The Origin of the Solar System

Formation and basic characteristics of the Solar System
The origin of matter

• All the building material necessary to make our Solar System was assembled in the process of nucleosynthesis in the early Universe, in stellar cores and during supernova explosions
• Protons, neutrons and electrons were made in the first 3 min. of the existence of the Universe
• Hydrogen, deuterium, helium, lithium and beryllium were made in the first 30 min.
• Heavier elements all the way up to iron were synthesized by nuclear fusion in stars
• All elements heavier than iron were made in supernova explosions
• We are made out of that stuff!!!
The origin of planets

- The most likely explanation of the creation of our Solar System involves the familiar process of star formation out of a collapsing molecular cloud of gas and dust. This is called the solar nebula theory.
- A rotating cloud, compressed by a passing shock wave, collapses into a flat, spinning disk with a protostar at its center.
- Planets are made out of the disk material in the process of condensation and coagulation of dust particles.
- When nuclear fusion begins in the central star and it becomes luminous enough, most of the remaining debris is cleared away (this process is seen in T Tauri stars).
Protoplanetary and debris disks around young stars

- Properties of the Solar System indicate that the solar nebula theory is the most plausible one.
- The solar nebula theory predicts that planets should form as a by-product of star formation.
- This means that protoplanetary disks should be common around other stars and so should be the planets.
- Observations show that ~50% of young, solar-mass stars have such disks and that some older stars have dusty debris disks around them that could hide planetary companions.
Planets around other stars

- First extrasolar planets, orbiting a neutron star, were found in 1992
- The first planet around a sun-like star was found in 1995 around 51 Pegasi
- This discovery was made by detecting Doppler shifts of lines in the stellar spectrum due to a wobble of the star around the center of mass caused by orbiting planets
- As of today, over 150 giant, Jupiter-mass planets have been found around other solar-type stars. About 5% of such stars appear to have gas giant planets around them. Unlike the Solar System planets, many of them have tight, elliptical orbits
- Current detection methods are not sensitive enough to detect Earth-like planets around other stars, but orbiting telescopes of new generation should be able to find them in the next 10-15 years
Basic properties of the Solar System

- Our planetary system consists of 8 planets, and many small bodies (comets, asteroids) left over from the time of its formation.
- Planets orbit the Sun close to a common plane. This plane roughly coincides with the equatorial plane of the Sun.
- Planets rotate counterclockwise around the Sun and they spin on their axes in the same direction, again in agreement with the solar rotation.
- These “clockwork” properties of the Solar System point to its origin in a rotating disk of matter that created the Sun.
Two kinds of planets

- Planets are clearly divided into two types: terrestrial (Earth-like) planets and Jovian planets (gas giants)
- Terrestrial planets, Mercury, Venus, Earth and Mars, lie in the inner Solar System, are small, rocky and dense, and have less dense atmospheres than the Jovian planets
- Jovian planets, Jupiter, Saturn, Uranus and Neptune, lie in the outer Solar System, are large, gaseous and low-density objects
- Pluto does not fit either of these two categories
Earth-like planets?

- The term “Earth-like” should not be taken too literally. It is only valid in terms of global properties of the terrestrial planets.
- Mercury resembles the Moon with its heavily cratered surface and has practically no atmosphere. Cratering is very typical in the Solar System.
- Venus is hot and has very dense atmosphere. Atmospheric clouds hide the surface of the planet from optical observers.
The two planetary families compared - I

- Venus can be viewed with the “radar eyes”, which reveal a rocky, volcanic, cratered, and entirely inhospitable terrain
- Mars, on the other hand, has a thin, transparent atmosphere and again, it is marked by volcanoes and impact craters
- The terrestrial planets are dense (3-5 g/cm$^3$) and have iron/nickel cores surrounded by rocky mantles
- The Jovian planets have low densities (average density < 1.75 g/cm$^3$), but their masses are large. For example, Jupiter is 318 times as massive as Earth
The two planetary families compared - II

- Interiors of Jupiter and Saturn are hot and metallic cores about 10 times the mass of Earth. Just above the cores, hydrogen is highly compressed and is believed to conduct electric current like metals → liquid metallic hydrogen

- Uranus and Neptune are not massive enough to form liquid hydrogen. They are believed to have metallic cores surrounded by oceans of water with deep, dense atmospheres on top of that.

- Jovian planets, in contrast with the terrestrial planets have rings and large systems of satellites.
Comets

Comet Hale-Bopp

- Comets appear as glowing heads with extensive tails, when approaching the Sun.
- The dirty snowball model postulates that cometary nuclei are balls of dirty ices (mostly water and carbon dioxide). The Sun’s radiation vaporizes the ices to produce a tail of gas and dust that is pushed away by the solar wind and light pressure.
- Comets come close to the Sun from the outer parts of the solar system and are icy leftovers from planet formation. This means that at least parts of the solar nebula were rich in ices.
Asteroids

• Asteroids are small, rocky bodies, most of which orbit the Sun at the average distance of ~2.8 A.U., between Mars and Jupiter.
• About 1000 out of some 20,000 identified asteroids have orbits that intersect with the orbits of inner planets, which sometimes leads to collisions
• About 200 asteroids are greater than 100 km in size
• Asteroids are believed to be remnants of a failed planet formation at the distance of ~2.8 A.U. from the Sun
Meteors, meteoroids and meteorites

The Leonids meteor shower

- **Meteors** are small chunks of rock and metal (typically not heavier than ~ 1 g) that fall into the Earth’s atmosphere and get vaporized by friction at ~80 km altitude. Meteoritic dust adds about 40,000 tons/year to Earth’s mass.

- When in space, these objects are called **meteoroids**. Meteors that are big enough to reach Earth’s surface are called **meteorites**.

- Meteorites are important in our studies of early history and age of the solar system.
Age and general properties of the Solar System

- The age of the Solar System can be estimated from radioactive dating of rocks (from Earth, the Moon, Mars and meteorites).
- The initial chemical composition of rocks changes over time, because radioactive elements contained in them decay into other (daughter) elements. For example, $^{238}\text{U}$ (uranium) decays into $^{206}\text{Pb}$ (lead) with half-life of 4.5 billion years.
- **Oldest Earth rocks**: 3.9 billion years old, **Moon rocks and Mars meteorites**: 4.5 billion years, **Solar System meteorites**: 4.6 billion years. **All Solar System bodies formed ~4.6 billion years ago**.

<table>
<thead>
<tr>
<th>Characteristic Properties of the Solar System</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Disk shape of the solar system</td>
</tr>
<tr>
<td>Orbits in nearly the same plane</td>
</tr>
<tr>
<td>Common direction of rotation and revolution</td>
</tr>
<tr>
<td>2. Two planetary types</td>
</tr>
<tr>
<td>Terrestrial—inner planets; high density</td>
</tr>
<tr>
<td>Jovian—outer planets; low density</td>
</tr>
<tr>
<td>3. Planetary ring systems for Jupiter, Saturn,</td>
</tr>
<tr>
<td>Uranus, and Neptune</td>
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<tr>
<td>4. Space debris—asteroids, comets, and meteors</td>
</tr>
<tr>
<td>Composition</td>
</tr>
<tr>
<td>Orbits</td>
</tr>
<tr>
<td>5. Common ages of about 4.6 billion years for</td>
</tr>
<tr>
<td>Earth, the moon, meteorites, and the sun</td>
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The Solar System formation: condensation of solids

- Chemical composition of the Sun reflects the composition of the solar nebula: mostly H with some He and traces of heavier elements.
- Differences in planet composition reflect the two different processes that have formed them.
- Jovian planets first formed cores of rock and ice by aggregation. When cores became massive enough (~10 Earth masses) they continued growing by gravitationally capturing H and He from the solar nebula.
- The terrestrial planets never grew massive enough to develop H/He envelopes → they are made of heavier elements.
- Planet densities and the condensation sequence tell us that the inner planets (high temperature) formed from high density metals and metal oxides, while the outer planets (low temperature) formed from low density ices.

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### 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>5.4</td>
</tr>
<tr>
<td>Venus</td>
<td>5.24</td>
<td>4.2</td>
</tr>
<tr>
<td>Earth</td>
<td>5.52</td>
<td>4.2</td>
</tr>
<tr>
<td>Mars</td>
<td>3.93</td>
<td>3.3</td>
</tr>
<tr>
<td>(Moon)</td>
<td>3.36</td>
<td>3.35</td>
</tr>
</tbody>
</table>

### The Condensation Sequence

<table>
<thead>
<tr>
<th>TEMP (K)</th>
<th>CONDENSATE</th>
<th>PLANET (EST TEMP 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></td>
<td></td>
<td>Mars (450)</td>
</tr>
<tr>
<td>175</td>
<td>H₂O ice</td>
<td>Jovian (175)</td>
</tr>
<tr>
<td>150</td>
<td>Ammonia-water ice</td>
<td>Plutonian (65)</td>
</tr>
<tr>
<td>120</td>
<td>Methane-water ice</td>
<td></td>
</tr>
<tr>
<td>65</td>
<td>Argon-neon ice</td>
<td></td>
</tr>
</tbody>
</table>
Planetesimals and protoplanets

- Small dust particles in the solar protoplanetary disk grew through **condensation**, by adding single atoms.
- As grains grew larger, **accretion** became more effective (sticking, attraction by static electricity).
- These processes have gradually produced **planetesimals**, which were objects ~1 km in size.
- Planetesimals massive enough to concentrate in the plane of the future Solar System. This helped to grow them even larger, by collisions and sticking, to the stage of **protoplanets**.
- Internal heat helped planetary cores to **differentiate** (heavier elements sunk down) and to create atmospheres by **outgassing** of interior matter. This is why the inner planets do not have original H/He atmospheres that they could not keep, because of heat and low gravity.
- The Jovian planets formed in about 10 million years, before the nebular gas was blown away by the Sun. The inner planets formed in < 100 million years.
The mature Solar System

- Characteristics of the Solar System support the solar nebula hypothesis
- The two types of planets can be understood with the condensation sequence caused by different conditions in the inner and the outer parts of the nebula
- The Solar System is different from the other planetary systems found so far: they frequently have Jovian planets close to parent stars (after migration caused by interaction with the nebular gas), and planetary orbits are significantly elliptical in most of them
- Jupiter prevented a planet from forming between it and the orbit of Mars
- After the planets formed, the system was almost cleared from gas and debris by radiation pressure, solar wind, sweep up of debris by planets (most craters were formed ~4 billion years ago → era of heavy bombardment), and gravitational ejection of material from the system