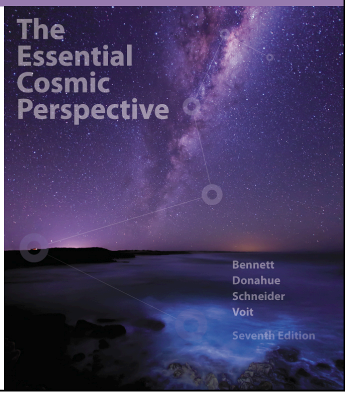
Lecture Outline

Chapter 10: Other Planetary Systems: The New Science of Distant Worlds

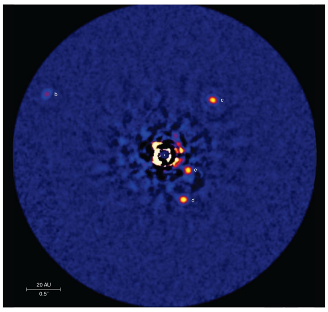


10.1 Detecting Planets Around Other Stars

Our goals for learning:

- How do we detect planets around other stars?

How do we detect planets around other stars?



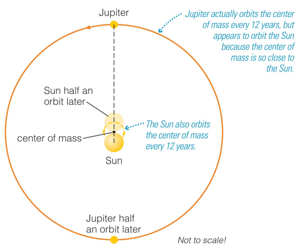
Why are extrasolar planets difficult to detect?

- 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

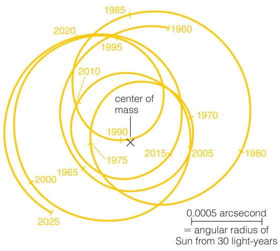
- **Direct:** pictures or spectra of the planets themselves
- **Indirect:** measurements of stellar properties revealing the effects of orbiting planets

Gravitational Tugs



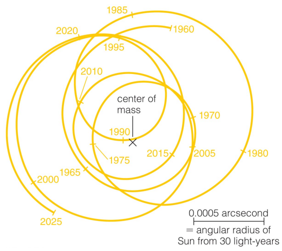
- The Sun and Jupiter orbit around their common center of mass.
- The Sun therefore wobbles around that center of mass with same period as Jupiter.

Gravitational Tugs



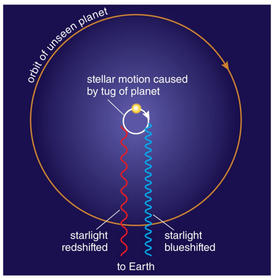
- The Sun's motion around the solar system's center of mass depends on tugs from all the planets.
- Astronomers around other stars that measured this motion could determine the masses and orbits of all the planets.

Astrometric Technique



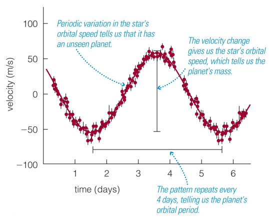
- We can detect planets by measuring the change in a star's position on sky.
- However, these tiny motions are very difficult to measure (~ 0.001 arcsecond).

Doppler Technique



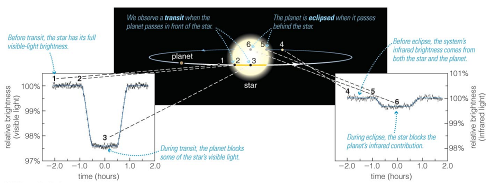
- Measuring a star's Doppler shift can tell us its motion toward and away from us.
- Current techniques can measure motions as small as 1 m/s (walking speed!).

First Extrasolar Planet



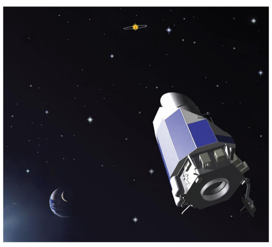
- Doppler shifts of the star 51 Pegasi indirectly revealed a planet with 4-day orbital period.
- This short period means that the planet has a small orbital distance.
- This was the first extrasolar planet to be discovered around a Sun-like star (1995).

Transits and Eclipses



- A **transit** is when a planet crosses in front of a star.
- This reduces the star's apparent brightness and tells us planet's radius.
- Sometimes an **eclipse** – the planet passing behind the star, can also be detected

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.

What have we learned?

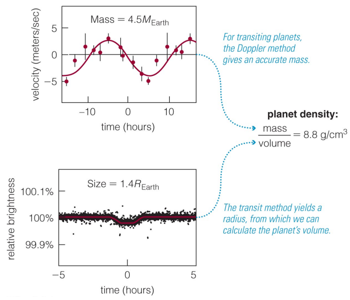
- How do we detect planets around other stars?
  - Direct starlight is billions of times brighter than the starlight reflected from planets, making imaging extremely difficult.
  - A star's periodic motion (detected through Doppler shifts or by measuring its motion across the sky) tells us about its planets.
  - Transiting planets periodically reduce a star's brightness.

10.2 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?



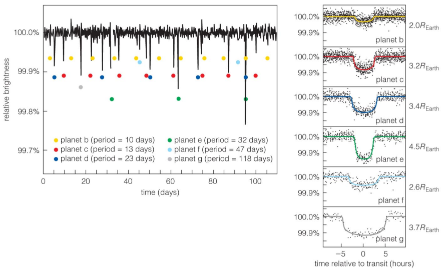
Measurable Properties

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

Planet Mass and Orbit Tilt

- 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.

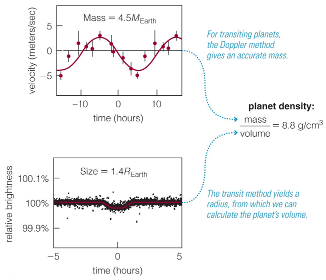
The Kepler 11 system



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.

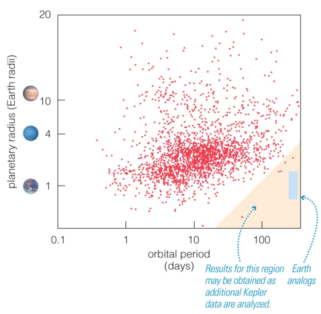


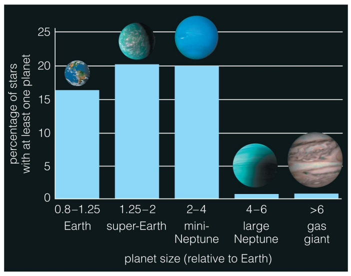
How do extrasolar planets compare with planets in our solar system?

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

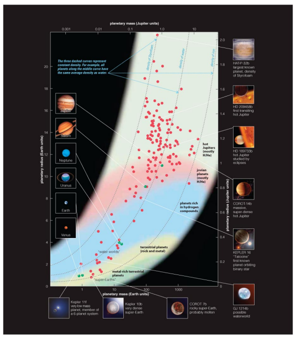
Orbits and sizes of extrasolar planets from *Kepler*





- Results from Kepler indicate that planets are common, and small planets greatly outnumber large planets!

Masses and sizes of extrasolar planets



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?

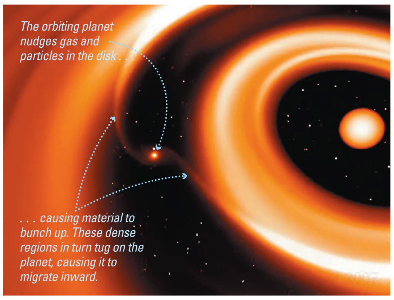
- How do extrasolar planets compare with planets in our solar system?
  - Planets with a wide variety of masses and sizes.
  - Many orbiting close to their stars and with large masses.

10.3 The Formation of Other Planetary Systems

Our goals for learning:

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

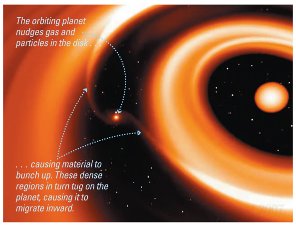
Do we need to modify our theory of solar system formation?



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.

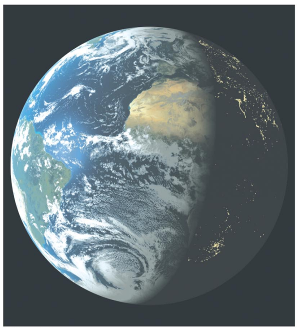
Planetary Types

- There seem to be a much greater variety of planet types than we find in our solar system.
- This includes gas giants with very different densities and water worlds.

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?



a This image (left), computer generated from satellite data, shows the striking contrast between the day and night hemispheres of Earth. The day side reveals little evidence of human presence, but at night our presence is revealed by the lights of human activity. (From the Voyage scale model solar system, developed by the Challenger Center for Space Science Education, the Smithsonian Institution, and NASA. Image created by ARC Science Simulations © 2001.)

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?
  - The answer is coming soon…