Notes 8: Planetary Atmospheres

8.1 Physics of Atmospheres

Atmospheres have been detected around all of the planets, though in some cases they are so tenuous they are not worth discussing – like the atmospheres of Mercury and the Moon. Regardless of their composition or thickness, all atmospheres follow the same set of rules and behave in similar ways based upon the laws of physics and chemistry.

**Pressure and Density**

The basic rule about the behavior of atmospheres and the way in which pressure, density and temperature interact is usually found by combining the relationship for hydrostatic equilibrium,

\[ \frac{dP}{dz} = -\rho \frac{GM}{z^2} \]

and the ideal gas law,

\[ P_{\text{gas}} = P = \frac{\rho k T}{m} \]

Where

- \( P = \) pressure
- \( z = \) distance up/above the surface (usually this is \( r \) in the formulas, but \( z \) is commonly used for atmospheres)
- \( M = \) mass of the planet
- \( G = \) gravitational constant
- \( k = \) Boltzmann’s constant
- \( T = \) temperature (K)
- \( m = \) mass of the gas molecule (depends upon composition)

Substituting for density you can solve the formula if we assume the atmosphere is isothermal (constant temperature), which gives us

\[ \frac{dP}{dz} = -\rho \frac{GM}{z^2} \]

\[ dP = -\frac{P m GM}{kT} \frac{dz}{z^2} \]

\[ \frac{dP}{P} = -\frac{mGM}{kT} \frac{dz}{z^2} \]

This looks pretty bad, but with the wonders of calculus we can convert it into a useful relationship that describes the pressure variation with altitude.

\[ P(z) = P_o e^{-\frac{mg_z}{kT}} \]

Where \( P(z) \) is the pressure at height \( z \) above the surface of a planet with a surface gravity of \( g \). \( P_o \) is the pressure at the surface. Obviously this isn’t entirely proper since the temperature isn’t constant at all elevations, but the variation in temperature isn’t extreme especially in areas where the atmosphere is well defined. And of course gravity isn’t exactly constant either, so that’s also an incorrect assumption (though not a source of significant error).
It should be noted that with the above relationship for the pressure variation, there is a similar relationship for the density variation with altitude, since we are using the ideal gas law and the pressure and density are proportional to one another. So the density would vary at the same rate as the pressure with height – again assuming hydrostatic equilibrium and the ideal gas laws are valid and the atmosphere is isothermic.

For simplification a value known as the pressure scale height, $H$, is often defined. This is just

$$H = \frac{kT}{mg} \hspace{1cm} 8-3$$

And it measures the distance for a drop by a factor of $e$ in the pressure (or a drop of a factor of $e$ in the density). It is a common scaling parameter for atmospheres.

So you can re-do the pressure-height relationship to read

$$P(z) = P_0 e^{-\frac{z}{H}} \hspace{1cm} 8-4$$

**Temperature**

Once the pressure and density structure are defined, the temperature structure of the atmosphere can also be defined (in reality all of the previous calculations would have been done without a constant temperature for the greatest accuracy, but that’s too complicated for us). The change in temperature with height is much more complicated than the change in density with height. Often the temperature may decrease and then increase at increasing heights as you go through various levels of the atmosphere. Regardless, we can map out the temperature variations with height to understand the physics of a planet’s atmosphere.

For planetary atmospheres the majority of the heating comes from the Sun, though it is possible for there to be internal heating that also influences an atmosphere. And things are further complicated by the presence of clouds or the variations in the opaqueness of an atmosphere, which is not consistent or constant in value. Any ways, there are many things that influence temperature such as:

1. The Sun, particularly in the highest layers of an atmosphere, but sunlight can also penetrate all of the way down to the surface of a planet and heat all levels of an atmosphere.
2. Internal energy sources which includes the giant planets that are still losing internal heat, as well as re-radiated sunlight from solid planet surfaces, though that is often at a different wavelength (usually IR).
3. Chemical reactions that change the composition of the atmosphere, which changes the opacity and thermal structure.
4. Clouds and/or photochemically produced haze layers change opacity, but also cause temperature changes due to cloud formation (release of latent heat) or evaporation (absorption of latent heat) – these are all part of the water cycle on the Earth.
5. Volcanoes, and geysers can modify atmospheres chemically, and change the opacity, which changes the temperature structure.
6. Chemical interactions of an atmosphere with a planet’s crust (oxidation), or ocean (sedimentation) alters the atmosphere’s composition. Again, this is part of the whole water cycle on the Earth.

7. On the Earth biogenic and anthropogenic processes change the composition of the atmosphere (plants, animals, cars, industry, etc.)

In general planetary surface temperatures will depend upon several factors including

1. Distance from the sun
2. Albedo
3. Angle of the Sun (for a specific location on a surface)
4. Rotation rate – does the surface reach an equilibrium temperature or does it continually heat up or cool down over time
5. Non-blackbody nature of objects – objects do not necessarily absorb and also emit energy perfectly. This can be measured by the emissivity ($\varepsilon$), which =1 for a perfect black body and values near 0 for a very reflective surface. Typically dark objects have $\varepsilon=0.8$, while reflective objects have $\varepsilon=0.1$. While you might think this is the same as albedo, it is not since albedo measures how much light is reflected by an object. So it is sort of similar, but not the same.

The angle of the Sun can have a fairly dramatic effect on the surface temperature of an object, since the low elevation of the Sun will not deliver light to the same size region as the Sun at a higher elevation, such as is seen from the Earth’s equator. For a location on the Earth during the equinox (when the Sun is directly over the Equator), the relation for the balance of surface temperature is

$$T = \left( \frac{F_{\text{sun}}(1-A)\cos\phi}{4\varepsilon\sigma} \right)^{1/4}$$

where $T$=temperature
$F_{\text{sun}}$ = solar constant, 1366 W/m$^2$ – the amount of sunlight received at the Earth
$A$=Albedo
$\phi$=latitude
$\varepsilon$=emissivity
$\sigma$=Stefan Boltzman constant

The tilt of a planet can have an influence on the temperature (the above relation is only valid for the date of the equinox), and the distance for the Sun can have an influence particularly for a much more eccentric orbit.

**Layers**

Even though atmospheres may have very diverse composition differences, there are some commonly observed temperature structures seen throughout the solar system. These structures are seen in the following order with distance from the “surface” –

- Troposphere – temperature decreases with height here, the lowest layer where the pressure is the highest. Clouds form in this region typically. It has a negative gradient (temperature goes down as elevation goes up).
- Tropopause – the temperature minimum is at this location, usually around ~0.1 bar. The temperature gradient changes from this location from a negative one to a positive one.
- Stratosphere – the temperature increases with height (so a positive gradient). On the Earth this is where the ozone layer is located.
- Stratopause – the boundary between the stratosphere and the mesosphere.
- Mesosphere – Another temperature point that varies depending upon the world. On Mars and Venus this region is nearly isothermal (constant T), while on Earth and Titan, the temperature decreases with elevation (negative gradient).
- Mesopause – another temperature minimum location on the Earth and Titan, but isn’t defined on other worlds.
- Thermosphere – temperature generally increases here due to solar interactions with the atmosphere (a positive gradient)
- Thermopause/Exobase – boundary region between the thermosphere and the exosphere.
- Exosphere – interface between space and the atmosphere. In this region there can be the loss of an atmosphere’s gas to space. This is basically the outermost layer of the atmosphere.

Another region of a planetary atmosphere that is often mentioned is the ionosphere. This is actually located in the thermosphere and upwards from there. It is where atoms can be ionized by the Sun. On the Earth the ionosphere is important in radio communication since radio signals are refracted by it and long range communication is possible. The ionosphere will change due to solar storms or by other high energy influxes.

Not all planets have the same temperature profile, and even a planet’s temperature profile can vary due to diurnal effects (daily), seasonal variations (especially with eccentric orbits), or the amount of solar activity. So any quoted values of the location of any of the above regions or their characteristics are only averages at best.

**Composition**

The compositions of atmospheres also vary from planet to planet. That will change the value of $\mu$ in the ideal gas law, which can impact the temperature and pressure profiles. Composition variations can also influence the formation of clouds, and the albedo of the cloud layers – which also changes the temperature and pressure profiles. The atmospheres can be divided into two major groups – for objects with small mass and those with high mass. Here are the gases in the small mass objects -

<table>
<thead>
<tr>
<th></th>
<th>Earth</th>
<th>Venus</th>
<th>Mars</th>
<th>Titan</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_2$</td>
<td>78%</td>
<td>3.5%</td>
<td>2.7%</td>
<td>95.1%</td>
</tr>
<tr>
<td>$O_2$</td>
<td>21%</td>
<td>few ppm</td>
<td>few ppm</td>
<td>---</td>
</tr>
<tr>
<td>$CO_2$</td>
<td>345 ppm</td>
<td>96.5%</td>
<td>95.3%</td>
<td>&lt;1 ppm</td>
</tr>
<tr>
<td>$H_2O$</td>
<td>~3% or less</td>
<td>50 ppm</td>
<td>~100 ppm</td>
<td>----</td>
</tr>
<tr>
<td>$Ar$</td>
<td>0.9%</td>
<td>70 ppm</td>
<td>1.6%</td>
<td>40 ppm</td>
</tr>
<tr>
<td>$CH_4$</td>
<td>3 ppm</td>
<td>---</td>
<td>---</td>
<td>4.9%</td>
</tr>
</tbody>
</table>

(ppm=parts per million, percentage wise 1 ppm=0.0001%).
Every other gas is a tiny fraction and not worth noting.

And with the difference in composition and planetary distance (influence of solar heating), there is also a range of conditions at each planet’s surface and within the atmosphere:

<table>
<thead>
<tr>
<th></th>
<th>Earth</th>
<th>Venus</th>
<th>Mars</th>
<th>Titan</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface T (K)</strong></td>
<td>288</td>
<td>733</td>
<td>215</td>
<td>94</td>
</tr>
<tr>
<td><strong>Surface P (bar)</strong></td>
<td>1</td>
<td>92</td>
<td>.0056</td>
<td>1.467</td>
</tr>
<tr>
<td><strong>Scale height (km)</strong></td>
<td>8.5</td>
<td>16</td>
<td>18</td>
<td>40</td>
</tr>
<tr>
<td><strong>Albedo</strong></td>
<td>0.29</td>
<td>0.75</td>
<td>0.16</td>
<td>0.27</td>
</tr>
<tr>
<td><strong>Exobase T (K)</strong></td>
<td>1000</td>
<td>275</td>
<td>350</td>
<td>150</td>
</tr>
</tbody>
</table>

And for the large mass objects in the solar system -

<table>
<thead>
<tr>
<th></th>
<th>Jupiter</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>86.4%</td>
<td>97%</td>
<td>83%</td>
<td>79%</td>
</tr>
<tr>
<td>He</td>
<td>13.6%</td>
<td>3%</td>
<td>15%</td>
<td>18%</td>
</tr>
<tr>
<td>H₂O</td>
<td>0.1%</td>
<td>---</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.21%</td>
<td>0.2%</td>
<td>2%</td>
<td>3%</td>
</tr>
<tr>
<td>NH₃</td>
<td>0.07%</td>
<td>0.03%</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>H₂S</td>
<td>0.008%</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
</tbody>
</table>

And there are structural variations as well…

<table>
<thead>
<tr>
<th></th>
<th>Jupiter</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>T (at P=1 bar)</td>
<td>165</td>
<td>135</td>
<td>76</td>
<td>72</td>
</tr>
<tr>
<td>Scale height (km)</td>
<td>18</td>
<td>35</td>
<td>20</td>
<td>19</td>
</tr>
<tr>
<td>Tropopause T (K)</td>
<td>111</td>
<td>82</td>
<td>53</td>
<td>52</td>
</tr>
<tr>
<td>Tropopause P (bar)</td>
<td>0.14</td>
<td>0.065</td>
<td>0.11</td>
<td>0.14</td>
</tr>
<tr>
<td>Exobase T (K)</td>
<td>900-1300</td>
<td>800</td>
<td>750</td>
<td>750</td>
</tr>
</tbody>
</table>

**Mediocre Atmospheres**

To be fair, there are other worlds apart from those mentioned above that also have atmospheres, though they are generally not significant in their densities or pressures.

- Mercury – a large amount of its atmosphere likely comes from the solar winds, though the decay of material on the surface can also release elements. The most common gases are molecular oxygen, sodium, hydrogen, helium with traces of K, Ar, Ne, Ca, Xe, Kr, N, CO₂, and H₂O. The atmospheric pressure is about 10⁻¹⁵ bar. The temperature range on the surface is 100 – 700 K.
- Moon – the atmosphere originates from the solar winds, out gassing, and radioactive decay. Composition includes H, He, Na, K and Ar. The atmospheric pressure is about 10⁻¹⁵ bar. The temperature range on the surface is 120 – 380 K.
- Pluto – the atmosphere is formed by the sublimation of surface ices into gas when the object is at perihelion. Composed mainly of N₂, CO, CH₄ and ethane.
Pressure is between $6.5 \times 10^{-6}$ and $2.4 \times 10^{-5}$ bar. Surface temperature is around 53 K.

- **Triton** – it may have had a thicker atmosphere in the past, but currently gases from geysers contribute to it. Mainly composed of $N_2$ and $CH_4$. Pressure is around $1.4 \times 10^{-5}$ bar and the surface temperature is around 40 K.

- **Io** – the atmosphere is from the volcanism, so it is comprised mainly of $SO_2$ and $SO$. Pressure is around $10^{-9}$ bar.

- **Europa** – the source of this world’s atmosphere is thought to be through solar radiation interacting with surface ices and particles from Jupiter’s magnetic field. Basically water is broken apart with the heavier $O_2$ molecule left behind, so its atmosphere is composed mainly of $O_2$, but $SO_2$ has also been detected. The pressure is probably about $10^{-12}$ bar.

- **Ganymede** – similar to Europa, but with a bit more variety. Oxygen in the form of $O$, $O_2$, and $O_3$ have been detected, as well as $SO_2$ and $CO_2$. Since Ganymede does have a substantial magnetic field it may be able to form a more complex atmosphere, one with an ionosphere, but it is still pretty wimpy, maybe $10^{-12}$ bar.

- **Callisto** – like the other icy Galileans, a world with $CO_2$ and $O_2$ in its atmosphere. And also a very low pressure, close to $10^{-12}$ bar.

- **Enceladus** – likely produced by the out-gassing from geysers. Composed mainly of $N_2$, $CO_2$ and $CH_4$, with a low, variable pressure. This atmosphere would be easily lost due to the low surface gravity.

Including Io and Enceladus in this list is a bit dubious, since both have atmospheres that depend strongly on seismic activity, but I’m putting them on the list (not that it makes much difference in the long run).

**Winds**

There are other weather physics that needs to be addressed, in particular circulation patterns. Why does the wind blow the way it does? Here are the various ways that winds are produced on planets.

**Thermal tidal winds** – The flow of hot air to regions that are cooler. This can occur if there is a large difference between day and night temperatures of a planet. There will be a flow from one side of the planet to the other. This is really only effective on the surfaces of planets with relatively thin atmospheres, such as Mars, or in thin parts of an atmosphere, such as in the thermospheres of Venus and Earth.

**Condensation winds** – When gas condenses out of the atmosphere, something has to fill in that void, or when it sublimes, something has to get out of the way. Basically the change in local density due to evaporation, condensation, or sublimation results in a change in pressure and therefore a gradient in the atmosphere. This is another effect that is seen on Mars, and also on Triton and Pluto, and possibly on other icy objects. The change in atmospheric pressure due to these processes can be quite dramatic. On Mars $CO_2$ will sublime from the polar ice caps into the atmosphere resulting in a change in atmospheric pressure of about 20% over the seasons. On Triton and Pluto nitrogen and methane are the ices/gases that are involved in the process.
Hadley circulation – If a planet has low obliquity, it gets a great deal of sunlight concentrated at the equator. This air rises in the atmosphere and moves to regions that are cooler, which on the Earth are towards the north and south. Further from the equator the air cools and goes to a lower altitude and head back towards the equator. For planets with fast rotations there can be multiple Hadley cells, while for slow rotations there are fewer cells. Venus has only one Hadley cell per hemisphere, while on the Earth there are 3 Hadley cells per hemisphere.

Other things also influence weather patterns such as pressure gradients, rotation (the Coriolis effect) and so on. Basically you should take a weather class to learn more about them. Generally speaking, the faster a planet’s rotation, the more complex the circulation patterns/clouds/storms.

You also have the complications that the winds change with elevation. They change as the pressure/temperature/composition/density gradient changes, so at various levels the speed and/or direction of the wind can be quite different compared to another atmospheric level. On the Earth we hear about this mainly in the high speed winds in the “jet stream”.

8.2 Atmosphere Evolution

What were the first atmospheres like? Looking at their current compositions may not provide enough information, since the atmospheres can change both chemically and structurally over time. Looking at the types of atmospheres and the masses of the planets associated with them gives you some clear division of types, which also shows divisions in composition.

The smaller worlds have atmospheres rich in CO₂, N₂, O₂, H₂O, etc., while the massive worlds have H, and He rich atmospheres with traces of CH₄, NH₃, H₂O, and H₂S (hydrogen sulfide). So why are they different? Is it really only just a matter of the planet’s mass? Well, yes, it is the mass of the planet. Or specifically it is the planet’s gravity which plays a significant role in the evolution of the atmosphere. High mass worlds are able to retain low mass gases in their atmosphere much more easily than the low mass worlds, which will lose the low mass gases easily.

How is an atmosphere “lost”? If the gases in the atmosphere travel very quickly then they can overcome the gravitational force holding them to the planet. The hotter the planet, the faster these gases will move and the harder it is for the planet to retain the gases. And of course low mass gases move faster than high mass gases, so those are the ones that are lost much more easily to space. Since this is a long term process and velocities of gases need to be preferentially away from the planet, atmospheres are not lost quickly. If the average velocity is greater than about ¼ the escape velocity of the planet, then the atmosphere will be lost.

The average velocity (known as the root-mean-square velocity) is given by the relation
And the escape velocity is

\[ v_{\text{esc}} = \sqrt{\frac{2GM}{r}} \]

Where
- \( k \) = Boltzmann’s Constant
- \( G \) = Gravitational constant
- \( T \) = temperature (Kelvin)
- \( m \) = mass of the gas (kg)
- \( r \) = radius of the planet (meters)
- \( M \) = mass of the planet (kg).

So if \( v_{\text{rms}} \geq 0.25 \, v_{\text{esc}} \) then the atmosphere will be lost. You have a better chance to lose gases if the planetary gravity is low, the temperature is high, or the mass of the gases is low.

Other things can also strip off an atmosphere, such as chemical reactions, photodissociation and solar winds, which aren’t part of the above calculation. And different parts of the atmosphere, such as the exosphere, may be more easily depleted than surfaces. But you need to remember that if the outer layers of an atmosphere are lost, this will likely result in an expansion of the lower layers outward and further depletion can occur.

**Photo-dissociation and Recombination**

*Photo-dissociation* is the absorption of energy by a molecule leading to the breaking apart of the molecule. This is more commonly observed at high altitudes. The reverse process, *recombination*, is more likely to occur at lower altitudes. In spite of the differences in location of these reactions, the circulation of an atmosphere leads to an equilibrium state, so that current atmospheres are balanced at both high and low elevations. Stable atmospheres will have these processes balancing each other despite differences in where the processes occur.

Many of these reactions are wavelength dependent, with many depletions occurring due to UV light. The various reactions are given below for the photo-dissociations (P), and recombinations (R) that are currently observed on various worlds.

A main component of the Earth’s atmosphere, \( O_2 \), can be broken apart fairly easily at high altitudes. The recombination requires usually a 3-body reaction which ends up being faster than a simple reversal of the break-up process. With the back and forth destruction and formation of \( O_2 \), there is a peak in the abundance of atomic oxygen in the middle of the atmosphere.

\[
\begin{align*}
\text{P: } & O_2 + \text{UV photon} \rightarrow O + O \\
\text{R: } & O + O + M \rightarrow O_2 + M
\end{align*}
\]

Where \( M \) = is a molecule (not a specific one).
Ozone is often the molecule that gets a lot of publicity, and it is easily destroyed by photons that are at the relatively low energy end of UV light.

\[
P: \text{O}_3 + \text{UV photon} \rightarrow \text{O}_2 + \text{O} \\
R: \text{O} + \text{O}_2 + \text{M} \rightarrow \text{O}_3 + \text{M}
\]

Ozone can also be depleted by reactions with other gases, such as H, NO, NO\(_2\), and Cl. The nitrogen oxides are an industrial by-product, though it isn’t clear how they can get up to that height in the atmosphere.

On Venus and Mars reactions occur to influence the relative amounts of CO\(_2\) and CO in their atmospheres, and on Venus you also have reactions that lead to the rather nasty clouds. Specifically there is sulfur dioxide which can react with oxygen atoms and water molecules

\[
\text{SO}_2 + \text{O} \rightarrow \text{SO}_3 \\
\text{SO}_3 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{SO}_4
\]

And H\(_2\)SO\(_4\) is sulfuric acid. This reaction occurs in the upper troposphere of Venus.

For the outer planets, the upper atmospheres have a mix of methane, ammonia, hydrogen sulfide, water and phosphine and these molecules will produce other compounds through photo-dissociation with UV photons.

Ammonia (NH\(_3\)): This can produce hydrazine gas in the upper parts of the atmosphere, particularly the hazy parts of the upper atmospheres. There is a depletion of ammonia near to and above the tropopause of the Jupiter and Saturn which supports this model. For Uranus and Neptune the temperatures for the tropopause are so low that ammonia freezes out of the atmosphere below the tropopause, so there is virtually no chance for this reaction.

Methane (CH\(_4\)): Various hydrocarbons form, including acetylene, ethylene, and ethane. Hydrocarbons have been observed in all of the outer planets’ atmospheres.

Hydrogen Sulfide (H\(_2\)S): The break-up of this molecule can form sulfur, ammonium polysulfide, and hydrogen polysulfide. These molecules are very colorful and it is possible that they contribute to some of the colorful clouds of Jupiter and Saturn.

Phosphine (PH\(_3\)): At high altitudes you have the formation of red phosphorus, which may explain the coloring of the Great Red Spot of Jupiter.

**Low Mass Atmosphere evolution**

The earliest atmospheres for the low mass objects in the solar system would likely have lost most of their primordial hydrogen (H\(_2\)) and helium due to their low mass. The end result is an atmosphere that is dominated by the remaining gases that were present during the planetary formation. Likely compositions would be atmospheres comprised primarily of CO\(_2\), Ne, N\(_2\) and COS, as well as Ar, Kr, and Xe at solar composition amounts.

But it isn’t really that simple. The amount of the heavier inert gases (Ar, Kr, Xe, Ne) is not the same as the solar abundance – there are quite different amounts of these elements.
on planets than you would expect to have by just removing the hydrogen and helium (they are much lower than expected). That’s why we believe that something has to be added to the atmosphere to decrease the relative abundances of the inert gases. The best bet is volcanism, out-gassing or the influence of water rich comets/asteroids which can contribute to the atmosphere and alter the chemical make-up of the atmosphere.

Earth’s atmosphere has evolved quite a bit over time. Early in its history, the surface was quite hot, which prevented the formation of icy reserves of material that could contribute to the atmosphere. The high temperature would have been not only due to out-gassing and volcanism, but also the composition of the atmosphere. The early atmosphere would have been rich in greenhouse gases such as H$_2$O, CO$_2$, CH$_4$, and NH$_3$. The CO$_2$ would have cycled into and out of the atmosphere in a regular pattern. It is removed through the Urey weathering reaction, where CO$_2$ is dissolved in water and reacts with silicates in the soil. This causes a release of calcium and magnesium ions and converts the CO$_2$ into bicarbonate which reacts with the ions to form other carbonate minerals. The CO$_2$ is released into the atmosphere through volcanism. This recycling process goes quickly when the temperature is high, which happens when the CO$_2$ acts like a greenhouse gas. In general it is likely that this cycle is a self-regulating system today, but of course we mess it up with the release of additional CO$_2$.

And without water in a liquid form, we would not be able to remove the CO$_2$ from the Earth’s atmosphere – this is an important distinction between our atmosphere and that of Venus. Along with the decrease in the CO$_2$ content, there was an increase in the Earth’s oxygen content over time. This is clearly seen in the fossil record. Oxygen is associated with the development of life which produced it as a waste product.

The evolution of Mars’ atmosphere is a bit tricky, since much of our information is implied by imaging, and not direct sampling. However it cannot be denied that the atmosphere in the past was much more complex than it is now. Evidence of water features dating back to the Noachian era (up to 3.8 Gyr ago) indicates that the atmosphere was thicker in the past. The early Martian atmosphere could have had pressures close to 1 bar, and surface temperatures close to 300 K, which would be quite comfortable. It is likely that this atmosphere was rich in CO$_2$ and H$_2$O. The CO$_2$ was lost through weathering processes, adsorption on to the regolith, and/or condensation on the surface. Surface impacts would also influence the atmosphere as well as the solar wind (or lack of a magnetic field). Both impacts and winds would help to deplete the atmosphere gradually over time. Current observations of Mars show that interactions with the solar winds result in a measureable loss of atmospheric gases, at both a steady rate and an accelerated rate when the winds are particularly strong.

Currently there should be a significant amount of CO$_2$ in the surface rock layers of Mars, which will remain there since the tectonic activity on Mar has pretty much stopped. So the CO$_2$ cycle that exists on the Earth is stopped on Mars. And without any liquid water, the weathering has also ceased. All that is now left is a small amount of CO$_2$ in the atmosphere. Even with the loss of CO$_2$ there should still be some water present, but odds are it has either been lost into space or frozen into the surface layers – there is evidence of
the latter. There are other likely influences on the evolution of Mars’ atmosphere apart from the lack of volcanism. One is the obliquity of the planet. Without a stabilizing satellite such as the Earth’s Moon, Mars’ obliquity has varied quite a bit in the past, perhaps up to 60°, which would have resulted in a large temperature imbalance on the surface. Also, Mars’ orbit is a bit more unstable with a varying eccentricity extending up to 0.12 (the Earth’s doesn’t get larger than 0.04). This will also influence the surface heating and cooling and could have influenced the atmosphere in the past. Either way, the ancient, wetter, warmer atmosphere of Mars is gone and the current atmosphere is a shell of its former self.

Venus has very little H₂O in its current atmosphere. Even though it is closer to the Sun it is not so close that water is impossible to form – it should have been part of the planet early in its history. Also when we look at the relative amounts of deuterium (D) to hydrogen, we see a ratio of D/H that is about 100 times that of the Earth. Since the D abundance can be used to trace the water abundance, this implies that there was quite a bit of water present on Venus in the past. It is possible that water could have dissociated (broken apart) with the oxygen remaining on the planet and the hydrogen lost into space. This can’t be the only option, since the rate at which the atmosphere is lost is relatively low, so there still should be quite a bit of water left on the planet. Currently the best reason to explain the loss of the water is via a runaway green house effect. On Venus there may have been tons of water but it would never form into a liquid due to the high temperature caused by water vapor and CO₂ in the atmosphere. It is ironic that water in one form prevented the formation of water in another form. And with such a large amount of water vapor present, the high altitude molecules would be dissociated with the hydrogen lost into space.

The evolution of other planetary atmospheres is not easily traced, since either they are in a rather consistent state (like Titan), or their atmospheres haven’t really changed much during their entire history.