VI. The Earth and the Planets

1. Magnetospheres

A) The Earth’s Magnetosphere

a) Plasma and magnetic trapping

In the near Earth environment, i.e. in the Earth's magnetosphere, we find particles from the sun, which have been identified as H⁺ (hydrogen ions that have lost their electron) and He²⁺ (Helium that has lost its 2 electrons). We will see, when talking about the sun, that the sun blows radially outward into all directions a solar wind mainly consisting of these ions. There are also ions found from our atmosphere:

- O⁺ (oxygen atoms that lost one electron)
- N⁺ (nitrogen that lost one electron)

The Earth’s magnetosphere is a region that is formed by the Earth’s magnetic field. The magnetic field on one hand keeps electrically charged particles (ions and electrons) locked in for some time. On the other hand ions and electrons from outside, i.e. the solar wind that flowing by the Earth, only make it in at certain locations. For the solar wind the magnetosphere acts like a “rock in a river”, it deflects most of the solar wind flow.

Why do these ions get trapped for some time in the magnetosphere and why is it so hard for them to get in the first place?

As I pointed out, the magnetosphere is formed by the Earth’s magnetic field. The Earth is a magnet. (magnetic compass)

What is trapped in the magnetic field or has a hard time to get in, is a plasma:

**Plasma:** Gas with free electrons and ions

**It conducts electricity.** (Like the plasma in the discharge lamps.)

99% of the universe is plasma

This is one of the reasons why we study plasmas in the solar system!

An electric current, which consists of moving charges (electrons and/or ions), can produce a magnetic field which influences other magnets. There is a magnetic force produced a current, or moving charges, that influences another magnet. According to Newton’s 3rd Law a magnet also exerts a force on moving charges. Therefore, charged particles are forced to spiral on earth's magnetic lines.

When the ions or electrons reach a stronger magnetic field they are reflected back towards the weaker field. Everything which is electrically conductive can be trapped in a magnetic field or when outside cannot easily move into a magnetic field!
Reasons:
Charged particles can only spiral along magnetic field lines and are reflected by stronger magnetic fields. Solar wind can make it in only at locations where the field is open, i.e. at the poles. Therefore, the magnetic field of the Earth creates a cavity in the solar wind, the "Magnetosphere". It contains the Earth's magnetism and plasma from Earth with some plasma from the solar wind.

b) Van Allen Radiation Belts
The best trapping of particles is seen in the Radiation Belts of the Earth, which were observed during the first space flights as regions with a tremendous radiation. This caused even doubt that astronauts would be able to cross this region without health risks due to radioactivity.

c) Geomagnetic Tail
Blowing against the magnetic field the solar wind produces a "geomagnetic tail" which points away from sun.

The bottle made up by the Earth's magnetic field is not perfect: plasma makes it in and out through this region.

In addition, the solar wind changes, squeezes and rattles the bottle. In particular, in the long tail magnetic field lines with opposite direction are pressed against each other.

Eventually, these field lines find it more convenient to connect in a different way. This phenomenon is called re-connection of field lines. But now they look like rubber bands, which have been tremendously stretched. What happens, if you let them lose?

This is a demonstration for one kind of particle acceleration observed in space. Now energetic particles run down along magnetic field lines. They join energetic particles that come in from the sun. All of these particles may hit the atmosphere:

d) The Aurora
In the atmosphere the energetic particles hit the oxygen and nitrogen atoms and make them emit light. (We will talk about this process a little later anyway). This is a similar effect like in the TV screen: energetic electrons hit the TV screen from behind and light is created.

What we see is an aurora or polar light. It can be seen where energetic particles (mostly electrons) come down along the field lines (close to the polar regions) the so-called auroral oval around the magnetic poles.

These ovals can be seen from above in the UV light. There are auroral ovals over the N & S hemispheres. The aurora is not likely direct overhead at the north and south geographic poles. They are found at a
distance around the magnetic poles, where the magnetic field lines reach to the edge of the magnetosphere.

B. Magnetospheres of Other Planets
All planets with a magnetic field also have magnetospheres like the Earth: Mercury, Jupiter, Saturn, Uranus and Neptune. Jupiter's magnetosphere is the largest "object" in solar system because of the very strong field of Jupiter. For example, strong auroral displays have been observed on Jupiter.

2. Planetary Magnetic Fields

A) Earth's Magnetism.
After we have talked about effects caused by the Earth's magnetic field let us now move to how the Earth produces its magnetic field. There are two basic possibilities for the generation of such a field:

1) permanent magnet:
2) electric current through a coil

We will see that magnetism can give valuable information about the planets' interiors.

A permanent magnet inside the Earth is impossible, since above about 1000 °C magnetism is destroyed. Already from drilling into the surface of the Earth we know that the interior of the Earth is very hot. The temperature rises rapidly with the depth, and we know that molten rock material comes out of the interior through volcanoes.

Therefore let us explore the second possibility. For this to work we need:

- an electrically conducting substance
- and motion (to produce an electric current)

in the Earth's interior. Then the magnetic field may change from time to time when the motion is changing, but it will be there as long as there is motion. Indeed the interior of the Earth is molten because it is so hot. So the material can move around.

B) The Earth's Interior
How can we be so bold and be so sure? Let us first get a crude picture of the Earth's interior.

The Earth consists of 3 Layers:

- Crust <100 km consists of the rocks that we know
- Mantle < 2900 km somewhat heavier material, the crust floats on it
- Core rest very heavy material, mainly iron and nickel

a) Density
The first tool to learn about the interior is the measurement of the Earth's density. We know the mass of the Earth and its size. Thus we can deduce the density. The Earth's density is twice as high as the typical density of rocks on the surface. Therefore, heavier material must be in the center. Iron would just do that. From observations we actually know only in detail the composition of 2/1000 (12 km) of the Earth (the outermost crust) from drilling. In a comparison where the Earth would be represented by an orange this is not more than just the paper wrapping around an orange. So how do we know more about the Earth's interior?
b) Seismic waves
In order to probe deeper we have to resort to other techniques. During earthquakes, waves from this disturbance travel through the Earth, and we can use them like X-Rays for the interior of our bodies.

An earthquake produces 2 types of waves:

- **compressional** (P, pressure) waves (like sound)  
  The air gets thicker and thinner in these waves like the spirals of "Slinky" get denser and less dense.
- **shear** (S, shear) waves (like waves on string).
  Slinky can produce both types of waves. Solid Earth behaves like Slinky: Both types of waves go through solid matter, but only P waves go through liquids.

**P waves** go through **solid and liquid** (you can hear underwater), and gas, of course!!

**S waves** go through **solid only**!

From the arrival pattern of these waves at seismic stations all over the Earth we deduce that the Earth has a liquid core and what its dimensions are:

c) Radioactivity
The hot interior of the inner planets is maintained by radioactive decay (Not from tidal flexing as on Jupiter's moon Io). Be reminded: Used fuel rod material from nuclear power plants has to be carefully cooled so that it cannot overheat! There is enough radioactive material inside the Earth's core to keep it hot. Thus the first condition for the Earth's magnetism is met.

d) Convection
As explained above the Earth is so hot in the center that the material is liquid. With the greatest heat in the center, the Earth produces **convection**. Hot material wants to travel upwards and cool material downwards, similar to boiling water in a pot. This is one source of the motion that is needed to generate magnetism. Together with the **rotation** of the Earth this becomes a very orderly pattern (while the motion in a cooking pot is not very organized). In a way the convection together with the Earth's rotating motion drives the current that makes the Earth's magnetic field. In fact the rotation must be fast enough to keep the current going.
C) Magnetism on Other Planets
As we just have learned, the necessary conditions for Earth to produce magnetism are:
- molten core
- rapid rotation.

Now we can compare Earth with other planets and see whether they also can have magnetism.

a) Inner planets

**Venus:** from the volcanic activity we conclude that it has a molten iron core (*evidence:* dense; active volcanoes), but it shows only very slow rotation (with a period of 240 days).

What about magnetism on Venus?
We have learned that the Earth's interior with its hot molten iron core together with the Earth's rotation provides the conditions for the production of the Earth's magnetic field.

On this table we will compile the information on the magnetism of all inner planets: We need
- a molten iron core
- rotation of the planet at a sufficient rate

However, Venus rotates only once every 243 days.

Thus **no magnetism on Venus.**

Indeed spacecraft have measured that there is no significant magnetic field on Venus.

### Planetary Magnetic Fields

<table>
<thead>
<tr>
<th></th>
<th>Earth</th>
<th>Venus</th>
<th>Mercury</th>
<th>Mars</th>
<th>Moon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic Field</td>
<td>Yes</td>
<td>No</td>
<td>Weak (Riddle)</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Liquid Iron Core</td>
<td>Yes</td>
<td>Yes</td>
<td>Iron but solid</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Rotation</td>
<td>24 hours</td>
<td>240 days</td>
<td>58 days</td>
<td>24.5 hours</td>
<td>28 days</td>
</tr>
</tbody>
</table>

**View VI.4**

**Mars:** has no magnetism in spite of fast rotation like the Earth.

Mars has no liquid iron core. *Evidence:* Mars has a low density, a lot of iron is in the surface, and it has no active volcanoes, only dead volcanoes.

**Mercury:** has a very weak magnetism

Mercury has an iron core (*Evidence:* dense), but it may not be molten (*Evidence:* no heat flow from interior). Mercury has a very slow rotation (∼59 days), but yet there is weak magnetism -- This is still a riddle.
b) Outer planets
When we move further out to the outer planets we find completely different bodies.

The next planets (Jupiter, Saturn, Uranus and Neptune) are much larger and contain much more mass than all of the inner planets together. They are giant planets. Let us start with Jupiter.

All what we see is the cloud cover. This sounds like Venus, but is still quite different. The density of Jupiter is 1.3 times that of water, as compared to a density of 5.5 for the Earth. This means Jupiter basically consists of lightweight stuff, i.e., 75% hydrogen, 23% helium, and only the rest heavier elements (pretty much like the sun, as we will see soon). In contrast, the inner planets have very little H and He. Jupiter’s composition is more or less the same as that for all giant planets.

When going deeper into the atmosphere of Jupiter, one would gradually go from a gas into liquid with the rising pressure of all the stuff above.

At a depth of 15,000 km the H atoms don’t withstand the rising pressure and temperature any more, and the electrons can move around freely. Hydrogen behaves like a metal. The interior of Jupiter is liquid metallic hydrogen. It is also hot. Together with the rapid rotation of Jupiter there should be a magnetic field. And sure enough, Jupiter has a huge magnetic field and a huge magnetosphere.

Saturn has a similar surface appearance, a similar interior and rotation rate. It also has a huge magnetic field.
Uranus has a similar appearance to all other planets. During the Voyager flyby the sun illuminated the northern hemisphere. Voyager found a strong magnetic field, but with its axis almost perpendicular to the rotation axis. This caused some confusion.

Neptune has also the gaseous and banded surface appearance of the other giant planets. Its axis is normal again, but the magnetic field is strongly tilted. Both planets, Uranus and Neptune, are much smaller than Jupiter and Saturn. They don't have metallic hydrogen.

Electric currents in the salt-water layers are thought to produce the magnetic fields. In both cases the magnetic fields are very unusual, the magnetic axis is not close to the rotation axis, and the magnetic field is not centered with the center of the planet. The magnetic axis shows a large tilt vs. the rotation axis. The details of these strange magnetic fields, which have only been found recently by Voyager, are still a riddle for scientists.

After studying the interior of the planets let us now move to the surface. Part of the surface structures will be controlled by what is going on in the interior. Partly it will be dictated by processes in the planets atmospheres and/or through water on the planets. Similarities and differences here will shape the planets.
3. Surface of Planets and Moons

Both from its interior forces and from the activity of water and the atmosphere the Earth is extremely active. Because of the atmospheric action, however, the Earth's early history has been erased. So we have to look at other planets, moons, asteroids, and comets to learn about the early solar system and how typical surface formations are. Therefore, we will immediately look around, how the other planets look like after we have talked briefly about the Earth.

A) Plate Tectonics

The Convection, which is caused by the hot interior of the Earth and leads to its magnetic field, has one other consequence in addition to magnetism, continental drift. Our continents are floating on the slowly moving material of the Earth's mantle.

The coast lines, or better the continental shelf lines fit like a jigsaw puzzle. The first to recognize this was Alfred Wegener around 1920, but he was not taken seriously by his fellow scientists. He brought together evidence from the same geological structures on both sides of the oceans and the same fossils. But only when finally in the 1960's the motion of the continents (2 - 4cm/year) could be measured with radar and new sea floor emerging from the interior in the center of the Atlantic ocean (mountain ridge in center of ocean) was observed, this model of the Earth's surface was adopted.

A consequence of the hot interior is volcanoes on the surface. On Earth most volcanoes are where the oceanic plates are pushed under the continental plates (ring of fire). This is a very violent volcanism where water meets fire. This is also where mountain chains are still being built up by the push of the plates.

Another category of volcanoes occurs over "hot spots". And here we can also observe directly the continental drift: Continental drift carries the Earth's surface across the hot spots, and thus the volcanoes don't have much time to grow. The results are chains of small volcanoes, with new ones emerging at the front end of the chain. (Example: Hawaii).

Comparison with other inner planets

Venus: Venus has active volcanoes (Evidence: we detect volcanic gases in Venus' atmosphere). We see the volcanic mountains in the relief of Venus, huge volcanic mountains. Venus has a similar topography as on Earth, except there are no drifting plates!! But how did we get this information? Venus has a thick cloud cover. And this is what we get the light from Venus from. These pictures have been made using a radar mapper. This is the latest survey of Venus' surface by the spacecraft Magellan.

In fact the survey of Venus' surface is more complete than any survey of the Earth. A lot of the Earth's surface is ocean.

But what is the difference between Earth and Venus? Venus has no Tectonic Plates, all crust material is very similar, no such variety as on Earth. This results in no Plate Tectonics. Straight forward evidence is: Volcanoes sit over hot spots. Therefore, huge volcanoes are formed. They don't move away and then stop firing like on Earth.

Mars: Mars has no continental drift either and thus produces no new virgin crust material!! We might have expected plates on Venus, since it has a molten core. But there is no
plate tectonics. Mars has no active core any more, but it had in the past: Olympus Mons is a huge volcano. The Earth is very special in this respect, it is the only planet, which constantly brings new material to the surface. This may have been crucial for its ability to produce the unique atmosphere and to host life. We don't know yet.

B) Volcanism in the Solar System

a) Earth-like volcanism

As we have just seen, Earth, Venus and Mars have or at least had volcanism. The driving force in these cases is radioactivity, which keeps material in the interior hot and molten. However, there are also other types of volcanism in the solar system.

b) Tidal Volcanism

Io shows volcanism as was observed by Voyager as a surprise. Io's volcanoes spit out sulfur, which covers the surface and is thrown into space. It produces a torus of sulfur around Jupiter, which was first observed by instruments on Voyager.

In Io's case the energy source is tidal flexing from the passage of the next moon Europa. The tides caused on Io by Europa are more than 100 m high. The crust of Io is strongly massaged by this effect. This leads to internal friction and thus heating. You can feel the effect of heating by friction, if you rub your hands very quickly. Ultimately this is an effect of gravitation.

We find similar effects on other moons with different materials: Europa has a smooth surface, and no craters. Its surface must be active to wipe out impact craters. Indeed it consists of a thick ice layer. And a water geyser as sign of volcanism has been found. Tidal flexing produces enough heat to turn water into steam. Water geysers were also found on Saturn's moon Enceladus along with snow and a bright surface.

Whereas volcanoes on Earth are produced from radioactive heating of the interior, the tidal heating of Io is sufficient to melt sulfur and produce volcanoes, likewise the tidal heating of Europa to produce geysers. Generally speaking, volcanic activity needs a heat source and material which is driven out of the surface. This material can be molten rocks (Earth), sulfur (Io) or water (Geysers on Earth). The heat source may be radioactivity (inner planets), tidal heating (Io, Europa, Enceladus), or solar heating, as we will see below.
c) Sun driven volcanoes
Yet another form of volcanism are ice geysers on Neptune's moon Triton. They are sun-driven liquid nitrogen volcanoes, liquid nitrogen evaporates due to solar heat and drives liquid nitrogen and ice out. Ultimately, we can also sub summarize the activity of comets close to the sun under volcanism.

When heated by the sun a comet throws out water and CO₂ etc. on very localized spots, as has been found by the Giotto probe when passing Halley's comet.

C) Craters on Moon and Mercury
If we look at our Moon and Mercury we find a structure very different from all these other bodies, but very similar for the two of them.

Mercury has many craters very much like the moon. Are these also volcanoes? The formations on Mercury and Moon are much different from volcanoes, very wide and no build-up of a mountain. There is no evidence of lava or other volcanic materials. The interior of the craters is deeper than the surrounding area contrary to volcanoes. We find some similar structures on Earth, many of which are well-hidden by other formations, and others, which are quite obvious, as in this case of the Baringer Crater in Arizona.

Obviously many such craters on Earth have been erased in the past. Otherwise craters would cover the Earth similar to the Moon and Mercury. On the moon and on Mercury there is no change by weather as on Earth since there is no atmosphere. And there is also no change by moving plates and other geological processes, such as huge sediments of carbonates produced by oceanic life forms. In contrast to Earth the fingerprint of the early history of the other planets is still visible. These objects seem to be in their original state.

a) Impact Craters
What is the reason for these craters, impacts or explosions?
Large explosions (from bombs) create craters. Similarly, falling objects can create craters.

The crater size depends on the energy of the object, not only on its size, i.e., on a combination of mass and speed. The creation of craters on the moon or on Mercury happened somewhat different than in the sand-box of our demonstration. The energy of the infalling object was so huge that part of the object's material and of the impact area evaporated so quickly that the gas erupted like an explosion.

b) Formation time
Most craters found throughout the solar system are the remains of the last objects to fall onto the planets or moons during their formation. The larger craters were formed first. This is obvious from many smaller craters on top of larger formations.

The most intense bombardment in the solar system occurred almost 3 billion years ago.

How do we know this? (evidence: dating lunar rocks). Because astronauts visited the Moon, we have material to study in the laboratory. Lunar material is the only material brought back from another object in space so far.

It has been extensively studied in laboratories.
c) Age of Surface Formations
To find the age of material the method of radioactive dating is used: We make use of 
**radioactive decay**. After the **half-life** of a radioactive material only one half is left, after 
another half-life only 1 half of the rest.

For example **Thorium** is changed through several steps into **Lead with a half-life of 1.4
$10^{10}$ years (14 Billion years)**. I.e., from the original amount of Thorium after 1.4 $10^{10}$
years half of the Thorium will be transformed into lead, or now the ratio of lead to thorium
would be 1:1. Since the lead, which stems from the decay of Thorium, is a different isotope
from the ordinary lead that is found in other formations, we even know how much Thorium
was there originally. The ratio of lead/thorium in the rock can be measured, and the age is
derived.

In this way also the age of the moon itself could be determined from rocks sampled by
Apollo astronauts. The oldest rocks found are $\approx 4.5$ billion years old, which is similar to the
age of oldest rocks on the Earth.

D). Formation of the Moon
Jupiter and Saturn have moon systems, which look like little planetary systems and thus
have been formed in the same way as our solar system. We will talk about this later in
connection with the stars. The moon of the Earth is special, because compared with the
size of the planet it is the largest moon in the solar system. Therefore, its formation requires
a separate treatment.

1) The moon may have been formed together with the Earth, but why such an uneven
twin system? And: the density of the moon is much lower than that of the Earth, more like
the Earth's mantle.

2) The moon may have been captured by the Earth, but this is very hard to achieve. If 2
bodies come close to each other they will almost certainly pass each other.

3) The moon may have formed from **impact of Mars-sized object** on Earth.

Evidence: Moon's composition similar to Earth's mantle and has no iron core. It could
have emerged out of the outer part of the Earth. The Moon contains **few** volatiles (gases,
water etc.) which could be evidence for heating during the impact? This big impact may
also explain the many impacts later on the moon, which formed the craters.

There may have been more early moons not just one. They may have collided with
each other and formed debris. Later the debris collided with the Moon and formed the
Moon's craters (?).
4. Planetary Atmospheres

In this respect our home planet indeed seems to be very unique:

- the unique atmosphere
- the water on Earth

The first remarkable speciality of our Earth is its atmosphere. Mercury and the moon don't have any atmosphere, as we can see from the very clear pictures we get from both. There is nothing to block the radiation. Mars has only a very thin atmosphere, which was noticed from dust storms going on quite frequently. Venus has a thick atmosphere, which doesn't allow us to look through. Why do some planets have atmospheres and others not?

A) Existence of Atmospheres

This has to do with the fact that objects with high enough speeds will leave a planet. They will escape the force of gravity. We have talked about this for the Earth when we introduced gravity: if the speed of an object is high enough it will start to orbit the Earth like our satellites. If we increase the speed even further a spacecraft will leave the Earth completely, like the space probes to moon and the planets. The same can happen to gases. All you need to know is what heat in gases means: If you feel hot air, it means that the gas molecules hit your skin with a higher speed, or you may also say with higher energy.

**high temperature <-> high average (energy) speed of the molecules**

At room temperature (≈ 20° C, or 68 F) oxygen and nitrogen have an **average speed of ≈ 500 m/sec**. We can view the gases as a swarm of bees buzzing around with this speed.

You notice I have used centigrade, which is basically used throughout the book. This scale for temperature is defined by:

- 0° C melting of ice
- 100° C boiling of water

The gas molecules are much too slow to escape the Earth's gravitation. But on the moon and Mercury this is different:

- both have less mass than the Earth -＞ gravitation weaker
- in addition Mercury is much hotter -＞ molecules are faster

All the gases have left these bodies.
B) Greenhouse Effect:
Venus, Mars and Earth all have atmospheres, but what is it that makes these atmospheres so different?

a) Selective absorption of light
The visible sunlight gets through the Earth's atmosphere. Most of it is absorbed on the Earth, the Earth is heated to a temperature at which it radiates Infrared light, since it is of course much cooler than the sun. But infrared does not get down to the Earth, and so it does not get out either. Thus the atmosphere is heated and the Earth gets warmer.

![Diagram: Sunlight to Earth's atmosphere with 29% absorption of IR, atmosphere absorbs 71% of IR and warms up.]

The atmosphere of the Earth works like a blanket or the glass roof of a glasshouse

b) Greenhouse gases
The main Greenhouse gases are:
- Water vapor (deserts, where it is dry, get cold at night).
- Carbon dioxide (CO₂). It is much talked about it since we increase the amount rapidly through burning of fuel
- Methane (not much methane but a very strong absorber).

If these gases were not in the atmosphere, it would be pretty cold on the Earth, but with more of it will get pretty hot.

We see the effect at Venus, which is kind of an overdone greenhouse. The temperature on Venus is with 480° C higher than the 400° C on Mercury, which is much closer to the sun.

c.f. Venus: CO₂ atmosphere → strong greenhouse → hellish place.

On the contrary
Mars has very little CO₂ in its atmosphere.

Most of it is frozen at the poles. Therefore, it is cold on Mars, much colder than it should be compared to Earth, if we only take the different distance into account.

Venus and Mars both have CO₂. Earth probably started also with lots of CO₂. Now its atmosphere consists to ≈ 80% of N₂ and 20% of O₂. Where did the Earth's CO₂ go?

1) The Earth has water: Water dissolves CO₂ (e.g. soda pop).

Water + CO₂ → carbonic acid.

If Carbonic acid meets Calcium or Magnesium salts it reacts and forms limestone (calcium carbonate) or magnesite (magnesium carbonate). These materials are found in sedimentary
rocks on the bottom of the oceans and in rock formations which were former oceans on the Earth.

2) **Life stored CO\textsubscript{2}**
   - e.g. all shell creatures produced chalk.
   - e.g. plants eat up CO\textsubscript{2} and produce cell material, such as wood.
A lot of this has been stored for eons as oil and coal deposits, and now we release it in less than 100 years.

There is also a natural supply of CO\textsubscript{2}. **Volcanoes release the CO\textsubscript{2}** stored in rocks, i.e. they recycle. This is another importance of volcanoes: They add CO\textsubscript{2} and water to the atmosphere, i.e., they enhance the greenhouse. This is a delicate balance between the geological forces and life on Earth, and now man adds to this inventory by releasing greenhouse gases that were stored for a long time. This is the most gigantic and uncontrolled experiment that we are performing with our atmosphere.

On Venus CO\textsubscript{2} is added by volcanoes, but nothing is taken out of the atmosphere. On Mars this may have happened in the past, but not recently, since the volcanoes are dead. On the Earth there is still a balance, but we have to be careful!!

### 5. Water on Planets

The second unique feature of Earth is the presence of water in its liquid form. It is crucial for life and as we just have seen it is even very important for the balance of CO\textsubscript{2} in the atmosphere.

**A) Moon, Mercury and Venus**

On the moon and Mercury water would have evaporated immediately, since there is no atmosphere.

On Mercury it also gets too hot in the sun (400°C on Mercury). On Venus it also gets extremely hot (480°C). Water vapor has been lost like gases on Mercury. As a recent surprise, ice has been found in crater regions at the poles of Mercury and the moon. Here the ice survives in the extreme cold. These regions act like cold traps.

Water has been evaporated on Venus, and the bulk of the molecules has been destroyed by the solar UV, when they were high up in the atmosphere. But what about Mars, it is much cooler?

**B) What do we know about Mars?**

Mars has white polar caps which show seasons. This was first believed to be water ice as on Earth. This fact became increasingly interesting when so-called "Canali" (very accurate straight lines) were reported by Secchi and Schiaparelli (1863 - 1877). The word "Canali" was translated as canals (artificial waterways) or canals to bring water to dry areas on Mars. This spawned many fantasy stories about Martians. However, these "Canali" were only seen with the human eye, not on photographs! They are an optical illusion. Quite often this is exactly the problem with eyewitness news! The eyes and brain tend to connect uncorrelated dots into lines.

Therefore, with the advent of photography the idea of canals had to be dismissed. Furthermore, it was found that it was impossible to keep water in its liquid form on Mars.
because of the very thin atmosphere. It was highly unlikely that the variation of the polar caps with the seasons could be caused by melting and accumulation of water ice. Therefore, it was thought that the caps mainly consist of dry ice (CO₂).

Although the artificial waterways had to be dismissed, space probes found that Mars indeed must have **had liquid water** (evidence: riverbeds) in the past. Thus it must have also had a thick atmosphere in the past. Now Mars has a low-pressure atmosphere, i.e. water cannot exist as liquid any more.

**Mars and beyond** 12727, 28, 29, 30

**Slides VI.38a, b**

But where did Mars' water go? It was found that at least part of the polar caps consists of water ice, but the rest, in particular, the changing part is dry ice. So part of the water might be there, but not much.

The water may have been transformed into vapor, which got **broken up by solar UV** into oxygen and hydrogen. The oxygen has probably reacted with minerals (such as iron into rust) on the surface, and hydrogen would have left the planet very quickly. Or water may be buried under the surface by **permafrost**. 12724

From recent Mars missions we have growing indications that this is indeed the case. Signs of massive water flow, which must have occurred not only in the distant past (because the terrain does not contain craters), are found in many locations on Mars. Also Mars Odyssey has recently found signs of hydrogen just below the surface. This is the most convincing evidence that water is still there, most probably in the form of permafrost.

6. Conditions for Life

We have now learned that the conditions on the Earth's surface are very special as compared with the rest of the solar system. Earth as the only planet in our system has a lively crust and has liquid water. Both are found nowhere else. Atmospheres are also found on other planets, although not on all of them. However, it may either be too thin to be effective protection and to warm up the surface (as in the case of Mars) or may lead to an overdone Greenhouse with hellish temperatures (as in the case of Venus). This provides us with the information when we talk about life possibly beyond Earth.

What are the conditions for life to exist? Let me collect a few conditions that are still widely accepted: Life thrives on organic molecules. This features a rather complex chemistry, which needs special conditions to work effectively and not be readily destroyed again.

1) If organic material is exposed to high temperatures (fry a potato in hot pan), it decays into carbon and some other residual materials.

   -> the **temperature cannot be too hot**

   On the other hand, it is impossible to build up complex molecules in a freezer

   -> we need a **minimum temperature**

   Typical range: 0 - 100 °C

   This condition excludes Mercury, Venus, and pretty much everything beyond Mars.

2) We need an **atmosphere with chemically active gases** (N, O, CO₂, methane etc.). Otherwise there would be no organic chemistry. Material locked in rocks does not react.

3) We need a **liquid** in which organic molecules can float around, once the first ones are formed. Otherwise the evolution would be much too slow.
There are a few more subtle requirements that play a role once life has advanced to higher levels: Destructive radiation (ultraviolet, X-Rays, energetic particles) have to be kept out, either by the atmosphere and/or by a magnetic field to avoid too many random mutations.

This pretty much seems exclusively reserve life for Earth, where we indeed find it. These conditions also set the stage for a search outside the solar system. How likely is life to form?
- planets have to be at the right distance from the central star -> right temperature
- planets have to have an appropriate atmosphere -> which reactive gases?
- planets have to have a liquid -> methane, water, ammonia?

There may be surprises! This seems very restrictive.

Therefore, the news of potential life forms from Mars, reported last year, were so exciting.

Presumably, microbes from Mars have been transported by a meteorite to Earth. However, the final result has yet to be accepted. We could be fooled, since
- the organic molecules could have formed in a different way
- the shapes that look like microbes could be due to some crystallization process

Therefore, a careful study on Mars will be necessary. It will probably be only life that has long been extinct on Mars, if it turns out to be true. However, finding a 2nd planet in our own system that once at least carried life for some time, would make the formation of life so much more likely.

Equally interesting is the finding that microbes were found in weird places on Earth:
- in hot springs (100 C)
- in sulfur rich environment (thought to be too acidic for life)

This would also increase the likelihood for life to form elsewhere.

If we ask the question: how many other civilizations are possibly out there?
we have to combine various highly unknown probabilities:
1) what percentage of the stars has planets?
2) what percentage of the planetary systems has at least one life bearing planet?
3) what is the likelihood to proceed to intelligent life forms?
4) how long would intelligent life forms be able to survive?

The preceding section only speaks as to number 2). Any additional life form, e.g. on Mars, live or extinct, will immediately raise the probability for 2)!!

We will briefly touch number 1) at the end of this chapter on the solar system. On 3) and 4) we can only come up with wild guesses.
7. Ring Systems

As a final feature of planetary systems let us discuss the ring systems. The beautiful ring system of Saturn has been known since long time. Slide VI.36
As a great surprise Voyager also detected a ring around Jupiter. This ring is not quite as spectacular as around Saturn, but makes it a more common feature. Slide VI.37

Saturn has the beautiful ring system Slide VI.37. This ring system could be studied in detail by the Voyager spacecraft. What are these rings? From the motion of the spokes it can be clearly seen that the rings are not a rigid structure. It consists of many small particles, which orbit Saturn. Slide VI.38

In the same way tides will prevent a moon from forming inside this distance. Almost all rings are inside the Roche limit. Till today rings have been confirmed for all giant planets. Also Uranus has a ring system, Slide VI.38 which is pretty complex similar to Saturn. Also Neptune has finally joined the group of ring planets. -> All giant planets have rings. Slide VI.39

a) Why a ring and no moon? -> Roche Limit.
The rings are left-overs from the planet and moon formation. It is material which got too close to the planet that it could not come together to form a moon. The reason for this is the increasing tidal force close to the planets. There is a competition:
Tides from the planet try to tear a moon apart.
Self-gravity tries to hold a moon together.
There is a certain limit around each planet or even each celestial body, inside which the tides win and everything falls apart: the Roche Limit.

b) Why are the rings so stable and sharply structured?
Normally one would expect that the debris, which orbits the planets, would disperse with time, and that finally an irregular cloud of junk would move around the planets. Slide VI.40

Like a flock of sheep without a guardian they would move apart. However, there are such guardians in the sky, called shepherd moons, which like shepherd dogs threaten those pieces in line again when they start to move out. The same is seen for Saturn's rings. Slide VI.40

It's all gravitational interaction! Shepherd moons "focus" skinny rings, which otherwise would be expected to "diffuse". View VI.12

\[ \text{slow moon reduces ring particles' energies} \]
\[ \text{ring particles have intermediate speeds} \]
\[ \text{fast moon increases ring particles' energies} \]

The Sharp edge of Saturn’s A ring due to a small moon, which orbits just beyond the ring. The famous Encke division in Saturn’s A ring is due to small moon inside the division, which is slinging particles out of the division.
A moon outside a ring orbits with a slower speed than the ring particles. Its gravitational pull slows down particles, which come close to it. I.e., they are pushed inward towards the ring. A moon inside a ring orbits with a faster speed than the ring particles. Its gravitational pull speeds up particles, which come close to it. I.e., they are pushed outward towards the ring.

8. Small bodies in the system

There is not only debris in the form of rings in orbit around planets. Even between the planets there are small bodies orbiting the sun.

A) Asteroids

After the distances of all planets was measured, a large gap between Mars and Jupiter was recognized, which did not seem to fit into the nice symmetric picture of the planetary system and let the solar system look incomplete. After the initial discovery of a first small object at New Years Eve 1800, a whole family of objects was found here: the Asteroids. They contain a lot of material, which didn't make it into planets.

There is an Asteroid belt between Mars and Jupiter: as it looks like, a small planet, which could not come together, probably because of Jupiter's gravity. The largest Asteroid (Ceres) has a diameter of \( \approx 1000 \) km, a few others have diameters of a few 100 km, and the rest is very small.

Recently, the Galileo spacecraft visited the first Asteroid en route, on its way to Jupiter.

B) Comets

a) Comet Orbits

Another completely different population of smaller debris in the solar system are the comets. In ancient times comets have been viewed as bad signs, as bringers of war or other evils, (Tapestry of Bayeux) or they have been connected with the advent of a new king or even a connection has been tried with the birth of Christ (Giotto).

This kind of comet fever even sustained through the beginning of this century, as can be seen from this cartoon during the time Halley's comet came close to the Earth in 1911 (cartoon in German newspaper).

At first it was not even clear, whether comets were effects of the Earth's atmosphere or objects of outer space. Edmond Halley, a friend of Newton, concluded that comets which were only visible close to the Earth for a few months must have a very elongated orbit on which they are far away from the Sun and thus the Earth for a long time. By using Newton's law of gravitation to a comet seen in 1531, 1607 and 1682, he found that these 3 must be
the same comet, and he predicted the reappearance in 1758. He died 16 years before the comet indeed came back, a huge triumph for the law of gravitation and for Halley, after whom the comet was named. (Orbit)

Comet Halley could now by traced back to 239 B.C.. There are many comets with even more elongated orbits. So to say, the comets come from the freezer at large distances into the warm sun, where they get active. Material is evaporated and then becomes bright in the light of the sun.

b) Oort Cloud
The elongated orbits of most of the comets suggest that they come very far away from the sun (10000 - 100000 AU). This is known as the Oort Cloud of comets -- way beyond Pluto, named after the Dutch astronomer Oort who first suggested this. Probably disturbances among those comets and/or disturbances from nearby stars send some of the comets to the journey inward.

The comets come from a deep freezer and therefore could keep all their original material including the volatiles. According to Whipple they are nothing else than dirty snowballs. The snow contains water and lots of CO2 in the form of dry ice

When coming close to the sun this stuff evaporates and makes up the huge comet that we can see.

Originally comets could not have been formed so far out, it was not enough material out there. They probably formed near Uranus and Neptune and got ejected by a gravitational slingshot. In the same way, some comets have altered their orbit again in a close encounter with one of the planets to end up with an orbit with periods of a few or a few 10 years like Halley's comet.

c) Comet Tails
The most remarkable feature of comets is their tail, or mostly 2 tails. Let's try what the tail tells us.

The direction of the tail does not tell anything about the direction comet moves. The tail is always directed away from the sun no matter which way the comet is heading. This was already known in the 16th century, as can be seen on this picture of Halley's comet in 1532.

A comet consists of a nucleus, which contains all its material and is pretty small (a few km), the coma which is the gas and dust cloud of evaporated material around the nucleus and the tail, which is material dragged away from the comet. (Schematic representation of a comet)
There are:

- The **dust tail**, which is basically driven by radiation pressure of the sun. Remember, light also behaves like particles (photons). When they hit dust particles, they give them a push and drive them away from the sun.
- The **plasma tail**, which is created from cometary gas from which has been ionized by UV light of the sun (atoms have lost electrons).

The **solar wind**, which blows away from the sun and drags along a magnetic field, now takes all electrically conductive materials with it. This forms the plasma tail. By the way, this was the first recognition of the solar wind, proposed by Biermann in 1949, long before spacecraft could measure it!

Christmas 1984, before the first space probes ever reached comet, we have studied this effect with active experiments in space. Canisters with Barium and CuO were ignited. They created a Ba vapor cloud, which was ionized by solar UV and the same things happened as with real comets. (AMPTE satellite)

One can actually create sound from the effects of a comet in the solar wind. It creates a lot of electromagnetic disturbances in the solar wind, which have frequencies in range of sound. By just using a loudspeaker you can hear

- the solar wind
- the initial disturbance, the braking of the solar wind which gets stopped
- and the pushing of the comet material

Scientists use this information to learn about the processes, which make the comet appear in the sky as it does. (Artificial comet)

d) Comet Nucleus

The appearance of a comet nucleus was not studied before spacecraft finally made it to Halley's comet in 1986. In this year there was a different kind of a comet fever: a complete Halley armada headed towards the comet. The **Giotto** spacecraft of the European Space Agency made it closest to Halley with about 500 km as shown in the artist's conception of the flyby. Because of the dust, which comes off the comet, it had to be protected by a huge shield, as can be seen on this photo of the spacecraft during assembly.

Along with gas, a lot of dust is thrown out by the comet. This is the dangerous environment, which finally hit Giotto and led to an interruption of the broadcast.
What you can hear now, are the impacts of dust particles on Giotto's shield taken with sensitive microphones. But the close approach made it possible for its camera to take a close view.

At first glance it is not so easy to identify, what is what. And I still remember vividly, how I struggled to explain what we saw, when we were sitting with friends at the TV, watching the incoming pictures.

The bright structures are huge geysers of evaporating material due to the heating by the sun. This is again a form of volcanism in the solar system. The somewhat darker structure (peanut-shaped) is the very nucleus of Halley, about 16 km long and about 8 km in width. In essence the comet is a dirty snowball of fluffy configuration (as proposed by Whipple). This means, it mainly consists of ice in which rocky inserts are imbedded. Heated by the sun, the water and other volatiles evaporate and take dust particles with them. The surface of the comet nucleus itself was found to be very dark, as a surprise. It is almost as dark as coal. Under the bombardment from the solar wind and cosmic rays a tar-like substance has been formed on the surface which keeps the comet material inside and leads to irregular outbursts through holes in the surface.

The heating by the sun, the outbursts and the loss of volatile material bears the future destruction of the comets in it. When comets come close to the sun very often, they may loose all the water and gases and become inactive. They may end up asteroid-like with just the rocky stuff left. Meanwhile the dust and smaller pieces from the rocky core ends up somewhere in the comet's orbit.

C) Meteors (only hands-on material for a long time)

Asteroids can collide and create small debris ("meteoroids") and can produce meteor showers in the same way. This may be responsible for the iron meteors, which are found as a subset of the meteors.
c) Meteors on Earth
When meteoroids finally hit the Earth's atmosphere, they are called "Meteors". They are called "meteorites" if they land, i.e., part of the meteor makes it through atmosphere unharmed.
Many meteorites have been found on Earth. One was even reported in the Boston Globe to have hit a car.

Iron and stony meteorites are found, i.e., in some asteroids rocks and iron must have been differentiated by gravitation. There are others which contain a lot of carbon so called Carbonaceous chondrites which contain volatiles. These look more like the remainder of comets and are a sample of the early solar system. Many were found on Antarctic ice, where they are preserved.
Carbonaceous chondrites contain water & complex molecules including amino acids, i.e., the building blocks of life were there even at the beginning of the solar system.

d) Impacts and life:
Therefore, comets and water-bearing asteroids may have been early sources of water and building blocks of life on Earth. However, bigger impacts have also terminated some life.

There was a major extinction of life 65 million years ago, which marked the end of the dinosaurs. Probably the dust, or CO₂, from the impact changed the climate sharply and killed the dinosaurs and other life forms?

As a fingerprint Iridium was found in layers of that time which is very rare in the earth's crust (it likes to be with iron so most of the iridium probably sunk to the Earth's iron core). Iridium is much more abundant in iron meteorites. 1980: Luis (Nobel prize for something else) and Walter Alvarez found a 65 million year old layer of rock with a lot of iridium. The conclusion: the iridium came from space. From the amount of iridium the object must have been 10 km across which would have made a crater 150-200 km in diameter. A crater of the right age and size has indeed been found recently in Yucatan. It has been even claimed that this is the largest impact crater in the solar system after the huge craters from very early times on the moon.

Riddle: Life began 3.8 billion years ago. But there was intense bombardment up to 3 billion years ago as we have learned from the moon. This means there was a dark and dusty sky and boiling water in the oceans. How did life start under these conditions?

e) Comet Destruction by Impact
Some comets come so close to the sun that they disintegrate in the solar atmosphere or even plunge into the sun. Recently a very rare event could be observed: the impact of comet fragments on to Jupiter. This event held information for scientists on:
• the atmosphere of Jupiter
• the structure and composition of the comet/asteroid
• the impact itself

Two years ago 3 asteroid and comet hunters found a strange comet, actually a string of comets

These objects where in orbit of Jupiter, presumably captured by a close encounter with one of the moons so that the parent object could be decelerated into orbit. Then it came too close to Jupiter that it broke apart in the tidal forces.. The comet was really fluffy and not very strong. Jupiter before the impact as comparison. Many predictions were made and the scientists were relatively uneasy about the popularity of the event, because it might show up as a flop. It was not clear
whether the fragments stayed together to really produce a visible effect upon impact as is assumed in the following simulation of the event. In addition, the impacts could not be seen directly, because they occurred behind the visible limb of Jupiter as seen from Earth. However, each of the impacts was indeed a spectacle, which could be seen right after the impact site rotated into vision from Earth. We have to bear in mind that the impact occurs into the thick atmosphere of Jupiter not into a solid crust! One spacecraft was positioned to see the impact immediately, Galileo, on its way to Jupiter. The impact occurred always in the dark, but illuminated the surface immediately. As a big surprise the impact sites showed up for many days after the event. The motion of the atmosphere did not wash it out right away. The heat was seen in IR, as were dark spots in visible light and UV.

The dark spots are tentatively identified as sulfur, H₂S (a bad smelling chemical), and ammonia which lasted for weeks. Some chemistry between stuff from the comet and from Jupiter's atmosphere must have gone on, but details are not known yet. Also silicon, iron and magnesium were found, which only could have come from the rocky parts of the comet or asteroid. At this point it is not 100% sure, whether it was a comet or an asteroid, but the comet hypothesis is favored by scientists, because the originally object broke up so easily in Jupiter's tidal forces.

9. General Features of Planets and Planets in Other Systems

Let us now summarize some general features of our planetary system, which seem to suggest something about the origin of this system:

A) Orbits

All planets and moon are almost in the same plane. Almost everything has the same sense of spin (orbits and rotation), including the debris which forms the rings! This seems to suggest that the sun and the planets have been formed together out of a cloud of material with exactly that sense of spin. While the material of the sun accumulated in the center, some material must have stayed outside, since the conservation of angular momentum commanded a flattening of the original cloud. Even planets have a larger diameter at the equator than over the poles. However, I won't talk more about this, before we have talked about the sun and the raw material between the stars.
B) Density and Composition of the Planets
Another remarkable observation in the solar system is that the inner planets are all
- small and
  - rocky or in other words consist mainly of heavy materials
as can be seen in this picture from the surface of Mars. The outer planets, Jupiter, Saturn, Uranus and Neptune are all
- giants and
  - have the composition of the sun (75% H and 23% He)
Obviously the proximity of the hot sun had its influence in removing the light and volatile elements from the inner planets, while they stayed with the outer planets which were too far away. An exception is Pluto,
shown here with its moon Charon on a picture taken by Hubble Space Telescope. Pluto might have been a moon of Neptune earlier, as is suggested by its orbit, which crosses that of Neptune.

Although the giant planets have the composition of the sun and thus the original stuff, all planets have gone through a substantial evolution, and the material found here is not in the form of the original stuff anymore. If we want to get a clue on the original material, we have to look for more primitive bodies in the solar system, which are leftovers: the debris in the solar system.

10. Planets around other stars (covered in Chapter X. Life Cycle of Stars)

With our solar system we have one basic scientific problem: in science we are usually not satisfied, if we can support a model or a theory only with one example. If we present a model of the formation of the solar system, we are just in that situation. There is only one solar system, i.e. the one that we live in. So using the general features that we just listed as the criteria for a scientific model may lead to a wrong result. Our solar system may not be a good example for systems with planets in general. One example may not be typical, and the model may be built on a very special case. More than one example is needed to validate a model. However, until 1995 we had only data about our solar system. Only then did we start to gain information about planets in other star systems. Therefore, the recent confirmation of planets in other star systems is a big leap forward.

Also, as mentioned already in VI.6, as humans we are pondering the question whether we are alone and special in the universe or only one out of many examples of intelligent beings. With confirming the first planets outside our solar system we have made a giant step towards potential clues on life in outer space. Together with
- potential life on ancient Mars and
- life found under very rough conditions on Earth
this increases the chances that there is more intelligent life out there. However, that does not necessarily mean that we may connect with them. The distances may still be much too large.

A) Planet Detection Techniques
Still, we have not seen these planets directly yet. The telltale is the periodic motion of the center star in response to the gravitational pull of its planets.
The motion is detected through a variable Doppler shift of spectral lines (the finger-print of the elements) from the star. The wavelength of light becomes longer (red-shifted), when the star is moving away from us, and shorter (blue shifted), when the star is moving towards
us. Because a larger planet moves the star more effectively, it is no wonder that so far only heavy planets, with a mass ≥ that of Jupiter have been found.

The ultimate goal will of course be the direct detection of planets, and even better to see some structures on them. We know that we need a large objective diameter for a telescope to improve its resolution. How large must the telescope be to see a crude resolution for a planet of the size of Earth in the orbit around Alpha Centauri, the nearest neighbor star? We would need a diameter of 10 km. This sounds extremely ambitious, but it could be done with several small telescopes working together in orbit or with an array of telescopes on Earth. This is similar to the radio interferometers.

B) Other Planetary Systems

It is interesting to see that new planets have been found around G-type stars, the star type of our sun. Yet they are relatively strange systems.

In one case the planet orbits much closer than Mercury and is much heavier than Jupiter. In another case the "planet" is 8 times as heavy as Jupiter and in a highly elliptical orbit. These are signs of so-called Brown Dwarfs, objects too heavy for a planet, but that missed to become stars because of too little mass. This will be picked up a little later. It is interesting to see that these new planetary systems have Jupiter-like planets where the rocky planets are in our system. Our favorite models explain the rocky planets as the remainder of material after the volatile elements got blown or evaporated away close to the sun. These models may need revision due to the new information, but this is not yet conclusive.

Some of the planets are in the "Goldilock region" as far as their distance from the central star is concerned, meaning that they are where moderate temperatures can be achieved on the planets' surface. They are in the region where life could evolve, not necessarily on the Jupiter-like planets, but there may be moons around as in the Jovian system.

Will it ever be possible to detect signs of life on such planets?