Planet Formation - Summary

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This summary is based on the book Chapter 23 from Carroll, Bradley W., and Dale A. Ostlie. An Introduction to Modern Astrophysics

1 Observational evidence to consider

- Proplyds
- Astroid belt in the Solar System
- The Kuiper belt
- The Oort cloud
- Sun contains 99.9% of the mass, it contains only about 1% of the angular momentum of the entire Solar System
- on average, main-sequence stars that are more massive rotate much more rapidly and contain more angular momentum per unit mass than do less massive ones.
- transport of angular momentum → plasma drag in a corotating magnetic field.
- angular momentum can also be carried away by the particles in the solar wind. The onset of surface convection in low-mass stars → development of coronae and mass loss.
- composition trends that exist among the planets in our Solar System:
  - terrestrial planets are small, generally volatile-poor, and dominated by rocky material,
  - gas and ice giants contain an abundance of volatile material.
- The same composition trend is seen in the moons on a smaller scale, e.g. the moons around Jupiter
- This points to either a composition gradient or a temperature gradient (or both)
- condensation temperature of water-ice must be reached at some point near the current position of Jupiter → "snow line," the "ice line,"
- **Heavy Bombardment:**
  - collisions in the past, leaving cratered surfaces on objects
  - the formation of the Moon
  - the very high density of Mercury
  - the axis tilt of planets
  - some impact craters on Earth
- other planetary systems
  - hot Jupiters → migration of planets
  - most common types of exoplanets are: gas giants and super earths
- time scales: planets need to form in the pre-main-sequence stage of star formation ← there needs to be a debris disk of material from which they can form and the planet formation needs to happen before the star reaches the main sequence. Once the star is on the main sequence it can very quickly clear out the leftover gas and dust from the system.

2 A model for the formation of the Solar System

- simultaneous formation of the Sun and the planets
- two formation models:
  - **"top-down" gravitational instability** → the dense parts of the disk start to collapse similar to how the star formation is happening. Issue: the timescales for the Solar System do not work for this. This process takes too long + does not explain the large number of smaller objects in the Solar System + does not explain the mass distribution of extrasolar planets
  - **"bottom up" formation through a process of accretion** of smaller building blocks → small grains with icy mantles collide and stick together → **gravitational influence (Hill radius)** pulls in more and more material → the larger grains grow more rapidly and eventually turn into planetary cores → the largest planets form first → they also collect most of the volatile materials → they are the gas giants → the rocky planets form a bit later, the warmer temperatures closer ti the Sun mean less volatile elements → rocky plantes are smaller in mass
  - if planets are massive enough → internal heat generated by decaying radioactive isotopes + energy released during collisions → gravitational separation → **chemically differentiated planets** (heavier elements are mostly in the core of the rocky planets)

- **gravitational perturbations** → resonant orbits with Jupiter are responsible for the formation of the asteroid belt between Jupiter and Mars.
- migration: **planets migrated** a bit in the Solar System before they settled in their current positions (e.g. Jupyter moved about 0.5 AU closer to the Sun, Saturn, Uranus, and Neptune migrated outward). This also explains the hot Jupiters in other systems.
  * Type I migration: density waves results in the simultaneous transfer of angular momentum outward and mass inward
  * Type II migration: viscosity within the disk can cause objects to migrate inward

3 Exoplanets

In October 2023 there are more than 5500 confirmed exoplanets. We know about 800 systems with more than 1 planet.

The **most common methods used to discover exoplanets** are the following:

- astrometry
- transit
- radial velocity
- direct imaging
- gravitational microlensing

Types of exoplanets:

- Neptune - like (large icy core)
- Gas giant
- Super Earth (rocky planet, but a few times larger then Earth in mass)
- Terrestrial (rocky planet similar to Earth in size)

The upper and lower limit of planets is not very well defined. Usually 13 times the mass of Jupiter (M_J) is considered to be the upper limit. Objects above these mass are **brown dwarfs,** which are more like stars, but with no stable H burning. Brown dwarfs may have some deuterium and Li burning.

There is no real lower limit considered for exoplanet masses. Within the Solar System, Mercury is the lowest mass planet with a mass of 0.055 times the mass of Earth.

- first discovered exoplanet: the pulsar planet system
- the first discovered exoplanet orditing a main sequence star: 51 Pegasi b
- lowest-mass planets being the most common
- planets that are orbiting close to their parent star tend to have circularized orbits, farther from their parent star may have high orbital eccentricities.
- high-eccentricity planets → usually found in multiple star systems (e.g. in binary star systems)
- There is at least one planet on average per star
- 1 in 5 Sun-like stars have an "Earth-sized" planet in the **habitable zone**
- correlation has been found between the metallicity of a star and the probability that the star hosts a giant planet,
- Jupiter-class planets have densities that are similar to those of the gas giants in our Solar System.
- hot Jupiters - Jupiter sized planets very close to their stars
- We can detect the atmospheres of some exoplanets with 2 methods:
  - transmission photometry or spectra
  - differencing the star plus planet light
- Detected elements in exoplanet atmospheres: hydrogen, carbon and oxygen around the planet. We have also detected water vapor and clouds.
- methane → possible signature of life
- The **Habitable zone** is the range of orbits around a star within which a planetary surface can support liquid water given sufficient atmospheric pressure.

3.1 Data base for exoplanets

`http://exoplanet.eu/catalog/` This data base has a downloadable data table and it can also make interactive scatter plots and histograms.