Chapter 8:

The Origin of the Solar System
The Solar Nebula Hypothesis

Basis of modern theory of planet formation:

Planets form at the same time from the same cloud as the star.

Planet formation sites can be observed today as dust disks of T Tauri stars.

The sun and our Solar system formed ~ 5 billion years ago.
Evidence for Ongoing Planet Formation

Many young stars in the Orion Nebula are surrounded by dust disks:

Probably sites of planet formation right now!
Dust Disks around Forming Stars

Dust disks around some T Tauri stars can be imaged directly (HST).
Survey of the Solar System

Relative Sizes of the Planets

Assume we reduce all bodies in the solar system so that the Earth has diameter 0.3 mm.

- **Sun**: ~ size of a small plum
- **Mercury, Venus, Earth, Mars**: ~ size of a grain of salt
- **Jupiter**: ~ size of an apple seed
- **Saturn**: ~ slightly smaller than Jupiter’s “apple seed”

**Uranus, Neptune**: Larger salt grains

**Pluto**: ~ Speck of pepper
Planetary Orbits

All planets in almost circular (elliptical) orbits around the sun, in approx. the same plane (ecliptic).

Sense of revolution: counter-clockwise
Sense of rotation: counter-clockwise (with exception of Venus, Uranus, and Pluto)

Orbits generally inclined by no more than 3.4°

Exceptions:
- Mercury (7°)
- Pluto (17.2°)

(Distances and times reproduced to scale)
Two Kinds of Planets

Planets of our solar system can be divided into two very different kinds:

Terrestrial (earthlike) planets: Mercury, Venus, Earth, Mars

Jovian (Jupiter-like) planets: Jupiter, Saturn, Uranus, Neptune
Terrestrial Planets

Four inner planets of the solar system

Relatively small in size and mass (Earth is the largest and most massive)

Rocky surface

The surface of Venus can not be seen directly from Earth because of its dense cloud cover.
Craters on Planets’ Surfaces

Craters (like on our Moon’s surface) are common throughout the Solar System.

Not seen on Jovian planets because they don’t have a solid surface.
The Jovian Planets

Much larger in mass and size than terrestrial planets

- Much lower average density
- All have rings (not only Saturn!)
- Mostly gas; no solid surface
Space Debris

In addition to planets, small bodies orbit the sun:
Asteroids, comets, meteoroids

Asteroid
Eros, imaged by the NEAR spacecraft
Comets

Icy nucleus, which evaporates and gets blown into space by solar wind pressure

Mostly in highly elliptical orbits, occasionally coming close to the sun
Meteoroids

Small (μm – mm sized) dust grains throughout the solar system

If they collide with Earth, they evaporate in the atmosphere.

→ Visible as streaks of light: meteors
The Age of the Solar System

Sun and planets should have about the same age.

Ages of rocks can be measured through radioactive dating:

Measure abundance of a radioactively decaying element to find the time since formation of the rock.

Dating of rocks on Earth, on the Moon, and meteorites all give ages of ~ 4.6 billion years.
Table 16-1  |  Characteristic Properties of the Solar System

1. Disk shape of the solar system
   Orbits in nearly the same plane
   Common direction of rotation and revolution

2. Two planetary types
   Terrestrial—inner planets; high density
   Jovian—outer planets; low density

3. Planetary rings and large satellite systems
   Yes for Jupiter, Saturn, Uranus, and Neptune
   No for Mercury, Venus, Earth, and Mars

4. Space debris—asteroids, comets, and meteors
   Composition, orbits
   Asteroids in inner solar system, composition like Terrestrial planets
   Comets in outer solar system, composition like Jovian planets

5. Common age of about 4.6 billion years measured or inferred for
   Earth, the moon, Mars, meteorites, and the sun
The Story of Planet Building

The planets were formed from the same protostellar material as the sun, still found in the Sun’s atmosphere.

Rocky planet material was formed from the clumping together of dust grains in the protostellar cloud.

Mass of less than ~ 15 Earth masses:
Planets can not grow by gravitational collapse.

Earthlike planets

Mass of more than ~ 15 Earth masses:
Planets can grow by gravitationally attracting material from the protostellar cloud.

Jovian planets (gas giants)
The Condensation of Solids

To compare densities of planets, compensate for compression due to the planet’s gravity:

Only condensed materials could stick together to form planets.

Temperature in the protostellar cloud decreased outward.

Further out → Protostellar cloud cooler → metals with lower melting point condensed → change of chemical composition throughout solar system

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**Table 16-2 | Observed and Uncompressed Densities**

<table>
<thead>
<tr>
<th>Planet</th>
<th>Observed Density (g/cm³)</th>
<th>Uncompressed Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>5.44</td>
<td>5.30</td>
</tr>
<tr>
<td>Venus</td>
<td>5.24</td>
<td>3.96</td>
</tr>
<tr>
<td>Earth</td>
<td>5.50</td>
<td>4.07</td>
</tr>
<tr>
<td>Mars</td>
<td>3.94</td>
<td>3.73</td>
</tr>
</tbody>
</table>

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**Table 16-3 | The Condensation Sequence**

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Condensate</th>
<th>Planet (Estimated Temperature of Formation; K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>Metal oxides</td>
<td>Mercury (1400)</td>
</tr>
<tr>
<td>1300</td>
<td>Metallic iron and nickel</td>
<td></td>
</tr>
<tr>
<td>1200</td>
<td>Silicates</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>Feldspars</td>
<td>Venus (900)</td>
</tr>
<tr>
<td>680</td>
<td>Troilite (FeS)</td>
<td>Earth (600)</td>
</tr>
<tr>
<td>175</td>
<td>H₂O ice</td>
<td>Mars (450)</td>
</tr>
<tr>
<td>150</td>
<td>Ammonia–water ice</td>
<td>Jovian (175)</td>
</tr>
<tr>
<td>120</td>
<td>Methane–water ice</td>
<td>Pluto (65)</td>
</tr>
<tr>
<td>65</td>
<td>Argon–neon ice</td>
<td></td>
</tr>
</tbody>
</table>
Formation and Growth of Planetesimals

Planet formation starts with clumping together of grains of solid matter: **Planetesimals**

Planetesimals (few cm to km in size) collide to form planets.

Planetesimal growth through **condensation and accretion**

Gravitational instabilities may have helped in the growth of planetesimals into protoplanets.
The Growth of Protoplanets

Simplest form of planet growth:

Unchanged composition of accreted matter over time.

As rocks melted, heavier elements sink to the center → differentiation

This also produces a secondary atmosphere → outgassing

Improvement of this scenario: Gradual change of grain composition due to cooling of the nebula and storing of heat from potential energy
The Jovian Problem

Two problems for the theory of planet formation:

1) Observations of extrasolar planets indicate that Jovian planets are common.

2) Protoplanetary disks tend to be evaporated quickly (typically within ~ 100,000 years) by the radiation of nearby massive stars.

→ Too short for Jovian planets to grow!

Solution:

Computer simulations show that Jovian planets can grow by direct gas accretion without forming rocky planetesimals.
Clearing the Nebula

Remains of the protostellar nebula were cleared away by:

- Radiation pressure of the sun
- Solar wind
- Sweeping-up of space debris by planets
- Ejection by close encounters with planets

Surfaces of the Moon and Mercury show evidence for heavy bombardment by asteroids.
Extrasolar Planets

The modern theory of planet formation is evolutionary.

→ Many stars should have planets!
→ planets orbiting around other stars = “Extrasolar planets”

Dust disks around newly-born stars suggest that there are planetary systems around other stars.
Extrasolar Planets

Extrasolar planets can usually not be imaged directly.

Detection using the same methods as in binary star systems:

Look for the “wobbling” motion of the star around the common center of mass.
Indirect Detection of Extrasolar Planets

Observing periodic Doppler shifts of stars with no visible companion:

Evidence for the wobbling motion of the star around the common center of mass of a planetary system

Over 100 extrasolar planets have been detected so far.
Direct Detection of Extrasolar Planets

Very few planets around faint stars have now been observed directly.

Planet 2M1207b orbits 7 AU from its brown dwarf “sun.”
An exoplanet or extrasolar planet is a planet that orbits a star other than the Sun. Over 2000 exoplanets have been discovered since 1988 (2086 planets in 1330 planetary systems including 509 multiple planetary systems as of 5 March 2016).
The Kepler instrument is a specially designed 0.95-meter diameter telescope called a photometer or light meter. It has a very large field of view for an astronomical telescope 105 square degrees, which is comparable to the area of your hand held at arm's length. The fields of view of most telescopes are less than one square degree. Kepler needs the large field of view in order to observe the large number of stars. It stares at the same star field for the entire mission and continuously and simultaneously monitors the brightnesses of more than 100,000 stars for at least 3.5 years, the initial length of the mission, which can be extended.
Smaller Orbits

The Kepler Orrery

\[ t_{[\text{BJD}]} - 2454900 = 65.0 \]

credit: D. Fabrycky