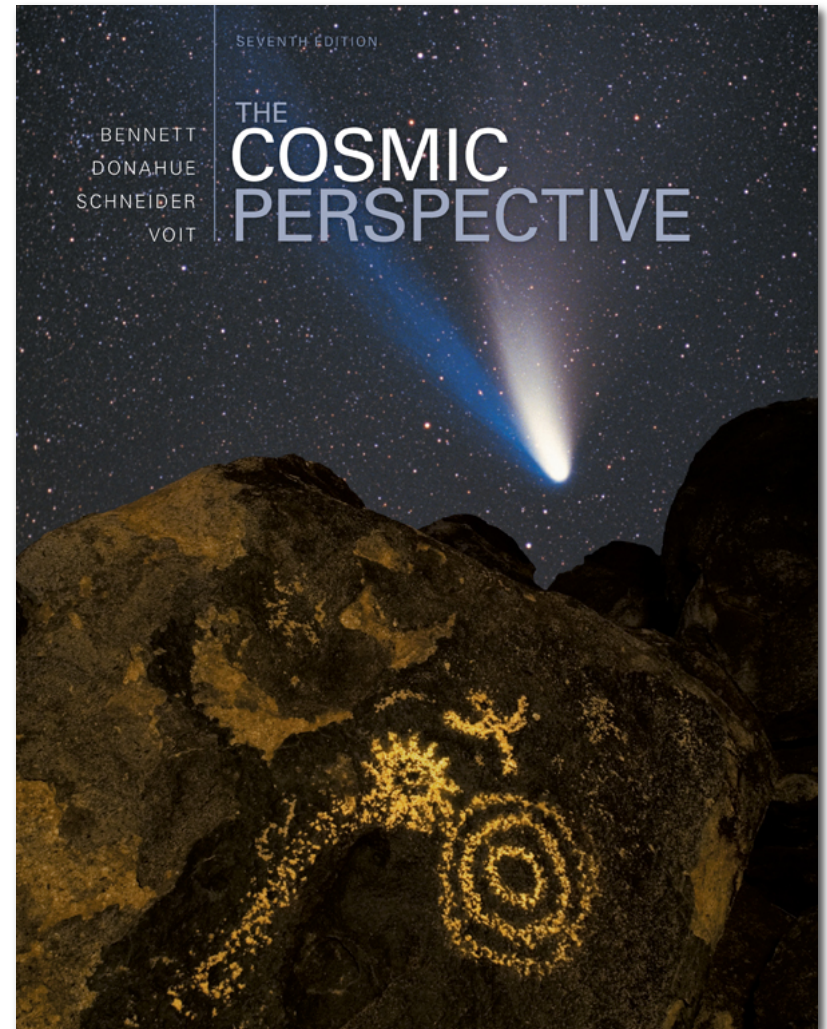


Chapter 13 Lecture

The Cosmic Perspective

Seventh Edition

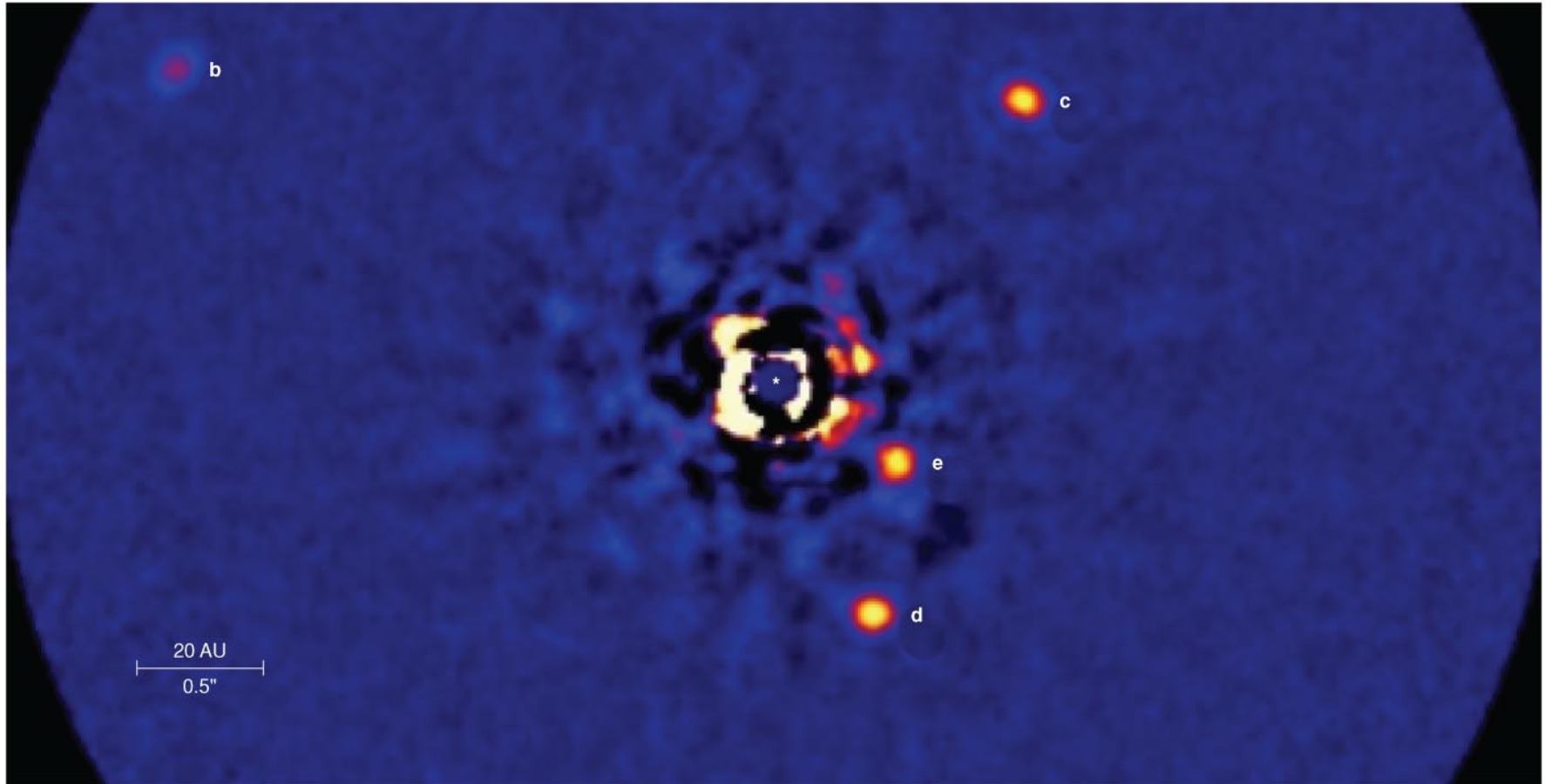
Other Planetary Systems: The New Science of Distant Worlds



13.1 Detecting Planets Around Other Stars

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

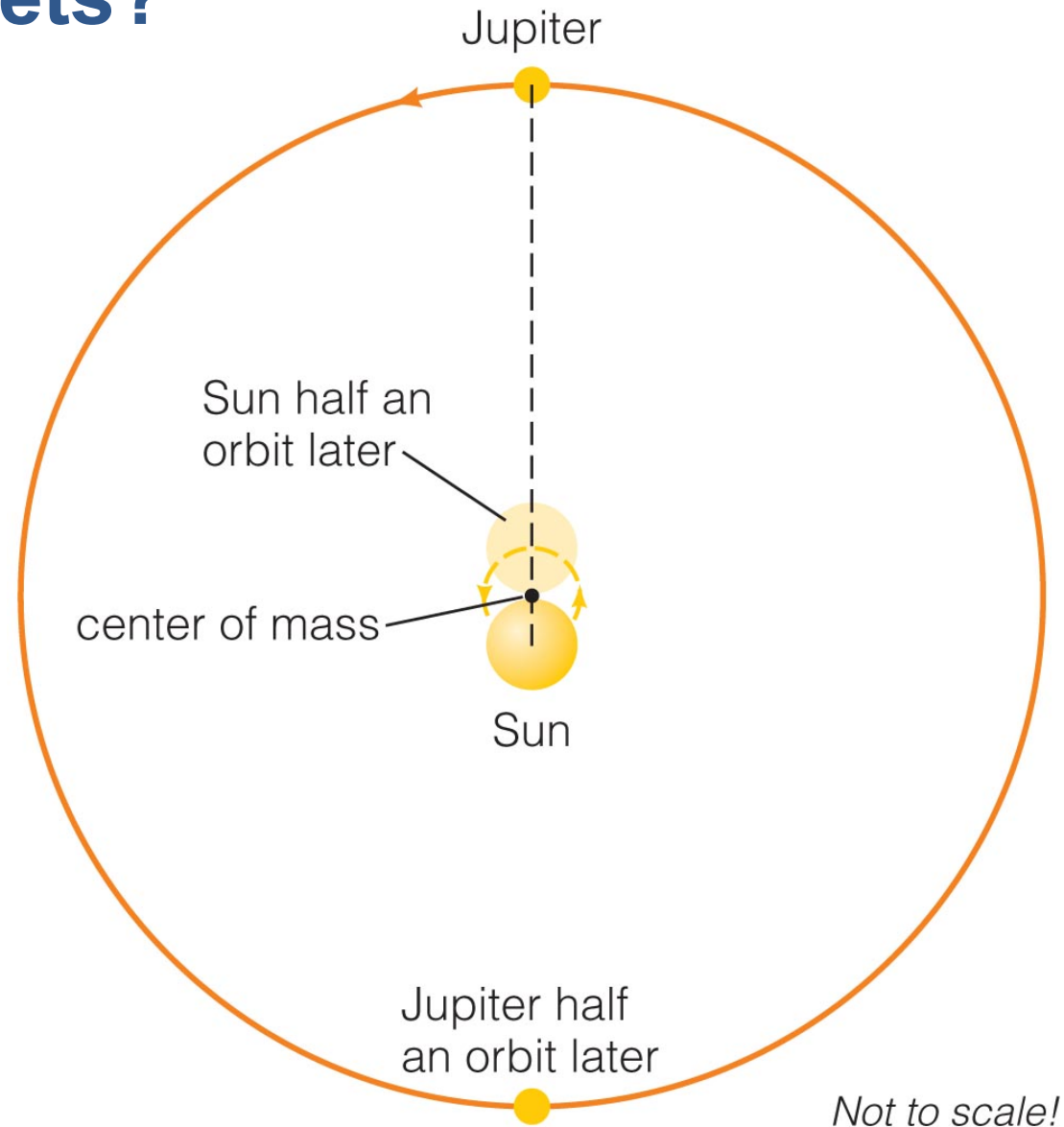
Why is it so challenging to learn about extrasolar planets?



Brightness and Distance

- A Sun-like star is about a billion times brighter in the optical band than the light reflected from its planets.
- Planets are close to their stars, relative to the distance from us to the star.

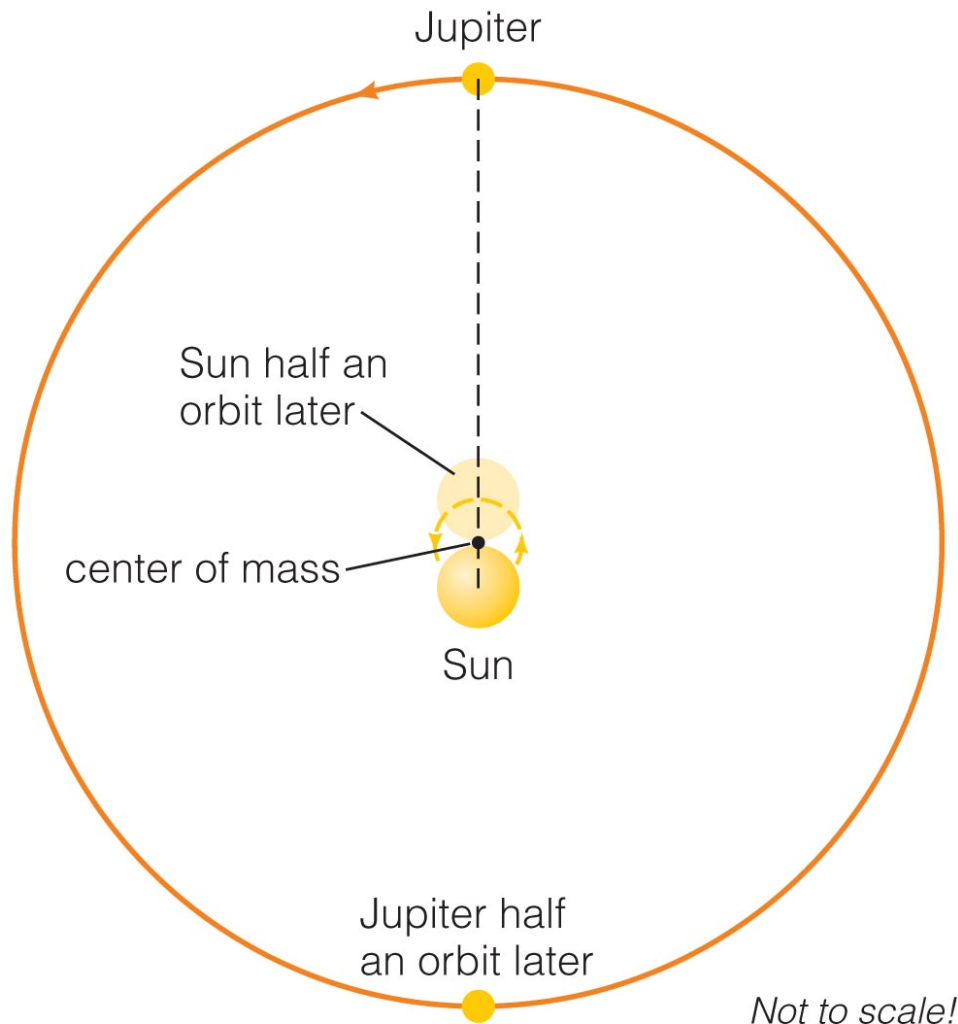
How can a star's motion reveal the presence of planets?



Planet Detection

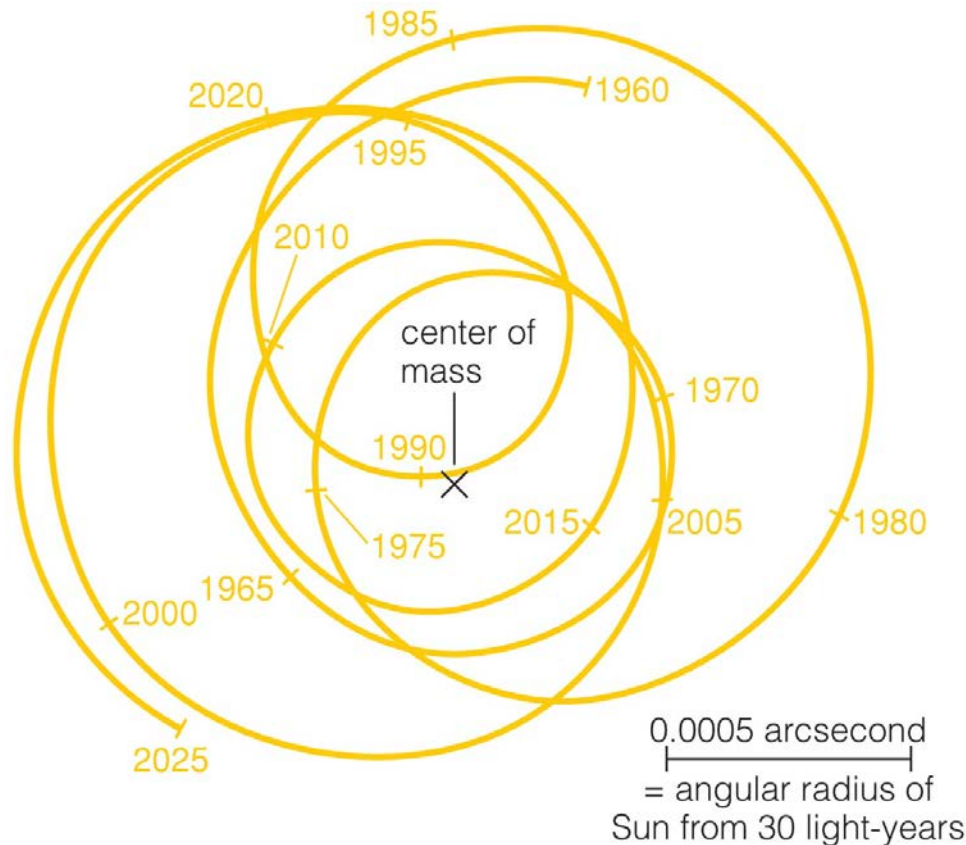
- **Direct:** pictures or spectra of the planets themselves
- **Indirect:** measurements of stellar properties revealing the effects of orbiting planets

Gravitational Tugs



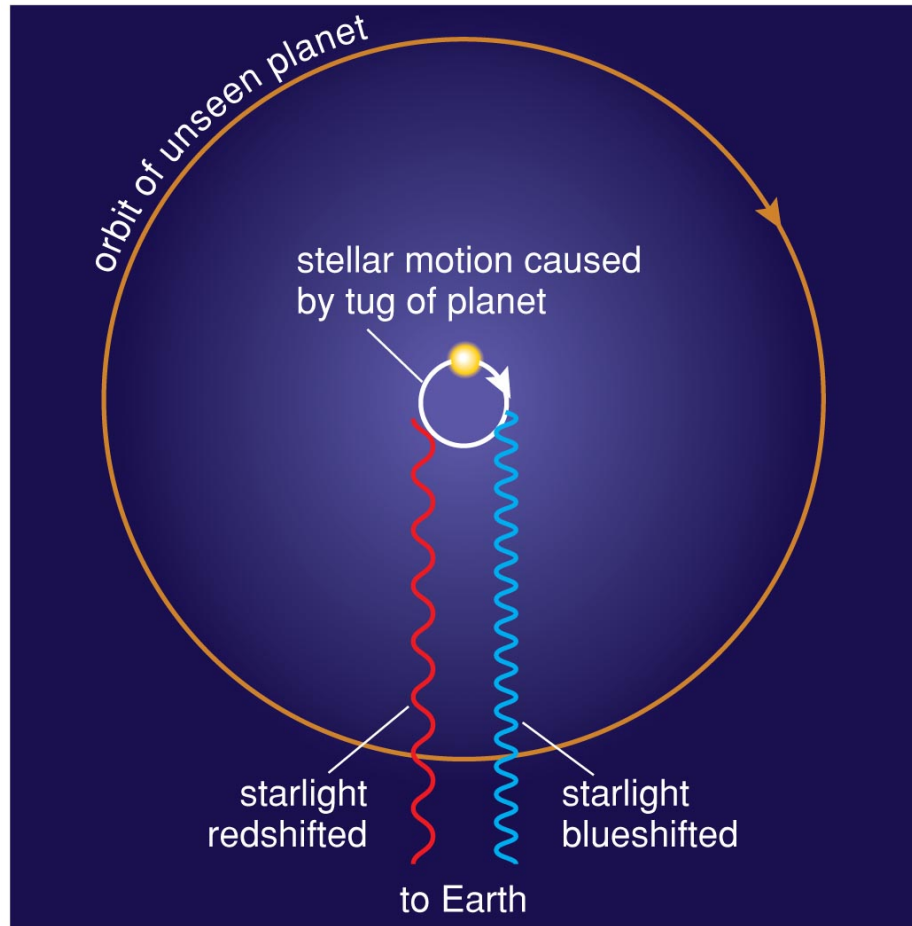
- The Sun and Jupiter orbit around their common center of mass.
- The Sun therefore wobbles around that center of mass with same period as Jupiter.

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).

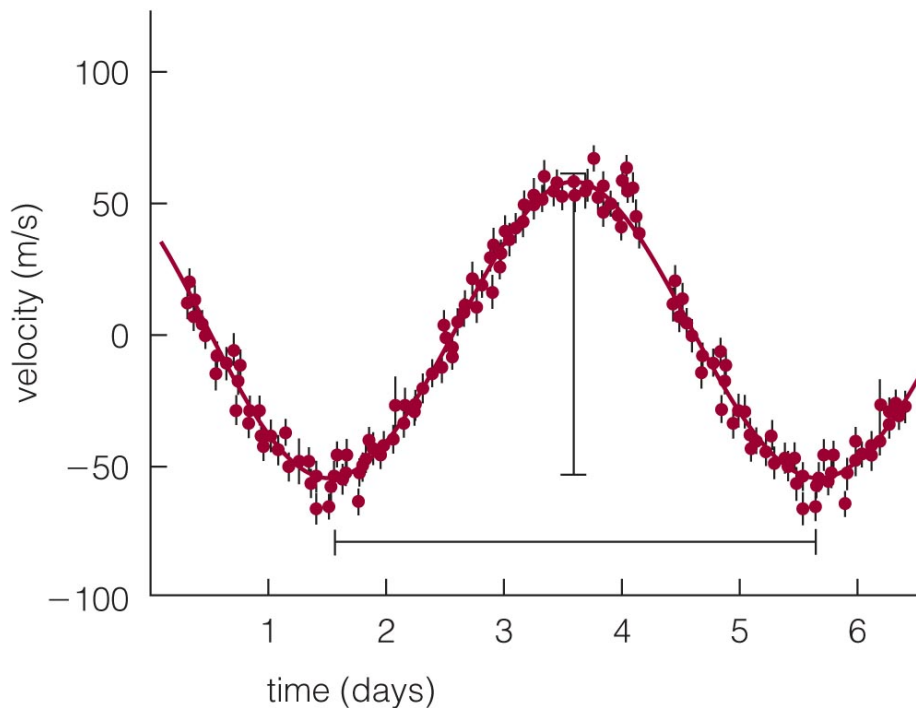
Doppler Technique



- 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!).

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

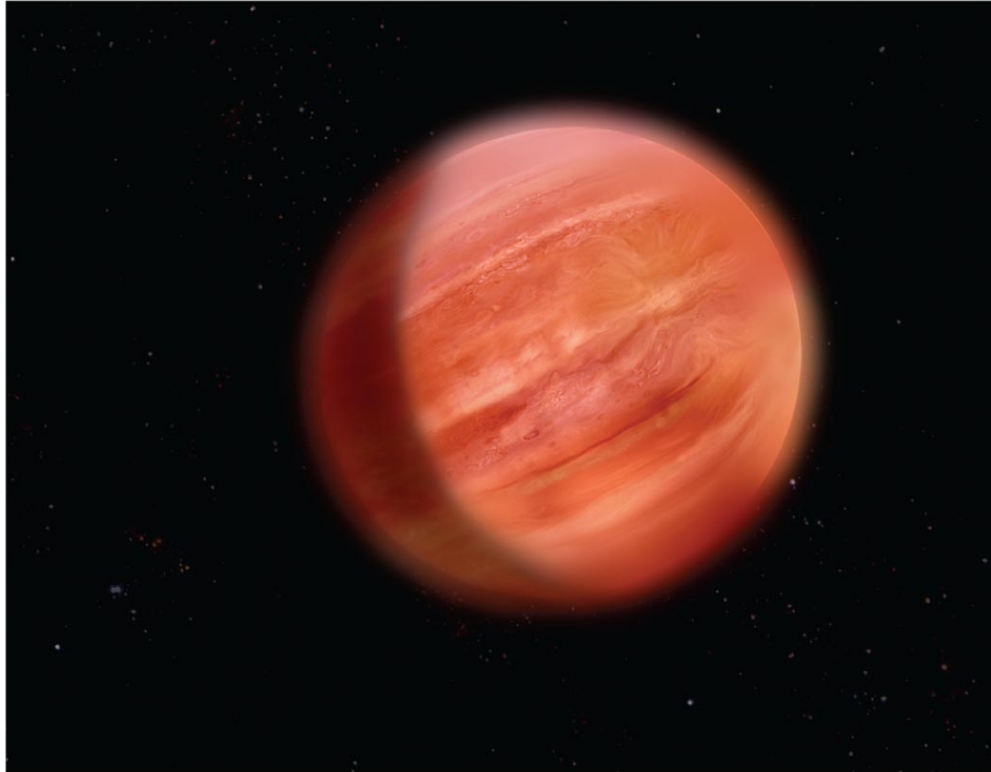
First Extrasolar Planet



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).

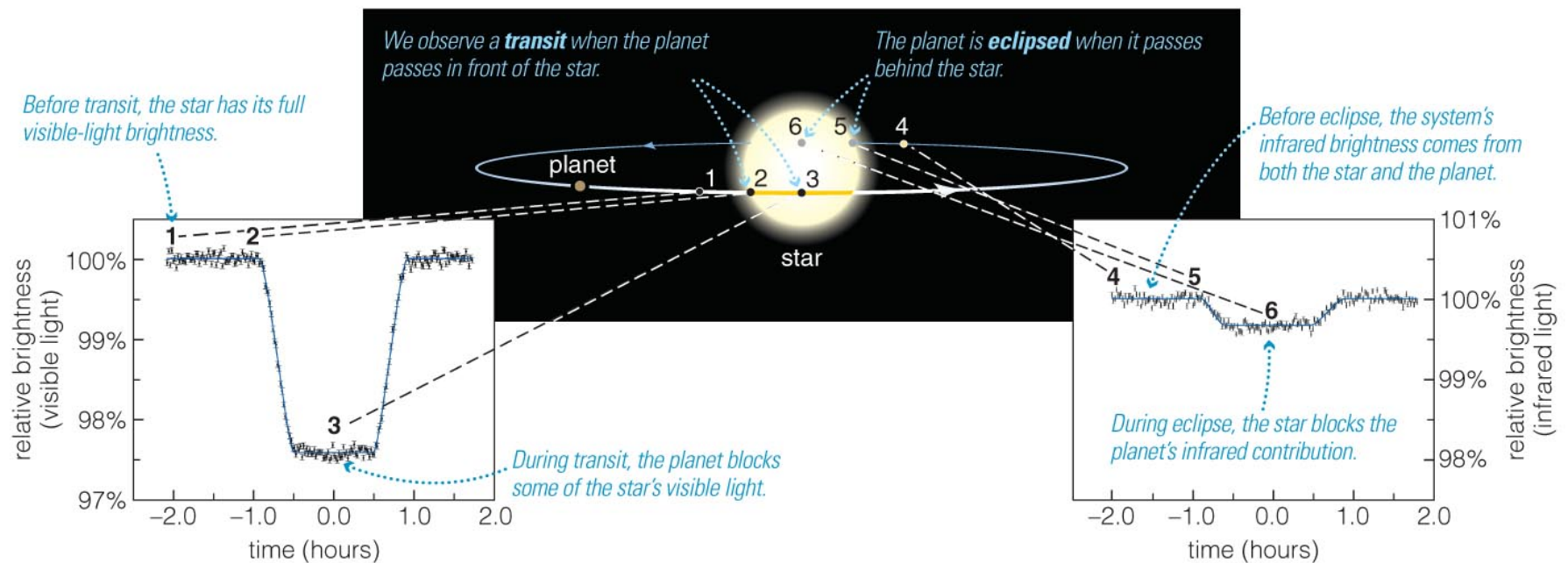
First Extrasolar Planet



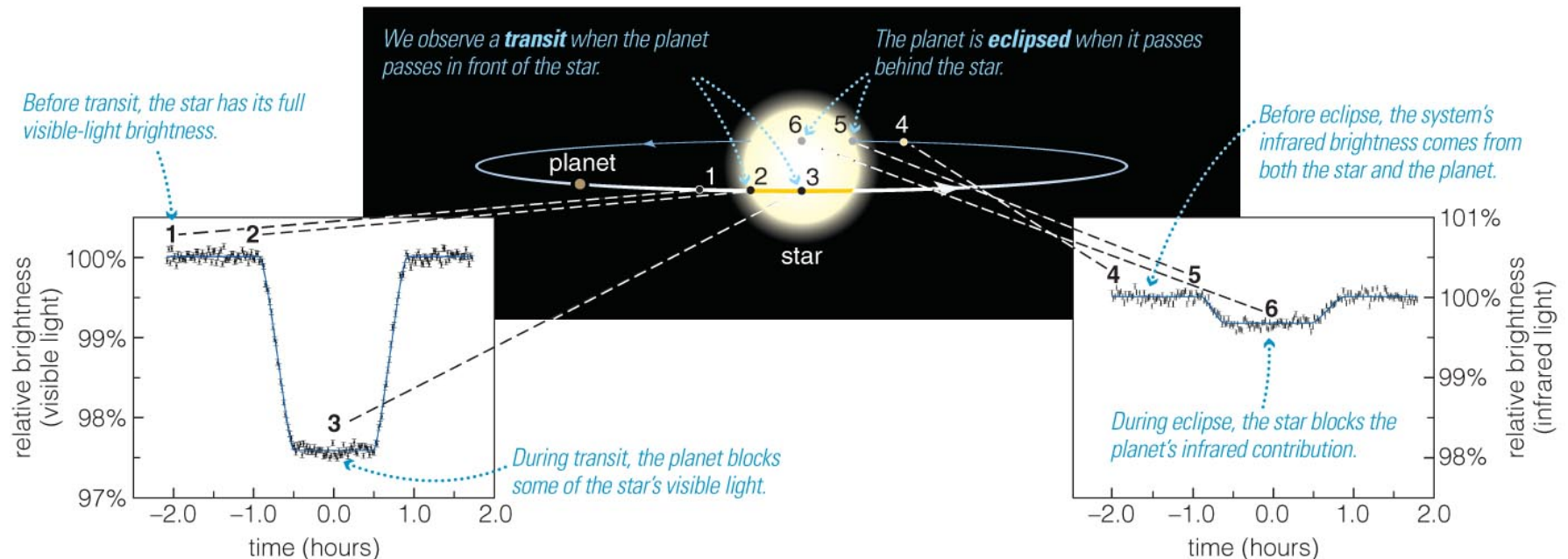
b Artist's conception of the planet orbiting 51 Pegasi, which probably has a mass similar to that of Jupiter but orbits its star at only about one-eighth of Mercury's orbital distance from the Sun. It probably has a surface temperature above 1000 K, making it an example of what we call a hot Jupiter.

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

How can changes in a star's brightness reveal the presence of planets ?

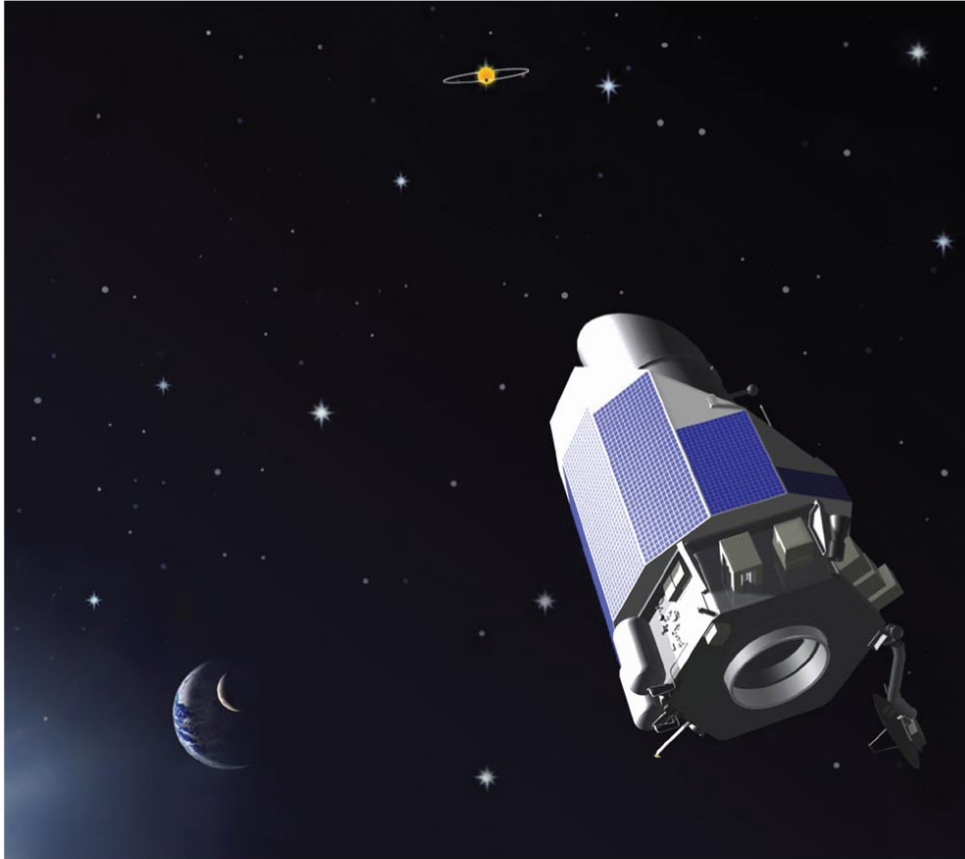


Transits and Eclipses



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

Kepler

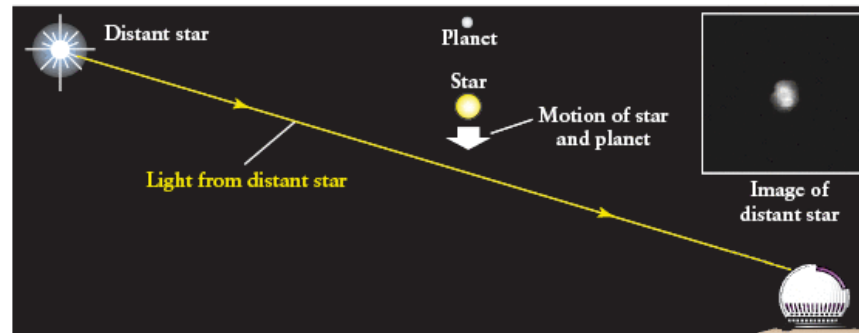


- NASA's *Kepler* mission was launched in 2008 to begin looking for transiting planets.
- It is designed to measure the 0.008% decline in brightness when an Earth-mass planet eclipses a Sun-like star.

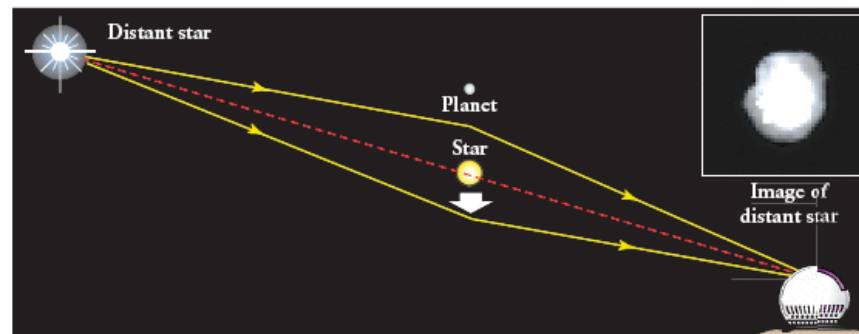
Other Planet-Hunting Strategies

- **Gravitational Lensing:** 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.

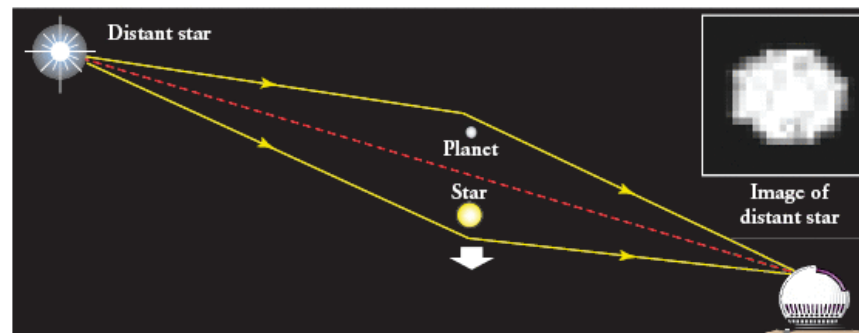
Other Planet-Hunting Strategies



(a) No microlensing

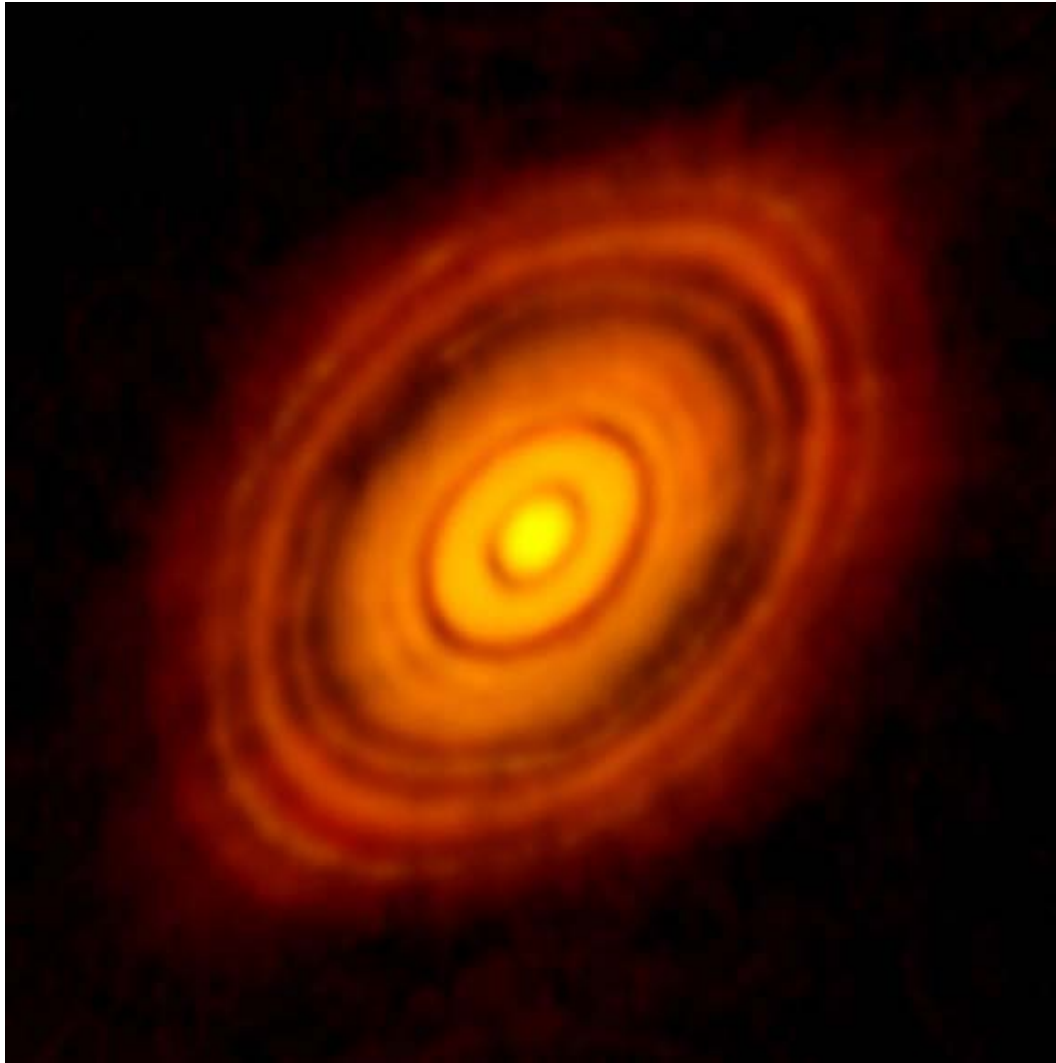


(b) Microlensing by star



(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.

What have we learned?

- **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 or by measuring its motion across the sky) tells us about its planets.
 - Transiting planets periodically reduce a star's brightness.

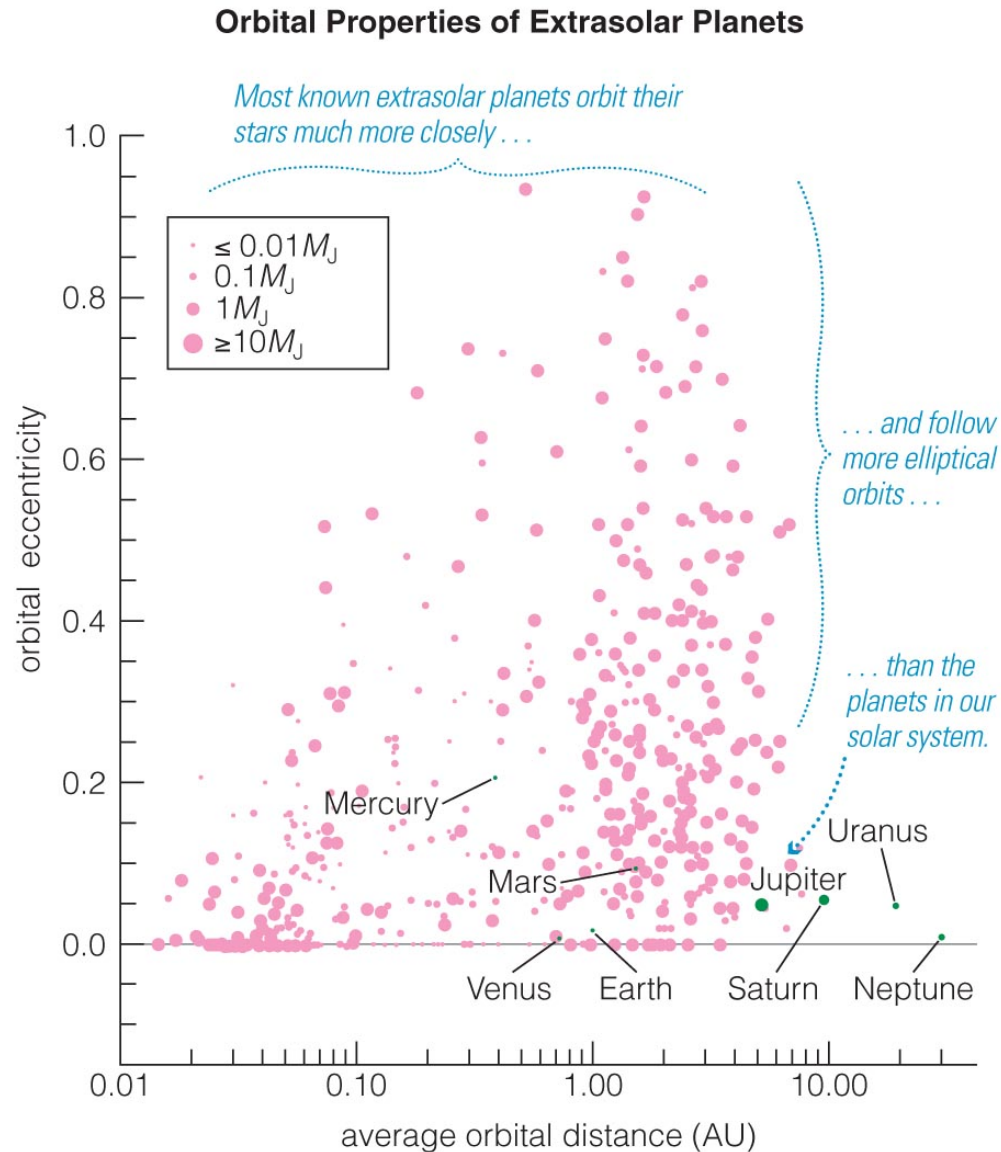
What have we learned?

- **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 candidates using this method.

13.2 The Nature of Planets Around Other Stars

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

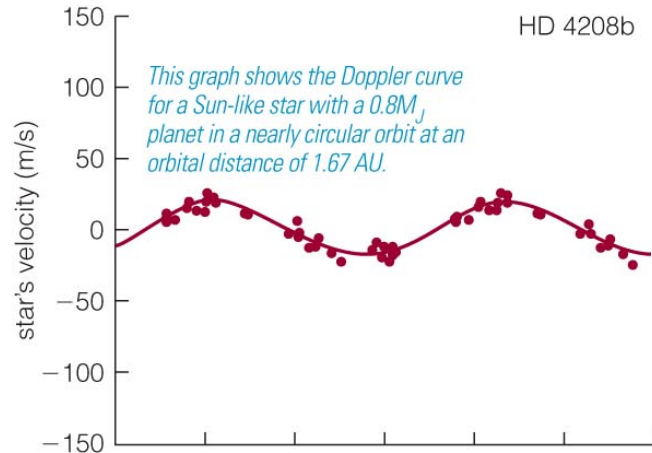
What properties of extrasolar planets can we measure?



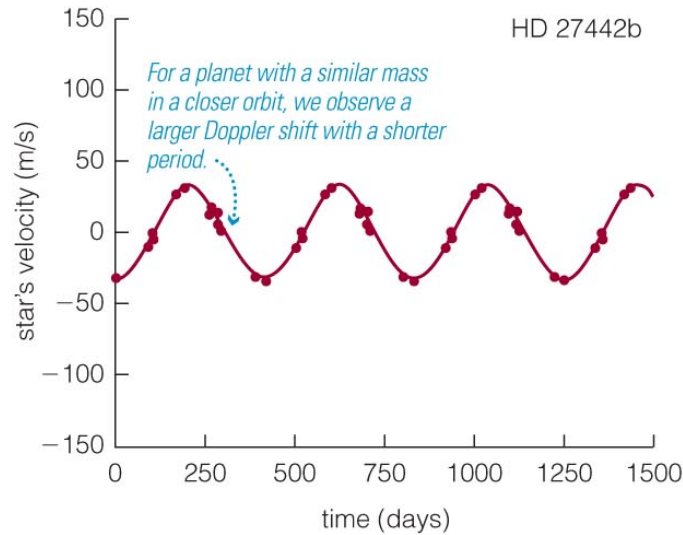
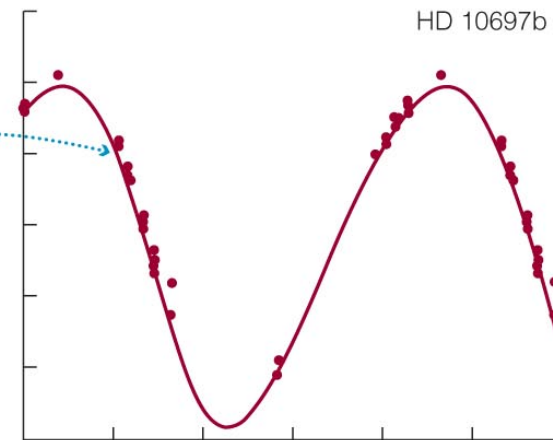
Measurable Properties

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

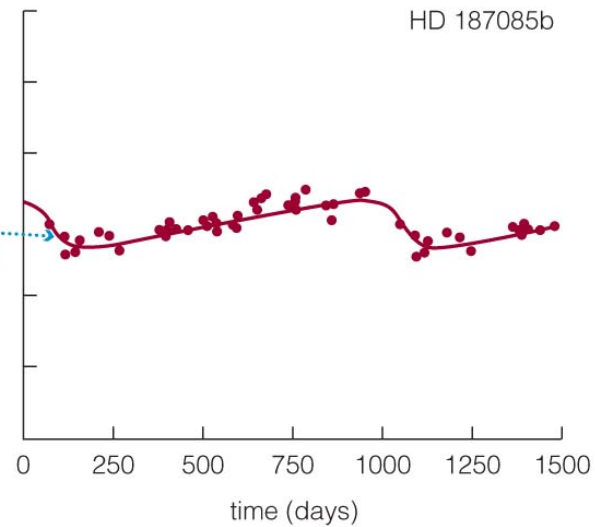
What can Doppler shifts tell us?



For a more massive planet in a similar orbit, we observe a larger Doppler shift with the same period.

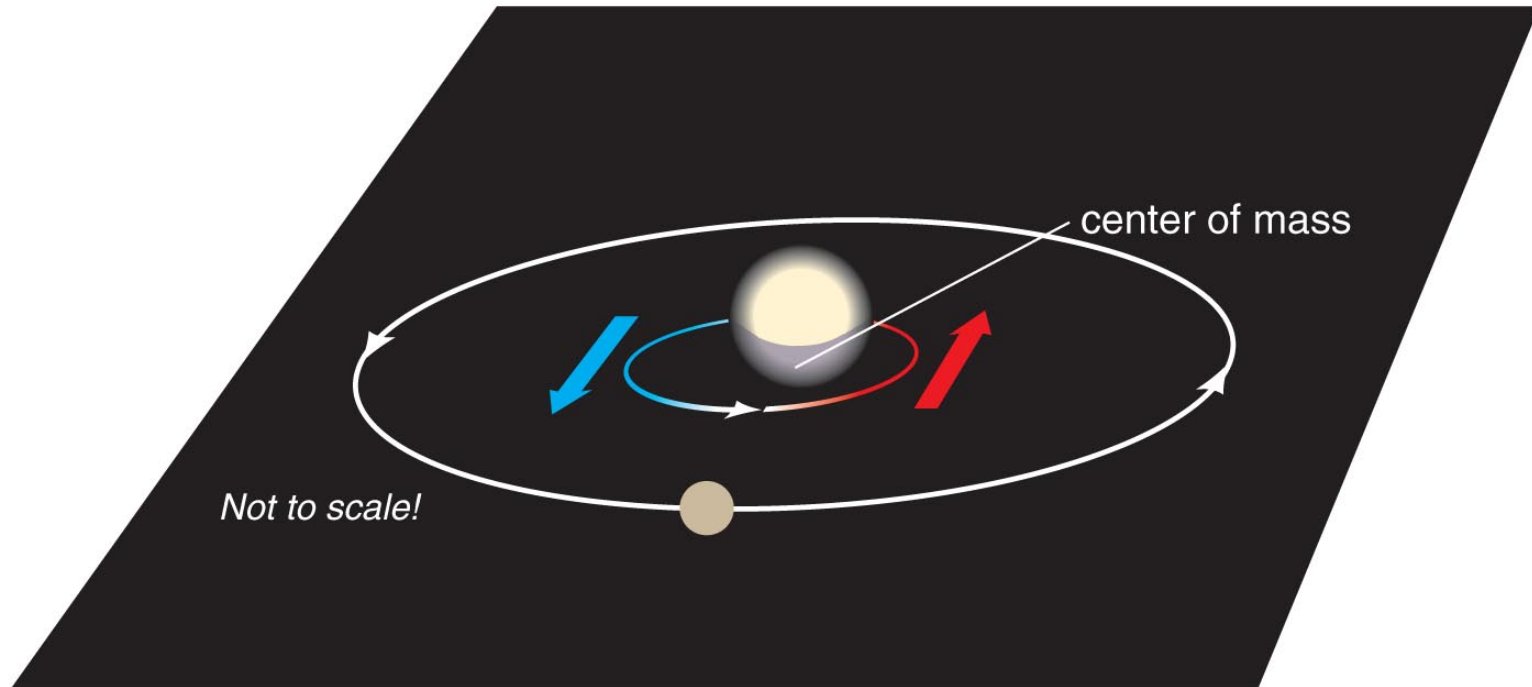


For a planet in a more eccentric orbit, we observe an asymmetric Doppler curve.



- 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?

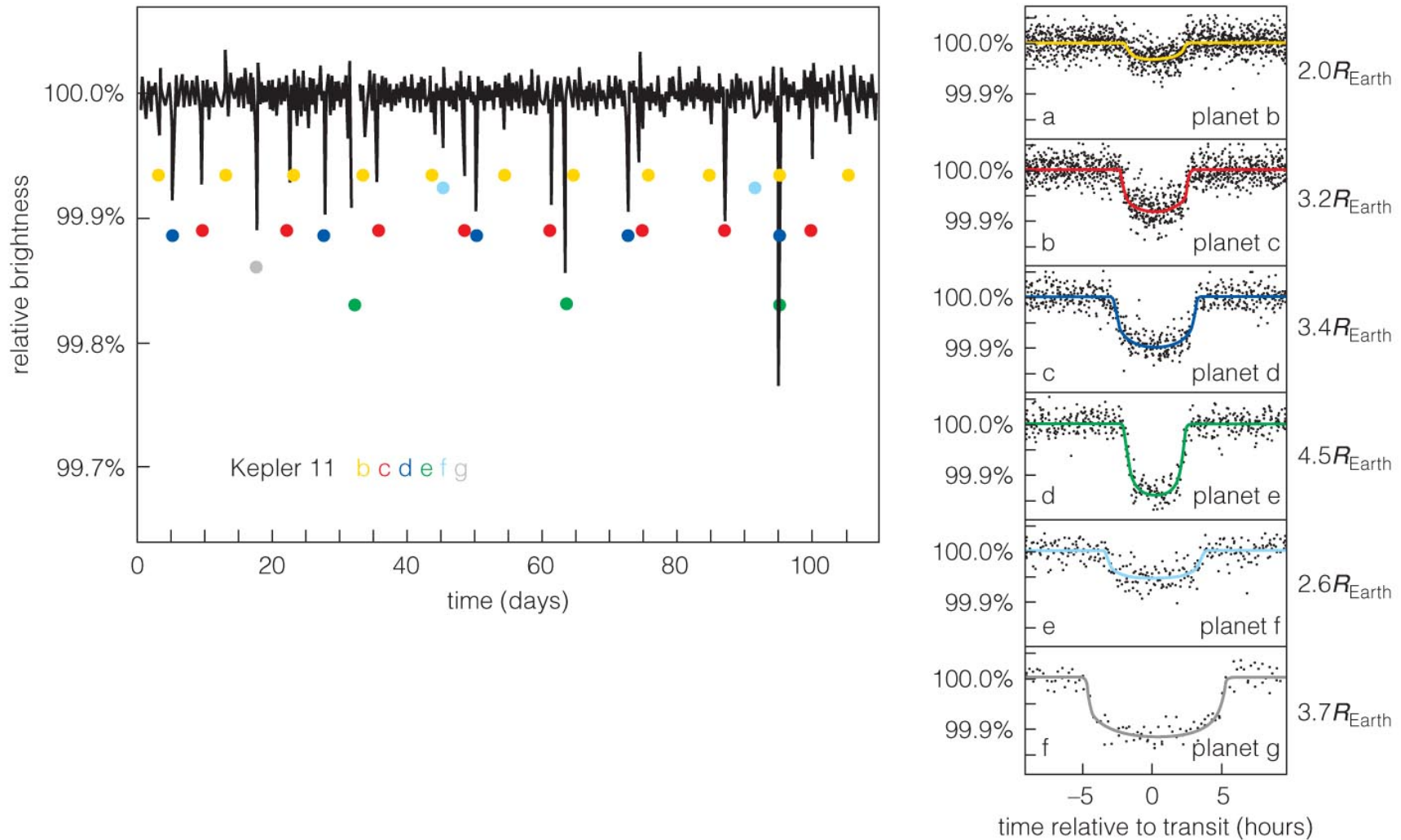
- A. It has a planet orbiting at less than 1 AU.
- B. It has a planet orbiting at greater than 1 AU.
- C. It has a planet orbiting at exactly 1 AU.
- D. It has a planet, but we do not have enough information to know its orbital distance.

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?

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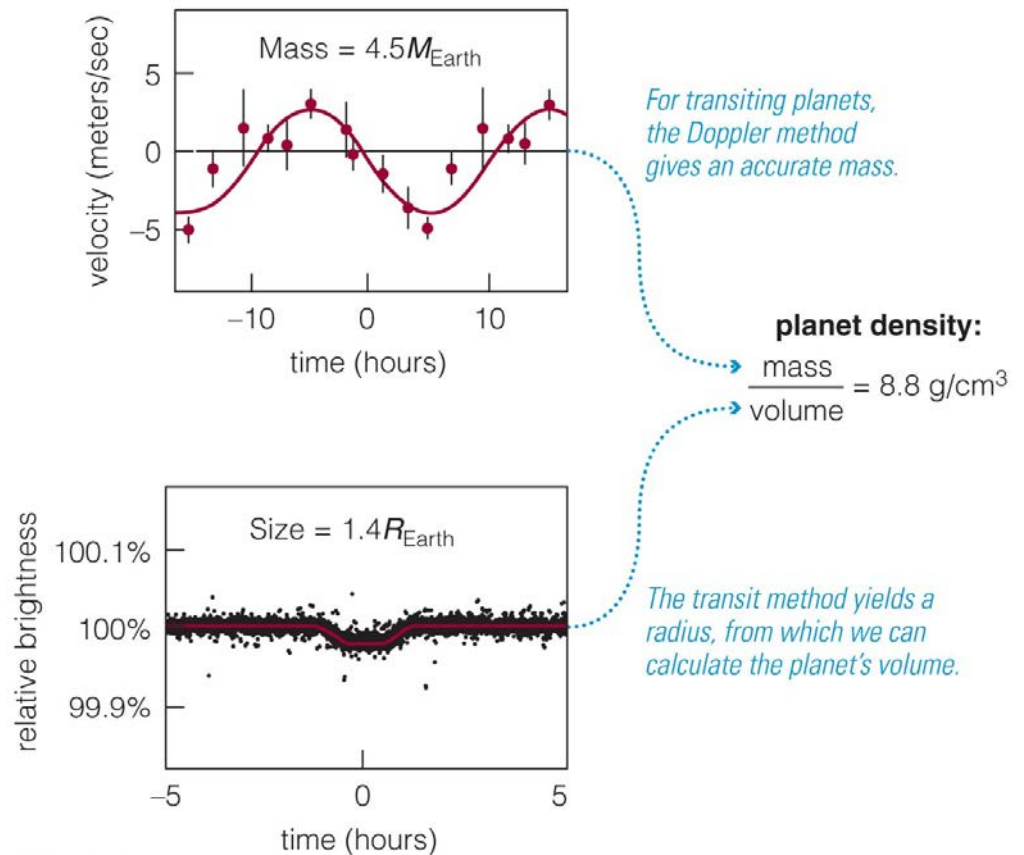
The Kepler 11 system



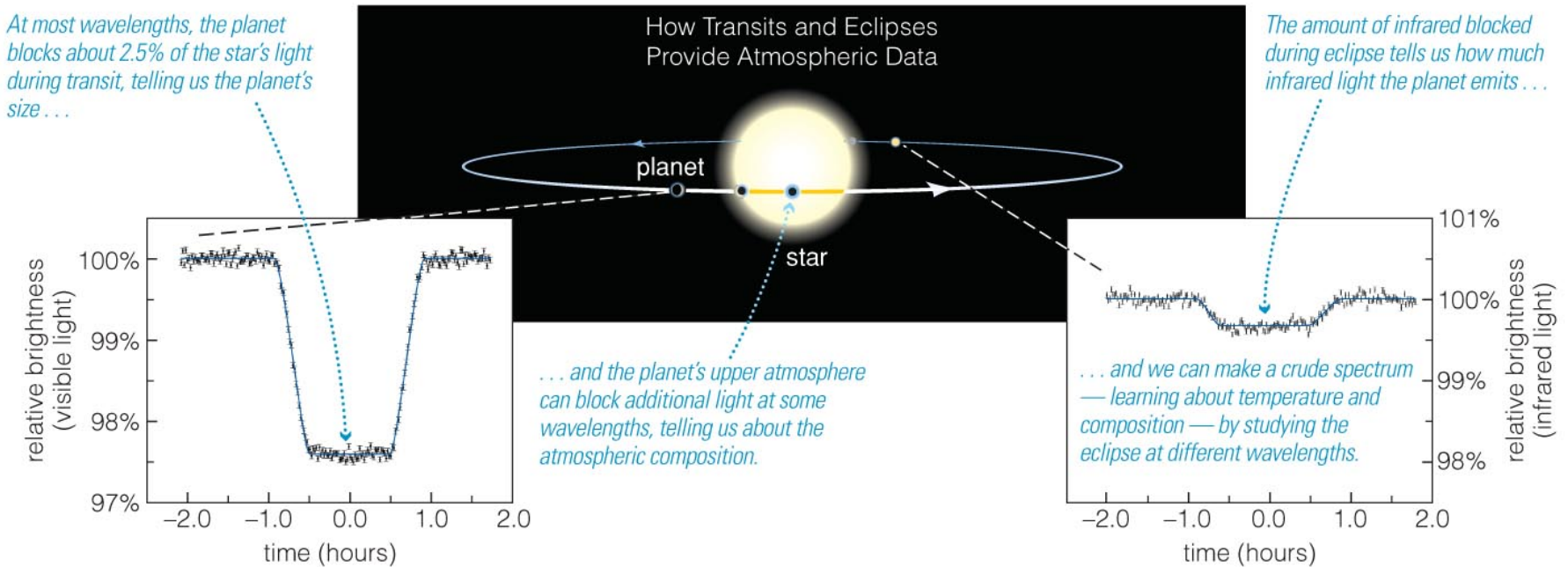
- The periods and sizes of Kepler 11's 6 known planets can be determined using transit data.

Calculating density

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



Spectrum During Transit



- During a transit some starlight will be absorbed by the planet's atmosphere, revealing its composition.
- During an eclipse of the planet, the decrease in the detected total infrared light is the infrared light emitted from the planet itself.

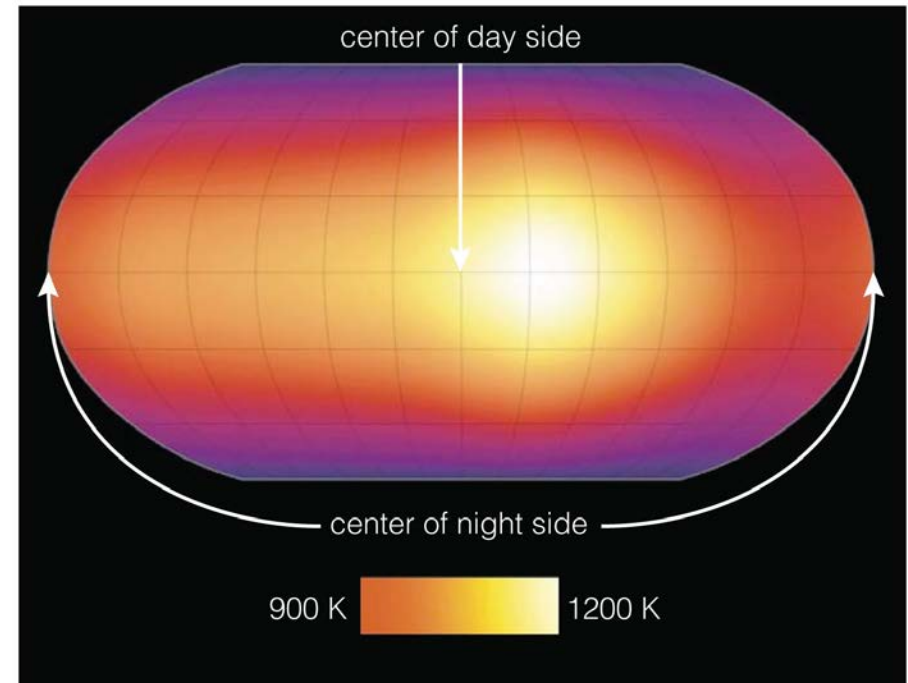
Surface Temperature Map

The observed total brightness (planet + star) will change as the **planet presents different phases as it orbits.**

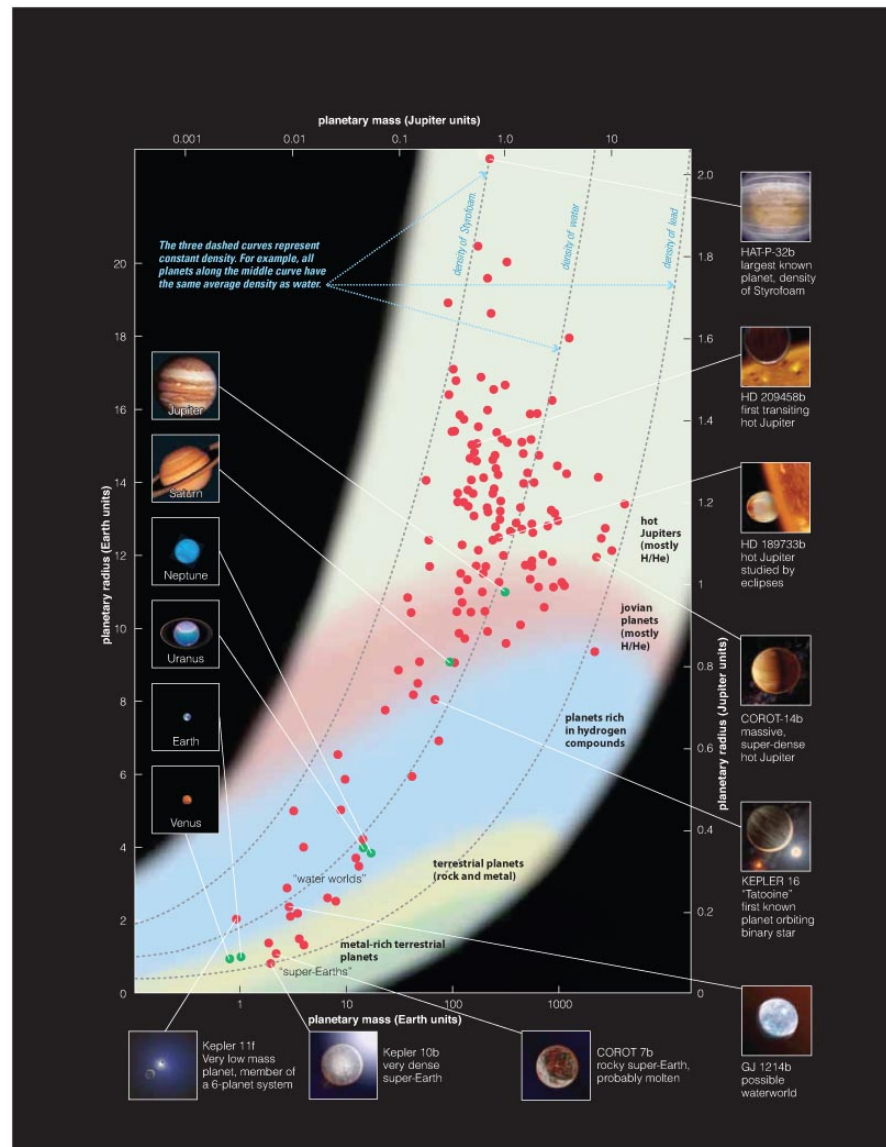
With infrared light we can detect **differences in the brightness of the night and day sides** of the planet as it orbits.

All planets in close orbits are expected to have synchronous rotation (always showing the same face towards the star.)

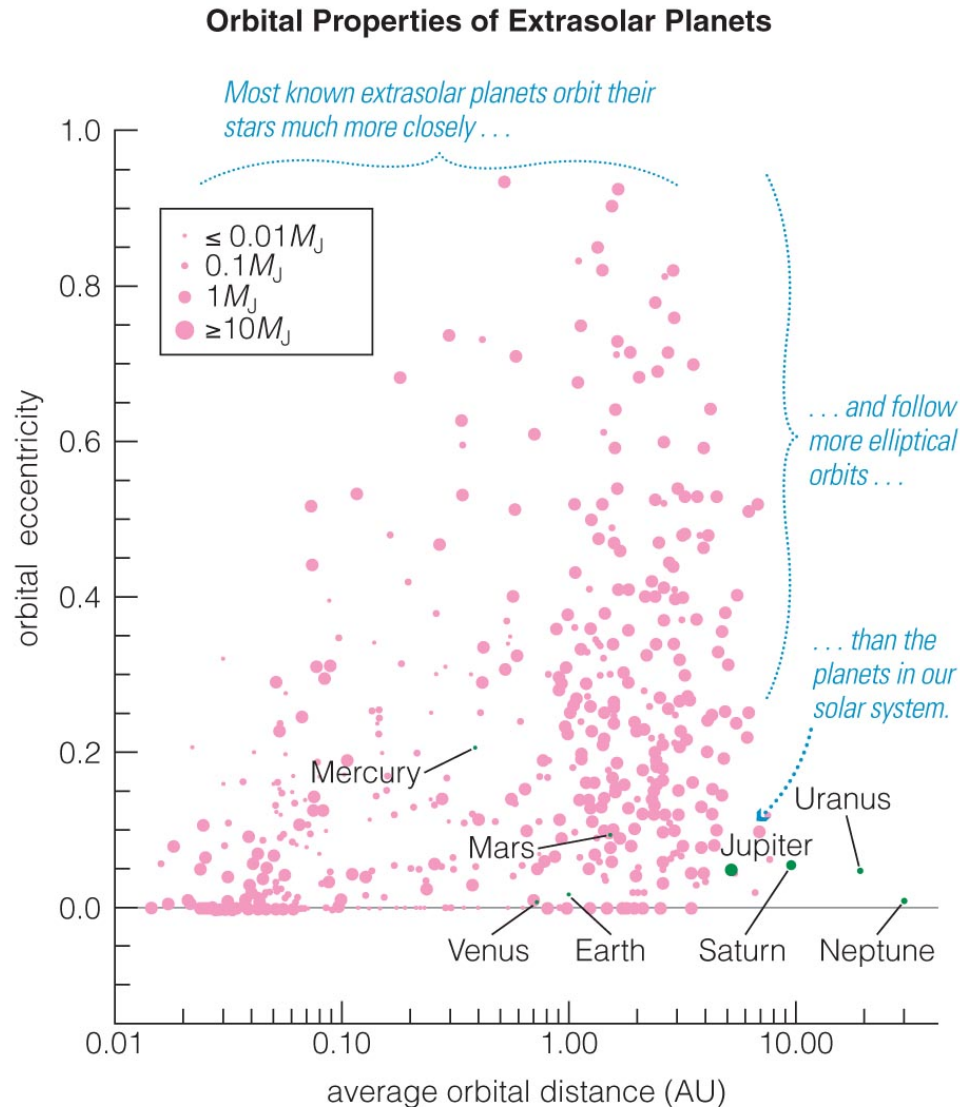
- Measuring the change in infrared brightness enables us to map a planet's surface temperature.



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

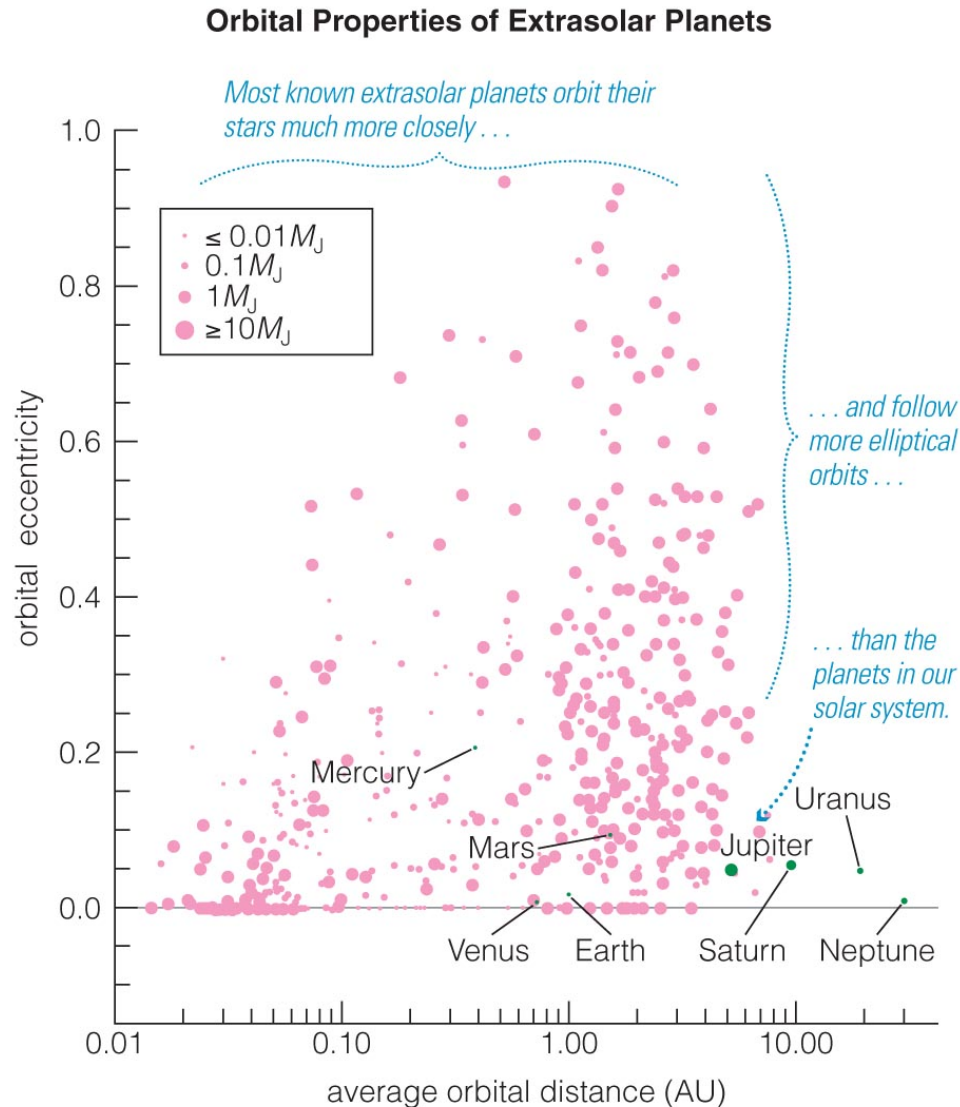


Orbits of Extrasolar Planets



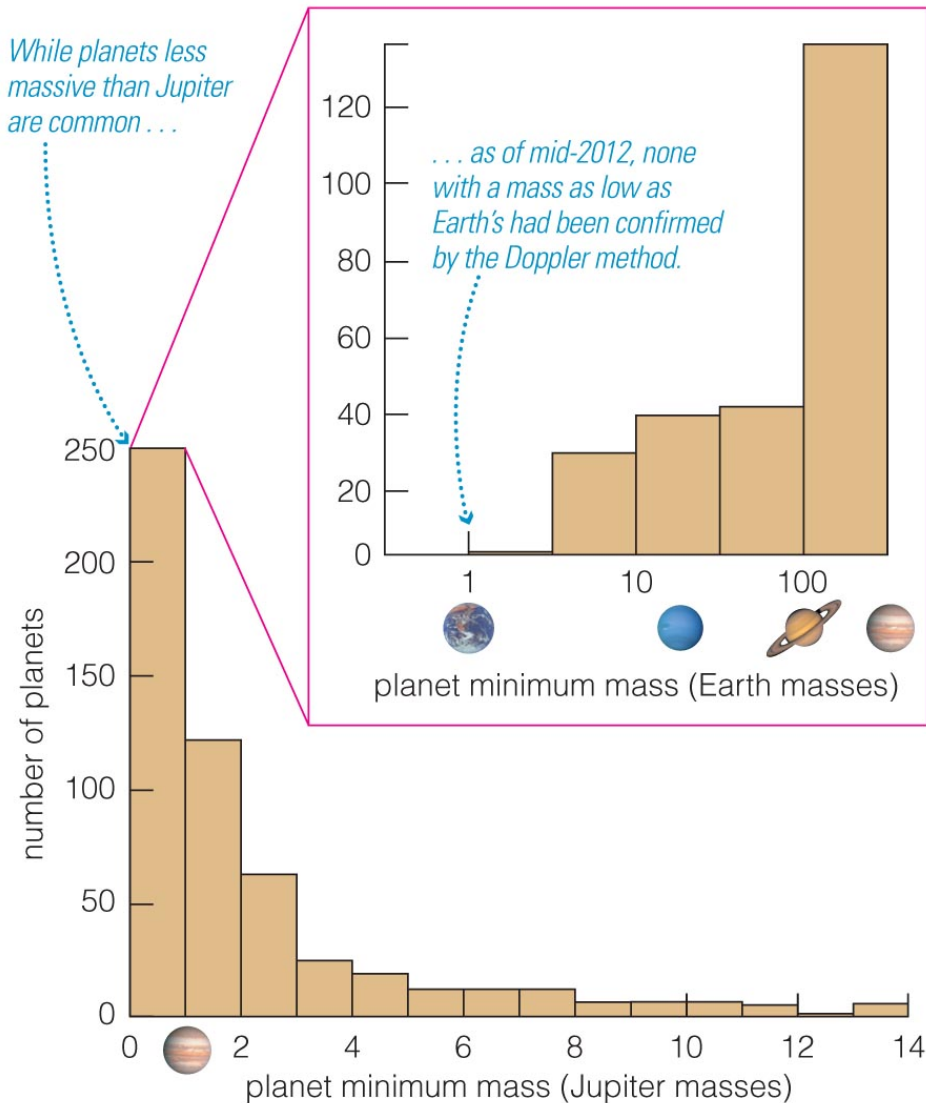
- Most of the detected planets have orbits smaller than Jupiter's.
- Planets at greater distances are harder to detect with the Doppler technique.

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



- Low-mass planets outnumber massive planets
- *Kepler* data not included here.
- 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.

What have we learned?

- **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.

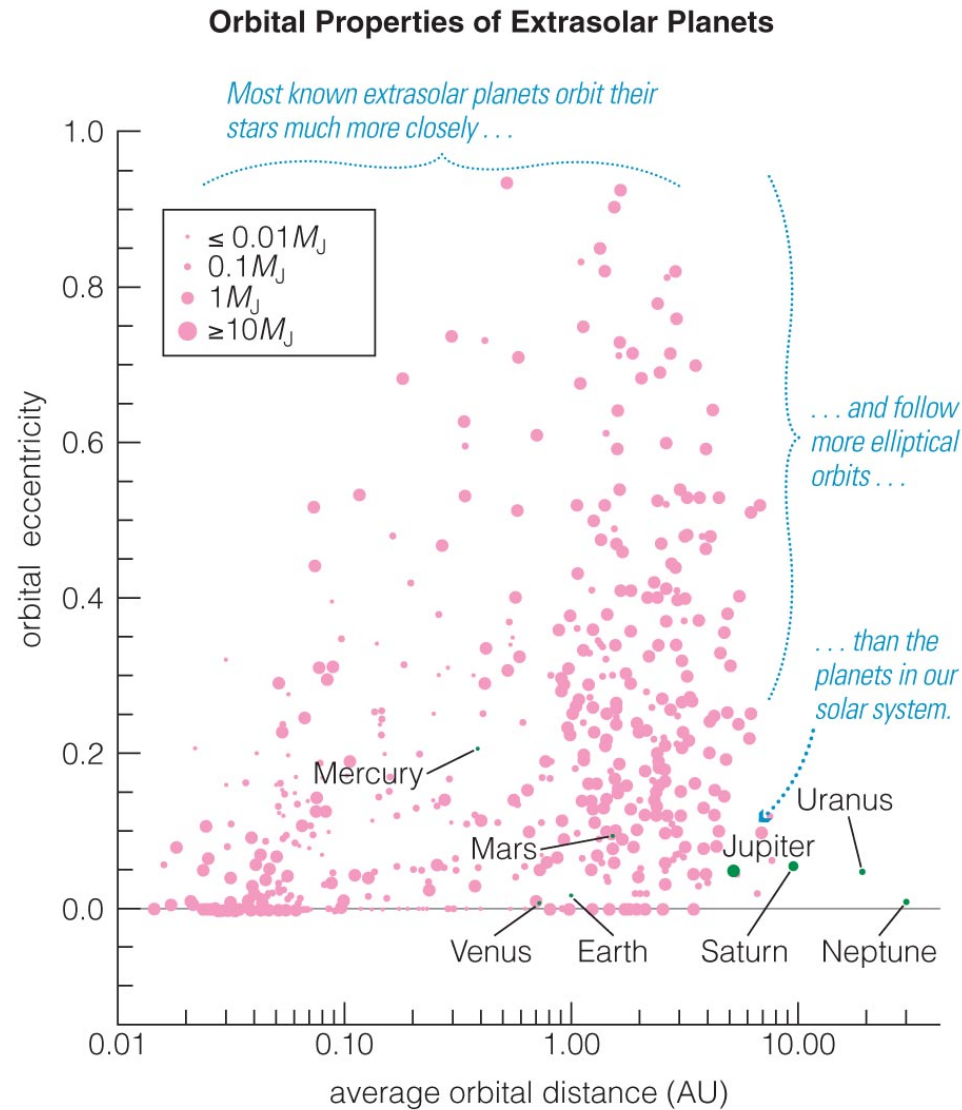
What have we learned?

- **How do extrasolar planets compare with 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:
 - **Can we explain the surprising orbits of many extrasolar planets?**
 - **Do we need to modify our theory of solar system formation?**

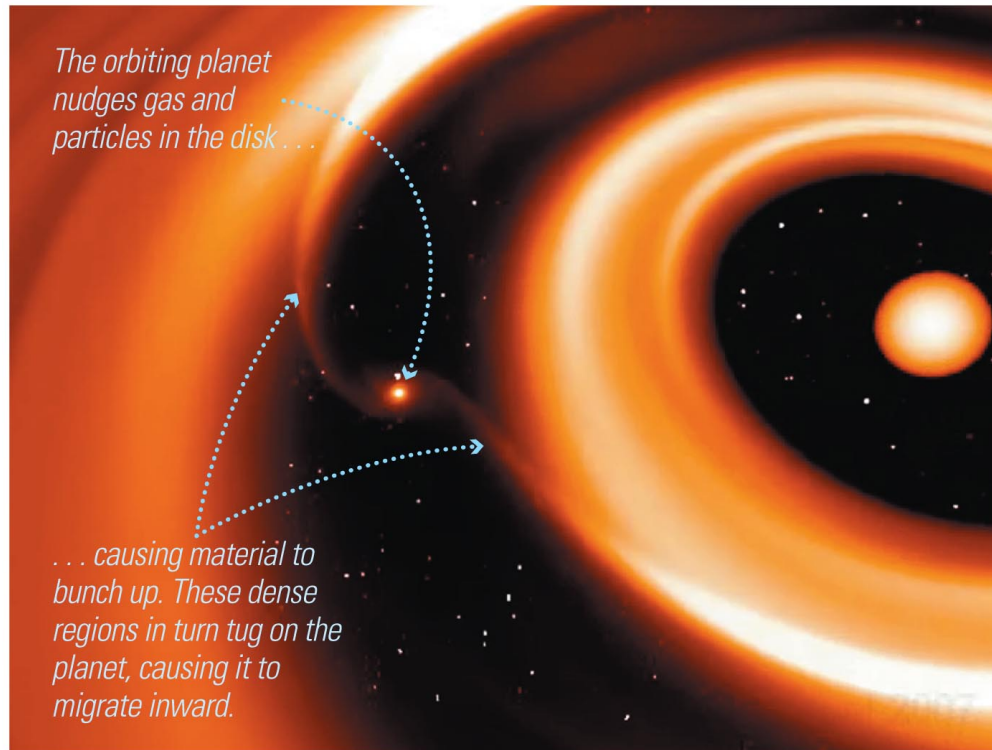
Can we explain the surprising orbits of many extrasolar planets?



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 migration.
- Resonances may also contribute.

Thought Question

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

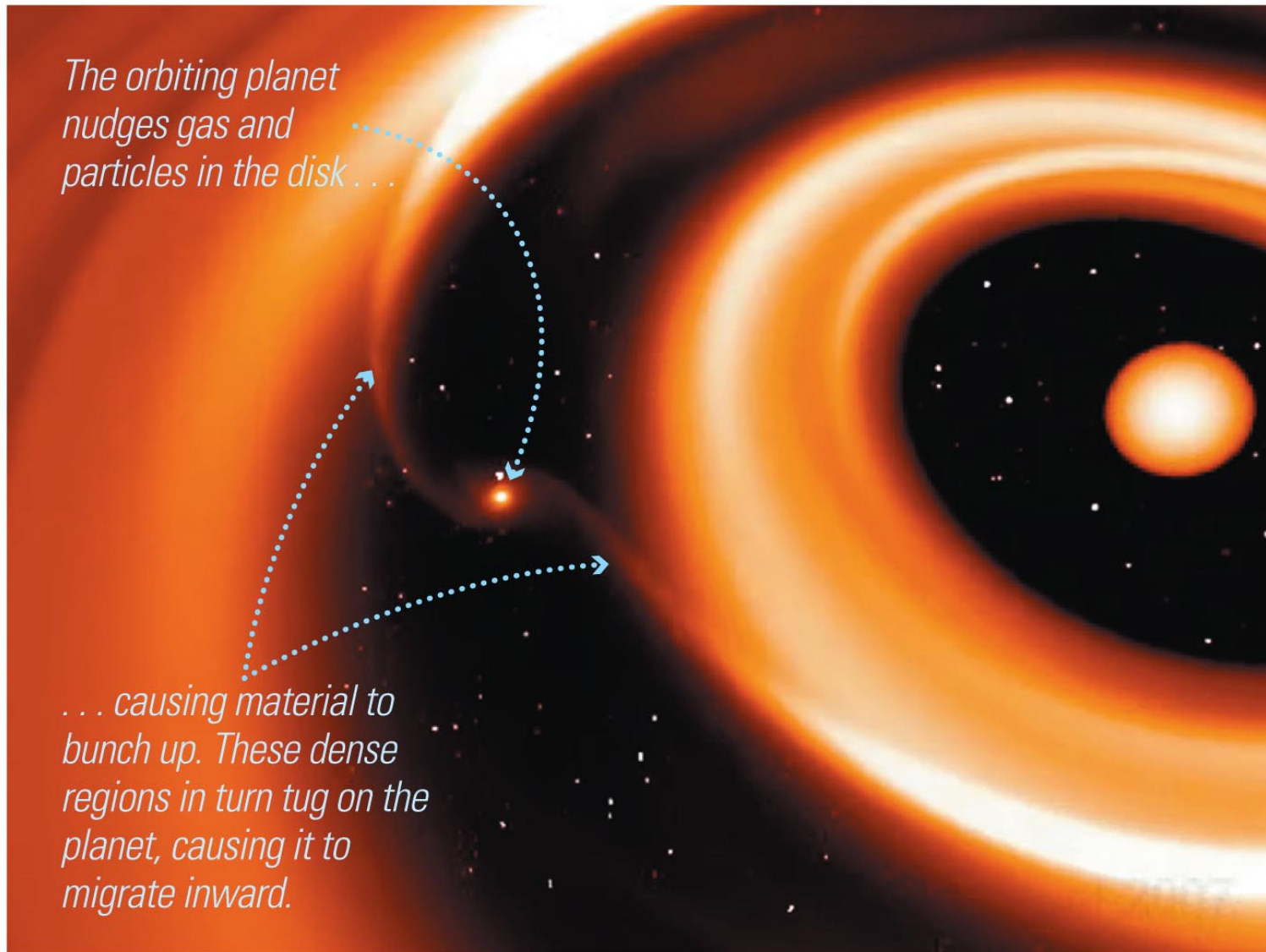
- A. It transfers energy and angular momentum to another object.
- B. The gravity of the other object forces the planet to move inward.
- C. It gains mass from the other object, causing its gravitational pull to become stronger.

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.

Do we need to modify our theory of solar system formation?



Modifying the Nebular Theory

- Observations of extrasolar planets have shown that the nebular theory was incomplete.
- Effects like planetary migration and gravitational encounters might be more important than previously thought.

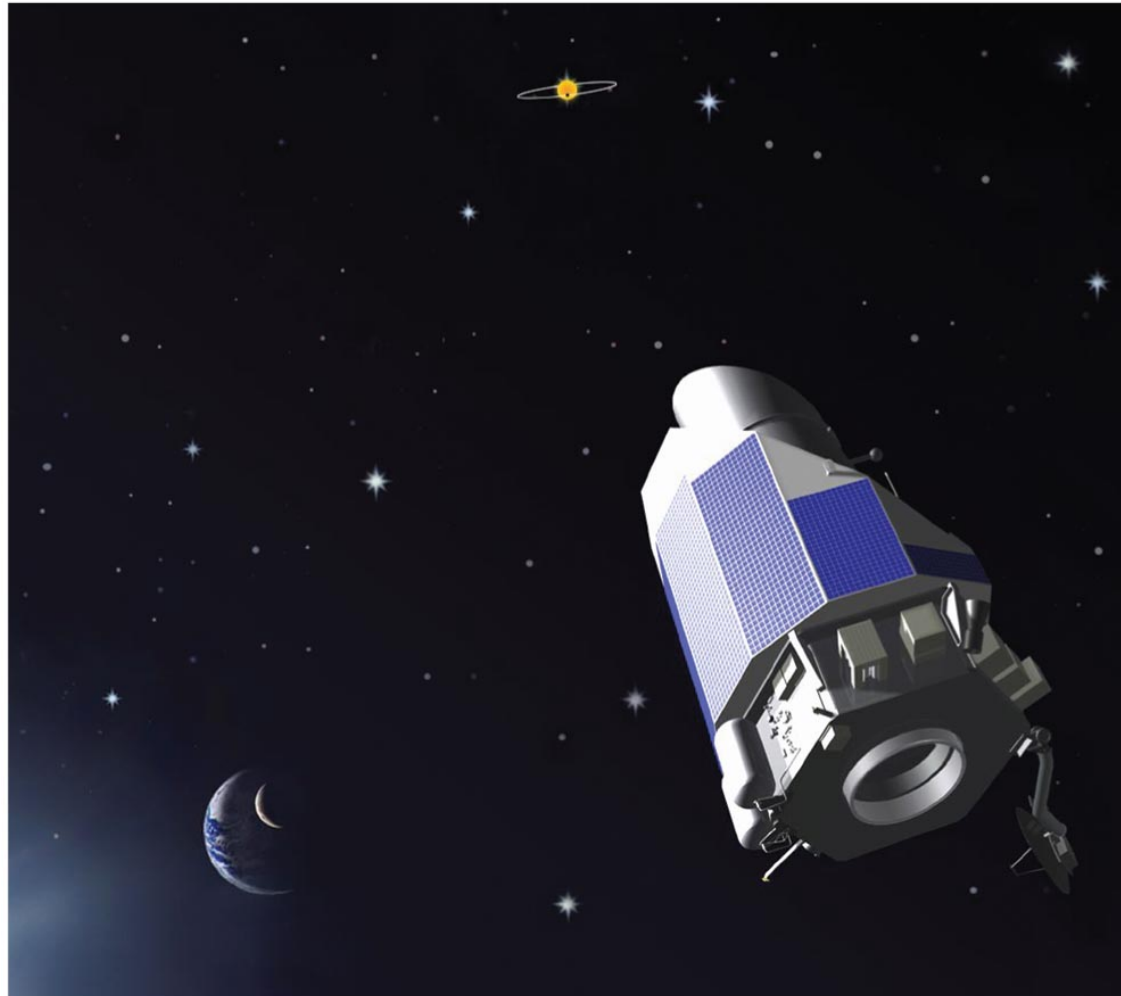
What have we learned?

- **Can we explain the surprising orbits of many extrasolar planets?**
 - Original nebular theory cannot account for the existence of hot Jupiters.
 - Planetary migration or gravitational encounters may explain how Jupiter-like planets moved inward.
- **Do we need to modify our theory of solar system formation?**
 - Migration and encounters may play a larger role than previously thought.

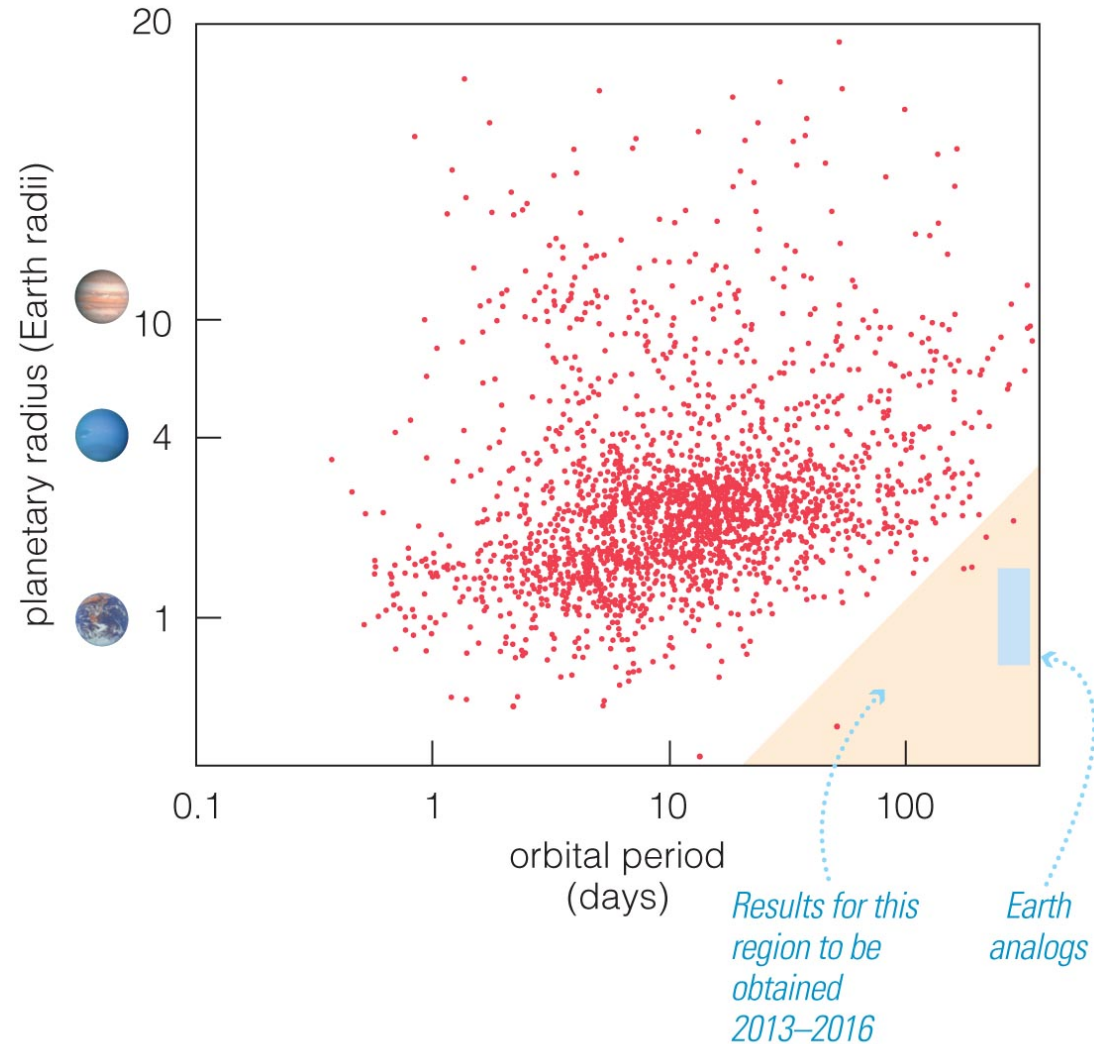
13.4 The Future of Extrasolar Planetary Science

- Our goals for learning:
 - **How will future observations improve our understanding?**

How will future observations improve our understanding?

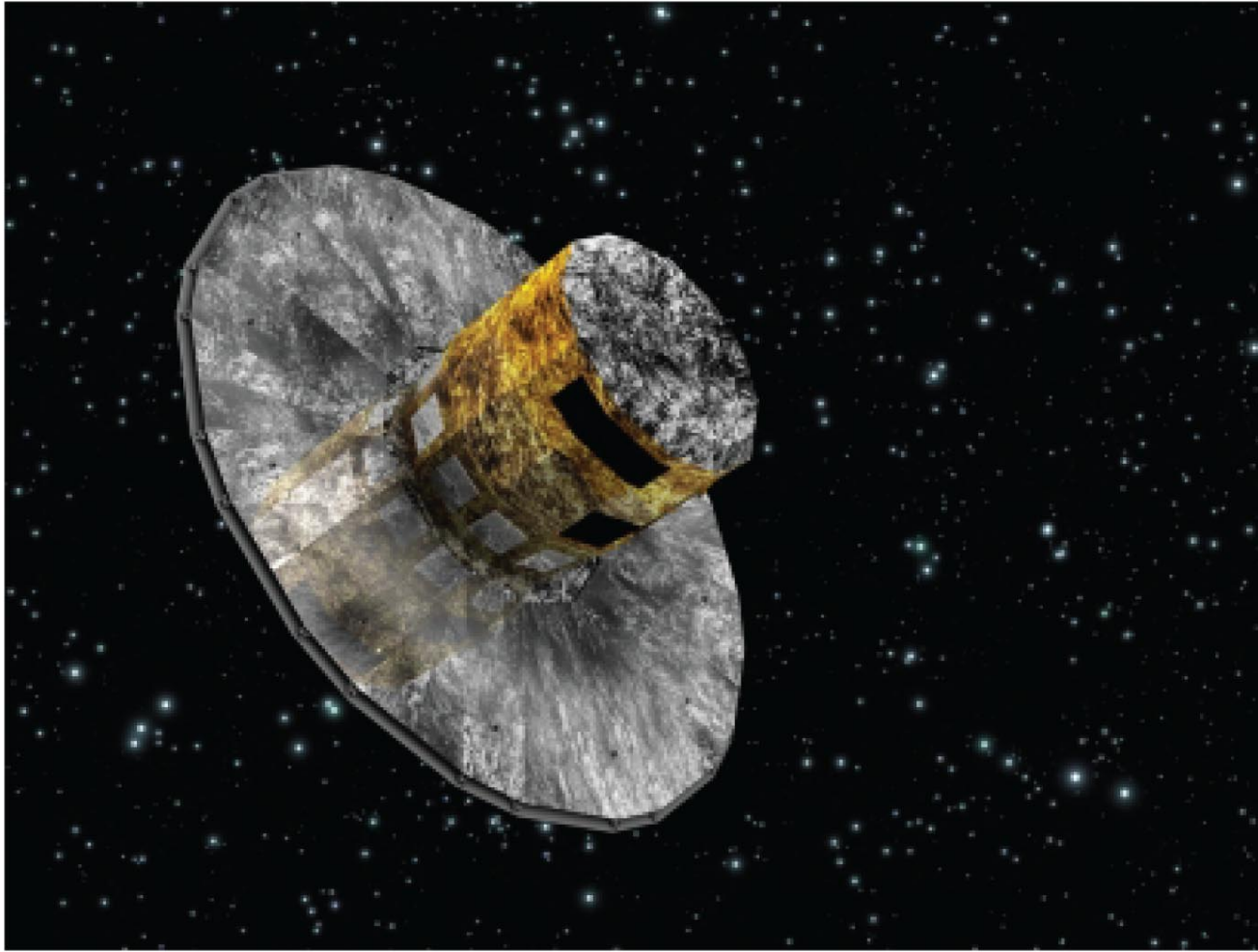


Kepler mission



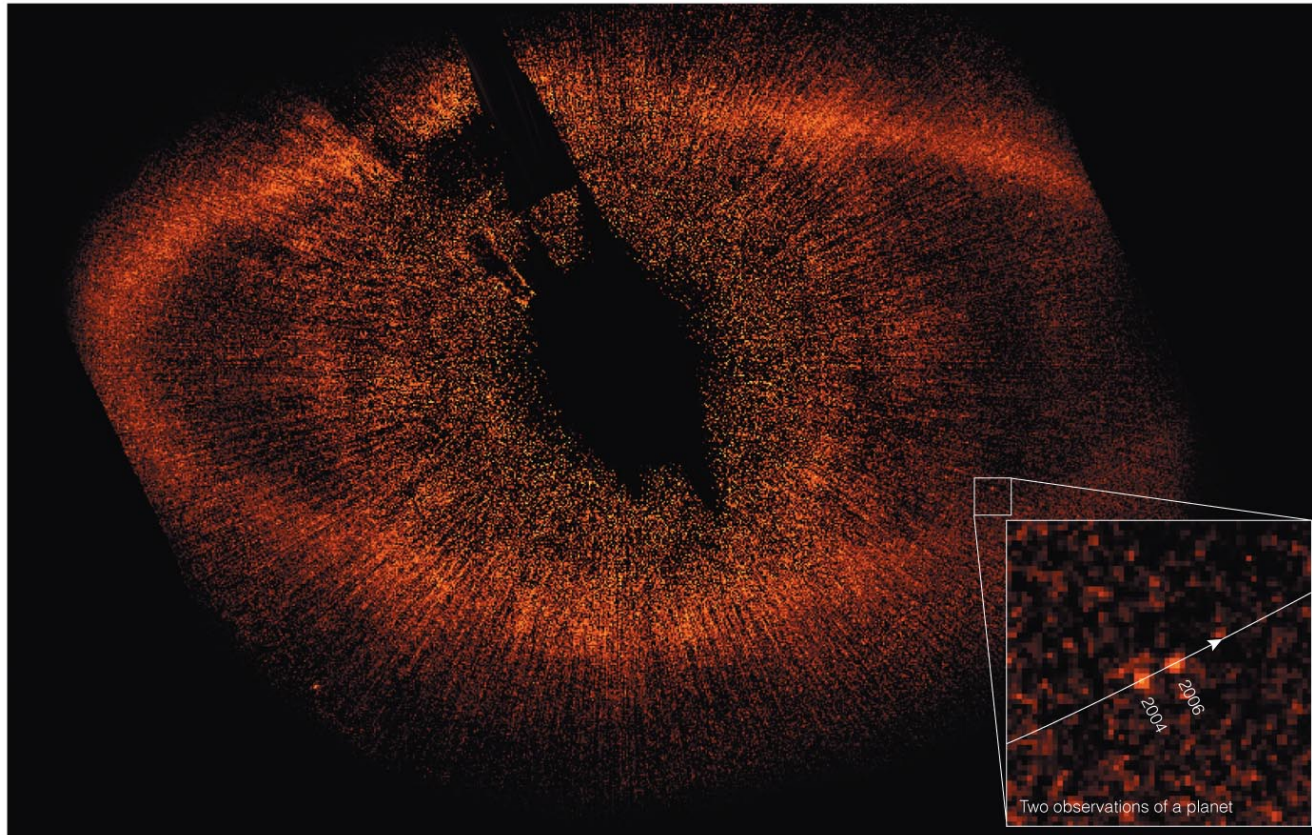
- The bottom right portion of the graph, where truly Earth-like planets reside, should be filled in by *Kepler* over the next few years!

GAIA mission



- *GAIA* is a European mission planned for 2013 that will use interferometry to measure precise motions of a billion stars

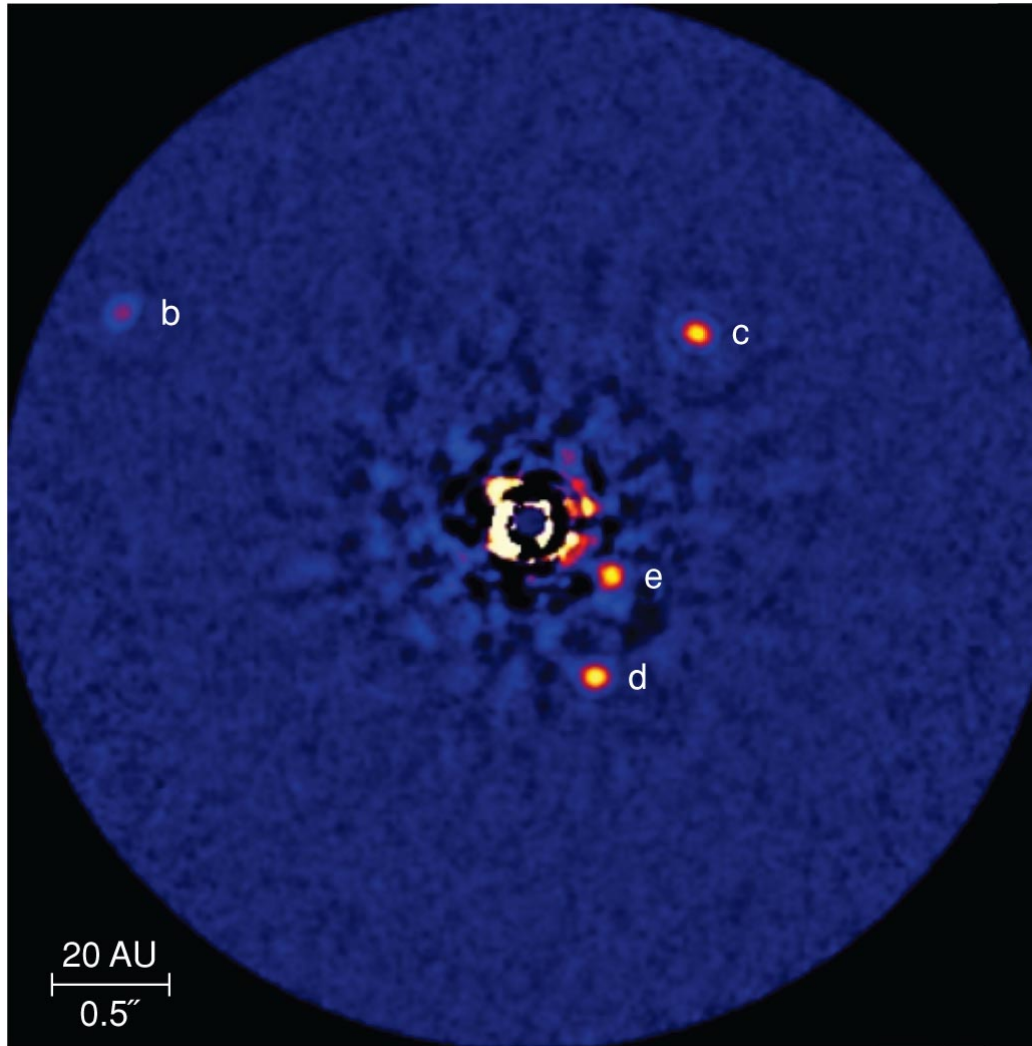
Direct Detection



- 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.

What have we learned?

- **How will future observations improve our understanding?**
 - Transit missions will be capable of finding Earth-like planets that cross in front of their stars.
 - Astrometric missions will be capable of measuring the "wobble" of a star caused by an orbiting Earth-like planet.
 - Missions for direct detection of an Earth-like planet will need to use special techniques (like interferometry) for blocking starlight.