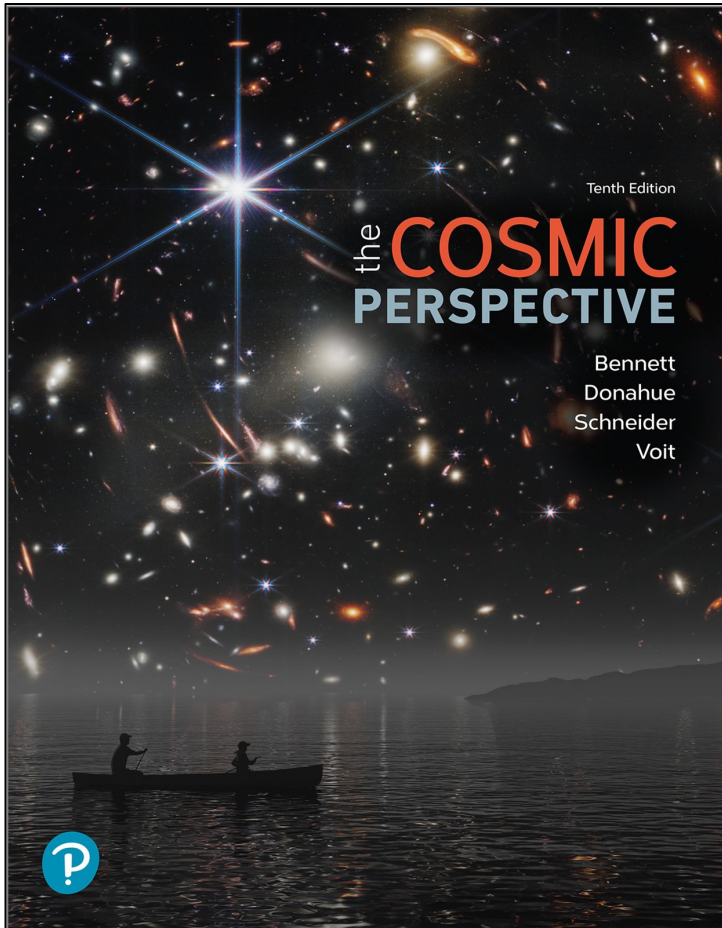


The Cosmic Perspective

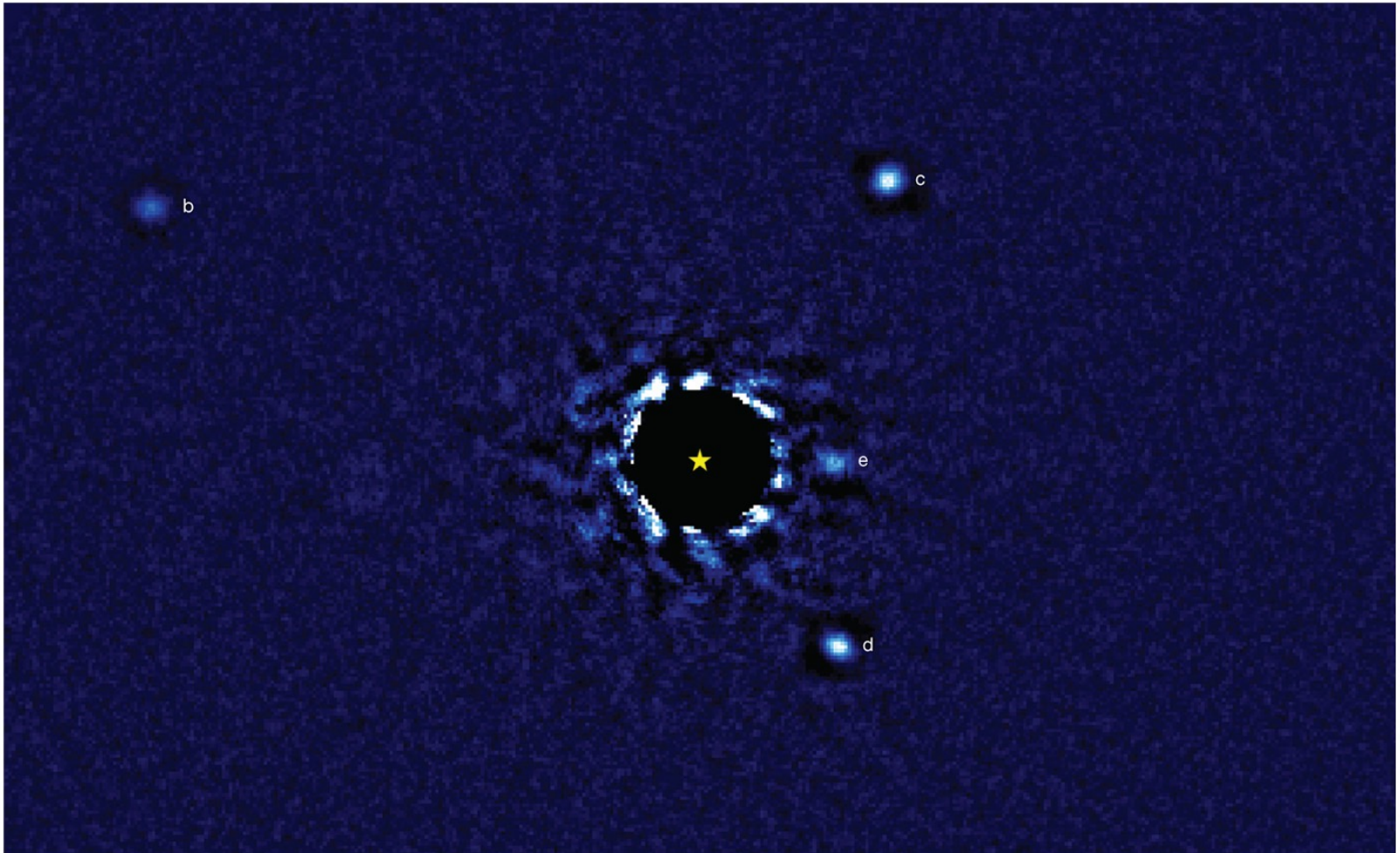
Tenth Edition



Chapter 13 Lecture

Exoplanets: The New
Science of Distant
Worlds

Detecting Planets Around Other Stars



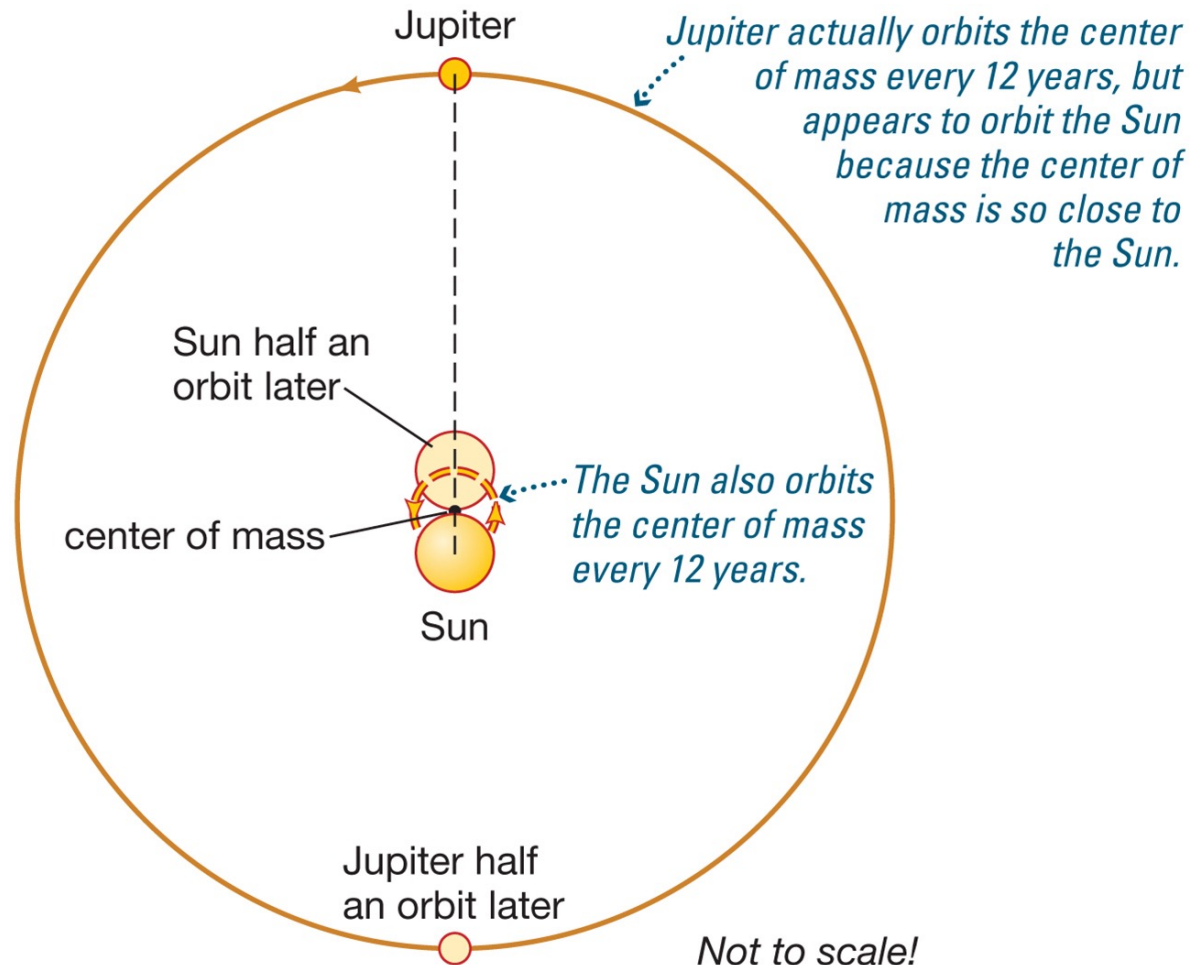
13.1 Detecting Planets Around Other Stars

- Our goals for learning:
 - **Why is it so challenging to learn about exoplanets?**
 - **How can a star's motion reveal the presence of planets?**
 - **How can changes in a star's brightness reveal the presence of 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.

How Can a Star's Motion Reveal the Presence of Planets?

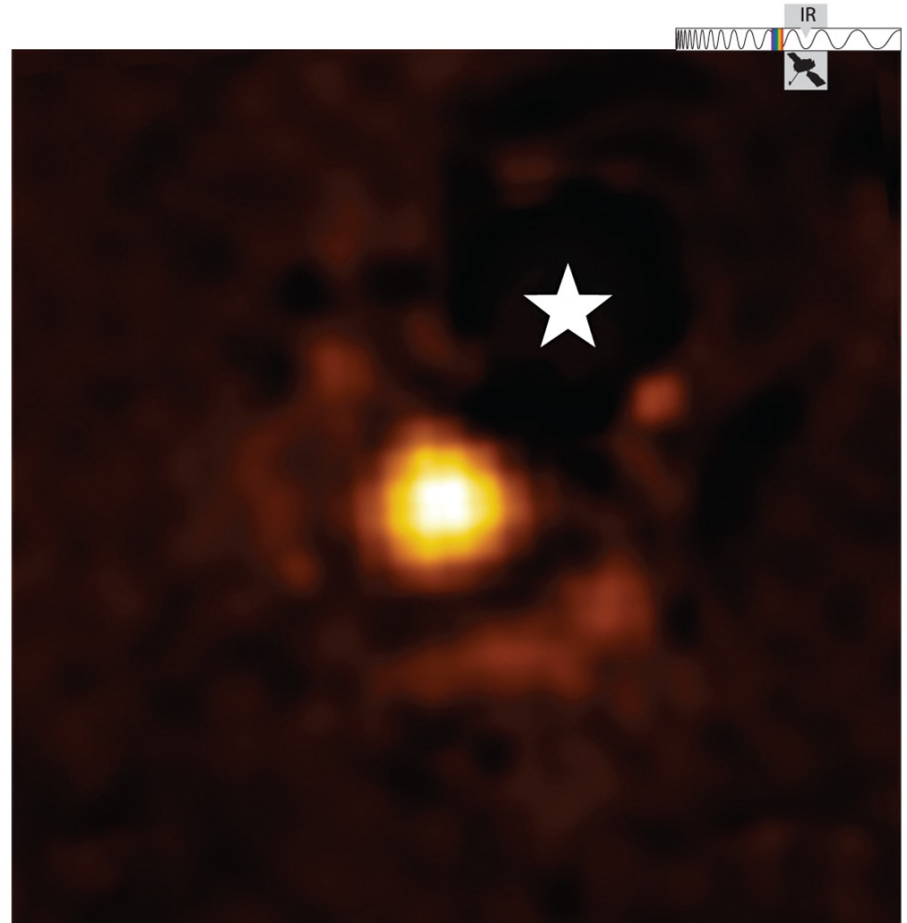


Planet Detection

- **Direct:** Pictures or spectra of the planets themselves:
 - Technology has made great improvements in this.
 - Opening **infrared image** is from the Keck Telescope.
 - The upcoming Extremely Large Telescope (ELT) should be capable of detecting Earth-sized planets.
- **Indirect:** Measurements of stellar properties revealing the effects of orbiting planets:
 - Observing the motion of a star to detect planets
 - Astrometric:** Looking for change in star's position
 - Doppler method:** Measuring Doppler shift over time
 - **Transit method:** Measuring changes in star's brightness when a planet passes in front of the star

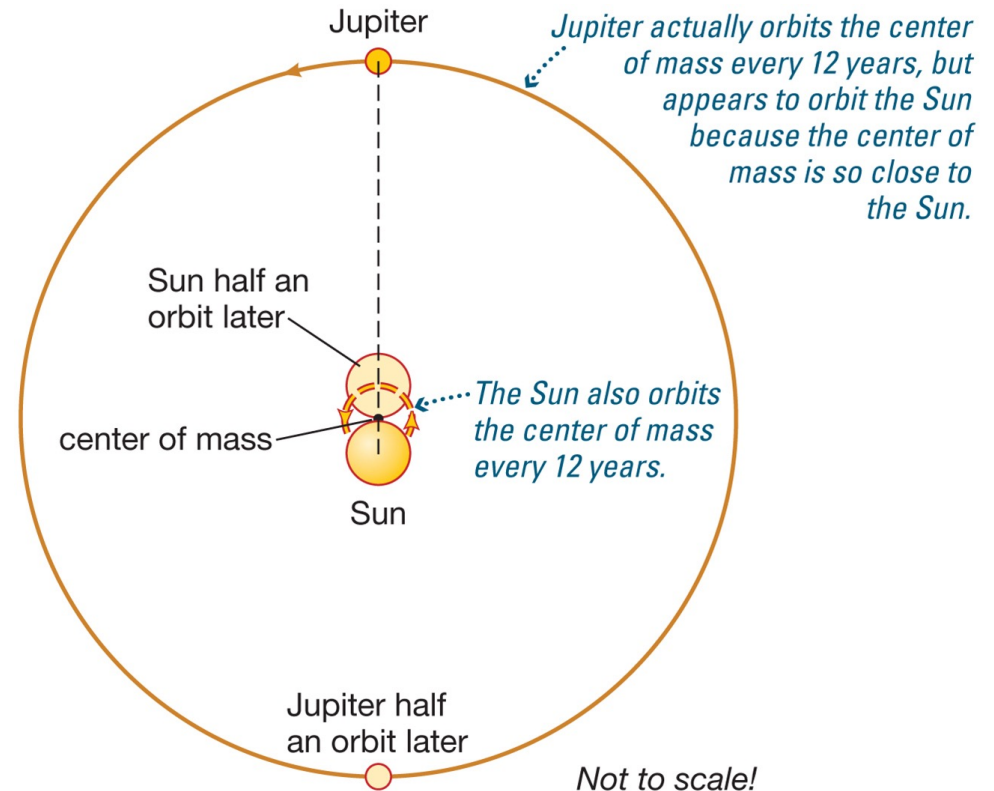
Direct Detection of Extrasolar Planets

- An exoplanet (HIP 65426b) detected with the James Webb Space Telescope (JWST).
- The blobs around the planet are artifacts of the camera and processing.
- The light from the star is blocked with a **coronagraph**.



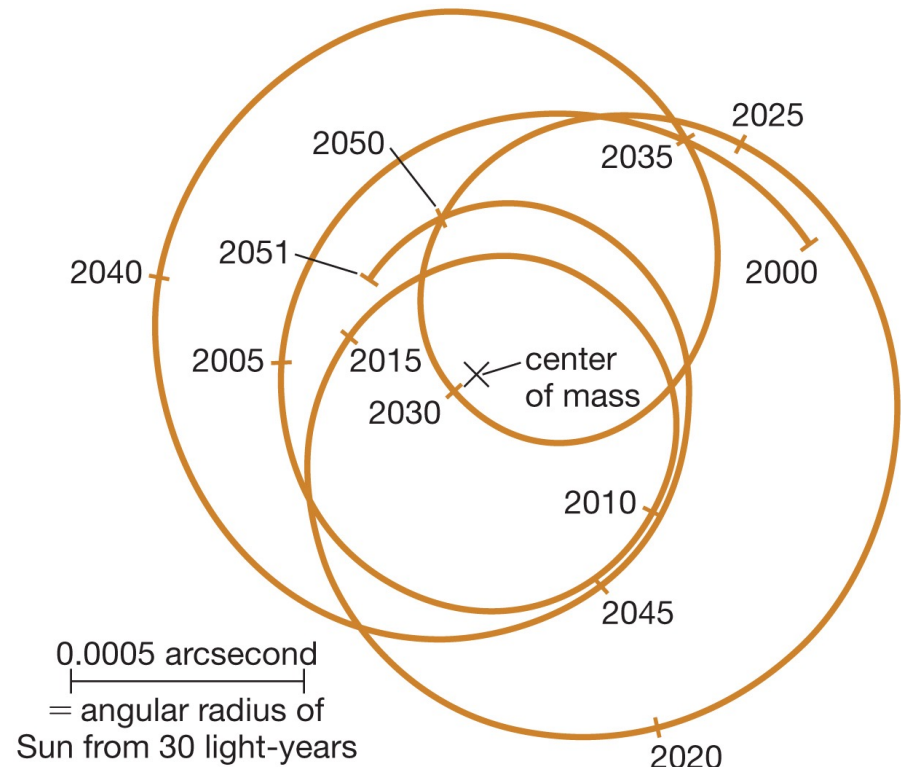
Gravitational Tugs (1 of 2)

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



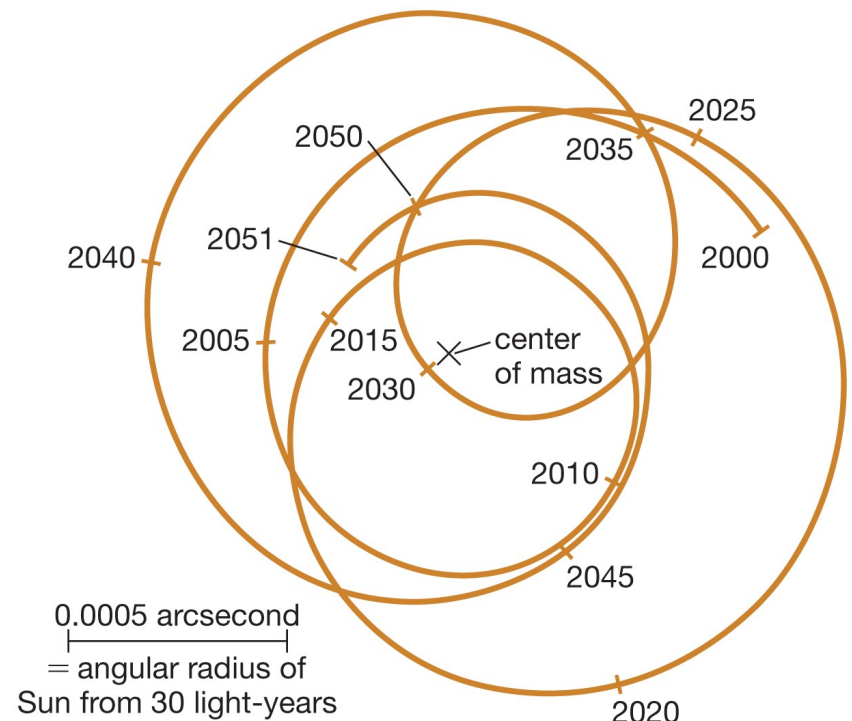
Gravitational Tugs (2 of 2)

- 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.



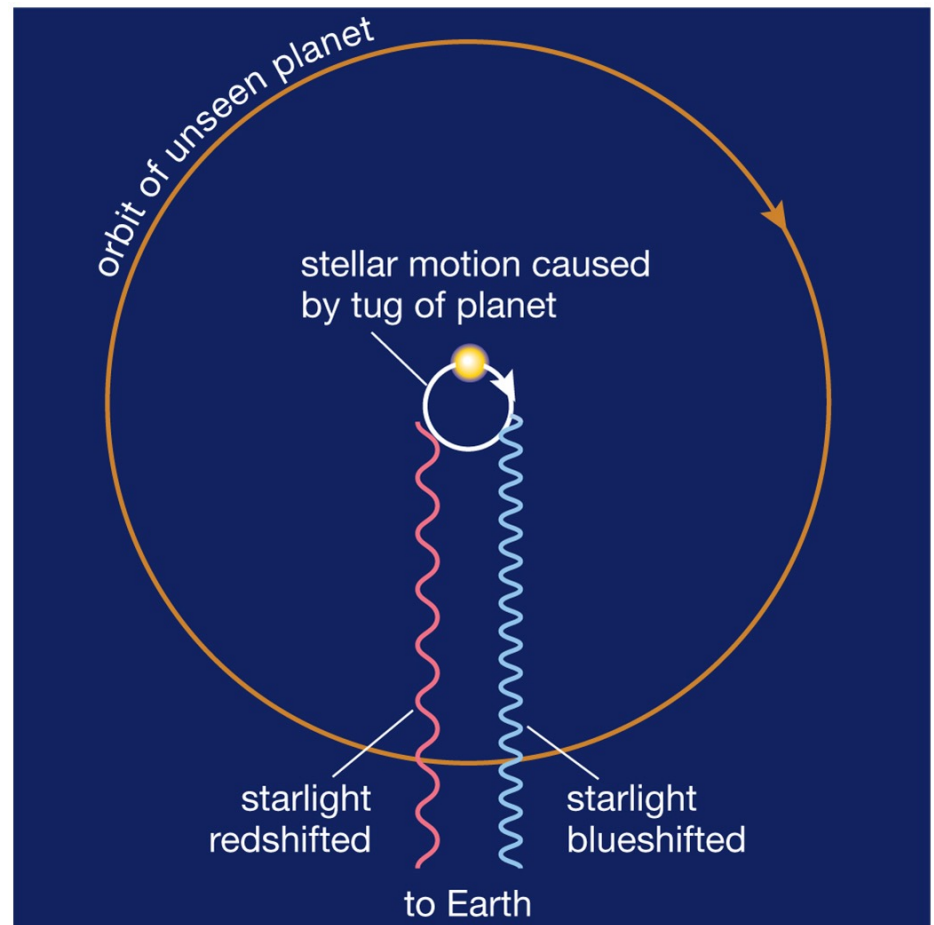
Astrometric Technique

- We can detect planets by measuring the change in a star's position in the sky.
- However, these tiny motions are very difficult to measure (~ 0.001 arcsecond).
- Analysis of data from GAIA spacecraft has detected 72 candidates (as of mid-2022).



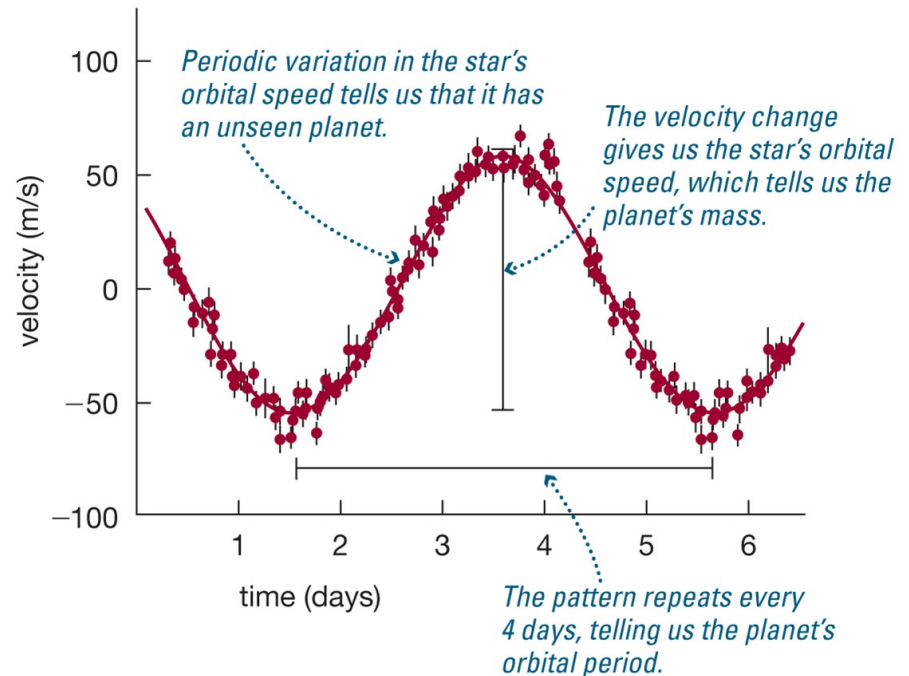
Doppler Technique

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



First Extrasolar Planet (1 of 2)

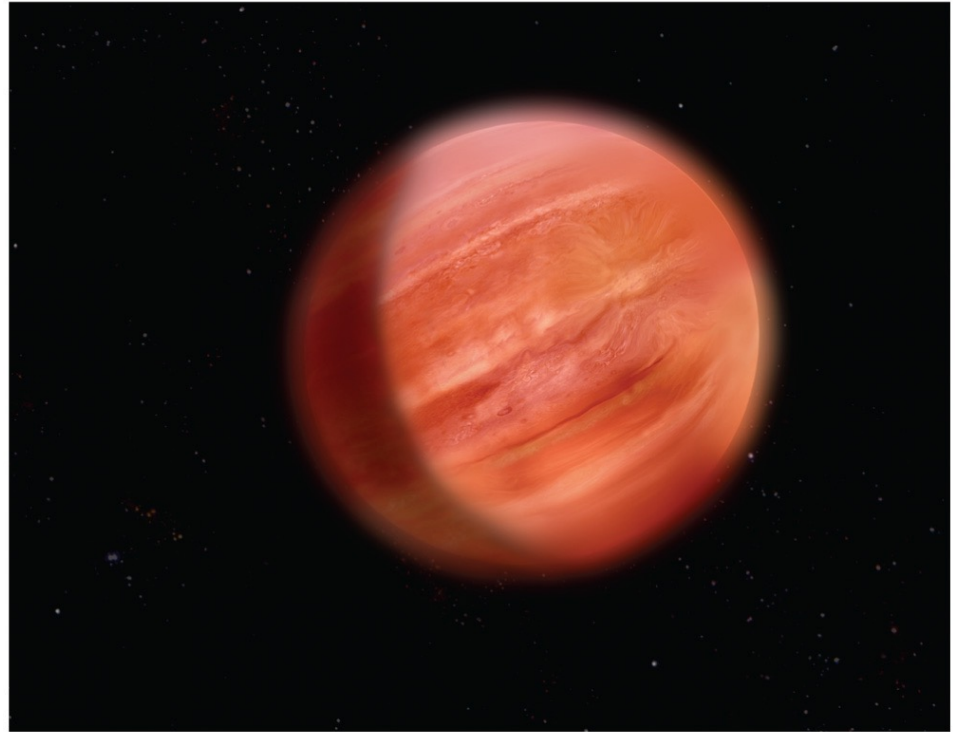
- Doppler shifts of the star 51 Pegasi indirectly revealed a planet with a 4-day orbital period.
- This short period means that the planet has a small orbital distance.
- This was the first extrasolar planet to be discovered around a Sun-like star (1995).



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.

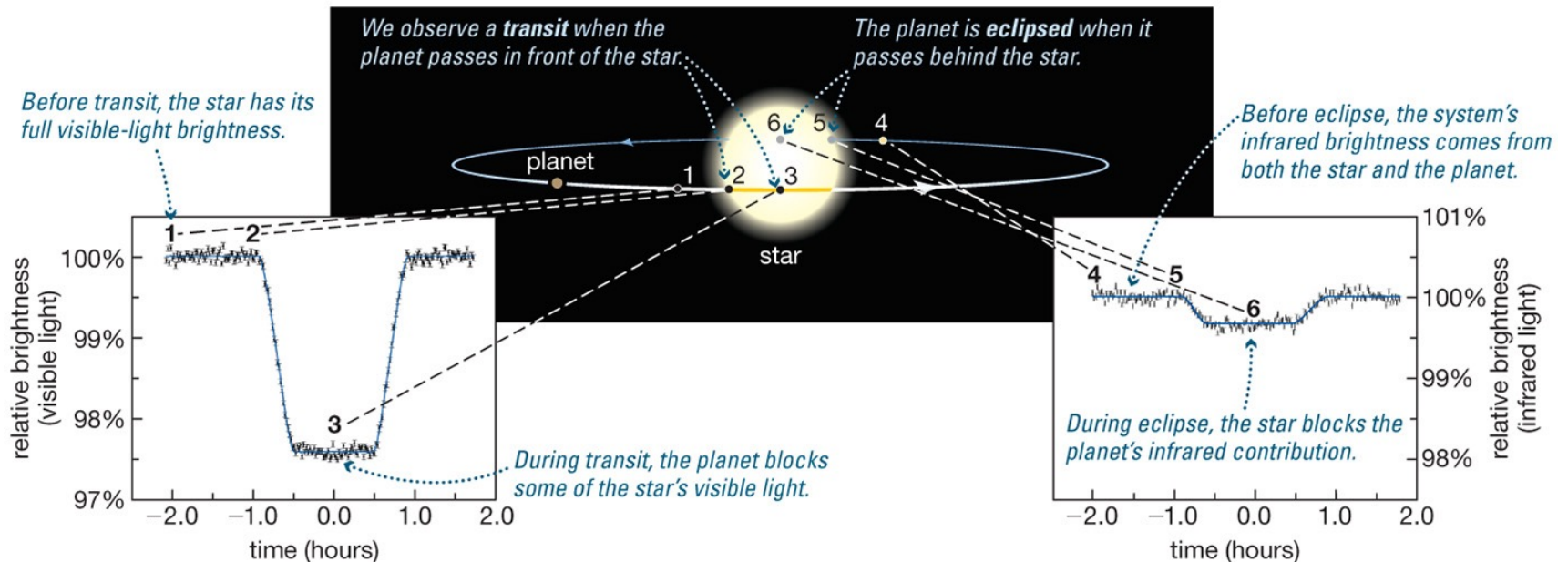
First Extrasolar Planet (2 of 2)

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

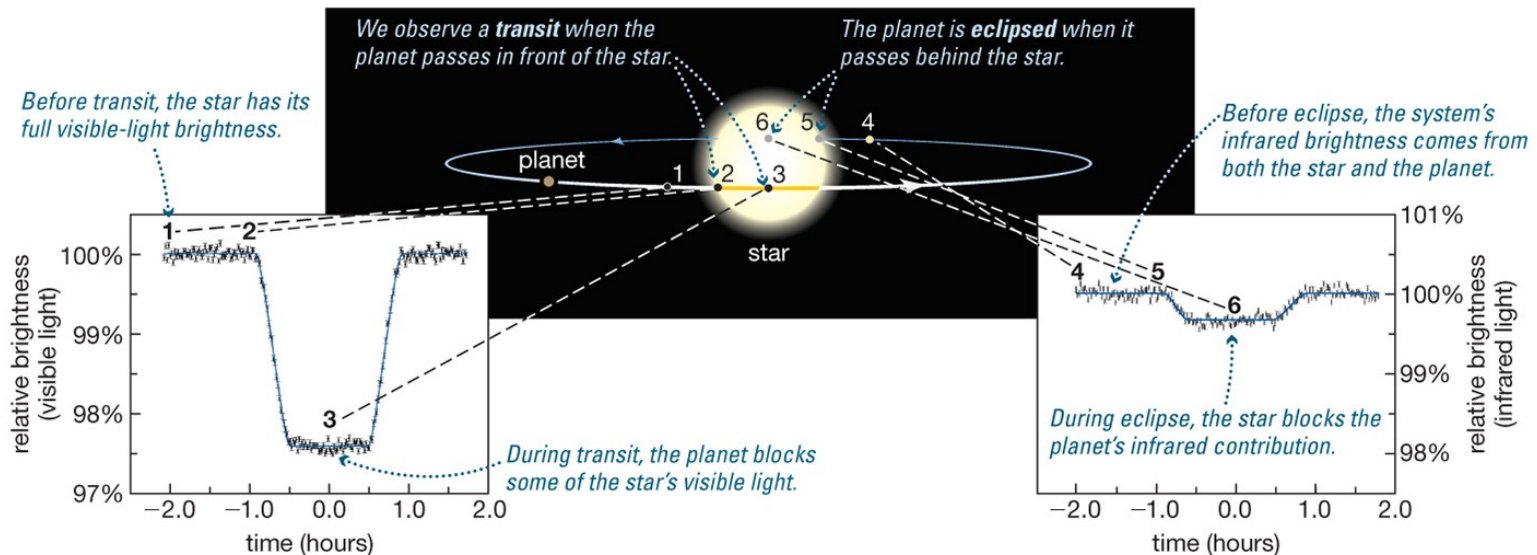


b Artist's conception of the planet orbiting 51 Pegasi, which probably has a mass similar to that of Jupiter but orbits its star at only about one-eighth of Mercury's orbital distance from the Sun. It probably has a surface temperature above 1000 K, making it an example of what we call a hot Jupiter.

How Can Changes in a Star's Brightness Reveal the Presence of Planets?



Transits and Eclipses



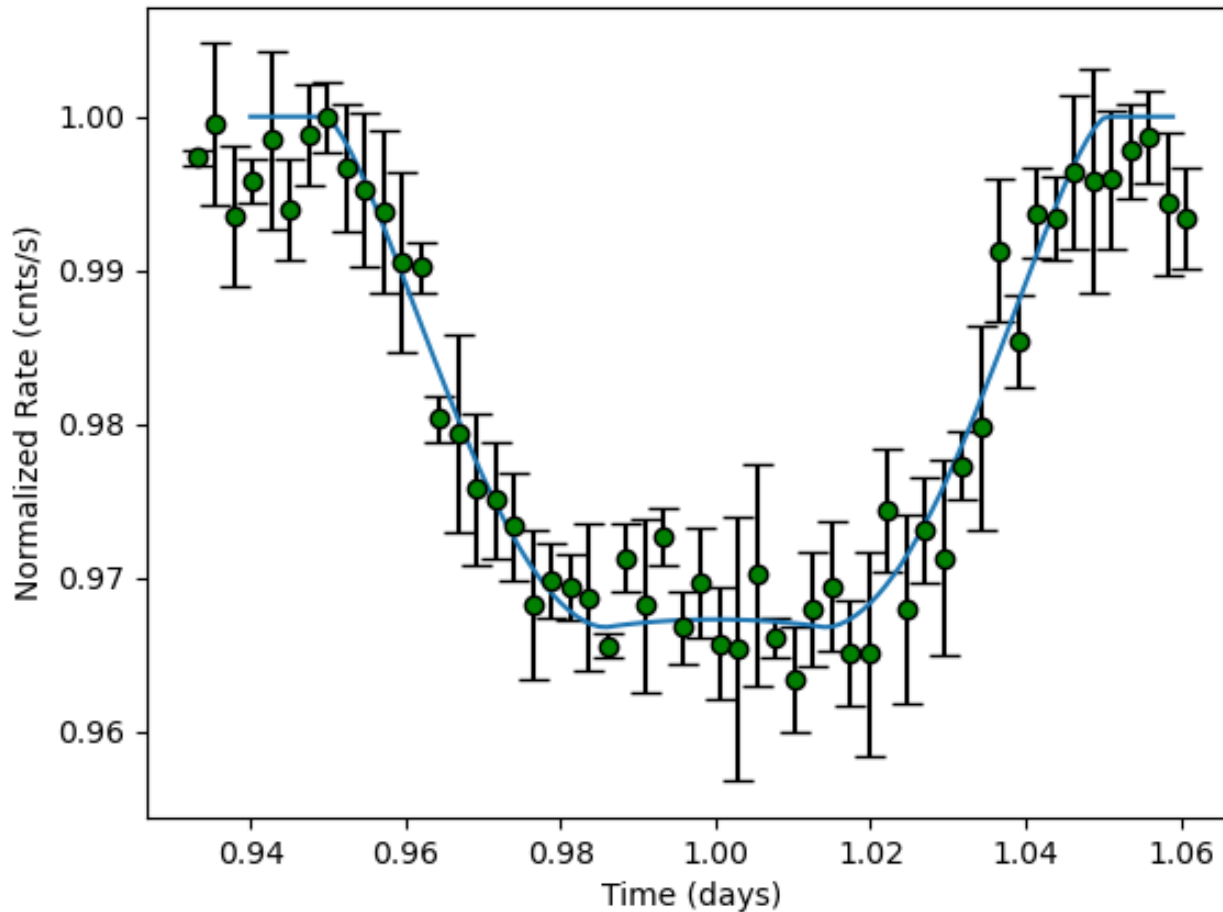
- A **transit** is when a planet crosses in front of a star, resulting in a dip in brightness.
- An **eclipse** is also sometimes seen, when the planet passes behind the star.
- No orbital tilt: accurate measurement of planet mass

Kepler

- NASA's **Kepler** mission was launched in 2008 and gathered data for more than 9 years.
- It is designed to measure the 0.008% decline in brightness when an Earth-mass planet eclipses a Sun-like star.
- It has found over 3200 confirmed planets as of 2022.

TES

- NASA's **TESS (Transiting Exoplanet Survey Satellite)** mission was launched in 2018 and added more than 200 confirmed planets (as of mid-2022).
- Thousands of candidate planets from both missions await confirmation by other methods.
- Some transits can even be seen through small personal telescopes.
 - A telescope as small as 3 inches in diameter has been used to discover an extrasolar planet!

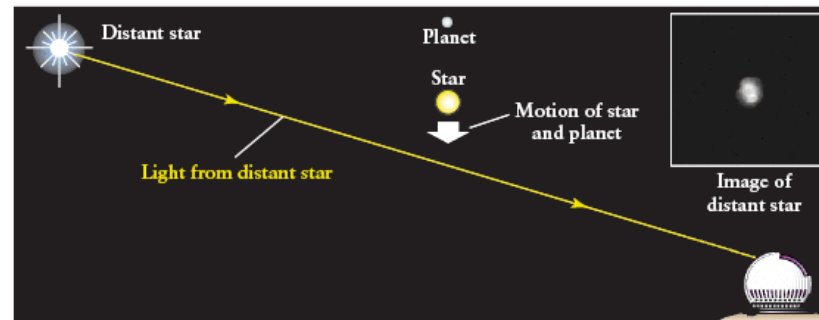


The transit of exoplanet WASP-10b observed with the CofC 0.6-meter telescope

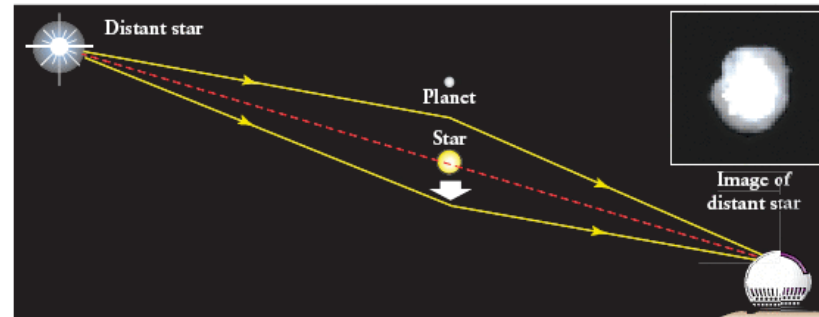
Other Planet-Hunting Strategies

- **Microlensing:** Mass bends light in a special way when a star with planets passes in front of another star.
- **Features in Dust Disks:** Gaps, waves, or ripples in disks of dusty gas around stars can indicate presence of planets.

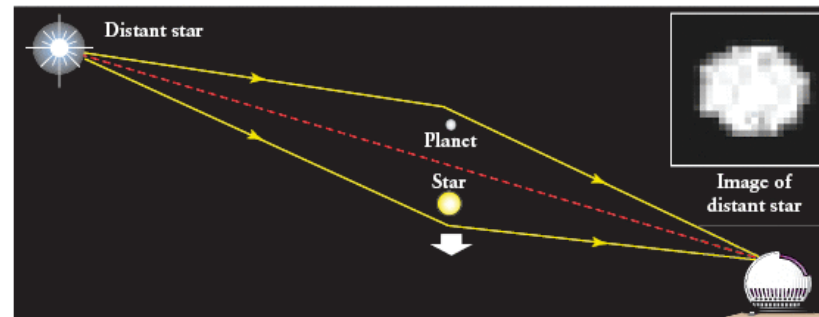
Other Planet-Hunting Strategies



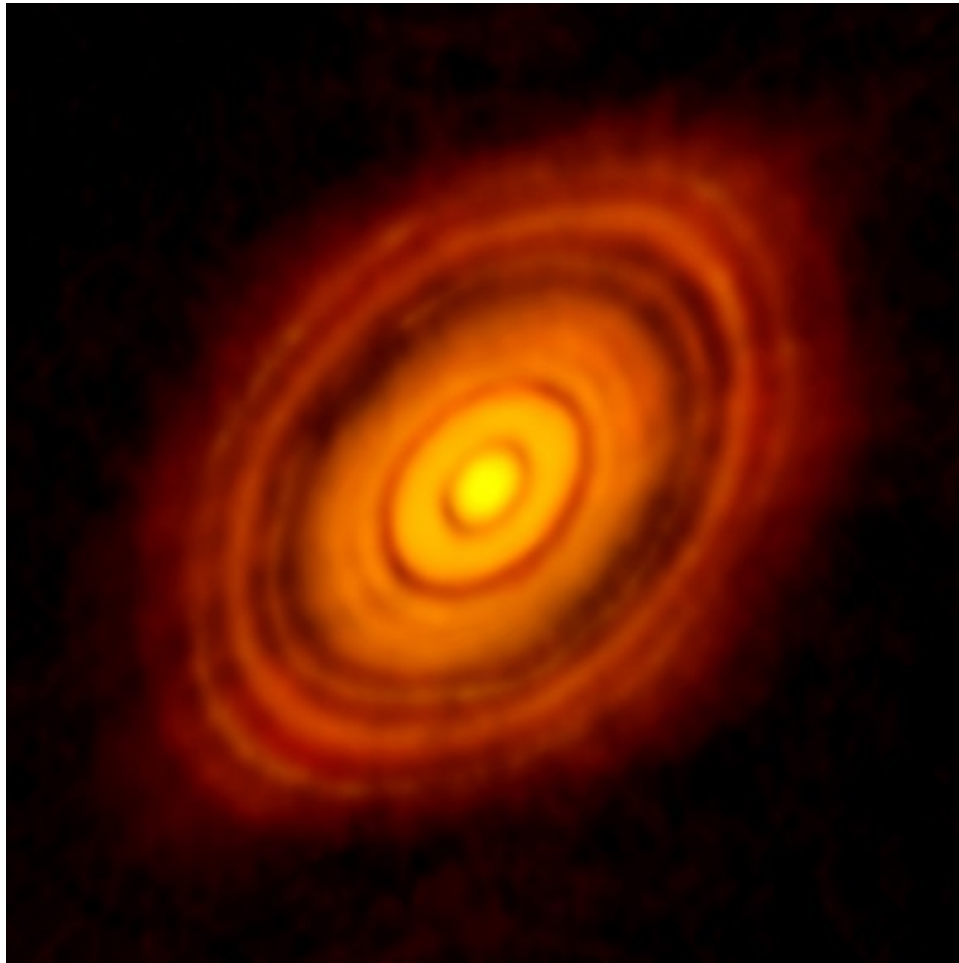
(a) No microlensing



(b) Microlensing by star



(c) Microlensing by star and planet



ALMA image of young star HL Tau and its planet-forming disk. Notice the multiple rings and gaps. This means planets are now emerging in the disk, and they are in the process of sweeping their orbits clear of dust and gas.

Thought Question 1 (1 of 2)

Suppose an alien was discovering the existence of Earth via the transit method. Where on the celestial sphere would the alien's exoplanetary system have to be?

- A. Near the northern polar star Polaris
- B. Near a southern polar star Sigma Octantis
- C. Along the ecliptic

Thought Question 1 (2 of 2)

Suppose an alien was discovering the existence of Earth via the transit method. Where on the celestial sphere would the alien's exoplanetary system have to be?

- A. Near the northern polar star Polaris
- B. Near a southern polar star Sigma Octantis
- C. Along the ecliptic**

What Have We Learned? (1 of 5)

- **Why is it so challenging to learn about extrasolar planets?**
 - Direct starlight is billions of times brighter than the starlight reflected from planets.
- **How can a star's motion reveal the presence of planets?**
 - A star's periodic motion (detected through Doppler shifts) tells us about its planets.
 - A star's precise position changes due to the gravitational interactions of its planets.

What Have We Learned? (2 of 5)

- **How can changes in a star's brightness reveal the presence of planets?**
 - Transiting planets periodically reduce a star's brightness.
 - The **Kepler** mission has found thousands of planets using this method.
 - **TESS** is continuing to find planets with this method.

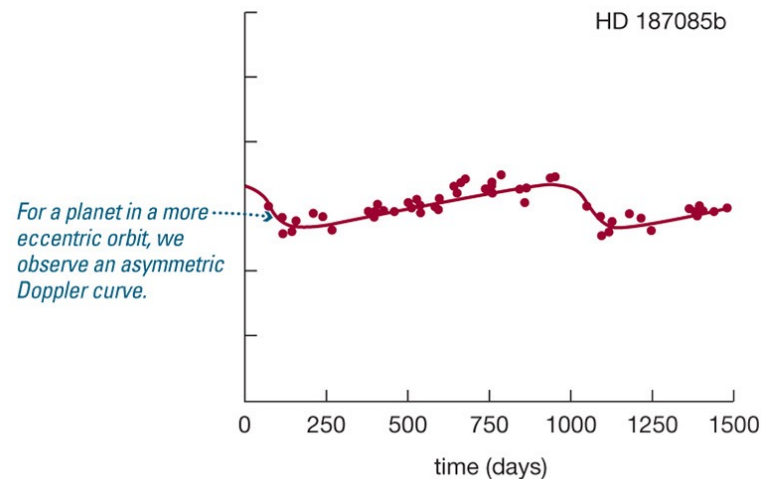
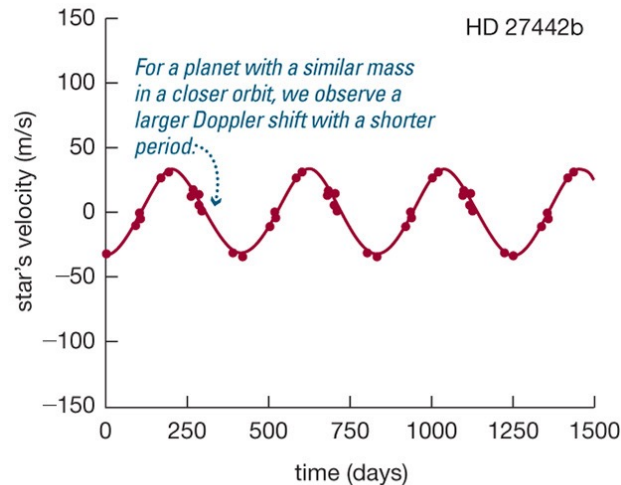
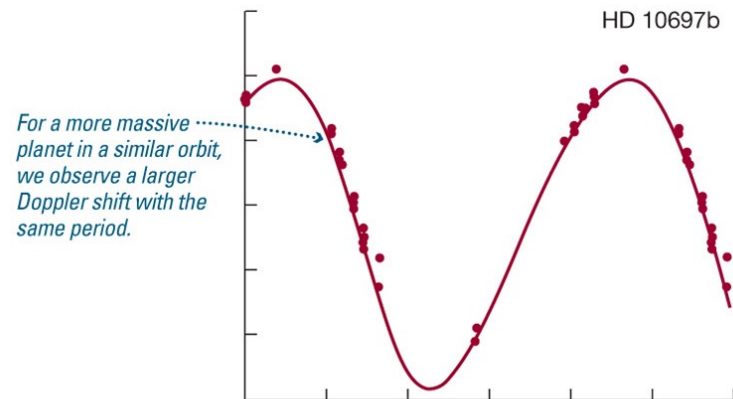
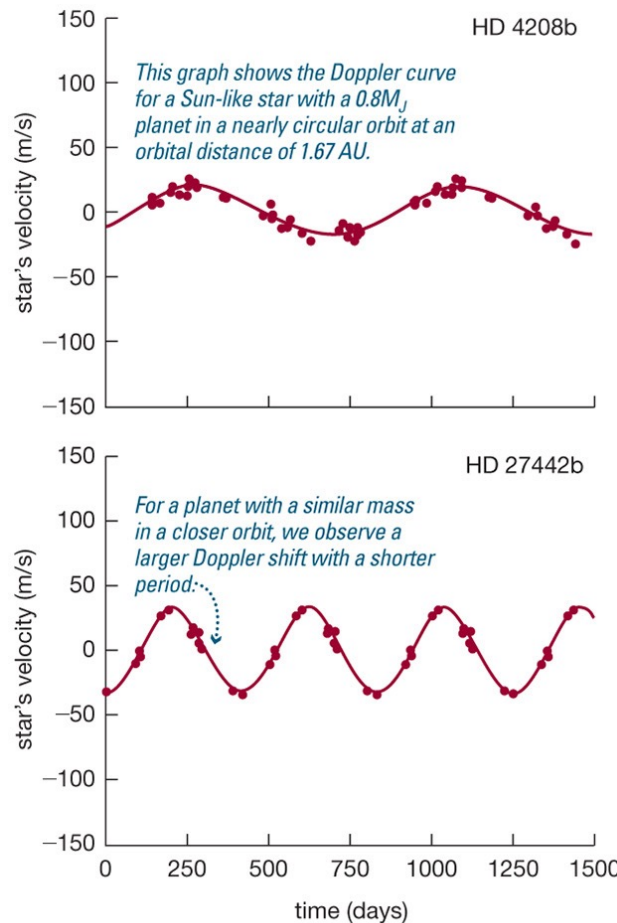
13.2 The Nature of Planets Around Other Stars

- Our goals for learning:
 - **What properties of exoplanets can we measure?**
 - **How do exoplanets compare to planets in our solar system?**

Measurable Properties

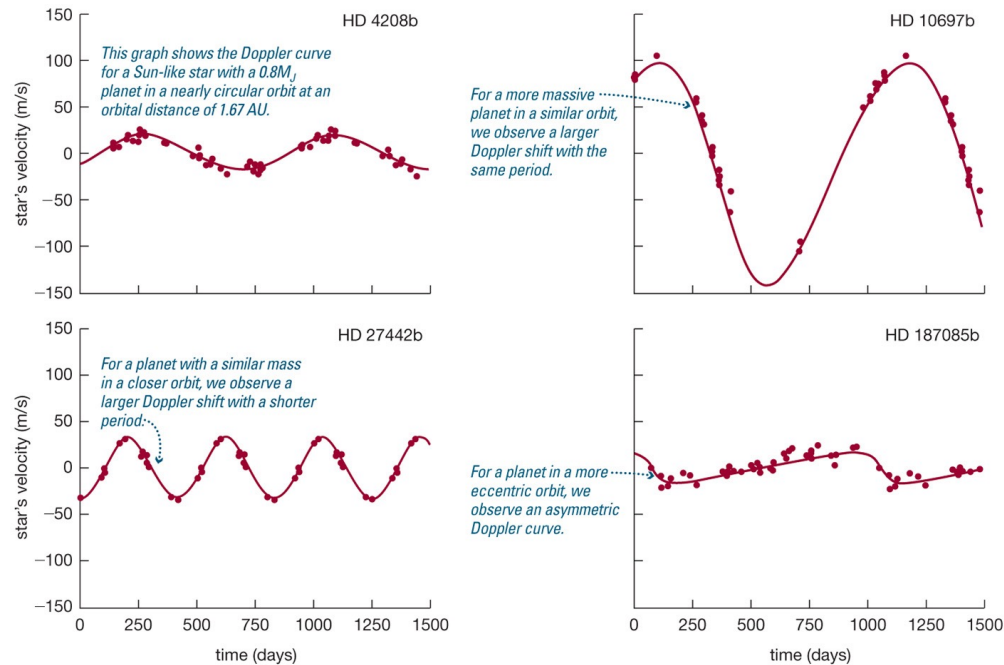
- Orbital period, distance from star, and shape of orbit
- Planet mass, size, and density
- Atmospheric properties

What Can Doppler Shifts Tell Us?



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

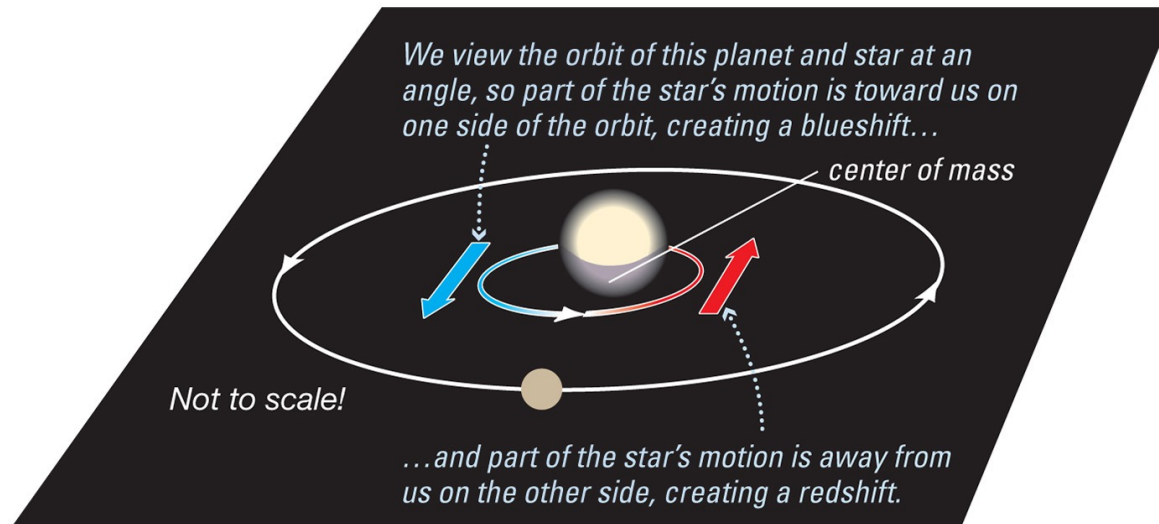
What Can Doppler Shifts Tell Us?



$$M_p \sin i = \frac{KP^{1/3}\sqrt{1-e^2}}{(2\pi G)^{1/3}M_*^{2/3}}$$

Where M_p = Mass of the exoplanet, i : Inclination of the planet's orbit relative to the line of sight, K : Radial velocity semi-amplitude of the star (m/s), P : Orbital period of the planet (s), e : Orbital eccentricity of the planet, M_* =Mass of the host star (kg), G : Gravitational constant

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 2 (1 of 2)

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?

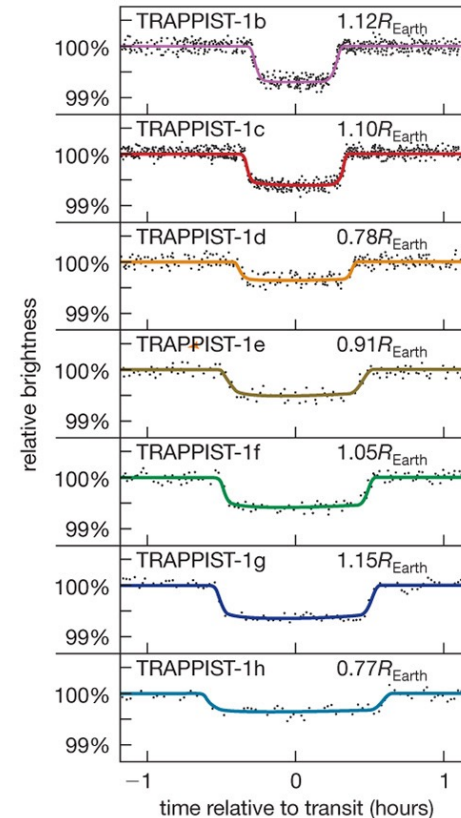
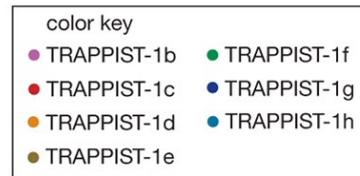
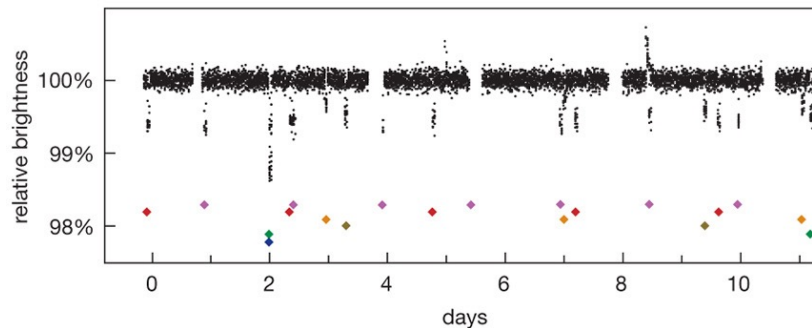
- A. It has a planet orbiting at less than 1 AU.
- B. It has a planet orbiting at greater than 1 AU.
- C. It has a planet orbiting at exactly 1 AU.
- D. It has a planet, but we do not have enough information to know its orbital distance.

Thought Question 2 (2 of 2)

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.

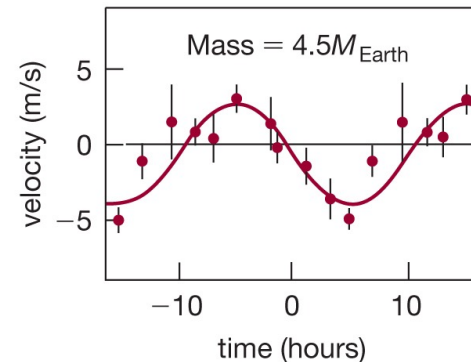
The TRAPPIST-1 System



- The periods and sizes of TRAPPIST-1's 7 known planets can be determined using transit data.

Calculating Density

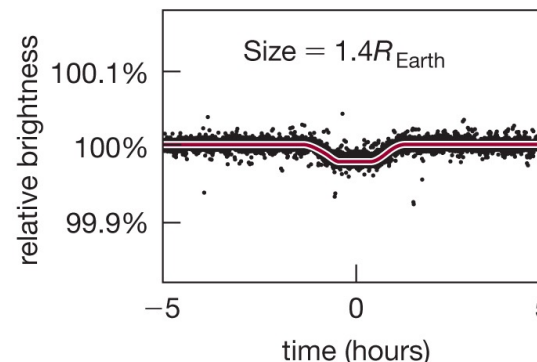
- Using mass, determined using the Doppler technique, and size, determined using the transit technique, density can be calculated.
- More recent measurements of Kepler 10b, the mass is refined down to about 3.2 times and radius 1.47 times the Earth's. This lowers the density to about 5.6 g/cm^3 .



For transiting planets, the Doppler method gives an accurate mass.

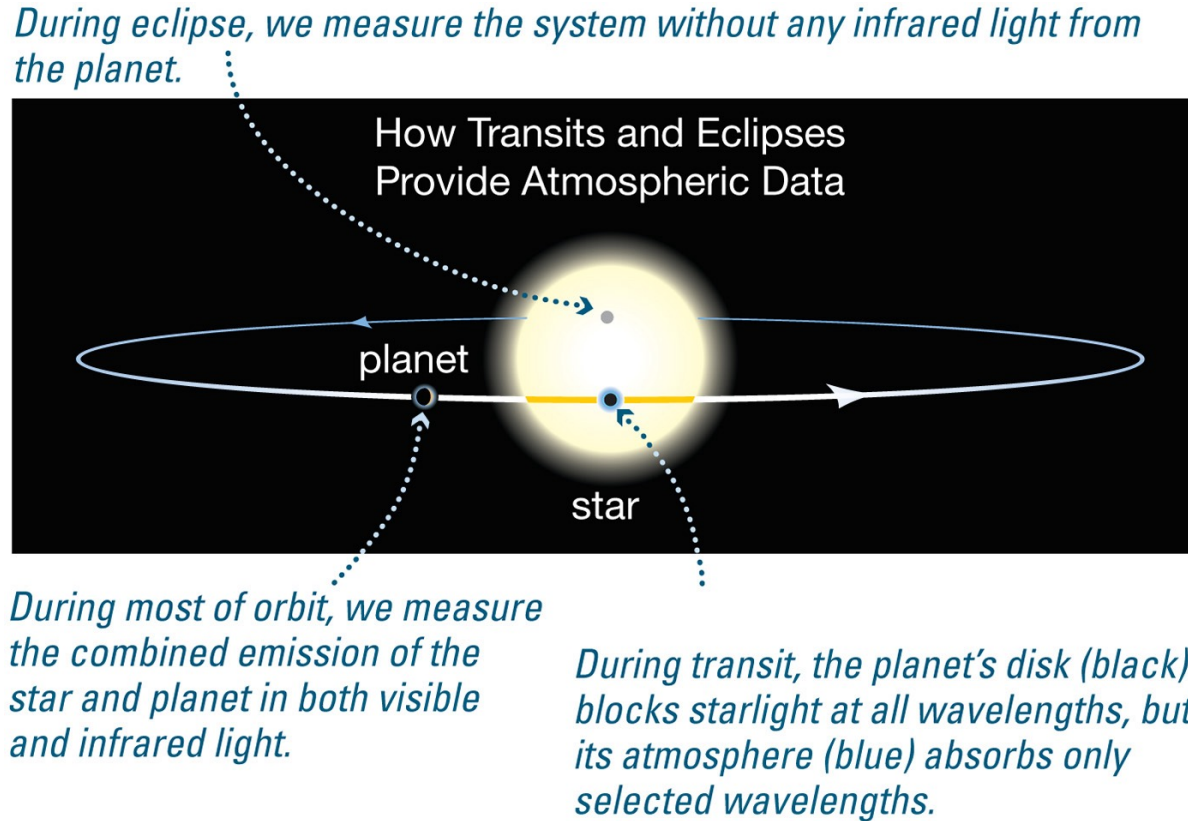
planet density:

$$\frac{\text{mass}}{\text{volume}} = 8.8 \text{ g/cm}^3$$



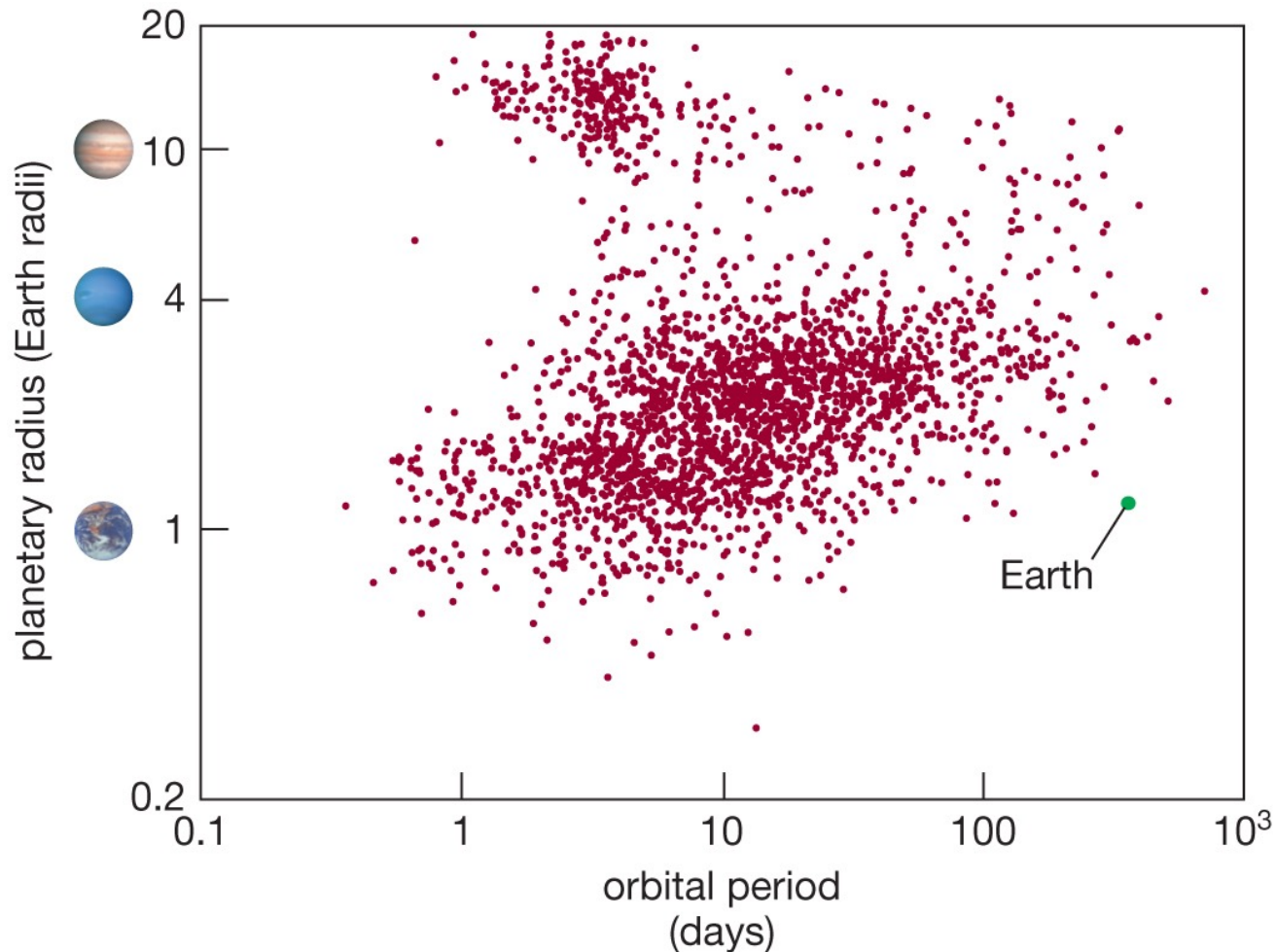
The transit method yields a radius, from which we can calculate the planet's volume.

Spectrum During Transit



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

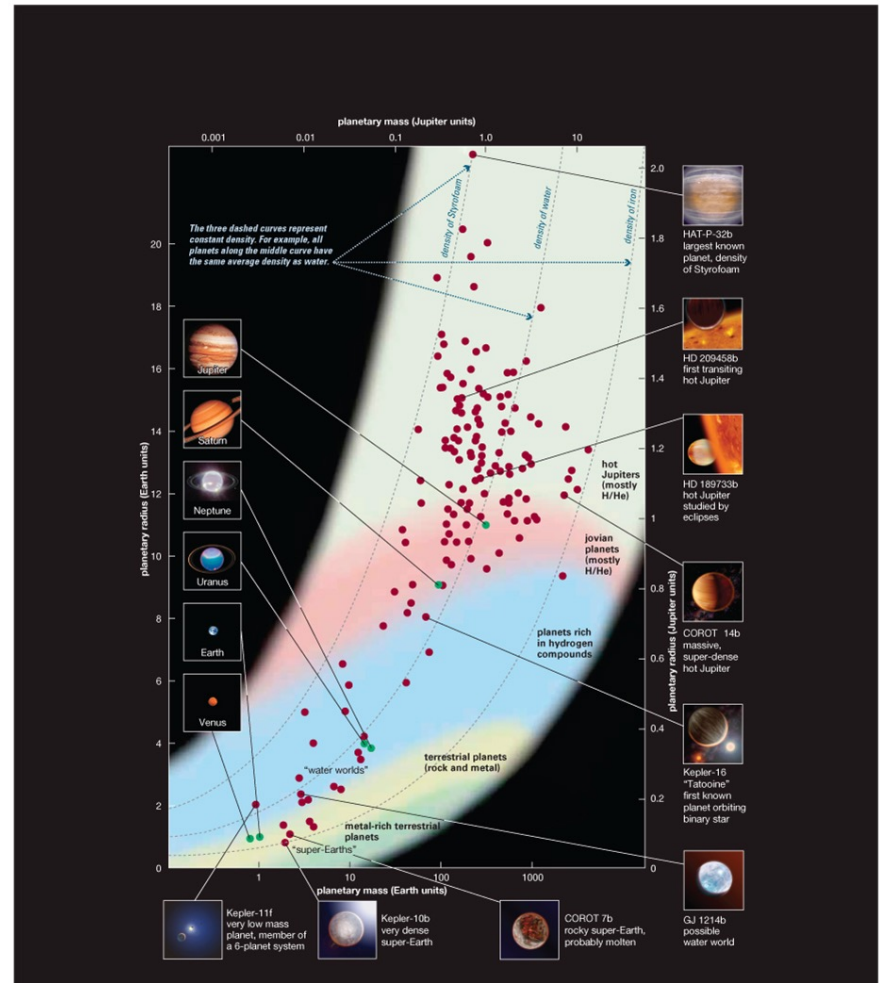
How Do Extrasolar Planets Compare to Planets in Our Solar System?



Orbits of Extrasolar Planets (1 of 3)

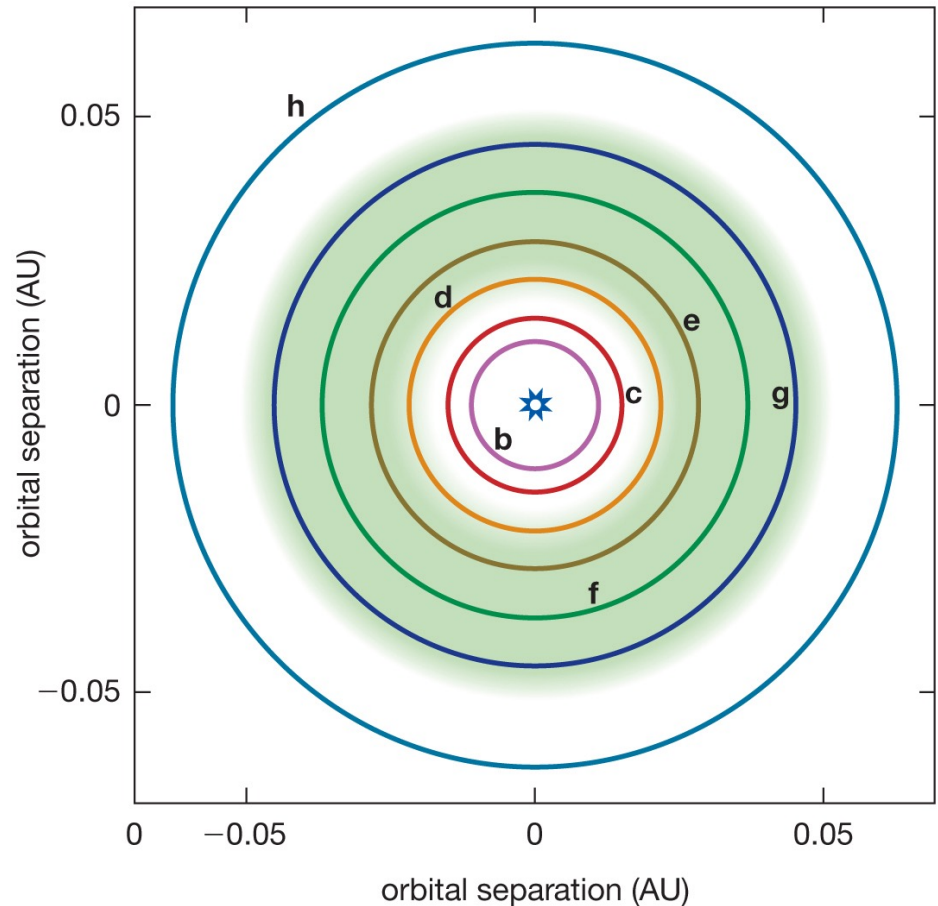
- Most of the detected planets have orbits smaller than Jupiter's.
- Planets at greater distances are harder to detect with the Doppler technique.

$$v = \sqrt{\frac{GM_{star}}{R}}$$



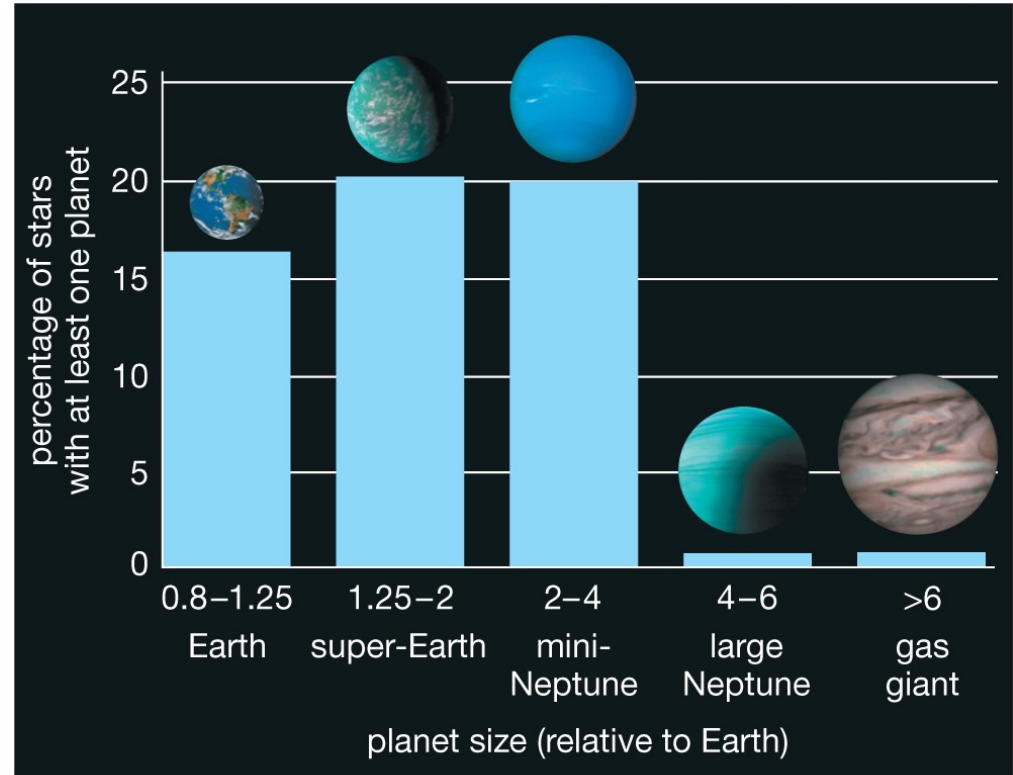
Orbits of Extrasolar Planets (2 of 3)

- More than 1000 multiplanet systems are now known.
- TRAPPIST-1 planets are very tightly packed (much closer than Mercury orbits the Sun) but are still in the habitable zone.
- Changes in transit timings are due to planets interacting.



Orbits of Extrasolar Planets (3 of 3)

- Most of the planets detected by **Kepler** and **TESS** have lower sizes than Jupiter.
- These percentages will certainly go up as we get better at discovering planets with longer periods.



Distribution of Exoplanet Sizes

Surprising Characteristics

- Some extrasolar planets have **highly elliptical orbits**.
- Planets show huge diversity in size and density.
 - Super-Earths and mini-Neptunes have dominated our findings so far, but our methods are biased toward finding these.
- Some massive planets, called **hot Jupiters**, orbit very close to their stars.

What Have We Learned? (3 of 5)

- **What properties of extrasolar planets can we measure?**
 - Orbital properties, such as period, distance, and shape
 - Planetary properties, such as mass and size
 - Atmospheric properties, such as temperature and composition

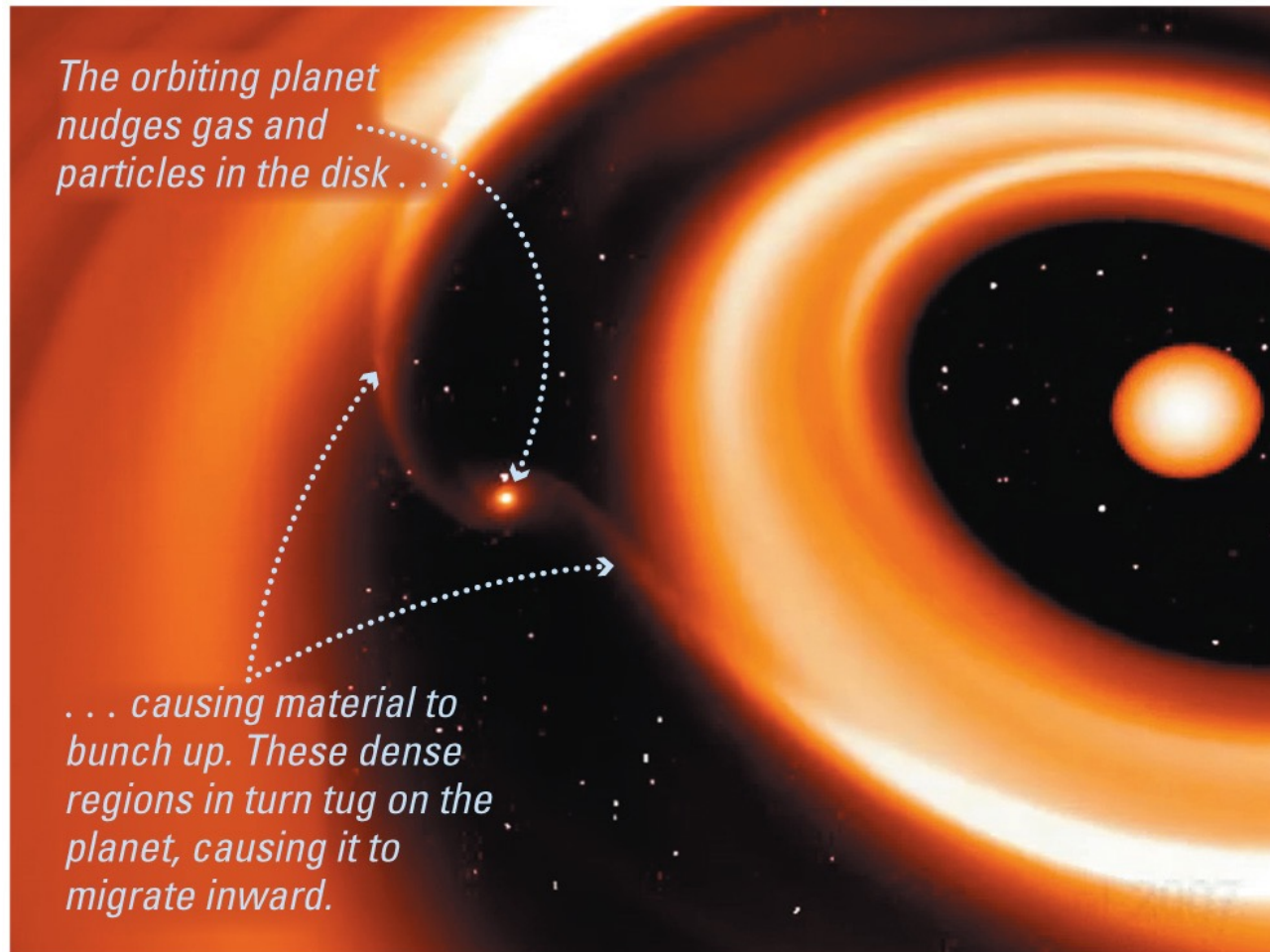
What Have We Learned? (4 of 5)

- **How do extrasolar planets compare to planets in our solar system?**
 - Planets with a wide variety of masses and sizes
 - Many orbiting close to their stars and with large masses

13.3 The Formation of Other Solar Systems

- Our goals for learning:
 - **How have other planetary systems altered our understanding of solar system formation?**
 - **Are planetary systems like ours common?**

How Have Other Planetary Systems Altered Our Understanding of Solar System Formation?

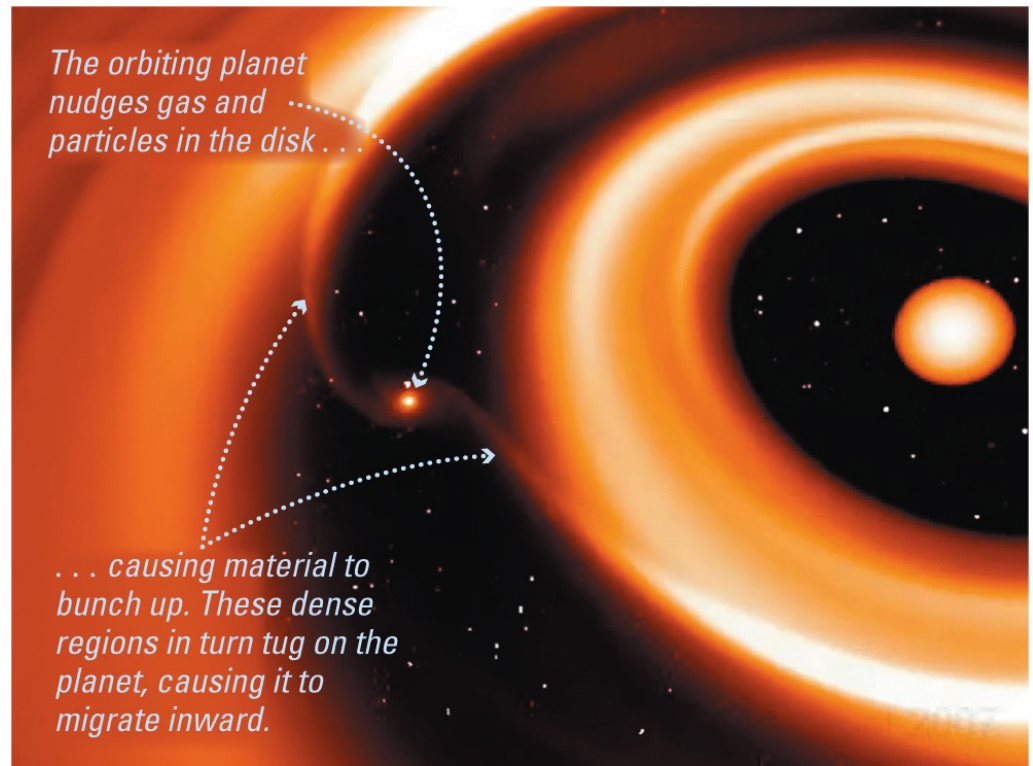


Revisiting the Nebular Theory

- The nebular theory predicts that massive Jupiter-like planets should not form inside the frost line (at $\ll 5$ 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.



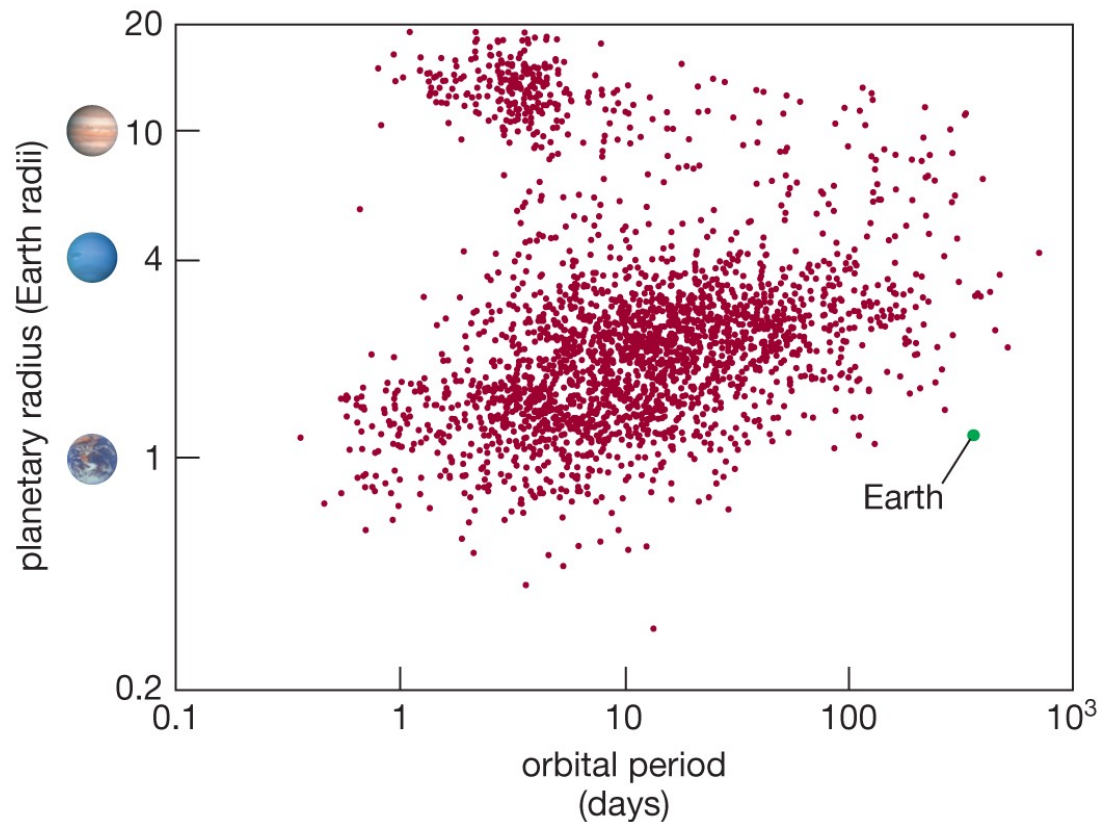
Gravitational Encounters and Resonances

- 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 or outward migration.
- Resonances between planets may also contribute.

Modifying the Nebular Theory

- Observations of extrasolar planets have shown that the nebular theory was incomplete.
- Effects like **planetary migration and gravitational encounters** are more important than previously thought.
- When a star clears its nebular gas may play a role in how large jovian planets grow. This could help explain mini-Neptunes.
- Better computer modeling can help us answer some questions of terrestrial and jovian planet formation. It may also help explain some features of our own solar system.

Is Our Solar System Rare?



- About 20% of all stars may have Earth-size planets in habitable zones.

Thought Question 4 (1 of 2)

If it is expected that each star within the Milky Way has at least one planet, about how many planets would there be in this single galaxy?

- A. One million (1,000,000)
- B. One-hundred million (100,000,000)
- C. One billion (1,000,000,000)
- D. One-hundred billion (100,000,000,000)

Thought Question 4 (2 of 2)

If it is expected that each star within the Milky Way has at least one planet, about how many planets would there be in this single galaxy?

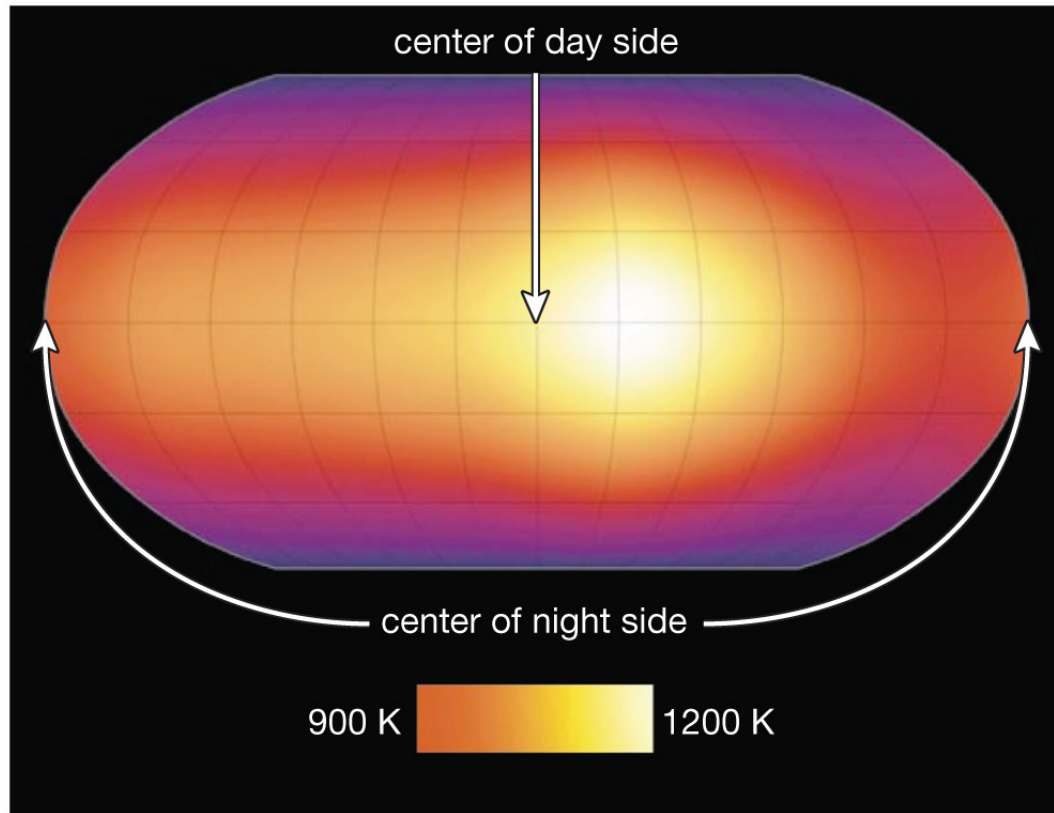
- A. One million (1,000,000)
- B. One-hundred million (100,000,000)
- C. One billion (1,000,000,000)
- D. One-hundred billion (100,000,000,000)**

What Have We Learned? (5 of 5)

- **Do we need to modify our theory of solar system formation?**
 - Original nebular theory cannot account for the existence of hot Jupiters.
 - Planetary migration or gravitational encounters may explain how Jupiter-like planets moved inward.
- **Are planetary systems like ours common?**
 - We don't know!

EXTRA

Surface Temperature Map



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

Thought Question 3 (1 of 2)

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.

Thought Question 3 (2 of 2)

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.

How Planet Properties Are Measured

Table 13.2 A Summary of How We Measure Properties of Exoplanets

Planetary Property	Method(s) Used	Explanation
Orbital Properties period	Doppler, astrometric, or transit	We directly measure orbital period.
Orbital Properties distance	Doppler, astrometric, or transit	We calculate orbital distance from orbital period using Newton's version of Kepler's third law (Mathematical Insight 13.1).
Orbital Properties eccentricity	Doppler or astrometric	Velocity curves and astrometric star positions reveal eccentricity (Figure 13.8).
Orbital Properties inclination	transit or astrometric	Transits identify edge-on orbits; astrometric data measure any inclination angle.
Physical Properties mass	astrometric or Doppler*	We calculate mass based on the amount of stellar motion caused by the planet's gravitational tug (Mathematical Insight 13.2).
Physical Properties size (radius)	transit	We calculate size based on the amount of dip in a star's brightness during a transit (Mathematical Insight 13.3).
Physical Properties density	transit and Doppler	We calculate density by dividing the mass by the volume (using size from the transit method). See Figure 13.11.
Physical Properties atmospheric composition and temperature	transit or direct detection	Transits and eclipses provide data on atmospheric composition and temperature; direct spectroscopy is now also possible in some cases.

*Transits in some multiplanet systems allow us to determine masses from the mutual gravitational tugs of the planets.

Major Extrasolar Planet Detection Methods

Table 13.1 Major Extrasolar Planet Detection Methods

	Description	Key Advantages	Major Limitations	Confirmed Planets (as of mid-2022)
Direct Detection	Obtain images or spectra of exoplanets	Only method that allows direct study of the planets themselves	Requires large telescopes and some means of blocking light from star itself	A few
Astrometric Method	Infer planet existence from small changes in star's position in sky	- Now possible with GAIA spacecraft - Detects planets in all orbit orientations	- Generally possible only for relatively nearby stars - Biased toward finding massive planets that orbit far from their stars - May require many years of observation to detect these planets (with large orbital periods)	A few
Doppler Method	Infer planet existence from star's motion toward/away from us revealed by Doppler shifts in its spectrum	- Possible from ground-based telescopes - Detects planets in all orbit orientations except face-on	- Biased toward finding massive planets with close-in orbits - Underestimates star's true motion except when system viewed edge-on - Requires stellar spectra, which means large telescopes and long observation times	More than 1000
Transit Method	Infer planet existence from slight changes in star's brightness as planet passes in front of (or behind) it	- Allows many stars to be observed at once - Can detect very small planets - Feasible with small telescopes - Can provide atmospheric data during some transits and eclipses	- Possible only for planets with edge-on orbits as viewed from Earth - For small planets, requires sensitivity possible only from space observatory	More than 3000