2. Formation and characteristics of the solar system

2.1. Outline of the solar system

There are 8 planets in our solar system (here listed by increasing distance from the Sun): ***Mercury***, ***Venus***, ***Earth***, ***Mars***, ***Jupiter***, ***Saturn***, ***Uranus***, and ***Neptune***. These planets can be divided into the ***inner planets*** or terrestrial (rocky) planets (Mercury, Venus, Earth, and Mars) and the ***outer planets***, also called the ***giant planets*** (Jupiter, Saturn, Uranus, and Neptune). Jupiter and Saturn are the ***gas giants*** (mainly composed of H, He) whereas Uranus and Neptune are often referred to as the ***ice giants*** (enriched in O, C, N). The inner and outer planets are separated by the ***Asteroid Belt***: a zone comprised between the orbits of Mars and Jupiter and composed of a large number of asteroids. ***Asteroids*** are irregularly shaped bodies with diameters of several hundreds of km or less. ***Pluto***, once considered a planet, is now officially identified as a ***dwarf planet***. The term "dwarf planet" was ascribed to several small planetary bodies discovered recently in the ***Kuiper Belt***, a zone of the solar system located beyond the orbit of Neptune. The definition of a dwarf planet is based on the following criteria:

- It orbits the Sun.
- It is not a satellite.
- Its shape is rounded.
- Unlike "true" planets, its gravitational field is too weak to have cleared its orbit, and objects of comparable size can share the same orbital path.

The Kuiper Belt is also characterized by thousands of smaller objects composed in large part of frozen volatiles (ices) and is thought to be an important reservoir of comets. Another dwarf planet is ***Ceres***, the largest object (950 km in diameter) and the only dwarf planet of the Asteroid Belt. Objects in orbit around planets or asteroids are called planetary ***satellites***, or ***moons*** (note that our Moon is written with a capital "M" to distinguish it from the moons of other planets).

2.2. Birth of the solar system: the Nebular Hypothesis

There are several important observations that should be explained by any model attempting to describe how our solar system formed:

1. The planets are all moving in the same direction (counterclockwise[*]) around the Sun.
2. The Sun is also rotating in a counterclockwise direction.
3. The orbits of the planets are nearly circular and lie very close to the same narrow plane which coincides with the Sun's equator.
4. Satellites in orbit around planets are revolving in the same counterclockwise direction[**].
5. The Inner planets are smaller, denser and mostly rocky; the outer planets are larger and mostly made of volatiles (gas, liquid or solid ice, depending on pressure and temperature conditions).

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[*] as seen from above (way above) the Earth's north pole (or the Sun's north pole).

[**] with the exception of Triton, one of Neptune's moons

Among several hypotheses, the most widely accepted nowadays is the ***Nebular Hypothesis***, proposed for the first time by the German philosopher Immanuel Kant (1724-1804). This hypothesis suggests that the solar system formed out of a rotating cloud of dust and gas (or ***nebula***) contracting under its own gravity.

Nebulae are composed of gas, primarily hydrogen (H_2) and helium (He), and solid particles (dust), such as silicates, one of the most common family of minerals on Earth, and ice particles (e.g. CO, CO_2, H_2O). The density of nebulae is not uniform. Some regions are denser than others. Some regions may become dense enough to attract surrounding particles by gravity and these regions begin to contract. As more matter is pulled toward the center, density increases and temperature rises. There are two important consequences of the contraction of a nebula:

1. ***As the cloud contracts, it spins faster***. This is explained by the law of conservation of angular momentum (see slides for explanations). Ice skaters use the same law when they wrap their arms around their body to spin faster.
2. ***As the cloud rotates faster, it flattens into a disk***. This is a consequence of the centrifugal force (inertia) which prevents the equatorial region of the rotating cloud from collapsing. The linear speed of particles in the equatorial plane being maximum and decreasing steadily toward the poles, the centrifugal force in this plane is also maximum and opposes the gravitational inward pull. At the poles, however, the linear speed is zero and particles fall "freely" toward the center of the cloud under the influence of gravity. To picture the effect of inertia on a spinning object, think about a spinning ball of pizza dough!

2.2.1. Formation of the Sun

The contracting nebula evolves into a fast-rotating, flattened disk, the center of which is occupied by a dense and bright star in formation. The temperature inside the proto-star is so high that elements exist in the form of atoms stripped of their electrons (plasma). When the temperature at the center of the disk reaches 12,000,000 ºC, the hydrogen nuclei (protons) overcome electrostatic repulsion and begin to fuse. This is the beginning of ***nuclear fusion***, a chain reaction producing a great amount of energy and responsible for our Sun's heat. The start of nuclear fusion marks the birth of a new star.

2.2.2. Formation of the planets

The region of the disk surrounding the proto-star is rich in dust and gas. Dust particles collide and begin to aggregate into larger chunks of matter. Large chunks of matter attract each other by gravity and form larger bodies called ***planetesimals*** (>1 km in diameter). These planetesimals attract each other and smaller objects crossing their path, ultimately forming planets. Since lighter, more volatile elements are blown away by the solar wind (stream of charged particles) and the heat produced by the proto-star, the planets forming in the outer region of the solar system are enriched in gas and ice. They are the outer planets, also referred to as the giant planets (Jupiter,

Saturn, Uranus, and Neptune). Conversely, the planets forming in the inner region of the solar system are composed mostly of rock consisting of refractory (resistant to heat) components (e.g. silicate minerals and metals). These planets are the inner planets, also called terrestrial or rocky planets (Mercury, Venus, Earth, and Mars). The distance from the proto-star where the temperature is low enough for volatiles (e.g., H_2O, CH_4, NH_3) to condense into solid ice is called the ***ice line*** (or frost line). Asteroids are the left-over of planetary formation, chunks of matter not incorporated into the planets or their satellites, or fragments of proto-planets formed during collisions in the proto-planetary disk. Rocky asteroids are concentrated in the Asteroid Belt whereas most icy objects are confined to the outskirt of the solar system, i.e. the Kuiper Belt.[*]
Since asteroids and comets are composed of the original raw material of the solar system which has not been modified by the process of planetary formation, they represent a tremendous source of information concerning the initial conditions of the solar system at the time of its birth. That is why so much effort has been put into the exploration of these objects (see slides). Conveniently for scientists, asteroids sometimes cross the Earth's path and the fragments fallen on Earth's surface (***meteorites***) can be collected for analyses. Since these meteorites are pristine material originating from the dawn of the solar system, they are used to date the age of the solar system and the planets. On Earth, plate tectonics has destroyed most of the oldest rocks. This is why we cannot determine the exact age of the Earth based on terrestrial rock samples (see next chapter for an explanation of the theory of plate tectonics). The current accepted age of the Earth (and the solar system) is ***4.56 billion years*** based on meteorites (see chapter "the age of rocks" for more information about the radiometric dating technique).

2.3. Formation of Earth's layers and Earth's atmosphere

2.3.1. Earth's internal structure

The Earth is thought to have been in a molten state at the beginning of its history. The primary sources of heat were:

1. The impacts of meteorites and large planetesimals (conversion of kinetic energy into heat)
2. Radioactive decay (still a direct source of heat today)
3. Gravitational contraction (conversion of gravitational potential energy into heat)

The molten state of the Earth meant that matter could move around and redistribute according to its density. Heavier components sank toward the center of the Earth whereas lighter components remained closer to the surface. This process is called ***gravitational differentiation*** and is responsible for the formation of Earth's layers:

- The dense ***core*** has a diameter of 3,500 km and is mainly composed of iron and nickel. It is divided into an ***inner core*** (solid) and an ***outer core*** (liquid).

[*] Astronomers think that there may be another more distant belt of icy objects far beyond the Kuiper Belt called the ***Oort Cloud*** which could also be a potential source of comets.

- The ***mantle*** is 2,850 km thick and its density is intermediate relative to the core and the crust. It is composed of silicates enriched in Fe and Mg. This layer is characterized by convection movements (hot matter rising, cold matter sinking) (see chapter on Plate Tectonics).
- The outermost layer is the ***crust*** which is thinner beneath the oceans (7 km) and thicker beneath continents (40 km). The former is called the ***oceanic crust*** and is denser, (silicates rich in Fe and Mg). The latter is called the ***continental crust*** and is lighter (quartz —SiO_2— and silicates rich in Al, K and Na).

2.3.2. Earth's atmosphere

One can think about two main possible sources for the gases (including water vapor) which accumulated around the earth to form the atmosphere: (1) volcanic eruptions releasing gasses trapped in the Earth's interior and (2) extraterrestrial input of volatiles from objects impacting the Earth (especially comets).
Most importantly, the primitive atmosphere did not contain free oxygen (O_2). Its composition was different from today. Oxygen was produced later, a probable source being ***photosynthesis*** (see chapter on the origin and evolution of life). Moreover, temperature was initially too high for water to be present at the liquid state. Only when surface temperature dropped below 100 ºC did water vapor present in the atmosphere condense in a liquid state. We know that between 3.7 and 3.8 billion years ago, a permanent ocean was present at the surface of Earth. Liquid water could probably be found earlier but the frequency of large meteorite impacts may have vaporized part or all of it repeatedly (see section 2.5.1).

2.4. The Moon

2.4.1. The formation of the Moon

Several theories exist regarding the formation of the Moon but the most widely accepted explanation is the ***Giant Impact Hypothesis***. Several observations must be accounted for to explain how the Moon formed:
1. Earth is the only inner planet of the solar system with a large moon.
2. The orbital plane of the Moon does not coincide with the orbital plane of the Earth around the Sun or with the Earth's equatorial plane.
3. The Moon has a remarkably small iron core compared to the inner planets.
4. The Moon is much less dense (3.3 g/cm^3) than the Earth (5.5 g/cm^3). The Moon's density is close to that of the Earth's mantle.
5. There are very little light, volatile elements (including water) on the Moon.

These observations indicate that the Moon may not have formed out of the same raw material which produced the Earth. The giant impact hypothesis suggests that a large planetesimal collided with Earth during the very early stage of solar system formation and that the Moon formed out of

the material ejected during the impact. The impact would have vaporized all the lighter, more volatile elements, explaining their rarity on the Moon. The material ejected during the impact may have come primarily from Earth's crust and mantle, explaining the low density of the Moon and the relatively small size of its iron-rich core. If the Moon is the product of an impact between Earth and another small planet, then one might expect to find the chemical signature of the impactor in the composition of Moon rocks. However, studies have shown that rocks from Earth and from the Moon have similar chemical compositions. If the Giant Impact Hypothesis is true, this implies that the small planet which collided with the Earth must have had a composition very similar to that of the Earth, perhaps because the impactor was formed in the same region of the nebula.
In addition to the formation of the Moon, the Giant Impact Hypothesis may also explain that the rotation axis of the Earth has a 23.5º tilt with respect to its orbital plane.

2.4.2. Characteristics of the Moon

The Moon is riddled with crater. Two types of surface can be identified:

1. Lowlands (maria, singular: mare, Latin word for "sea"): surface with few craters consisting of basalt (rock formed by solidification of magma) that has filled larger craters.
2. Highlands: surface with many craters.

In planetary science, a very useful technique to determine the relative age of planetary surfaces is ***crater counting***. In brief: the more crater, the older the surface. Hence, the surfaces called lowlands are younger than the surfaces called highlands. Scientists have been able to determine the age of these surfaces by dating rocks collected on the Moon and brought back to Earth by the US Apollo missions and the Soviet Union Luna missions. The age of the highlands falls between 4.5 and 4 billion years (4.5-4 Ga) and that of the lowlands ranges from 4 to 3.2 billion years (4-3.2 Ga). The number of impacts was highest during the earliest stage of the history of the solar system and then progressively declined. This is called the ***Heavy Bombardment***. A second event, called the Late Heavy Bombardment, may have occurred at 3.9 Ga another but its existence is controversial and not unanimously accepted.

2.5. Characteristics of the inner planets

The inner planets of the solar system must have originated from a similar raw material in the region surrounding the proto-Sun. Yet the inner planets differ greatly in many aspects: size, interior dynamics, atmospheric composition, and landscape (see slide with comparative table).

2.5.1. Mercury

Mercury is the planet closest to the Sun. It has almost no atmosphere and its surface is very old. The planet is therefore riddled by meteoritic craters like the Moon. Except for the occasional meteorite impacts, Mercury is geologically very quiet. The surface is characterized by numerous escarpments which are thought to be faults formed shortly after the planet's formation when the crust contracted as it cooled. It has been recently suggested that Mercury is still contracting and faults are forming today. Surface temperature varies greatly depending on the exposure to sunlight.

2.5.2. Venus

Venus is characterized by an extremely dense atmosphere composed of 96% of CO_2, the 4% left being primarily Nitrogen, and other gasses including water vapor and sulfuric acid. Due to its thick atmosphere, 80% of the incoming solar radiation is reflected back to space. However, the greenhouse effect resulting from the extremely high concentration of CO_2 is so intense that the surface temperature is maintained at a staggering 460 ºC (enough to melt lead!). Venus has been (and probably still is) geologically active and its surface is littered with volcanoes. The tectonics of Venus is very different from that of the Earth (described in next chapter). One hypothesis is that intense convection movements in the Planet's interior generate many cracks at the surface breaking up the thin crust into flakes (hence the term "flake tectonics" that has been used to describe the tectonic activity on Venus). Unlike Earth, there are no large plates and no subduction zones. The surface of Venus is mostly composed of fractured plains and volcanoes. Due to volcanic activity, crust deformation, and shielding effect of the dense atmosphere, there are relatively few meteoritic craters.

2.5.3. Mars

Why is Mars red?

Mars is red because of the widespread presence of iron oxide (Fe_2O_3) and iron hydroxide ($FeO(OH)$) dust (rust) on its surface. These minerals form on Earth mainly by oxidation of iron-bearing silicates (e.g. $(Fe, Mg)_2SiO_4$). There is very little free oxygen (O_2) on Mars and the reaction of oxidation is very slow. However, there is evidence indicating that free oxygen may have been more abundant in the distant past of the planet. But why is iron oxide much more common on the surface of Mars than on the surface of Earth? One hypothesis suggests that the temperature of the Earth at the beginning of its formation was higher than that of Mars and that more iron-bearing compounds were melted and therefore more elemental iron migrated toward Earth's core. On Mars the melting of iron-bearing compounds may not have been as complete due to the overall lower temperature, and consequently more iron oxide remained in the planet's outer layer. This may also explain why Mars has a relatively tiny metallic core.

Note: the reddish dust covering most of Mars surface is sometimes blown in the air by strong winds on a global scale during dramatic planet-wide dust storms!

Mars topography

From a topographic viewpoint, there is a striking difference between the northern and southern hemisphere. The northern hemisphere is characterized by lower elevations with few craters (smoother surface) whereas the southern hemisphere is characterized by higher elevations with many craters (rougher surface). One hypothesis involves a catastrophic impact with a large object the size of a small planet which would have completely altered the topography of the northern hemisphere.

Mars topography is also characterized by extremes in elevation. The tallest mountain is 25 km high (Olympus Mons, a large shield volcano). The deepest canyon is 8 km deep (Valles Marineris).

Water on Mars

The current conditions of temperature and atmospheric pressure on Mars are not favorable for the presence of liquid water on the planet's surface. Water is present as vapor in the atmosphere but exists primarily as ice:

- Polar ice caps
- Subsurface ice (or ground ice) directly beneath the Martian soil
- Ephemeral frost depositing on the Martian soil in winter

Note 1: the Martian polar ice is composed of both water ice and "dry ice" (CO_2 ice). Dry ice sublimates in summer (seasonal ice) which causes large variations in atmospheric pressure.

Note 2: Satellite imagery has also revealed the presence of ancient glaciers at relatively low latitudes beneath a layer of Martian dust protecting them from sublimation. The presence of ice so far from the poles may indicate that the planet experienced ice ages characterized by ice caps larger than today (similar to Earth's glaciations).

There is undeniable evidence of liquid water flowing on the surface of Mars in the past. Three supporting lines of evidence exist:

1. Satellites orbiting Mars have captured images of ***landforms*** clearly related to the presence of running liquid water, such as meandering channels and fan deltas.
2. The rover Curiosity revealed the presence of layers of ***sedimentary rocks*** composed of rounded gravels analogue to those found in river beds on Earth. There are also ***sedimentary structures*** (laminations, bedding, cross-stratified layers) indicating the presence of sediments deposited under water.
3. Specific ***minerals*** thought to have formed in contact with liquid water have also been reported, such as clay minerals or spherules composed of hematite (Fe_3O_4).

Liquid water cannot exist today at the surface of Mars (although seasonal seeps of brines have been suggested to exist) but it is possible that water occurs beneath ground surface where temperature is higher due to the Planet's internal heat. If life exists on Mars, reservoirs of groundwater beneath the planet's surface may well be the place to find it!