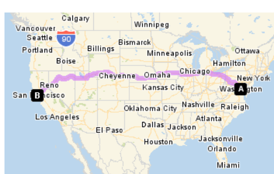
Chapter 13
Other Planetary Systems

Why is it so difficult to detect planets around other stars?

Size Difference

- Planets are small compared to interstellar distances
- 10 billion to 1 scale
  - Sun is size of a grapefruit
  - Jupiter is the size of a marble
  - Earth is the size of a pinhead
  - Nearest star is in San Francisco!



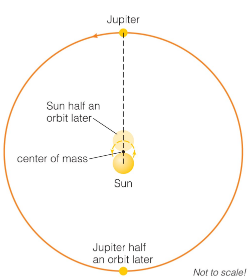
Brightness Difference

- A Sun-like star is about a billion times brighter than the sunlight reflected from its planets
- Like being in San Francisco and trying to see a pinhead 15 meters from a grapefruit in Washington, D. C.

How do we detect planets around other stars?

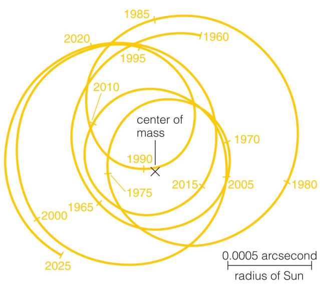
- **Direct:** Pictures or spectra of the planets themselves
- **Indirect:** Measurements of stellar properties revealing the effects of orbiting planets

Gravitational Tugs



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

Gravitational Tugs

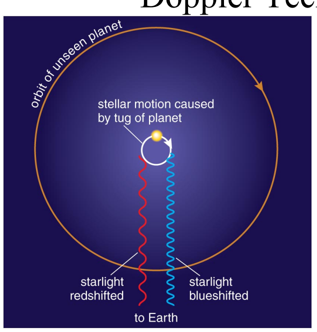


- Sun’s motion around solar system’s center of mass depends on tugs from all the planets
- Astronomers around other stars that measured this motion could determine masses and orbits of all the planets

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

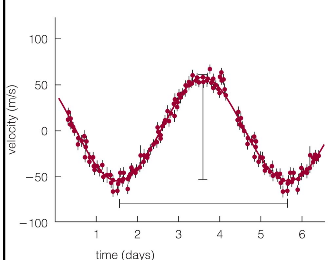


- Measuring a star’s Doppler shift can tell us its motion toward and away from us
- Current techniques can measure motions as small as 1 m/s (walking speed!)

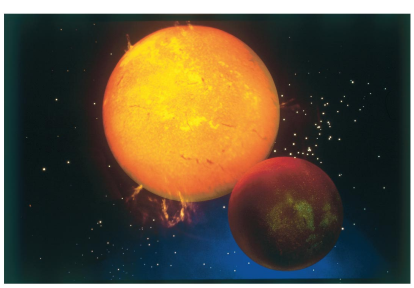
The orbital period of an unseen planet:

a) Will be the same as period of the star's Doppler shift
b) Will be much larger than the star's
c) Will be much smaller than the star's

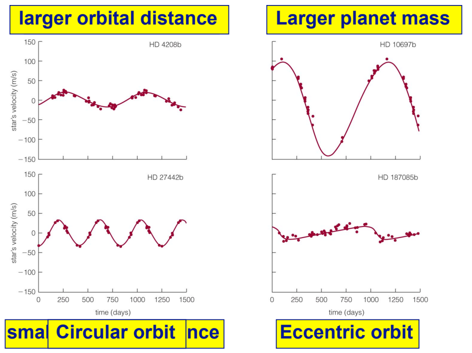
First Extrasolar Planet



- Doppler shifts of star 51 Pegasi indirectly reveal a planet with 4-day orbital period
- Short period means small orbital distance
- First extrasolar planet to be discovered (1995)



Planet around 51 Pegasi has a mass similar to Jupiter's, despite its small orbital distance

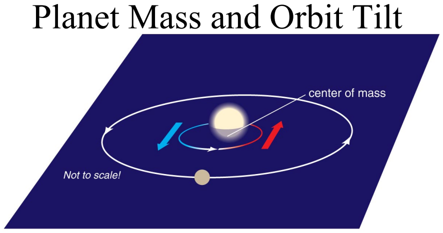


- Doppler data curve tells us about a planet's mass and the shape of its orbit

Suppose you found a star similar to the Sun moving back and forth with a period of 2 years. What could you conclude?

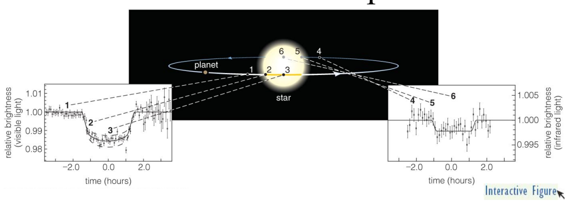
a) It has a planet orbiting at less than 1 AU.
b) It has a planet orbiting at greater than 1 AU.
c) It has a planet orbiting at exactly 1 AU.
d) It has a planet, but we don't know its mass so we can't know its orbital distance for sure.

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 gives us lower limits on masses

Transits and Eclipses

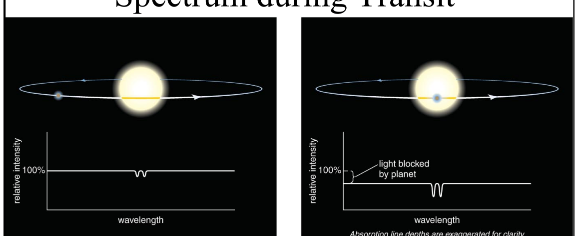


- A **transit** is when a planet crosses in front of a star
- The resulting eclipse reduces the star's apparent brightness and tells us planet's radius
- No orbital tilt: accurate measurement of planet mass

Jupiter is about 1/10 the diameter of the sun. If it transited (passed in front) how much would the sun's light dim?

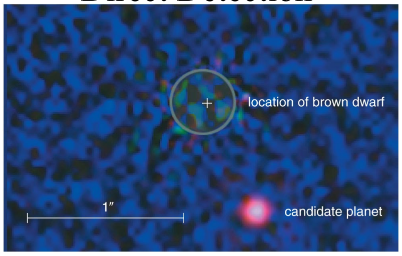
a) About 10% (It would be 90% of its regular brightness.)
b) About 1% (It would be about 99% its regular brightness.)
c) It would be about half as bright
d) None of the above

Spectrum during Transit

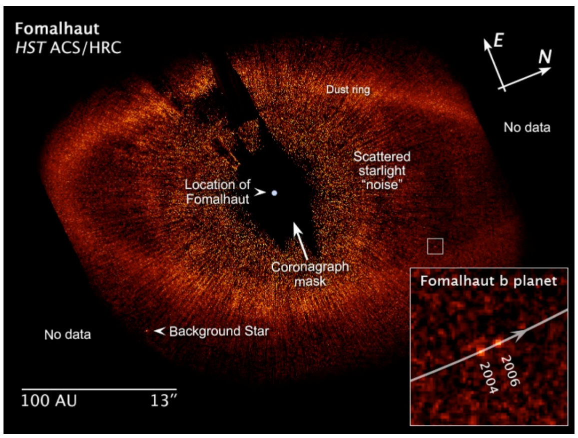


- Change in spectrum during transit tells us about composition of planet's atmosphere

Direct Detection



- Special techniques can eliminate light from brighter objects
- These techniques are enabling direct planet detection

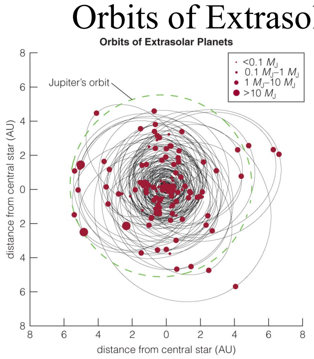


What have we learned about extrasolar planets?

Measurable Properties

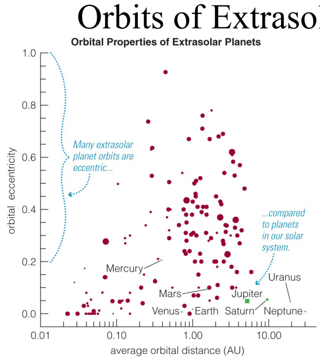
- Orbital Period, Distance, and Shape
- Planet Mass, Size, and Density
- Composition

Orbits of Extrasolar Planets



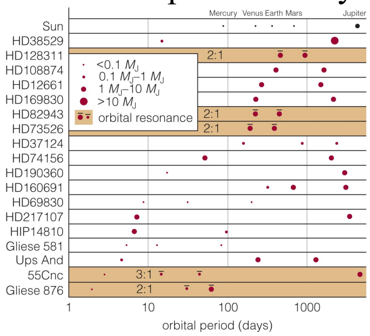
- Most of the detected planets have orbits smaller than Jupiter's
- Planets at greater distances are harder to detect with Doppler technique

Orbits of Extrasolar Planets



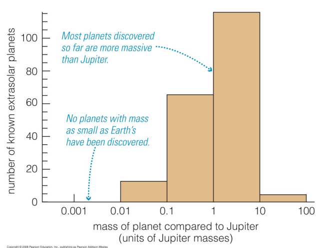
- Orbits of some extrasolar planets are much more elongated (greater eccentricity) than those in our solar system

Multiple-Planet Systems



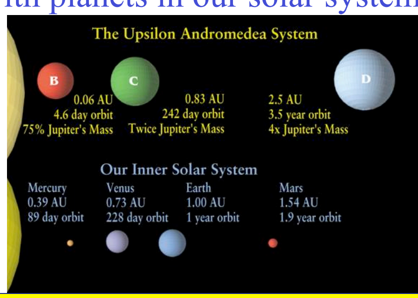
- Some stars have more than one detected planet

Masses of Extrasolar Planets



- Most of the detected planets have greater mass than Jupiter
- Planets with smaller masses are harder to detect with Doppler technique

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

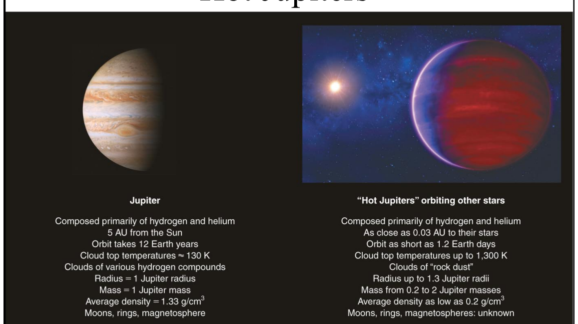


Unlike our solar system, the Upsilon Andromedea System has large planets orbiting close to the star

Surprising Characteristics

- Some extrasolar planets have highly elliptical orbits
- Some massive planets orbit very close to their stars: “hot Jupiters”

Hot Jupiters

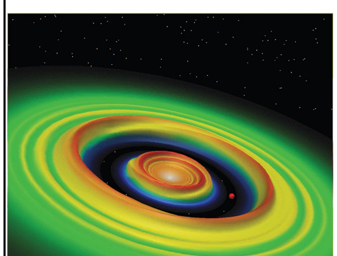


Can we explain the surprising orbits of many extrasolar planets?

Revisiting the Nebular Theory

- Nebular theory predicts that massive Jupiter-like planets should not form inside the frost line (at << 5 AU)
- Discovery of “hot Jupiters” has forced reexamination of nebular theory
- “Planetary migration” or gravitational encounters may explain “hot Jupiters”

Planetary Migration

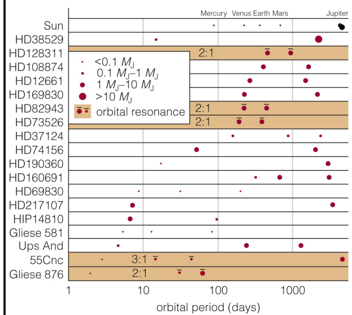


- A young planet’s motion can create waves in a planet-forming disk
- Models show that matter in these waves can tug on a planet, causing its orbit to migrate inward

Gravitational Encounters

- 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

Orbital Resonances



Resonances between planets can also cause their orbits to become more elliptical

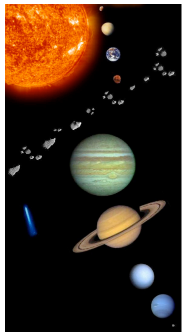
Do we need to modify our theory of solar system formation?

Modifying the Nebular Theory

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

Is our Solar System unusual?

- No true Earth-like planets found yet
- But the data aren't good enough to tell if they are common or rare
- Detection method is most sensitive to BIG planets CLOSE to their star
- More sensitive observations are needed

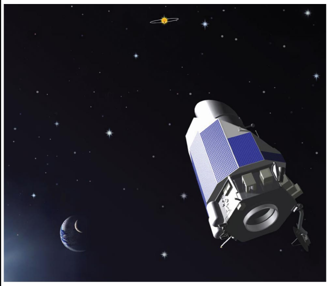


Planets: Common or Rare?

- One in ten stars examined so far have turned out to have planets
- The others may still have smaller (Earth-sized) planets that current techniques cannot detect

How will we search for Earth-like planets?

Transit Missions

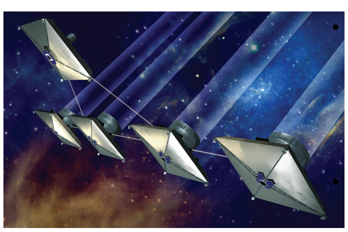


- NASA's *Kepler* mission is scheduled to begin looking for transiting planets in 2009
- It is designed to measure the 0.008% decline in brightness when an Earth-mass planet eclipses a Sun-like star

Astrometric Missions

- *GAIA:* A European mission planned for 2011 that will use interferometry to measure precise motions of a billion stars
- *SIM:* A NASA mission that will use interferometry to measure star motions even more precisely (to 10^{-6} arcseconds)

Direct Detection



Mission concept for NASA's Terrestrial Planet Finder (TPF)

- Determining whether Earth-mass planets are really Earth-like requires direct detection
- Missions capable of blocking enough starlight to measure the spectrum of an Earth-like planet are being planned