The atmosphere of our Earth, of planets of our solar system and of exoplanets

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10. Atmospheres of Planets and of Exoplanets
10.1 The Planets of our Solar System:
General Considerations

Atmospheres: Definition and Layers

The Atmosphere is defined as the gaseous layer surrounding celestial bodies such as Stars and Planets. It consists most often on a mixture of different gases which are attracted by the gravitational force of the celestial body. The Density of the Atmosphere is densest at the surface (s. pp 25, 30) and at sufficiently large altitudes it smoothly merges into the interplanetary space. It is possible to distinguish between the following Atmospheres:

- Atmospheres of Earth-like Planets (inner Planets)
  - Giant Gas Planets (exzernal Planets)
  - Extrasolar Planets (Exoplanets)
    - Moons
    - Stars.

With increasing altitude, it is usually possible to distinguish between the following layers of the Atmosphere (s. Chapter 2):

a) Troposphere (innermost layer)
b) Stratosphere
c) Mesosphere
d) Thermosphere
e) Exosphere (outermost layer)

This segmentation is only a rough classification; and not each of these layers is present in all the different Atmospheres.
Atmospheres of Inner Planets

- **Mercury** does not have an Atmosphere in the traditional sense, but rather an Exosphere which is comparable with the Exosphere of the Earth. The high concentrations of Hydrogen and Helium originate probably from the solar wind.
- The Atmosphere of **Venus** consists mainly on CO₂, but apart from that, it is similar to that of the Earth.
- The **Earth’s Atmosphere** consists on a mixture of Oxygen (O₂) and Nitrogen (N₂) (see Chapter 2). Our Atmosphere is able to bear heavy elements as Argon (Ar); light elements such as hydrogen (H₂) and Helium (He) have been lost during its development.
- As **Venus**, the Planet **Mars** has a CO₂-Atmosphere. The largest part of its Atmosphere has probably been strippet off by the solar wind and disappeared into space (pp 353 – 356).

Atmospheres of Moons

- The **Earth’s Moon** has no Atmosphere in the common sense, but only an Exosphere. It consists to about equal parts on Helium, Neon, Hydrogen and Argon. The origin of this Exosphere is due to captured particles from the Solar wind (s. Ref. R.10.1.4).
- **Saturn’s Moon Titan** has a dense Atmosphere, consisting to a large part of Nitrogen.
- The **Jupiter Moons** Europe and Ganymede possess a thin Oxygen-Atmosphere which is attracted by gravitational forces but they are not of biological origin.
- The **Jupiter Moon Callisto** has a thin Carbon dioxide (CO₂) Atmosphere.
- The **Jupiter Moon Io** has a thin Sulfur Dioxide (SO₂) Atmosphere.
- The **Neptun Moon Triton** (a single Planet – Moon system) has a thin Nitrogen-Methan-Atmosphere.
- The **Saturne Moon Rhea** consists of a thin Atmosphere of Carbon.
- The **other satellites (Moons) of the Solar system** as well as the Moon of the Earth and the Planet Mercury (s. p. 408) have only an Exosphere.
**Atmospheres of the outer Solar systems: Gas Giants**

- The compositions of the Gas Giants (outer Planets) such as Jupiter, Saturn, Uranus and Neptune are essentially based of Hydrogen and Helium. Their cores are, however, cold and similar to the Stars, there is no radiation pressure.
- The interior of Jupiter and Saturn consist of liquid Hydrogen and Helium with a core of metallic Hydrogen.
- Uranus and Neptune have, however, a mantel and core of Water and Ice or of Ice, Ammonia, Methane and Rocks.

**The Sun: Structure and Atmosphere**

In the «Atmosphere» of the outmost shell of the Sun, three different layers can be distinguished, namely the «Photosphere», the «Chromosphere» and the «Corona». In leaving the Sun, the Atmosphere becomes thin and thinner, until it merges the interplanetary space. The mass of the Sun is $1.988 \times 10^{30}$ kg and its mean radius is 696'000 km.

- The Photosphere is the surface of the Sun which is visible to our eye. It consists of about 70% H$_2$ and 28% He. Thickness about 200 km, temperature about 6'000 °C.
- Above the Photosphere there is the Chromosphere. Thickness $\approx$ 10'000 km, Temperature up to 10'000 °C.
- Outermost layer: «Corona»; temperature up to 2 Million °C. After several millions of kilometers it approaches the interplanetary space.
### The Solar System: Distances, Masses and Revolution Periods of Planets

<table>
<thead>
<tr>
<th>Planet</th>
<th>Average distance from the Sun (km)</th>
<th>Mass compared to Earth Mass</th>
<th>Revolution Period in Earth years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neptune</td>
<td>$4.50 \times 10^9$</td>
<td>17.1 x</td>
<td>164.8</td>
</tr>
<tr>
<td>Uranus</td>
<td>$2.87 \times 10^9$</td>
<td>14.4 x</td>
<td>84.0</td>
</tr>
<tr>
<td>Saturn</td>
<td>$1.43 \times 10^9$</td>
<td>95.2 x</td>
<td>29.4</td>
</tr>
<tr>
<td>Jupiter</td>
<td>$7.78 \times 10^8$</td>
<td>317.8 x</td>
<td>11.9</td>
</tr>
<tr>
<td>Mars</td>
<td>$2.28 \times 10^8$</td>
<td>0.11 x</td>
<td>1.88</td>
</tr>
<tr>
<td>Earth</td>
<td>$1.49 \times 10^8$</td>
<td>$5.97 \times 10^{24}$ kg</td>
<td>1</td>
</tr>
<tr>
<td>Venus</td>
<td>$1.08 \times 10^8$</td>
<td>0.815 x</td>
<td>0.62</td>
</tr>
<tr>
<td>Mercury</td>
<td>$5.79 \times 10^7$</td>
<td>0.055 x</td>
<td>0.24</td>
</tr>
</tbody>
</table>

### Properties of Planets

<table>
<thead>
<tr>
<th>Planet</th>
<th>Diameter (km)</th>
<th>Mean velocity (km/h)</th>
<th>Aggregation state</th>
<th>Density (g/cm³)</th>
<th>Day-duration (in Earth days)</th>
<th>Min. Temp. (°C)</th>
<th>Max. Temp. (°C)</th>
<th>Neigung der Rotationsachse (deg)</th>
<th>Magnetic field (x Earth-field at Equator)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>4'879</td>
<td>172'332 s</td>
<td>g / l / s</td>
<td>5.427</td>
<td>58.65</td>
<td>- 173</td>
<td>427</td>
<td>~ 0</td>
<td>~ 0.01</td>
</tr>
<tr>
<td>Venus</td>
<td>12'103</td>
<td>126'072 s</td>
<td>g / l / s</td>
<td>5.243</td>
<td>243.02</td>
<td>+ 437</td>
<td>497</td>
<td>177.36</td>
<td>~ 0</td>
</tr>
<tr>
<td>Earth</td>
<td>12'734</td>
<td>107'208 s</td>
<td>g / l / s</td>
<td>5.515</td>
<td>1.00</td>
<td>- 89</td>
<td>58</td>
<td>23.45</td>
<td>1.0</td>
</tr>
<tr>
<td>Mars</td>
<td>6'772</td>
<td>86'868 s</td>
<td>g / l / s</td>
<td>3.933</td>
<td>1.026</td>
<td>- 133</td>
<td>27</td>
<td>25.19</td>
<td>~ 0.001</td>
</tr>
<tr>
<td>Jupiter</td>
<td>138'346</td>
<td>47'052 g / l / s</td>
<td>g / l / s</td>
<td>1.326</td>
<td>0.413</td>
<td>- 108</td>
<td>- 108</td>
<td>3.13</td>
<td>~ 13</td>
</tr>
<tr>
<td>Saturn</td>
<td>114'632</td>
<td>34'884 g / l / s</td>
<td>g / l / s</td>
<td>0.687</td>
<td>0.449</td>
<td>- 139</td>
<td>- 139</td>
<td>26.73</td>
<td>~ 1.3</td>
</tr>
<tr>
<td>Uranus</td>
<td>50'532</td>
<td>24'516 g / l / s</td>
<td>g / l / s</td>
<td>1.270</td>
<td>0.718</td>
<td>- 197</td>
<td>- 197</td>
<td>97.77</td>
<td>~ 0.74</td>
</tr>
<tr>
<td>Neptune</td>
<td>49'105</td>
<td>19'548 g / l / s</td>
<td>g / l / s</td>
<td>1.638</td>
<td>0.665</td>
<td>- 201</td>
<td>- 201</td>
<td>28.32</td>
<td>~ 0.42</td>
</tr>
</tbody>
</table>

*g: gaseous / l: liquid / s: solid
Earth's magnetic field: 31 μT = 0.31 Gauss at Equator, (1T = 1 Tesla = 10⁴ Gauss; the quoted relative fields are very approximative)
The Graph shows the velocities of the Planets orbiting around the Sun. We have quoted average values because the Planets are not moving with constant velocities: since they are moving on elliptical orbits, they are moving somewhat faster in Perihelion (closer to the Sun) and somewhat more slowly in Aphelion (farther from the Sun). The fundamental physical laws have been derived by J. Kepler (s. Reference R.10.1.2).

Together with the below Figure, it is seen that the average velocities of the Planets are the slower, the further away they are orbiting around the Sun: The innermost Planet Mercury is the fastest one; it is moving with the gigantic speed of 172’000 km/h. On the other hand, the most distant Planet Neptune moves much more slowly: its velocity is only about 20’000 km/h. It is, however still about 100 times faster than a car moving with 200 km/h!
The numerical eccentricity $e$ of the elliptic orbits of Planets with semi-axis $a$ and $b$ is defined by $e = \left(\frac{1}{a}\right) \cdot \left(a^2 - b^2\right)^{1/2}$; if $a = b \rightarrow$ circular orbit with $e = 0$. 

![Numerical eccentricities of Orbits of Planets around the Sun](chart)

- Mercury: $0.206$
- Venus: $0.017$
- Earth: $0.009$
- Mars: $0.093$
- Jupiter: $0.048$
- Saturn: $0.056$
- Uranus: $0.046$
- Neptune: $0.009$
10.2 Specific Properties and Atmospheres of the Planets of our Solar System

10.2.1 The Planet Mercury

Messanger of the Gods - or God of Merchants, of Travelers and of Poets, Son of Zeus
Mercury: General Properties

With a Planet diameter being close to 4'880 km and with an average orbital diameter of 58 million km from the Sun, Mercury is the Planet closest to the Sun and for this reason, it is also the fastest moving of the Solar System. His maximum daily temperature is ± 430 °C and the night temperature is as low as -170 °C; it has the largest temperature fluctuations of all Planets (s. p. 413 and picture below). Due to its size and chemical composition, it belongs to the Earth-like (or terrestrial) Planets. Due to its peihelion, it is difficult observable from the Earth. Equator diameter: 4'878 km; mass: 3.3x10^{23} kg; average density: 5.420 g/cm^3; acceleration due to gravitation: 3.70 m/s^2; rotation period: 87.96 d (0.241 y); atmospheric pressure at surface: ~ 0 bar; eccentricity: 0.206.

Because of the difficult elusiveness of the orbit at the Solar neighborhood and the associated danger due to the intense Solar wind, hitherto only two Spacecrafts, Mariner 10 (1970) and Messenger (2008), have visited and studied the Planet. The lunar-like surface, the surface interspersed with craters consisting of rough and porous rocks reflects the Sun light only weakly. The average spherical Albedo is 0.06, i.e. the surface is scattering at the average only 6% of the intense radiation.

The density of Mercury is only slightly smaller than that of the Earth. It is assumed that about 70% must be located in an iron core which amounts to about 75% of the radius; at the outer shell, there are about 30% silicates. Because of the high temperature in the direction of the Sun and the small mass, Mercury essentially can not hold an Atmosphere. (s.p. 421).

Elliptic Orbit (to scale) ot Mercury around the Sun

Mercury describes an elliptic orbit around the Sun; the Sun is located at one of the foci of the ellipse having the semi-axis a and b and the excen-tricity e. ε is the numerical excentricity.

\[ a = 57.908 \times 10^6 \text{ km} \]
\[ b = 56.671 \times 10^6 \text{ km} \]
\[ e = (a^2 - b^2)^{1/2} = 11.9 \times 10^6 \text{ km} \]
\[ e = e/a = 0.205624 \]

Smallest distance from the Sun = \( a - e = 46.00 \times 10^6 \text{ km} \)

Largest distance from the Sun = \( a + e = 69.82 \times 10^6 \text{ km} \)

Orbit time around Sun (siderial period): 0.241 Earth-ys = 87.969 days

Mean velocity: 172'332 km/h
**The Atmosphere of Mercury - 1**

So far it was a riddle: How is it possible that the low-mass intermost and hottest Planet can keep a permanent Atmosphere, even though this Atmosphere is extremely thin? On the day side, the surface temperature of Mercury is over 400°C (s. p. 419). Due to the strong radiation of the Sun, the components of its Atmosphere would evaporate in a short time by photoevaporation, i.e. by ionization and acceleration of the particles with escape velocity into the free space. Since Mercury can, however, maintain his residual Atmosphere over long periods of time, there must exist a constant replenishment of particles (s. p. 422).

It must, however, be kept in mind that in the case of Mercury, it is strongly exaggerated to speak from a real Atmosphere. At the surface, the atmospheric pressure is only one quadrillionth of 1 bar ($p_{\text{Mercur}} = 10^{-15}$ bar = $10^{-10}$ Pa). Under terrestrial conditions, this would correspond to a high vacuum.

The absence of an Atmosphere is also responsible for the extreme temperature fluctuations of the Planet. On other Planets, the Atmosphere acts as a protection shield which acts as an efficient heat contribution. At Mercury, however, the extremely thin atmospheric layer does not shield the incoming Sun and does not stabilize the temperature. Since the distance between Mercury and the Sun is so small, the day side of the Planet is exposed to the Sun without protection, while the night side is extremely cold. The absence of an Atmosphere on Mercury does, however, not mean that Mercury is the hottest Planet of our solar system. This honor must rather be attributed to the Planet Venus because of its runaway global warming (s. Section 10.2.2.0).

**The Atmosphere of Mercury - 2**

The extremely small atmospheric pressure of Mercury is partially due to the fact that its magnetic field is incomplete (patchy). Particles of the solar wind can then penetrate through these gaps and reach the surface of the Planet, thereby «refreshing» its surface. In addition, by degasing of the surface, an additional contribution to the Atmosphere is generated.

Nethertheless, the Planet Mercury does not have an Atmosphere in the traditional sense, because its gas pressure is smaller than a laboratory achievable vacuum; its atmosphere is similar to that of our Moon. The «atmospheric» contributions are Hydrogen ($H_2$, 22% by volume), and Helium ($He$, 6 %) which most probably are due to the solar wind. On the other hand, oxygen ($O_2$, 42%), Sodium (Na, 29%) and Potassium (K, 0.5%) are probably released from the material of the surface of the Planet.

**Main components of Mercury’s Atmosphere**

- Sodium: 29%
- Oxygen: 42%
- Hydrogen: 22%
- Potassium and others: 1%
- Helium: 6%

**Surface, covered with craters**
10.2.2 The Planet Venus

Godhdes of love and beauty

With an average Sun distanc of 108 million km, Venus is the second innermost Planet and with a diameter of 12’100 km it is the the third-smallest Planet of the Solar system. It belongs to the four Earth-like Planets which are also referred to as terrestrial or rocky Planets. On his orbit, Venus is the Planet with approaches the Earth to a minimal distance of only 38 million km. Its size is essentially the same as that of the Earth (right-hand picture), but differs from the Earth mainlly by ist Geology and with regard to its Atmosphere. After the Moon, it is the brightest natural object at he twilight sky or at the natural starry sky. Venus is therfore also referred to a «Morning Star» or «Evening Star».

Properties of its Orbit:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-major axis a</td>
<td>108.209 x 10^6 km</td>
</tr>
<tr>
<td>Numerical excentricity e</td>
<td>e = e/a = 0.00679</td>
</tr>
<tr>
<td>Excentricity e</td>
<td>e = 0.7347 x 10^6 km</td>
</tr>
<tr>
<td>Small semiaxis b</td>
<td>b = 108.206 x 10^6 km</td>
</tr>
<tr>
<td>Orbit time around Sun</td>
<td>224.701 days</td>
</tr>
<tr>
<td>Average orbit velocity</td>
<td>35.02 km/s</td>
</tr>
</tbody>
</table>

Venus in natural colors

Comparision of Venus (left) with Earth

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Venus: More Data and Properties

Properties of the Planet:

- Mean radius: \( R_{\text{Venus}} = 6051.8 \text{ km} = 0.949 \text{ Earth-radii} \);
- Mean Earth-Radius \( R_{\text{Earth}} = 6371 \text{ km} \);
- Mean Mass: \( M_{\text{Venus}} = 4.869 \times 10^{24} \text{ kg} \);
- Mean Mass of the Earth: \( M_{\text{Earth}} = 5.973 \times 10^{24} \text{ kg} \);
- Mean Density: \( \rho_{\text{Venus}} = 5.243 \text{ g/cm}^3 \);
- Mean Density of the Earth: \( \rho_{\text{Earth}} = 5.515 \text{ g/cm}^3 \);
- Surface: \( F_{\text{Venus}} = 4.60 \times 10^8 \text{ km}^2 \);
- Surface of the Earth: \( F_{\text{Earth}} = 5.1995 \times 10^8 \text{ km}^2 \);
- Gravitational acceleration: 8.87 m/s\(^2\);
- Gravitational acceleration of the Earth: 9.81 m/s\(^2\);

Layers of the Atmosphere of Venus

The Atmosphere of Venus is much denser and hotter than that of the Earth. The Temperature at the surface is 467 °C, while there, the pressure is 93 bar! The Atmosphere of Venus contains opaque clouds of sulfuric acid (H\(_2\)SO\(_4\)); this Atmosphere makes observations from the Earth and from spaceships impossible. Information regarding the Topography could only be obtained by Radar Image Techniques. The blue curve in the picture below shows the temperature \( T(h) \) as a function of the altitude.

The most important atmospheric gases are Carbon dioxide (CO\(_2\)) and Nitrogen (N\(_2\)). For other trace gases see p. 427. The Atmosphere is in a state of violent circulations and Super-Curls. Similar to the Atmosphere of the Earth (s. pp 7 and 9, Chapter 1) it is possible to subdivide the Atmosphere of the Venus into several layers. The Troposphere starts at the surface of the Planet and extends up to 100 km. In the vicinity of the surface, the winds are weak, but at the upper end of the Troposphere, the temperatures and pressures are reaching values similar to that of the Earth and the velocities of the winds are up to 100 m/s! The pressure of CO\(_2\) at the surface is so high, that there is no gas but rather a supercritical liquid.

About 99% of the mass of the Atmosphere of Venus is contained in the Troposphere; 90% of the Atmosphere is contained in a layer of 28 km above its surface.
The Atmosphere of Venus consists mainly of Carbon dioxide, $\text{CO}_2$ (96.5%) and in addition it contains a much smaller amount of Nitrogen, $\text{N}_2$ (3.5%) (left-hand Figure). There exist also number of trace gases, namely Sulfurdioxide ($\text{H}_2\text{SO}_4$): 150 ppm, Argon (Ar: 70 ppm), Water ($\text{H}_2\text{O}$: 20 pp), Carbonmonoxide (CO: 17 ppm); Helium (He: 12 ppm), and Neon (Ne: 7 ppm) (right-hand Figure).

Because of the large total amount of mass, it contains about five times as much Nitroge as in the Earth’s Atmosphere and as a consequence, its pressure is about 93 bar at the middle floor level. This corresponds to a pressure at a depth of 910 m sea level on Earth. At the surface, the density is about 50 times larger than at the Earth.

Viewed from outside, the Atmosphere of Venus is compleately opaque. This is due to a permantly closet cloud cover. The underside of this cloud cover is located at an altitude of about 50 km and its thickness is about 20 km. Its main constituent consists of about 75% droplets of sulfuric acide. In addition, there are also chlorine- and phosphourus aerosols.
The Planete Earth

Gaia: Goddess of the Earth - personalized Earth in Greek mythology

The Earth - General

The Earth is the densest, the fifth-largest and the third closest Planet to the Sun. Its age is about 4.6 billion years. The Earth is the home of all living creatures in our Solar system. Because of its prevailing chemical composition, the Earth is also referred to as a terrestrial Planet; this notion is also used for the Planets Mercury, Venus and Mars.

Main Orbital Properties:
- Semi-major axis: 149.6 Mio. km
- Numerical excentricity e: 0.0167
- Orbital speed: 29.78 km/s

Physical Properties of Planet:
- Equatorial diameter: 12'756 km
- Polar diameter: 12'713 km
- Mass: 5.972 x 10²⁴ kg
- Average density: 5.515 g/cm³
- Gravitational acceleration: 9.80665 m/s²
- Escape velocity: 11.186 km/s
- Rotational period: 23 h 56 min 4.1 s
- Inclination of rotational axis: 23.44°
- Geometrical Albedo: 0.367

Properties of the Atmosphere:
- Pressure (at Sea level): 1.014 bar
- Minimum Temperature: -89 °C
- Average Temperature: 15 °C
- Maximum Temperature: 58 °C

Composition of Air (in % by volume):
- Nitrogen (N₂): 78.084%; Oxygen (O₂): 20.946%;
- Argon (Ar): 0.934%; CO₂: ≈ 0.04 %;
Mars: General Data and Properties

Viewed from the Sun, Mars is the fourth Planet in our Solar system and it is the outer neighbour of the Earth (s. p. 408). It belongs to the four terrestrial Planets of our Solar system.

Mars in natural colours; the Data for the picture have been obtained on 1999 from the «Mars Global Surveyer».

**Orbital Properties:**
- Semi-major axis: 228 Mio. km
- Excentricity: 0.0935
- Average orbita velocity: 24.13 km/s

**Physical Properties:**
- Average diameter: 6'772 km
- Mass: 6.419 x 10^23 k
- Average density: 3.933 g/cm³
- Gravitational acceleration: 3.69 m/s²

**Properties of the Atmosphere:**
- Pressure: 6 x 10^-3 bar
- Minimal temperature: -133 °C
- Average temperature: -55 °C
- Maximum temperature: +27 °C

**Gases of the Atmosphere:**
- Carbon dioxide (CO₂): 95.97 %
- Nitrogen (N₂): 1.89 %
- Argon (Ar): 1.93 %
- Oxygen (O₂): 0.146 %
- Carbon monoxide (CO): 0.0357 %
**Comparision: Earth - Mars**

<table>
<thead>
<tr>
<th></th>
<th>Mars</th>
<th>Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (km)</td>
<td>6'772</td>
<td>12'7345</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>6.419 x 10^{23}</td>
<td>59.74 x 10^{23}</td>
</tr>
<tr>
<td>Atmospheric pressure at surface (bar)</td>
<td>6 x 10^{-3}</td>
<td>1.014</td>
</tr>
</tbody>
</table>

**Surfaces of South- and Northern Hemispheres of Mars**

The reddish colour of the Planet is due to iron oxide dust which has spread over the surface and into the Atmosphere.

The two Hemispheres of Mars are strongly different:

- The **Southern Hemisphere** is a vast upland which is on the average 2 – 3 km over the global level and contains extended shield volcanoes. The large number of impact craters originate from the very high age of about 4 billion years.
- This is in contrast to the **Northern hemisphere** representing a lowland plane lying about 3 – 5 km below zero level. It has lost its original structure by a yet unknown geological process (eventually by collisions?).

**Temperature and Pressure of the Atmosphere as a function of altitude**

As Venus, the Atmosphere of Mars consists mainly on CO₂ (pp 426, 427, 434).

The Atmosphere of Mars is very thin, about 100 times less dense as that of the Earth. There do not exist clouds of Water vapour but only a few clouds consisting of Water-ice.

Clouds which are observed in an altitude of 50 km consist primarily on CO₂ – Ice and dust.

Both, temperature and pressure at the surface of Mars are low. At the immediate surface, the temperature is about 250 K (−23 °C) and in altitudes between 80 and 120 km it is about 123 K (−150 °C).

The average atmospheric pressure at the surface of Mars is only about 6.36 hPa = 6.36 mbar. In comparison to the average pressure of 1013 hPa = 1.013 bar = 1 atm this amounts only to 0.63% of the average pressure at sea level on the Earth and corresponds to the air pressure at an altitude of 35 km. Most probably, the Atmosphere of Mars has been gradually removed by the Solar wind and entrained into space.
Chemical composition of the Mars Atmosphere

![Chemical composition of the Mars Atmosphere](image)

### Composition of the Atmosphere on Mars

<table>
<thead>
<tr>
<th>Gas</th>
<th>Formula</th>
<th>Distribution (Percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide</td>
<td>CO₂</td>
<td>95.4</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N₂</td>
<td>2.7</td>
</tr>
<tr>
<td>Argon (40)</td>
<td>Ar-40</td>
<td>1.6</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O₂</td>
<td>0.13</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>CO</td>
<td>0.07</td>
</tr>
<tr>
<td>Water</td>
<td>H₂O</td>
<td>0.03*</td>
</tr>
<tr>
<td>Argon (36)</td>
<td>Ar-36</td>
<td>0.0005</td>
</tr>
<tr>
<td>Neon</td>
<td>Ne</td>
<td>0.0003</td>
</tr>
<tr>
<td>Krypton</td>
<td>Kr</td>
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<tr>
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<td>O₃</td>
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</tr>
<tr>
<td>Xenon</td>
<td>Xe</td>
<td>0.000008</td>
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*Abundance varies with season and location*
### 10.2.5 The Planet Jupiter

**King of the Gods - Master of the Olympus**

### Jupiter: General Data and Properties

With its equatorial diameter of about 143'000 km, Jupiter is the largest Planet of our Solar system. Its distance from the Sun is about 778 million km and it is the fifth Planet of our Solar system. Because of its chemical composition it belongs to the so-called **Gas giants** («Gas giants») and therefore it has no visible outer surface.

The other Gas giants are therefore also called **Jovian Planets** or Jupiter-similar Planets. In our Solar system, they belong to the group of the four **Outer Planets**.

#### Properties of the Orbit:
- Semi-major axis: 778.5 million km
- Excentricity: 0.0484
- Average orbital velocity: 13.07 km/s
- Orbital period: 11.86 years

#### Physical properties:
- Equatorial diameter: 142'984 km
- Polar diameter: 133'708 km
- Mass: 1.899 x 10²⁷ kg
- Average density: 1.326 g/cm³

#### Main components:
- Hydrogen (H₂): 89.8 %
- Helium (He): 10.2 %
- Methane (CH₄): 0.3 %
- Ammonia (NH₃): 0.026 %

#### Further Properties:
- Gravitational acceleration: 24.79 m/s²
- Rotational period: 9 h 55 Min 30 s
- Albedo: 0.52
- Temperature: 105 K (- 108 °C)

#### Rings of Jupiter:
- s. Ref. R.10.2.5.1

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<td>Average orbital velocity:</td>
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<td>Orbital period:</td>
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<td>0.52</td>
</tr>
<tr>
<td>Temperature:</td>
<td>105 K (- 108 °C)</td>
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Jupiter has the largest planetary Atmosphere in our Solar system; its altitude is about 5'000 km. Since Jupiter has no solid surface, the base of the Atmosphere is defined at the point where its atmospheric pressure is 10 bar, i.e. at the altitude where the pressure is 10 times larger than the atmospheric pressure at the surface of the Earth.

The dark point at the left is the shadow of the Moon Europe. The large red spot something at the bottom right is a permanently sustained storm. At the surface, Jupiter is covered by huge cloud structures which form bright and dark regions parallel to the Equator. The bright regions are areas which are caused by gases rising from the interior of the Planet; the dark regions are marking sinking matter.

The Atmosphere of Jupiter is very dense and cold and therefore the lower atmospheric layers are liquid rather than gaseous. In the region in which atmospheric behaviour is observed, the pressure is 5 to 10 times larger than the atmospheric pressure at the surface of the Earth (1 bar).

The Atmosphere of Jupiter consists of 89.8% molecular hydrogen (H₂) and 10.2% Helium (He). In addition, there exist some other compounds: crystallites and clouds of ammonia (NH₃), of water (H₂O), and of ammonium hydrosulfide (NH₄SH) (see left-hand Figure).

The layers of the Jupiter – Atmosphere (Pressure in bar)
10.2.6 The Planet Saturn

One of the Titans - God of agriculture

Saturn is the sixth Planet of the Solar system (s. p. 412) and with its Equatorial diameter of 120',500 km (9.5 times the diameter of the Earth) it is the second largest Planet after Jupiter. Its mass is 95 times larger than the Earth mass, but its mass is only 30% of that of Jupiter.

The investigated upper layers consist of 96% of hydrogen. With its small density of only about 0.69 g/cm³, it has the smallest density of all Planets of the Solar system.

From the other Planets, Saturn differs by its distinct rings which consist to a large extent of rocks.

**Properties of the orbit**
- Semi-major axis: 1'433.5 Mio. km
- Excentricity: 0.05648
- Average orbital velocity: 9.69 km/s

**Physical properties**
- Equatorial diameter: 120,'536 km
- Polar diameter: 108,'728 km
- Mass: 5.685 x 10²⁶ kg
- Average density: 0.687 g/cm³

**Main components**
(Composition of the upper layer)
- Hydrogen (H₂): 96.30 %
- Helium (He): 3.25 %
- Methane (CH₄): 0.45 %
- Ammonia (NH₃): 0.026 %

**Further properties**
- Gravitational acceleration: 10.44 m/s²
- Inclination of rotational axis: 26.7°
- Rotational period: 10 h 47 min
- Geometric Albedo: 0.47
- Surface temperature: -139 °C
Structure and chemical composition of Saturn

**Inside Saturn**

- **Structure:**
  - Saturn is a gas planet with a rocky core from silicates followed by a liquid Hydrogen layer and a subsequent layer of molecular Hydrogen.
  - The Atmosphere has a layer structure consisting of Hydrogen (H$_2$), Helium (He), Methane (CH$_4$), and Ammonia (NH$_3$).

- **Chemical composition:**
  - According to current knowledge, Saturn essentially consists of a single large “Atmosphere” with the following composition:
    - Hydrogen (H$_2$): 96.30 %
    - Helium (He): 3.25 %
    - Methane (CH$_4$): 0.45 %
    - Ammonia (NH$_3$): 0.0125 %
    - Hydrogen Deuterium (HD): 0.011 %
    - Ethane (C$_2$H$_6$): 0.0007 %

**Atmosphere of Saturn**

- The composition of the Atmosphere of Saturn is similar to that of Jupiter (s. p. 438). Its average temperature is, however, somewhat smaller. This is due to its larger distance from the Sun. In addition, its total thickness (~ 200 km) is larger than that of Jupiter (~ 80 km).
- The Troposphere contains three distinct cloud layers indicated by the three pairs of horizontal and vertical dashed lines: The mean (h,T)-values are: at about (~ 270 km; 260 K (-13°C)) it consists of Water-ice (H$_2$O), at about (~190 atm; 210 K (-63°C)) the main composition is Ammoniumhydroxysulfide-ice, (NH$_4$)$_2$SH, and at about (~115 atm; 150 K (-123°C)), Ammonia-ice (NH$_3$) is present.
  - Above the clouds, there is a Haze. At still higher altitudes the Stratosphere is present.
The spacecraft Cassini has made a discovery on Saturn which has never been observed on the other Planets: a Hurricane-like storm at the South Pol of the Ringplanet with a clearly marked eye which is surrounded by towering clouds. The storm system has a diameter of about 8'000 km, i.e. of two third of the diameter of the Earth.

The storm rotates clockwise with a speed of 550 km per hour around the South Pol of Saturn. Cassini also discovered the shadow of towering clouds which are rotating around the eye of Saturn. In contrast to the Hurricane moving on Earth which are formed over the Oceans, the discovered whirlwind does not move away from the Pole of Saturn.

The North Pole region of Saturn shows one of the strangest phenomena which has been discovered up to now – a stable, hexagonal cloud pattern.

The formation of this pattern is still unclear. Recent laboratory experiments could help to solve the riddle. The Hexagon at the North Pole has already been discovered by Voyager and the spacecraft Cassini confirmed it at 2006: The observation showed in fact a rotating Hexagon with a side length of 13'900 km having a circular period of 10 h and 40 seconds.

Scientists from the University of Oxford have conducted experiments and were able to simulate the phenomenon (s. Ref. R.10.1.6.5).

The Rings of Saturn

The rings of Saturn are forming a ring system which is surrounding the Planet. These rings are the most prominent feature of the Planet and can be observed already using a telescope with a magnification of 40. The rings consist essentially of Water-Ice but they contain also rocks which are orbiting Saturn. The sizes of the particles varies between dust and several meters. The rings of the system are separated by many larger and smaller gaps. Its maximum diameter is nearly one million kilometers but the thicknesses of the individual rings are only a few 100 meters (according to NASA between 200 and 3'000 meters), and viewed relatively, they are extremely thin.

Today it is well known, that more than 100'000 individual rings with different compositions and shades exist which are separated from each other by sharply define gaps. The innermost ring begins alread 7'000 km above Saturn’s surface (radius of Saturn: ~ 60’000 km) and the ring diameter is about 2 times 67’000 km = 134’000 km; the outermost ring is about 420’000 km above the surface and its diameter is as large as 960’000 km.

Concerning the mechanism of the formation of the rings, there is still no consensus. Some features suggest a relatively recent origin. On the other hand, theoretical models suggest, that the rings developed already shortly after the formation of the Solar system.
10.2.7 The Planet Uranus

Primordial God of heaven - Father of Cronus
begotten with his mother Gaia,
the primordial mother.

The average distance of Uranus from the Sun is 2.9 billion km; it is the seventh Planet in the Solar system and has been discovered at 1781 by Wilhelm Herschel.

The diameter of this Planet is more than 51’000 km and is about four times as large as that of the Earth (s. picture below). Its volume is about 65 times larger than the volume of the Earth.

Physically, Uranus is comparable with Neptun and its mass is around 14 times larger than the mass of the Earth. In the solar system, Uranus is the Planet with the fourth largest mass. With regards to its diameter, it is only slightly larger than Neptun: it is the third largest Planet. Uranus is an Ice-giant, because in the inside, methane in the form of ice is present.

Properties of the Orbit

• Large semi-major axis: 2’872.4 million km
• Excentricity: 0.0472
• Average orbital speed: 6.81 km/s

Physical Properties

• Equatorial diameter: 51’118 km
• Polar diameter: 49’946 km
• Mass: 8.683 x 10^25 kg
• Average density: 1.27 g/cm³

Main components

Composition at the upper ice cloud layer:

• Hydrogen: 82.5 %
• Helium: 15.2 %
• Methane (CH₄): 2.3 %

Composition in the interior:

• Water, Ammonia, Methane Ice

Further Properties

• Gravitational acceleration: 8.86 m/s²
• Inclination of rotational axis: 97.77° (!!)
• Rotational period: 7 h 14 min 24 s
• Geometrical Albedo: 0.51
• Surface temperature at 1 bar: -197 °C
Internal Structure

- In the "Standard Model" of the structure of Uranus, three layers are distinguished: 1) A rocky core (silicate-iron-nickel) in the center, 2) an "icy" coat in the middle, 3) An outer gaseous envelope of hydrogen and helium.
- Core: relatively small with 0.55 Earth masses and a radius of less than 20% of the Uranus radius. Density about 9 g/cm³ and a pressure of about 8 million bar or 800 GPa; the temperature is about 5'000 K.
- Mantle: Bulk-mass with about 13.4 Earth masses.
- Inner and outer Atmosphere

Chemical composition

According to current knowledge, Uranus consists essentially on a single large "Atmosphere" if the central core is ignored.

This Atmosphere has the following composition:
- Hydrogen (H₂): 82.5%
- Helium (He): 15.2%
- Methane (CH₄): 2.3%
- Hydrogen-Deuterium (HD): 0.00148%

Axis of rotation and orbit – Extreme seasons

With the expection of Uranus, the axis of rotation of the Planets are almost perpendicular to their orbital planes (s. Table, p. 413). This is not the case for the Planet Uranus for which the axis of rotation R is very inclined, even overtitled (s. Figure below and Appendix 10-A-3-5): The axis of rotation forms an angle of about 98° to the vertical V. With respect to the orbital plane (marked by the oblique dashed blue lines) it forms an angle of 8°. Uranus is therefore "rolling" around the Sun.

In position A of Uranus, the largest part of the Southern Hemisphere S is in the sunlight, while the Northern Hemisphere lies in the shade. In position C, however, the situation is just reversed: the largest part of the Southern Hemisphere lies in the shade while the Northern Hemisphere is exposed to the Sun. The orbital period from A → B → C → D → A is 84 Earth years and the rotation period around the axis N – S has been determined by the spacecraft Voyager 2: it amounts to 17.2 hours. In the intermediate positions B and D, there are relatively "normal day and night conditions with a day-night time of 17.2 hours.

[With its small excentricity of e = 0.0472 the orbit is nearly a circle. The elongated ellipse shown above arises through the rotation of a circle around the axis A-C toward a plane which is almost perpendicular to the drawing plane].

Structure and chemical composition of Uranus

Internal structure of Uranus

Chemical composition of Uranus

Internal Structure

- Hydrogen (H₂): 82.5%
- Helium (He): 15.2%
- Methane (CH₄): 2.3%
- Hydrogen-Deuterium (HD): 0.00148%
The Atmosphere of Uranus - 1

In the structural model, Uranus is considered as a liquid Planet with a gaseous upper layer or Atmosphere which is not clearly bounded. Since with increasing depth the pressure increases above the critical point, the gas shell transforms from the gaseous state to the liquid state without phase transition. The «surface» is defined as the region, at which the pressure is 1 bar.

The sunlight is partially reflected by the upper cloud level. These cloud layers are located below a layer of Methane gas (CH₄). If the light transverses this CH₄-layer, the reddish part of light is strongly absorbed by the CH₄-gas, whereas the blue part is scattered and reflected. Therefore, Uranus appears in a blue-green color.

Uranus in natural colors; Photograph from Voyager 2, 1986

Uranus with a southern, dense and bright cloud band. Courtesy of NASA / ESA / M. Showalter (SET)

The Atmosphere of Uranus - 2

The Atmosphere of Uranus can be divided into three layers. The Troposphere is located in a height scale between ~ 300 and 50 km and the pressures is between 100 to 0.1 bar (the zero point of the height scale, i.e. of the «surface», is fixed at a pressure of 1 bar). The Stratosphere extends from 50 to 4'000 km and the pressures are between 0.1 and 10⁻¹⁰ bar. The Thermosphere/Corona extends from 4'000 km to 50'000 km above the surface.

The Troposphere

The Troposphere is the lowermost and densest part of the Atmosphere. Its temperature decreases with increasing altitude. At the lowest part of the Troposphere, which is located at about 300 km below the 1 bar level, the temperature is about 320 K (~ 47°C). Up to the top of the Troposphere, at an altitude of about 50 km, the temperature drops to about 53 K (~ 220 °C). The Troposphere contains almost the whole mass of the Atmosphere and is also responsible for the planetary thermal radiation (radiation in the infrared region of the spectrum).

The clouds consist probably of frozen particles of methane (CH₄), which went up from deep levels as hot gases and condensed in the upper layers. It is assumed that the lower clouds consist of water, while the upper clouds consist of methane. The wind velocities are up to 200 m/s or about 700 km/h (!). At 1 bar, the temperature is about 76 K (~ 197 °C), at 0.1 bar it is about 53 K (~ 220 °C).

The Stratosphere

In the Stratosphere, the middle layer of the Atmosphere of Uranus, the temperature generally increases with increasing altitude. At the lower limit at about 50 km (at the Troposphere) the temperature is still 53 K, while at an altitude of 4'000 km (at the limit of the Thermosphere) the temperature is as high as 800 to 850 K (527 – 577 °C). The reason for the heating of the Stratosphere is due to the absorption of UV- and IR-radiation by methane and other hydrocarbons; in these altitudes, the gases are generated by the production of methane protolysis (processes by which methane molecules are broken into smaller units through the absorption of light). In addition, the heat transport from the hot Thermosphere could also contribute to the heating of the Stratosphere.
The Atmosphere of Uranus – 3; The Ring-system

**Thermosphere and Corona**

The outermost layer of the Uranus-Atmosphere is the Thermosphere and Corona. It has a uniform temperature of 800 to 850 K (527 – 577 °C). This latter temperature is considerably higher than the 420 K (150°C) of the Thermosphere of Saturn. The necessary heat sources are not known. Neither solar UV-light nor polar light activities are able to provide the necessary heat. Reduced heat radiation due to the lack of hydrocarbons could contribute to the maintenance of the high temperatures. In addition to molecular hydrogen (H₂), the Thermosphere and the Corona contain a large amount of free hydrogen atoms (H). The small masses of both, H₂ and H, together with the high temperatures, could explain the extremely large extension of the Corona (up to 50'000 km, a distance corresponding to two radii of the Uranus-Planet).

This extended Corona is a unique feature of Uranus. The small particles orbiting the Uranus are decelerated by the Corona. As a consequence, the rings of Uranus have a very low dust concentration.

**Rings and Moons of Uranus**

As all gas planets of the Solar system, Uranus is surrounded by a large concentration of very small bodies and particles which are orbiting around the Planet in the direction of its rotation. Their densely populated different orbits are forming a system of concentric rings. Most of these rings are orbiting in the equatorial plane of the Planet.
With reference to the Sun, Neptune is the eighth and outermost Planet of our Solar system; its mean distance from the Sun is about 4.5 billion km.

Its diameter is almost 50'000 km which is nearly five times the diameter of the Earth while its volume is about 57.57 times the volume of the Earth. It is the fourth largest Planet of the Solar system (remember that Uranus is the third largest Planet).

Together with Uranus, Neptune belongs to the subgroup of the so-called Ice Giants. Neptune is dominating the outer zone of the planetary system. At present, 14 Moons of Neptune are known! By far the largest Moon is Triton having a diameter of 27'000 km.

**Properties of the Orbit**
- Semi-major axis: 4'495 million km
- Excentricity: 0.0113
- Siderical period: 164.79 years
- Average orbital speed: 5.43 km/s

**Physical properties**
- Equatorial diameter: 49'528 km
- Polar diameter: 48'682 km
- Mass: 1.024 x 10^26 kg
- Average density: 1.638 g/cm^3

**Main components**
- Hydrogen (H\textsubscript{2}): 80.0%
- Helium (He): 19.0%
- Methane (CH\textsubscript{4}): 1.5%
- Hydrogen deuterium (HD): ~ 0.019%
- Ethane (C\textsubscript{2}H\textsubscript{6}): ~ 0.00015%
- Different Ices (NH\textsubscript{3}, H\textsubscript{2}O, CH\textsubscript{4}, ...)

**Further Properties**
- Gravitational acceleration: 11.15 m/s\textsuperscript{2}
- Inclination of axis of rotation: 28.32°
- Rotation period: 15 h 57 min 59 s
- Geometric albedo: 0.41
- Temperature: -201 °C
Neptune's Interior and chemical composition

**Neptune's Interior**

Similar to the structure of Uranus, three layers can be distinguished: 1) a rocky core of about 1 to 1.5 Earth masses made of rock in the center, 2) a mantle of 10 to 15 Earth masses of a mixture of rock, water (H$_2$O), Ammonia (NH$_3$) and Methane CH$_4$, and 3) an upper layer of about 1 to 2 Earth masses of H$_2$O, He and CH$_4$.

- **Core:**
  - The pressure is several million bar, about twice as large as that in the center of the Earth.
  - The temperature in the center is up to 7000°C.

- **Mantle:**
  - A liquid with high electrical conductivity.

- **Inner and outer gaseous Atmosphere**

**b) Chemical composition**

Apart from the core, Neptun consists essentially of a single large «Atmosphere». The Atmosphere has the following composition:

- Hydrogen (H$_2$): 80.0 %
- Helium (He): 19.0 %
- Methane (CH$_4$): 1.5 %
- Hydrogen-Deuterium (HD): 0.0142 %
- Benzene (C$_6$H$_6$): 0.00015 %

[The temperature at 1 bar is about 72 K (≈ -200°C) and at 0.1 bar it is about 55 K (≈ -218°C).]

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**The Atmosphere of Neptune - 1**

Similar to the Atmosphere of Uranus, the Atmosphere of Neptune can be subdivided into three layers:

- **Troposphere** starts immediately above the surface. In the Troposphere, the temperature decreases with increasing altitude.
- In the next layer, the **Stratosphere**, the temperature increases slightly with increasing altitude. The reason for this increase is not well understood. It is, however, believed that this increase is related to the motion inside the Planet's core which heats Neptune more than the rays from the distant Sun.
- The next layer is the **Thermosphere** (not shown in the Figure), where pressures are lower.
- The very outer edge of the Atmosphere is known as the **Exosphere**.

The minimum temperature is about – 225 °C. (about 48 K).

In comparison to Uranus with an axis of rotation at an angle of 98° (s. p. 446), Neptune has a normal rotation behavior since the inclination of its axis of rotation is only 28.3° (s. p. 453).
The Atmosphere of Neptune is similar to that of the other Ice-giants of the Solar system: It consists mainly of (H₂) and Helium (He); in addition, traces of Methane (CH₄), Ammonia (NH₃) and other Ices. But in contrast to the other Planets of the Solar system, Neptune has a great part of Ices in the form of Ice particles of Methane in its outer Atmosphere → deep blue color.

The upper cloud layers appear where the pressure is sufficiently small such that Methane can condense out. Astronomers have photographed these high-altitude clouds; these clouds form shadows on the underlying clouds. (see left-hand picture).

In the highest altitudes, in which the Atmosphere passes into space, it consists of 80% hydrogen and 19% Helium. As already mentioned, the Atmosphere contains in addition traces of Methane. The light we are observing is the Sunlight reflected and scattered by Neptune. From the total spectrum of the Sunlight, the traces of Methane absorb the red light component (see the Fals-color image of the red margin in the right-hand picture) while the blue light is backscattered and reflected.
10.3 Exoplanets: History – Methods of Observations and Examples

10.3.1 Observations of Stars and Search of Exoplanets
Giordano Bruno (1548 – 1600) coined the phrase:

«There are countless Stars and countless Earths which are orbiting in the same way as our seven Planets around our Solar System [...]. The countless worlds in the Universe are not less and worser habitated than our Earth.»

Giordano Bruno was sentenced to death by the Inquisition. On this judgement, Bruno responded with the famous phrase: «Perhaps you pronounce this sentence against me with greater fear than I receive it». At February 17 of the year 1600 he was burned at the stake at the Campo di Fiori in Rome.

**Supernova (SN) – Remnant of the Starburst from 1572**

At the beginning of November 1572, the bright lightning of a Star was observed in the constellation of Cassiopeia in our Milky Way Galaxy. The most prominent observer was the astronomer Tycho Brahe. Such a bright lightning arises from a huge explosion at the end of the lifetime of a Star. The luminosity due to this explosion increases by a million to billions of time; for a short time it is so bright as a large Galaxy.

The picture shows the Supernova remnant of SN-1572 as it was observed from its emitted X-ray emission by the Chandra X-ray Observatory – Satellit.

This observation showed that also the fixed Stars are not invariable, i.e. they have a finite lifetime.


### Astronomy in the 17th and 18th Century

The invention of the telescope (1608): No other invention revolutionized Astronomy more than the invention of the telescope. In 1608, the Dutchman Lippenhey (1560 – 1619) had constructed the first telescope that allowed a three-to four fold magnification.

Galileo Galilei constructed a telescope having a 9 times and later even a 30 times magnification and aligned them toward the sky. With these telescopes he discovered that our Milky Way Galaxy was a huge collection of Stars. The Inquisition sentenced him to a life-long house arrest. Galileo recognized that the Earth was not the center of the Universe but rather orbited around the Sun. From Galilei comes the sentence: «And yet it moves !» - «E pur si muove !»

Johannes Kepler (1571 – 1630): Through careful observations and conclusions, Kepler established his three famous laws (s. Appendix 10-A-1-2). At 1618 he published his work «Harmonice mundi» which contains the third law of Kepler. Combined with Newton’s gravitational constant it still plays an important role for the determination of the parameters of Exoplanets (s. pp 462 – 470).

Isaac Newton (1643 – 1727): He was undoubtedly one of the greatest scientists of all times. In his «Principia», he established the three laws of Newton; among others, it contains also the gravitational constant designated so by himself. This constant allows the evaluation of the force of gravity or the determination of the orbital period of a Planet.

Christian Huygens (1629 – 1695): He was concerned with the existence of life on other Planets and postulated that the basic requirement for life was the existence of liquid water. In addition he postulated that aliens too have a human-like appearance. His most interesting theory is, however, that life has to adapt to the Planet.

Friedrich Wilhelm Herschel (1738 – 1822) constructed telescopes with diameters of up to 122 cm. With the powere of these telescopes he discovered the Planet Uranus, some Moons and Nebula and he created a statistic of the Milky Way.

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### Importance of Parallax in Astronomy

Parallax

The Mathematician and Astronomer Friedrich Wilhelm Bessel (1784–1846), made a significant discovery, namely the Parallax, an apparent angular displacement of nearby Stars due to the movement of the Earth around the Sun. For Astronomy, the Parallax \( p \) is of central importance because it allows the evaluation of the distance between a Star and the Sun.

Let \( R = AU = \text{Astronomical Unit} \) (distance between Earth and Sun: \( R = 1 \text{ AU} = 149.6 \text{ Mio. km} \)), \( D = \text{distance between Sun and Star} \), and \( p \) the angle of Parallax. Then it follows: \( D = R / \tan(p) \) or \( A = R / \sin(p) \).

**Example:** For the Star Alpha Centauri C, the distance \( D \approx 4.243 \text{ lightyears} \) \( (l) \) \( = 40.14 \times 10^{12} \text{ km} \) \( [1 \text{ l} \approx 9.4605284 \times 10^{12} \text{ km}] \) one obtains:

\[
\tan(p) = R/D \approx 3.726 \times 10^{-6} \quad \text{or} \quad p=3.726\times 10^{-6} \text{ radians} \approx 2.135 \times 10^{-4} \text{ degrees} \\
= 0.768 \text{ arcseconds} = 0.768 ^\prime \]  

\([1 \text{ degree} = 3^\prime 600 ^\prime \prime]\).
**Discovery of Exoplanets with the help of the Doppler-Effect**

Christian Doppler (1803 – 1853) calculated the frequency changes of the light waves depending on whether the source and the observer are moving towards or away from each other: The light is shifted to the reddish end of the spectrum if the object (in the present case a Star) is moving away from us and a shift to the blue end if it is moving toward us.

The Doppler technique is a good method for discovering Exoplanets. With the help of the Doppler effect, the movements and properties of the Stars and the Planets can be analyzed. Both, the Star and the Planet are moving around a fixed common point, the center of mass of Star and Planet. A more detailed description of the Figure below is found in Appendices 10-A-3-1 and 10-A-3-2.

![Doppler Effect Diagram](image)

a) The Doppler shifts allow us to detect the slight motion of a Star caused by an orbiting Planet.

b) A periodic Doppler shift in the spectrum of the Star 51 Pegasi shows the presence of a large Planet with an orbital period of about 4 days. Dots are actual data points; bars through dots represent measurement uncertainty.

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**Transit – Methode for the observation of Exoplanets**

Transit-methode of Planet WASP-3b at his Central Star WASP-3

For the transit- method one is interested in Planets, which are transiting over a central Star if viewed from the Earth. During such a transit, the brightness of the Star is reduced. This small reduction of brightness can be observed. For a Planet of the size of Jupiter which is orbiting around a Sun-like Star, a reduction of brightness of ~1% is observed.

But a single transit is not sufficient to discover a Planet with certainty. After all, there are other phenomena which can reduce the brightness of a Star. Examples of such phenomena are Star spots or pulsations of a Star. In fact, it is necessary to observe three periodically occurring minima of brightness.

The Figure shows a plot of brightness of the Star versus observing time. Here, it is common practice to measure the brightness in units of millimagnitudes = 10^-3 magnitudes. [A magnitude is a logarithm measure of brightness; see Ref. R.10.3.1.5].

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Transit passage at the Star WASP-3
Resonance of two Planets orbiting around a Star

In the observation of Planet WASP-3b (p. 464) and a more precise analysis around the Star WASP-3 by a team of astronomers from Germany, Bulgaria and Poland, a small variation of the expected orbit time of WASP-3b has been detected. It could be shown that this so-called transit time variation was due to another Planet, the so-called Planet WASP-3c (see Figure).

By combination of more exact observations and Computer simulations of the data, the existence of the Planet could be confirmed. Its orbit is farther out than that of the gas giant WASP-3b and is related by the former with a so-called 2:1 Resonance. This means that the time needed for two orbits of the gas giant WASP-3b is just the same as for one orbit of the newly discovered Planet WASP-3c. If \( T_{3b} \) and \( T_{3c} \) are the corresponding orbit times, we then have: \( T_{3b} = 2 T_{3c} \), \( T_{3b} = 1.847 \) d \( \rightarrow T_{3c} = 3.694 \) d (1d = 1 day).

The orbit of Planet 3b is almost circular. We assume that this is also the case for the Planet 3c. If \( r_{3b} \) and \( r_{3c} \) are the radii of the circular orbits, Kepler's third law (p. 10-A-1-2) gives: \( (T_{3b}/T_{3c})^2 = (r_{3b}/r_{3c})^3 \) and with \( T_{3b}/T_{3c} = 2 \) it follows: \( r_{3b} = 4 \) \( r_{3c} = 1.587 \) \( r_{3b} \). This is in good agreement with the dimensions of the adjacent Figure. With \( r_{3b} = 4.74225 \times 10^6 \) km one obtains \( r_{3c} = 7.528 \times 10^6 \) km.

The mass of WASP-3b is \( M_{3b} = 3.912 \times 10^{27} \) kg and that of the Planet WASP-3c is \( M_{3c} = 15 \) \( M_{E} \) where \( M_{E} = 5.972 \times 10^{24} \) kg is the mass of the Earth (s. p. 429). \( M_{3b} = 8.958 \times 10^{23} \) kg, i.e. \( M_{3b}/M_{3c} = 43.7 \). Hence, the mass of the Planet 3c is about 44 times smaller than the mass of the Planet 3b or \( M_{3c} = 0.023 \) \( M_{3b} \) (\( M_{3c} = 2.3 \) % of \( M_{3b} \)).

The orbit velocities around the Star WASP-3 are \( v_{3b} = 2 \pi r_{3b}/T_{3b} \) and \( v_{3c} = 2 \pi r_{3c}/T_{3c} \). It then follows: \( v_{3b} = 188.6 \) km/s and \( v_{3c} = 148.1 \) km/s.

\[2 : 1 \text{ Orbital resonance of the Planets WASP-3b and WASP-3c around the Star WASP-3}\]
10.3.2 Discovery and Systematics of Selected Exoplanets

Exoplanets in habitable Zone

Explanation to Figure: s. p. 468
Comments of Exoplanets in the habitable Zone

In the Figure of p. 467, the habitable zone of some Stars are shown. In the habitable zone (blue marked area), liquid Water can exist at the surface of the Planet.

The inner Planets of our Solar System are shown at the top of the Figure. Here, the Earth and Mars are in the habitable zone.

The Star Kepler-62 is at a distance of about 1200 light years (ly) from the Earth. It is considerably colder than the Sun and it is orbited by at least five Planets. Here, the two Planets Kepler-62e and Kepler-62f are in the habitable zone.

The Star Kepler-69 is a Sun-like Star, which has a distance of 2'700 ly from the Earth. It is orbited by at least two Exoplanets. In April 2013, NASA has discovered a new Planet, the Planet Kepler-69c. It is assumed that Kepler-69c is possibly also a habitable Planet.

The Star Kepler-22 is a Star at a distance of about 600 ly from the Earth. In its planetary system the Planet Kepler-22b is located. It is one of the smallest Planets found so far and it is possibly a mini-Neptune (pp 452, 453), i.e. it is a very small gas Planet.

The designation «empirical habitable zone» means that Water is present at the surface of the Planet and in addition that it has a sufficient layer of clouds. On the other hand, the designation «conservative habitable zone» means, that liquid Water can exist at the surface but without a layer of clouds.

Radius als Funktion der Masse für ausgewählte Exoplaneten

Erläuterungen zur Graphik: s. p. 471

M in Einheiten der Erdmasse $M_E$:
$M_E = 5.972 \times 10^{24}$ kg

R in Einheiten des mittleren Erdradius $R_E$:
$R_E = 6'371$ km

Erläuterungen zur Graphik: s. p. 471
Masses and sizes of selected Planets:
Explications of the Graph at p. 469

The curves in the Figure of p. 469 show the radii $R$ as a function of masses $M$ [average densities $\rho = M/V$; Volumes $V = (4\pi/3)R^3$] for different types of Planets.

- The blue line indicates the locii of Planets made mostly (75%) of Water.
- The black line indicates Planets similar to the Earth which consist almost exclusively of rock (represented here by the mineral Entstatite, $(\text{Mg}_2\text{SiO}_3)_2$, a member of the pyroxite silicate mineral series that makes up most of the Earth’s mantel).
- The measured radii of Kepler-62e and Kepler-62f plus an estimate of their masses places them in a region (blue areas) where it is highly probable for them to be Earth-like Planets, that is: Planets with a solid mantel surface (possibly covered with Water).
- The Planet Kepler-11f, on the other hand, is a Mini-Neptune, showing clearly that a comparatively low mass does not necessarily make for a solid Planet (Image: L. Kaltenbrunner (MPIA)).
- The Star Kepler-62 in the constellation Lyra is about 1200 light-years from the Earth. It is somewhat colder than the Sun and is orbited by at least 5 Planets.
- The radius of Planet Kepler-62e is 1.61 times the Earth’s size and circles the Star in 122.4 (Earth days). Its core consists probably on silicates and iron and is covered by a considerable quantity of Water.
- The radius of the Planet Kepler-62f is 1.4 times the size of Earth, and orbits its Star Kepler-62 in 267.3 days. It is located in the habitable zone of his Star and is probably completely covered with Water. Previously, the smallest Planet with known radius inside a habitable zone was Kepler-22b, with a radius of 2.4 times that of the Earth.
10.3.3 Our Milky Way Galaxy

The observable Universe contains about 100 – 400 billions (100 - 400 * 10^9) Galaxies of similar sizes as our Milky Way Galaxy. 1 light-year (ly) is 9.46 * 10^12 km! The oldest known Star in our Milky Way Galaxy is about 13.2 billion years (13.2 * 10^9 years).

Our Milky Way Galaxy

- Diameter:
  ~ 10^5 light-years
  (9.5 * 10^17 km)

- Thickness:
  ~ 10^3 light-years
  (9.5 * 10^15 km)

- Age:
  ~ 13.6 billion years
  (13.6 * 10^9 years)

- Number of Stars:
  ~ 300 billion
  (300 * 10^9 Stars)
Edwin Hubble studied and classified the types of Galaxies: He distinguished between elliptical, lenticular and spiral Galaxies. The spiral Galaxies are disc-shaped with spiral arms (s. Figure p. 472 of the Milky-Way System).

An elliptic Galaxy is a Galaxy having an approximately elliptic shape with a smooth and nearly uniform brightness profile. Depending on the Galaxy, they range from almost spherical to strongly flattened shapes. Lenticular (linsenförmige) Galaxies have shapes and properties ranging between elliptical and spiral Galaxies.

The Milky Way, or simply the Galaxy, is the Galaxy in which our Solar System is located. It is a barred spiral Galaxy that is part of the Local Group of Galaxies. It is one of billions of Galaxies in the observed Universe.

The stellar disk of the Milky Way (s. pp 472, 473) is approximately 100'000 light-years (ly) (9.5 \times 10^{15} \text{ km}) in diameter, and is considered to be, on average, about 1'000 (ly) (9.5 \times 10^{15} \text{ km}) thick. It is estimated to contain at least 200 billion stars and possibly up to 400 billion stars; the exact figure depends on the number of very low-mass stars, the number of which is highly uncertain.

As a guide to the relative physical scale of the Milky Way, if it were reduced to 10 m in diameter, our Solar System, including the Oort cloud (spherical cloud of Comets), would be no more than 0.1 mm in width! This is a factor of 100'000 (!).

By including the estimated age of the stars in the globular cluster (about 13.4 billion years), the age of the oldest stars in the Milky System has been estimated to about 13.6 billion years. Based upon this newest scientific result, the Galactic thin disk is estimated to have been formed between 6.5 and 10.1 billion years ago.

The galactic disk, which bulges outward at the galactic center, has a diameter between 70'000 and 100'000 ly. The distance from our Sun to the galactic center is now estimated at 26'000 ± 1400 ly.

The galactic center harbors a compact object of very large mass as concluded by the motion of material around the center. The intense radio source named Sagittarius A*, thought to mark the center of the Milky Way, is newly confirmed to be a «Supermassive Black Hole». Most Galaxies are believed to have a supermassive black hole at their center.
The Fermi–Hart Paradoxon

The Fermi-Paradoxon is a contradiction which has been formulated by the physicist Enrico Fermi in 1950. The Paradoxon questions the probability for extraterrestrial intelligent life. Its aim is to try to answer a fundamental question: «Are humans of the Earth the only technically advanced civilization?»

In our Galaxy there are about 100 billion of Stars. If only a very small fraction of these Stars are orbited by Planets in which a technological civilization has been developed, a very large number of such civilizations must exist. If only a few of these cultures have developed civilizations which have been spread out with a small fraction of the velocity of light (0.01 c to 0.1 c), Planets of next Stars could be populated; this population could then have spread out over the whole Galaxy. For this reason, our whole Galaxy would be populated within some millions of years. Since the age of the Galaxy is billions of years, our Earth should have been visited and colonized a very long time ago.

A detailed scientific investigation of this problem has been started in the early 1970'th by studies of Michael H. Hart (born 1932), and therefore the term Fermi - Hart Paradoxon is used. According to Michael H. Hart, the conclusion is the following:

«We observe that no intelligent beings from outer space are now present on Earth. It is suggested that this fact can best be explained by the hypothesis that there are no other advanced civilizations in our Galaxy. Reasons are given for rejecting all alternative explanations of the absence of extraterrestrials from Earth».

Drake– and Seager Equations

In contrast to the hypothesis of M.H. Hart (p. 475), according to which no highly developed civilizations exist in our Galaxy, the Astronomer Frank Drake tried to estimate in 1961 the number N of Planets having technical and intelligent civilizations in our Milky Way Galaxy. One variant of the equation for N is: \[ N = N^* \cdot f_p \cdot n_h \cdot f_l \cdot f_e \cdot f_c . \] In this equation, the significance of the factors for N is:

- \( N^* \): Number of Stars in Milky Way Galaxy;
- \( f_p \): fraction of Stars having «habitable» Planets; \( \text{[existence of liquid Water and life-friendly Atmospheres]} \)
- \( n_h \): number of habitable Planets per Star;
- \( f_l \): fraction of Planets in \( n_h \) in which life is really developing;
- \( f_e \): fraction of \( f_l \) in which intelligent (civilizations) is developed;
- \( f_c \): fraction of \( f_e \) which is communicating.

The Drake equation lists the factors for the evaluation of N. For the actual evaluation of N, however, it is not really useful. The equation assumes, that all factors are of equal importance (probability = as well as= for independent events). In addition, the last 4 factors, \( f_p \), \( f_l \), \( f_e \) and \( f_c \), can hardly been estimated.

In the following, we give an example:

\[ \begin{align*}
N^* &= 100 \times 10^4; \ f_p = 2\% = 0.02; \ n_h = 1; \ f_l = 10\% = 0.10; \ f_e = 10\% = 0.10; \\
&= 10\% = 0.10; \ f_c = 50\% = 0.50; \Rightarrow N = 1 \times 10^6 \text{ in Milky Way Galaxy} \\
&= \text{The estimation is extremely inaccurate!}
\end{align*} \]

A new equation for the estimation of N is based on the 30'000 discovered Planets and has been put forward by Sarah Sieger in 2013 [s. Ref. R.10.3.2.9 – ff]. This evaluation is based on the large number of data which have been gained in the meantime about the Atmosphere of the Planet (s. pp 484, 485; 489).
Planetary Masses versus Year of Discovery

Planetary masses (in Jupiter masses)

- \( M_{\text{Jupiter}} = \text{Mass of Jupiter} \)
- \( M_{\text{Jupiter}} = 1.899 \times 10^{27} \text{ kg} \)

Exoplanets of nearby Stars: Masses vs Semi–axis of Orbits

- J: Jupiter
- S: Saturn
- U: Uranus
- N: Neptune
- E: Earth
- V: Venus
- Ma: Mars
- Me: Mercury

AU = Astronomic Unit
1 AU = 149'597'870.7 km
= mean distance between Earth and Sun
Earth Mass \( M_{\odot} \)
\( M_{\odot} = 5.97219 \times 10^{24} \text{ kg} \)
Planetary Masses versus Year of Discovery:

p. 477: The Graph shows the mass-spectrum as a function of years between 1988 to 2013; note the logarithmic mass- and semi-axis scales. The masses are normalized with respect to the Jupiter mass. Unconfirmed data and pulsars have been excluded.

Planets which have been discovered by using the Doppler- method are shown in gray circles, those which have been observed by using the Transit- method are shown in red circles. The Figure also indicates the mass- positions of the Earth, of Neptune and of Jupiter: the latter is the reference Planet with mass 1.

Exoplanets of nearby Stars: Masses vs Semi-axis of Orbit

p. 478: More than 400 Planets are known to orbit nearby, Sun-like Stars. As regard to the Exoplanets discovered recently, the Figure of p. 10-A-3-4 should also be considered. The Figure of p. 478 belongs to Prof. Seager’s favorite diagrams. It shows the masses of Exoplanets as a function of the semi-axis of the orbits. The diagram (updated every month) shows that Exoplanets have all masses and semi-major axes possible, showcasing the random nature of Planet formation and migration. The different Planet detection techniques are shown in the diagram. Parts of the diagram with no Planets are where technology can not yet reach Exoplanets. The red letters indicate Planets of our Solar System: Me: Mercury; Ma: Mars; V: Venus; E: Earth (Earth: normalized semi-axis = 1, normalized mass = 1); U: Uranus; Ne: Neptune; S: Saturn; J: Jupiter.

Some important Earth-like Exoplanets

Recently, scientists have discovered two new Exoplanets, Kepler-62e and Kepler-62f, which are orbiting in a distance of 1'200 light-years (ly) from the Earth around their Star Kepler-62. At the top right of the Figure, the Planets Earth and Mars are shown. The Planets Kepler-62e and Kepler-62f are the smallest Planets which have been discovered by the Kepler-Mission. The numbers added to the Planets (for example 0.82 for Kepler-62e) are the so-called ESI- values (Earth Similarity Index), which are a measure for the similarity of the Planets with respect to the Earth [ESI (Erde) = 1, ESI (Kepler-62e) = 0.82]. The ESI value depends on the radius, on the the mean density, on the escape velocity and on the surface temperature of the Planet.
An international team of scientists, to which also Lisa Kaltenegger from Max-Planck Institute for Astronomy (MPIA) is a member, have announced in May 2013 two potentially Earth-like Planets, namely Kepler-62e and Kepler-62f. This discovery was made with NASA's Space Telescope Kepler. (The distance between the Earth and Kepler 62 is about 1’200 light-years (!); Kepler 62 is somewhat colder than the Sun. Judging by their relatively small radii (the radius of Kepler-62e is only 1.62 times and the radius of Kepler-62f is 1.41 times larger than the radius of the Earth), these Planets are expected to be rocky Planets. If this is the case, they would be the best candidates for life-friendly Planets. The investigations of Dr. Kaltenegger show, that both Planets are located in the habitable zone [liquid Water and Earth-like Atmosphere].

The illustration shows a comparison of the planetary system Kepler-62 with our own Solar System. The Planet’s orbits (shown above and below) are relativ to each other at the right scale; the same applies for the sizes of the Planets. The habitable zones are shown in green. As mentioned above, they have solid surfaces and are located in the habitable zone. At this point it should, however, be mentioned that the list of References, ([Ref. R.10.3.2.13 c] and d]) contains other candidates for habitable Planets.
10.4 The Atmospheres of Exoplanets

American Astronomers have developed a new method for the measurement of the mass of an Exoplanet. This method is based on the investigation of various parameters of the Atmosphere of the celestial body. The new technique could make possible to gain important insight in remote Earth-like objects and in addition, it could contribute to provide a basis for the existence of life. Although this method has been tested up to date only for large Jupiter-like gas Planets, scientists believe that with the help of more powerful Telescopes generations which are under development (see p. 488), it is also possible to investigate small Earth-like Planets.

Until January 2014 more than 900 Planets have been discovered which are orbiting around their Stars; in addition, 2'300 further celestial bodies have been discovered, which look like Exoplanets. Most of these Planets are similar to the gas Planet Jupiter (pp 435 – 438) because it is much simpler to observe these gigantic gas Planets with the help of the presently existing Telescopes (for example Hubble, Herschel, Spitzer). Nevertheless, several Earth-like rocky Planets have also been found. The Astronomers expect that with the help of next-generation Telescopes (for example with the James Webb Space Telescope (s. p. 488)), much more small rocky Planets will be detected.

[The Atmosphere of our Planet Jupiter is in the range, which is accessible to direct observation; it lies in the pressure range between a few 10 bar and a few hundreths bar. For a Planet, the «surface» is defined at a gas pressure of 1 bar.]

Artistic representation of the Planet «hot Jupiter» HD 189733b during his transit between the Earth and his Star HD 189733. Note the Planet's Atmosphere.
Masses of Exoplanets - Wobbling motion of Stars

It is expected that the chemical composition of an Exoplanet contains important information of whether a Planet can sustain life. Information about the inner composition of an Exoplanet is obtained from its density \( \rho \); the density is the ratio of mass \( M \) and volume \( V = 4\pi r^3 \) (\( r \) = radius of the Exoplanet); \( \rho = M/V \). The mass \( M \) of an Exoplanet can be obtained from the fact that its orbit generates a small wobbling motion of the Star: The Star moves very slightly toward the Earth and this displacement is then followed by a slight displacement away from the Earth. This wobbling motion of the Star is due to its rotation around the center of gravity of the Star and the Planet. It generates a Doppler–effect of the starlight (Red- and Blue shift, s. p. 463 and Appendix 10-A-3-1 and 10-A-3-2). If this information is compared with an independent estimate of the mass of the Star, an upper limit of the Planet's mass can be estimated.

This method gives good results for Jupiter-like Planets as well as for Earth-like Planets which are orbiting very close around a bright Star. But the method fails for rocky Planets orbiting in large distances around the Star as is the case for our Earth orbiting around the Sun. But life is expected to exist just on these latter Planets.

Now, Sara Seager and Julien de Wit from the Massachusetts Institute of Technology (MIT) have developed a new method for measuring the masses of Planets which are periodically orbiting around their Star. This so-called Transit-method has been described at pp 464 and 465. There we have explained that «Transit Planets» are blocking part of the Star-light observed from the Earth. By measuring the resulting partial extinction of the Star-light, both, the orbital period as well as the diameter of the Planet relativ to the Star can be determined.

Absorption of Starlight by the Atmosphere of Exoplanets - 1

With the help of Transit – measurements, important additional information can be obtained: If the Planet transits its Star, a small fraction of the Starlight traverses the Atmosphere of the Planet before reaching the Earth and another part will be scattered. From these observations, the Astronomers were able to gain important information concerning the chemical composition, the density and the temperature of the Atmosphere.

In their new scientific research, De Wit und Seager have extended their investigations to the atmospheric pressure. In particular they were interested to study the dependence of the atmospheric pressure as a function of the altitude above the surface of the Exoplanet. Their studies have shown that the pressure gradient (decrease of atmospheric pressure with increasing altitude), the density and the temperature of the Atmosphere are related to the mass of the Planet by relative simple equations. In addition, they have demonstrated that all properties mentioned above can be measured independently from the Transit – spectrum, allowing an independent determination of the mass.

Seager and De Wit have tested their method by evaluating the mass of a newly discovered Exoplanet, the distance of which is about 63 light-years from the Earth. It is the Exoplanet HD 189733 b; this «hot Jupiter» is orbiting around its Mother-Star in a very short circulation period of only 2.2 days. Since for the presently available Telescopes, this Planet is an ideal candidate, its mass could be well determined. Within about 5%, its mass is about 1.16 times larger than the mass of our Jupiter.

Unfortunately, the presently existing Telescopes such as Hubble, allow only the study of gas-giants, but small Earth-like Planets can not be investigated. However, scientists are confident that with the successor of the Hubble – Telescope, the so-called gigantic «James Webb Space Telescope» (JWST), which will be put into operation in 2018 (s. p. 488), small Earth-like Planets can be investigated. The reason for this assumption lies in the fact, that the Telescope is installed on bord of the Space craft and for this reason, it will be far superior to the Telescopes of today.
Absorption of Starlight by the Atmospheres of Exoplanets

Under certain conditions it is possible today, to study the Atmosphere of Exoplanets. For the identification of the Atmosphere of Exoplanets, it is advantageous to observe Planets orbiting around a large and bright Star; it is then possible to analyze the Planet by subtraction of the two spectra, it is possible to obtain the absorption spectrum of the Atmosphere.

The light from the Star is partially scattered and partially absorbed by the atoms and molecules of the Atmosphere. By observing the spectra of the light before entry into the Atmosphere and after leaving the Atmosphere and by subtraction of the two spectra, it is possible to obtain the absorption spectrum of the Atmosphere.

The WASP- Project (WASP = Wide-Angle Search for Planets) is well suited for such studies, because it is specially designed for the investigation of large Jupiter-like Planets which are orbiting close to its Star. NASA has investigated three WASP- Planets, WASP-12b, WASP-17b and WASP-19b. Thereby, a broad absorption band at a wavelength of 1.4 micrometers (µm) in the Near-Infrared region of the spectrum has been observed which is caused by the absorption of Water in the gaseous state.

Two young Astronomers explore the Atmospheres of Exoplanets

Lisa Kaltenegger from the Heidelberger Max-Planck-Institute for Astronomy (MPIA) studies the Atmospheres of Exoplanets. By Computer-supported research she is exploring spectral fingerprints of the Atmospheres of extrasolar terrestrial Planets which provide decisive evidence of potential traces of life. The aim of these studies is to find indications of Water (H₂O), Oxygen (O₂) and other gases such as Carbon dioxide (CO₂) and Methane (CH₄). The combination of O₂ with a reducing gas such as CH₄ is considered as a proof for the existence of biological activity on a Planet.

For her important contributions, Lisa Kaltenegger has obtained the «Heinz Maier - Leibnitz – Prize».

The working group of Kevin Heng at the «Center for Space and Habitability (CSH)» at the University of Bern is not devoted to the discovery of new Exoplanets but is rather searching Exoplanets which have an Atmosphere. The Atmospheres of Exoplanets are of interest for three reasons:

- Exoplanetary Atmospheres can harbor a complex climate system → Information about chemical and physical relationships.
- Exoplanetary Atmospheres can be observed already today from afar.
- Analysis of exoplanetary Atmospheres may possibly show signs of life.

Kevin Heng is an ETH Zwicky Prize Fellow in Astrophysics.
Planetary radii versus Orbital Periods

Transit-experiments of 603 Exoplanets orbiting around their Stars. The Graph contains the results of the planetary-radii as obtained with the Kepler-Telescope, as a function of the orbital periods. The colour scale (0 – 100%) on the right side of the Graph shows the Survey Completeness. It should be mentioned that at an orbital period of about 300 days, two Earth-like Planets have been discovered, the radii of which are about twice the Earth-radius.

Planets with «Biomarker Gases»: Astrobiology – Sara Seager

In Exoplanet - Science, «Biomarker Gases» are defined as gases, which are produced by life. [On the Earth, the most important biomarker gas is Oxygen (O2), which is produced by plants, algae and some bacterial groups (see Chapter 6, p. 251)]. Such gases can accumulate in the Atmosphere of Planets in sufficiently high concentrations so that they can be observed with the help of distant Telescopes. It is assumed, that the living beings absorb and store energy by chemical processes and that the chemical processes necessary for life then produce vital gaseous products.

In contrast to the Drake-equation (p. 476), which tries to estimate the Planets having technical and intelligent civilizations in our Galaxy, Sara Seager from MIT (pp 484, 485) is more modest: she is not considering intelligent life but she is rather searching for life itself. The Sara Seager equation can be written in the form: 

\[ N = N^* \cdot F_O \cdot F_{Hz} \cdot F_{L} \cdot F_S \]

where

- \( N \) = Number of Planets with observable signs of life
- \( N^* \) = Number of observable Stars
- \( F_O \) = Fraction of «Quite Stars», i.e. of Stars which are not changing in their brightness
- \( F_{Hz} \) = Fraction of Stars with rocky-like Planets in the «Habitable Zone»
- \( F_{L} \) = Fraction of those Planets which can be observed
- \( F_S \) = Fraction of Planets harboring life

Examples:

a) Sara Seager: 
\( N^* = 30'000 \); \( F_O = 0.2 \); \( F_{Hz} = 0.15 \); \( F_L = 0.001 \); \( F_S = 0.5 \); 
\( N \approx 0.45 \); Seager rather quotes a value of \( N = 2 \); but this latter value follows for \( F_O = 1 \):
\( N = 2 \cdot 0.25 = 0.5 \); The value for \( F_O \) seems to be quite uncertain!

b) With the «James Webb Space Telescope» (p. 490 b)), which will be taken into operation in 2018, the following values will be predicted by Seager’s equation:
\( N^* = 500'000 \); \( F_O = 0.2 \); \( F_{Hz} = 0.15 \); \( F_L = 0.001 \); \( F_S = 0.5 \); 
\( N \approx 7.5 \)

c) Milky Way: 
\( N^* = 100 \times 10^6 \); \( F_O = 0.2 \); \( F_{Hz} = 0.15 \); \( F_L = 0.001 \); \( F_S = 0.5 \); 
\( N \approx 1.5 \times 10^6 \)
The diameter of the JWST will be 6.4 meters. Receiving surface is about 7 times larger than that of the Hubble – Telescope.

- Consists of 18 hexagonal mirror segments
- Mirror segments will be unfolded only in Space
- JWST is an Infrared Telescope
- Weight: 6.2 tons
- Costs: about 8.7 billion US-Dollar

The Hubble – Telescope which is in operation since 1990 has delivered already extremely important information (s. p. 10-A-4-1).
An estimation suggests that in the observable (*) Universe, there are about $7 \times 10^{22}$ or $\approx 10^{23}$ Stars. The question arises as to the average number of Planets per Star. This is a hard question to answer: Scientists can only be sure that there is on the average at least one Planet per Star, but don't know much more than that. For the time being we assume that there are 1 to 2 Planets per Star and arrive at a total number of Planets of about $10^{23}$ to $2 \times 10^{23}$ Planets in the observable Universe.

(*) Note; The observable Universe consists of the Galaxies and other matter that can, in principle, be observed from the Earth at the present time, because light and other signals from these objects has had time to reach the Earth since the beginning of the cosmological expansion. Assuming the Universe is isotropic, the distance to the edge of the Universe is roughly the same in every direction. That is, the observable Universe is a spherical volume, a ball, indicated by the blue circle in the present Figure. This ball is centered on the observer and its diameter is estimated to be $D = 8.8 \times 10^{26}$ m $= 28.5$ Gpc $= 93$ Gly. $[1 \text{Gpc} = 1 \text{Gigaparsec} = 3.0857 \times 10^{22}$ m; $1 \text{Gly} = 1 \text{Gigalightyear} = 9.461 \times 10^{24}$ m and hence $1 \text{Gpc} = 3.26$ Gly.

In other words: some parts of the Universe are too far away for the light emitted since the Big Bang to have had enough time to reach Earth, so these portions of the Universe lie outside the observable Universe (indicated by the blue circle in the Figure).
**Origin and Expansion of the Universe**

The generally accepted theory of scientists which describes the origin and development of the Universe is the theory of the Big Bang. According to this theory, the Universe originates from an extremely dense and hot initial state that existed about 13.8 years ago.

The law of Edwin Hubble (s. pp 472, 473, 494 - 496) (Hubble law) states: The Galaxies are moving away from us, and their escape velocities are the faster, the faster away they are from us.

If a Galaxy is observed at a double distance, than its escape velocity \( v \) is doubled. In the meantime one knows that not the Galaxies are moving but rather the space between the Galaxies is increasing. Despite of these fact one still speaks about the escape velocities of the Galaxies. It should not be forgotten, however, that we are dealing here with a problem in 4- dimensional space with 3 space coordinates \( x, y, z \) and the time coordinate \( t \). Because of the very large expansion velocities, the problem must be treated with the Theory of General Relativity (Alexander Friedmann (1924) and George Lemaitre (1927))

In order to simplify, we discuss in the following a 3- dimensional model with two space coordinates \( x, y \), and the time coordinate \( t \). We consider an expanding sphere with radius \( R(t) \), and we assume that the Galaxies are located at the surface of this sphere. The location of a Galaxy on the surface of the sphere is given by two coordinates \( x \) and \( y \). This model is called the balloon model. In this model, the Galaxies are two-dimensional and we can imagine that they are pinned on the surface of the inflating spheric balloon.

![Balloon model of space](image1)

Flattening of the space in the balloon model.
The radius \( R \) increases over time: \( R = R(t) \)

---

**The Hubble Law: \( v = H_0 \cdot d \)**

\( H_0 = H(t_0) = \) present value of the Hubble parameter \( H(t) \)

- \( v = \) Expansion velocity; \( d = \) Distance between observer \( O \) and Galaxy \( G \) (s. Figure below).
- \( H_0 = 74.3 \text{ km} / (\text{s} \cdot \text{ Mpc}) = 2.4 \cdot 10^{-18} \text{ s}^{-1}; \) \([1 \text{ Mpc} = 1 \text{ Megaparsec} = 3.08567758 \cdot 10^{19} \text{ km}];
- Because of the distance of the Galaxy \( G \) from the observer \( O \) with velocity \( v \), \( O \) observes a redshift \( \Delta \lambda = \lambda - \lambda_0 \) of the light. For \( v < c \) we have: \( z = \Delta \lambda / \lambda_0 = v / c = (H_0 / c) \cdot d \). For larger velocities \( v \), the problem must be treated by the Theory of General Relativity (s. Appendix 10-A-5-1).
- It is assumed, that the present universe is nearly flat as represented by means of the balloon model (s. p. 493, right-hand Figure).

![Hubble Law](image2)

---
The fact that all Galaxies are moving away from us does not mean that we are at the center of the Universe. One rather would observe from all Galaxies that the other Galaxies are moving away from us. An expanding raisin bread in the oven is a good model. If one is sitting at an arbitrary raisin in the oven, one can observe how all the other raisins are moving away. The individual raisins are not growing.

\[ H_0 = 74.3 \, \text{km} / (\text{s} \cdot \text{Mpc}) \]

(1 Mpc = 1 Megaparsec ≈ 3.08568 \times 10^{19} \text{km})

More about the Big Bang and the Expansion of the Universe

The Big Bang does not refer to an explosion in space but rather to the common creation of matter, space and time from an original singularity (= peculiarity, anomaly, abnormality).

The Big Bang is the starting point for the creation of matter and space-time. Based on cosmological theories, such a starting point is obtained by astronomers from the observed expansion of the Universe and by counting back until a time at which all matter and radiation was concentrated in a narrow space area. The real Big Bang is prior to that time and designates the formal point of time at which the energy density was infinitely large. Since the established physical theories such as Quantum Field Theory and General Theory of Relativity presupposes the existence of space, time and matter, the real Big Bang cannot be described on the basis of these concepts.

Predictions from the Big Bang model: The Big Bang models with the above characteristics are the generally accepted explanations of the present state of the Universe. The reason for this is that they are able to predict some central facts which agree well with the observed state of the Universe. The most important predictions are: The Expansion of the Universe, the Cosmic Background Radiation as well as the Distribution of the Elements, in particular the proportion of Helium (He) to the total mass of the atoms. In addition, the most important properties of the temperature fluctuations of the cosmic background radiation can be explained in the context of the Big Bang models on the basis of cosmological perturbation theory.
Interstellar Gas: An extremely diluted «Atmosphere» - 1

About 99% of the interstellar medium exists in the gaseous state, from which 90% consists of hydrogen. Thereby, about half of this gas is bound to interstellar gas clouds. Depending on temperature, these gases have different properties:

In the coldest and densest regions of the interstellar medium, one finds clouds, whose cores contain mainly, molecular hydrogen (H₂). Molecular H₂ can only be found under these conditions, since it takes only a very small energy to break up the molecules. This happens if the light of Stars can penetrate deep enough into the clouds and can be absorbed by the molecules. The temperature of these molecular clouds is about 10 K (~263 °C). Furthermore, the clouds contain a high concentration of dust. In the core of the cloud, this dust protects the molecular H₂-gas from dissociation by photons. In addition, compounds have been discovered, for example CH₃⁺- ions, suggesting that these ions are functioning as a kind of cosmic Oil-Refinery.

Occasionally, one finds gas clouds in the vicinity of hot Stars, which heats up the gas to a temperature of 10'000 K. In this case, the radiation from the Star heats up the H-atoms such that they are ionized, i.e. they are loosing their electrons. By the recapture of an electron, red light with a wavelength of 656.3 nm is emitted (1 nm = 10⁻⁹ m). The resulting gas clouds are referred to as emission nebulas which consist of ionized H⁺. Astronomers are referring them as HII – clouds.

![Horsehead Nebula: Orion – Nebula, containing dust and H₂ in the core.](image)

Gases of the interstellar Medium - Table

Remarks: The enormously large collision times and mean free paths implies that the temperatures are not due to collisions between the molecules. The concentrations of the gases are enormously small implying a ballistic movement of the particles. The partially very high temperatures are rather generated by thermal radiation of neighbouring stars (in analogy with the Thermosphere, pp 49-53, Chapter 2).

<table>
<thead>
<tr>
<th>Properties Media</th>
<th>Hydrogen</th>
<th>Temperature T(K)</th>
<th>Particles per cm³</th>
<th>Collision-times (s)</th>
<th>Mean free paths (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coronal Gas</td>
<td>H⁺</td>
<td>1'000'000</td>
<td>0.01</td>
<td>10¹¹</td>
<td>10¹⁴</td>
</tr>
<tr>
<td>Diffuse Nebulae</td>
<td>H⁺</td>
<td>1'000</td>
<td>100 – 1'000</td>
<td>10⁷</td>
<td>10⁹</td>
</tr>
<tr>
<td>Between the Nebulae</td>
<td>H</td>
<td>10'000</td>
<td>0.1</td>
<td>10¹¹</td>
<td>10¹³</td>
</tr>
<tr>
<td>Diffuse clouds</td>
<td>H, H₂</td>
<td>50 - 100</td>
<td>10 - 100</td>
<td>10⁹</td>
<td>10¹⁰</td>
</tr>
<tr>
<td>Dark clouds</td>
<td>H₂</td>
<td>10 - 50</td>
<td></td>
<td>10² - 10⁷</td>
<td>10⁴</td>
</tr>
<tr>
<td>Giant molecular clouds</td>
<td>H₂</td>
<td>10</td>
<td>500</td>
<td>10⁹</td>
<td>10¹⁰</td>
</tr>
<tr>
<td>Earth’s surface</td>
<td>Air</td>
<td>300</td>
<td>~ 10¹⁹</td>
<td>~ 10⁻⁶</td>
<td>~ 10⁻⁷</td>
</tr>
</tbody>
</table>

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10–51
An Inter-Galactic-Medium (IGM), also referred to as an intergalactic gas, is hydrogen gas, which is not bound to individual galaxies, but rather exists in the vast space between the galaxies. It consists mainly of ionized hydrogen gas H\(^+\), the so-called Plasma HII (pp 497, 498). The concentration of neutral hydrogen H (also called HI) is only about one millionth of the total medium. IGM should not be confused with the interstellar medium consisting of H\(_2\) and H (pp 497, 498) which is located between the Stars of the galaxies. The boundary between the intergalactic and interstellar region is, however, a smooth transition.

Cosmologists have suspected for a long time that the large-scale structure of the Universe resembles a spider web. Formidable filaments of hydrogen gas are traversing the dark expanses of the Universe. They constitute a branched network with nodes in which matter accumulates and galaxies such as our Milky Way are formed. Since the diffuse gas of cosmic filaments does not, however, emit light, cosmologists were forced to study the intergalactic network only by means of Computer simulations.

Thanks to a pure coincidenc, the astronomer Sebastiano Castalupo from the University of California in Santa Cruz and his colleagues were now able for the first time to observe a part of the mysterious network. At the W.M. Keck Observatory in Haway they were just studying the quasar UM287 as they discovered something very unusual: On their telescope recording they discovered suddenly a vast filament of hydrogen which extended over a distance of almost two million light-years into the intergalactic space. It was the enormous radiation of a quasar that caused the intergalactic gas to glow.

In the present picture (a simulation), the galaxies are only tiny dots in the nodes of the network!
Appendix: Chapter 10

Vincent van Gogh: «The Starry Night» (1889)
Johann Wolfgang Goethe  
(1749 - 1832)

Faust: Prologue in Heaven

RAPHAEL
The sun-orb sings, in emulation, 
Mid brother-spheres, his ancient round:
His path predestined through Creation 
He ends with step of thunder-sound. 
The angels from his visage spendid, 
Draw power, whose measure none can say; 
The lofty works, uncomprehended, 
Are bright as on the earliest day. 

(Bayard Tayler)

Kepler's Law of Orbit (1571 – 1630)

1. First Law:
The orbit of a Planet P is an ellipse with the Sun S in one of the foci.

S: Sun - P: Planet

Second Law:
A line segment joining a Planet and the Sun sweeps out equal areas during equal time intervals: If t is this interval, then $A_1 = A_2 = A_3 = A$.

Third Law:
Let $M_s$ be the mass of the Sun which is orbited by two Planets 1 and 2 having masses $M_1$ and $M_2$ and semi-major axis $a_1$ and $a_2$, respective and let $G$ be the gravitational constant. Furthermore, let $T_1$ and $T_2$ be the orbit times of Planets 1 and 2. The exact formula for orbit time $T_1$ is then:

$$T_1^2 = \left( \frac{4 \pi^2}{G (M_s + M_0)} \right) a_1^3$$

and a similar formula applies for $T_2$. Since $M_0 \ll M_s$, $M_1 \ll M_s$, it follows immediately for the two Planets 1 and 2:

$$\left( \frac{T_1}{T_2} \right)^2 = \left( \frac{a_1}{a_2} \right)^3.$$
According to pp 416 and 10-A-1-2, the orbits of Planets around the Sun are ellipses with the Sun in one of the foci. Since according to p. 416, the numerical eccentricities ε are small for most Planets, we approximate the orbit of a Planet by a circle with Radius $R_p$. Let $M_s$ = mass of the Sun, $M_p$ = mass of a Planet and $v$ is the constant magnitude of its orbit velocity. Then, the net centripetal force $F_{cf}$ acting upon a Planet at each point of the circle is given by

$$F_{cf} = M_p \frac{v^2}{R_p},$$  \hspace{1cm} (1)$$

The net centrifugal force is balanced by the gravitational force $F_G$ which is given by

$$F_G = G \frac{M_p M_s}{R_p^2},$$  \hspace{1cm} (2)$$

where $G = 6.673 \times 10^{-11}$ N m$^2$/kg$^2$ is the gravitational constant. In equilibrium, $F_G = F_{cf}$ and one obtains from eqs. (1) and (2).

$$v^2 = \frac{G M_s}{R_p} = \left(2 \pi \frac{R_p}{T}\right)^2$$  \hspace{1cm} (3)$$

where $T$ is the time period of the Planet around the Sun. Substituting (3) into (1) one obtains;

$$F_{cf} = M_p \left(4 \pi^2 \frac{R_p}{T^2}\right)$$  \hspace{1cm} (4)$$

From $F_{cf} = F_G$ one obtains from eqs. (2) and (4) the result:

$$T^2 = \left(\frac{4 \pi^2}{G M_s}\right) R_p^3.$$  \hspace{1cm} (5)$$

This is Kepler’s third law for a Planet with a circular orbit (s. p. 10-A-1-2). The constant magnitude of the velocity $v$ of the Planet orbiting around the Sun implies Kepler’s second law: $A_1 = A_2 = A$. [Note that for the vectors $\vec{F}_G = \vec{F}_{cp}$ = centripetal force where $\vec{F}_{cp} = - \vec{F}_{cf}$].

\[10-A-1-3\]

In the following we consider the acceleration forces associated with the orbital motion around the Sun. Since the magnitude of $v$ is constant, there is no tangential force $a_t$; there is, however, a radial acceleration force $a_r \neq 0$. This latter acceleration can be defined from

$$F_{cf} = F_G = M_p \frac{v^2}{R_p} = G \frac{M_p M_s}{R_p^2} = M_s a_r \rightarrow a_r = \frac{(G M_s)}{R_p^2}$$  \hspace{1cm} (6)$$

**Terrestrial example:** The International Space Station is a LEO (Low Earth Orbit) at a distance $R = R_E + h$, where $R_E = \text{Radius of the Earth}$, $h = \text{altitude above surface of the Earth})$. The acceleration is given by $a_r(R) = g(R) = (G M_s) / R^2$. Let $R_1 = R_E + h_1$ and $R_2 = R_E + h_2$. With $R_E = 6371$ km, $h_1 = 100$ km, $h_2 = 400$ km, $M_E = 5.98 \times 10^{24}$ kg one obtains: $a_r(R_1) = g(R_1) = 9.53$ m/s$^2$ and $a_r(R_2) = g(R_2) = 8.71$ m/s$^2$. For $h = 0$ we have $a_r(R_E) = \frac{g \cdot (G M_s)}{R_E^2} = 9.81$ m/s$^2$ = gravitational acceleration at Sea level. \[10-A-1-4\]
Much Water in the Atmosphere of the jung Venus

To some extent, the Earth and Venus are twins. Scientists assume that the today so different Planets – similar to the Planet Mars – have been formed about 4.5 billions of years ago from the same matter constituents (Prof. Bochslter from the Departement of Space Exploration and Planetology of the University of Bern (Switzerland)). This involves a hypothesis, according to which there existed a large water volume on the extremely dry Venus of today. Today, this assumption from the Bernise scientists is supported by about 40 scientists from Europe and the US. Data from the ESA Spacecraft «Venus Express» which is collecting information for several years strongly suggest that in the Venus-Atmosphere, water vapor was actually present (Prof. Peter Wurz; Univeristy of Bern).

The researchers were able to prove, that besides of a small amount of Helium – the observed ratio of hydrogen to oxygen was present in in the same ratio of 2 : 1 as for water of our Earth. As commented by Prof. Wurz; «This result has not been unambiguously expected». The existence of a former water resource had been expected, but it is still a large surprise that the molecular composition was exactly the same as for our terrestrial water. The H_2O-molecules once present have then been carried away into space.

Earth’s Moon

The Moon is Earth’s only natural Satellite. Since the discovery of other Trabants of other Planets of the Solar System which in a transferred sense are also called Moons, our Moon is also called Earth’s Moon. Owing to its relative proximity, it is the only foreign celestial body who has been visited by humans.

Properties of the Orbit:
Semi-major axis: 384’400 km; Excentricity: 0.0549;
Period: 27.3217 days; Average orbital speed: 1.023 km/s;

Physical properties:
Mean diameter: 3474.8 km; Mass: 7.349 x 10^{22} kg;
Average density: 3.341 g/cm^3; Gravitational acceleration: 1.62 m/s^2;

The Atmosphere of the Moon:
The Moon has no Atmosphere in the proper meaning of the word; it has only an Exosphere (a thin atmosphere-like sheath which surrounds the Moon). It consists of approximately equal parts of Helium (He), Neon (Ne), Hydrogen (H_2) and Argon (Ar). The presence of an Exosphere is due to trapped particles from the Solar wind. A very small part arises also through degassing from the lunar interior. Of special importance is ^{40}Ar, which is produced by the decomposition of ^{40}K inside the Moon.
The Planets of the Solar System are shown on the central horizontal line; the blue region shows the habitable zone in the Solar System as a function of the size of five Stars. Star 1 is our Sun.

The Earth is located in the habitable zone. If the Earth would be shifted by 5% or by about 8 million km closer towards or farther away from the Sun, the simultaneous conditions for the three forms of Water (liquid, solid and gaseous) would not be fulfilled!

Jupiter's Moon Europa

With a diameter of 3121 km, Jupiter is the second innermost and smallest of the four large Moons of Jupiter.

Although the temperature at the surface of Europa reaches -150 °C, it is suspected that below a crust of water ice an Ocean of water with a depth of up to 100 km could be present.

Images of the Hubble – Space Telescope provided evidence to the presence of a very thin Atmosphere of oxygen with an extremely small pressure of 10^{-11} bar. It is assumed that oxygen is formed by the radiation of sunlight onto the ice crust and that water ice is decomposed into oxygen and hydrogen. The light-weight hydrogen escapes while the heavy oxygen is held in place by gravity.
Remarks: Oblique axis of rotation of Uranus

At p. 448 we have discussed the oblique axis of rotation and the corresponding consequences for the seasons. Uranus is the only Planet of the Solar system, the axis of rotation of which form an angle of 98° with respect of the orbital plane. All the other 7 Planets have relatively small angles with respect to the vertical direction of the orbital plane; for the Earth, this angle is only 23.44° (s. p. 429).

What is the reason for the unusually large inclination of the axis of rotation of Uranus? For the time beeing, there is no clear answer to this question. Two hypothesis have, however, put forward:

1) Uranus has been hit by an unusually large planetoit, thereby changing the rotation axis from its original normal direction to the present inclined direction. A similar collision occured probably in the history of our Earth, thereby generating the Moon. The difference in the results was probably due to the different geometry, i.e. a head-on collision for the Earth but a grazing collision for Uranus.

2) An alternative theory explains the exceptional direction of the axis of rotation of Uranus as a result of gravitational interaction: When the young and much more compact solar system was spread out, it was possible that temporary, Saturn and Jupiter were in a 2 : 1 orbital resonance relationship (*). Some models suggest that such a resonance was responsible for the change of the rotational axis.

(*) In celestical mechanics, an orbital resonance occurs if two planets orbiting around the Sun (in this case Jupiter and Saturn) exert a gravitational fore on each other if the two orbital periods have a ratio of two small integers, for example 2 : 1.

---

Escape velocities \( v_{esc} \) from Planets of Solar System

The escape velocity \( v_{esc} \) of a mass \( m \) from a Planet \( P \) of Mass \( M_p \) and radius \( R_p \) can be calculated from the kinetic energy \( E_{kin} = (1/2) m v^2 \) and from the gravitational binding energy \( E_g \). The gravitational force is \( F_g = G m M_p / R_p^2 \), where \( G \) is the gravitational constant \( (G = 6.674 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}) \) and \( R_p \) is the distance between the masses \( m \) and \( M_p \). The gravitational binding energy is given by the integral of \( F_g \):

\[
E_g = \int_{R_1}^{R_2} F_g (R) dR = \frac{G M_p}{R^2} \int_{R_1}^{R_2} dR = - \frac{G M_p}{R} \left[ \frac{1}{R_2} - \frac{1}{R_1} \right]
\]

If the mass \( m \) is launched from the surface of the Planet with the escape speed \( v_{esc} \), then \( R_1 = R_p \) and \( R_2 = \infty \). It then follows: \( (1/2) m v_{esc}^2 = G M_p / R_p \) and for the escape speed one obtains:

\[
v_{esc} = \sqrt{\frac{2 G M_p}{R_p}}
\]

Note that \( v_{esc} \) is independent on the escaping mass \( m \).

The Table contains the escape speeds (minimum speeds) from the celestial bodies, including the Moon and the Sun.

The evaluation of \( v_{esc} \) has been performed without taking into account the retarding forces due to an eventually existing Atmosphere.

<table>
<thead>
<tr>
<th>Celestial body</th>
<th>( v_{esc} ) at equator in km/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Merckury</td>
<td>4.3</td>
</tr>
<tr>
<td>Venus</td>
<td>10.2</td>
</tr>
<tr>
<td>Earth</td>
<td>11.2</td>
</tr>
<tr>
<td>Moon</td>
<td>2.3</td>
</tr>
<tr>
<td>Mars</td>
<td>5.0</td>
</tr>
<tr>
<td>Jupiter</td>
<td>59.6</td>
</tr>
<tr>
<td>Saturn</td>
<td>35.5</td>
</tr>
<tr>
<td>Uranus</td>
<td>21.3</td>
</tr>
<tr>
<td>Neptune</td>
<td>22.3</td>
</tr>
<tr>
<td>Pluto</td>
<td>1.1</td>
</tr>
<tr>
<td>Sun</td>
<td>617.3</td>
</tr>
</tbody>
</table>
The Heliosphere of our Solar System

The Heliosphere is a spacious, interplanetary area around the Sun, in which the solar wind (pp 353–358, Chapter 8) with its entrained magnetic field is effective. In this range of the solar system, the particle current of the Sun displaces the interstellar matter as far as to the Heliopause (the theoretical limit where the solar wind is limited by the interstellar medium). For electrically neutral atoms contained in the interstellar medium, it is possible that they can penetrate deeply into the Heliosphere. Besides the few particles which accomplish this goal, nearly the whole quantity of particles in the Heliosphere originates from the Sun.

While the regions near the Sun are marked by the solar wind itself as well as by the heliospheric current sheet, other phenomena become important after a distance of about 100 AU (1 AU = 1 Astronomical Unit = 150 million km); this is due to the interactions with the interstellar gas: since the solar winds are moving away from the Sun with a velocity of several 100 km/s, there must exist limits after which the solar wind is decelerated and penetrates with a smaller velocity into the interstellar medium. Finally, deceleration occurs down to the “velocity of sound”, $v_s$, in the interstellar medium ($v_s = 100$ km/s). The last limit after which the solar wind does not produce any material effects is the Heliopause at a distance of 110 to 150 AU.

Because of the very large distances, the investigation of the effects proofs to be difficult (for a distance of 100 AU the travel time of a spacecraft is about 30 years). Only the two spacecrafts Voyager 1 and 2 have reached the Heliosphere in the years 2004 and 2007; Voyager 1 at a distance of 94 AU and Voyager 2 at a distance of 84 AU.
**Doppler Technique for the Observation of Exoplanets**

**Explanation to the Figure of p. 463:**

The Doppler technique is a good method for the discovery of new Exoplanets. It is based on the Doppler effect for the analysis of the movement and properties of the central Star and the Planet. The Star and the Planet are rotating around the common center of mass. (s. pp 463 and 10-A-3-2).

In our Solar System, all Planets and also the Sun rotate around the common center of mass. Since the mass of the Sun is very much larger than the masses of the Planets, the center of mass is located inside the Sun! Therefore, the Sun is wobbling back and forth, causing a corresponding modulation of the spectrum of the sunlight. Now, we are not primarily interested in our Solar System but rather for the spectral displacement of other Stars in order to find out if these Stars are orbited by one or several Planets. If the Star moves toward us, its radiated light has a shorter wavelength, resulting in a blueshift (see blueshifted starlight in left Figure of p. 463). If, on the other hand, the Star moves away from us, its light has a longer wavelength, resulting in a redshift (see redshifted starlight in left Figure of p. 463).

The Doppler effect is often used for the investigation of extrasolar Planets. It must, however, be emphasized that it can best be used for very massive Planets which in addition are orbiting closely around their Stars. The reason for this restriction is due to the fact, that the central Star is wobbling more strongly if it is orbited by a massive and nearby Planet, producing a larger and more easily detectable spectral shift. In fact, most of the Exoplanets which have been detected by this method have indeed a very large mass and are orbiting very closely around their Star.

In Appendix 10-A-3-2 we show the different phases of a Planet and Star, which are orbiting around its center of gravity.

---

**Orbit of a Star S and a Planet P around Center of Mass CM**

Let CM (O) be the center of mass of a Star S with mass M and let m be the mass of the orbiting Planet P, where m ≪ M. (In reality, CM is eccentric within the Star (p. 10-A-3-1); for demonstration purposes, we have located CM outside the Star S).

Let R and r be the distances between S and P and S and CM, respectively and the distance between CM and P is D = R + r.

The center of mass is given by

\[ r / R = m / M \]  
with \[ R = D - r \]

\[ r = (m / M) R = (m / M) (D - r) \]  

From equation (3) it follows:

\[ r = \left[ m / (M + m) \right] D = \left[ 1 / (1 + M / m) \right] D \]  

Since \( M / m \gg 1 \) one obtains approximately:

\[ r \approx (m / M) D \]

Since \( m \ll M \) and \( r \ll R \) it follows \( R = D \), i.e. that most of the center of mass CM are located inside the Star S and are even close to the center of the Star.

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10 - 60
The discovery of new exoplanets became possible in 2014 by a new method, called the «Verification by Multiplicity». This technique is based on the following basis: If one images a star with a bunch of stars around him, the mutual gravities of each object would throw their relative orbits into a chaos. A star with a bunch of planets around it would, however, have a much more stable configuration. So if scientists see multiple transits of objects across a star’s face, its assumption is that it would be several planets.

«This physical difference, the fact that you can’t have multiple star-systems that look like planetary systems, is the basis of the validation by multiplicity,» said Jack Lissauer, a planetary scientist at the «NASA Ames Research Center» who was involved in the research.

The 715 exoplanets shown by the yellow bar at right are orbiting 305 stars (from NASA 26.2.2014). They have been observed by Kepler’s Space Telescope.

These 715 exoplanets have been found by the method of «Verification by Multiplicity».

From the new exoplanets discovered by this method, 95% are smaller than the planet Neptune, and four of these planets are smaller than 2.5 times the size of the Earth.
New Earth-like Exoplanet Kepler 186f - Comparison with Earth

In Section 3 (pp 467, 468; 476, 480, 481) and in Section 4 (pp 484, 489), some habitable Exoplanets have been discussed and we have made rough estimates for the number of technically intelligent civilisations (p. 476) or with observable signs of life (p. 489).

Estimates suggest that in the observable Universe about 10²⁴ Planets exist (a number with a 1 and 24 zeros !). Among this giant number of Planets it would be almost a miracle if our Earth would be the only Planet with living creatures. It should, however, be realized, that all large Gas – Planets are excluded and that for the existence of Earth-like life, only the rocky Planets having a life friendly Atmosphere and liquid Water at the surface are good candidates.

A promising top candidate for an Earth-like Planet has recently been discovered by NASA. The Planet of interest is the Exoplanet Kepler 186f. Its distance from the Earth is more than 500 light-years and its diameter is only 10% larger than the diameter of the Earth. Its mass and its chemical composition are not yet known.

The Planet Kepler 186f is quite close to its Star 186, about three times closer than the distance of the Earth from the Sun. Therefore, its orbit period is only 130 days. On the other hand, the temperature of its central Star is only about 3'500 °C, considerably lower than the temperature of our Sun. For this reason, Kepler 186f may well be located in the habitable zone of its Star. Therefore, the probability exists that the Planet has an Earth-like Atmosphere and liquid Water at its surface.

The Hubble Space Telescope

Operator: NASA
Launch mass: 11'110 kg
Dimensions: 13.2 m x 4.2 m
Power: 2'800 watts
Launch date: April 24, 1990
Focal length: 57.6 m
Collecting area: 4.5 m².

The Hubble Space Telescope (HST) is a space telescope that was launched into low Earth orbit in 1990, and remains in observation. With a 2.4 – meter mirror, Hubble’s four main instruments observe in the near ultraviolet, visible, and near infrared spectra. The telescope is named after Edwin Hubble (s. p. 494).

Hubble’s orbit outside the distortion of Earth’s Atmosphere allows it to take extremely high-resolution images with negligible background light. Hubble has recorded some of the most detailed visible-light images ever, allowing a deep view into space and time. Many Hubble observations have led to breakthroughs in astrophysics, such as accurately determining the rate of expansion of the Universe.

The HST is one of the NASA’s Great Observatories, along with the Compton Gamma Ray Observatory, the Chandra X-ray Observatory, and the Spitzer Telescope.
Relativistic Redshift of Light of Galaxies

If the escape velocity $v$ is much smaller than the velocity $c$ of light, one obtains the relative Doppler shift $z = \Delta \lambda / \lambda = v / c$ (s. p. 493). For very large velocities $v$, however, the relativistic time dilation must be taken into account. The velocity $v(z)$ is then given by:

$$v(z) = H_0 \cdot d(z) = \frac{(1+z)^2 - 1}{(1+z)^2 + 1} \cdot c$$

or

$$d(z) = \frac{(1+z)^2 - 1}{(1+z)^2 + 1} \cdot \frac{c}{H_0}$$

with $z = \Delta \lambda / \lambda = [(c + v) / (c - v)]^{1/2} - 1$

Doppler effect
10.0 Atmospheres: General

R.10.0.0 p. 405: Atmospheres of Planets and Exoplanets (Title)

R.10.1.1 p. 406: Atmospheres of the Planets of our Solar System (Title)


R.10.1.3 p. 408: Atmospheres of Inner Planets

a) The Inner or Terrestrial Planets - http://www.e-education.psu.edu/astro801/content/111_p4.html
c) Picture of Inner Solar System - www.google.ch/science (Names of Planets added by P. Brüesch)

R.10.1.4 p. 409: Atmosphere of Moons of our Solar System

a) How Many Moons are in the Solar System? - http://www.universetoday.com/15516/how-many-moons-

b) Which Moons have Atmospheres? - www.fromquarkstoquasars.com/Missions


d) 410: Atmosphere of the outer Solar System - Giant Gas-Planets

a) Picture: www.google.ch/search (Names of Planets added by P. Brüesch)
b) Atmosphäre (Astronomie) - http://de.wikipedia.org/wiki/Atmosph%C3%A4re_(Astronomie)

d) 411: Structure and Atmosphere of the Sun

a) Windows too the Universe - The Solar Atmosphere
   http://www.windows2universe.org/sun/solar_atmosphere.html

d) Space tornado power the atmosphere of the Sun
   http://www.scieddaily.com/release/2012/06/120628131402.html
g) Lexikon - http://www.redshift-live.com/de/kosmos-himmelsjahr/lexikon/Sonnenatmosph%C3%A4re.html
h) Sonne – LEIFI Physik - http://www.leifiphysik.de/themenbereiche/sonne

Bild links: Space tornadoes power the atmosphere of the Sun
10.2 The Planets of our Solar System: Properties of the Atmospheres

R.10.2.0 p. 417: 10.2 The Planets of our Solar System: Properties and Atmospheres (Title)

Liste der Planeten des Sonnensystems
(List of the Planets of our Solar System)
https://de.wikipedia.org/wiki/Liste_der_Planeten_des_Sonnensystems

R.10.2.1.0 pp. 418 – 422: 10.2.1 The Planet Mercury: Title (The Roman messenger of the Gods)

R.10.2.1.1 pp. 419: Mercury (Planet)

a) Mercury (planet): http://en.wikipedia.org/wiki/Mercury_planet
b) Merkur (Planet): http://www.wikipedia.org/wiki/Merkur_(Planet)


c) Text aus: «Ein Rätsel der Merkur-Atmosphäre gelöst»

R.10.2.1.2 p. 420: Elliptic Orbit of Planet around the Sun

a) Scale Figure of Mercur Orbit (from Literature Data: P. Brüesch) (Semi-axis a and b, eccentricity e, numerical eccentricity c, Distances from Sun and average velocity).


c) Text aus: «Ein Rätsel der Merkur-Atmosphäre gelöst»

R.10.2.1.3 p. 421: Mercury’s Atmosphere– 1

a) http://www.space.com/18644-mercury_atmosphere.html
b) Mercury (Planet): http://en.wikipedia.org/wiki/Mercury_planet

c) Text aus: «Ein Rätsel der Merkur-Atmosphäre gelöst»

R.10.2.1.4 p. 422: Mercury - Atmosphere – 2

b) Ein Rätsel der Merkur – Atmosphäre gelöst http://www.raumfahrer.net/news/astrokramkiste.de/merkur-atmosphaere


b) Ein Rätsel der Merkur – Atmosphäre gelöst http://www.raumfahrer.net/news/astrokramkiste.de/merkur-atmosphaere

R.10.2.2.0 p. 423: 10.2.2 The Planet Venus (Title) - Paintings of Sandro Boticelli (1445 – 1510)

R.10.2.2.1 p. 424: The Planet Venus – General
c) Venus (Planet) - http://de.wikipedia.org/wiki/Venus_(Planet)
d) Bild Links: aus: www.google.search - Images

R.10.2.2.2 p. 425: More Data and Properties of Venus
b) Ref. R.10.2.1.c): Venus (Planet)

R.10.2.2.3 p. 426: The Layers of the Atmosphere of Venus
b) Venus ...Earth's not really sister planet - http://ode.nw.edu/SC12108/course_documents/solar_system/innerplanets/venus/venus.html
(Figur: Temperatur – Höhe – Druck. p. 5 in diesem Artikel)

R.10.2.2.4 p. 427 The Composition of the Venus Atmosphere
b) Picture from - www.google.ch/search unter «Composition of Venus Atmosphere»

R.10.2.3.0 p. 428: 10.2.3. The Planet Earth - Gaia

R.10.2.3.1 p. 429: The Earth
a) Earth: https://en.wikipedia.org/wiki/Earth
b) Erde: http://de.wikipedia.org/wiki/Erde
c) Gaia - Encyclopedia Mythica - http://www.pantheon.org/article/g/gaia.html - Picture from Google

R.10.2.4.0 p. 430: 10.2.4. The Planet Mars (Title)
R.10.2.4.1 pp 431 - 434: Mars
b) Mars (Planet) - http://de.wikipedia.org/wiki/Mars_(Planet) - Pictures: pp 431, 432

R.10.2.4.2 p. 433: The Atmosphere of the Planet Mars
Atmosphere of Mars - http://www.daviddarling.info/encyclopedia/M/Marsatmos.html
Text and Graph with Temperature and Pressure as a function of altitude
R.10.2.4.3 p. 434: The Atmosphere of the Planet Mars
c) Mars (Planet) - http://de.wikipedia.org/wiki/Mars_(Planet)
d) Atmosphere of Mars and the Search for Life - Lecture 14: The Atmosphere on Mars
Prof. Robert L. Nowack

R.10.2.5.0 p. 435: 10.2.5 The Planet Jupiter (Title)
R.10.2.5.1 p. 436: General Data and Properties

R.10.2.5.2 p. 437: Jupiter: The Atmosphere of Jupiter - 1
Jupiter: http://en.wikipedia.org/wiki/Jupiter (in English)
R.10.2.5.3 p. 438: The Atmosphere of Jupiter – 2
a) http://burro.astr.cwru.edu/stu/advanced/jupiter.html (left-hand Picture)
c) Jupiter: Giant of the Solar Planets - http://pages.oregon.edu/jimbrau/astr121/Notes/chapter11.html (Right-hand picture: Figure retouched!); Picture from «Layers of Jupiter’s Atmosphere» → Pictures
d) Welcome to Space - http://www.welcometospacelog.com/2012/01/jupiter.html

R.10.2.6.0 p. 439: 10.2.6 The Planett Saturn (Title)
R.10.2.6.1 p. 440: The Planet Saturn – General
b) Saturn - Rings, Moons, Exploration – Crystallinks
http://www.crystallinks.com/saturn.html
c) Saturn (Planet) - http://de.wikipedia.org/wiki/Saturn_(Planet)

R.10.2.6.2 p. 441: Structure and chemical composition of Saturn
a) Inside Saturn - Atmosphere and planetary composition
Top image: Atmosphere and Planetary Composition
http://www.entschantedlearning.com/subjects/astronomy/planets/saturn/saturninside.shtml
b) Lower picture: Chemical composition of Saturn - http://burro.astr.cwru.edu/stu/advanced/saturn.html

R.10.2.6.3 p. 442: The Atmosphere of Saturn
a) Saturn's Atmospheric Composition
Picture on the left side and Text: Saturn's Atmospheric composition
http://www.castlerock.wednet.edu/~imamura/121/lecture-6/saturn_atmosphere.ppt
(b) Saturn's hexagon - http://en.wikipedia.org/wiki/Saturn's_hexagon
b) Saturn’s Atmosphere - (right-hand Picture and Text)
http://astronomy.nju.edu.cn/~lix/GA/ATA/ATA12/HTML/AT41202.htm

R.10.2.6.4 p. 443: South Pole Storm and hexagonal Jet stream at North Pole
a) Spectacular storm rages on Saturn's South Pole
c) Saturn’s hexagon - http://en.wikipedia.org/wiki/Saturn’s_hexagon
d) Has the mystery of Saturn’s 20'000 mile wide hexagonal storm solved?
Researchers believe it could be controlled by a giant jet stream
http://www.dailycole.co.uk/scienceTech/article-26001784/Has-mystery_Saturns-hexagonal-storm-
solved/Researchers-believe-extraterrestrial-jet-stream.html...
e) Das Hexagon am Saturn: im Labor reproduziert!
http://scienceblogs.de/astrodicticum-simple/2010/04/10/das-hexagon-am-saturn-im-labor-reproduziert/

R.10.2.6.5 p. 444: The Rings of Saturn
a) NASA - Saturn’s A Ring From the Inside Out – Cassini: Unlocking Saturn’s Secret
contains picture with ring system
b) Saturn: Rings - https://solarsystem.nasa.gov/planets/profile.cfm?Object=Saturn&Display_Rings
(contains picture with ring system)
d) Planet Saturn - Eine Welt der Ringe und Monde

R.10.2.7.0 p. 445: 10.2.7 The Planet Uranus (Title)
R.10.2.7.1 p. 446, 447: General – Structure – Chemical Composition
c) Uranus: http://burro.astr.cwru.edu/advanced/uranus.html
R.10.2.7.2 p. 448: Rotation axis - Orbit - Extreme Seasons
   c) Chapter 13.3 Uranus and Neptun in Bulk - Masses and Radii - Rotation Rates
      http://iffeng.lamont.org/courses/astrotoday/CHA/SS/AT313/HTML/AT31303.HTM
   d) Der Planet Uranus - http://home.arcor.de/jenras/Uranus.html
   e) URANUS: http://www.gutekunst-astro-de/Uranus.html

R.10.2.7.3 p. 449: Atmosphere of the Planet Uranus - 1

R.10.2.7.4 p. 450: Atmosphere of the Planet Uranus - 2

R.10.2.7.5 p. 451: Atmosphere of the Planet Uranus - 3 and Ring-system
   b) Uranus Thermosphere Temperature Profile - http://www.windows2universe.org/uranus/atmosphere/U_thermosphere_2.html
   c) Uranus: Moons - http://solarsystem.nasa.gov/planets/profile.cfm/Object=Uranus&Display=Sat
   d) Thermosphäre und Korona (Text) - http://de.wikipedia.org/wiki/Uranus_(Planet)

R.10.2.8.0 p. 452: 10.2.8 The Planet Neptune

R.10.2.8.1 p. 453: The Planet Neptune - General
   b) Neptun (Planet) - http://de.wikipedia.org/wiki/Neptun_(Planet)

R.10.2.8.2 p. 454: Neptune's Interior and chemical composition
   a) Text: Reference R.10.1.8.1 - a)
   c) Neptune - Lower Picture: «Neptunian Elemental Composition»
      www.bruno.astr.cwru.edu/stu/advanced/neptune.html
   d) Der Aufbau von Neptun - http://www.hs.uni-hamburg.de/DE/Ins/Bib/neptun.html

R.10.2.8.3 p. 455: Atmosphere of Planet Neptune – 1
   a) http://astronomyonline.org/SolarSystem/Neptune/Introduction.asp?Cate=SolarSystem&SubCate=Neptune&SubCat2=NT01
      AstronomyOnline.org: Figur der Temperatur als Funktion der Höhe: T(h)
   b) Neptun’s Atmosphere: Composition, Climate & Weather
      Text zu Figur von T(h) - www.space.com/18922-neptune-atmosphere.html

R.10.2.8.4 p. 456: Atmosphere of Planet Neptune – 2
   a) Neptune – Voyager 2
      Left-hand picture; contrast-enhanced image - April 1989
      nssdc.gsfc.nasa.gov/imgr/l/full/534965.html
   c) Neptune’s Atmosphere and the great dark spot
      http://www.enhancedlearning.com/subjects/astronomy/planets/neptune/atmosphere.shtml
   d) A look at what Neptune’s Atmosphere is made of
      http://www.windows2universe.org/uranus/atmosphere/N_atm_compo_overview.html
   e) Planet der wilden Stürme - www.goerlitzer-sternfreunde.de/html/neptune.html (Bild rechts auf p. 456)
10.3 Exoplanets: History and Methods of Operation

R.10.3.1 Exoplaneten: Die Suche nach einer zweiten Erde

R.10.3.2 Elefanten im All - Unser Platz im Universum - Ben Moore
(Aus dem Englischen von Friedrich Griese und Monika Niehaus)
Copyright © 2012 by Klein & Aber AG Zürich – Berlin


b) Unser Mathematisches Universum - Max Tegmark - Ullstein (2014)

R.10.3.0.1 p. 458: Observation of Stars and the Surch of Exoplanets (Title)
R.10.3.1.1 p. 459: L'Universe populaire

R.10.3.1.2 p. 460: Giordano Bruno / Die Supernova of 1572
a) Libertes Philosophica: Giordano Bruno - visionary and heretic
https://forteanatheist.wordpress.com/2013/06/02/libertes-philosophica-giordano-bruno-visionary-and-heretic/
d) Supernova (SN) von 1572 - Bild des Überrestes der Supernova (SN) 1572
http://en.wikipedia.org/wiki/SN_1572

R.10.3.1.3 p. 461: Astronomy in the 17th and 18th Century
a) Reference R.10.3.1 (pp 7 – 17)
b) Vom Augenrohr zum Weltraumteleskop - Jahr der Astronomie - Berliner Zeitung (31.8.2015)
http://www.berliner-zeitung.de/Archiv/JahrDerAstronomie--VorVierHundertJahren-Bewiesen-Galileo-galilei-

R.10.3.1.4 p. 462: Importance of Parallax in Astronomy - Determination of the distance between the Sun and a Star
a) Astronomy 101 Specials: Measuring Distance via the Parallax Effect
http://www.eq.bucknell.edu/physics/astronomy/astr101/specials/parallax.html
b) Distance measurement in Astronomy
http://www.schoolphysics.co.uk/age14-16/Astronomy/text/Measuring_astronomical_distances/index.html
c) Stellar Parallax - HyperPhysics "Astrophysics - by R. Nave
Distance Measurement in Astronomy - HyperPhysics
http://www.hyperphysics.phy-astr.gsu.edu/hbase/.../distance.html
d) How do astronomers measure the distance to Stars? Is it accurate?
e) from: Reference R.10.3.1 - Kapitel 1. Geschichte der Planetensuche - p. 17
f) Der Sternhimmel ist dreidimensional - http://news.astronomie.info/sky/200606/thema.html
g) Picture and Text - http://www.astro.uni-jena.de/.../index.html
h) Angle Conversions - How to convert degrees to radians or radians to degrees

R.10.3.1.5 p. 463: Discovery of Exoplanets with the help of the Doppler Effect
Text of right-hand picture improved for better readability
c) Die Suche nach extrasolaren Planeten

R.10.3.1.6 p. 464: The Transit-Method
a) Transit Method – Las Cumbres Observatory - http://lcogt.net/spacebook/transit-method
b) New 15 Earth-mass planet discovered with the new Transit Timing Variation Method
with Telescopes in Jena/Germany and Rozhen/Bulgaria - http://www.astro.uni-jena.de/wasp-3/
c) Magnitude (astronomy) - http://en.wikipedia.org/wiki/Magnitude_(astronomy)
d) Aus den Herzen der Sterne zu fernen Welten
http://www.uni-koeln.de/~lcarone/german/Exoplanet/Transitmethode
### R.10.3.1.7 p. 465: Transit-Method and Resonance

   In celestial mechanics, an orbital resonance occurs when two orbiting bodies exert a regular, periodic gravitational influence on each other, usually due to their orbital periods being related by a ratio of two small integers.

b) WASP-3 - [http://en.wikipedia.org/wiki/WASP-3](http://en.wikipedia.org/wiki/WASP-3)

c) WASP-3b - [http://en.wikipedia.org/wiki/WASP-3b](http://en.wikipedia.org/wiki/WASP-3b)

d) Planet WASP-3c - [http://exoplanet.eu/catalog/wasp-3_c/](http://exoplanet.eu/catalog/wasp-3_c/)

e) New 15 Earth-mass planets discovered with the new Transit Time Variation method with telescopes in Jena/Germany and Rozhen/Bulgaria - [http://www.astr.uni-jena/wasp-3](http://www.astr.uni-jena/wasp-3)

  with Figure of Modell for WASP-3 – Planet

  Figur von P. Brösch zur Veranschaulichung durch Einflüßen von Radien und Geschwindigkeiten ergänzt.

f) Welt der Physik: Mini. Exoplanet mit neuer Methode entdeckt
   [www.weldderphysik.de/de/...mini.exoplanet.mit.neuer-methode-entdeckt/](http://www.weldderphysik.de/de/...mini.exoplanet.mit.neuer-methode-entdeckt/)

### R.10.3.2.0 p. 466: Discovery and Systematics of Selected Exoplanets (Title)

### R.10.3.2.1 p. 467: Exoplanets in the habitable Zone

a) NASA's Kepler Marks 1,000th Exoplanet Discovery: Uncover more small Worlds in habitable Zone

b) The Fermi Paradox: An Approach

### R.10.3.2.2 p. 468: Comments to Exoplanets in the habitable zone:
s. References in R.10.3.2.1)

### R.10.3.2.3 p. 469: Exoplanet: Radius as a function of mass for selected Exoplanets

Figure from: [http://www.mpia.de/Public/menus_q2.php?Actualles/PR/2013/PR_2013_05/PR_2013_05_de.html](http://www.mpia.de/Public/menus_q2.php?Actualles/PR/2013/PR_2013_05/PR_2013_05_de.html)

### R.10.3.2.4 p. 470: Exoplanet: Comments to p. 469

a) Reference R.10.3.2.1 b), p. 467

c) NASA's Kepler Discovery – Its Smallest «Habitable Zone» Planets to Date (April 18, 2013)

Contains information about Kepler-62e, Kepler-62f and other small «Habitable Zone» Planets


### R.10.3.2.5 p. 471: Our Milky Way Galaxy (Title)

### R.10.3.2.6 pp 472 - 474: The Milky Way Galaxy

a) A Map of the Milky Way - [http://www.allabouttheuniverse.com](http://www.allabouttheuniverse.com)
   [Found under «The Milky Way» »Bilder»]

b) Astro - Info - [http://www.wirzrolland.ch/astro_info.htm](http://www.wirzrolland.ch/astro_info.htm)

c) The layered Milky Way Galaxy and Classification of Galaxies
   [This is an outstanding Overview about the subject!]


e) Das Milchstrassensystem - [http://home.arcor.de/hs/Weitall/Milchstrasse.html](http://home.arcor.de/hs/Weitall/Milchstrasse.html)

### R.10.3.2.7 p. 475: Das Fermi – Hart Paradoxon


b) An Explanation for the Absence of Extraterrestrials on Earth

c) The Fermi Paradox: An Approach Based on Percolation Theory


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10 - 70
R.10.3.2.7  e) p. 475: The Fermi Paradox: An Approach Based on Percollation Theory
   Geoffrey A. Landis
   NASA Lewis Research Center, 302-1; Cleveland, OH 44135, U.S.A
   «I propose a model for the problem based on the assumption that long-term colonization of the
galaxy proceeds via «percolation» process similar to the percolation problem which is well
studied in condensed-matter physics».  

R.10.3.2.8  p. 476: The Drake equation and the Seager equation
   c) Intelligent Life in the Universe - http://www2.astro.psu.edu/users/dfox/A001/Notes/lec37.html
   (Contains 58 Literature citations and 9 «External links»)
   d) Ref. R.10.3.1: pp 152, 153 in this Book
   e) Ref. R.10.3.2: pp 220, 221 in this Book
   f) A New Equation Reveals Our Exact Odds of Finding Alien Life...
      The Seager Equation - http://seagerexoplanets.mit.edu/research.html (contains present contribution: «Scatterplot showing masses and orbital periods of exoplanets
discovered up to 2010 (with colors indicating method of detection).»)
   g) The Drake Equation versus the Fermi Paradox: Is There Intelligent Life out There? 
      http://www.noeticscience.co.uk/the-drake-equation-versus-the-Fermi-paradox-is-thereintelligent-life-out-there?

R.10.3.2.9  pp 477, 479 Planetary Masses versus Time of Discovery
      Graph of Planetary masses vs Year of discovery (1985 – 2013)
      (Observations by Doppler effect and Transit-Method)
   b) p. 479: Extrasolar Planet
      http://de.wikipedia.org/wiki/Extrasolar_Planet (Part of Text translated to English)

R.10-14

R.10.3.2.10  pp 478, 479: Masses vs Orbital semi-major axis of Exoplanets
      Figure of p. 478: Labeling of axes and Comments to Figure from P. Brüesch
      p. 8 in present contribution: «Scatterplot showing masses and orbital periods of exoplanets
discovered up to 2010 (with colors indicating method of detection).»
      (contains discovered Exoplanets up to 2015)

R.10.3.2.11  p. 480: Some important Earth-like Exoplanets
   a) Popular Science - The Math: What Life on Kepler.62e Would Be Like ?
   d) PHL – Planetary Habitability Laboratory
   e) Kepler 62e and f. Zwei erdähnliche Exoplaneten?

R.10.3.2.12  p. 481: The planetary system Kepler 62 – Comparison with Solar System
   e) System mit zwei vermutlich lebenfreundlichen Exoplaneten entdeckt – 16. April 2013
      http://derstandard.at/1363708472171/System-mit-zwei-lebensfreundlichen-Exoplaneten-entdeckt

R.10-15
10.4 Atmospheres of Exoplanets


R.10.4.3 p. 482: Atmospheres of Exoplanets (Title)

R.10.4.4 pp 483 - 484: Atmosphären von Exoplaneten


Definition of Thickness of Absorborsphere and surface of Gas Planets


R.10.4.5 p. 485: Absorption of Starlight by the Atmosphere of Exoplanets - 1

a) Reference R.10.4.4 b)

c) Der Planet HD 189733 b - http://de.wikipedia.org/wiki/HD_189733

d) p. 486: Absorption of Starlight by the Atmosphere of Exoplanets - 2


Figure: Absorption of Starlight by the Atmosphere of Exoplanets

R.10.4.6

R.10.4.7 p. 487: Zwei junge Astronomen erschließen die Atmosphären für Exoplaneten


b) Atmosphären von Exoplaneten Ein Interview mit Prof. Dr. Kevin Heng - [PDF] www.exo-time.net/download/file/id/67

R.10.4.8 p. 488: Planetary Radii vs Orbit Period

Earth-size exoplanets in habitable orbits are common - The Figure has been slightly modified. Physics Today - January 2014, pp 10 – 12 - Bertram Schwarzschild

Actual Figure from Internet - The Figure has been slightly modified. Publication is also contained in: [PDF] www.geo.umass.edu/.../Exoplanets%20Schwar...


c) An Astrophysical View of Earth-Based Metabolic Biosignature Gases – Review Article Sara Seager, Matthew Schrenk, and William Bains

ASTROBIOLOGY – Volume 12, Number 1, 2012 - dispacex.mit.edu/openaccess-dissiminate/1721...7307...

d) Ref. R.10.3.1: Sven Piper – Exoplaneten; Kapitel 6; pp 73 – 79


g) Extrasolare Planeten - Auf der Suche nach fremden Welten Dominique M. Fluri, ETH Zürich - April 2012 www.physik.ethz.ch/heiml/.../DFluri_NV_Extraexoplaneten.pdf - Abschnitt 4.2; Spektrale Signatur von Leben

h) An Equation to Estimate Probability of Identifying an Inhabited World the Next Decade Sara Seager, MIT – 2013 (PDF) - www.cfa.harvard.edu/events/.../Seager.pdf
### 10.5 Galaxies and Universe

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#### R.10.5.0  p. 491: Galaxies and Universe (Title)


**c)** Newton Model of Expanding Universe: [http://hyperphysics.phy-astr.gsu.edu/hbase/astro/expuni.html](http://hyperphysics.phy-astr.gsu.edu/hbase/astro/expuni.html)

**d)** BIG BANG - Autor: Simon Singh  
Der Ursprung des Kosmos und die Erfindung der modernen Naturwissenschaft  


**f)** Die Geburt des Universums - Kapitel 1: Expansion, Strahlungs- und Materiedichte  
[http://www.pa.op.dem私立t-online.de/myb4.htm/chap25.htm](http://www.pa.op.dem私立t-online.de/myb4.htm/chap25.htm)

**g)** Left-hand picture: Schematic representation of the expanding Universe  

**h)** Right-hand picture in: The Flattness Problem – Inflation Flattens the Universe – JPEG.Image  
[http://archive.ncsa.illinois.edu/Cyberia/Cosmos/Flattness/Problem.html](http://archive.ncsa.illinois.edu/Cyberia/Cosmos/Flattness/Problem.html)

**i)** The Flattness Problem - [http://archive.ncsa.illinois.edu/Cyberia/Cosmos/Flattness/Problem.htm](http://archive.ncsa.illinois.edu/Cyberia/Cosmos/Flattness/Problem.htm)

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#### R.10.5.1  p. 492: The observable Universe


**b)** How many Stars are in the Universe? -  

**c)** How Many Planets Are There In The Universe? -  

**d)** The Universe Beyond Our Reach - (Contains Figure reproduced in this page) -  

**e)** How Many Stars Are In There In The Universe? -  
[http://www.esa.int/Our_Activities/Space_Science/Herschel/How_many_stars_are_there_in_the_Universe](http://www.esa.int/Our_Activities/Space_Science/Herschel/How_many_stars_are_there_in_the_Universe)

**f)** What is the average number of planets per star? -  

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#### R.10.5.2  p. 493: Origin and Expansion of the Universe


**c)** Newton Model of Expanding Universe - [http://hyperphysics.phy-astr.gsu.edu/hbase/astro/expuni.html](http://hyperphysics.phy-astr.gsu.edu/hbase/astro/expuni.html)

**d)** BIG BANG - Autor: Simon Singh  
Der Ursprung des Kosmos und die Erfindung der modernen Naturwissenschaft  


**f)** Die Geburt des Universums - Kapitel 1: Expansion, Strahlungs- und Materiedichte  
[http://www.pa.op.dem私立t-online.de/myb4.htm/chap25.htm](http://www.pa.op.dem私立t-online.de/myb4.htm/chap25.htm)

**g)** Left-hand picture: Schematic representation of the expanding Universe  

**h)** Right-hand picture in: The Flattness Problem – Inflation Flattens the Universe – JPEG.Image  
[http://archive.ncsa.illinois.edu/Cyberia/Cosmos/Flattness/Problem.html](http://archive.ncsa.illinois.edu/Cyberia/Cosmos/Flattness/Problem.html)

**i)** The Flattness Problem - [http://archive.ncsa.illinois.edu/Cyberia/Cosmos/Flattness/Problem.htm](http://archive.ncsa.illinois.edu/Cyberia/Cosmos/Flattness/Problem.htm)
R.10.5.3 p. 494: The Hubble Law

a) The Expanding Universe and Hubble’s Law
http://www.physics.ucf.edu/universe/topics/bigbang_expanding.html

b) Figure: Hubble-Law: Velocity of Expansion vs. Distance
http://astro.lpl.arizona.edu/astrostories/article/The-Hubble-Relation - (Figur von P. Brüesch leicht retouchiert)


d) Das Hubble-Gesetz und kosmologische Entfernungsbestimmung - Univ. Regensburg - Fakultät für Physik)
Ausbildungsseminar zur Kosmologie – im Wintersemester 07 / 08 – Sebastian Putz
(Bild von Hubble auf p. 4)
www.physik.uni-regensburg.de/.../KosmologischeEntfernungen.pdf


R.10.5.4 p. 495: Raisin cake model of the Universe and Hubble’s Law

a) Expanding Universe - Hubble law and the expanding Universe
Contains picture and Text to: A rising loaf of raisin bread
http://hyperphysics.phy-astr.gsu.edu/hbase/astro/Hubble.html (Text and Figure slightly modified by P. Brüesch)

b) Rosinenkuchenmodell in: Das Universum
[PDF] www.tphys.uni-heidelberg.de/~huefner/ENTPGYS/14-Kosmologie.pdf

c) Win de Boer, Karlsruhe – Kosmologie VL, 25.10.2012 - Einteilung der VL
www.epam.physik.uni-karlsruhe.de/~deboer/html/.../VL2_Hubble_sw.pdf

R.10.5.5 p. 496: Big Bang and Expansion of the Universe

a) Speed of Universe’s Expansion Measured Better Than Ever


c) Hintergrundstrahlung - https://de.wikipedia.org/wiki/Hintergrundstrahlung

d) Hydrogen – Helium Abundance (on the Universe)
http://hyperphysics.phy-astr.gsu.edu/hbase/astrohydro.html

R.10.5.6 p. 497: Interstellar Gas: An extremely diluted «Atmosphäre» - 1


b) Interstellares Gas - http://www.uni-protekt.de/Lexikon/Interstellares_Gas.html


e) Molekülwolke - http://de.wikipedia.org/wiki/Molek%C3%B6lwolke

f) Kosmische Raffinerie - Forschung / Aktuelles / 2012 / Kosmische Raffinerie (Cosmic Refinery)
http://www.mpg.de/663008/Pferdekopfnebel - Picture: Horsehead Nebula in the Constellation Orion

R.10.5.7 p. 498: Ref. g) of p. 497): Gigantische Chemiereaktionen: Molekulare Riesenwelken im interstellaren Raum - Molekül-Mix 3

R.10.5.8 p. 499: Intergalactic Gas: An extremely diluted «Atmosphäre» - 2

a) Outer space http://en.wikipedia.org/wiki/Outer_space
http://en.wikipedia.org/wiki/Outer_space

b) Space and Astrophysics - Research

c) Distant quasar illuminates a filament of the cosmic web
http://www.ucsc.edu/2014/01/cosmic-web.html


e) Planck discovers filament of hot gas linking two galaxy clusters
[contains picture of wispy network of clusters, filaments and voids known as the cosmic web]
Appendix: Chapter 10


  c) Kepler's Laws - http://hyperphysics.phy-astr.gsu.edu/hbase/kepler.html
  d) Deriving Kepler's Laws from the Inverse-Square Law - Michal Fowler, Uva http://galileo.phyx.virginia.edu/classes/152mlfi.spring02/Leplers/laws.htm
  g) Planetenbahnen und Himmelsmechanik - http://www.l中国文化.net/astromanie/ sites/planetenbahnen.aspx


Radial acceleration - https://physics.tutorvista.com/motion/radial-acceleration.html (Text and Figure from P. Brüesch)


  a) BBC – KS3 Bitesize Science – Astronomy and space science, Page 3
     Right-hand Figure:
  b) Radial acceleration a, for Planets calculated from $a = \frac{GM}{R^2}$ calculated by P. Brüesch
  c) Left-hand Figure: Radial acceleration of the Earth
     Terrestrial examples for «Low Earth Orbits»: Calculations and Figure by P. Brüesch
  d) Mathematics of Satellite Motion - The Physics Classroom - www.physicsclassroom.com - u614C3.gif


  a) Where is the Water on Venus?
     http://www.vanderbilt.edu/Anh/physics/astrocourses/AST101/readings/water_on_venus.html
  b) Viel Wasser in der Atmosphäre der jungen Venus
     Text und Bild von: «Auf der Venus gab tatsächlich Wasser»

10 - 75
a) Earth’s Moon - https://ginnew.sirdesign.net/solsys_planetes_earth_moon.html
c) Mond - https://de.wikipedia.org/wiki/Mond


b) Europa Moon – Conamara Chaos

c) Europa (Mond) - http://de.wikipedia.org/wiki/Europa_(Mond)
d) Europas Chaosregionen. Viel Wasser im Eis


c) Atlass der Atmosphäre
www.meteo.physik.uni-muenchen.de/lehre/.../Teil_T_WS2005-04.pdf


e) Struktur der Atmosphäre

c) Voyager: The Interstellar Mission – found under: Heliosphere of our solar system
d) Heliosphäre - http://de.wikipedia.org/wiki/Heliosph%C3%A4re

e) Aufbruch zu den Sternen
Dr. Bernd Wöbke: Presse- und Öffentlichkeitsarbeit – Max-Planck Institut für Sonnenforschung
idw - Informationsdienst Wissenschaft - https://idw-online.de/pages/de/news/2982

10-A-3-1 p. 10-A-3-1: Doppler-Technique for the search of Exoplanets
s. Reference R.10.3.1-4- c). p. 463

10-A-3-2 p. 10-A-3-2: Orbit of _a Star and a Planet around Center of mass
Figure and Text from P. Brüesch from Literature data

10-A-3-3 p. 10-A-3-3: Exoplanets – Planetary masses versus Orbital periods
«A Batch of More than 60 New Planets and Development of the Mass-Period Diagram» - by Dr. T. Yaqoob (2012)


a) Mega Discovery! 715 Alien Planets Confirmed Using A New Trick On Old Kepler Data
By Elisabeth Howell on February 26, 2014
c) List of Exoplanets discovered using Kepler spacecraft
Contains the Histogramm of Exoplanet Discoveries – gold bar displays new planets - verified by Multiplicity (2014)

e) Kepler’s Last Stand - Verification by Multiplicity http://exoplanets.wordpress.com/-
f) Kepler: 715 neue Exoplaneten entdeckt (27. Februar 2014 von Michael Kahn)
www.scilogs.de/gp-for-lainch/kepler-715-neue-exoplaneten-entdeckt

R-10-A-3
R-A-3-5  p. 10-A-3-5: New Earth-like Planet Kepler 186f
a) NASA's Kepler Discovers First Earth-Size Planet in The «Habitable Zone» of another Star
   http://www.nasa.gov/ames/kepler/nasa-kep1r-discovers-first-earth-size-planet-in-the-habitable-zone-of-another-

b) Astronomers discover Earth-like planet
   The Sydney Morning Herald – Technology - Nicky Phillips – April 18, 2014

   With picture: «Comparison of the Kepler 186f system and the Solar system 17 April 2014]

d) How Many Planets Are In The Universe?
   http://scienceblogs.comstartswithabang/2013/01/05/how-many-planets-are-in-the-universe/
   (Estimate: in the observable Universe there are about $10^{24}$ Planets)


f) Neuer Spitzenkandidat unter den erdähnlichen Planeten

g) Erdgrosser Planet in bewohnbarer Zone entdeckt - Frankfurter Allgemeine – Wissen – 17.04.2014
   http://www.faz.net/aktuell/wissen/weltraum/ferne-welten-erdgrosser-planeten-in-bewohnbarer-zone-aufgespurt-12900773


R-A-5-1  p. 10-A-5-1: Relativistic Redshift of Light from Galaxis


b) Der Doppler-Effekt - Astrophysik – Weltall
   Figur: relative Rotverschiebung $z$ als Funktion von $v/c$ - http://www.jgiesen.de/astro/stars/DopplerEffekt

c) Rotverschiebung: (mit relativistischer Herleitung) - http://de.wikipedia.org/wiki/Rotverschiebung

R-10-A-4