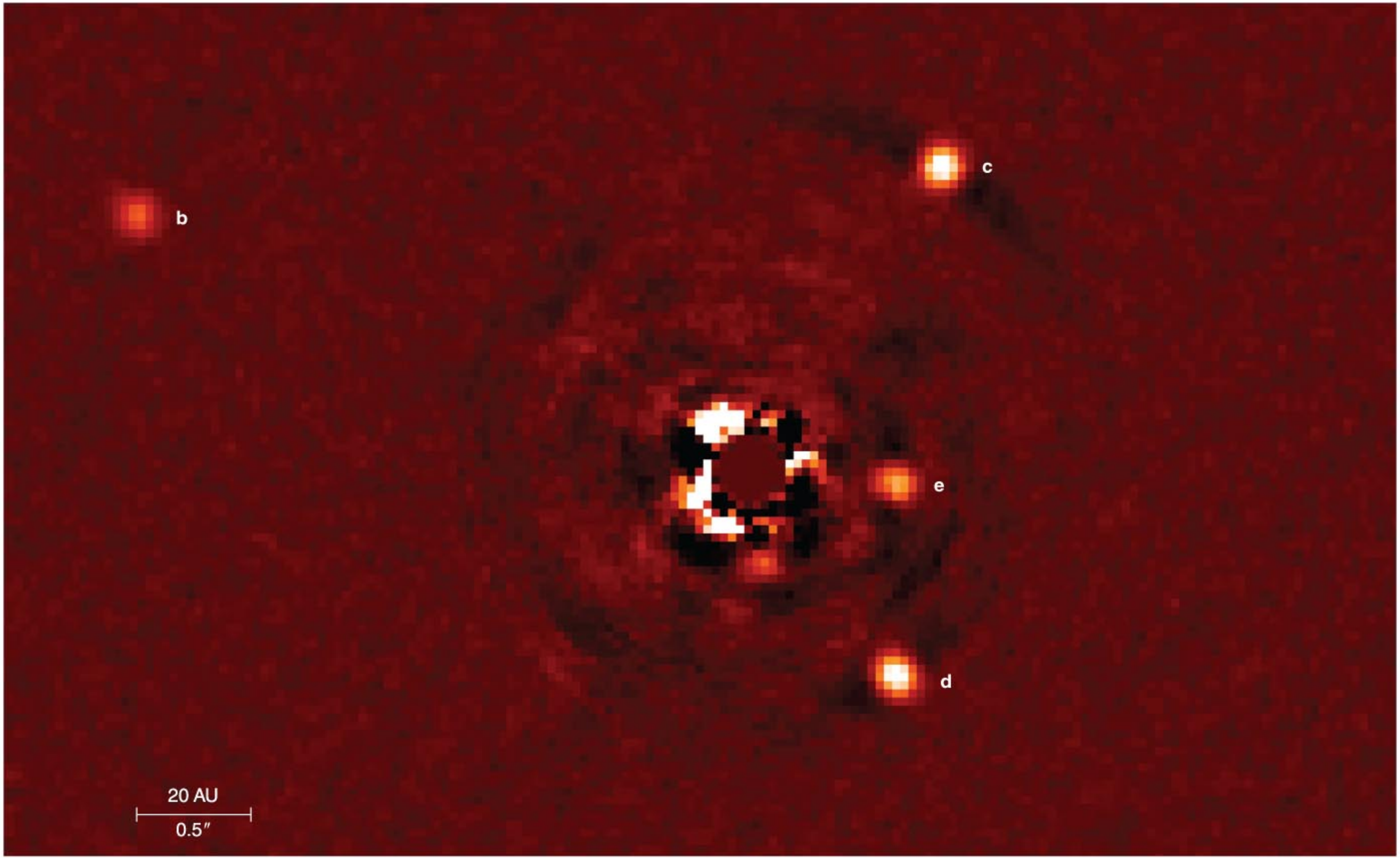
Chapter 13: Other Planetary Systems: The New Science of Distant Worlds

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?



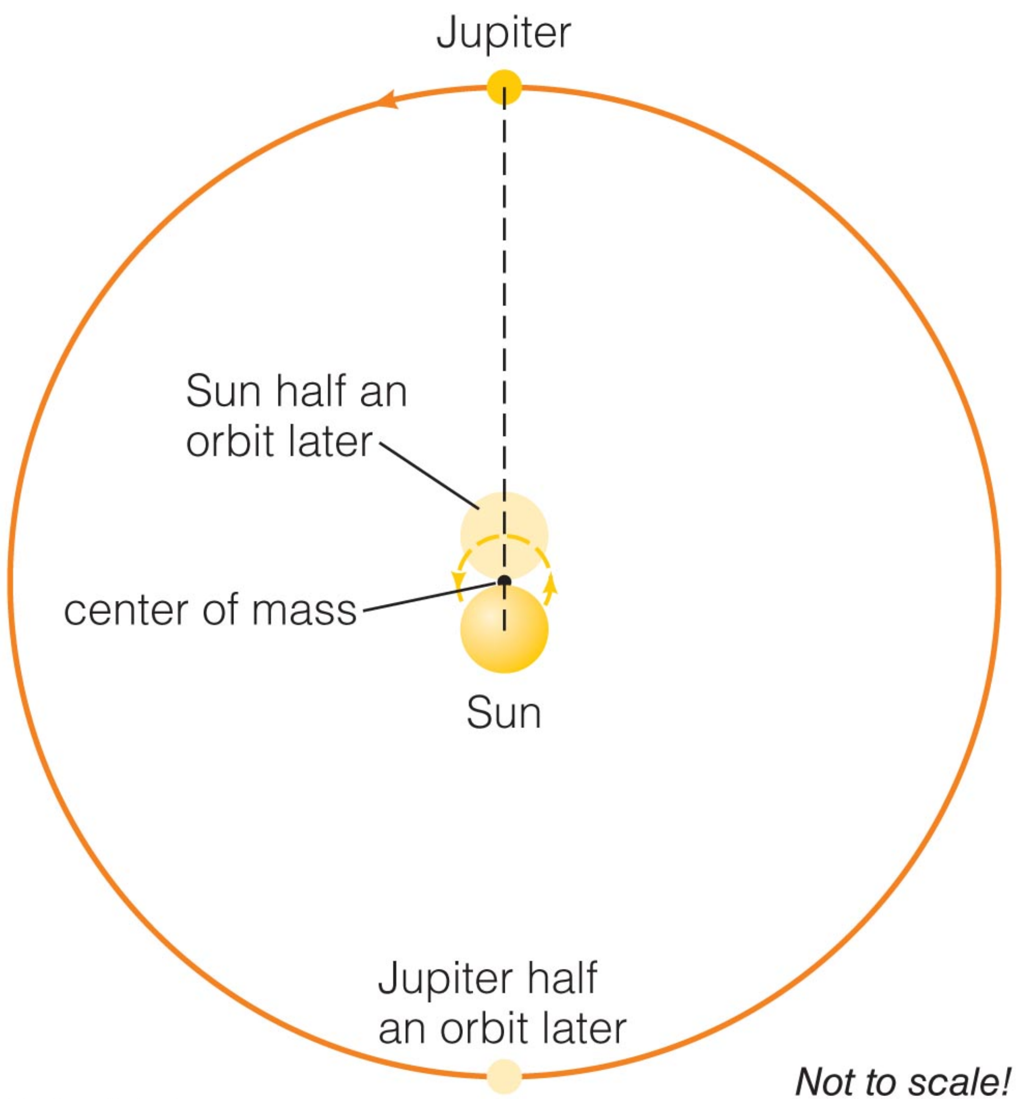
Brightness and Distance

- A Sun-like star is about a billion times brighter 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.

Special Topic: How Did We Learn That Other Stars Are Suns?

- Ancient observers didn't think stars were like the Sun because Sun is so much brighter.
- Christian Huygens (1629–1695) used holes drilled in a brass plate to estimate the angular sizes of stars.
- His results showed that, if stars were like Sun, they must be at great distances, consistent with the lack of observed parallax.

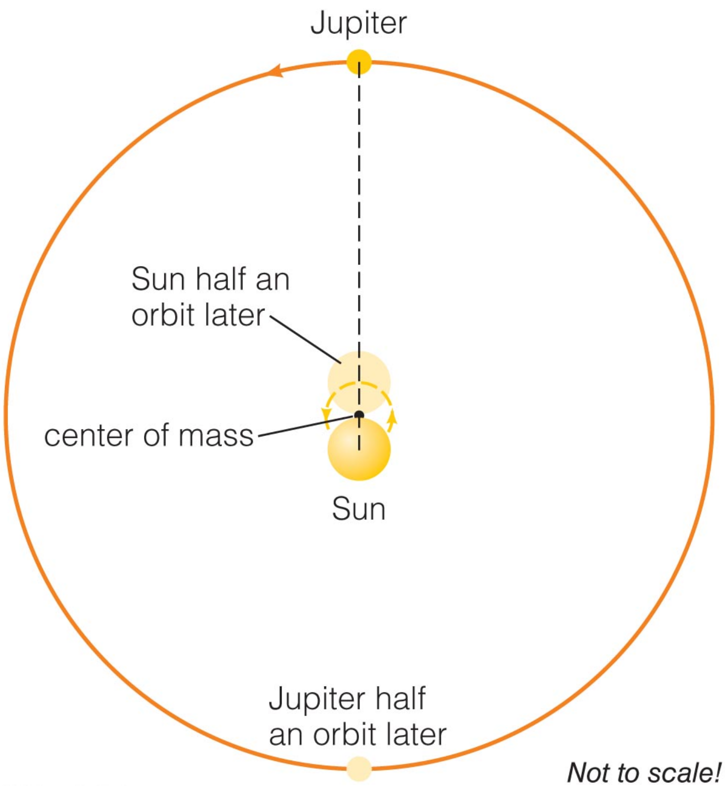
How can a star's motion reveal the presence of planets?



Planet Detection

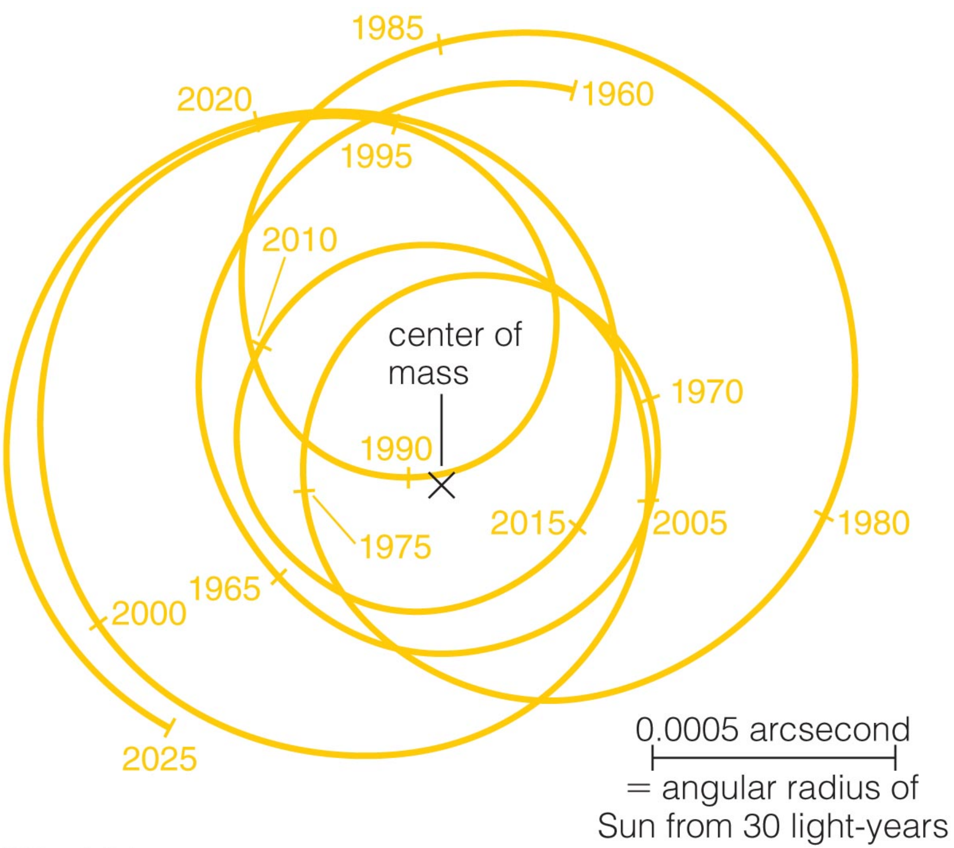
- **Direct:** pictures or spectra of the planets themselves
- **Indirect**: measurements of stellar properties revealing the effects of orbiting planets

Gravitational Tugs



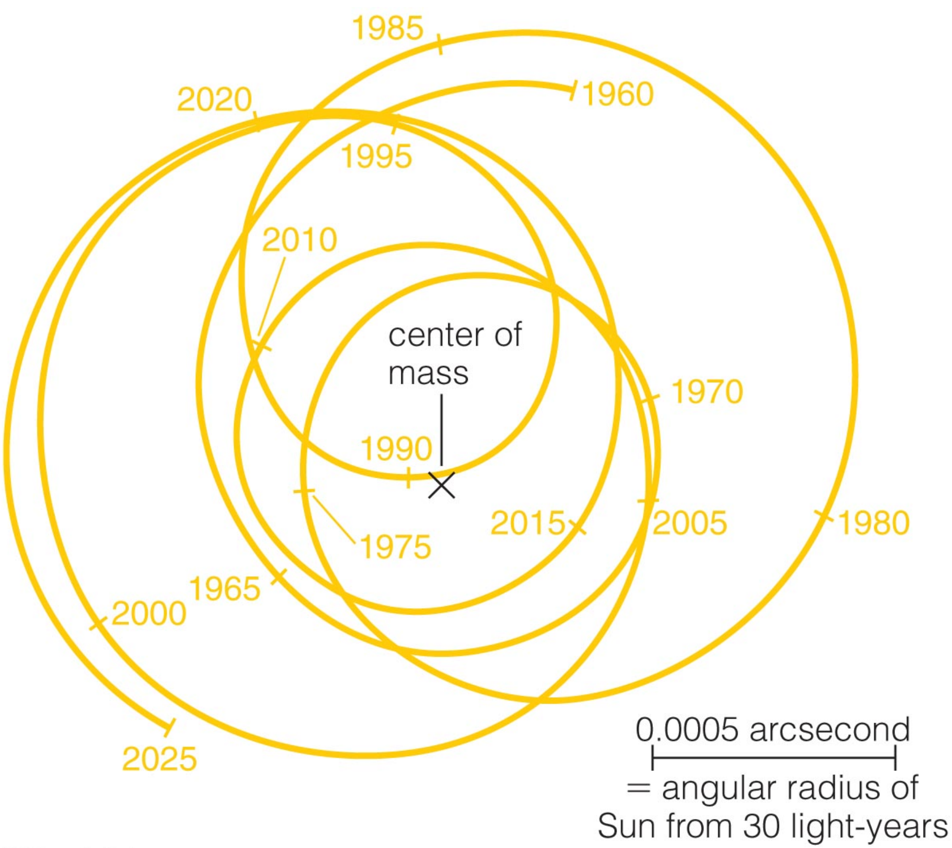
- The Sun and Jupiter orbit around their common center of mass.
- The Sun therefore wobbles around that center of mass with same period as Jupiter.

Gravitational Tugs



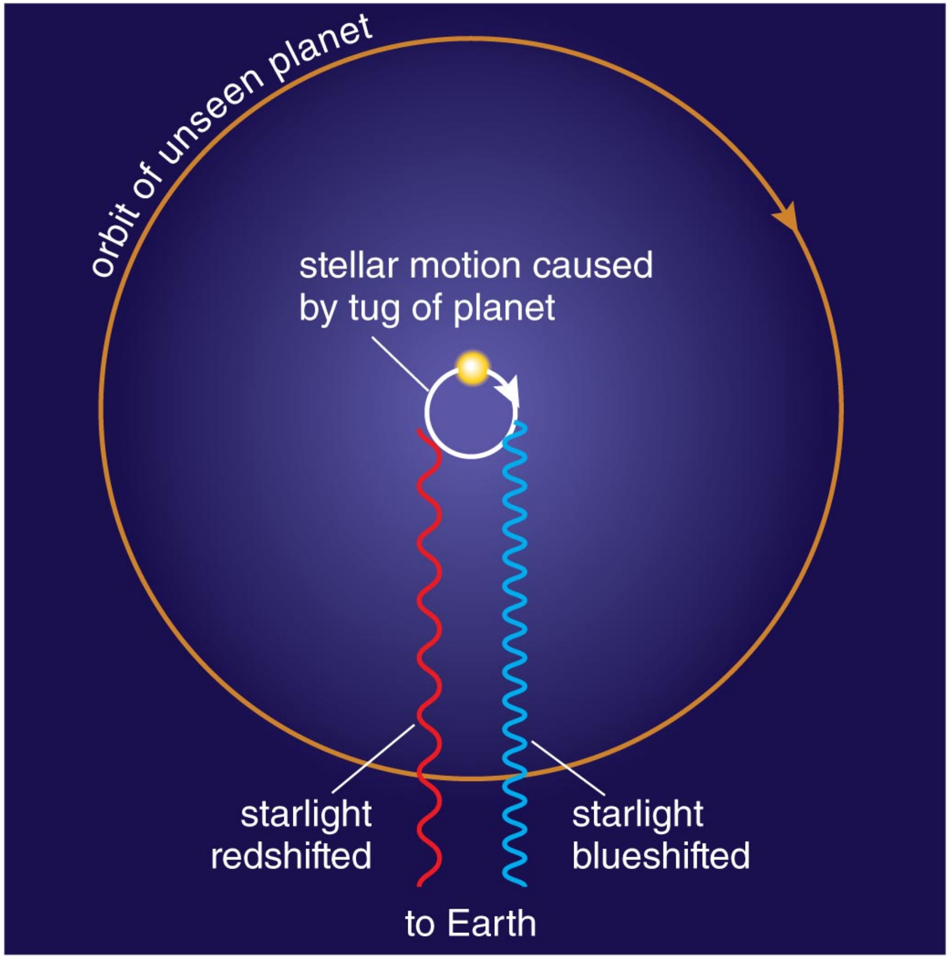
- The Sun's motion around the solar system's center of mass depends on tugs from all the planets.
- Astronomers around other stars that measured this motion could determine the masses and orbits of all the planets.

Astrometric Technique



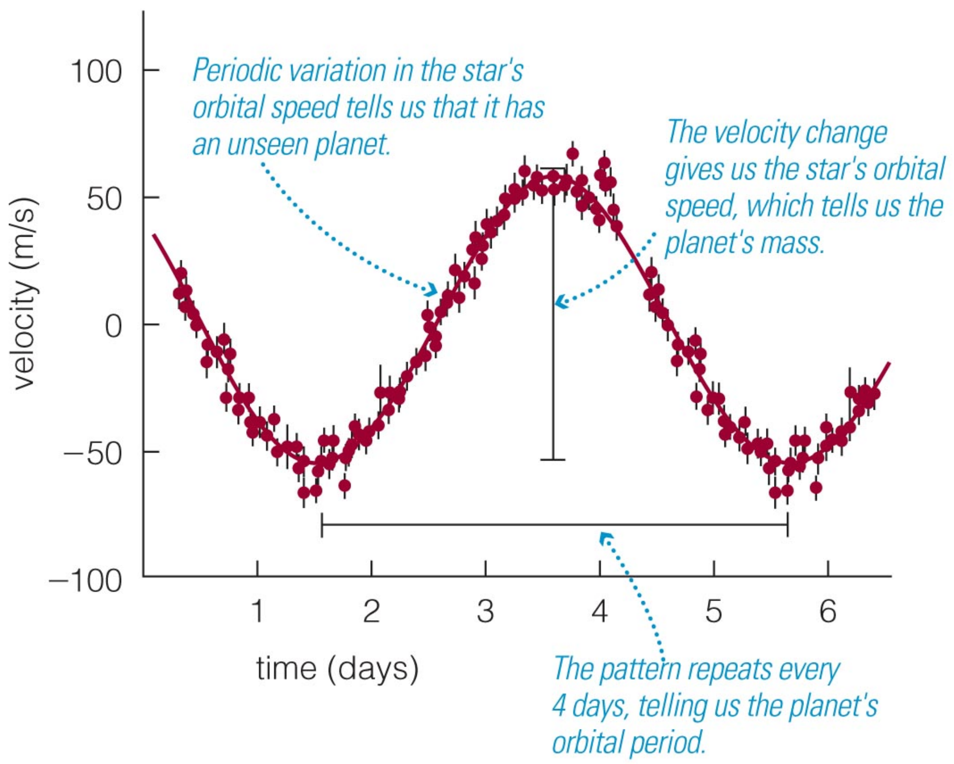
- We can detect planets by measuring the change in a star's position on sky
- However, these tiny motions are very difficult to measure (~ 0.001 arcsecond)
- GAIA spacecraft determines the position of stars in our galaxy with an accuracy of 0.00002 arcsecond and better

Doppler Technique



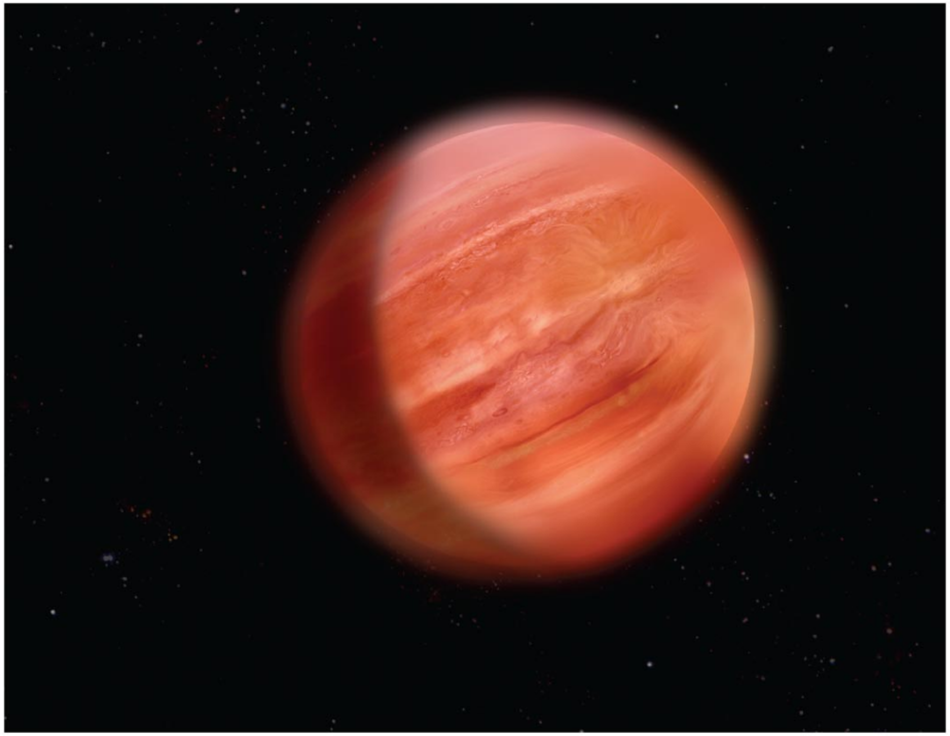
- Measuring a star's Doppler shift can tell us its motion toward and away from us.
- Current techniques can measure motions as small as 1 m/s (walking speed!).

First Extrasolar Planet



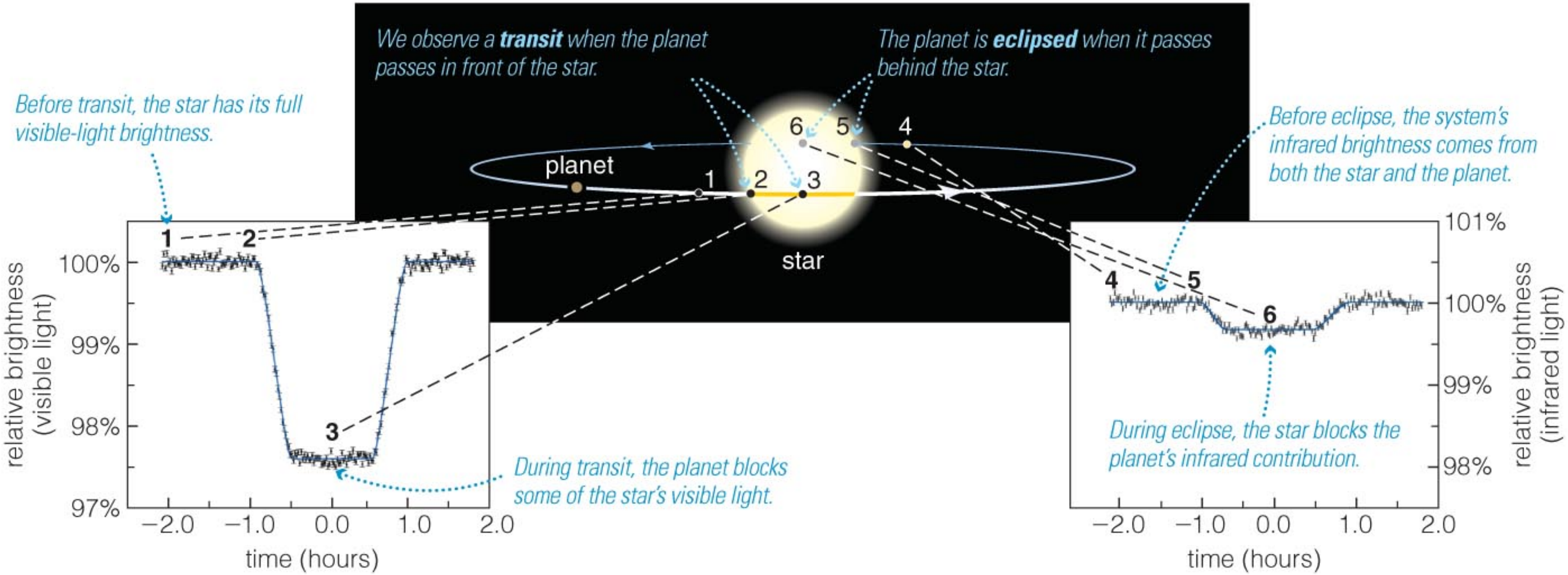
- Doppler shifts of the star 51 Pegasi indirectly revealed a planet with 4-day orbital period.
- This short period means that the planet has a small orbital distance.
- This was the first extrasolar planet to be discovered around a Sun-like star (1995).

First Extrasolar Planet

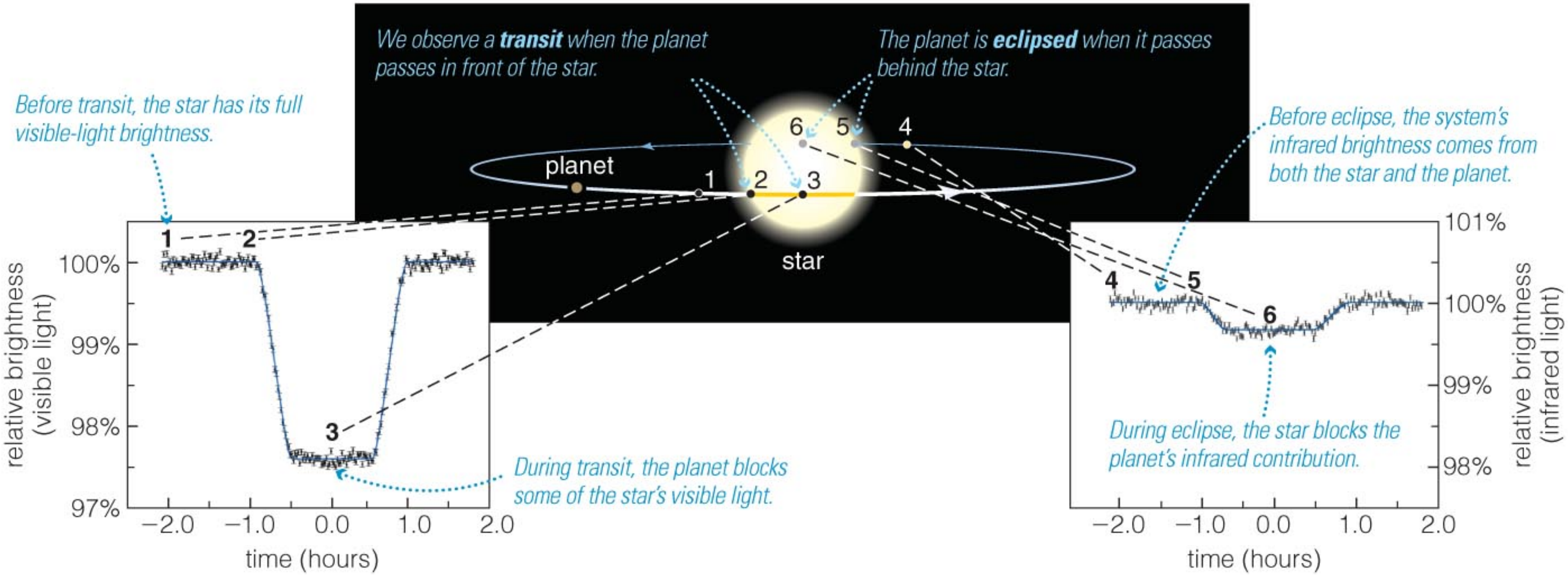


- The planet around 51 Pegasi has a mass similar to Jupiter's, despite its small orbital distance.

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, resulting in a dip in brightness.
- An **eclipse** is also sometimes seen, when the planet passes behind the star.
- Depth of dip: accurate measurement of planet size.

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.
- It has found just under 4000 planets at its retirement on October 30, 2018.

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.

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.

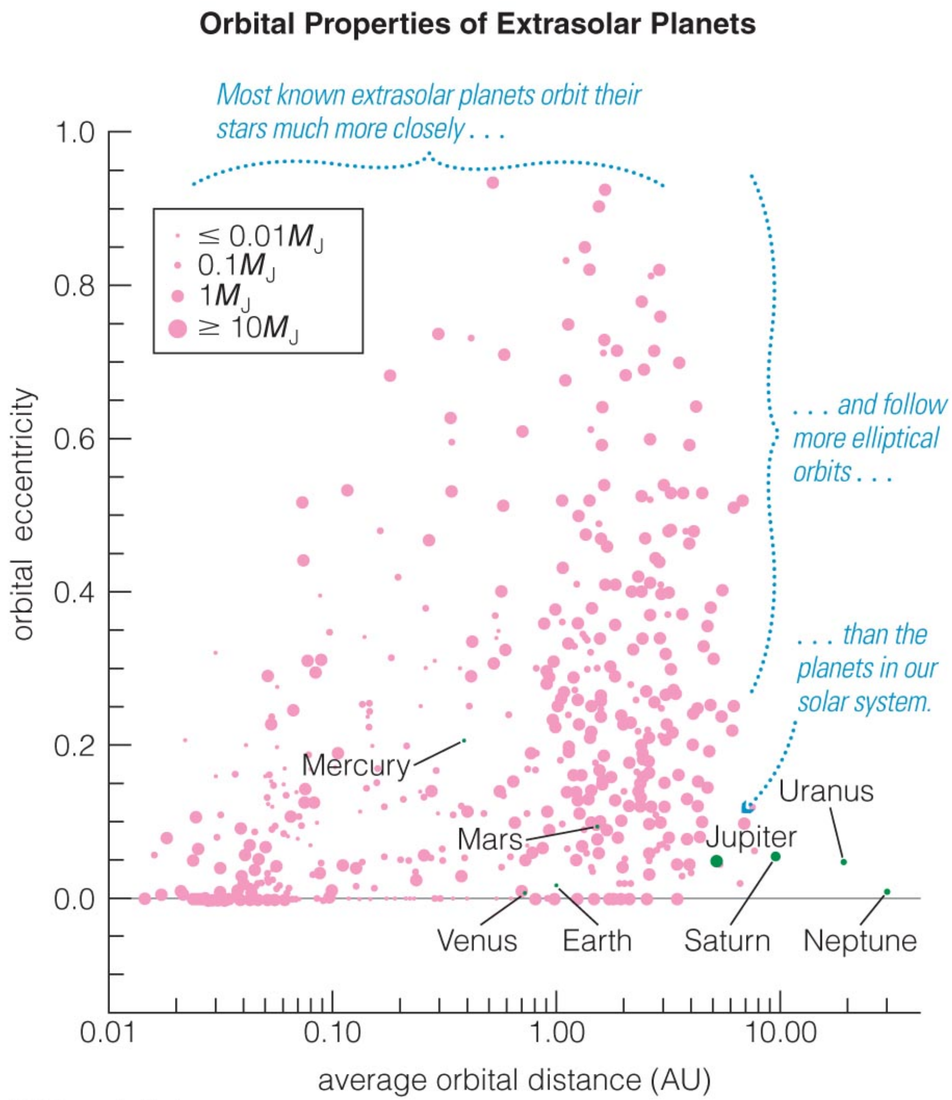
What have we learned?

- **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 just under four thousands of planets 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?**

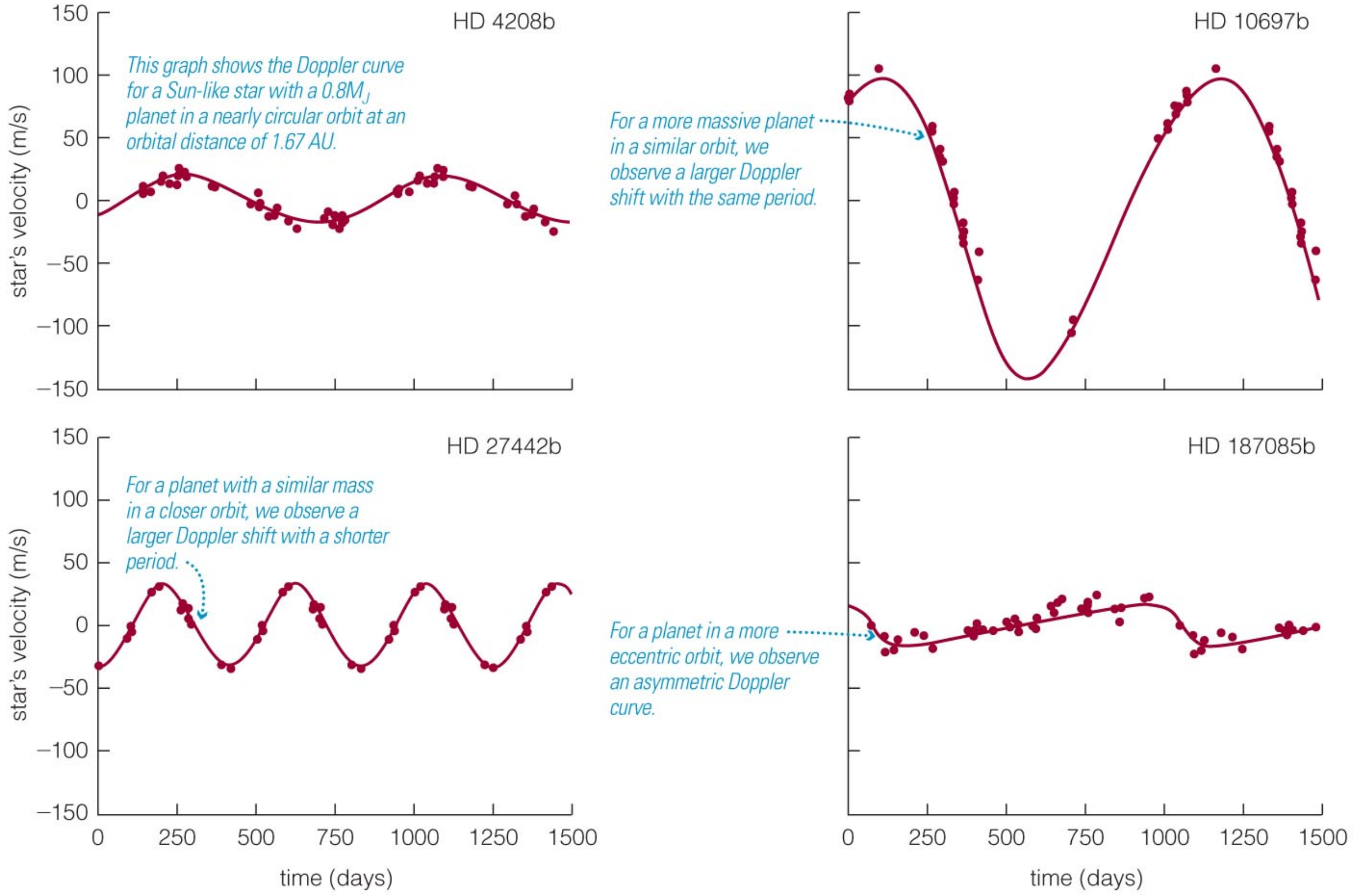
What properties of extrasolar planets can we measure?



Measurable Properties

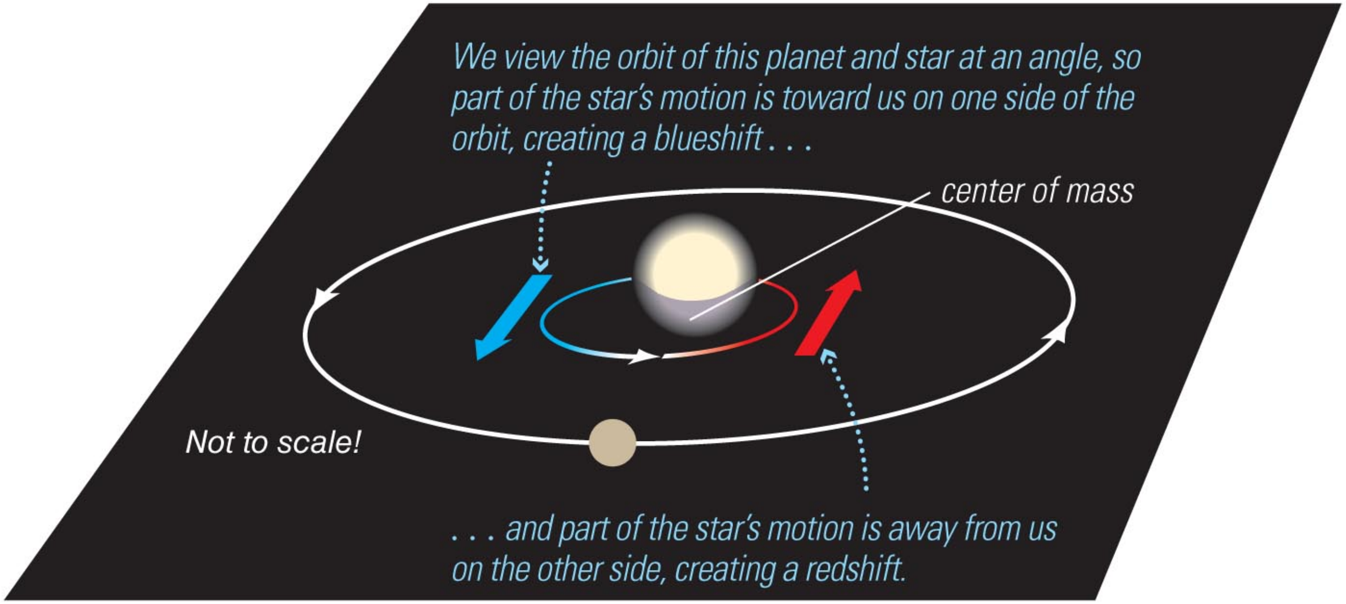
- Orbital period, distance, and shape
- Planet mass, size, and density
- Atmospheric properties

What can Doppler shifts tell us?



- 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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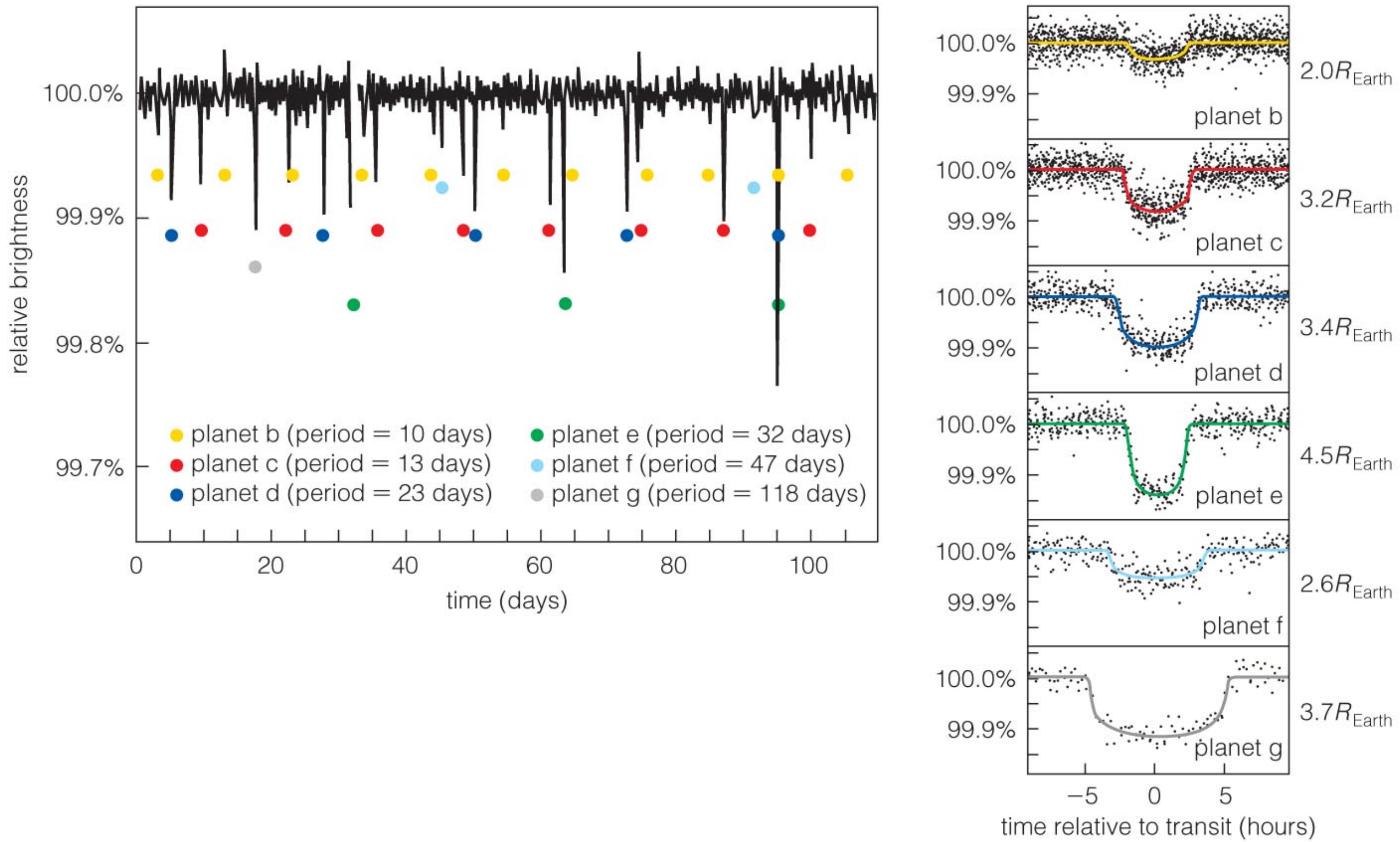
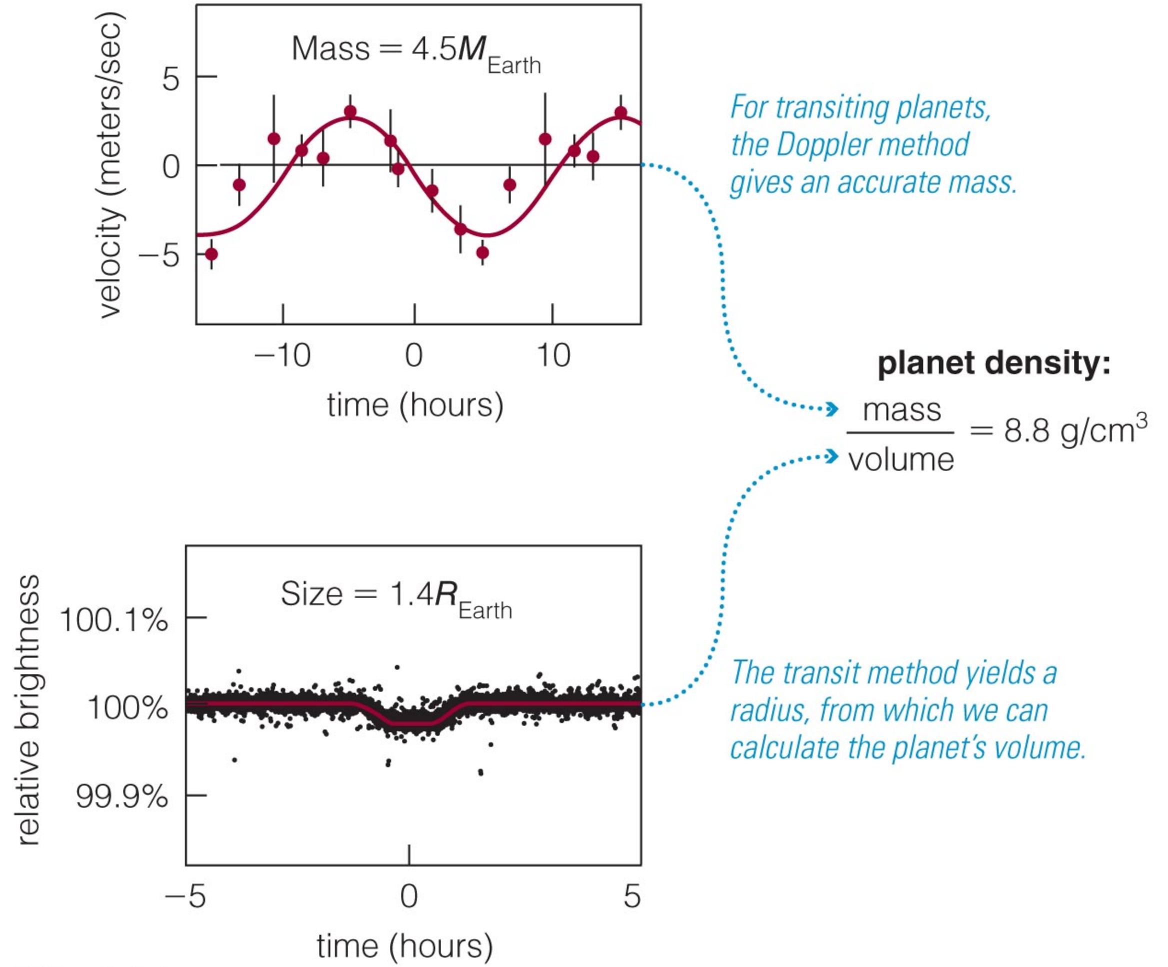
The Kepler 11 system



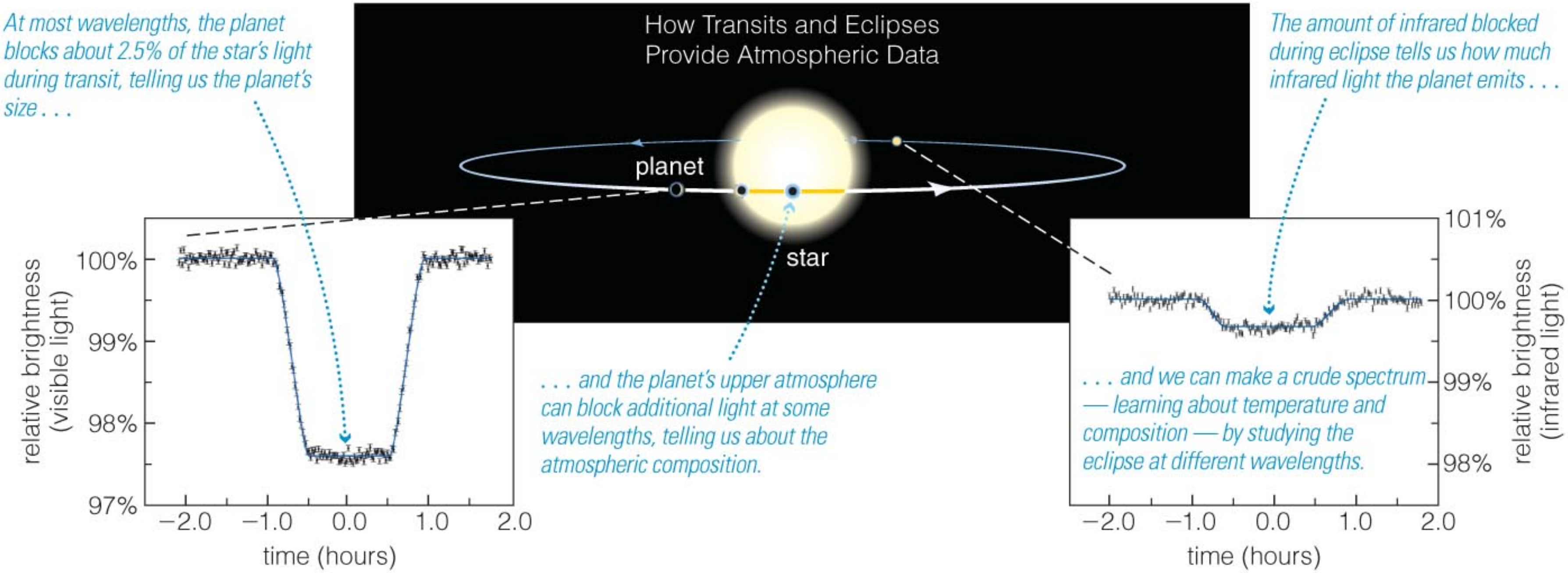
- The periods and sizes of Kepler 11's 6 known planets can be determined using transit data.

Calculating Density

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

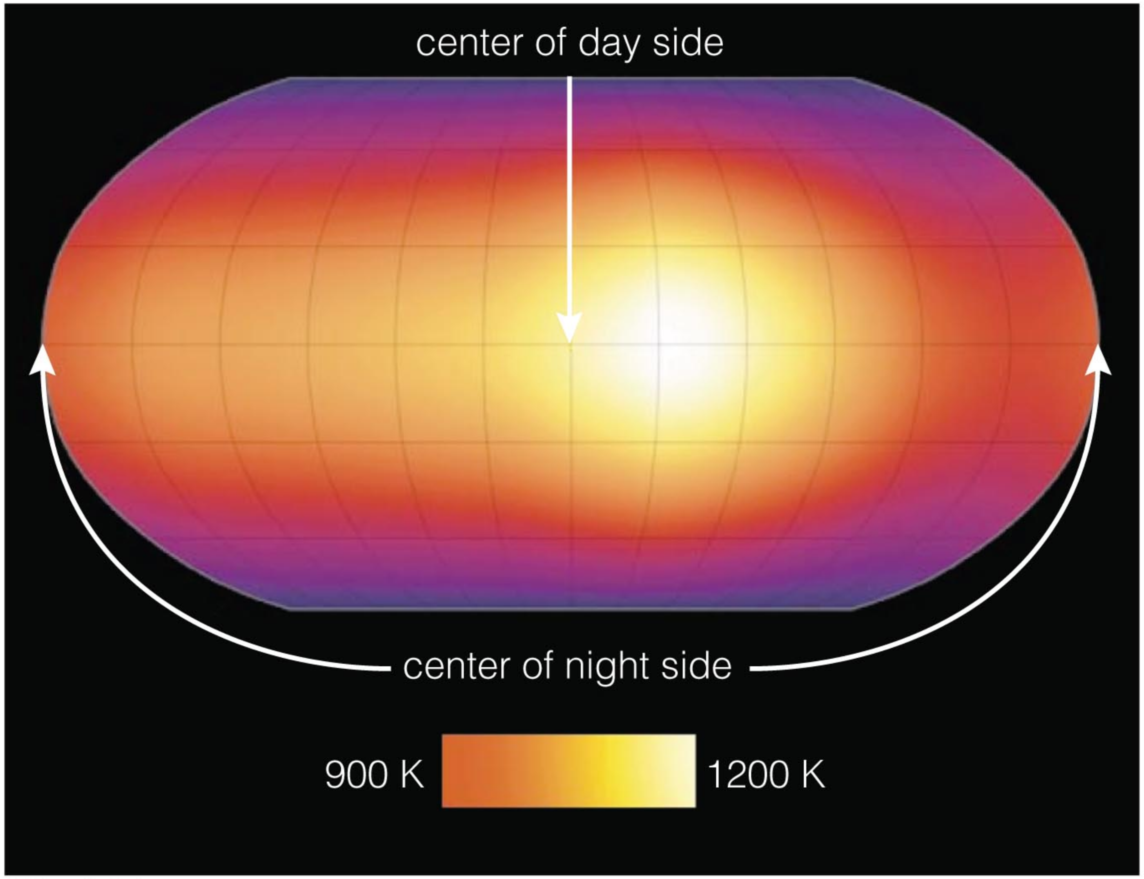


Spectrum During Transit



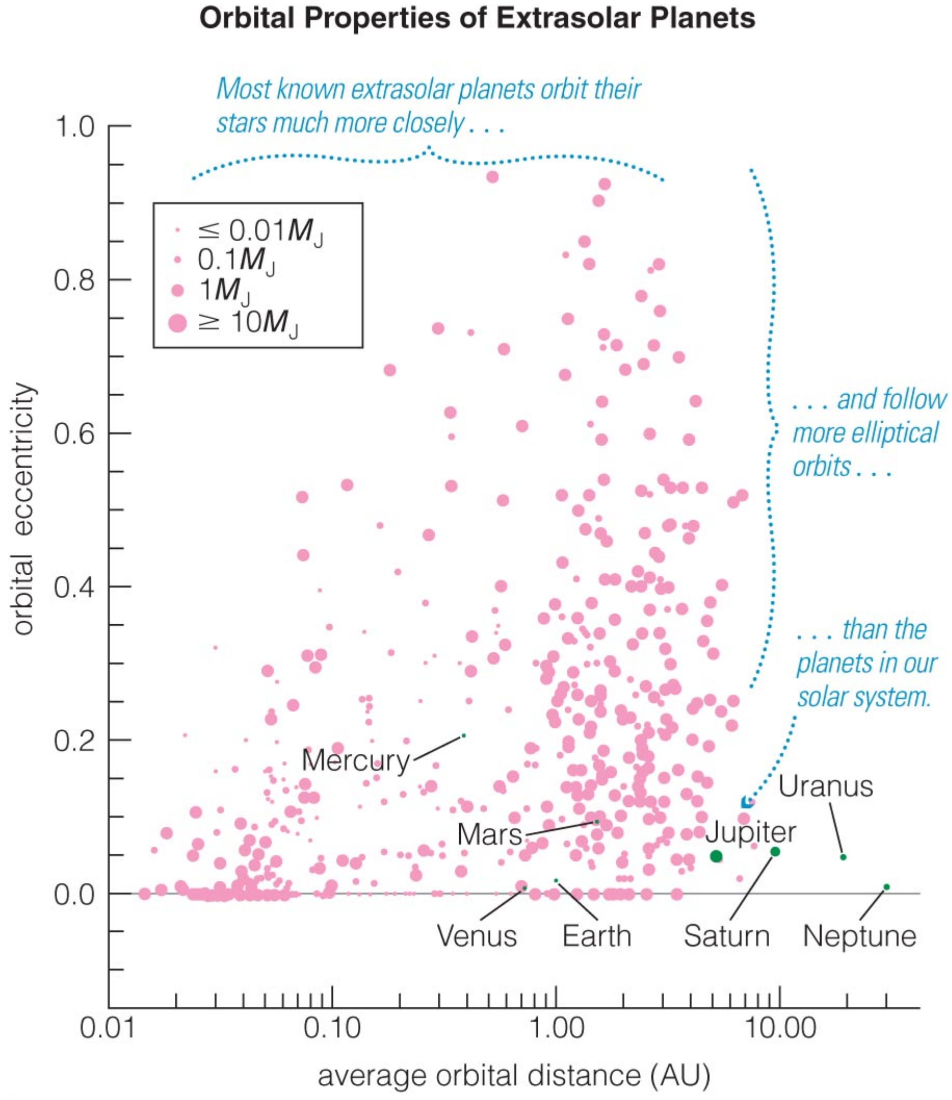
- Change in spectrum during a transit tells us about the composition of planet's atmosphere.

Surface Temperature Map

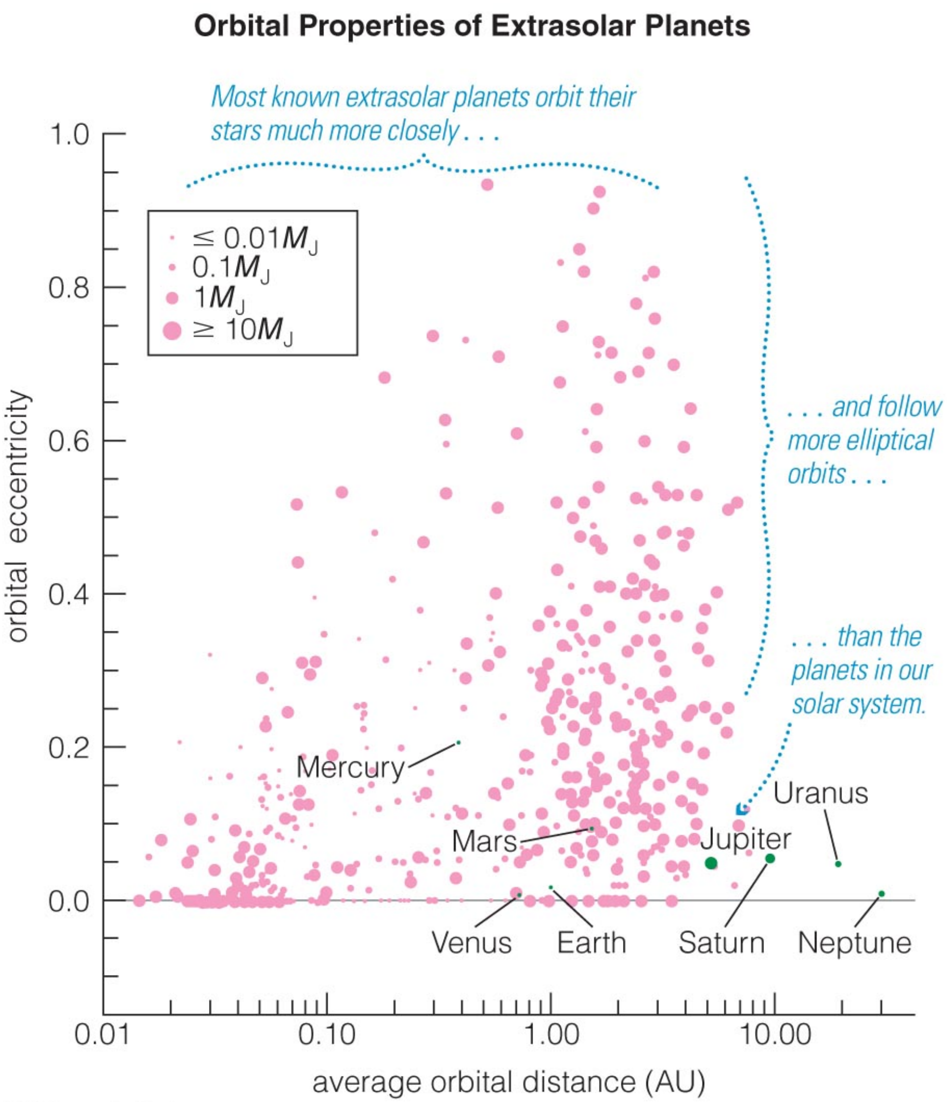


- Measuring the change in infrared brightness during an eclipse enables us to map a planet's surface temperature.

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

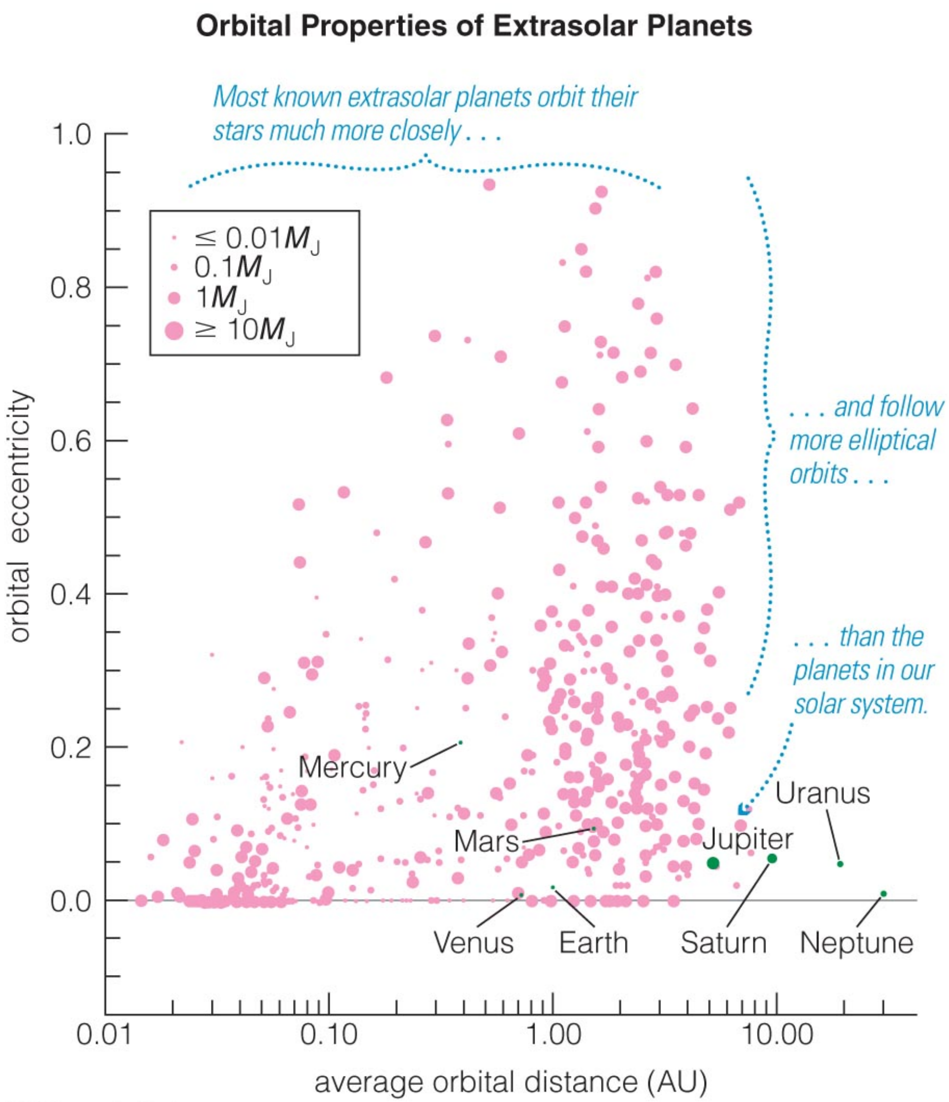


Orbits of Extrasolar Planets



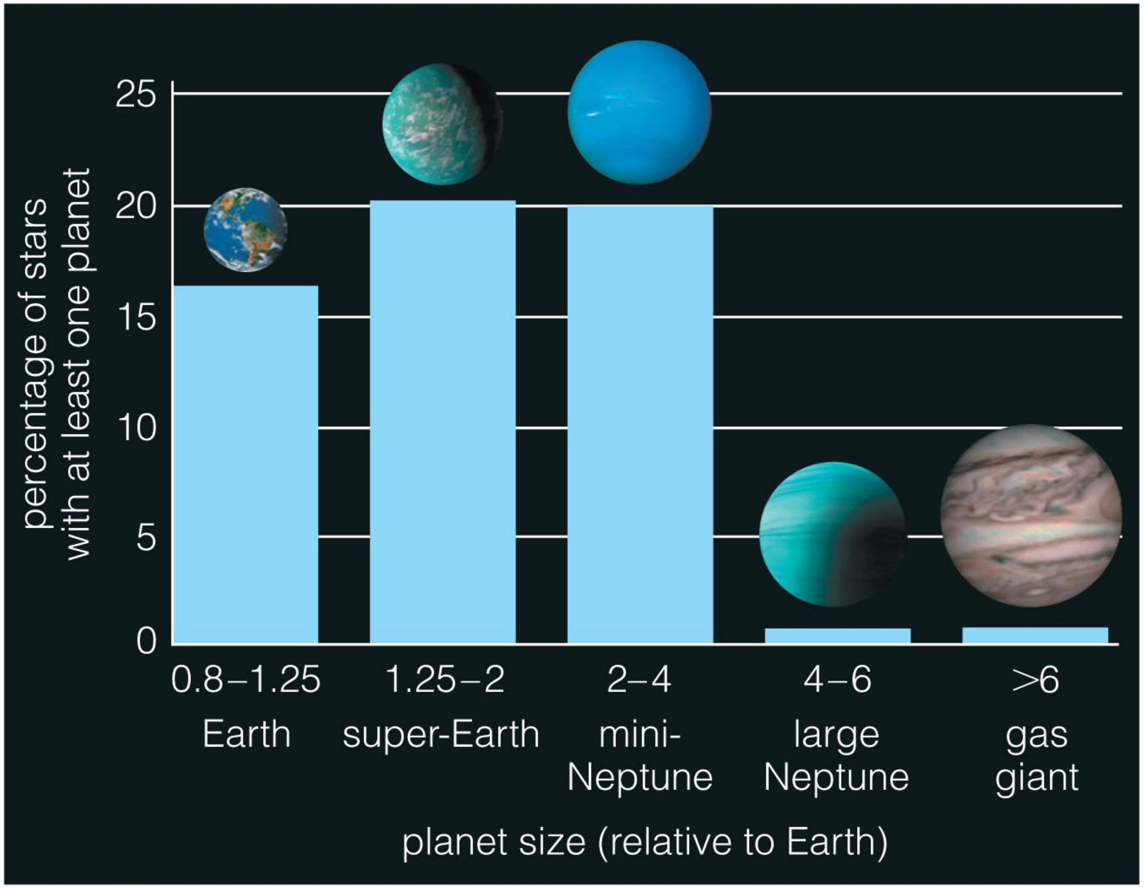
- Most of the detected planets have orbits smaller than Jupiter's.
- Planets at greater distances are harder to detect with the Doppler technique.

Orbits of Extrasolar Planets



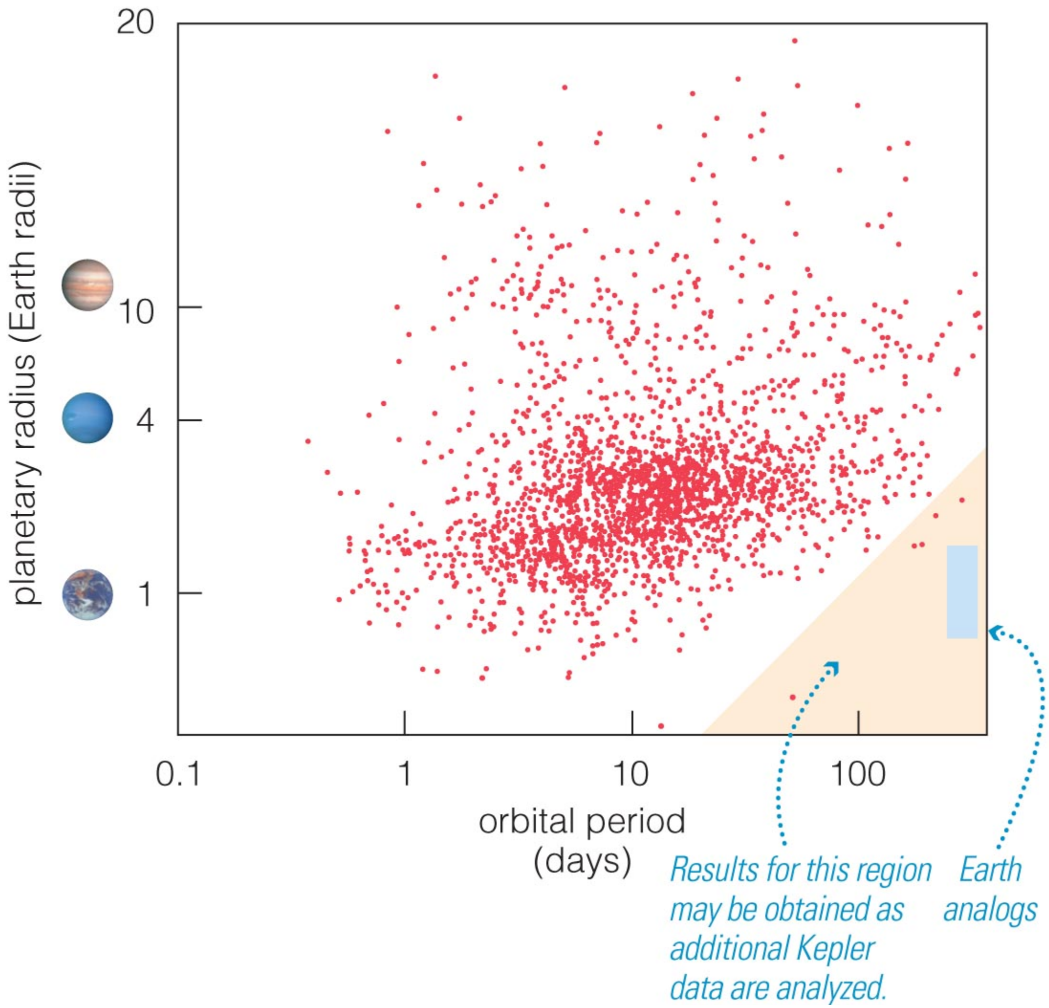
- Orbits of some extrasolar planets are much more elongated (have a greater eccentricity) than those in our solar system.

Orbits of Extrasolar Planets



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

Orbits of Extrasolar Planets



- More data will help us fill in the shaded region.

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
- Solar system is quite special: planets all have nearly circular orbits, and Jupiter is very large for a planet

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.

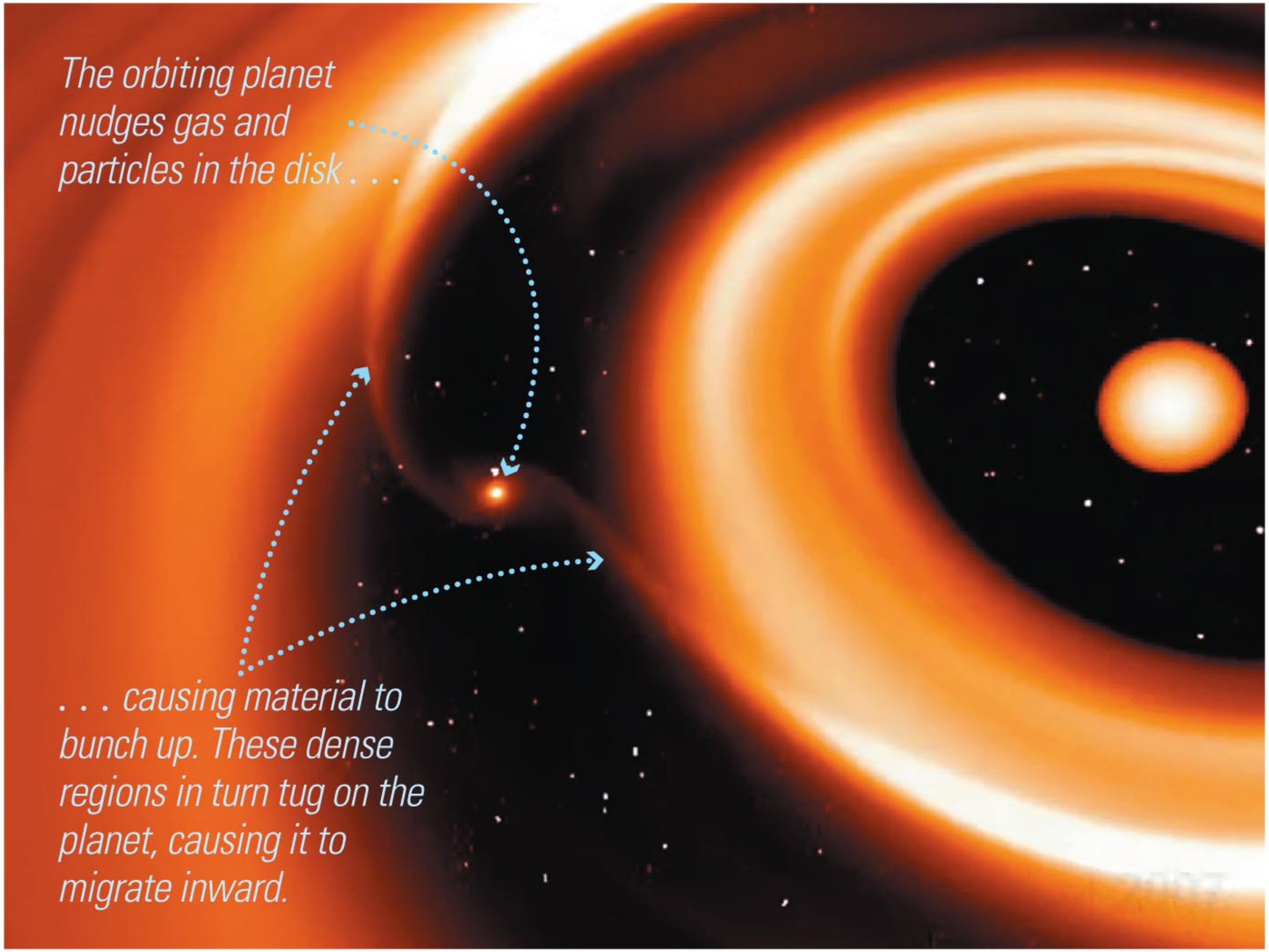
What have we learned?

- **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:
  - **Do we need to modify our theory of solar system formation?**
  - **Are planetary systems like ours common?**

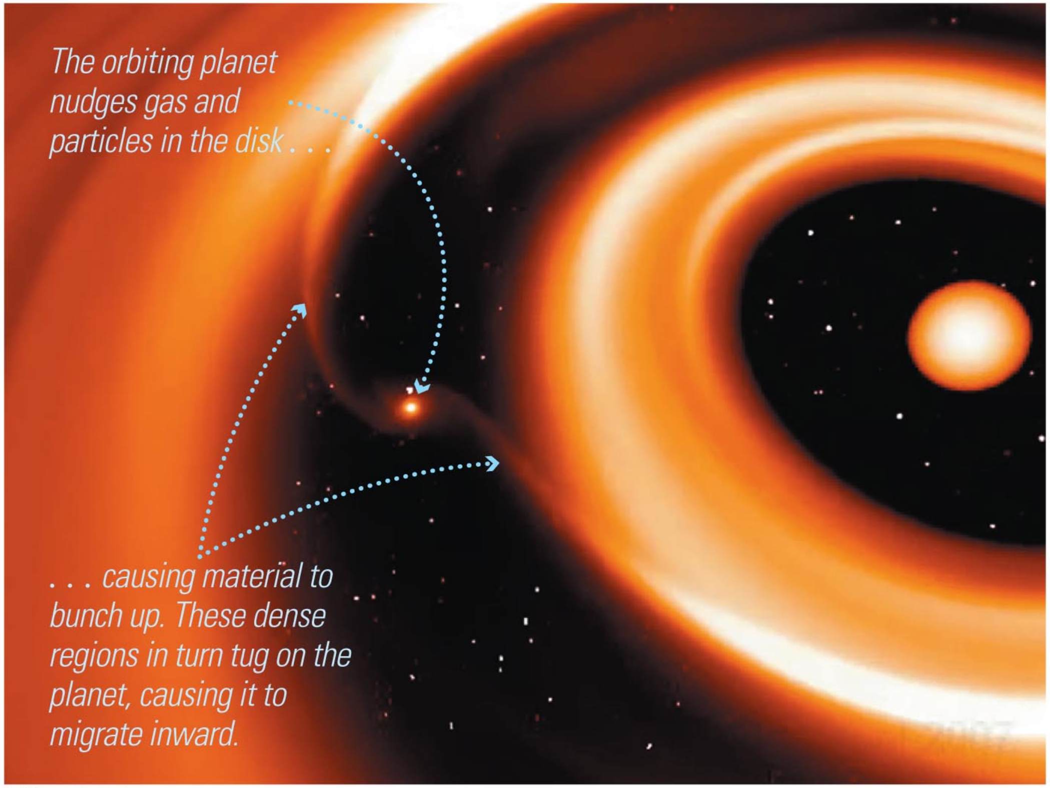
Do we need to modify our theory of solar system formation?



Revisiting the Nebular Theory

- The nebular theory predicts that massive Jupiter-like planets should not form inside the frost line (at << 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?

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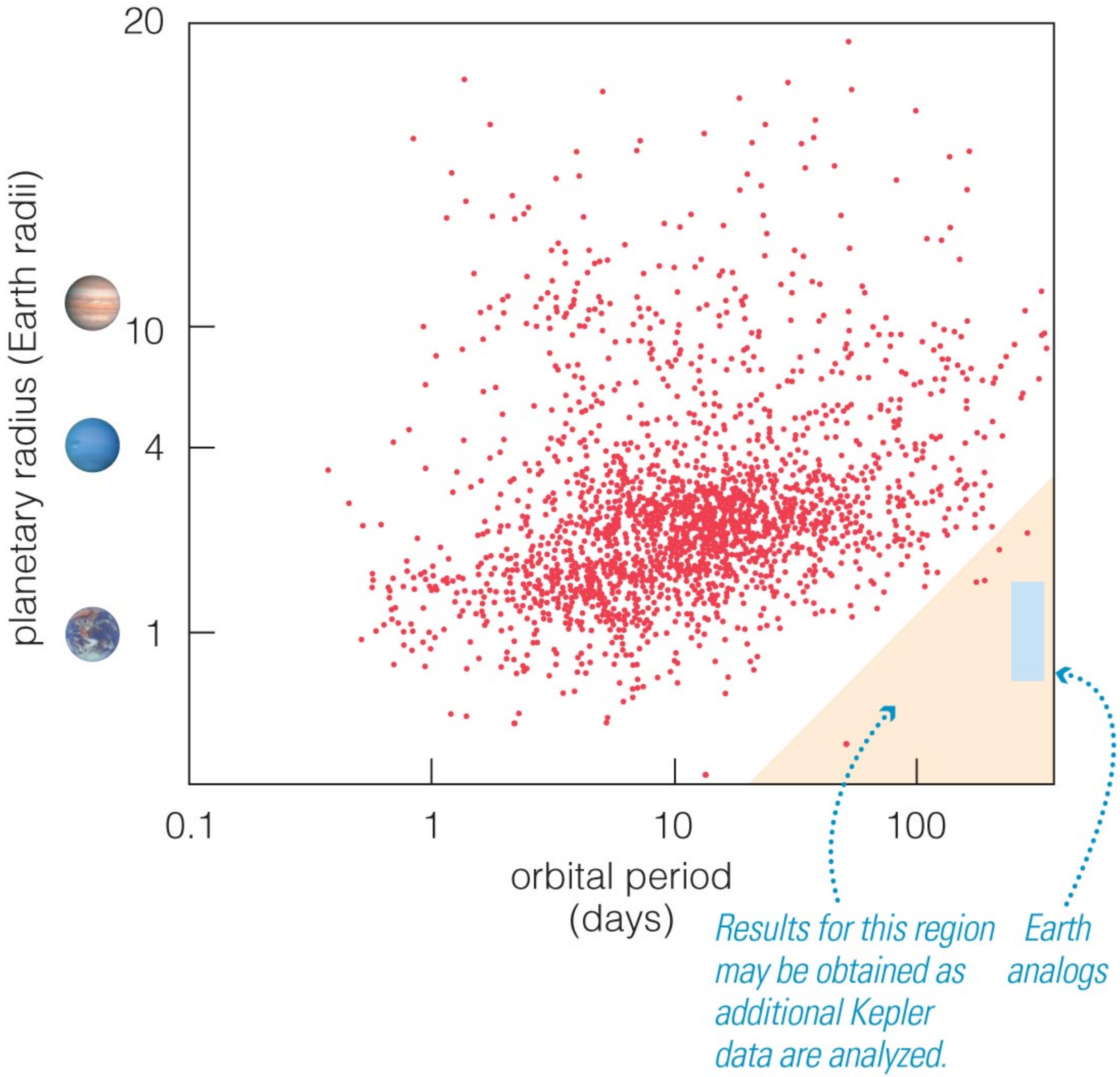
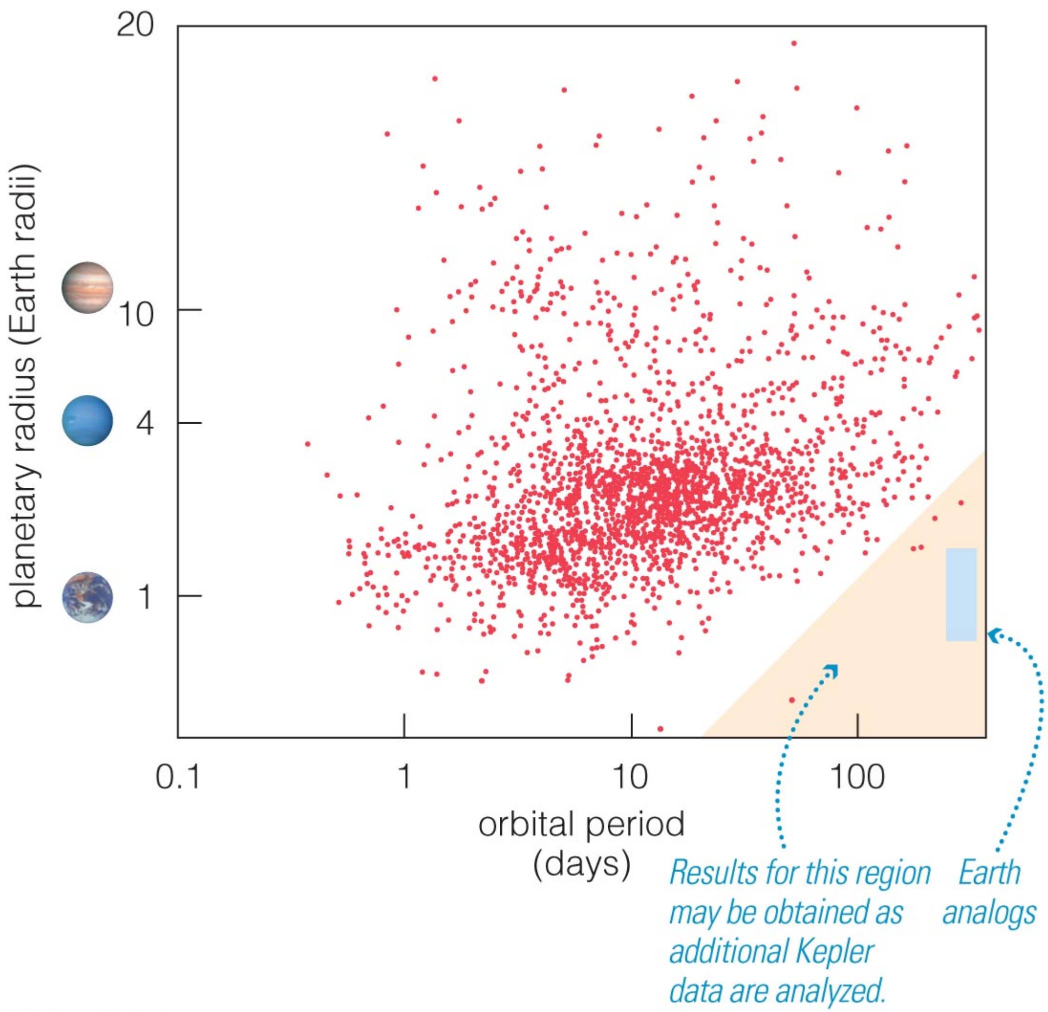
Modifying the Nebular Theory

- 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.

Are planetary systems like ours common?



Is our system rare?



- As many as 20% of stars may have Earth-like planets in habitable zones.

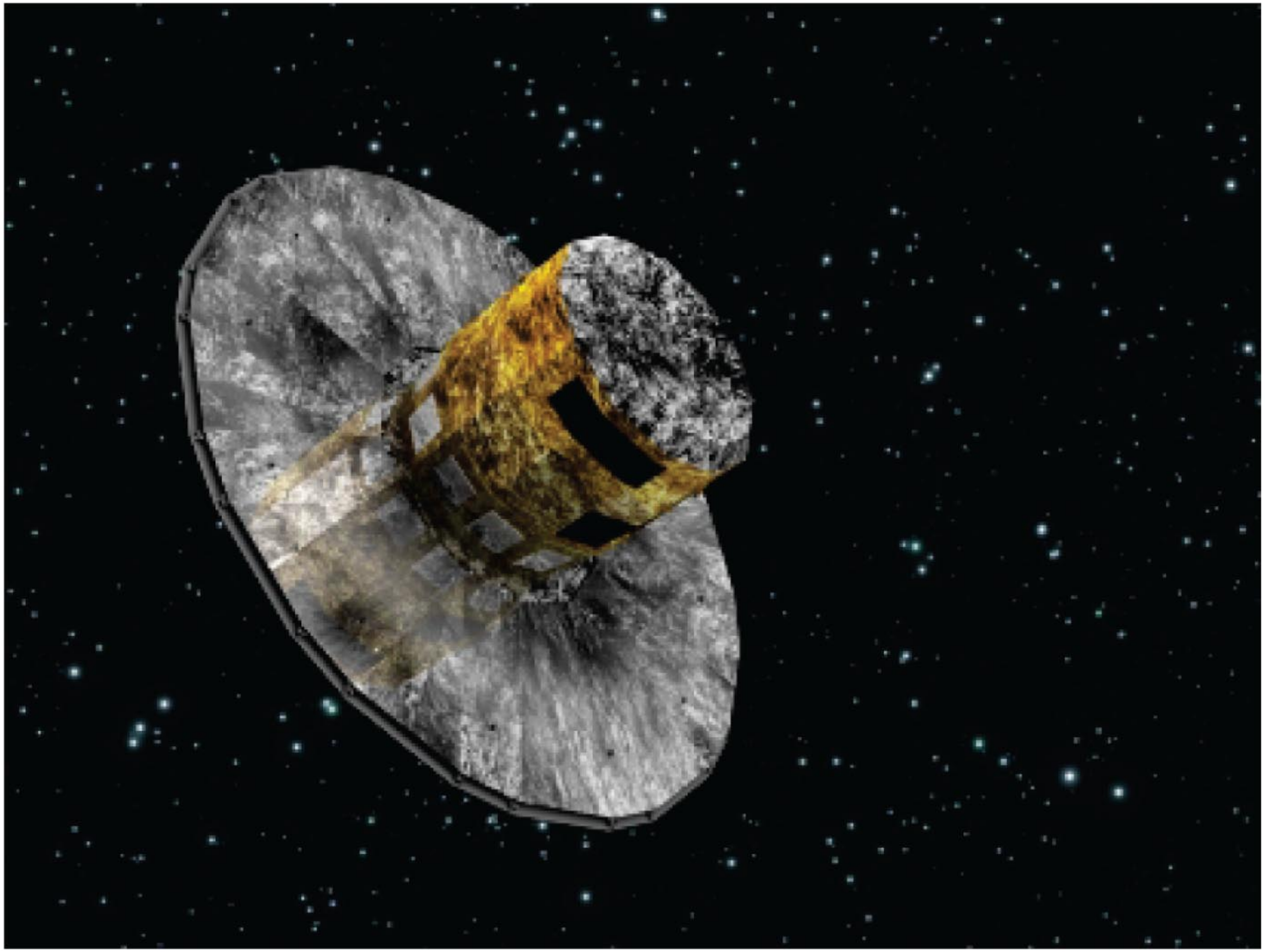
What have we learned?

- **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!

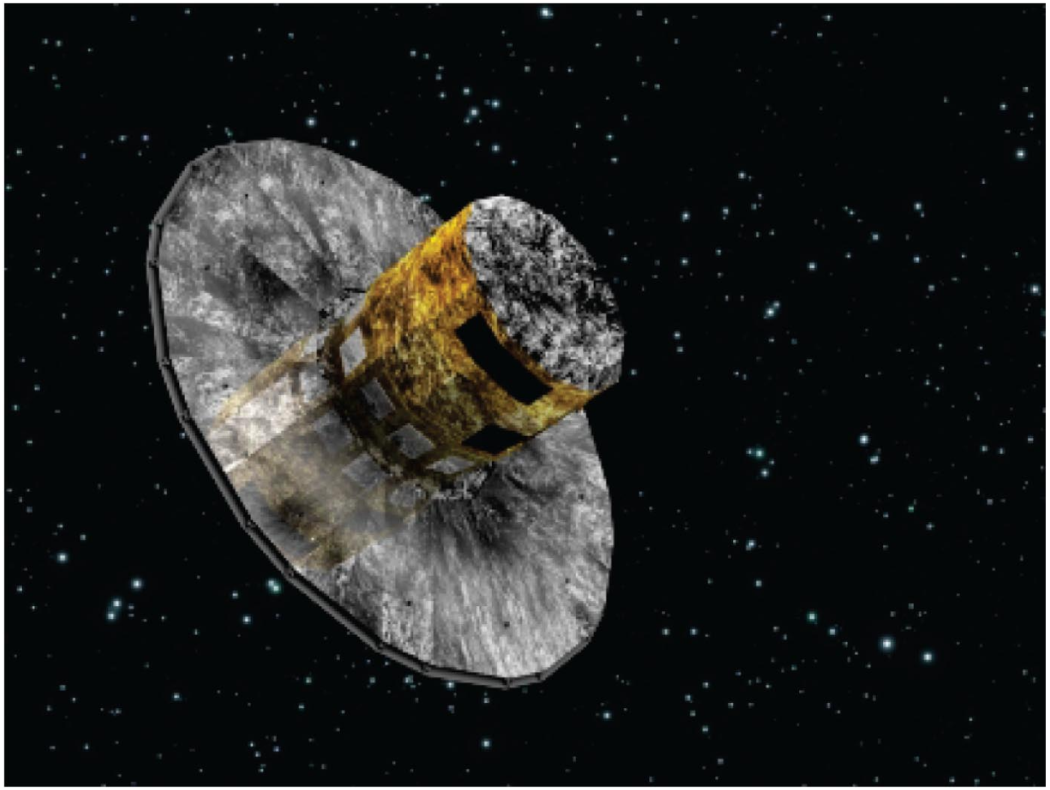
13.4 The Future of Extrasolar Planetary Science

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

How will future observations improve our understanding?



GAIA mission

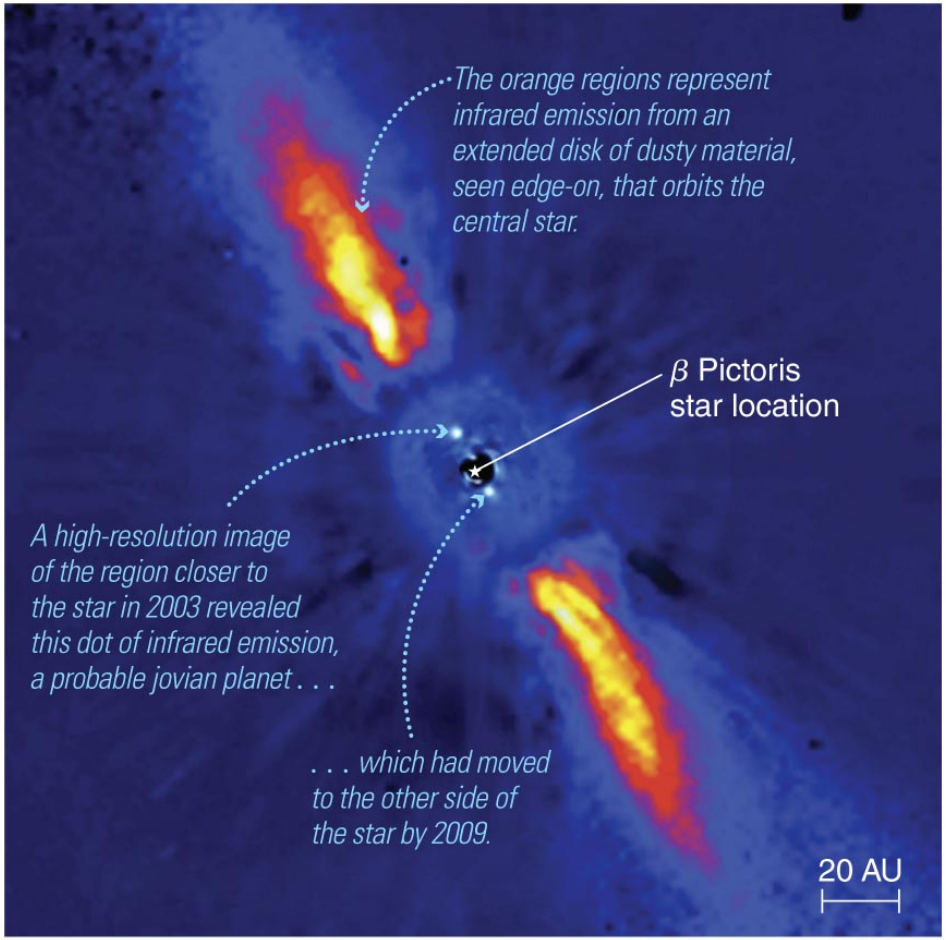


- *GAIA* is a European mission launched in 2013 that uses interferometry to measure precise motions of a billion stars

TESS and CHEOPS

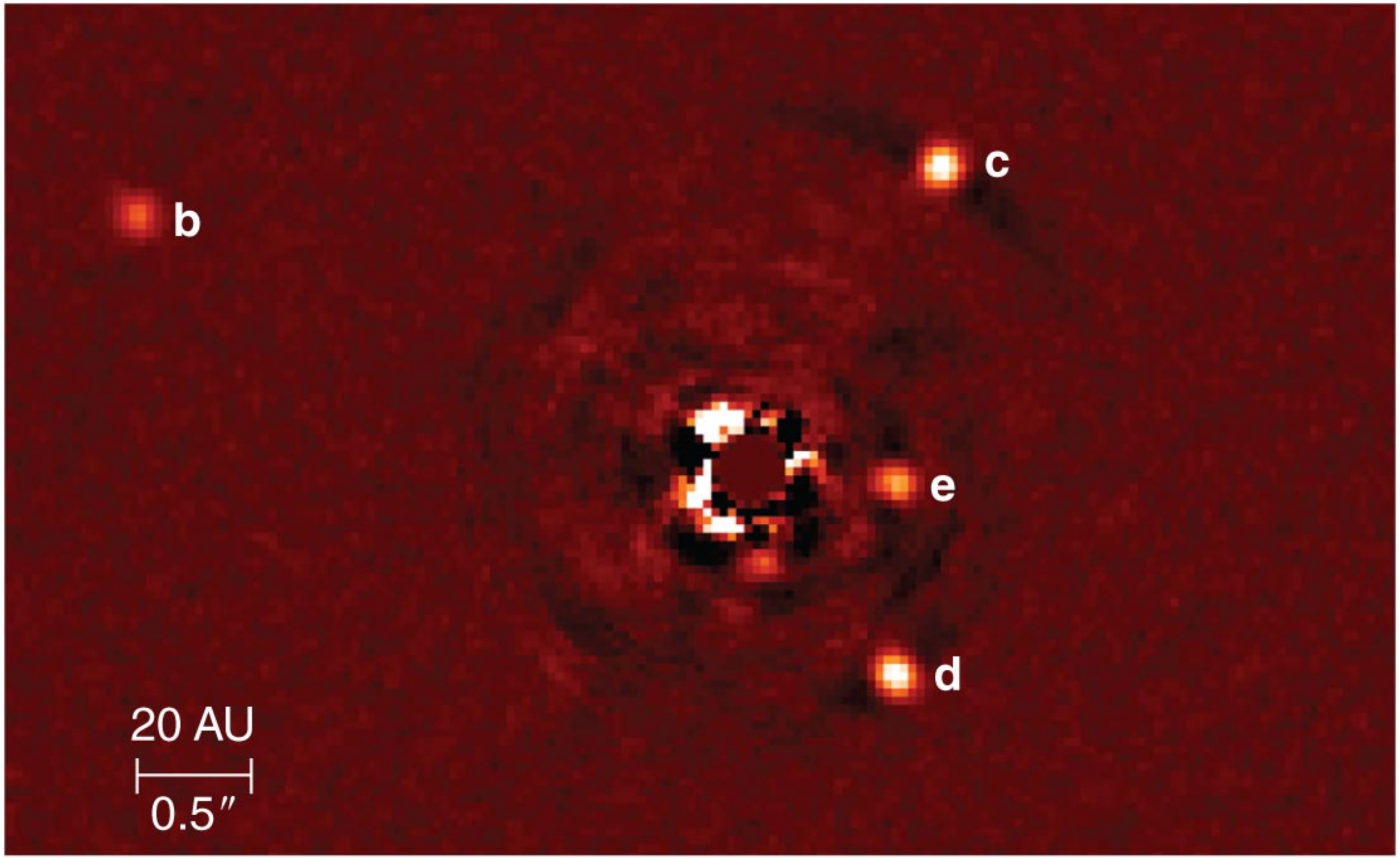
- Missions that will build on the success of the *Kepler* mission.
- TESS is a NASA mission, launched in April 2018, that uses the same strategy as Kepler.
- CHEOPS is a planned European Space Agency mission that will carefully measure properties of known planets using transits.

Direct Detection



- Special techniques like adaptive optics are helping to enable direct planet detection.
- The James Webb Space Telescope should also be useful.

Direct Detection

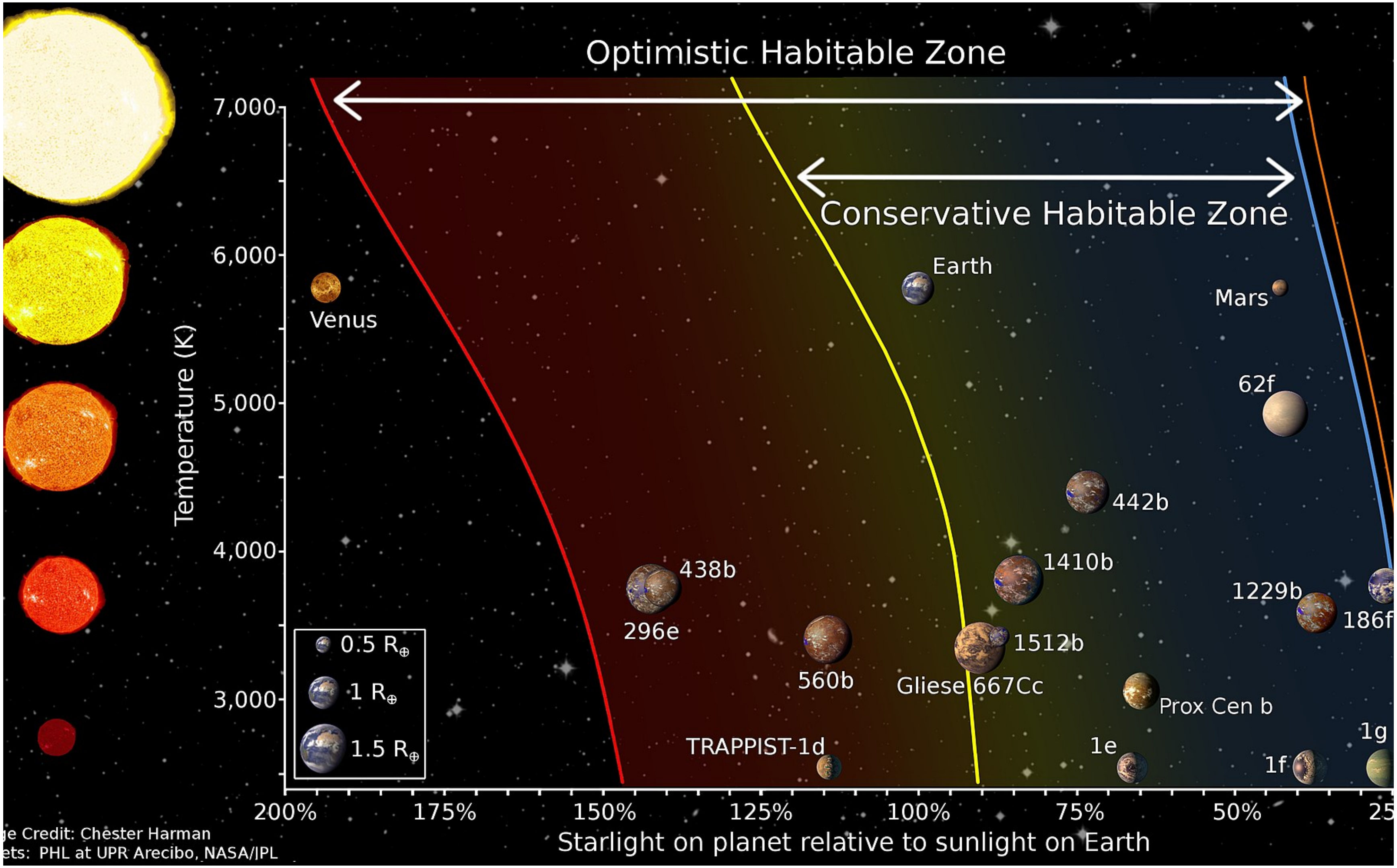


- Techniques that help block the bright light from stars are also helping us to find planets around them.

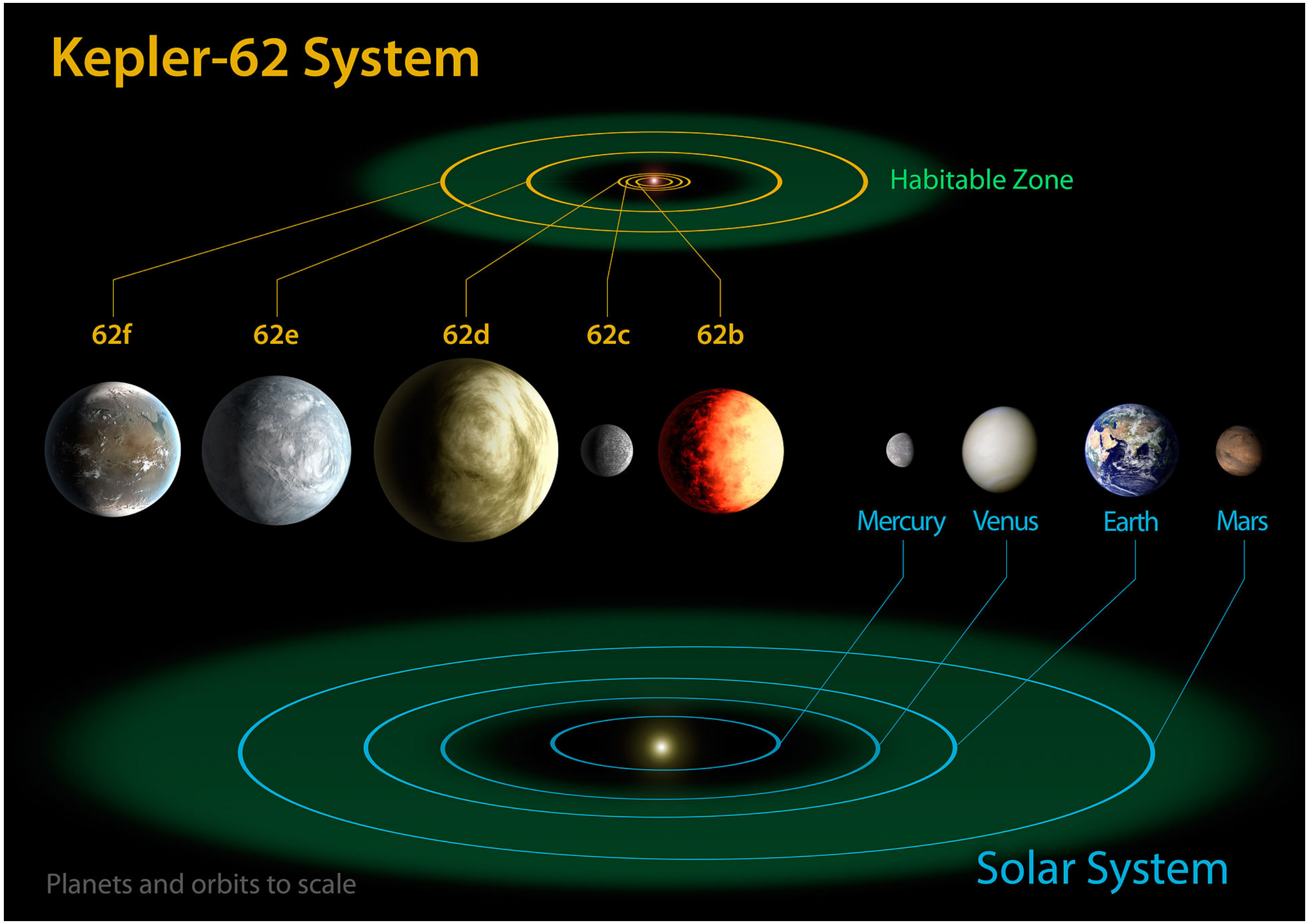
What have we learned?

- **How will future observations improve our understanding?**
  - Transit missions are capable of finding Earth-like planets that cross in front of their stars.
  - Astrometric missions are 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.

What do we have so far?



Kepler 62 e and 62f, the most promising



62: 0.69 mass of Sun 0.64 radius of Sun; 7 billion years old

62e: 1.61 radius of Earth; 4.5 Earth masses Covered with oceans?

62f: 1.4 Earth radii, 1.4 – 2.6 Earth masses; needs strong greenhouse effect for comfortable temperature; oceans?

What are other worlds like?

Pablo Picasso:

“We have invented nothing new”, after seeing the cave paintings at Lascaux France.

“After Altamira, all is decadence”, when he exited the paleolithic caves in his native Spain.

Altamira: dying bull