Origin of the Solar System

Look for General Properties

Dynamical Regularities

Orbits in plane, nearly circular

Orbit sun in same direction (CCW from N.P.)

Rotation Axes  \( \perp \) to orbit plane

(Sun & most planets; Uranus exception)

Planets contain 98\% of angular momentum

Spacing and Composition

Spacing increases with distance

(roughly logarithmic)

Composition varies with distance

inner 4: rocky, small, thin atmospheres

outer 4: gaseous, large, mostly atmosphere

Sun contains 99.9\% of mass

\[
\frac{d_2}{d_1} \approx 1.5 - 2
\]
### The Solar System

#### Distance from Sun

<table>
<thead>
<tr>
<th></th>
<th>.1</th>
<th>1</th>
<th>10</th>
<th>100 AU</th>
</tr>
</thead>
<tbody>
<tr>
<td>M V E M J S U N P</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
</tbody>
</table>

M (M☉) 0.06 1 < .001 95 17

.82 .11 318 15 0.1

Terrestrial Gas Giants

Asteroids

#### Composition (%)

<table>
<thead>
<tr>
<th></th>
<th>Rocky</th>
<th>“Icy”</th>
<th>Gaseous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrestrial</td>
<td>100</td>
<td>&lt;1</td>
<td>0</td>
</tr>
<tr>
<td>Jupiter</td>
<td>6</td>
<td>~13</td>
<td>~81</td>
</tr>
<tr>
<td>Saturn</td>
<td>21</td>
<td>~45</td>
<td>~34</td>
</tr>
<tr>
<td>Uranus</td>
<td>~28</td>
<td>~62</td>
<td>~10</td>
</tr>
<tr>
<td>Neptune</td>
<td>~28</td>
<td>~62</td>
<td>~10</td>
</tr>
<tr>
<td>Comets</td>
<td>~31</td>
<td>~69</td>
<td>~0</td>
</tr>
</tbody>
</table>

Enhancement to get ☉ abundance

300-500 2-40 10-60 30-140 30-115

Rocky - iron, silicates, …

“Icy” - at time of formation (H₂O, NH₃, CH₄, …)

Gaseous - H, He
Theory of Solar System Formation

All start with rotating disk

Minimum mass: 0.01 $M_\odot$

Sum of planets $\sim 0.001$ $M_\odot$ but most of $H_2$, He lost

Note: Similar to masses of disks around forming stars

Some models assume more massive disks

Temperature, Density decrease with distance from forming star

(Observations suggest slower decrease than models usually assume)

DUST PLAYS A KEY ROLE
Dust Cores
Iron, Silicon, Oxygen, Carbon

No Dust

Terrestrial Planets

Outer Planets

Dust cores and Icy Mantles
(H₂O, NH₃, CH₄)
Fig. 2.13. In the spinning preplanetary solar nebula the dust retreats to the equatorial plane due to the energy losses that occur in the collision process illustrated in Figure 2.12 (from Boris Levin, The Origin of the Earth and the Planets, Foreign Languages Publishing House, Moscow, 1956).
Dust Processes

Dust sinks to midplane

Gravitational instability \rightarrow \text{planetesimals (~1 km in size)}

\begin{align*}
&\sim10^4\text{yr} \\
&\text{and/or} \\
&\text{Accretion of dust grains}
\end{align*}

\begin{align*}
&10^6 - 10^8 \text{ yr} \\
&\text{Collisions between planetesimals} \rightarrow \text{rocky planet cores}
\end{align*}

Gas Processes (Outer Planets)

Accretion of gas/gravitational collapse onto rocky cores

\rightarrow H, \text{He in atmosphere}

Rings, moons (minature solar system)
Planet Forming in a disk
**Dust and Ice**

Interstellar dust - core + mantle

- Silicate \((\text{Si} + 0 + \ldots)\)
or Graphite

Mantle: \(\text{H}_2\text{O}, \text{NH}_3, \text{CH}_4, \ldots\)

- ?
- Planet types
  - Inner: Only rocky cores, little or no ice survives \(\rightarrow\) rocky planets
  - Outer: Ice survives \(\rightarrow\) comets, icy moons of outer planets

**Outgassing**

- Planet heats internally \(\rightarrow\) ice \(\rightarrow\) gas \(\rightarrow\) thin atmosphere
  - (if pressure, T ok \(\rightarrow\) liquid \(\rightarrow\) ocean)
Conclusions

1. Planet formation in a rotating disk with icy dust can explain most of the general facts about our solar system.

2. Planetary systems are likely to be common since disks with \( M \geq M_{\text{min}} \) are common around forming stars.

If we are typical,

3. Expect other planetary systems will have \(~10\) planets, logarithmic spacing, different planet types.
Caveats

• Other planetary systems are quite different
  – Big planets in close
  – But this is probably due to selection effect
• Locations may differ with mass of star
  – Ices survive closer to lower mass star
  – May get ice giants in close
  – Also planets may migrate inwards
  – May prevent formation of terrestrial planets
Formation of Earth

Solid particles $\rightarrow$ silicate + iron

No gas collected $\rightarrow$ atmosphere outgassed

Radioactive heating $\rightarrow$ molten core

$\text{ice} \rightarrow \text{gas}$

$\text{H}_2\text{O} \rightarrow \text{gas} \rightarrow \text{liquid} \ (\text{oceans})$

$\text{CO}_2 \rightarrow \text{dissolve in oceans} \rightarrow \text{carbonate rocks}$

$\text{N}_2 \rightarrow \text{gas}$

Early Earth Atmosphere

$\text{N}_2, \text{CO}_2, \text{H}_2\text{O} \quad \text{(CH}_4, \text{NH}_3, \text{H}_2 \ ?)$

Reducing $\quad (\text{No free O}_2) \quad \text{Neutral ?}$

Energy Sources
Differentiation of the Earth

Impact heating by planetesimals (release of gravitational potential energy)

Radioactive nuclei decay (release of nuclear potential energy)

Nuclear potential energy

unstable nucleus

Smaller nuclei
(Fission)

Also emit \( \alpha \) particles (He)

electrons, gamma-rays

\[ \rightarrow \text{Kinetic energy} \rightarrow \text{heat} \]

Result: molten Earth

Iron-Nickel \( \rightarrow \) center (core)

Silicates float \( \rightarrow \) upper levels (mantle)

Differentiation released Grav. Potential energy \( \rightarrow \) hot core

Radioactive heating continues
Results in layered Earth (like a soft-boiled egg)

1. Inner solid core
2. Outer liquid core
3. Lower mantle - iron rich silicates, solid
4. Asthenosphere (upper mantle) pliable
5. Lithosphere - rigid silicates (crust)

Lithosphere can “float” on asthenosphere

Continental Drift, Earthquakes, Volcanos
Continental Drift Reconstructed

Shows motion of continental plates over last 150 Myr. Red and green dots show locations of ocean drilling.

http://www.odsn.de/odsn/index.html
Formation of Earth and Moon

\[ \frac{M_{\text{Moon}}}{M_{\text{Earth}}} \quad \text{Larger than all but Pluto} \]

Most terrestrial planets have no moons
(Martian moons are captured asteroids)
Moon most likely resulted from giant impact

\[ 0.15 \, M_\oplus \quad \text{(Earth)} \]

Earth gets more iron \( \square_\oplus = 5.5 \, \text{g cm}^{-3} \)

Moon mostly silicate \( \square_{\text{Moon}} = 3.3 \, \text{g cm}^{-3} \)

Temperature was very high after impact (10,000 - 60,000 K)
Any icy material left?
**Origin of Atmosphere**

Certain “Noble” gases (e.g. Neon) are more rare in Earth atmosphere than in solar nebula. Atmosphere not collected from gas

Reason: Earth is small gravity is weak

Temperature in solar nebula is high - atoms moving fast, harder to hold

**Outgassing:** “Icy” material vaporized by high temperatures

→ vents, volcanos

[Ultraviolet Light]

H₂O, NH₃, CH₄ → H₂O, N₂, CO₂

[Chemical Reactions]

Rain

Oceans

Main constituent of atmosphere

CaCO₃ sediments

No O₂ on early Earth; No ozone (O₃), so no protection from ultraviolet light

Alternative: Icy materials brought by comets.