

Gravitational Tugs



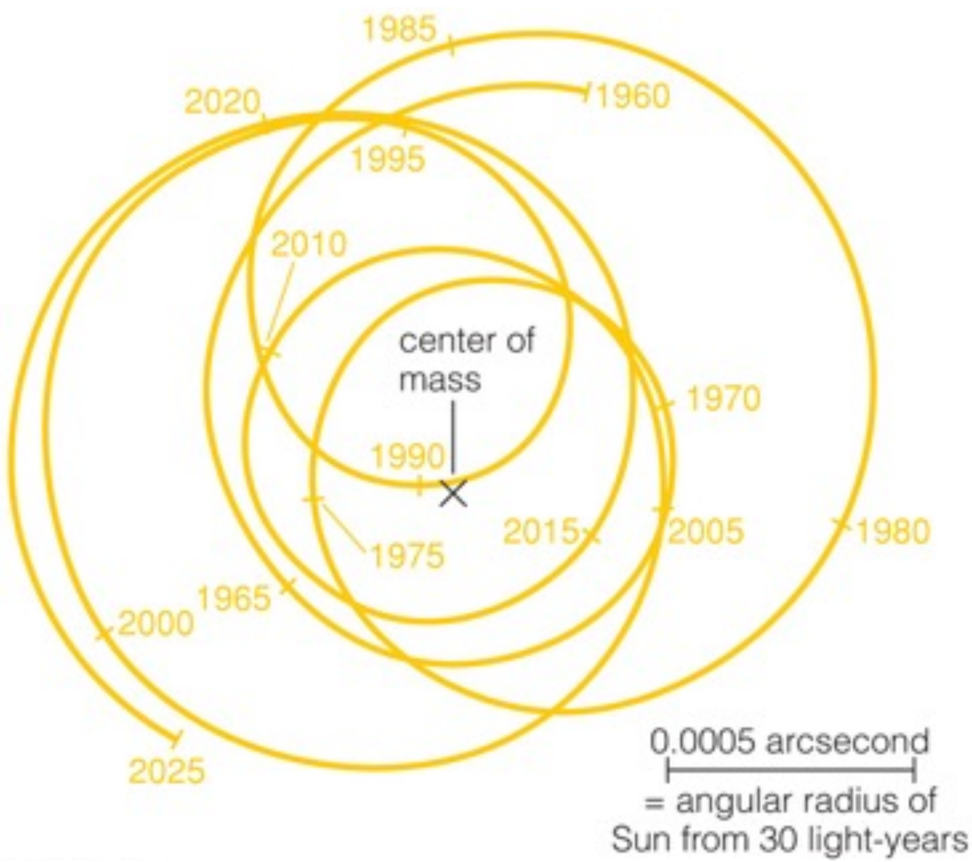
- The Sun and Jupiter orbit around their common center of mass.
- The Sun therefore wobbles around that center of mass with same period as Jupiter.

Gravitational Tugs



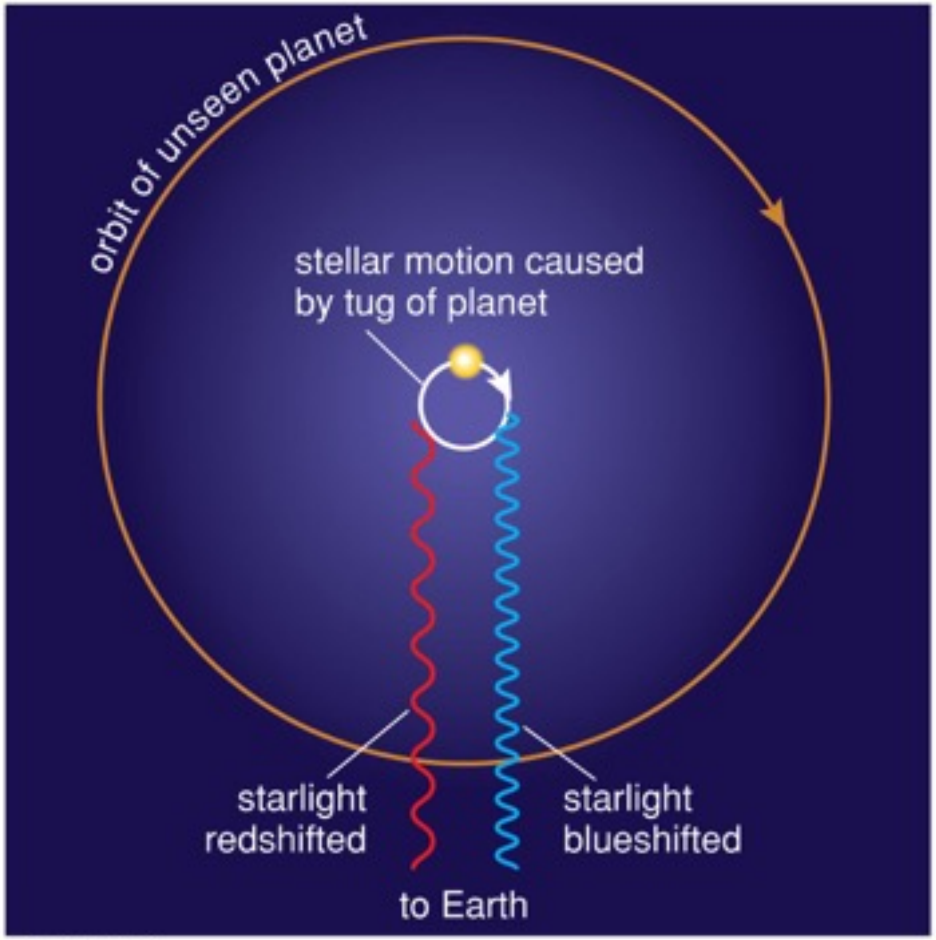
- The Sun's motion around the solar system's center of mass depends on tugs from all the planets.
- Astronomers around other stars that measured this motion could determine the masses and orbits of all the planets.

Astrometric Technique



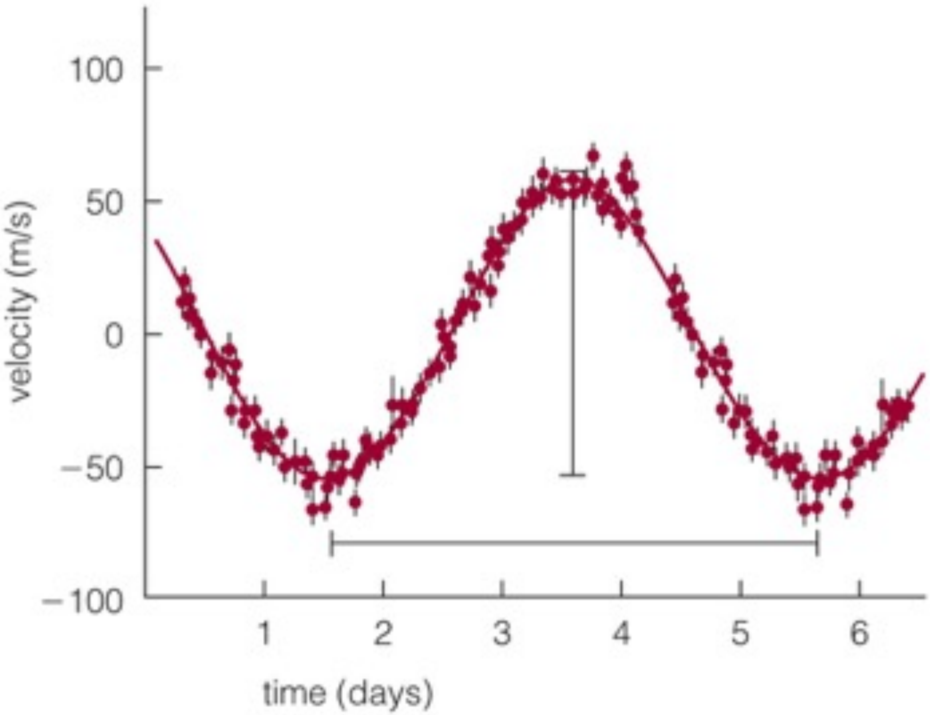
- We can detect planets by measuring the change in a star's position on sky.
- However, these tiny motions are very difficult to measure (~ 0.001 arcsecond).

Doppler Technique



- Measuring a star's Doppler shift can tell us its motion toward and away from us.
- Current techniques can measure motions as small as 1 m/s (walking speed!).

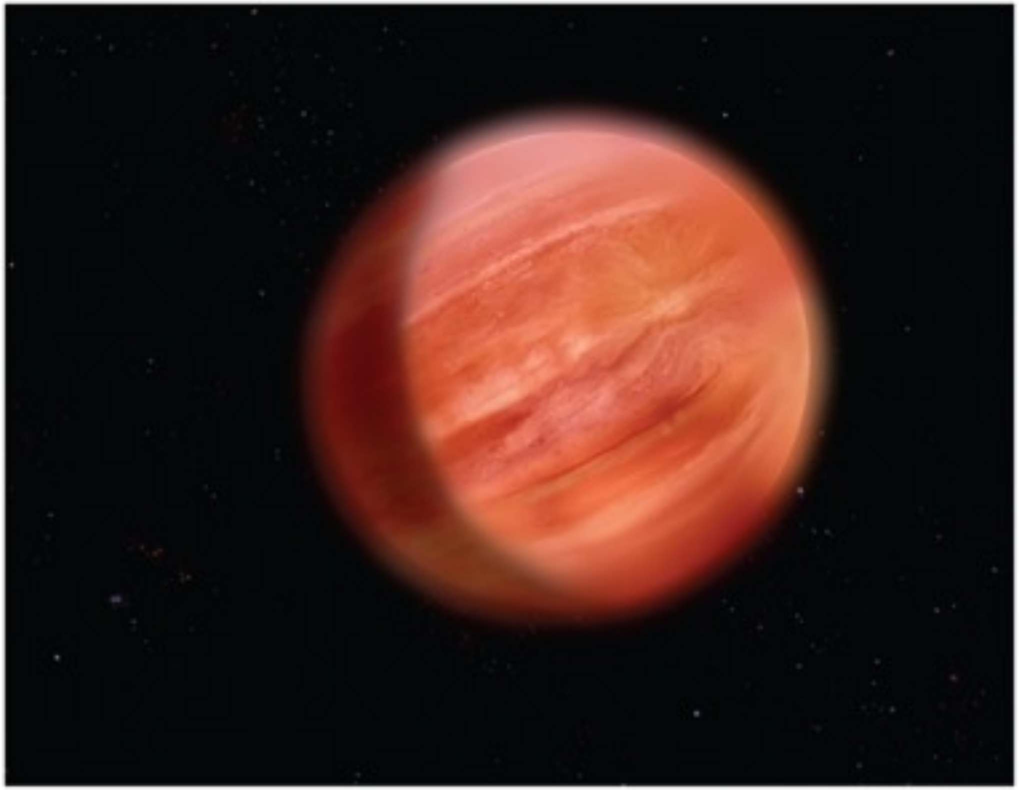
First Extrasolar Planet



a 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.

- Doppler shifts of the star 51 Pegasi indirectly revealed a planet with 4-day orbital period.
- This short period means that the planet has a small orbital distance.
- This was the first extrasolar planet to be discovered around a Sun-like star (1995).

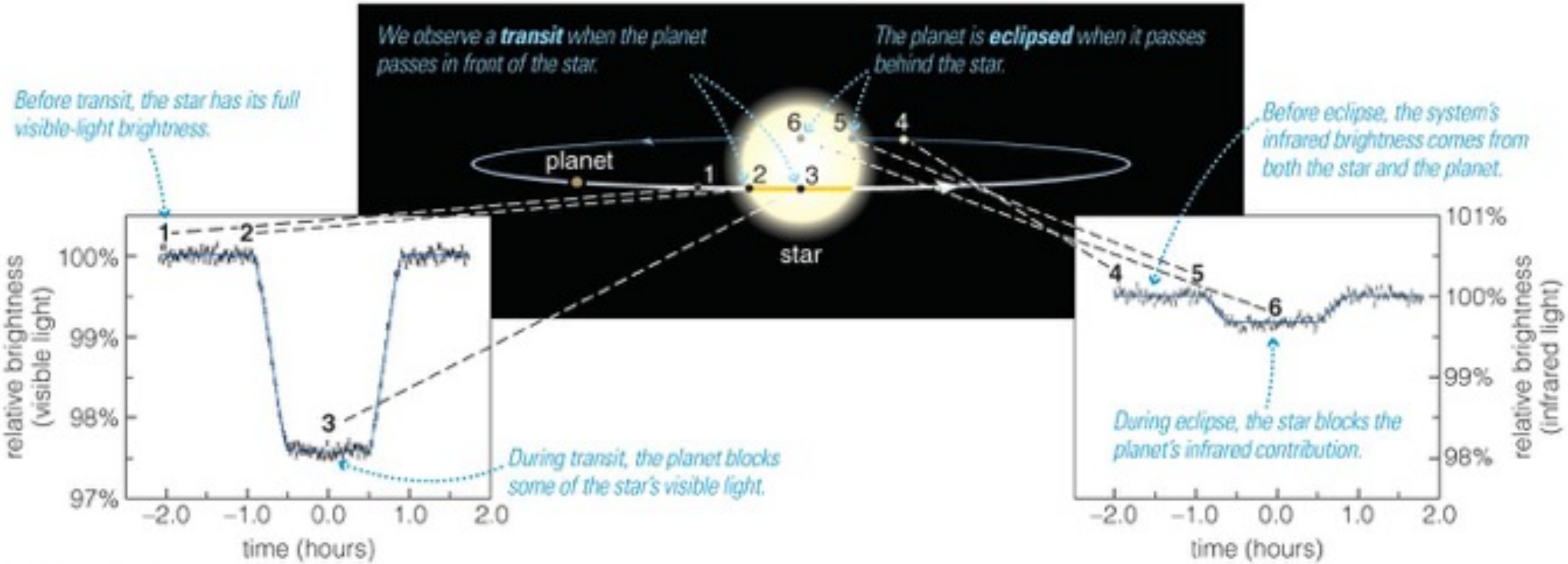
First Extrasolar Planet



b Artist's conception of the planet orbiting 51 Pegasi, which probably has a mass similar to that of Jupiter but orbits its star at only about one-eighth of Mercury's orbital distance from the Sun. It probably has a surface temperature above 1000 K, making it an example of what we call a hot Jupiter.

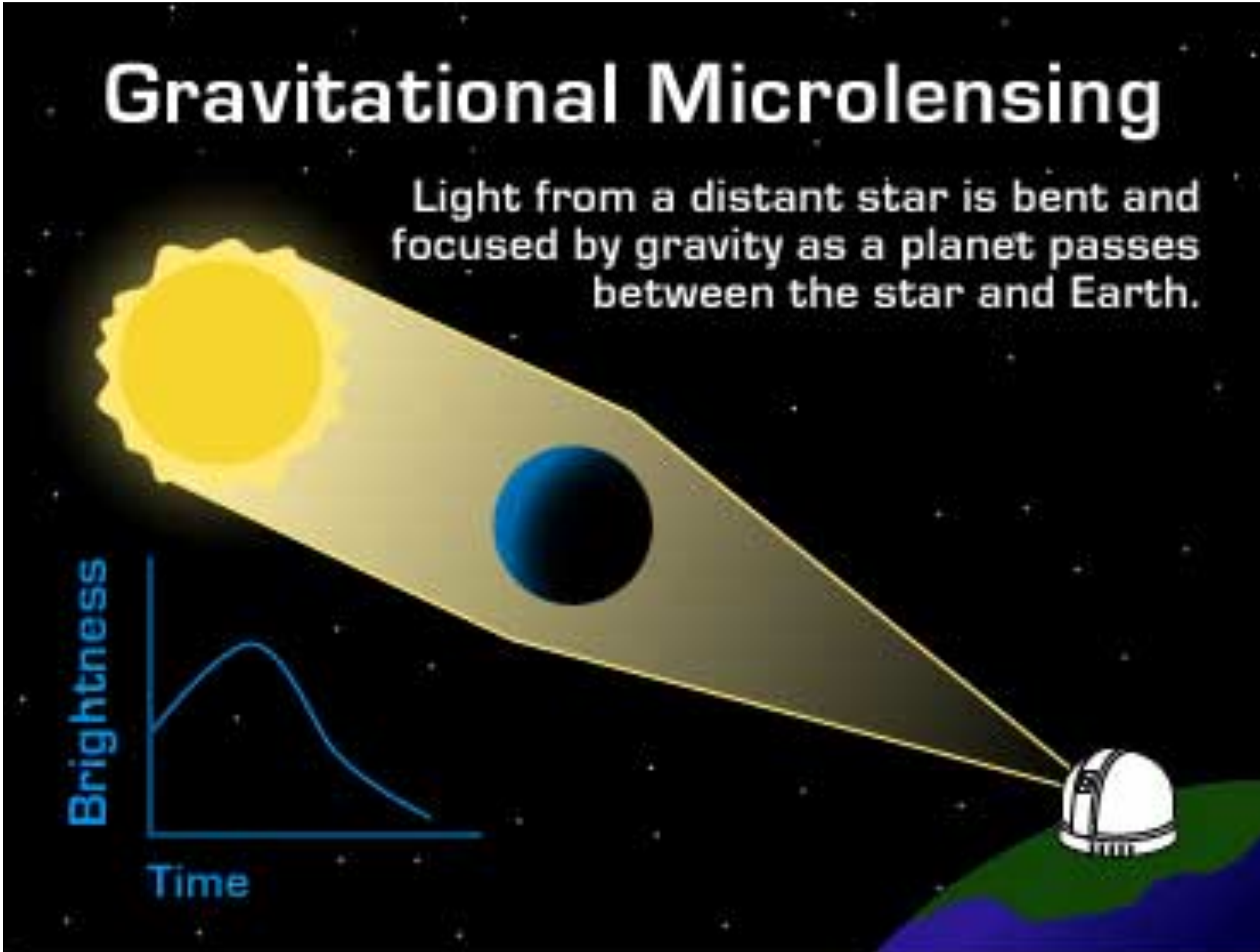
- The planet around 51 Pegasi has a mass similar to Jupiter's, despite its small orbital distance.

Transits and Eclipses



- A **transit** is when a planet crosses in front of a star.
- The resulting eclipse reduces the star's apparent brightness and tells us planet's radius.
- No orbital tilt: accurate measurement of planet mass

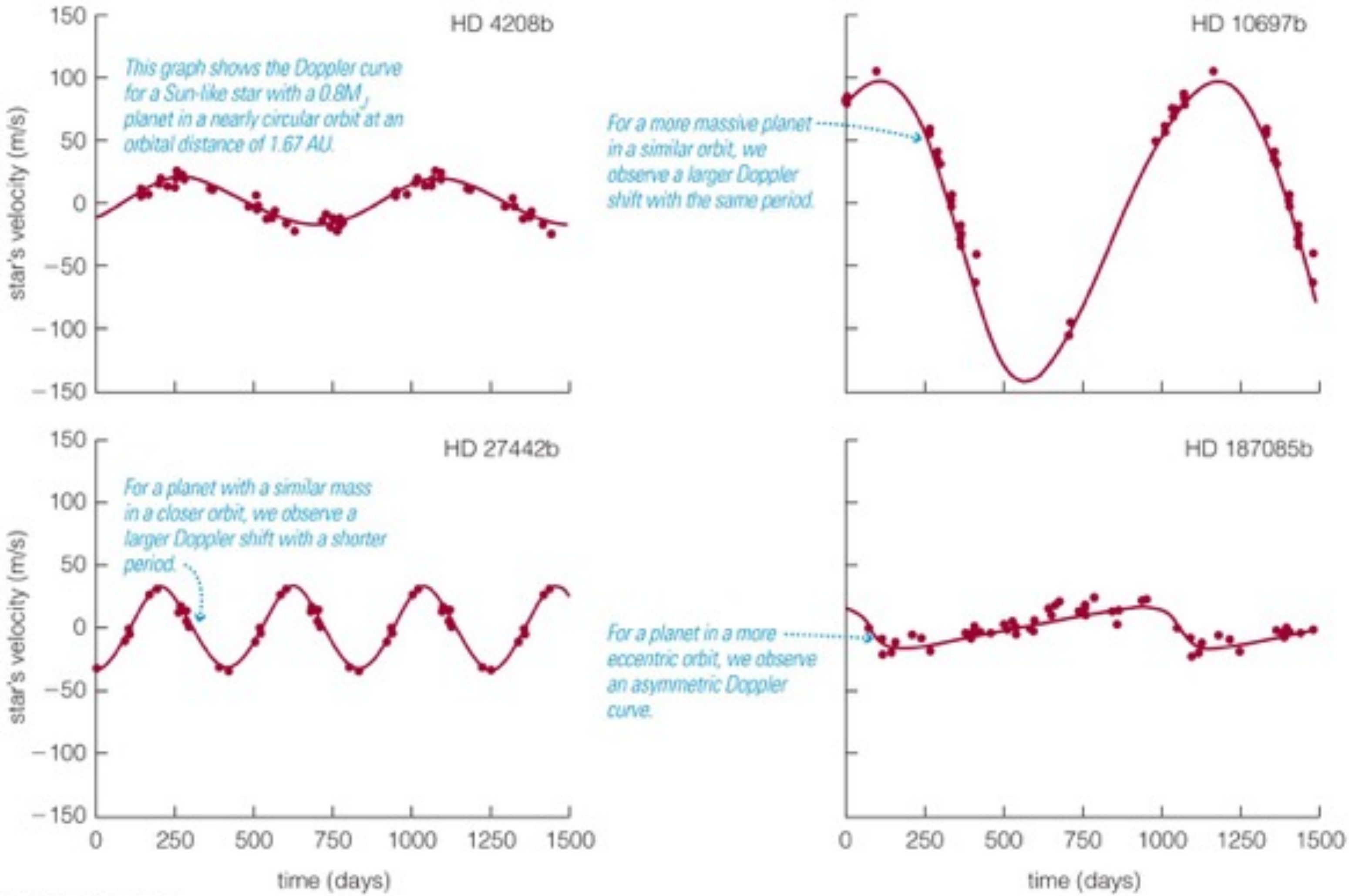
Gravitational Microlensing



What properties of extrasolar planets can we measure?

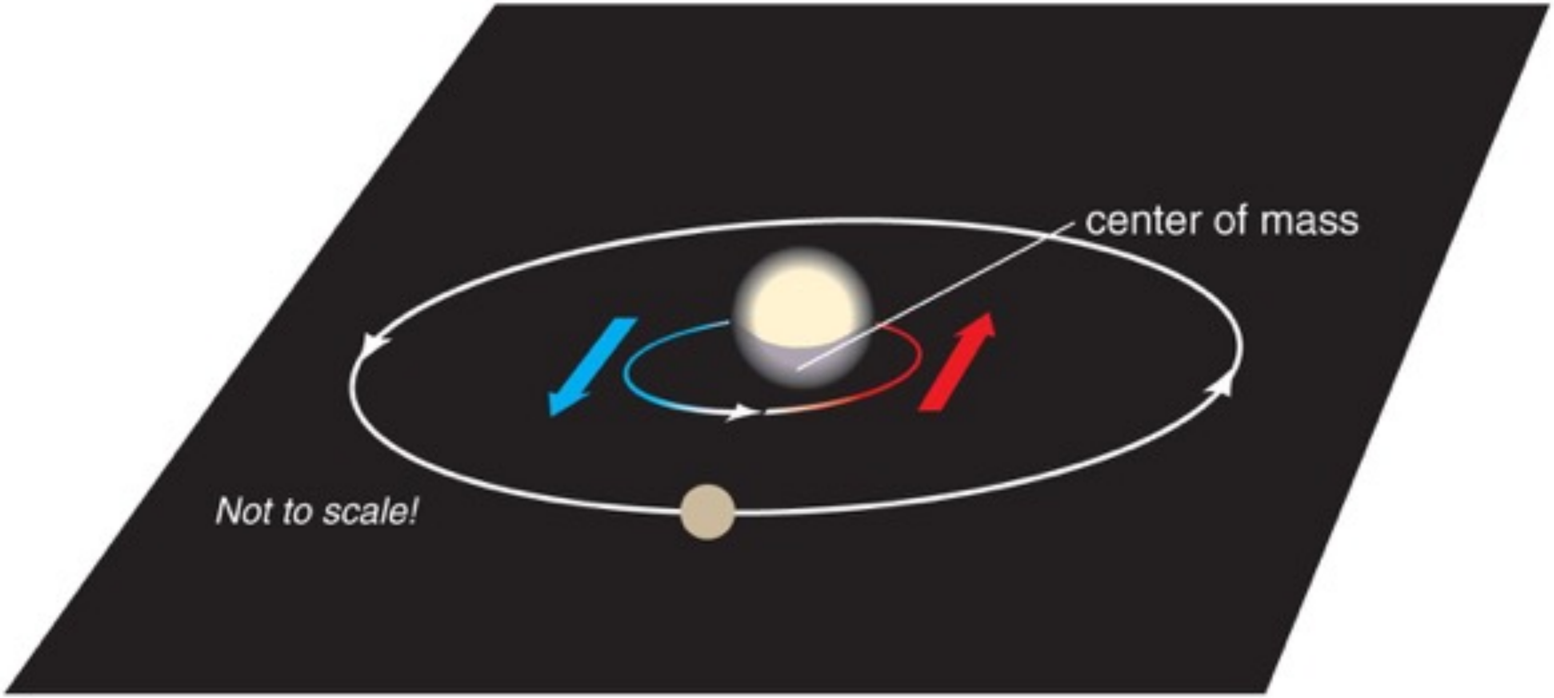
- Orbital period, distance, and shape
- Planet mass, size, and density
- Atmospheric properties

What can Doppler shifts tell us?



- Doppler shift data tell us about a planet's mass and the shape of its orbit.

Planet Mass and Orbit Tilt



b We can detect a Doppler shift only if some part of the orbital velocity is directed toward or away from us. The more an orbit is tilted toward edge-on, the greater the shift we observe.

- We cannot measure an exact mass for a planet without knowing the tilt of its orbit, because Doppler shift tells us only the velocity toward or away from us.
- Doppler data give us lower limits on masses.

Thought Question

Suppose you found a star with the same mass as the Sun moving back and forth with a period of 16 months. What could you conclude?

A. It has a planet orbiting at less than 1 AU.
B. It has a planet orbiting at greater than 1 AU.
C. It has a planet orbiting at exactly 1 AU.
D. It has a planet, but we do not have enough information to know its orbital distance.

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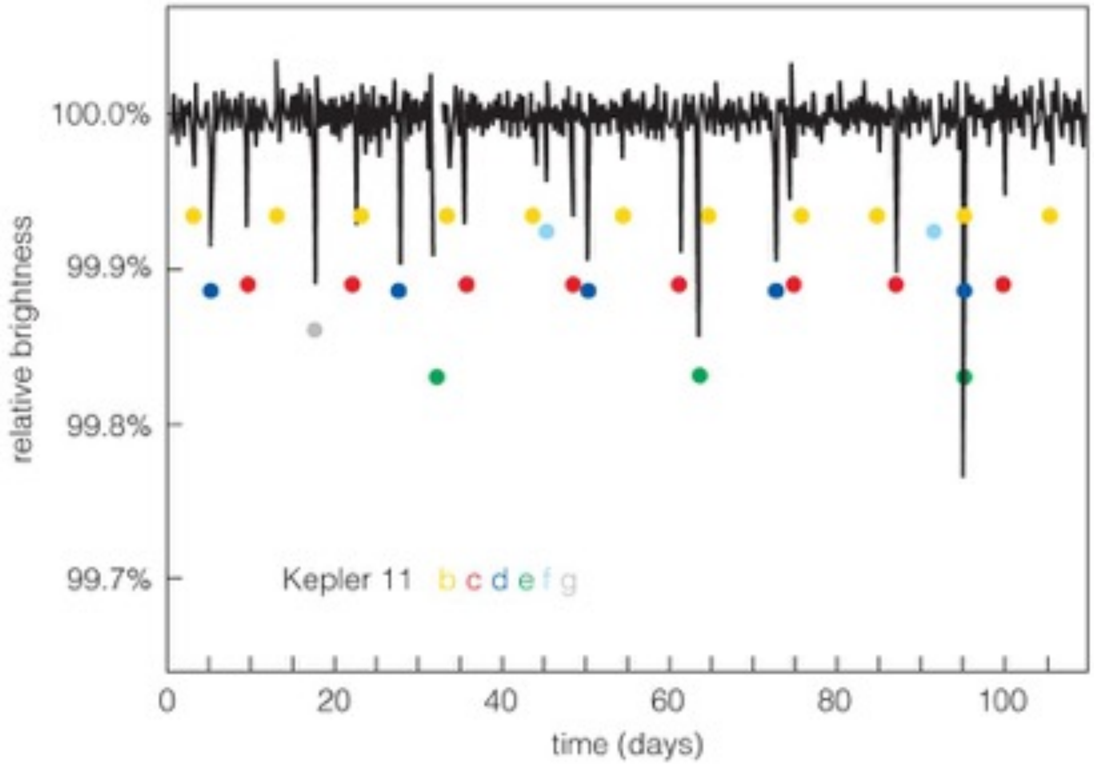
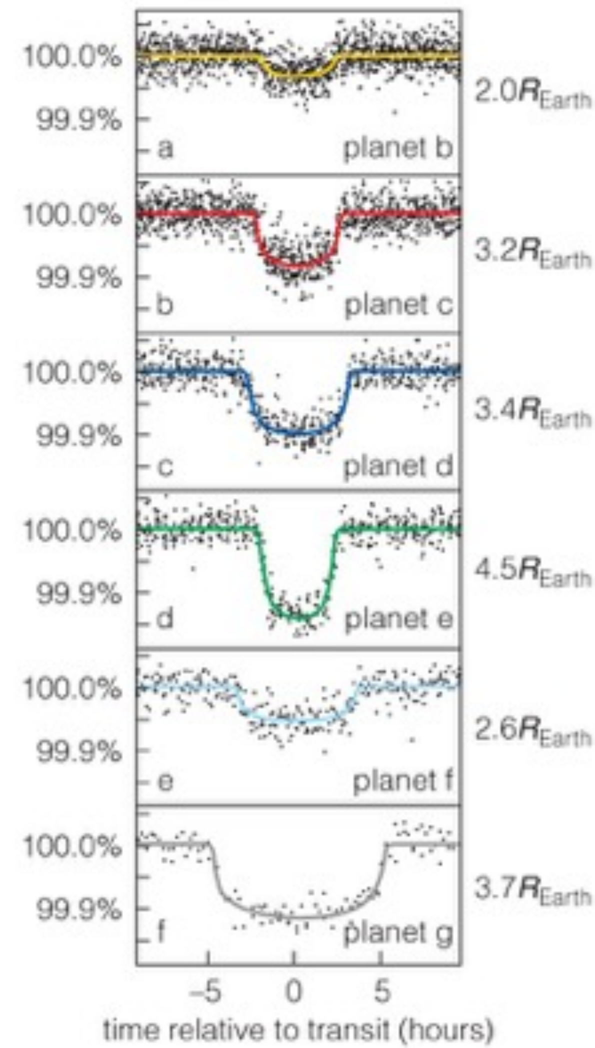
What can transits tell us?



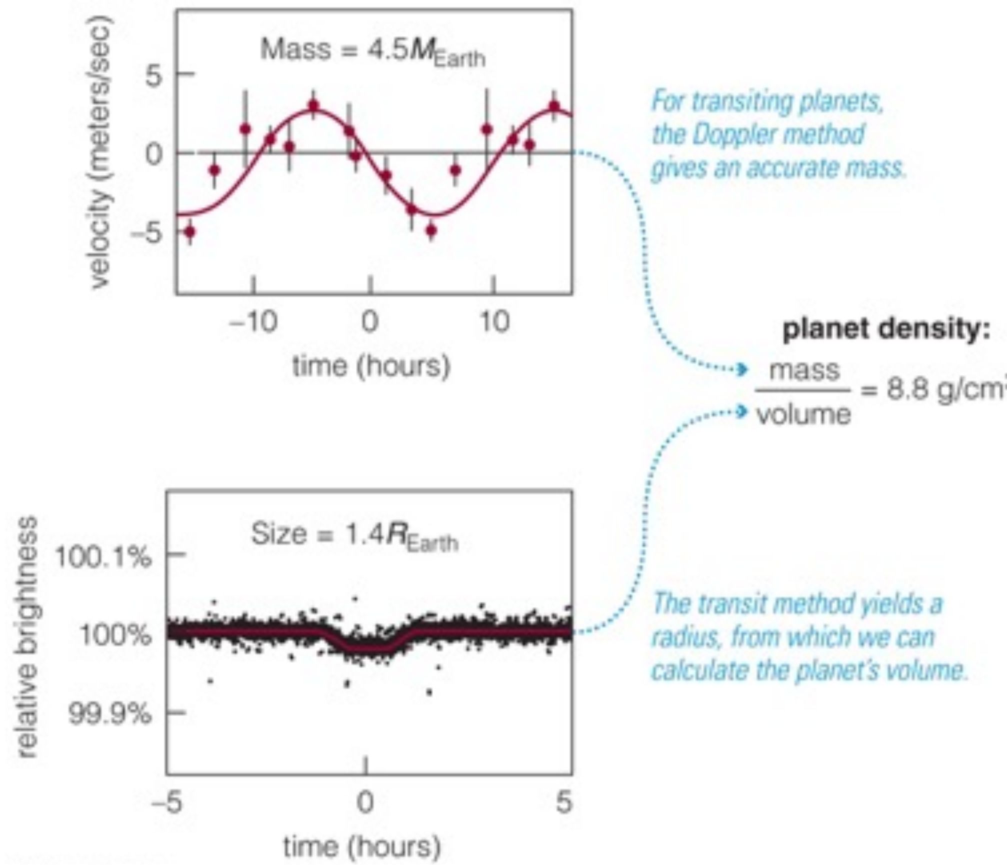


Keppler 11

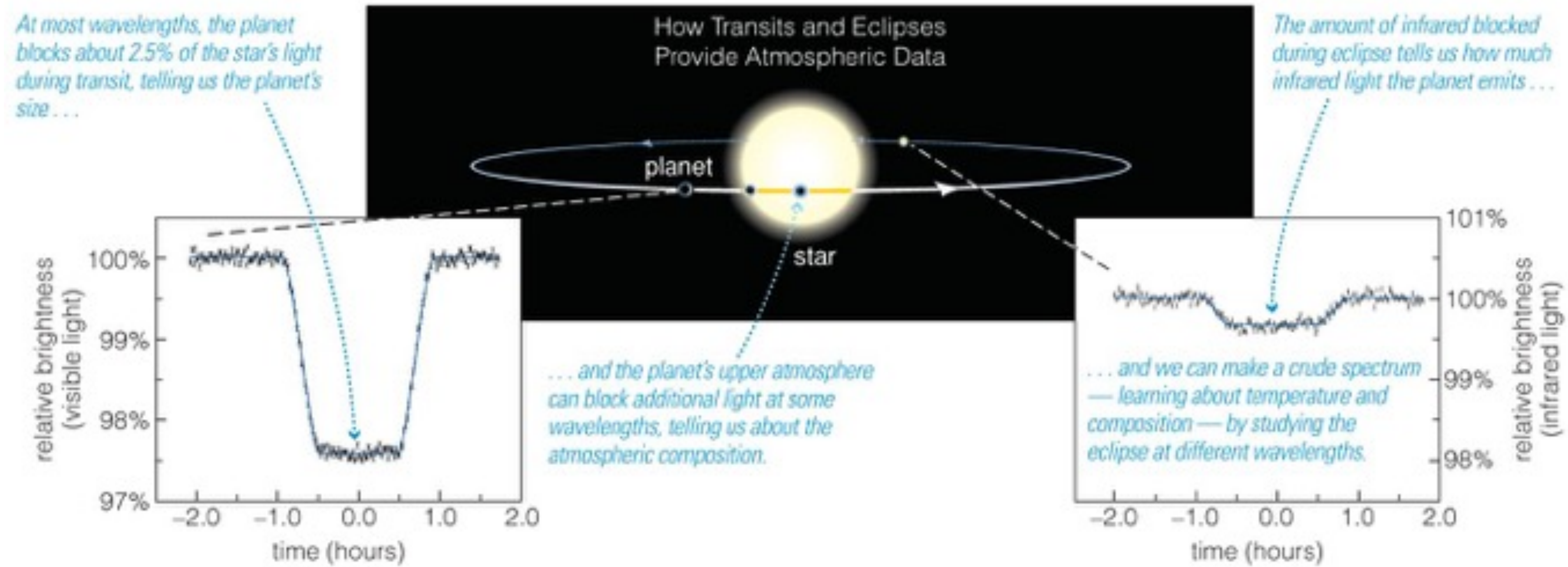
- The orbital periods and sizes of planets can be determined using transit data.

Combining Doppler and transit data

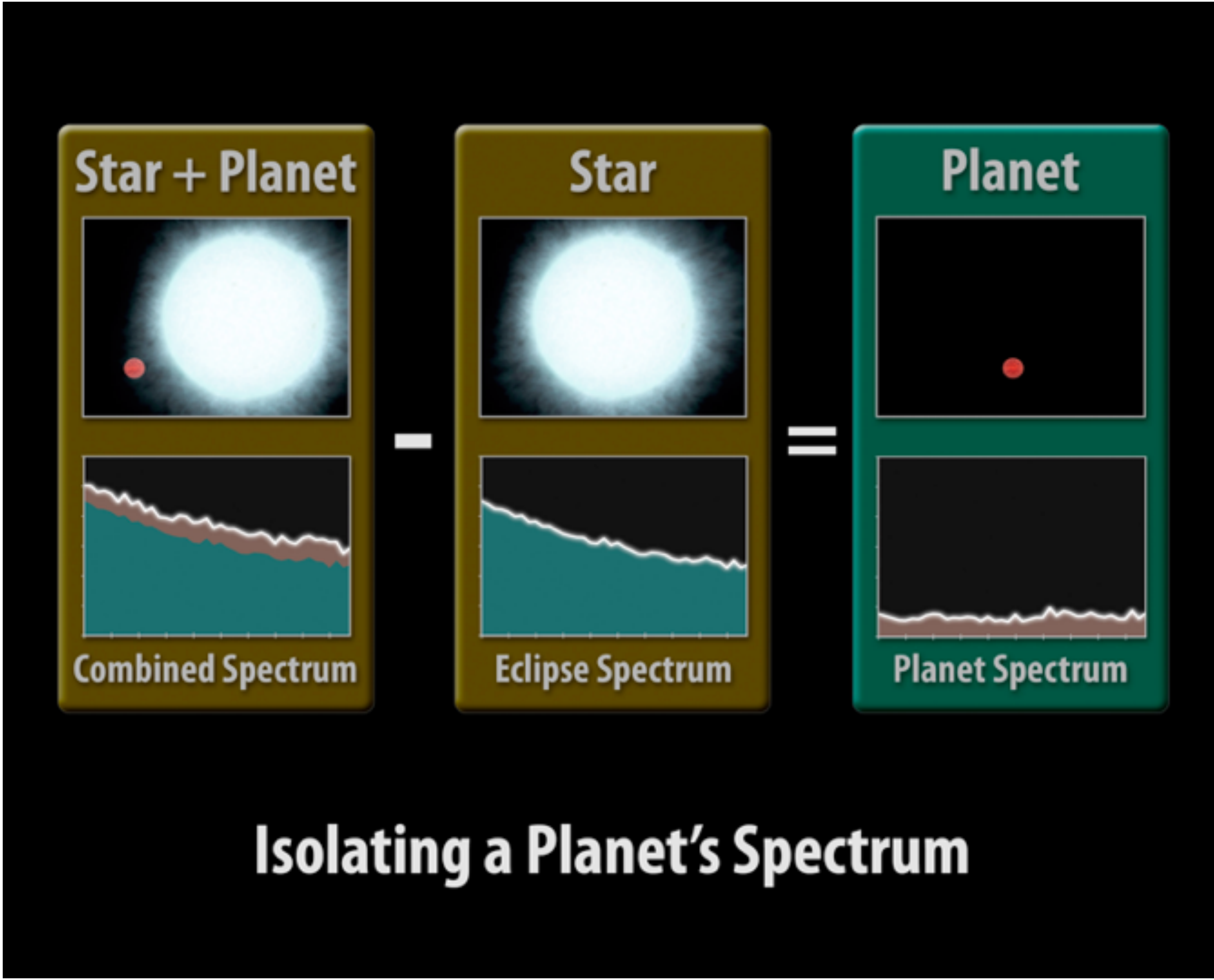
- Using mass, determined using the Doppler technique, and size, determined using the transit technique, density can be calculated.

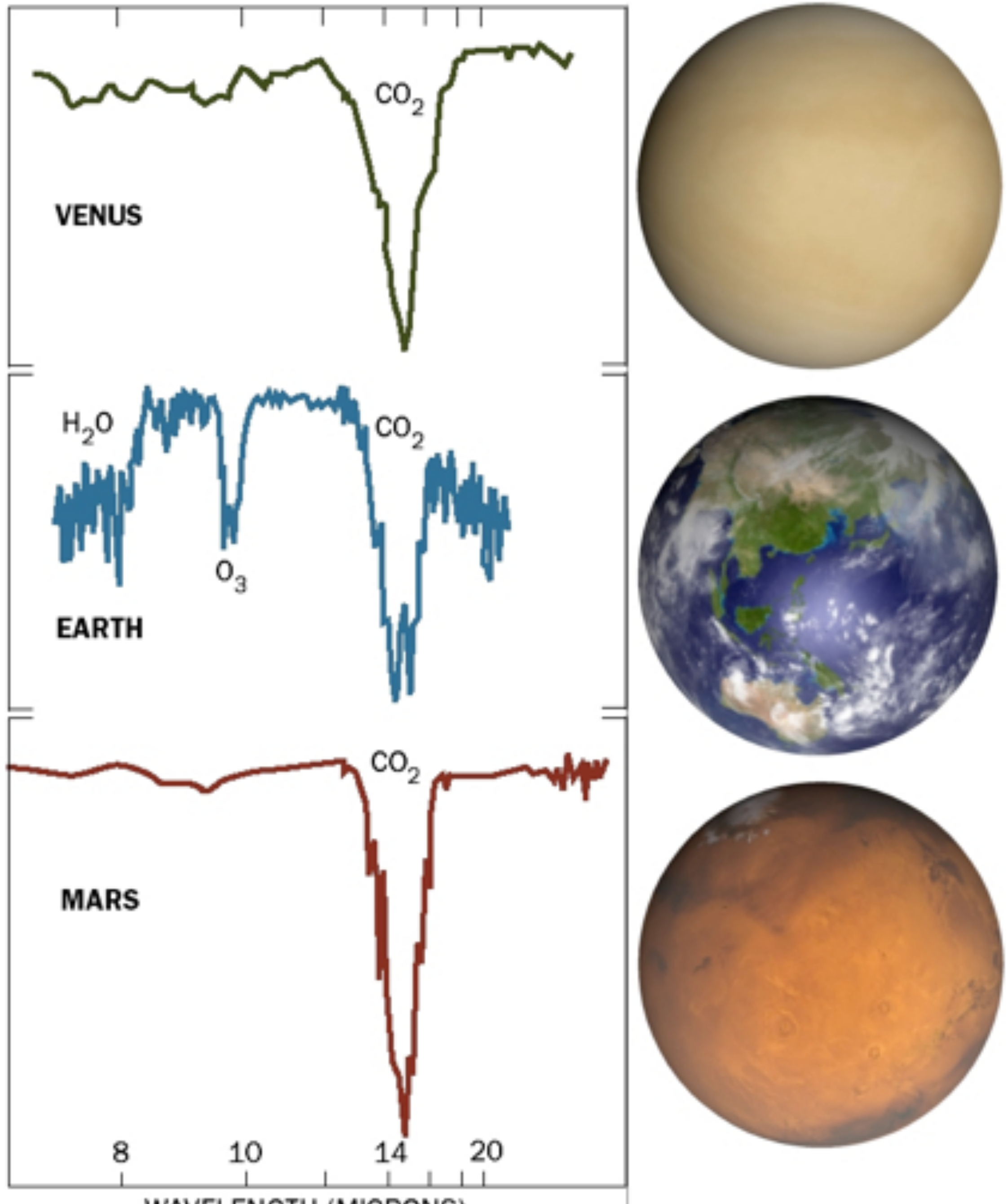


Planetary atmospheres



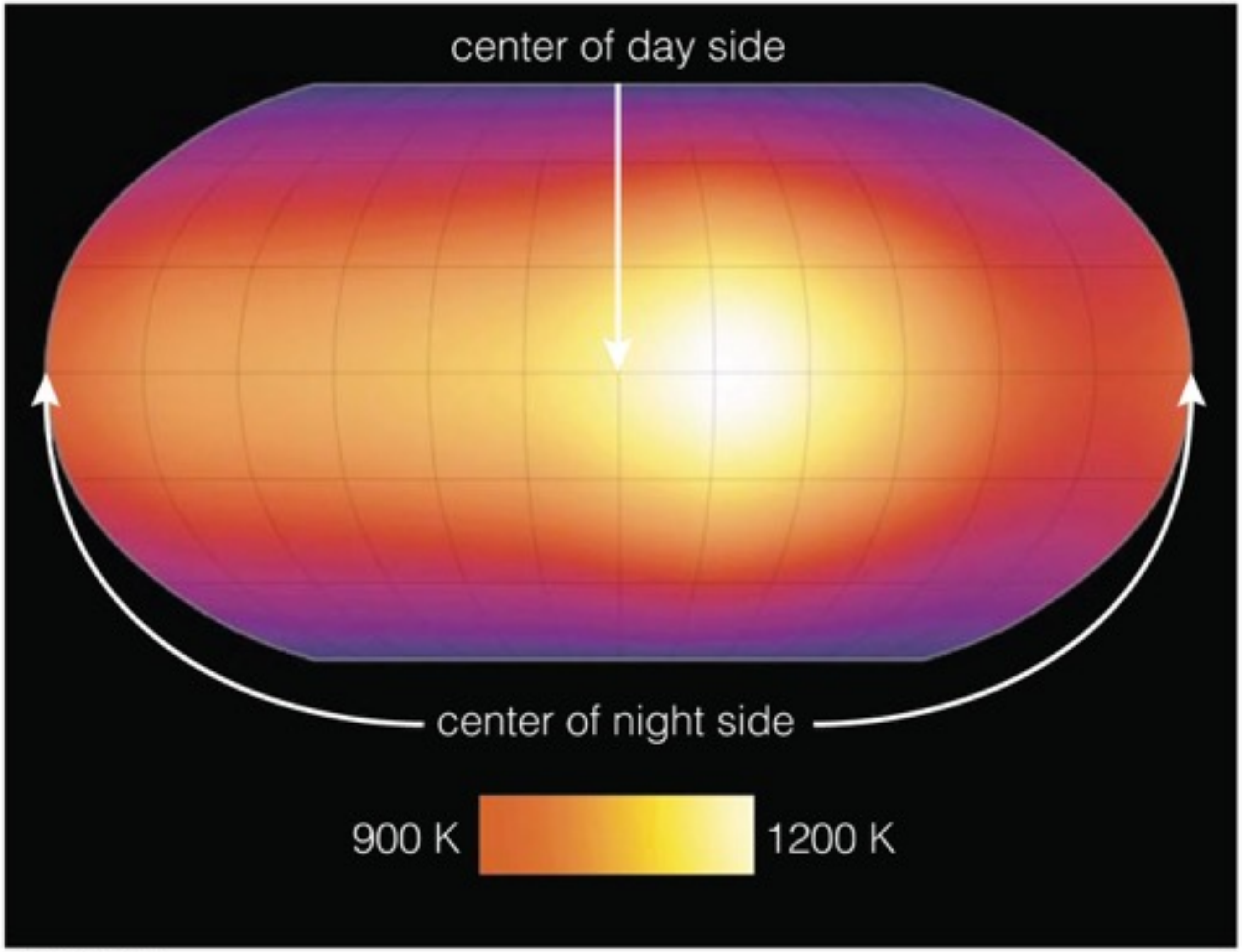
- Change in spectrum during a transit tells us about the composition of planet's atmosphere.


Star + Planet
Combined Spectrum
Star
Eclipse Spectrum
Planet
Planet Spectrum
Isolating a Planet's Spectrum



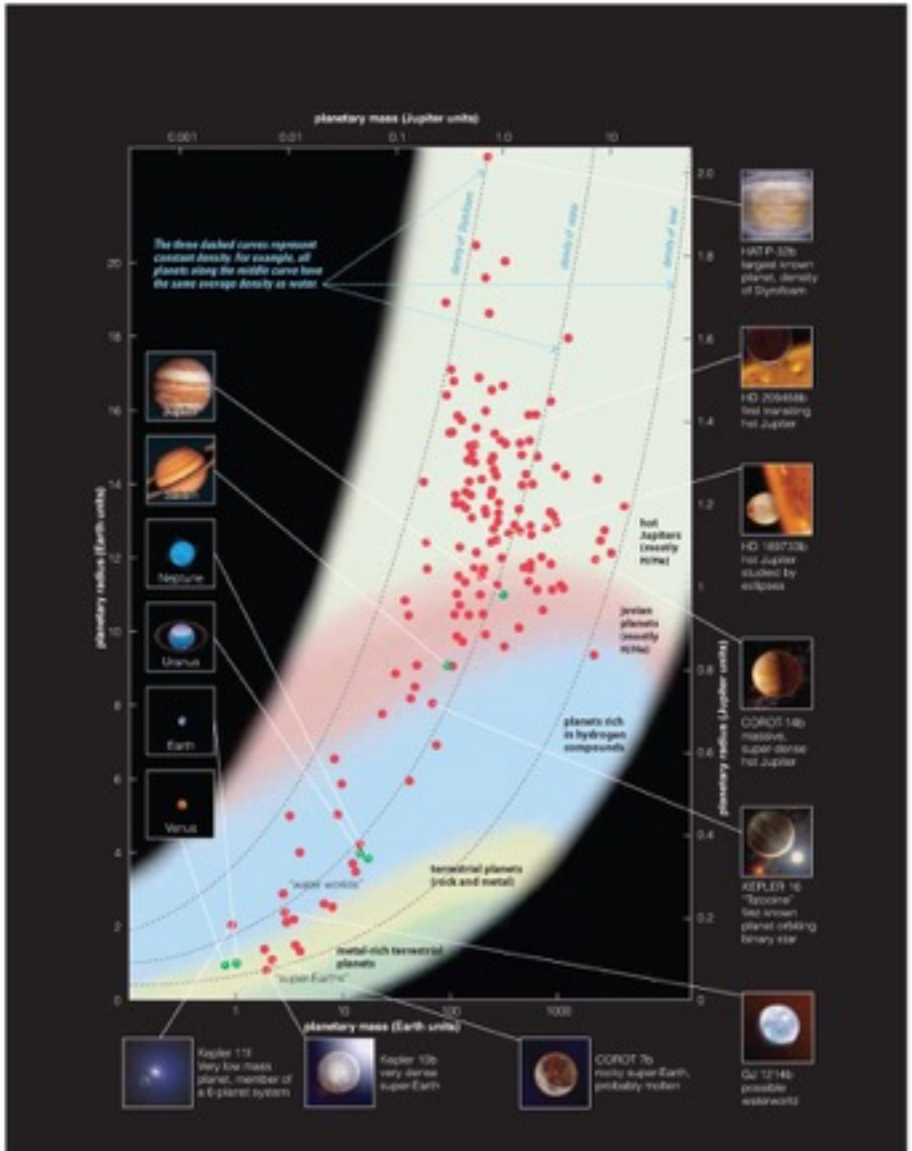
VENUS
CO_2
H_2O
CO_2
O_3
EARTH
CO_2
MARS
8
10
14
20
WAVELENGTH (MICRONS)

Surface Temperature Map

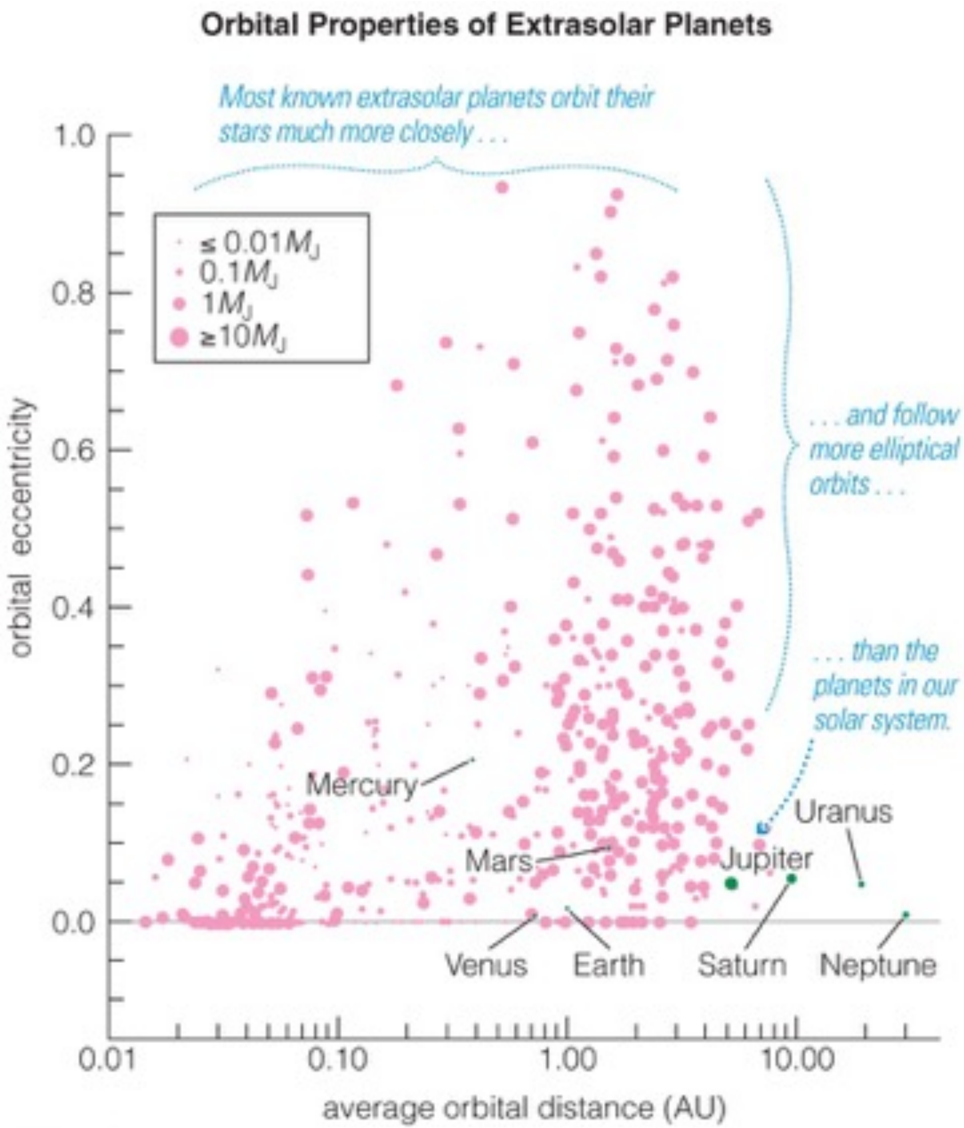


- Measuring the change in infrared brightness during an eclipse enables us to map a planet's surface temperature.

How do extrasolar planets compare with planets in our solar system?

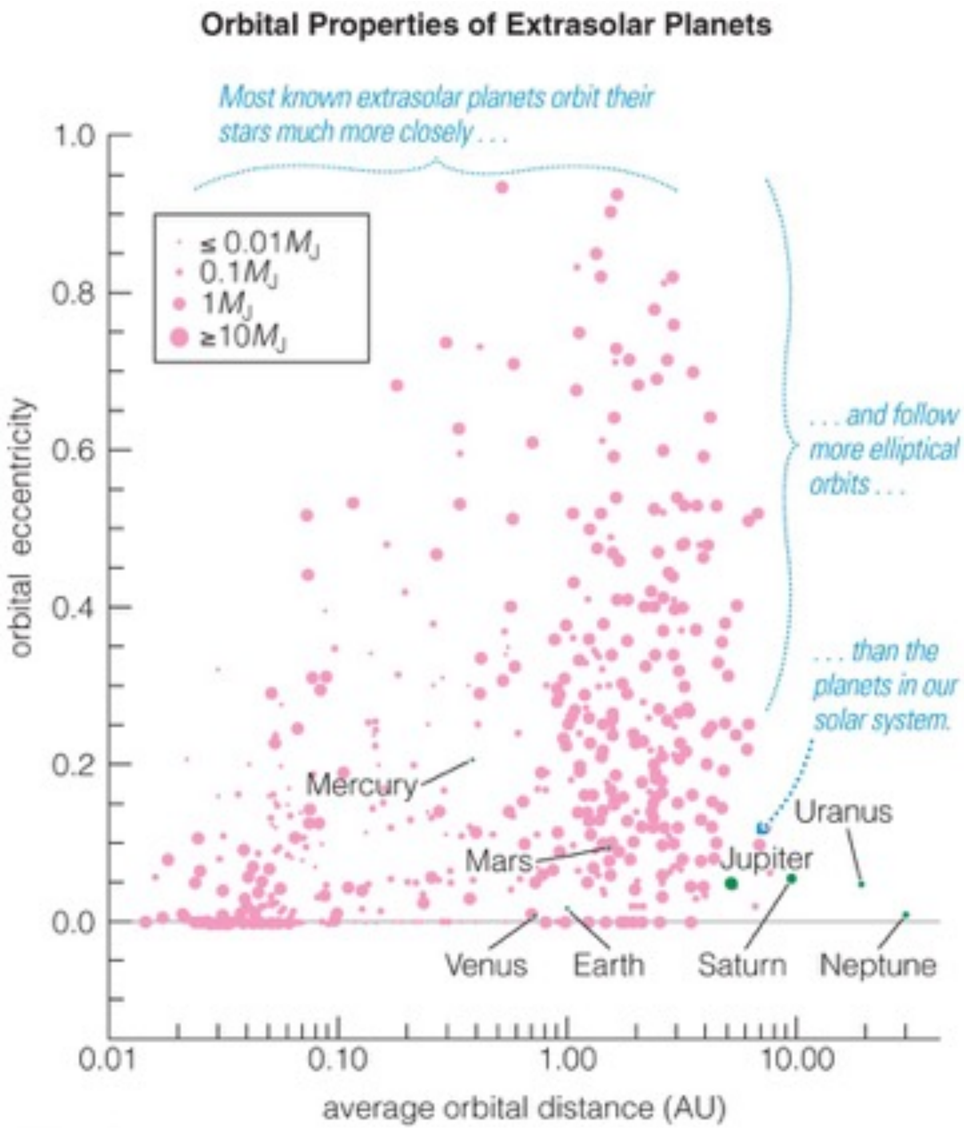


Orbits of Extrasolar Planets



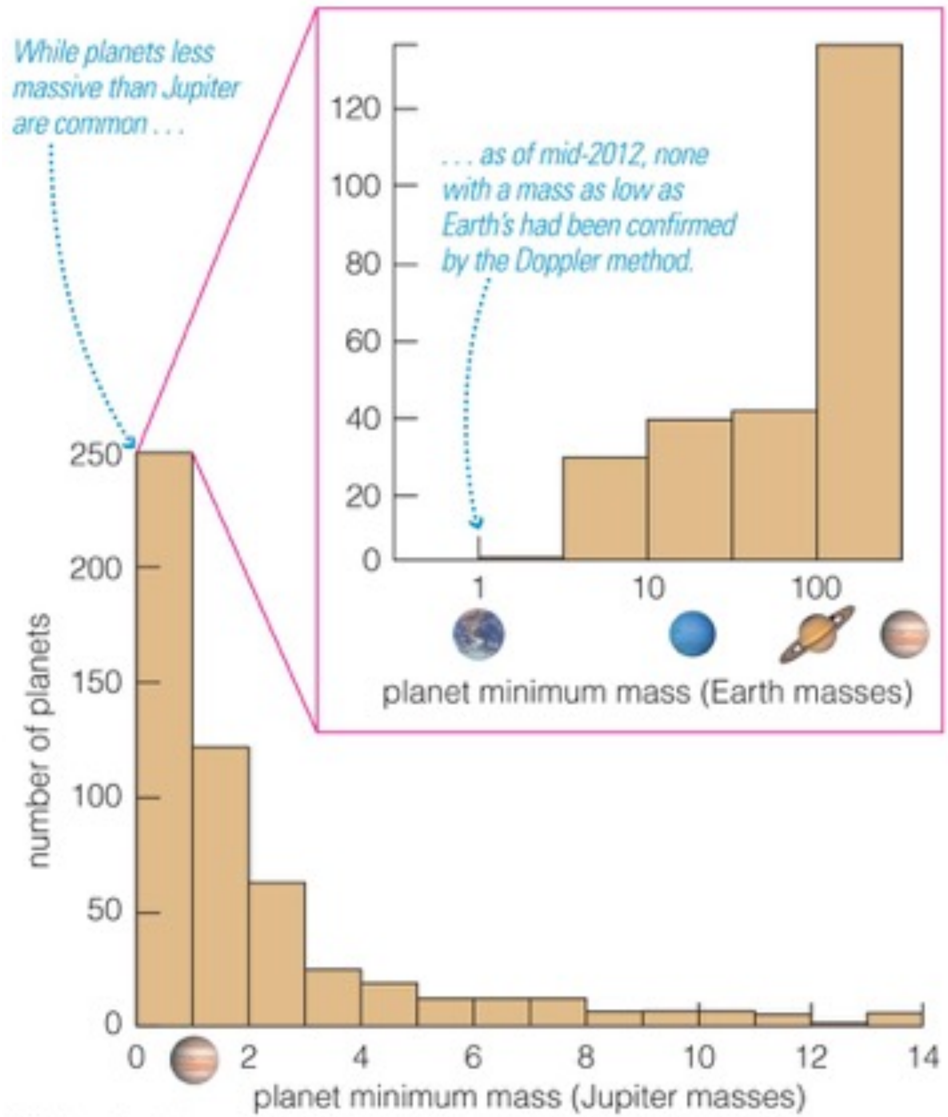
- Most of the detected planets have orbits smaller than Jupiter's.
- Planets at greater distances are harder to detect with the Doppler and transit methods.

Orbits of Extrasolar Planets



- Orbits of some extrasolar planets are much more elongated (have a greater eccentricity) than those in our solar system.

Orbits of Extrasolar Planets



- Most of the detected planets have greater mass than Jupiter.
- Planets with smaller masses are harder to detect with Doppler technique.

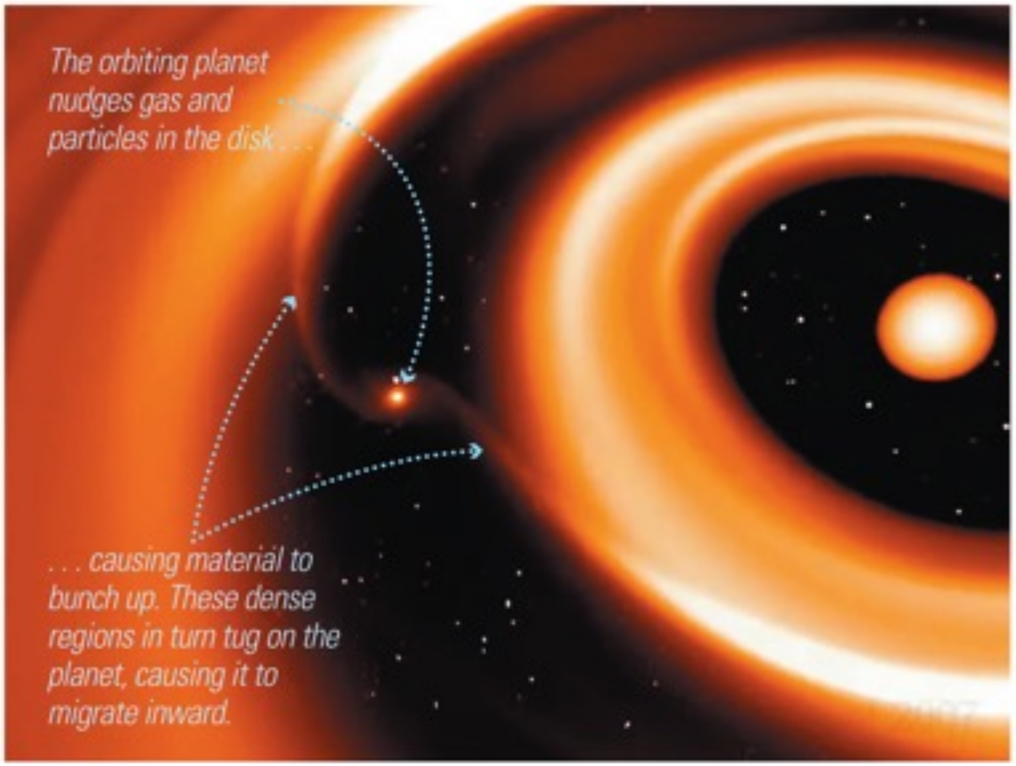
Surprising Characteristics

- Some extrasolar planets have highly elliptical orbits.
- Planets show huge diversity in size and density.
- Some massive planets, called *hot Jupiters*, orbit very close to their stars.

Revisiting the Nebular Theory

- The nebular theory predicts that massive Jupiter-like planets should not form inside the frost line (at << 5 AU).
- The discovery of hot Jupiters has forced reexamination of nebular theory.
- *Planetary migration* or gravitational encounters may explain hot Jupiters.

Planetary Migration



- A young planet's motion can create waves in a planet-forming disk.
- Models show that matter in these waves can tug on a planet, causing its orbit to migrate inward.

Gravitational Encounters and Resonances

- Close gravitational encounters between two massive planets can eject one planet while flinging the other into a highly elliptical orbit.
- Multiple close encounters with smaller planetesimals can also cause inward migration.
- Resonances may also contribute.

Thought Question

What happens in a gravitational encounter that allows a planet's orbit to move inward?

A. It transfers energy and angular momentum to another object.
B. The gravity of the other object forces the planet to move inward.
C. It gains mass from the other object, causing its gravitational pull to become stronger.

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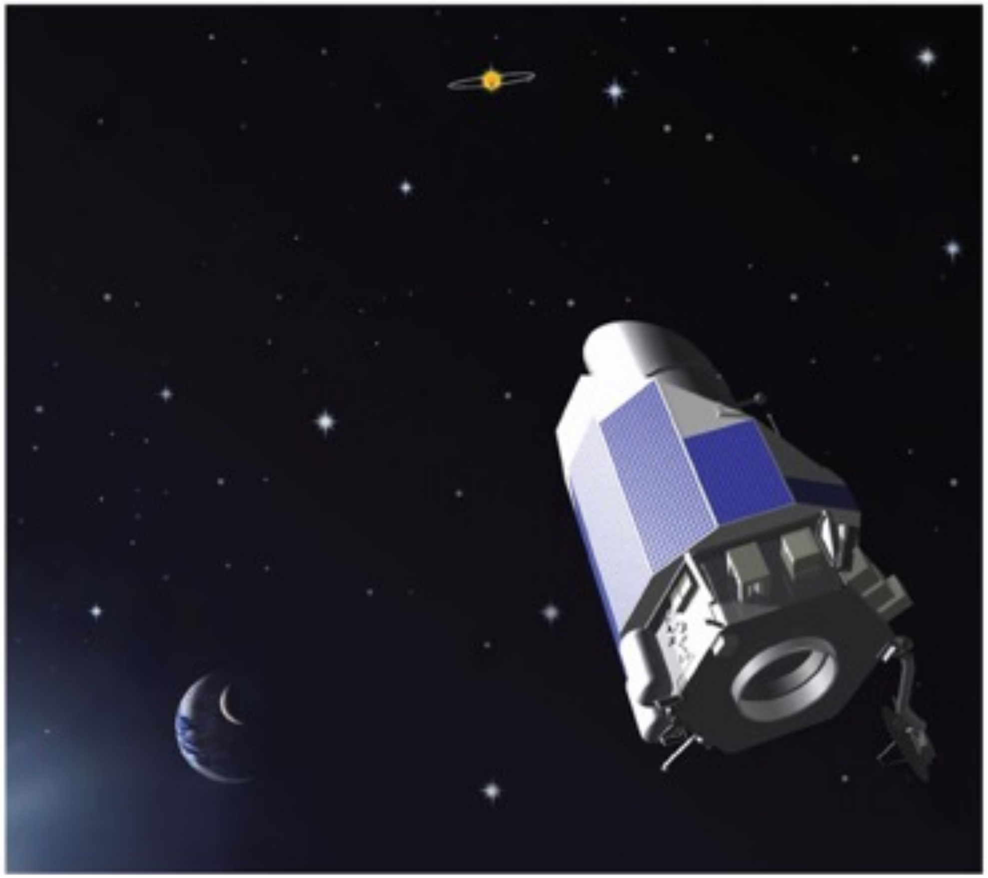
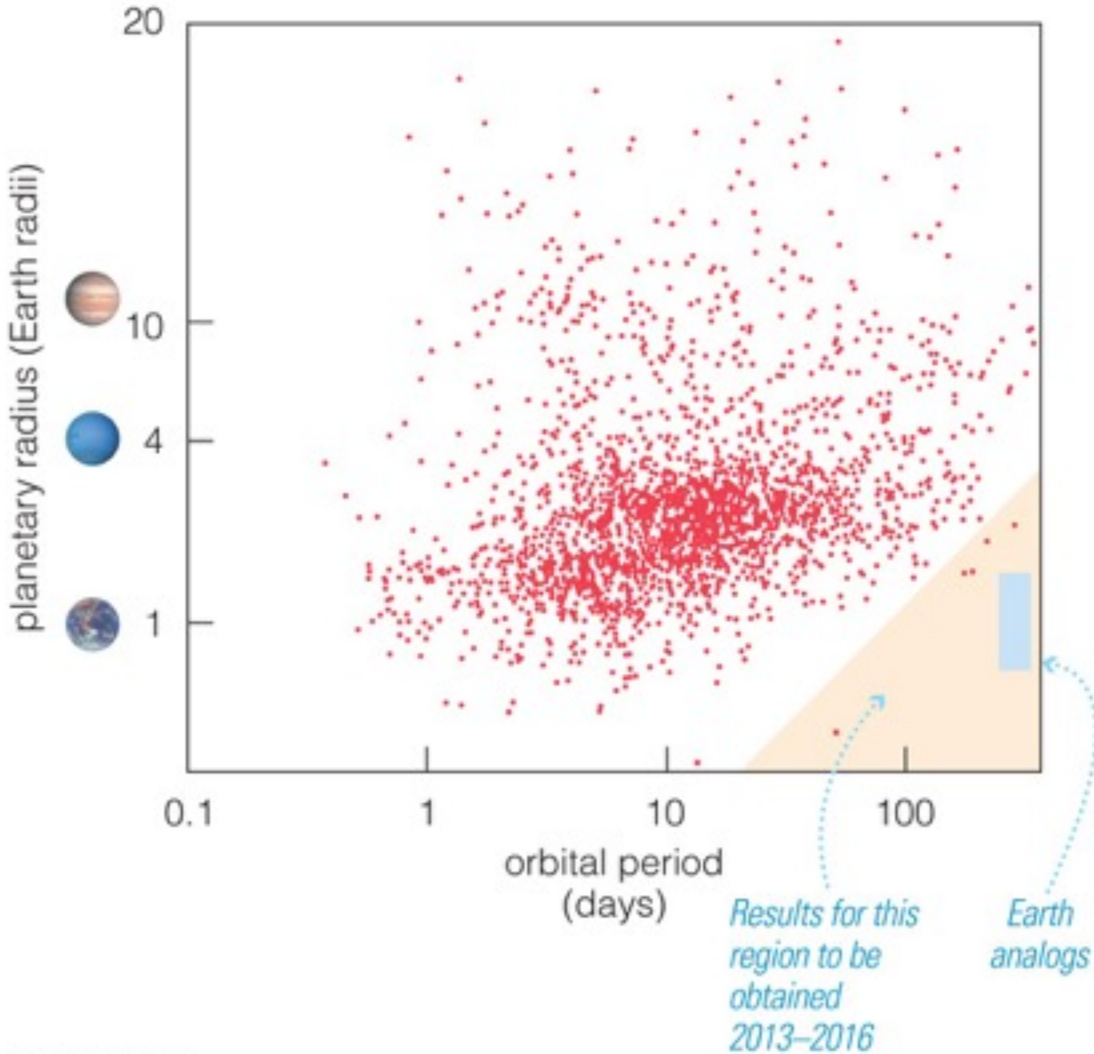
Kepler



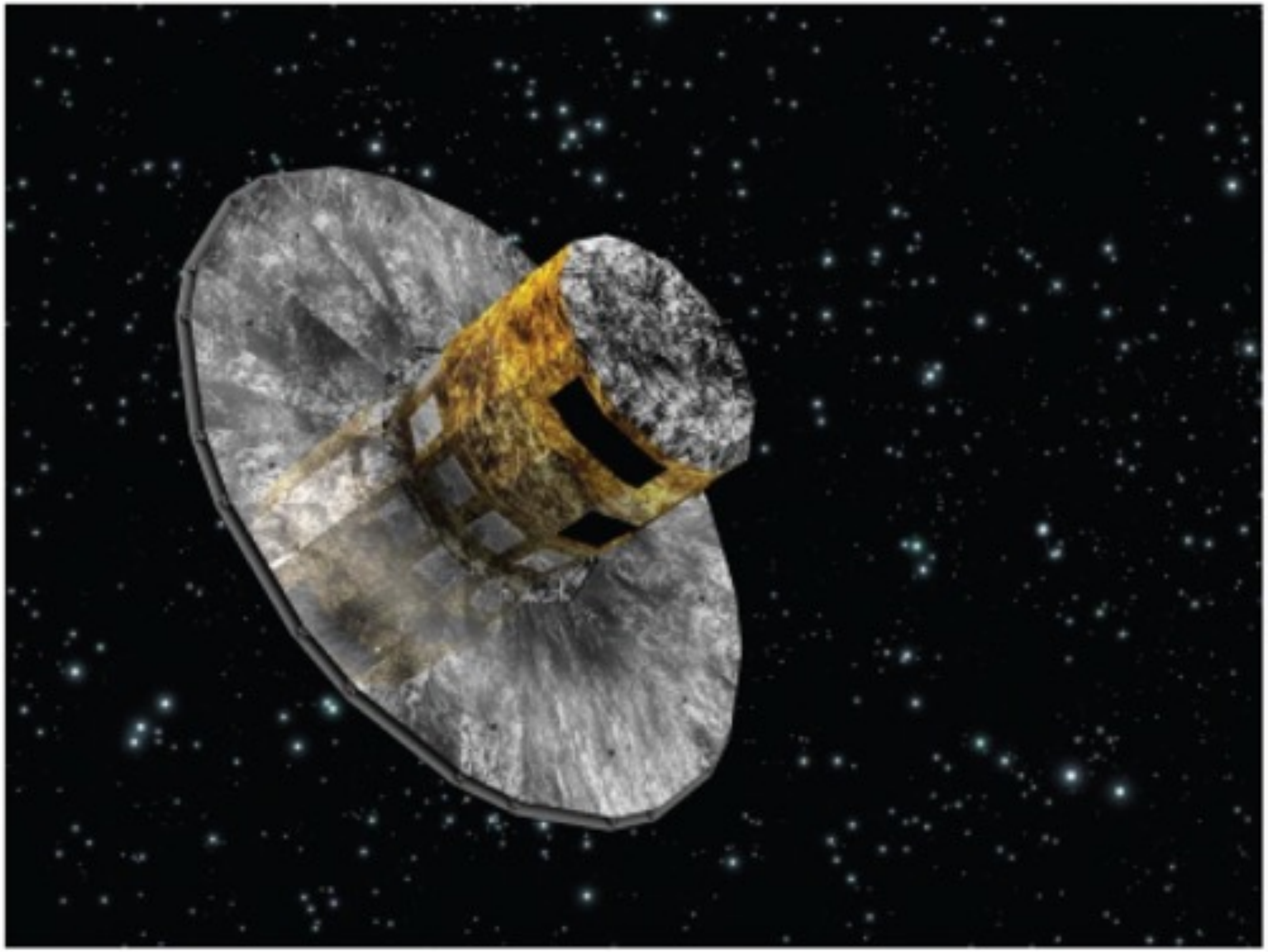
- NASA's *Kepler* mission was launched in 2009 to begin looking for transiting planets.
- It was designed to measure the 0.008% decline in brightness when an Earth-mass planet eclipses a Sun-like star.
- Reaction wheel failed in 2013.

Kepler mission



- The bottom right portion of the graph, where truly Earth-like planets reside, was supposed to be filled in by *Kepler*

GAIA mission



- *GAIA,* launched in 2013, will use interferometry to measure precise motions of a billion stars