Planetary Atmospheres

- ## Formation and Evolution of Planetary Atmospheres

Hydrogen and Helium are by far the most abundant elements in the universe. For every 1000 atoms of Hydrogen there are nearly 100 of Helium and only one or two of all the other elements. Most of the Helium, it is believed, was formed during the Initial Explosion (Big Bang) of our expanding universe, probably something like 10 billion (10^{10}) years ago. A substantial amount, is also produced through the continuous "burning" of Hydrogen to Helium in the interior of the stars.

Our solar system was formed approximately 5 billion (5×10^{9}) years ago from galactic matter already enriched in heavy elements. The most common of these elements are O, C, N, Ne, Si, Mg, S, Fe, Al, Ca but they still comprise only about 2% of the total mass of the solar system.

A vastly enhanced solar wind in the early stages of the sun's life stripped the inner planets (Mercury, Venus, Earth and Mars) of all their gaseous matter. What remained were essentially the chemically condensable materials which represented only a small fraction of the total initial mass. The outer planets were too far to suffer any significant losses at this stage. Thus all of them (Jupiter, Saturn, Uranus and Neptune) are much more massive than the inner planets and their composition is probably very similar to the composition of the initial nebula from which the solar system was formed.

The formation of the first solid bodies in our solar system took place approximately 4.7×10^9 years ago. Studies of rocks and minerals on the surface of the earth show that these minerals have remained unchanged for not more than 3.6×10^9 years. As a result, we know very little about the first one billion years of the history of our planet.

Chemical analysis of ancient rocks shows that the early atmosphere of the earth was reducing, i.e., it was lacking in free Oxygen and contained mainly H_2, CH_4, N_2, NH_3 ,CN, CO and H_2O. Part of the water vapor condensed later to from lakes and seas, and at the same time the different sources of energy available such as lightning, volcanic action, solar ultra-violet radiation, etc…, acted to from amino-acids and other organic substances from the above mentioned atmospheric constituents. The organic compounds were then dissolved in the water bodies on the surface of the earth and formed what is sometimes referred to as the **primordial soup**.

In the depth of the lakes, protected from the hazardous ultra-violet radiation of the sun, these organic chemicals combined through different catalytic reactions to form dioxyribonucleic acid (DNA), ribonucleic acid (RNA), and certain proteins called enzymes, which are the beginning of life. This took place on the earth probably close to 3.5 billion years ago. The early organisms resided in a molecular **Garden of Eden** because they could feed, without doing any work, on the organic substances that was dissolved in the primordial soup. It was not too long, however, before all the available food was consumed, and the survival of living organisms had to depend on their ability to develop new feeding processes. The crisis was solved by some organisms which managed to start synthesizing their food from H_2O, the CO_2 that was naturally dissolved in the waters, and the energy of the solar rays. This new process, which has Oxygen as its by-product, is called photosynthesis and it is believed that it appeared on earth approximately 3 billion years ago.

During the pre-Paleozoic (pre-Cambrian) era (700 – 600 million years ago) the process of photosynthesis allowed the accumulation in the atmosphere of small amount of Oxygen, which in turn gave rise to minute traces of Ozone (O_3). Ozone is a very essential element in the evolutionary process of life because it stops the ultra-violet radiation from the sun before it can reach the ground and cause irreparable damage to all unprotected living organisms.

In the beginning of the Paleozoic era, i.e., about 600 million years ago, the Oxygen probably reached a level of about 1% of its present abundance, and the Ozone that was formed allowed life to survive even at very shallow depths of water.

In the late Silurian, i.e., about 400 million years ago, Oxygen was probably close to 10% of its present level and Ozone had reached a level their permitted the existence of life outside the water. Living organisms again underwent and evolutionary explosion, and by the early Devonian, i.e., about 380 million years ago, great forests appeared on the surface of the Earth. This produced a rapid increase in Oxygen and, therefore, more protective Ozone. Amphibians and insects appeared on the land.

It is estimated the amount of CO_2 that has been released over the ages in the atmosphere of the earth through volcanic action is of the order of 2×10^5 times the present content, i.e., about 4×10^{23} gr. ($gr = gran$ and $50mg \approx 0.77gr$)

If all this CO_2 had remained in the atmosphere, it would have produced a CO_2 atmosphere similar to the one of Venus with a ground pressure of about 80 a.t.m. Most of this CO_2, combined with metal oxides to form carbonic rocks and minerals such as limestone ($CaCO_3$) and dolomite ($MgCO_3$). A Substantial part of it was also taken out from the atmosphere by living organisms and was converted, through photosynthesis, to organic matter with the simultaneous release of free Oxygen. An important fraction of this organic matter is continuously withdrawn from the cycle of photosynthesis and oxidation as the remains of dead organisms are mixed with the soil or buried at the bottom of the oceans. If all dead organic matter were burned back into CO_2, it would consume all the available Oxygen and it is only sedimentation of organic matter that has allowed the accumulation of Oxygen in the atmosphere. Unfortunately only a very small fraction ($\sim 3 \times 10^{18}$ gr) of these carbon-containing sediments was transformed into the valuable, concentrated deposits (coal, petroleum, natural gas, etc…) which are known as **fossil fuels**.

If the earth did not have any water, life would have not evolved on our planet to change CO_2 to organic matter and Oxygen, and ultimately help to withdraw part of the carbon in the form of organic sediments. Furthermore, there would have no weathering of the silicate rocks to produce metal oxides which, combined with CO_2, to form carbonic rocks and minerals. As a result, without water the earth would have had a thick atmosphere of CO_2, probably very much like the one of Venus.

• The Structure of the Terrestrial Atmosphere

To facilitate the study of the atmosphere, we usually divide it into shells with common properties. These shells bear names ending in sphere (e.g., stratosphere) and the boundaries between them follow the name of the lower layer with the ending pause (e.g., stratopause). The several layers into which the atmosphere is divided vary depending on the principle properties of the atmosphere under investigation. One of the most common classifications is when the temperature is used as the guiding parameter. In this case we recognize the following regions of the terrestrial atmosphere:

Troposphere: This is the lowest layer and extends from the ground to about 13 km. The heat source for this region is the surface of the Earth, at a temperature of 290 ± 20 K and, therefore, as we move away from the ground, the temperature decreases at a rate of $\sim 7\ K\ km^{-1}$ reaching a minimum of 210 ± 20 K at the tropopause.

Tropopause: The upper boundary of the troposphere occurring at an altitude of 13 ± 5 km.

Stratosphere: The temperature beings to rise in this region reaching a maximum of 270 ± 20 K at the stratopause. The heating of the stratosphere is due to the absorption of the ultraviolet radiation in the 2000 - 3000 $\overset{o}{A}$ range by the Ozone in the ozonosphere. The Ozone layer reaches a maximum concentration around 20 – 25 km.

Stratopause: The upper boundary of the stratosphere occurring at an altitude of 50 ± 5 km.

Mesosphere: The temperature starts decreasing with height in the region due to an energy sink provided by the CO_2 and Oxygen emission in the far infrared. It reaches a minimum of 180 ± 20 K at the mesopause.

Mesopause: The upper boundary of the mesosphere occurring at an altitude of 85 ± 5 km.

Thermosphere: The temperature increases steeply with height in this region reaching its peak value of 1500 ± 500 K at the thermopause. The very effective heating source of this layer is the far ultra-violet (100 – 2000 A°) radiation from the sun which is absorbed in this region causing the photodissociation and photoionization of the atmospheric constituents. Solar particles and meteors also make a small contribution to the heating process.

Thermopause: The upper boundary of the thermosphere occurring at an altitude of 350 ± 100 km. Above this height the atmosphere, due to its high thermal conductivity, maintains the same high temperature which it first reached at the thermopause.

The physical parameters of an average atmosphere are shown in the following figure and are listed in the following table.

TABLE 1.5-I

Name	Symbol	Distance in A.U.	Radius in R_0	Mass in M_0	Gravity in m/s^2	Esc. Vel. in km/s	Albedo
Mercury	☿	0.387	0.38	0.054	3.6	4.2	0.06
Venus	♀	0.723	0.96	0.815	8.7	10.3	0.75
Earth	⊕	1.000	1.00	1.000	9.8	11.2	0.4
Mars	♂	1.524	0.53	0.108	3.8	5.0	0.15
Ceres (Asteroid)		2.767	0.055	0.0001	0.3	0.5	0.07
Jupiter	♃	5.203	11.19	317.8	26.0	61.0	0.5
Saturn	♄	9.540	9.47	95.2	11.2	37.0	0.5
Uranus	⛢	19.180	3.73	14.5	9.4	22.0	0.5
Neptune	♆	30.070	3.49	17.2	15.0	25.0	0.5
Pluto	P	39.440	~0.4	~0.2	~12.3	~7.6	~0.4

1 A.U. = 1.5×10^{13} cm
1 $R_{\oplus}$ = 6.38×10^{8} cm
1 $M_{\oplus}$ = 5.48×10^{27} gr

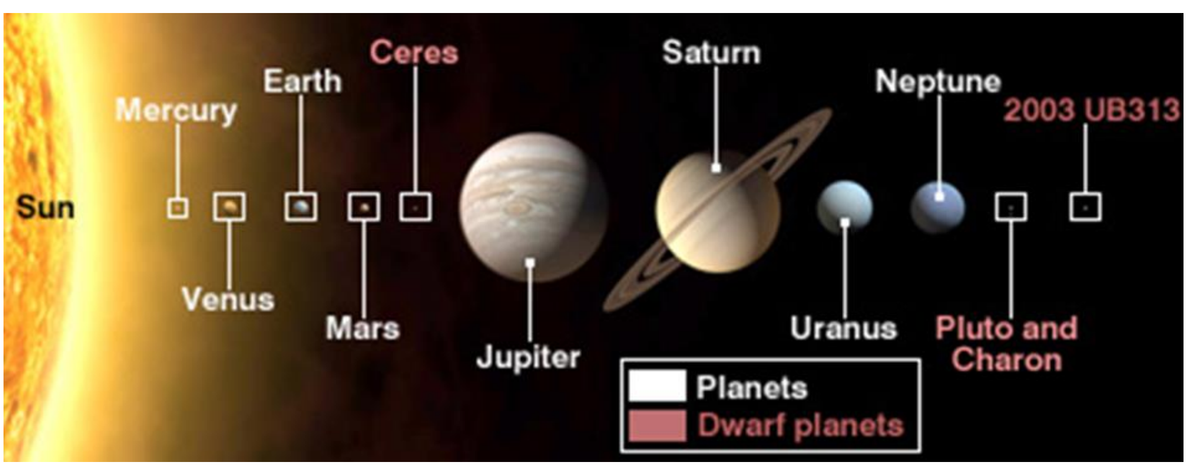

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TABLE 1.2-I

Altitude in km	Temperature in °K	Density in gr/cm^{-3}	Mean Mol. Weight	Pressure in dyn/cm^2	Mean Free Path in m	Accel. Grav. in cm/s^2
0	288	1.23×10^{-3}	28.96	1.01×10^{6}	6.63×10^{-8}	981
2	275	1.01×10^{-3}	28.96	7.95×10^{5}	8.07×10^{-8}	980
4	262	8.19×10^{-4}	28.96	6.17×10^{5}	9.92×10^{-8}	979
6	249	6.60×10^{-4}	28.96	4.72×10^{5}	1.23×10^{-7}	979
8	236	5.26×10^{-4}	28.96	3.57×10^{5}	1.55×10^{-7}	978
10	223	4.14×10^{-4}	28.96	2.65×10^{5}	1.96×10^{-7}	978
20	217	8.89×10^{-5}	28.96	5.53×10^{4}	9.14×10^{-7}	975
40	250	4.00×10^{-6}	28.96	2.87×10^{3}	2.03×10^{-5}	968
60	256	3.06×10^{-7}	28.96	2.25×10^{2}	2.66×10^{-4}	962
80	181	2.00×10^{-8}	28.96	1.04×10	4.07×10^{-3}	956.
100	210	4.97×10^{-10}	28.88	3.01×10^{-1}	1.63×10^{-1}	951
140	714	3.39×10^{-12}	27.20	7.41×10^{-3}	2.25×10	939
180	1156	5.86×10^{-13}	26.15	2.15×10^{-3}	1.25×10^{2}	927
220	1294	1.99×10^{-13}	24.98	8.58×10^{-4}	3.52×10^{2}	916
260	1374	8.04×10^{-14}	23.82	3.86×10^{-4}	8.31×10^{2}	905
300	1432	3.59×10^{-14}	22.66	1.88×10^{-4}	1.77×10^{3}	894
400	1487	6.50×10^{-15}	19.94	4.03×10^{-5}	8.61×10^{3}	868
500	1499	1.58×10^{-15}	17.94	1.10×10^{-5}	3.19×10^{4}	843
600	1506	4.64×10^{-16}	16.84	3.45×10^{-6}	1.02×10^{5}	819
700	1508	1.54×10^{-16}	16.17	1.19×10^{-6}	2.95×10^{5}	796

As we mentioned earlier, the atmosphere is divided in to different layers for different subjects of study. We have already seen the division according to temperature. When our main interest is the chemical composition of the terrestrial atmosphere, we recognize the following regions.

Homosphere: It extends from the ground to about 100 km and is the region where a complete mixing of the atmospheric constituents takes place. The homosphere has a uniform chemical composition with a 28.96 mean molecular weight. It should be noted that layers of minor constituents, such as the Ozone layer around 20 km, are nothing more than traces and, they do not violate the basic picture of homogeneity prevailing in this region.

Hetrosphere: This is the region above 100 km where, due to diffusion and molecular dissociation (e.g. $O_2 \rightarrow O + O$), the chemical composition varies with height, decreases with altitude. Thus, around 600 km the average molecular weight is near 16, because pre-dominant atmospheric constituent is atomic Oxygen. Nitrogen dissociates at a slower rate recombines faster than Oxygen so there is very little atomic Nitrogen in the upper atmosphere. At even higher altitudes atomic Oxygen gives its place to Helium and finally Helium to Hydrogen.

Heliosphere: A layer roughly 1000 km thick between 1000 and 2000 km where Helium becomes the main atmospheric constituent.

Protonosphere: The region above about 3000 km where the main constituent is atomic and ionized Hydrogen.

❖ Other regions of the upper atmosphere characterized by some common property other than temperature or chemical composition are the following:

Exosphere: It defines the regions from which neutral atoms can escape the gravitational attraction of the Earth and extends from approximately 600 km on up.

Ionosphere: This is the region where a partial ionization of the atmospheric constituents takes place. The ionosphere extends from about 70 km on up and reaches a maximum of ionized particle density around 300 km.

Magnetosphere: This is the region where the motion of the ionized particles is governed by the Earth's magnetic field. It is rather difficult to define the beginning of the magnetosphere, and one can only roughly place it near 1000 km. The upper limit of the magnetosphere is clearly defined and as expected it is called the magnetopause. On the sunlit side of the Earth the magnetopause occurs at approximately 10 earth radii, whereas, on the night side of our planet it takes the shape of a long (100 earth radii) cylindrical magnetic tail. The magnetopause defines the boundary of the terrestrial domain beyond which, after a transitional region which is called the magneto-sheath, stars the vast realm of the interplanetary space.