Chapter 13: Other Planetary Systems

The New Science of Distant Worlds

Extrasolar planets (Exoplanets)

- Planets orbiting stars other than the sun
- First discovered in 1995
- More than 100 known today
- Significance
  - Planets may be more numerous than stars in the universe
  - Some may be hospitable for life
  - Chances of life elsewhere in the universe increased enormously

Early Thinkers

Giordano Bruno (1548-1600)
Burned at the stake for believing Copernican and extraterrestrial life

Christian Huygens (1629-1695)
Deduced stars were distant suns

Learning Goals

13.1 Detecting Extrasolar Planets

- Why is it so difficult to detect planets around other stars?
- How do we detect planets around other stars?

13.2 The Nature of Extrasolar Planets

- What have we learned about extrasolar planets?
- How do extrasolar planets compare with those in our solar system?

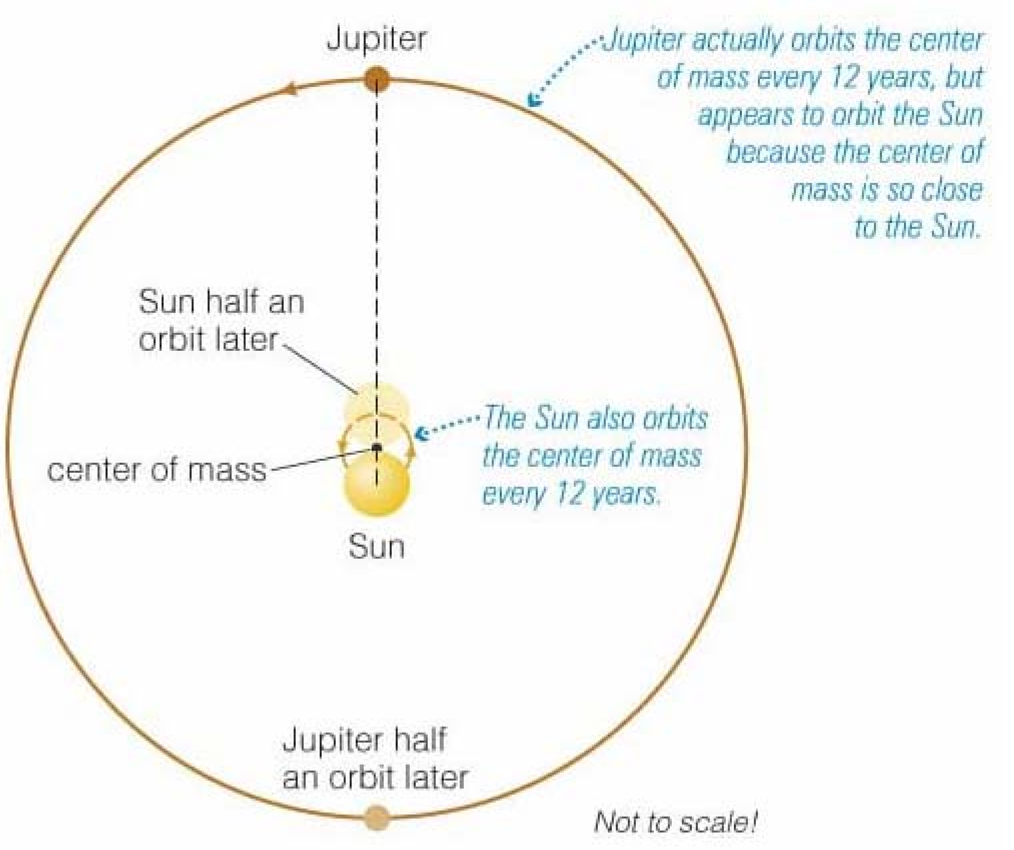
13.3 The Formation of Other Solar Systems

- Can we explain the surprising orbits of many extrasolar planets?
- Do we need to modify our theory of solar system formation?

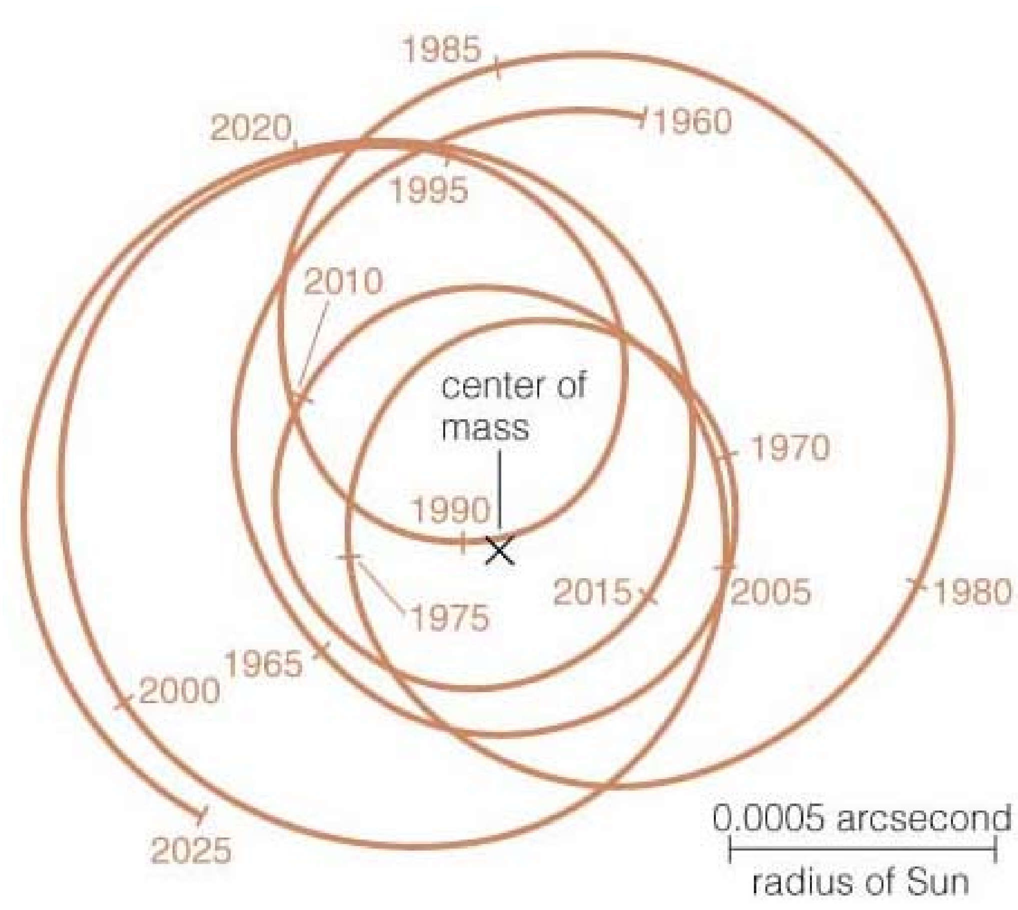
13.4 Finding New Worlds

- How will we search for Earth-like planets?

Gravitational tugs

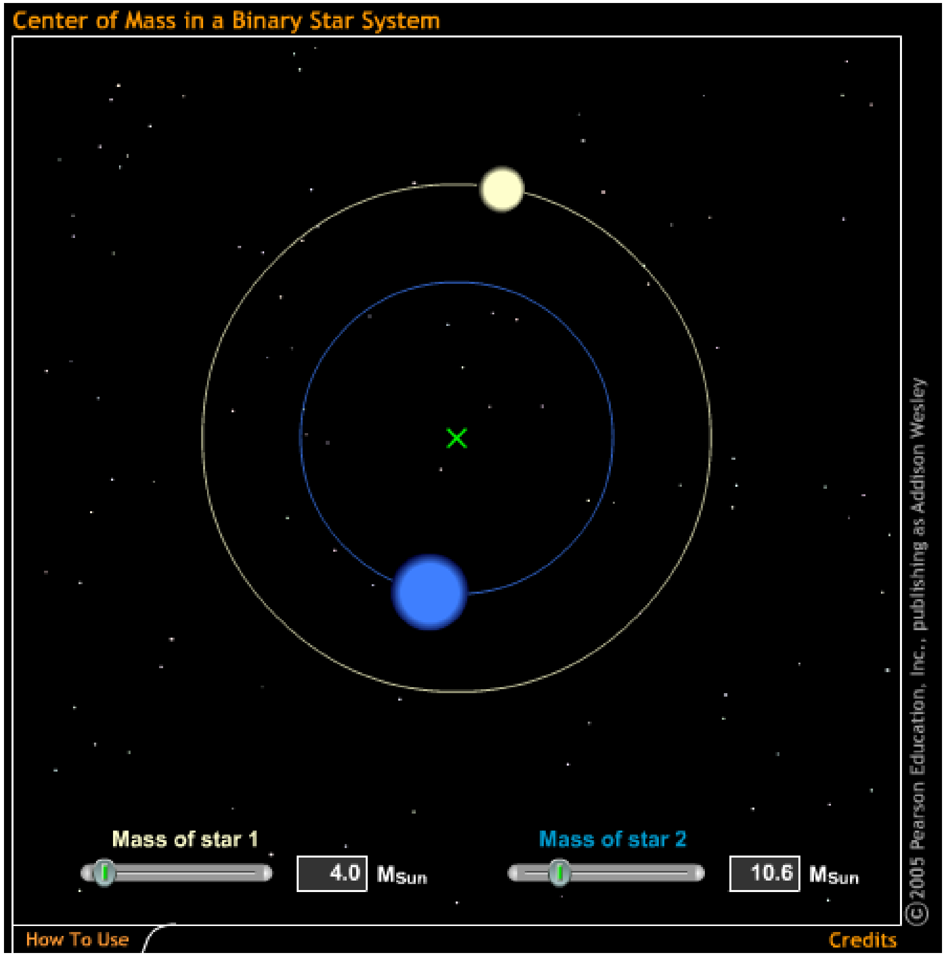


Sun's motion as seen from 30 light years distance



Astrometric technique not yet feasible with current telescopes

Detecting planets around other stars



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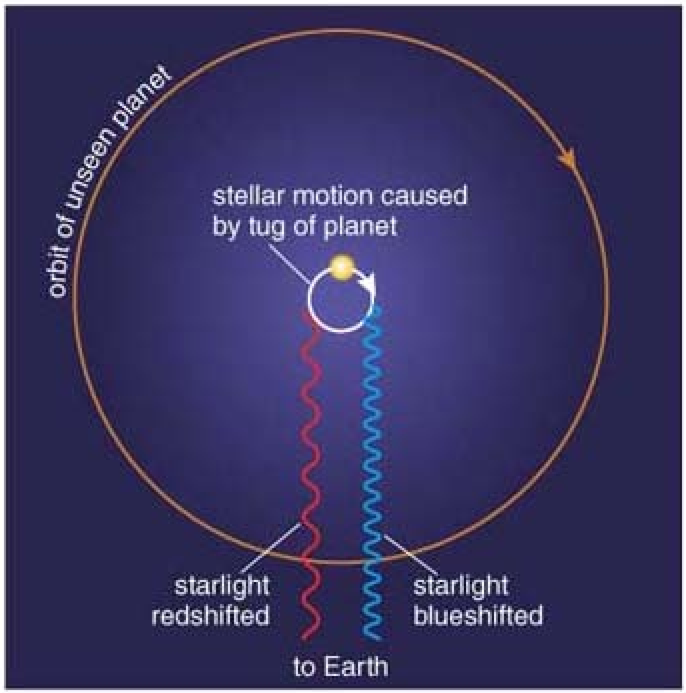
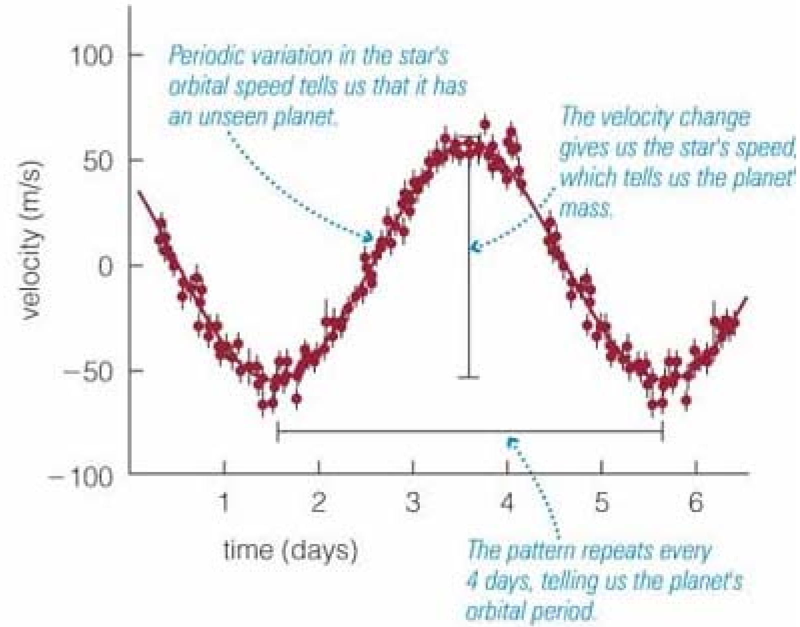
Doppler technique

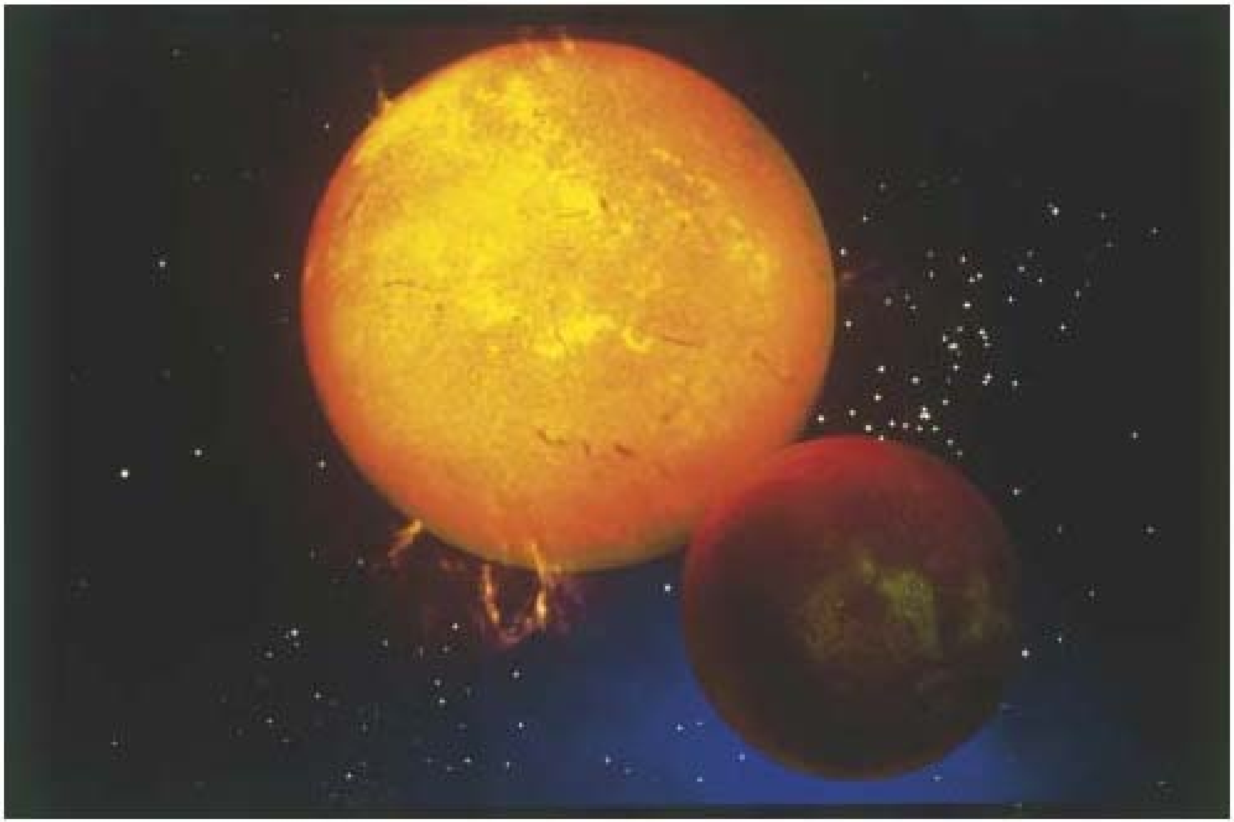


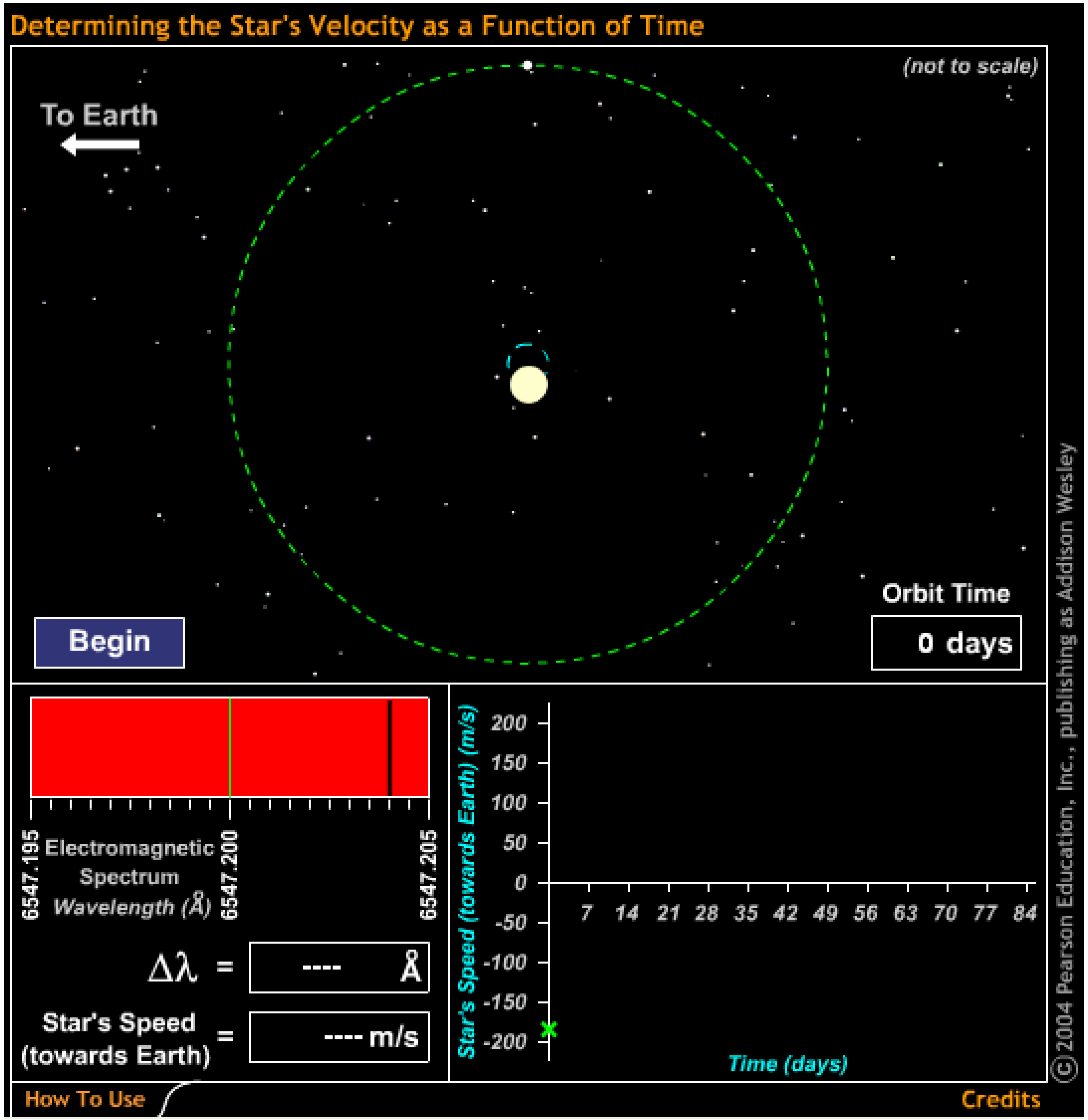
a Doppler shifts allow us to detect the slight motion of a star caused by an orbiting planet.



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.

51 Pegasi: first star with exoplanet discovered in 1995





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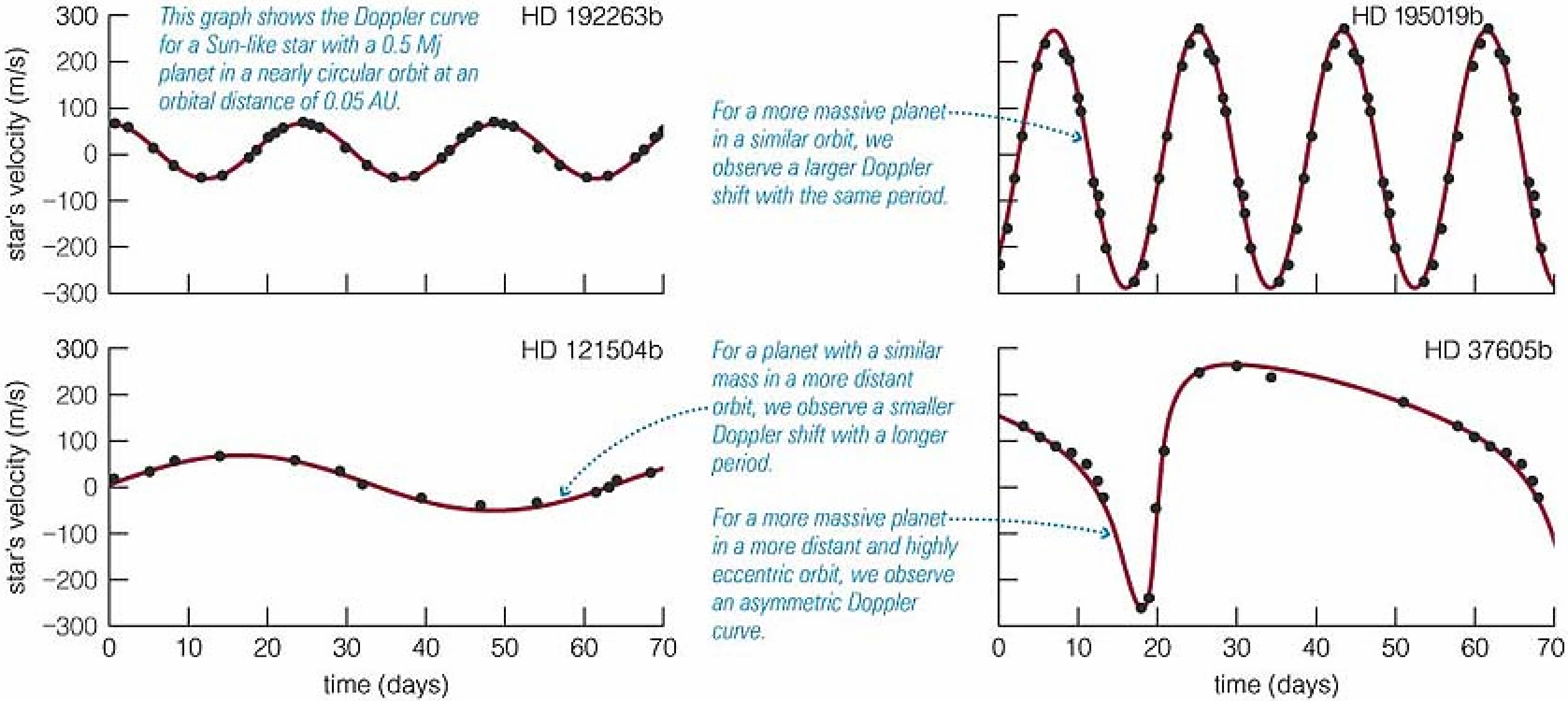
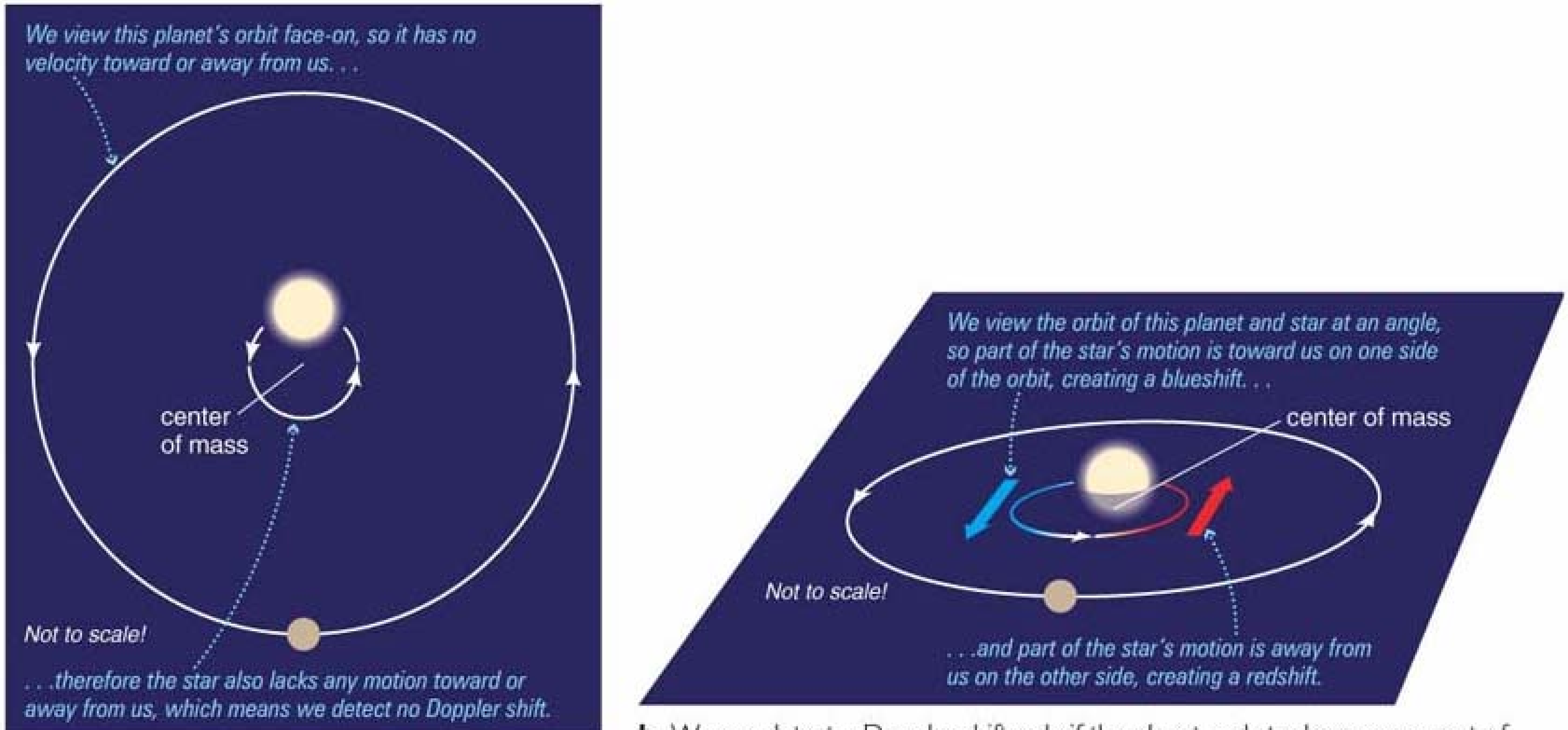
Actual measurements



Effect of orbital inclination



a If we view a planetary orbit face-on, we will not detect any Doppler shift at all.

b We can detect a Doppler shift only if the planet and star have some part of their orbital velocities directed toward or away from us. The more the orbit is tilted toward edge-on, the greater the shift we'll observe.

MATHEMATICAL INSIGHT 13.1

Finding Orbital Distances for Extrasolar Planets

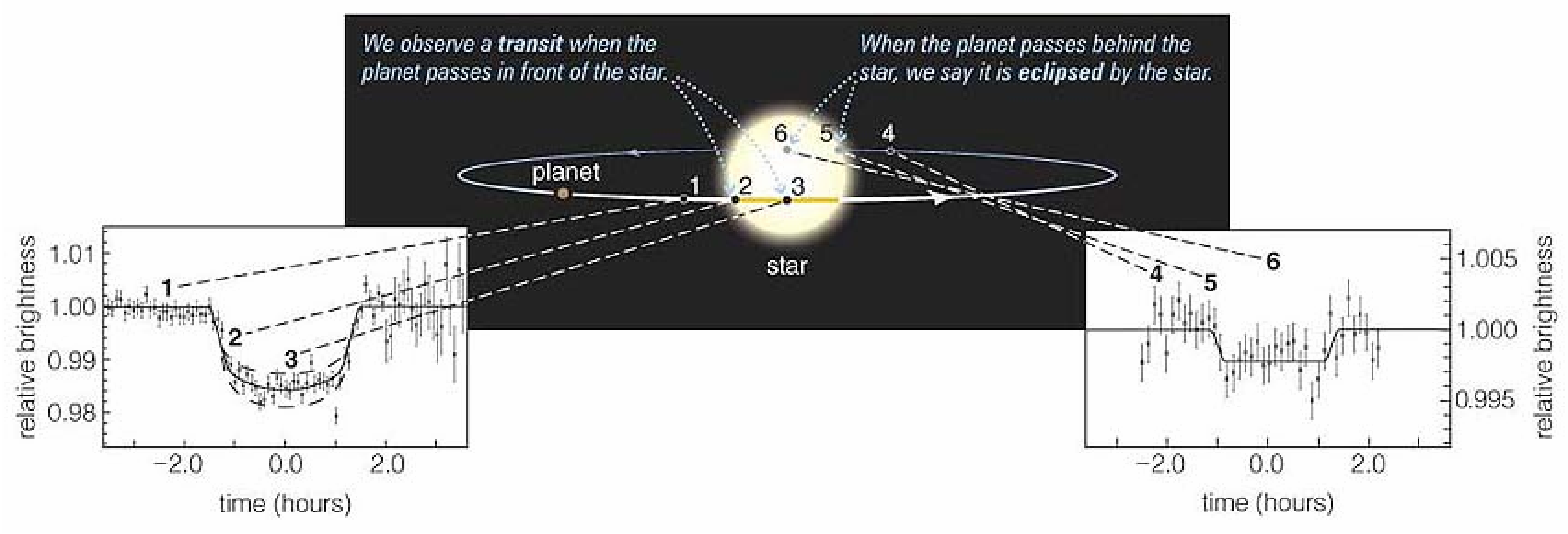
The Doppler technique directly tells us a planet's orbital period. We can then use this period to determine the planet's orbital distance. If the planet were orbiting a star of exactly the same mass as the Sun, we could find the distance by applying Kepler's third law in its simplest form: $p^2 = a^3$. In fact, many of the planets discovered to date *do* orbit Sun-like stars, so this law gives a good first estimate of orbital distance. But for more precise work, we must use Newton's version of Kepler's third law. As discussed in Mathematical Insight 4.3, this law reads:

$$p^2 = \frac{4\pi^2}{G(M_1 + M_2)} a^3$$

In the case of a planet orbiting a star, p is the planet's orbital period, a is its average orbital distance (semimajor axis), and M_1 and M_2 are the masses of the star and planet, respectively. (G is the gravitational constant; $G = 6.67 \times 10^{-11}$ m^3/(kg $\times$ s^2).) Because a star is so much more massive than a planet, the sum $M_{star} + M_{planet}$ is pretty much just M_{star}; that is, we can neglect the mass of the planet compared to the star. With this approximation, we can rearrange the equation to find the orbital distance a:

$$a \approx \sqrt[3]{\frac{GM_{star}}{4\pi^2} p_{planet}^2}$$

Transit method



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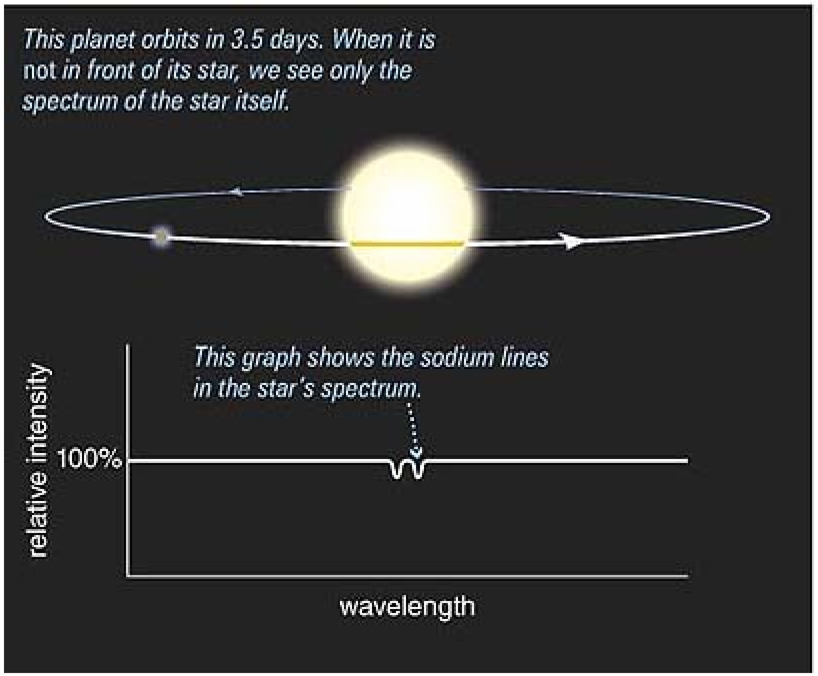
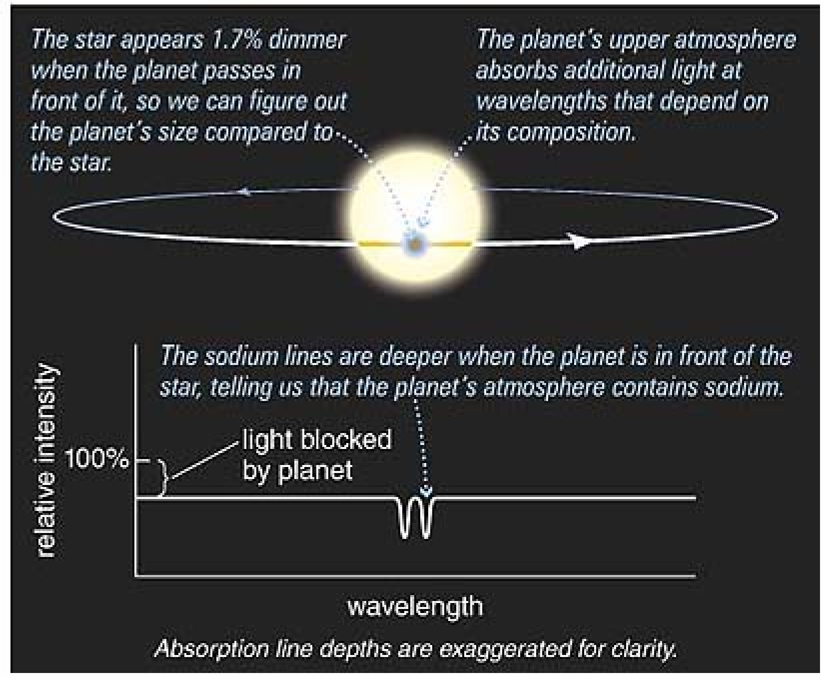
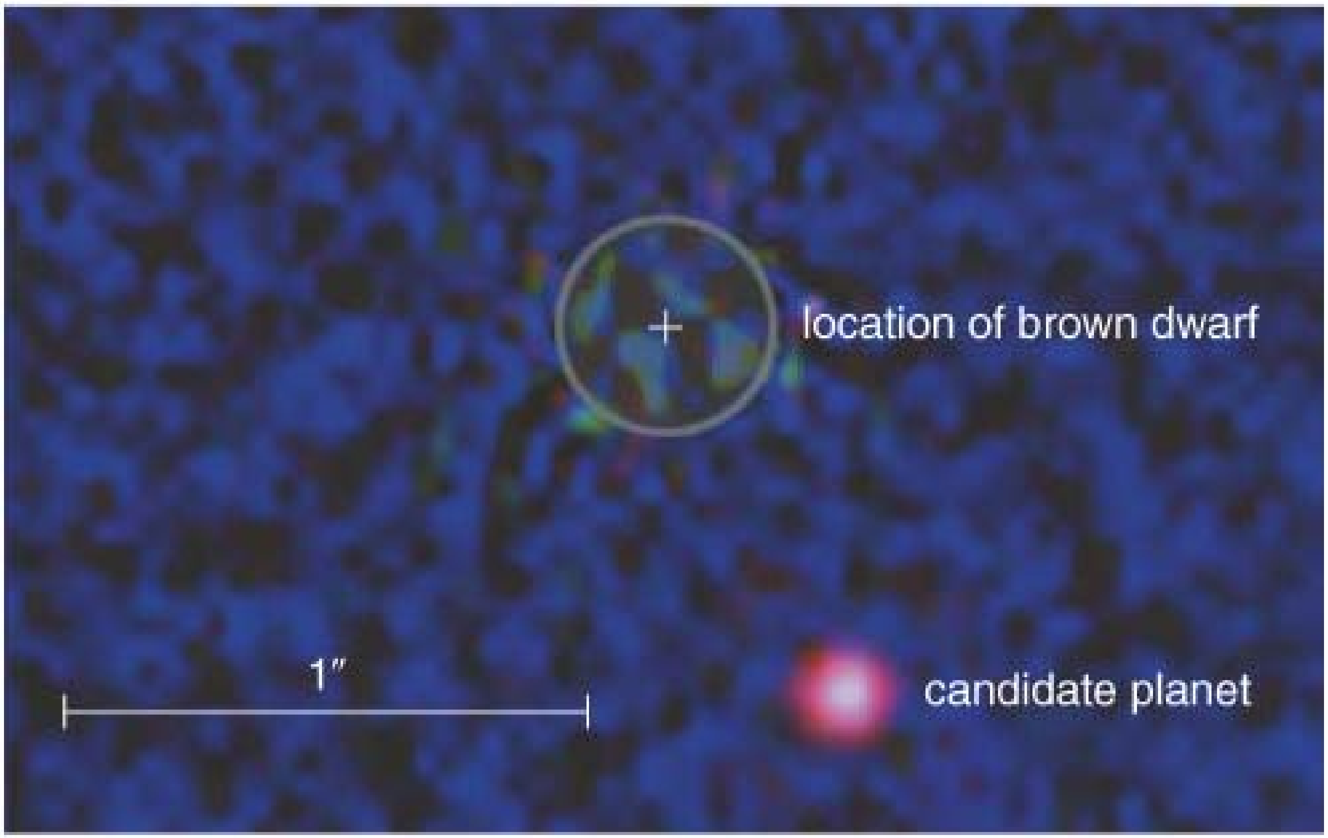
Using transits to probe planet's atmosphere





Hubble Space Telescope detects exoplanet orbiting brown dwarf



Planet emits thermal radiation in infrared

Finding Sizes of Extrasolar Planets

While finding the masses of extrasolar planets was a breakthrough suggesting that we were detecting jovian planets, it wasn't until astronomers measured extrasolar planet sizes that we gained confidence in their jovian nature. Transits provide the needed size information in a simple geometric fashion.

Like other extrasolar planet measurements, the technique relies on a good understanding of the host star. In particular, we need to know the physical size of the star's disk even though we cannot resolve it with our telescopes. If the star's light can be considered uniform over its disk, then the fractional light drop that occurs during a transit will be:

$$\begin{matrix}\text{fraction of} \\ \text{light blocked}\end{matrix} \approx \frac{\text{area of planet's disk}}{\text{area of star's disk}} = \frac{\pi r_{\text{planet}}^2}{\pi r_{\text{star}}^2} = \frac{r_{\text{planet}}^2}{r_{\text{star}}^2}$$

Note that we used the formula for the area of a circle (πr^2) because from a distance the planet and star should look like circular disks. The equation should also make sense if you look at Figure 13.7a.

We can now rearrange the equation to find the planet's radius; you should confirm that solving for r_{planet} gives us the following formula:

$$r_{\text{planet}} \approx r_{\text{star}} \times \sqrt{\text{fraction of light blocked}}$$

What have we learned?

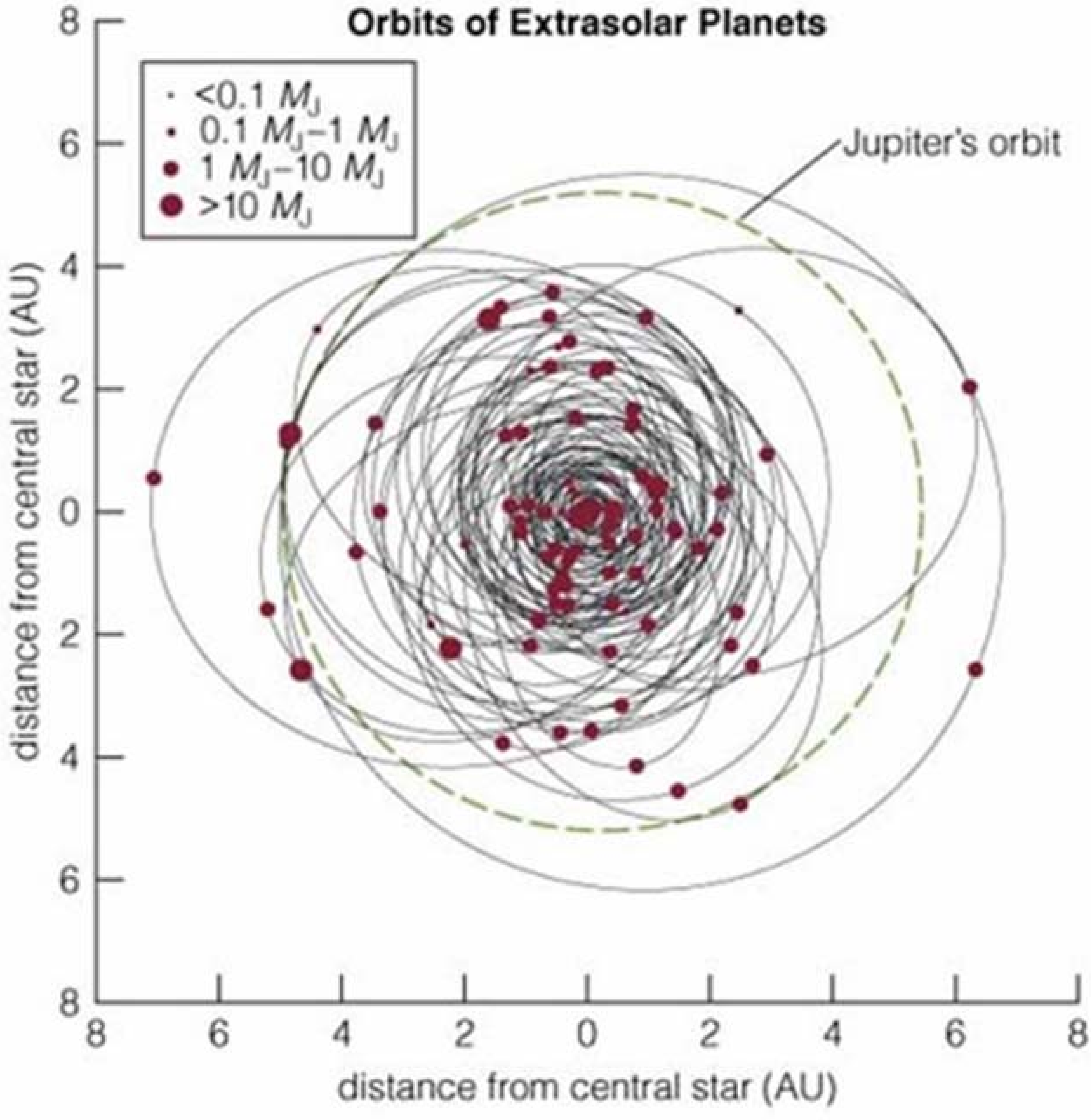
- *Orbital period:* All three indirect techniques that we discussed (astrometric, Doppler, and transits) tell us the orbital period of detected planets.
- *Orbital distance:* Once we know orbital period and the mass of the star, we can calculate orbital distance by using Newton's version of Kepler's third law.
- *Orbital shape:* We need data spanning an entire orbit to determine orbital shape—that is, whether the orbit is nearly circular or a more eccentric ellipse. Both the astrometric and Doppler techniques can provide the needed data. Transits give us data only for the small part of the orbit during which the planet passes in front of its star and hence do not tell us orbital shape.

What have we learned?

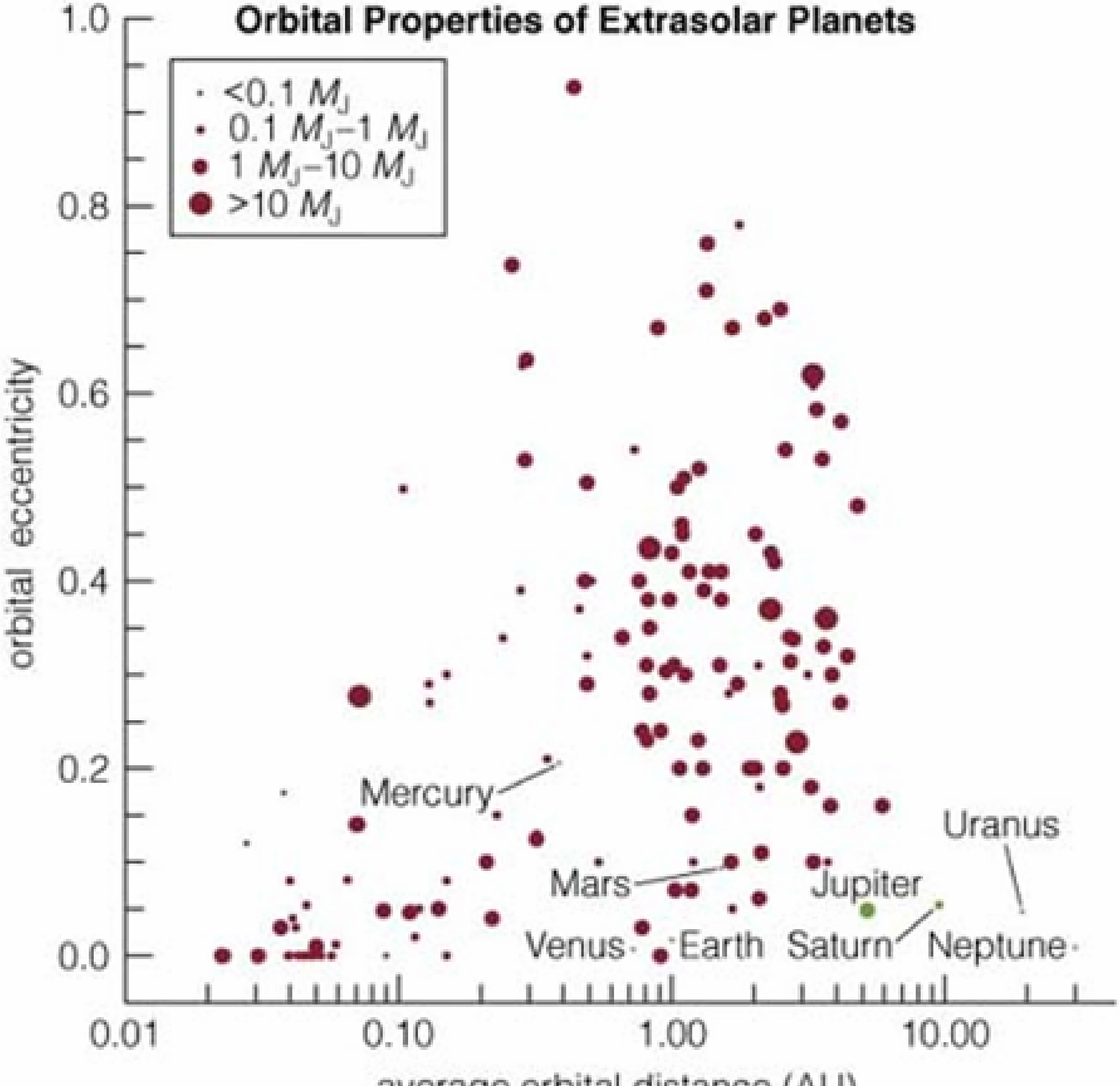
- *Mass:* We can determine an extrasolar planet's mass from its orbital period, the mass of its star, and the speed at which it makes its star orbit their mutual center of mass. In principle, we can learn a star's full orbital speed with the astrometric technique, while the Doppler technique tells us only the part of the speed directed toward or away from us. Thus, the Doppler technique tells us a minimum mass for the planet, and gives us a precise mass only if we also know the angle of the orbit to our line of sight. We cannot learn mass from transits alone.
- *Size (radius):* We can learn a planet's size only by observing transits. The dip in the star's brightness during a transit tells us the fraction of its light blocked by the planet, which allows us to calculate the planet's radius.

What have we learned?

- *Density:* We can calculate a planet's average density from its size and mass. Because we get size only from transits, we can determine density only for planets that produce transits and for which we also have mass data from the astrometric or Doppler techniques.
- *Composition:* We learn composition from spectra. Transits can provide limited information about the composition of a planet's upper atmosphere if the star shows absorption during the transit that is not present at other times. Eclipses can also provide limited spectral information. More detailed information about composition requires spectra from direct detections.

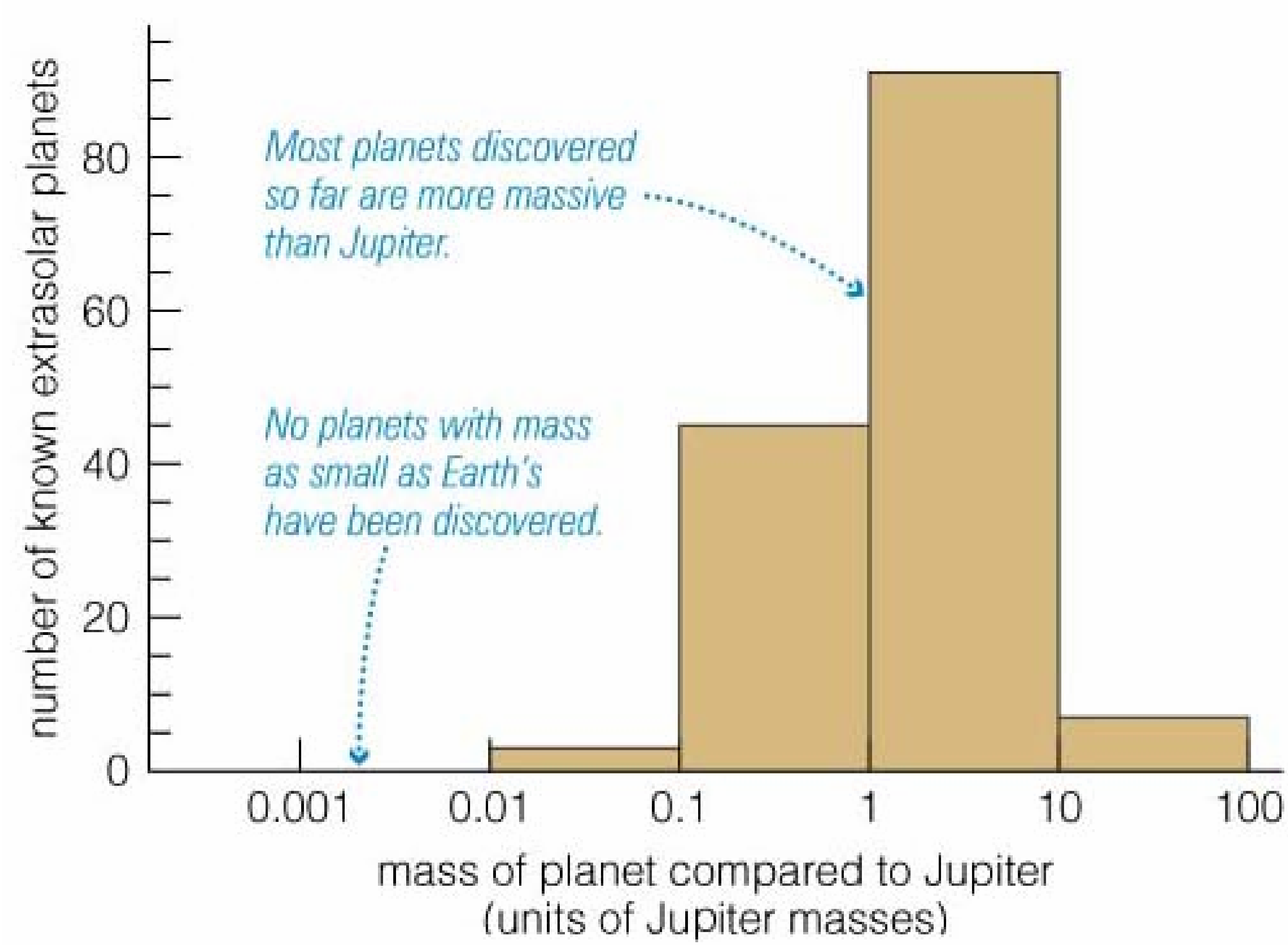


Orbits of Extrasolar Planets
<0.1 M_J
0.1 M_J–1 M_J
1 M_J–10 M_J
>10 M_J
Jupiter's orbit
distance from central star (AU)
distance from central star (AU)
8
6
4
2
0
2
4
6
8

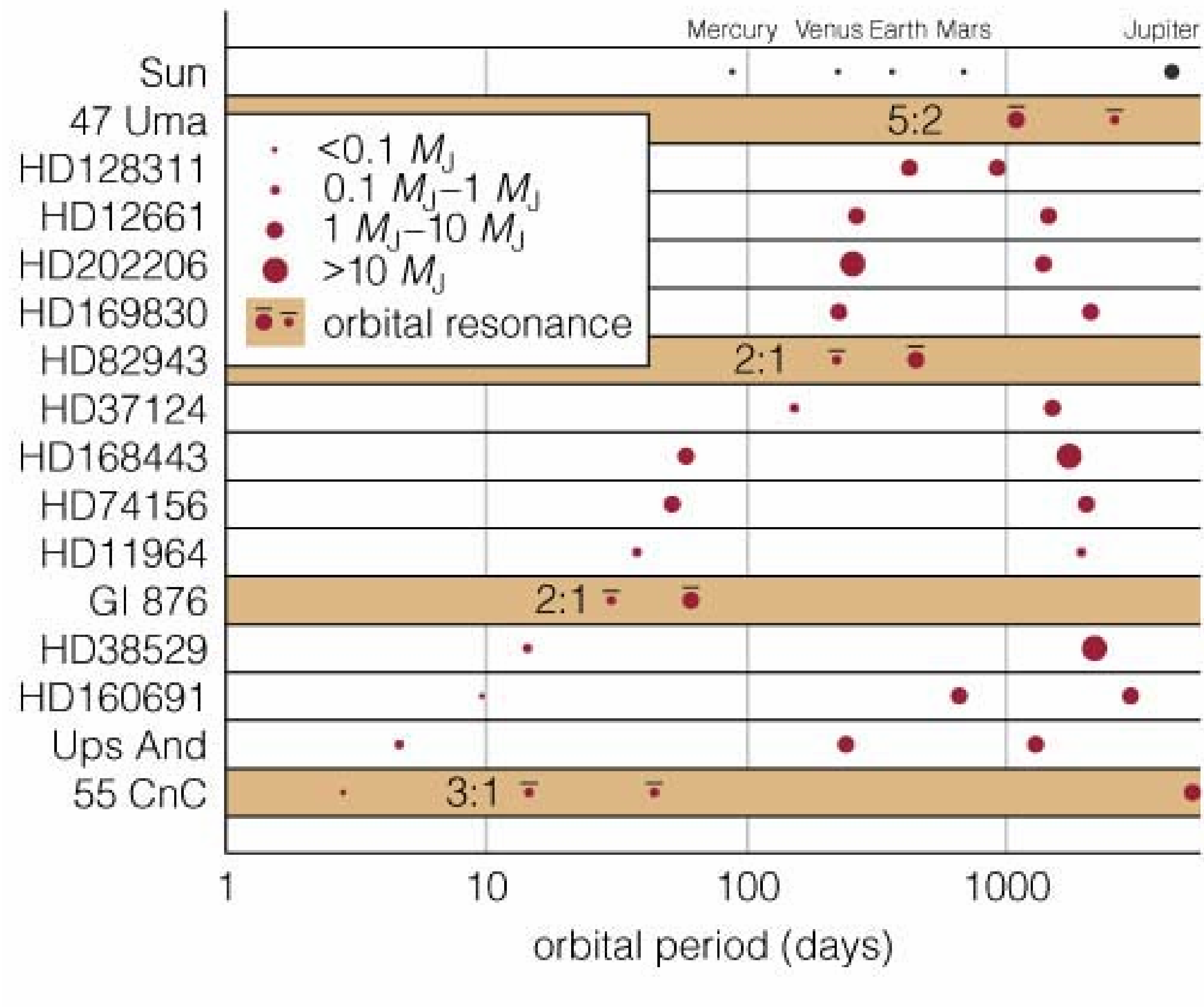


Orbital Properties of Extrasolar Planets
<0.1 M_J
0.1 M_J–1 M_J
1 M_J–10 M_J
>10 M_J
orbital eccentricity
1.0
0.8
0.6
0.4
0.2
0.0
0.01
0.10
1.00
10.00
average orbital distance (AU)
Mercury
Mars
Venus
Earth
Jupiter
Saturn
Uranus
Neptune

Mass distribution



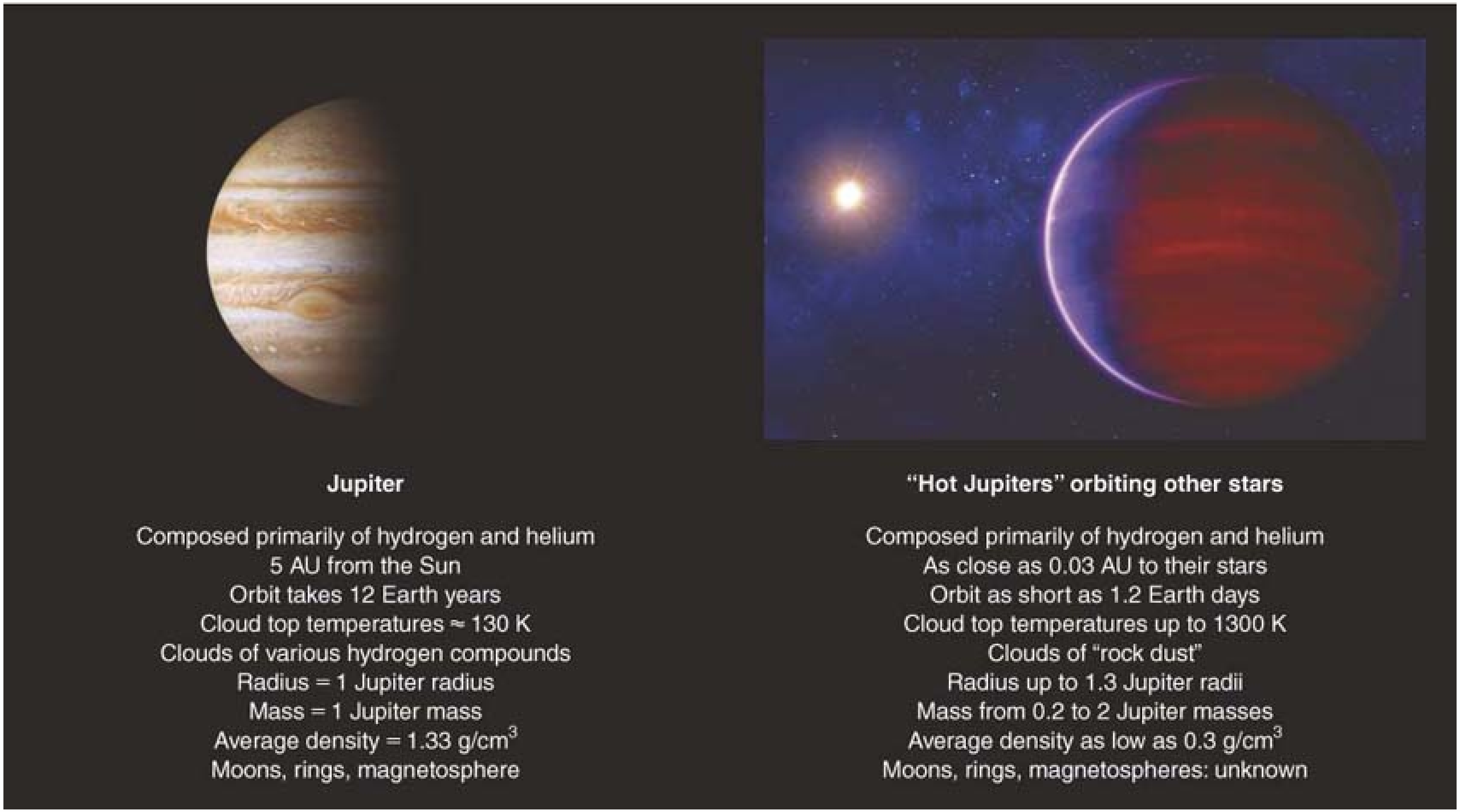
15 systems have multiple exopolanets



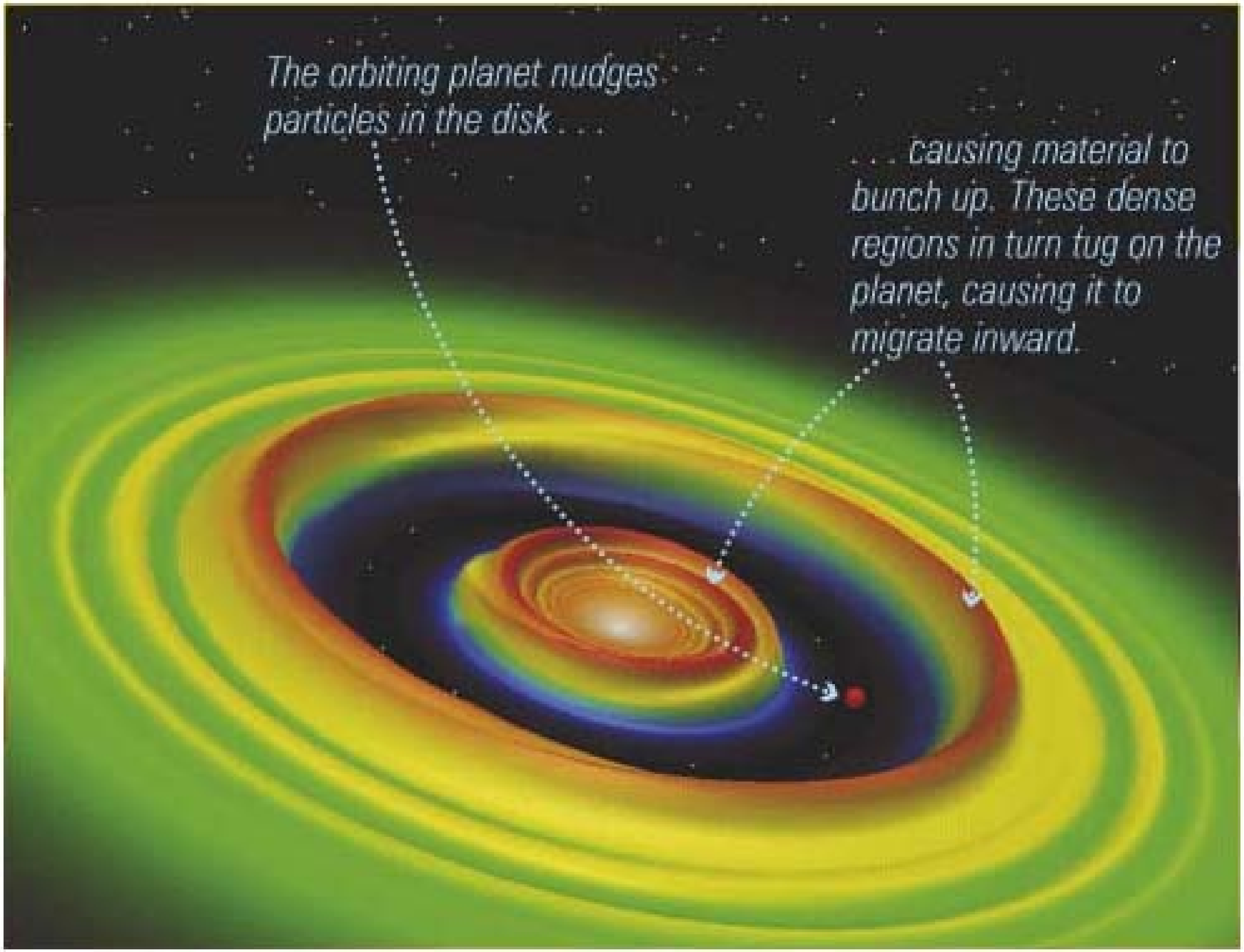
A puzzle

- In our solar system, jovian planets in nearly circular orbits far from the sun
- In extrasolar planetary systems, many Jupiter-like planets are closer to their stars and in highly elliptical orbits
- Which is more peculiar?
  - Based on available data, we are

“Hot Jupiters”



Mechanism for planet migration



Formation of Other Solar Systems

- Can we explain the surprising orbits of many extrasolar planets?
  - Planet migration: planet forms more distant (like Jupiter), but migrates inward due to "drag" with solar nebula
  - Encounters and resonances: close gravitational encounters my sling planets into eccentric orbits

Kepler: A transit mission
tentative launch 2008

TPF-I (Terrestrial Planet Finder): a direct imaging mission *tentative launch by 2020*