**Origin of the Solar System**

An ideal theory of the solar system should provide strong reasons for the observed characteristics of the planets yet be flexible enough to allow for deviations.

**Planetary Properties**

- Each planet is relatively isolated in space - *not bunched*
- All planets orbit in the same direction – *eastward*
- Orbits are nearly in the same plane (except Pluto)
- Most planetary orbits are circular (except Pluto, Mercury)
- Nearly all planets rotate in an eastward direction (except Venus, Uranus, and Neptune)
- Mostly all moons show prograde rotation but some also exhibit retrograde rotation.
- The Solar System is “differentiated” – terrestrial planets close in, Jovian planets far out
- The asteroids are rocky objects of very old age - *mostly between Mars & Jupiter*
- Comets are icy (plus some dirt)
  - they originate in the outer solar system
  - *Oort cloud and Kuiper belt (including Pluto)*

**Formation of the Solar System**

**Nebular theory**

- A large cloud of gas and dust began to collapse under its own gravity.
- As cloud collapsed, it began to spin faster, to conserve angular momentum and a rotating disk formed called solar nebula.
- Matter at the center (mostly H, He) formed the protosun and eventually evolved into the Sun.
- Gases in solar nebula accreted into protoplanets and became planets.

**Condensation theory**

This theory builds on the nebular theory by incorporating the effects of particles of dust.

- dust helped cool the nebula and acted as condensation nuclei (onto which matter condensed), allowing the planet-building process to begin.
- dust grains form the nuclei of “clumps” and they grew by *accretion*.
- clumps collide to form *planetesimals* (small moon size), whose gravitational fields were strong enough to accelerate the accretion process.
- collision of planetesimals formed inner terrestrial planets and cores of outer planets.
- core of outer planets became so large that they could capture the H, He etc. gases in the solar nebula.
**Observational Evidence**
- Discovery of dust disk around other stars

![Infrared image of HR 4796A](image)

**Why didn’t the inner planets accumulate gases?**
- The temperature of the solar nebula would be expected to decrease with increasing distance from the Sun.
- At any given location, the temperature would determine which materials could condense out of the nebula and so control the composition of any planets forming there.
  - *Inner regions were too hot for gases to condense.*
- Hence, terrestrial planets are rocky because there only rocky and metallic materials condensed out.

**Where did the terrestrial atmospheres come from?**
- Outgassing from interior (mostly CO₂)
- Some H₂O, other gases from comet collisions.
- Mercury too small to hold an atmosphere.

**Where did the Jovian moons come from?**
- Original planetesimals too small to hold gases.
- Captured by Jovian planets, some formed simultaneously.

**Where did the asteroid belt come from?**
- The asteroid belt is a collection of planetesimals that never managed to form a planet, because of Jupiter’s gravitational influence.

**Planets Beyond the Solar System (Extrasolar Planets)**

![Painting of a Jupiter-mass planet discovered at a distance of only 0.05 AU from a Solar-type star](image)
Extrasolar Planets

Advances in this fascinating area have come not because of dramatic scientific or technical breakthroughs but rather through steady improvements in telescope and detector technology and computerized data analysis.

- Since 1994, about 70 extrasolar planets have been found.
- No extrasolar planet has been seen directly.
- There are two techniques, based on motion of the star around the star/planet center of mass:
  1) Apparent motion of star in the sky
  2) Doppler shift of star’s spectral lines
- All confirmed discoveries have made use of the Doppler effect. It also allows us to estimate the planet’s mass. (difficult to detect a star’s wobble in direct images)

Detection of Extrasolar Planets

- As a planet orbits its parent star, it causes the star to “wobble” back and forth. (The greater the mass of the planet, the larger the wobble.)
- The Doppler shift of the spectral lines give the radial velocity
- From the velocity and period, you can get the planet’s mass

Constraints using Doppler Effect

1) Can we detect all types of planets with this technique? No, because detection are biased toward large (Jupiter size) planets that are close to the star.

2) Are we able to determine the true mass of the planet?
   - In most cases, only a lower limit to the mass is obtained, because most orbits are inclined to our line of sight and Doppler observations cannot distinguish between low-speed orbits seen edge-on and high-speed orbits seen almost face-on.
   - However, in one case we know that the planet eclipses the star – system is edge on.

Parameters of Planet around HD 209458
- Mass: 0.6 times that of Jupiter
- Distance from Star: 0.05 AU
- Size: About 1.5 times diameter of Jupiter
- Density: only 200 kg/m³
- Orbital period ~ 3.5 days
- A “hot Jupiter” mostly H and He, bloated by heat from the star
Some 70 extrasolar planets are now known, by observing the wobbling of parent star (except one).

- Smallest planet detected: mass of Saturn
- Most planets discovered to date are hot Jupiters.
- About 5% of the stars surveyed show these systems.
- Most planets are on highly eccentric orbits
  - Few of these systems resemble our on Solar System!
- How many terrestrial systems are there? – don’t know
  - Detection of terrestrial planets requires greater precision

**Space Interferometry Mission (SIM) - 2009**

- will determine positions of stars accurately
- attempt to detect motions due to terrestrial planets

**Terrestrial Planet Finder (2012?)**

Four 3.5 meter telescopes flying in formation