Chapter 7: A Clement Climate

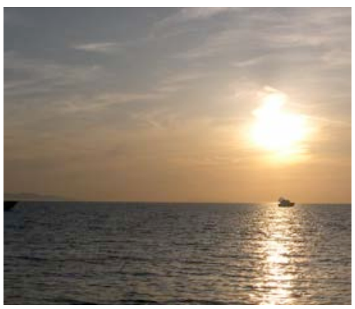
Is not their climate foggy, raw, and dull,

On whom, as in despite, the sun looks pale

The Life of King Henry the Fifth, Act III. Scene V.

William Shakespeare (1564–1616).

The Oxford Shakespeare, 1914



(D7.1. Sun, water, and clouds) Bruno thought that even the surfaces of stars are habitable. Galileo was more cautious. He could safely discuss the habitability of the Moon, especially as a con. This had the effect of bringing up the possibility of other inhabited worlds to an alert reader without being explicit enough to trouble the censors. He saw that there were no clouds on the Moon and hence no rain. (A pro might have got away with claiming that there were many gold-hoarding heathens to convert once flying machines were available, but Galileo was a scientist constrained by the data.) Galileo's few sentences started our understanding of the relationship between atmospheres and planetary habitability, based on remote observations and rational requirements for life. Modern astrobiologists, like Galileo, follow the water to prime habitable real estate.

Galileo did not fully comprehend the airless waste on the Moon, but his work quickly led to the concept of air pressure and in turn to its relationship with the density of air and the reality of space. Careful attention to detail led to the discovery that air contains oxygen and to the science of meteorology. We need to understand when a planet can have air and the processes that govern its surface temperature. It took well into the twentieth century for scientists to relate these ideas to the general issue of planetary habitability.

The Earth's Atmosphere

Today the basic issues with regard to the Earth are so widely known that imagination is needed to visualize the conditions on other planets. Air travel and car travel across mountains are now common. You may have had empty closed water bottles collapse when who returned from the mountains. Your ears pop with air escaping as the pilot depressurizes a plane on take-of and pop again as the cabin pressure increases on landing.

Physically air has weight that pushes down. When you are near sea level and there is more air above you than there was when you were in the mountains. It is much like diving down in water. The weight of the water above you puts pressure that you feel on your ears. I briefly discussed that pressure increases with depth within stars in the last chapter. In addition, air is quite springy. As a gas, it fills the available space. Bike tires and air mattress take advantage of this springiness. The pressure of the air compresses it, like when you pump air into a bike tire.

As a practical experiment, say that we opened water bottles and then sealed them at 3 kilometers elevation in the mountains where the pressure is only 3/4 of the pressure at sealevel. Water bottles are not very strong and crush until the pressure of the air is the same outside as inside. The volume left in the crushed bottle at sealevel is 3/4 of what it in the mountains. (See exercise at end of chapter.)

Finding air.

A fish does not know water until it finds air.

Reputed Chinese proverb

Classical science provided a meager understanding of air. Aristotle made air one of his four elements. It filled a spherical shell between elements water and earth and the heavenly element fire. He made stars out of his fifth element, quintessence. Galileo dislodged this relationship when he found the moons of Jupiter. Kepler sensed the emptiness of the vast space between stars and planets. It took practical matters for scientists to discover that a thin atmosphere lies between the surface of the Earth and space.

In 1638, water pumps were in common use in Italy. There were two practical types. One type pushed the water up from below. The other sucked it up from above. Everyone thought they knew how the latter type of vacuum pump works. One pumps out the air at the top of a tube. You do this when you suck on a straw. Water at the bottom rises because nature abhors a vacuum. This catchy axiom did not stand the test of data.

There were practical problems. A vacuum pump could suck water up more than 10 m. (I use modern units.) The difficulty was not with how the pump was made. Galileo checked the problem out and confirmed the result. He was aware that air has weight.

(You can weigh air yourself. [see Do it Yourself with Air]) Galileo was in poor health and did not survive long enough to resolve the problem.

His student, Evangelista Torrcelli (1608-1647), continued the study. He worked with mercury, a more dense manageable substance for this experiment than water. He could get it in quantity, as it was useful for treating syphilis. He found that mercury can rise only 76 centimeters. The weight per area of mercury in the 0.76-m tube is the same as the water in the 10-m tube (Figure 1). He realized that the weight of the mercury and the water balance the weight of the air in the atmosphere. He had invented the barometer. Air pressure, like water pressure, acts in all directions. We do not normally notice it unless there is an imbalance, like with our ears popping as the outside pressure increases when a plane descends.

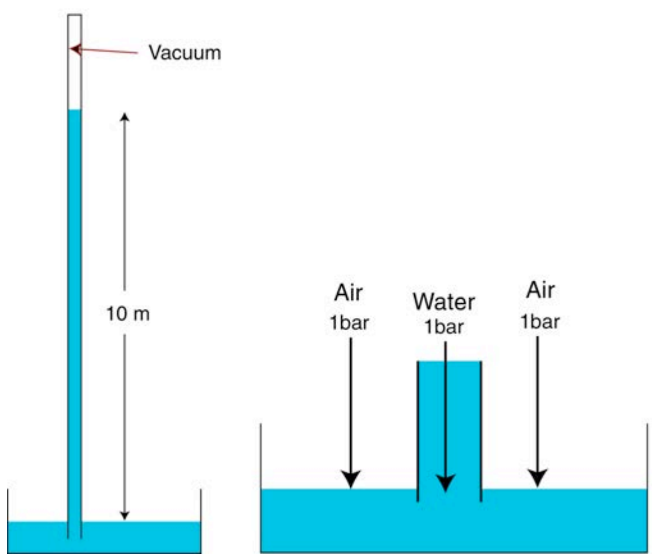


Figure 1: Here is how to make a water barometer, which requires a hose sealed on one end and a large tub. The hose will need to be transparent if you want to see the results. You will also need to be able to lift the hose at least 10 meters. This experiment is a pain to do, but water can fill a sealed tube with a vacuum at the top only to 10 meters above the water surface. This is the limit for a vacuum pump. The weight per area (pressure) of the water in the tube is balanced by the atmospheric pressure. A similar device with liquid mercury made the traditional barometer. As mercury is denser than water, the column is only 76 centimeters high.

In modern terms, it is easier to visualize the above situation with units of mass. Water weighs 1 gram per cubic centimeter, mercury 13.6 grams, and air 0.0012 grams. The mass per area in all the columns is 1 kilogram per square centimeter. The air column is 8 kilometers high.

Pressure and elevation. Correctly, the force per area is the pressure. The density is the mass per volume and the specific weight is the force per volume given by the density times the acceleration of gravity. The acceleration of gravity does not change much from about 10 newtons per kilogram over a few kilometers elevation, justifying using masses and densities in a quick calculation. Because we will need units of pressure later, I repeat the calculation. Water weighs 10,000 newtons per meter squared. The weight per area of a 10-m column is 100,000 newtons per meter squared. Mercury weighs 13,600 newtons per meter cubed so that the weight per area of the column is also 100,000 newtons per meter squared. (100,000 newtons per meter squared makes a convenient unit (the bar) as it is about the same as sealevel atmospheric pressure on the Earth. Scientists use bars to express pressure for this reason.)

We can easily conduct Torrcelli's experiment in an afternoon in the laboratory, if we ignore the safety issues of having an open container of mercury around. It took Torrcelli more time. He needed to show that his results were reproducible. For example, he showed that the shape of the tube does not matter. Torrcelli noted that the height of mercury in his barometer changed from day to day. He correctly associated this with the weather. He deduced that winds result from the different movements of hot and cold air. This eventually killed the ancient notion that exhalations from the interior of the Earth produce winds.

Torrcelli's results did not please the Church. Aristotle's physics was still effectively dogma, even though he is mentioned nowhere in the Bible. A vacuum was forbidden. Unlike Galileo, Torrcelli did not get into serious trouble. His invention was easy to make and the concept of pressure useful. Torrcelli wisely avoided philosophical discussions about vacuums.

A simple prediction arose from Torrcelli's work. The weight of the overlying atmosphere should decrease as one ascends upward. Blaise Pascal (1632-1662) in 1648 persuaded his more athletic brother-in-law to climb the mountain Puy du Dôme three times in one day with a mercury barometer. This confirmed the prediction. Since then, explorers, hikers, and aircraft pilots routinely use barometers as altimeters to determine their elevation. This is an easy do it yourself project. An ordinary weather barometer (which uses springs rather than mercury) will suffice in a several story building.

Still Pascal and Torrcelli did not know what air was made of. They only knew its weight and that they could measure air resistance on falling objects. A new science, chemistry, was needed for progress.

Alchemy becomes chemistry

An arcane concoction.

Fillet of a fenny snake,

In the cauldron boil and bake;

Eye of newt, and toe of frog,

Wool of bat, and tongue of dog.

Macbeth, Act IV. Scene I.

William Shakespeare (1564–1616).

The Oxford Shakespeare, 1914

Shakespeare's witches provide a dramatic but basically accurate description of the state and status of what is now called chemistry in 1600. Apothecaries formulated their elixirs empirically with the secrecy of a medieval guild. Ingredients, like snake and bat wool, shared the pot with potentially active substances. Newt is an active but dangerous ingredient in a potion. It contains tetrodotoxin, the poison also found in pufferfish. British newts have not been the subject of much study and are probably not highly toxic. The toxicity of newts varies locally. Even a nibble from a species in Oregon to central California would be lethal to a person.

Medieval potion makers used a mixture of generalization from experience and the idea that the shape of a plant indicated its use. The folk treatment foxglove is the source of the heart medicine digitalis. Conversely, in traditional Chinese medicine, the value of ginseng depends on its resemblance to the shape of a man, not its chemical content. Dogwort, which resembles a canine tooth, was a futile treatment for rabies.

The technology for extracting metals from ores was similarly cloaked in mysticism and secrecy. ("Arcanist" is an obsolete term for "metallurgist.") Alchemists futilely sought the philosopher's stone that would turn lead into gold; sometimes they then profitably became con men. The Italian Borgia family eliminated opponents with easily concealed poisons. Gunpowder added to the carnage when intrigue led to war.

Some concepts of chemistry existed since people could observe many processes. For example, the fenny snake in the witches' brew comes from a fen, an alkaline swamp found typically on top of limestone. A bog, meanwhile, is acidic, typically from decaying organic matter. Many in Shakespeare's audience probably knew the difference between the alkaline swamp and the acidic bog, but not the reason behind it. As a matter of taste, acid is sour. Vinegar is a weak acid; hydrochloric acid (found in your stomach) and sulfuric acid (in most car batteries) are strong acids.

To reintroduce some chemistry started in Chapter 4, acids release hydrogen ions into the water in which they are dissolved. For example,

HCl (hydrochloric acid) --> H+ (hydrogen ion in solution) + Cl- (chlorine ion in solution)

A strong acid almost completely dissociates into ions. A weak one doles out only a little of its available hydrogen as ions.

Alkaline is bitter or basic. Baking soda is a weak base. Quick lime (CaO or $Ca(OH)_2$, available as an additive to soil; I continue to give simple chemical formulas for those familiar with them) is an intermediate base. Lye (NaOH, used for opening drains) is a strong base. Bases release hydroxyl ions into a solution. For example,

NaOH (sodium hydroxide) --> Na+ (sodium ion in solution) + OH- (hydroxyl ion in solution)

Acids neutralize bases (and vice versa). For example, hydrochloric acid and lye react violently to form water and table salt

[H+ + Cl-] (dissolved hydrogen and chlorine ions) +

[Na+ + OH-] (dissolved and ionized sodium hydroxide) -->

H_2O + [Na+ + Cl-] (dissolved sodium and chlorine ions, table salt in solution)

Do not try this yourself. It is also idiotic to use taste as a primary method for studying chemicals. The early chemists, however, had little choice.

The mechanics of air. Seventy years passed after Shakespeare before chemistry became one of the new sciences. In 1670, Robert Boyle of England attempted to make some sense of the morass of what is now chemistry. His methods were like those of Galileo. He did a lot of simple experiments and recorded what happened. He was not bound by medieval ideas or by the then current concept that every chemistry experiment must be immediately useful for medicine. He found dyes, akin to litmus paper, that change color depending on whether a substance is base, neutral or acid. He attempted to identify reproducible substances like ammonia and sulfur. He defined a chemical element in the modern sense as a substance that cannot be decomposed into simpler substances.

He then turned his effort to air. He realized that air is springy. In fact, air behaves just like a mechanical spring. Boyle's associate, Robert Hooke, found that the compression on a spring bearing a load (like a bathroom scale) is proportional to the force on the spring. (Most schoolbooks discuss the equivalent experiment where the load hangs on a spring.) Boyle found that the volume of a batch of air is inversely proportional to the pressure. Its density (mass per volume) is linearly proportional to the pressure. He found that this elasticity never wears our, unlike a metal spring that may stretch or break.

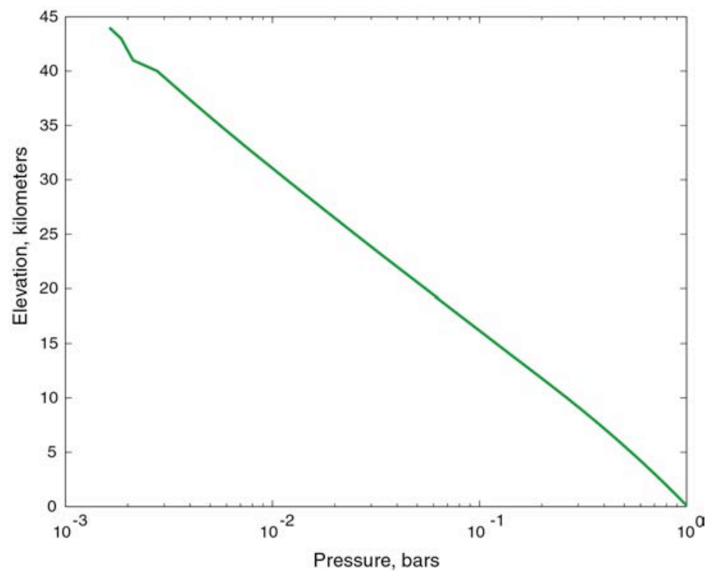


Figure 2: Atmospheric pressure in bars (log-scale) decreases with elevation. The plot in close to a straight line as expected from the exponential equation. Mathematically for those not familiar with log plots, this results because ln [exp (x)] = x where x is any quantity. You can verify this with the natural log "ln" button on your hand calculator.

If we (for now) ignore the effect of temperature, this relationship gives us the variation of pressure and air density with elevation. In terms of mass, 1 kilogram of air pushes downward on every square centimeter. The sea-level air has a density, for convenience, of 1 unit. The density, the pressure and the mass of the atmosphere above us decrease gradually as we ascend. The whole atmosphere is equivalent to a column 8 km high. The density varies continuously with elevation. For example if we go up 5.5 km, the mass per area above us, the density, and the pressure are only 1/2 those at sea level. Half of the atmosphere is below us. If we go up another 5.5 km, the density, pressure, and mass above us are 1/4 those at sealevel. An analogy is a spring on a table loaded by its own weight. The bottom of the spring is compressed while the top has is original shape. Mathematically the pressure and density of the air are an exponential function

P = (Surface pressure) * exponential (-Elevation / (scale height))

The scale height is by definition the elevation over which air pressure significantly decreases. The effect of temperature is in fact modest; 7 km is a better (rounded) estimate than 8 km that we obtained above. See the graph in Figure 2.

Fair and foul air. In casual conversation, air and oxygen are almost equivalent. The difference becomes clear to the uneducated only when the local air becomes dangerously depleted in oxygen. In the 1600s, mine operators knew the need to ventilate mines, but not why. There was no need for noblemen to further ventilate their castles or peasants their hovels.

Boyle found that 1/5 of the air is consumed when a metal is heated in a closed space. We now know that 1/5 of the air is oxygen and that the oxygen reacts with the metal to form an oxide. Nitrogen and minor amounts of inert gas remain in the air. This simple observation, however, was misleading to Georg Ernst Stahl (1660-1734). He postulated that a substance called phlogiston existed. It, like electricity and heat, had no tangible form. Stahl's hypothesis explained what was then known about combustion and became very popular.

To illustrate this hypothesis, I consider the burning of carbon. In modern chemistry, the reaction is

carbon (charcoal) + oxygen (in air) --> carbon dioxide (gas)

[or in chemical notation]

$C + O_2$ --> CO_2

In the phlogiston hypothesis the reaction is

carbon (with phlogiston in it) --> air (with phlogiston)

The reaction to make iron from rust or iron ore is

iron oxide (rust) + carbon (charcoal) --> iron metal + carbon dioxide (gas)

$2Fe_2O_3 + 3C$ --> $4Fe + 3CO_2$

With phlogiston the reaction is

rust + carbon (with phlogiston) --> iron metal (with phlogiston).

The hypothesis came into trouble when Joseph Black (1728-1799) began to weigh reaction products. In quaint terms, one may *slake* limestone by heating it. (For those wanting another obscure English word, this is done in a *kiln*.) The reaction is

limestone --> calcium oxide (quicklime) + carbon dioxide (gas)

$CaCO_3$ --> $CaO + CO_2$

The limestone weighs more, by a fixed ratio, than the quicklime product. The carbon dioxide produced by burning carbon, slaking limestone, and breathing are identical. In another example, rust loses weight when it transforms into iron indicating that phlogiston has a negative weight. To say the least, this was not a pleasing attribute for an intangible substance.

Joseph Priestly (1733-1804) isolated oxygen but was still bound to the phlogiston hypothesis. He called the gas "dephlogisticated" air. The French aristocrat Antoine Lavoisier (1743-1794) recognized oxygen as a distinct gas. He found that the oxygen consumed by reacting with the metal mercury has the same volume as what is later released when the mercury oxide is strongly heated. He knew that oxygen and hydrogen (so named since hydro is Greek for water and "gen" is short for generation) react to form water. He went about identifying elements and oxides of elements.

Lavoisier perished at the guillotine in the French revolution but not for his science. The Deist revolutionaries and Napoleon were patrons of science, eager to rid the world of superstition. Lavoisier was a director of the French tax farm, which gathered taxes from petty merchants. Even though he tried to straighten out its finances, the tax farmers were not liked any more than Marie Antoinette, who had a reputation for high living from these taxes. Priestly had less serious political troubles. He went to America in 1776 because of his liberal political views.

By 1794, chemistry was recognizably modern. Chemists weighed the reactants and measured volumes of gas. They identified the major components of air, nitrogen (78%) and oxygen (21%). It took some time for them to show that these gases are molecules made of two atoms (N_2 and O_2). Water vapor (in variable quantities depending on the weather) and carbon dioxide (CO_2, then 300 parts per million) are minor components.

Chemists in the early twentieth century to sorted out and isolated other naturally occurring elements. The last major breakthrough related to air came when the third Baron Rayleigh attempted to find out why the atomic weight of nitrogen produced by decomposing a nitrogen compound like ammonia differed from nitrogen obtained by removing the oxygen from the air. William Ramsay and Rayleigh removed the nitrogen from the air by reacting it with hot magnesium metal. About 1% of the original air did not react. They had discovered the rare gas argon. They did many experiments to show that this gas is really inert; the name means lazy. Further work quickly yielded other gases in trace quantities, neon (new), krypton (cryptic or hard to detect) and xenon (foreign). These chemists found the rare gas helium after astronomers detected it in the spectrum of the Sun.

As we will see, nitrogen, oxygen, and carbon dioxide all have important effects on planetary habitability. Rare gases provide information on the behavior of planetary interiors. For example, the Ar (isotope 40) that is 1% of our air comes from decay of the radioactive isotope (potassium-40) in the Earth's interior discussed in the last chapter.

Geochemists routinely detect it and other rare gases in recently erupted volcanic rocks. This indicates the Earth's interior is still actively degassing.

Lots of atoms

"For the substance for the building of all bodies is the minimum body or the atom, and for building a line or a surface, the minimum is the point."

Giordano Bruno (1548-1600) *De minino*, Lib. 1, Cap. 2
(Op. lat., 1, iii, 138-140) (Singer, page 74)

Bruno argued that atoms make up matter. His reasoning was philosophical since his atomic theory offered no quantitative predictions. By 1800, atoms seemed real to chemists. They explained simple observations of chemical reactions. For example, a fixed ratio of hydrogen and oxygen react to form water because water is H_2O, two hydrogen atoms and one oxygen atom. It took chemists some time to sort out that the ratio is 2:1 and not 1:1.

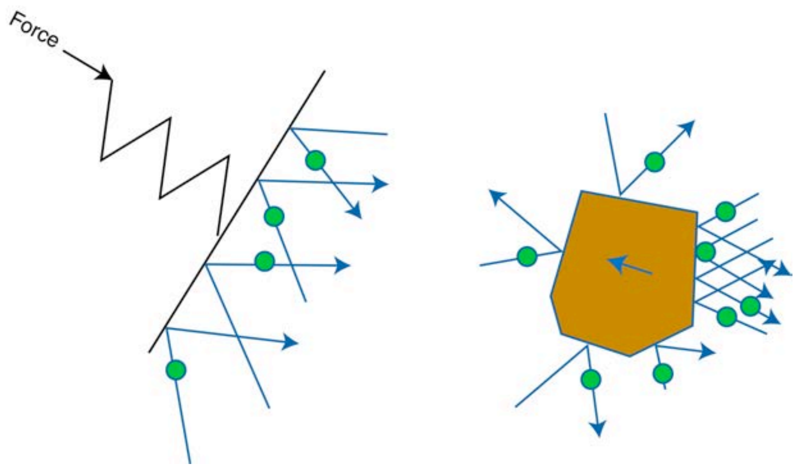


Figure 3: You can verify that atoms exist by seeing Brownian motion in a good optical microscope. It is easiest to see in water but the effect in air is simpler to explain. Air molecules bounce off a wall on the left. They accelerate as they change direction. The equal and opposite force is the macroscopic pressure on the wall. Brownian motion of small particles occurs because the molecules move randomly (right). Sometimes more hit one side of a small dust grain than the other side. The imbalance of forces accelerates the grain causing Brownian motion.

Still, there was a tendency to regard atoms as a useful fiction until 1904 when the physics of subatomic particles was just taking off. The reason for this is that atoms are very tiny, though finite. The number of atoms in any macroscopic object is huge and the effects of individual atoms are hard to see. There are about $6x10^{23}$ atoms in a gram of hydrogen (6 with 23 zeros or 600 billion trillion).

To get an idea of this number, consider the glass from which Socrates drank hemlock. For convenience in this quick calculation, the glass contained 180 grams with $6x10^{24}$ molecules of water. Socrates died immediately of the hemlock. His body rotted and the water from the glass has since dispersed worldwide. There are $1.7x10^{24}$ grams of water in surface environments (mainly the ocean). Each gram has statistically about 3 molecules from the fateful glass. A teaspoon of water (5 grams) contains 15 molecules from Socrates' glass.

Brownian motion provides a do it yourself way to confirm that atoms exist. Small dust particles in water move erratically. You can see this easily in an ordinary microscope. On the level of molecules, each water molecule continually moves, hitting other ones. Pressure results from the force needed to accelerate molecules when they bounce off an object like the dust grains. As we have already seen there are a vast number of molecules in a macroscopic volume of water. Essentially the same number of molecules hit both sides of a macroscopic object and the pressure is the same on both sides. The dust grains are small enough, however, that the finite number of molecules becomes an issue. Randomly more (or more energetic) molecules will hit one side of the grain than the other. The unbalanced forces on each side of the grain accelerate it causing the erratic motion.

In 1904 Albert Einstein, using a sophisticated analysis of Brownian motion, deduced the mass of an atom and hence the number of atoms in a macroscopic object. He used the then well-established kinetic theory of gases (which included atomic theory). Air (or any other mixed gas) contains molecules (including some like argon that are just one atom). The molecules continually collide with each other. On the average each molecule has the same amount of kinetic energy. This energy is proportional to its mass and its velocity squared. However, like billiard balls after a hard break, some molecules are more energetic than others. Conversely, the velocity of a molecule is statistically inversely proportional to the square root of its mass. The sound velocity is the mean velocity of the molecules divided by the square root of 2 (to correct for the fact that the molecules are not (statistically) moving in the direction of the sound wave).

If we use absolute temperature, the volume of a batch of gas is directly proportional to the temperature. The average kinetic energy of molecules is proportional to their absolute temperature. (These are ways to define absolute temperature.) As noted already, the pressure on a surface is the force needed to accelerate the molecules when they hit and turn around. With some algebra (not given here), the pressure is proportional to the number of molecules in a volume and independent of what gas is present. Mathematically,

Pressure × volume = constant × (number of molecules) × (absolute temperature)

The left-hand side is the energy associated with the macroscopic pressure of the gas and the right-hand side the sum of the kinetic energies of the molecules.

Maintaining a planetary atmosphere. Atomic and kinetic theory of gases led to quantitative theories for planetary climates and planetary atmospheres. Astrobiologists, like Galileo, often assume that life needs liquid water. They are not really comfortable with this assumption since the Earth is their only real example. Still, the assumption makes discussion manageable. I begin with the retention of atmospheres by planets and then discuss the existence of clement temperatures at their surfaces.

With regard to the first issue, a finite though tenuous atmosphere is needed for liquid water to exist. Below a pressure of 0.6% of a bar, water can exist as ice or vapor but not liquid. The pressure on much the surface of Mars is just above this. Liquid water can exist transiently when the Sun melts ice in the pores of rock. Sodium chloride (table salt) brine can exist down to -21°C at a pressure with a vapor pressure of 0.1% of a bar. (Road crews spread salt on roads because ice will melt down to -21°C. They often ignorantly spew salt when the temperature is below this.)

A more substantial atmosphere is needed for open water to exist. That is, the pressure needs to be high enough that water vapor is only a minor constituent in the atmosphere. For a planet near freezing, a few percent of a bar should do but there are no detailed calculations.

The edge of space. Continuing from Galileo's observation that there are no clouds on the Moon, astronomers established that there is no air. In fact the Moon would be considered an excellent vacuum in any industrial laboratory. The space program showed that there is a slight concentration of air near the Moon relative to space. This is mostly a measure of the precision of their instruments. The Moon's entire "atmosphere" would fit into a SCUBA tank. Why does the Moon have no air and the Earth plenty? Gravity clearly has something to do with it. The Moon's surface gravity is 1/6 that of the Earth.

An adequate theory for quick calculations comes from kinetic theory of gases. Air molecules near the surface of the Earth continually collide. There are more energetic molecules and less energetic ones. The frequent collisions keep the energy partitioned and prevent molecules from escaping the atmosphere. Escape occurs at the transition between the upper atmosphere and space. At very high altitudes (above 500 km on the Earth), the air is thin enough that molecules rarely collide. The most energetic molecules can escape to space if they happen to be moving upward. The less energetic molecules eventually fall to lower altitudes where they collide with other molecules (Figure 4).

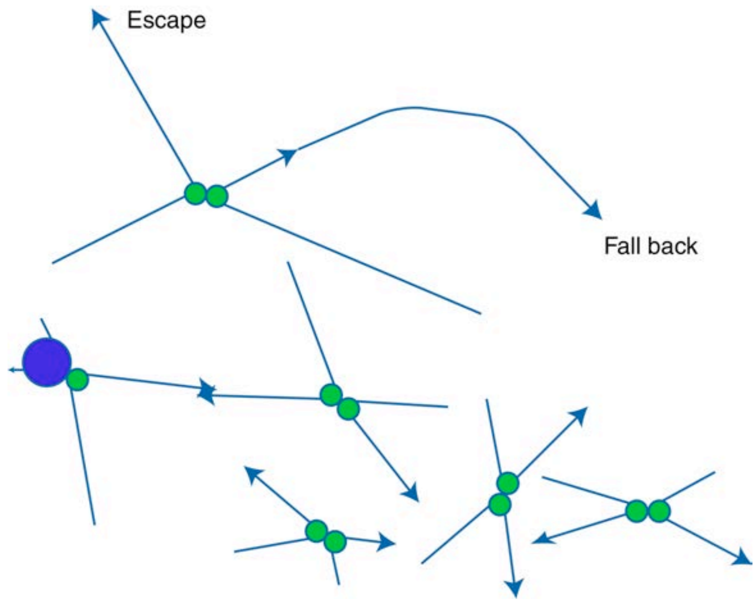


Figure 4: Molecules escape from the very top of planetary atmospheres, about 500 km elevation on the Earth. Molecules bounce off each other. On average, all the molecules have the same kinetic energy. The more massive molecule (blue) moves slower. Molecules safely go a very short distance before they collide in the lower atmosphere. In the uppermost atmosphere, some molecules escape to space without colliding. The fastest molecules escape while the others fall back and collide with other molecules.

The less massive molecules like hydrogen and helium typically move faster than the more massive oxygen and nitrogen molecules. At 0°C, helium moves at about 1.3 kilometers per sec. The escape velocity of the Earth is 11 kilometers per second. If the uppermost atmosphere were in fact that cool, helium would seldom reach escape velocity and would stay in the atmosphere. Actual helium atoms are accelerated by the solar wind and by ultraviolet light. The heat associated with this process causes the temperature to reach 2500 degrees Kelvin. Basically, any helium and hydrogen atoms that reach the top of the atmosphere escape. Nitrogen and oxygen are too heavy to escape.

Hydrogen escape is complicated in that it is present within water vapor (Figures 5 and 6). The lower atmosphere (the troposphere) convects vigorously as hot air rises and cold air sinks. Water vapor condenses in clouds up to the top of the troposphere (about 8 to 18 kilometers up depending on place and season). The air in the stratosphere passed through this cold trap. It is quite dry. (You may have noticed how dry the air is within passenger airplanes.) The region above the troposphere, the stratosphere, is stable because the temperature increases with elevation. Air molecules move around the stratosphere by diffusion. That is, randomly bumping into each other. This process is quite slow. There is a net sink of hydrogen and hence water at the top of the atmosphere. The water vapor molecules preferentially move upward to replace those lost by a sink. The current rate of hydrogen escape would deplete only a few meters of water off the top of the ocean over the history of the Earth.

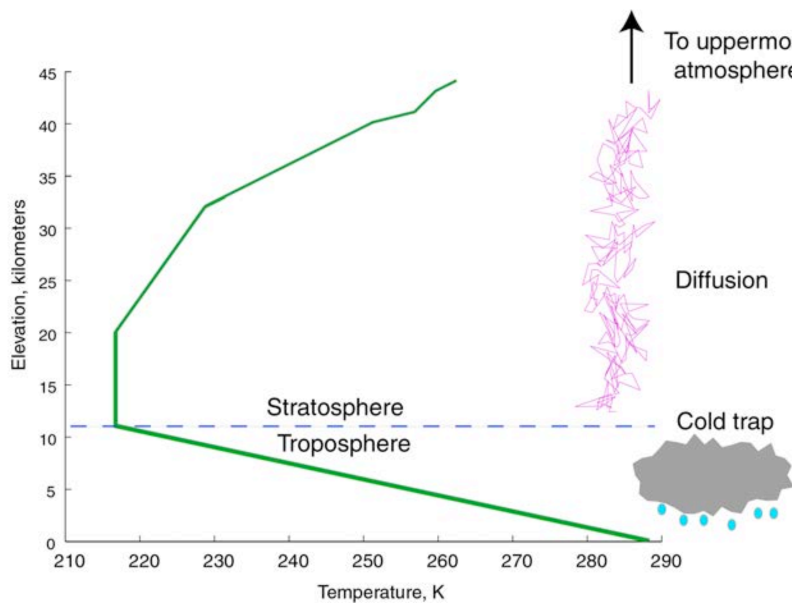


Figure 5: Laterally averaged temperature in the Earth's lower atmosphere in the Earth's atmosphere decreases with elevation. The troposphere below 11 kilometers vigorously convects causing weather. Water molecules condense in clouds. The top of the troposphere is a cold trap for water vapor. The air in the stratosphere is stable; the temperature increases upward at high elevations. Water vapor once in the stratosphere diffuses toward space but the process is very slow. More precisely, feeble winds in the stratosphere enhance mixing to 100 km elevation, chemical diffusion dominates above that altitude. There is no cold trap for molecules that do not condense like methane and hydrogen gas. The upper part of the troposphere radiates heat to space. Its effective temperature is 256 K

The overall cycle escape of inert helium is simpler. It vents from the Earth's interior. The top of the atmosphere is continually depleted in helium. Diffusion occurs where each atom statistically makes its way up from the Earth's surface to the edge of space. The abundance of helium in the atmosphere is that where the upward diffusion matches the supply at the surface and the loss at the top.

You can see a cold trap in action in an old refrigerator. The air circulates through the freezer compartment and the water vapor freezes out. The remaining air that returns to the refrigerator compartment is quite dry and it dehydrates vegetables. Modern refrigerators supply water to the vegetable compartment so that this does not happen.

You can visualize diffusion by looking at the movement of armadillos near a new freeway. Initially, they are randomly distributed but some wander out on the freeway and get hit. (The chicken crossed the road to show the armadillo it was possible.) This depletes the rangeland near the freeway of armadillos. There are few live armadillos near the freeway to wander back into the open range but many in the open range to wander toward the freeway. Even though the movement of any single armadillo is random, there is a net flux of armadillos toward doom on the freeway.

Figure 6: You can see that temperature decreases with elevation in the troposphere for yourself in the mountains. There are nice snowfields at 4 kilometers elevation on the tropical island of Hawaii. This is the top of Mauna Loa. The black rock is young basalt. There were glaciers on nearby Mauna Kea ("mount snow" in Hawaiian) during the Ice Age. There is now skiing part of the year. Photo by the author.

It is hard to get a good appreciation of how slow molecular diffusion is in air because moving currents typically redistribute foul smells much more rapidly. Much faster mixing by currents makes it is even difficult to view diffusion of smells in air or of a dye placed in stagnant water. As with heat diffusion, the distance increases with the square root of time. It is 5 mm for a second, 30 meters in a year, and 30 kilometers in a million years.

Returning to the Moon, its escape velocity is 2.37 kilometers per second. This is similar to the average velocity of H_2 at 0°C so it quickly escapes. Nitrogen and oxygen escape more slowly as their velocities are around 0.5 kilometers per second. Again, ultraviolet light and the solar wind aid in the escape.

Mars is just at the point that it can retain a tenuous atmosphere. Hydrogen and some oxygen escape to space. On the short term CO_2 freezes out as dry ice near the poles. There is much evidence from space photos and landers that liquid water once flowed on the surface. The ancient atmosphere may have been more substantial.

Planetary surface temperatures

We want to see where clement temperatures exist on planets circling around stars. It is obvious that planets near the Sun should be hot and those farther away should be cold. No one would move toward a campfire to get cool. We have all felt heat radiate from hot objects or seen red heat, like in a toaster. Night vision glasses detect the feeble amounts of heat radiated from objects near room temperature. The region near a star is too hot for life and the distant region too cold. Naively, there is a habitable zone in between. We might take it to be the zone around a star where the predicted surface temperature comes out somewhere between 273 K (0°C) and maybe up to 373 K (100°C) for microbes.

Primer on radiation of heat. Although the basic effects were known from antiquity, scientists did not quantify these processes until the advent of quantum mechanics in the early 1900s. The red heat and the less intense thermal radiation from room temperature objects are forms of electromagnetic radiation, just like radio waves and ordinary visible light. I discussed thermal radiation form stars in the last chapter. I refer here to all electromagnetic radiation as light that may or may not be visible. In quantum theory, light comes in packets called photons. The light you see has so many photons that you do not perceive them, just like you do not perceive atoms. Your eye uses a quantum process to detect photons one at a time, but your brain has evolved to see the macroscopic light. Much of modern astronomy equipment uses quantum effects to turn photons into electricity. Photographic film captures one photon at a time causing a chemical reaction.

The rate that photons produce electricity depends on the intensity of the light. However, some electrons are produced in the feeblest light as long as the right wavelength of photon is present. This is evident from such experiments that in a quantum process the energy of the photon is either completely absorbed or not absorbed. Albert Einstein received the Nobel Prize for the photoelectric effect. Relativity was still controversial in 1921. In retrospect, the photoelectric effect is the basis of a vast number of useful inventions from lasers to digital cameras.

A hot surface emits and absorbs photons. If it is much hotter than its surroundings, there are few incoming photons for it to absorb. A specific amount of energy is required to make a photon. Short-wavelength photons (like x-rays and gamma rays) require a lot.

Long-wavelength photons (like radio waves) require very little. Visible light is in between. For planets, we need to worry about visible light, light that is somewhat shorter wavelength (ultraviolet) and somewhat longer wavelength (infrared).

(D72. Toaster) Consider a toaster oven wire. It is red-hot maybe 800°C (or in absolute temperature ~1100K). The iron atoms in the wire are in motion. On average, the energy of the photons is in equilibrium with the energy of the atoms and both are proportional to the absolute temperature. The photons' energy is distributed randomly like the kinetic energy of molecules in a gas. There is not enough energy to produce ultraviolet photons so almost none get produced. There is enough energy to produce red light photons. The wire also radiates infrared photons but each carries little energy. The net effect is that the heat radiated per surface area increases by the fourth power of the absolute temperature and that the dominant wavelength of light decreases with temperature. We have already used these relationships discussing stars.

Airless planets. This formalism suffices to describe the behavior of an airless rocky or icy surface. The surface receives light from the Sun. A fraction of this light (the *albedo*) reflects back into space and the rest gets absorbed. The net energy reaching the surface is then the solar heat per area times one minus the albedo. The surface maintains a temperature to radiate this heat. As an equation,

$$(\text{temperature})^4 = \text{constant x } (1 - \text{albedo}) \text{ x } (\text{solar flux})$$

The solar flux varies inversely with the square of distance from the Sun, so the surface temperature decreases with the square root of distance. This formulation works with the airless surfaces of the Moon, Mercury, and the large satellites of Jupiter. It works OK with Mars, which has a tenuous atmosphere. Mars is now on average 218 K at the surface, about what one expects. This is not surprising; the surface pressure is about 0.6% a bar. It is too thin to blanket a strong greenhouse.

(7.3. Greenhouse) Greenhouse planets. However, the calculated temperature for the Earth comes out freezing at 256 K, so we see that there are limitations with treating planets as exposed rocks. There is also evidence of water flow and maybe seas on early Mars, which the present climate precludes. The atmospheres of the Earth and Venus have major effects on surface temperature. I also consider the local seasonal and daily variation of temperature on the surface of a planet, particularly Mars.

With regard to physics, we all have returned on a sunny day to find the air inside our car hotter than the outside. This can be pleasant in the winter but very uncomfortable in the summer. What happens is the sunlight comes through the window and is absorbed by the interior of the car. This energy becomes heat and the interior becomes hot. The hot surfaces radiate in the infrared (they are hot enough only to send out wimpy photons). These photons, however, do not readily pass through the windows. The heat cannot get out efficiently.

A key aspect here is that the photons bringing in the energy (visible light) are a different wavelength than the infrared photons taking it out. Greenhouse glass lets one in but not the other out. You have all seen tinted glass that lets some colors (wavelengths) of visible light through and not others.

Application to the present Earth. In the case of the Earth, the Sun emits mainly visible light with some ultraviolet and infrared. Much of the visible light gets through the atmosphere except where it reflects off of clouds or is partly absorbed by haze. Our eyes have evolved (though not perfectly) to detect the light that actually gets through. Ultraviolet photons are intense enough to disrupt molecules in the air and cause sunburn. Ozone (O_3) in the upper atmosphere is a significant absorber. Minor changes in energy levels in molecules absorb infrared photons. Molecules with 3 or more atoms have closely spaced energy levels that can absorb infrared, for example water and carbon dioxide.

The Earth's surface absorbs sunlight and becomes warm. You have walked across hot sand or pavement. It radiates in the infrared but the troposphere is not very transparent in that wavelength. It acts like greenhouse glass keeping the heat in. The surface heats the air that rises. As Torrcelli suspected, the rising currents of hot air drive the weather.

Still the heat must get out to space, as the surface does not keep heating up over geological time. The atmosphere is not fully opaque to infrared radiation so heat escapes from a range of altitudes, mainly in the upper troposphere. It is more opaque at some wavelengths than others because the molecules can absorb some energy levels better than others. If the atmosphere were a single gas, even CO_2, there would be holes in the absorption spectrum where infrared light could sneak out. Trace greenhouse gases absorb in these holes partly blocking the escape. (The full calculation is one of the most intensive done by planetary scientists, but simple scaling gives the gist.) The Earth radiates at an effective temperature of 256 K while the surface on average is 283 K. The difference is the greenhouse effect of 37 K. The top of the troposphere is 218 K.

The partial opaqueness of the atmosphere implies that adding more greenhouse gas makes it more opaque. Carbon dioxide from fuel burning is currently having this effect. This causes global warming of the surface as the greenhouse effect increases. See Chapter 14.

The need for air to convect determines the gross magnitude of the greenhouse effect. We all know the basic observation. Hot air rises. A hot air balloon is a nice yuppie diversion. An observation directly related to the thermal gradient is that it is typically colder on a mountain than in a valley. Gas theory allows scientists to compute the variation of temperature with height in the troposphere. Rising air expands as it encounters lower pressure. The expansion requires energy from the air and the air cools. Similarly, descending air compresses and heats up. (For those with some physics, the phenomenon is called adiabatic expansion and compression.) The adiabatic gradient for dry air is 10 K per kilometer. The actual gradient (called the lapse rate) in the troposphere is about 6.5 K per kilometer. The difference results because water vapor in the atmosphere condenses in updrafts to form rain and snow. This heats the ascending air. The saturation adiabat, like within a cloud, can be as low as 5K per kilometer.

Air makes a fine blanket. In fact, the insulation of blankets depends on small air pockets between the fibers. In terms of physics, air is a very poor thermal conductor. It can transmit heat only by radiation and convection. The lapse rate is the (wet) adiabatic gradient within lower regions of the atmosphere that are too opaque to transmit by radiation. There is enough upward heat transport in the upper part of the Earth's troposphere to keep it adiabatic. That is, much of the heat escapes at the effective temperature of 256 K, but this number is an average that includes escape at somewhat higher temperatures to the temperature at the top of the troposphere, which is 218 K.

The Earth over geological time. Planets occur at various distances from their stars. As we have seen in Chapter 6, stars become hotter with time. The latter effect causes both the inner and outer edges of the habitable zone to move outward as the star ages.

I first consider the history of the Earth. We know what the Earth is like now and we have a geological record. There has been glaciation, but liquid water has been present on the surface probably back to at least 4.4 billion years ago. We also know that the Sun was 70% as luminous as the modern Sun early in the Earth's history. Thinking too simply, one might expect that the effective temperature of the Earth was $(0.7)^{1/4}$ of the current effective temperature of 256 K. The result 234 K implies 261 K at the surface does not seem all that bad until we remember that water freezes at 273 K. Glaciers, contrary to the geological record, would have covered much of the Earth. The situation becomes more troubling when we realize that ice reflects sunlight back to space, increasing the albedo. (You can get sunburned while skiing by the reflection from the snow.) High ice albedo implies an even cooler climate.

The difficulty with this reasoning is that I let the greenhouse gas CO_2 remain constant over time. In fact, very little of the Earth's CO_2 is in the air. Rather most of it is in carbonate rocks like limestone. There are also large amounts of CO_2 in the Earth's mantle. The Earth is an active planet. Volcanoes continually vent CO_2 to the surface and limestone reacts with silica (SiO_2 the compositions of ordinary beach sand and quartz crystal) to release CO_2 when it is deeply buried. (Perrier water comes from a natural CO_2 seep in the Alps.) These sources build up CO_2 in the air until a balancing sink appears. Most obviously, weathering leaches Ca ions from exposed silicate rocks like basalt. The calcium ions combine with CO_2 to make more limestone. The net reaction is

$CaSiO_3 + CO_2 \text{-->} CaCO_3 + SiO_2$

calcium silicate (in rock) + carbon dioxide (in air) -->

calcium carbonate (limestone) + silica (in sedimentary rocks)

The heating of limestone at depth, called metamorphism, reverses the reaction. (Marble is metamorphosed limestone that frequently still has some calcium carbonate.) The forward reaction, weathering, requires liquid water. It goes faster with increasing temperature. This implies that CO_2 builds up in the air until the greenhouse is effective enough that liquid water is present at the surface and that the amount of CO_2 stabilizes at the temperature where weathering balances sinks. That is, the effective temperature of 234 K was farther up in the atmosphere than the present effective temperature of 256 K and the blanketing adiabatic region extended down to above freezing temperatures (like 283 K) at the surface. The greenhouse effect is 49 K in this simple example. I return to the issue of the ancient greenhouse gas after I discuss internal processes within planets that lead to metamorphism and volcanism in Chapter 8.

What went wrong with Venus? The cloud-cloaked surface of Venus piqued pre-spacecraft science fiction writers. A primordial dinosaur-infested swamp made a nice stage for paradise and adventure. The actual surface resembles Baptist Hell.

The surface temperature is 730 K and the surface pressure is about 90 bars. This is dense enough that the lower atmosphere does not transmit much heat by radiation. Rather convection carries the heat and the temperature gradient is adiabatic from the surface into the clouds. The surface of Venus is hot because the atmospheric blanket is quite thick. Trace gases including various sulfur (brimstone) compounds plug holes in the absorption spectrum. An adiabatic gradient of 7.5K per kilometer extends up 70 km from the surface to the cloud tops. Crudely, the greenhouse effect is product of these numbers, 525 K, compared with the actual effect of 510 K. Its effective temperature at the cloud tops is 220 K, colder than the Earth. The clouds shroud Venus and reflect most of its incoming sunlight.

This situation results from Venus being close to the Sun. A rocky planet with a tenuous atmosphere would have an average temperature of 300 K, which is like a warm day in the summer. Jim Kasting (b. 1953), Jim Pollack, and Tom Ackerman, then at Ames NASA, addressed this issue in 1984. The key is that water is a greenhouse gas.

Returning to the Earth, both water and CO_2 are greenhouse gases. The abundance of CO_2 fine-tunes the atmosphere (by plugging holes in the absorption spectra) so that there is liquid water and weathering at the surface. The concentration of water vapor (absolute humidity) decreases rapidly upward in the atmosphere. Crudely it is at saturation (called the dew point) where it condenses in clouds. It is a lousy greenhouse gas when the atmosphere is cooler than the present effective temperature of 256 K but becomes an excellent one above that temperature. Note that if the Earth had Venus' allotment of nitrogen (3.5 Earth atmospheres), the surface temperature would be about the present one. The cloud tops would be around 1 bar where the effective temperature would be about the present one. More precisely, the additional total atmospheric pressure increases the greenhouse effect of carbon dioxide making the surface modestly hotter.

Future Earth. Now consider the Earth in a time in the future when the Sun is more luminous or equivalently the present Earth closer to the Sun at the distance of Venus. The abundance of CO_2 will drop to a low level and it will cease to be a greenhouse gas. Water will take over. Water vapor is an effective blanket for infrared light in humid air above 262 K so the effective temperature is below this temperature. The planet needs to radiate at 300 K to balance the incoming sunlight. It cannot do both at the same time.

If the sunlight is only intense enough to raise radiating temperature to a little bit above 262 K, the planet's atmosphere reorganizes so that water becomes a major constituent. It resolves this minor imbalance by becoming a wet greenhouse. The surface then is 100-200°C and the albedo of the continuous cloud tops reflects enough sunlight that radiating at 262 K suffices. If the sunlight is a little brighter than this, a full runaway occurs. The entire ocean vaporizes and the surface reaches 1500 K, near the melting point of basalt. The atmosphere is somewhat transparent to visible light generated at this temperature and a balance is reached between heat radiated out from the hot surface and incoming sunlight. Both of these situations are fatal to life. The Earth will enter the wet greenhouse phase in about a billion years when the Sun is 10% brighter unless a high-tech civilization intervenes. The exact number depends on the unknown effect of clouds. The full runaway requires about a 40% increase in brightness.

Early Venus. Why then is there very little water in the Venus atmosphere? Four and a half billion years ago, the Sun was 0.7 as bright as at the present. The solar flux at Venus was then 1.35 times the present flux on the Earth. This is in the wet but not the runaway greenhouse range. A wet greenhouse with habitable temperatures for microbes below 100°C is conceivable.

Water escapes quickly when it is a major constituent as runaway is approached. There is no cold trap to keep water in the troposphere. Some water comes out to form clouds, but a significant fraction remains as vapor. Water reaches the uppermost atmosphere in large quantities. There it gets hit by ultraviolet light and dissociates into hydrogen and oxygen. The intense ultraviolet light of the young Sun drives off the hydrogen. (Astronomers observe that young sunlike stars have high ultraviolet fluxes.) Oxygen is too heavy to escape from the modern Earth and Venus, but hydrogen escapes so rapidly from early Venus that its outward flow entrains oxygen. Both gases escape. The oxygen that does not escape mixes with the atmosphere. It then reacts with ferrous iron in rocks to rust the crust. The efficacy of that process depends on how readily tectonics overturns the crust, bringing up more ferrous iron to rusting.

Martian canals and reality. To this point, I have modeled planetary atmospheres with global averages. This approach misses marginally habitable cold planets.

In 1900, a debate raged in the popular press and the scientific community. An upstart astronomer claimed to see evidence of an advanced civilization on Mars, canals going from the pole to the equator. Percival Lowell (1855-1913) was wrong here. The human eye has evolved to resolve lines and does so (even when they are not present) in a random pattern. (This is an example of cost-benefit trade off.) Some of his features were real, like the Vallis Marineris canyon. Others were just his eye connecting unresolved craters and volcanoes.

Lowell, who had no initial training in astronomy, had done his homework. He realized that a dry mountainous region is a fine place to get above fuzzy effects of the atmosphere. No one immediately had a better telescope; significantly better resolution came only with spacecraft.

The idea of intelligent civilization on Mars captured the interest of anyone with even a passing interest in science, including me as a child. Part of the debate focused on whether Mars is too cold for liquid water. Alfred Wallace (1823-1913), the co-discoverer of natural selection, pointed out correctly that Mars is farther from the Sun and damn cold. He lacked accurate theory as the effective temperature and albedo of the Earth were not then well constrained but his point was obvious. In retrospect, some of Lowell's arguments involved incorrect estimates of the Earth's albedo and solar flux.

Lowell had been living in a desert region with strong annual and daily temperature variations. He had traveled widely and knew that climate varies from place to place. He had in fact found the best climate for telescopes. He argued that a locality on Mars need only occasionally warm up enough for liquid water. Life would then bloom, like the desert after a rain. His Martians had merely helped the process along with canals. Lowell was right about local climate, but most scientists flushed this argument into his canals.

Figure 7: The Dry Valleys in Antarctica see frequent scientific visitors. Liquid water is rarely present. Typically the Sun melts ice on rock faces and snow on the ground. The run-off in small streams fills ponds. Life outside the ponds waits in stasis until water appears. Even spitting will supply water and disrupt the natural ecology. (Spitting is a time-honored amusement in the extreme cold; spit can freeze before it hits the ground at -60°C.) Photo by Rob Dunbar.

The importance of transient conditions did not become evident until the 1990s. A hydrologist studied stream courses in the dry valleys of Antarctica. Despite the name, there are ponds and occasionally flowing streams. Diane McKnight (b. 1953) found that the streambeds team with dormant life. The life blooms only when it is inundated. It must wait a hundred to a thousand years for this to happen. She, like Lowell, realized the folly of considering only average conditions. The rare warm spells that lead to liquid water are all that matter.

Modern Mars has tenuous air and large extremes of daily and annual temperature. The thick atmosphere of Venus efficiently transports heat and damps daily variation to about 1 K. The Earth is somewhere in between. You can see the effect in the mountains where the air is a little thinner than at sealevel. Frost on tents is common even in the summer.

The daily temperature on Mars frequently rises above freezing and much of the planet comes above the freezing point of brines, -21°C. This alone does not do the trick. The vapor pressure of water in the Mars atmosphere is low and any exposed body of water or brine would evaporate quickly. The rocks and ice at the surface act as a trap for the liquid water. Drops that form when sunlight heats the inside of the rocks or ice are not in direct contact with the surface. The water vapor must diffuse out. We have already seen that gases diffuse slowly. In addition, ice and rock act as greenhouses. The sunlight can get in, but like the window of a car it must get out by conduction. This happens on cliff faces in Antarctica. You may have seen this effect where sunlight melts the bottom of a snow pile even though the air is below freezing. Dust particles in lake ice catch sunlight and heat up. They can melt their way down, honeycombing the ice. This can make spring ice quite unsafe. Sea ice biota have evolved to harness this effect to maintain habitable brine. The bottom line is that local, seasonal, and daily variations in temperature extend the habitable zone out beyond that obtained from averages.

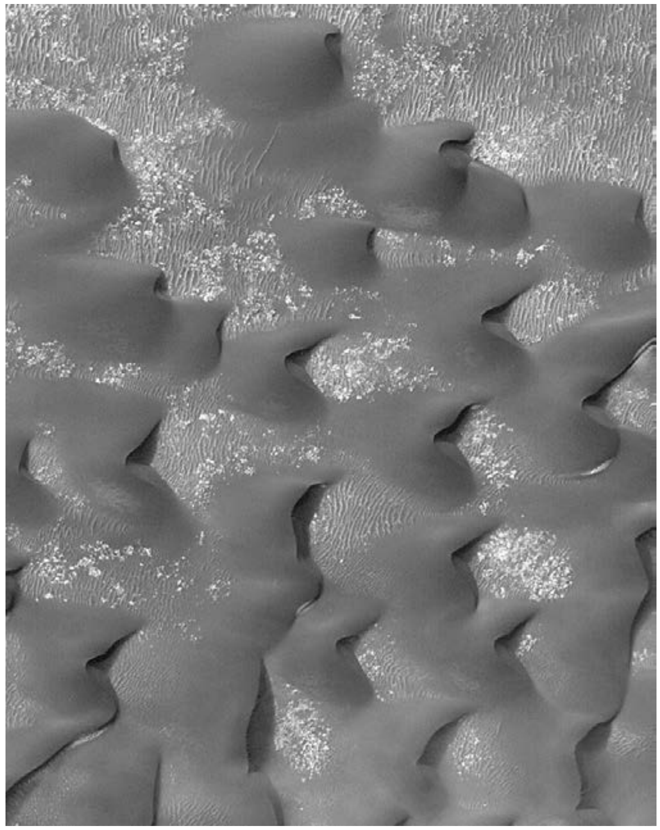


Figure 8: Dune filed on Mars. The tenuous atmosphere transports windblown dust. Photo is 3 km across by Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC).
http://mars.jpl.nasa.gov/gallery/sanddunes/20020418b.html

Dune. Frank Herbert (1920-1986) set his *Dune* novel on a planet that is hot enough that clement conditions exist only near the poles. Can such a planet exist inside the greenhouse limit of the habitable zone? Probably yes, even though we have no example in our solar system. Only generalized climate models have been done, so I stay qualitative.

Let's move Mars to the distance of Venus. We will keep it rapidly rotating for now. We will also keep the tilt of the axis down so it is always winter at both poles. The radiating temperature and the average surface temperature as we have already seen is 300 K. The tenuous atmosphere keeps the polar regions cold, away from hot low-latitude winds.

Widespread oceans would fatally start a runaway greenhouse, but Mars has little water. The polar regions act as a cold trap for its meager reservoir. The humidity adjusts so that rain and snow can reach the ground in polar regions. Lakes and rivers form there, but cover only a small fraction of the surface. Occasional lower-latitude downpours recharge ground water. Globally the cool polar regions set the humidity. It is too low for water to be a runaway greenhouse gas.

Now I let the planet rotate slowly like the real Venus. The day lasts Earth months. With the tenuous atmosphere, it gets damn cold in the night. Water vapor moves back and forth between the light and dark side. It becomes liquid before it evaporates. Equatorial microbes must either be able to survive the intense heat of the day or retreat down a meter where the mean annual temperature prevails.

A synchronously rotating planet like the Moon where one face points to the star is a favorite of science fiction writers like Larry Niven (b. 1938). It is always twilight at the edge of the lit region. The cold backside makes a nice cold trap where massive glaciers might trap lots of water. The actual situation is complicated in that the atmosphere needs to be tenuous enough that global temperature variations persist, but not so tenuous that all of it gets trapped on the backside.

Executive summary

Atmospheres blanket planets that have enough gravity to hold them. The Moon is too small. The Earth and Venus hold on to all but the lightest gases. Mars is just at the edge of being big enough to hold its air. A habitable zone where it is not too hot or too cold exists around stars. This concept is useful but fuzzy. If Venus and Mars had formed in each other's place, both might be habitable. A modest CO_2 greenhouse would allow clement conditions on Venus. There would be too little water for Mars' greenhouse to runaway.

Internal processes, like tectonics and volcanism, influence the abundance of gases in planetary atmospheres. They have a big say on the amount of surface water and the amount of surface CO_2 in limestones. We need to consider them to understand the fates of Mars, the Earth, and Venus. This is the focus of the following chapter.

Notes

The rare gases are not completely inert. Krypton and Xenon form compounds at room conditions. All the rare gases form weakly bound compounds at low temperatures and elevated pressures. Argon is a potentially biological material for hypothetical life in liquid methane, as on the Saturn moon Titan.

Exercises

Weighing air with freezer

You can find out the properties of air and the atmosphere with equipment available to the Greeks. You will probably have easier access to a modern scale rather than to a goldsmith's balance. Soft drink bottles substitute for sealed goatskins. The first objective is to weigh air. Then you will find some of its other properties. You can easily qualitatively see the effects of temperature and pressure on air using soft drink bottles. You can see that air as weight by filling the bottles with cold air in the freezer and weighing them. Allow the bottle to warm to room temperature. This produces compressed air. Vent the bottles and reweigh them.

For the full experiment, you will need: 20 OZ plastic soft drink bottles (or another size), freezer, scale precise to at least 0.1 gram, and graduated cylinder or kitchen volume measurer in which the drink bottle fits.

The physics is simply that

pressure * volume = (number of molecules) * constant * (absolute temperature)

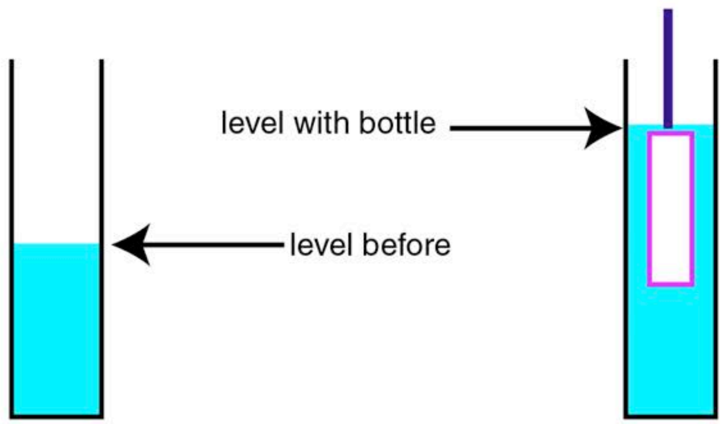
density = (number of molecules) * (mass of 1 molecule) / volume

The formula use these relationships but I have done the algebra already

Measuring volume change

You will use graduated cylinder to measure the volume of crushed and filled soft drift bottles. From the label the volume on the inside of drink is about 600 milliliters. You will need to set your initial water level in the graduated cylinder so that there is room for this much more displaced water. Record the before level.

You will do two pairs of measurements. One with the bottles from the freezer and one with the bottle filled at the hill top. You will record the crushed and the filled filled displacement. Their difference is the change in volume. Use prod to push bottle cap first until it is just below the surface of the water and record water level in cylinder



Freezer bottles

Displaced volume = level with bottle - level before

Crushed volume=________________ = ______________ - __________

Filled volume= _____________= ______________ - __________

Hill bottles

Displaced volume = level with bottle - level before

Crushed volume=________________ = ______________ - __________

Filled volume= _____________= ______________ - __________

Step 1. Fill a bottle with water. Pore into measured cylinder.

Record **Filled volume** = ________________________

Place empty bottles in freezer. Record **temperature in freezer** = ____________________

Leave one bottle open and one bottle sealed with cap. Wait a while for the bottles to cool. The sealed bottle will collapse. From the formula, cold air has less volume than room temperature air. The number of molecules of air does not change because the bottle is capped. Cap the open bottle when you remove it from the freezer. Work quickly with sealed bottle while it is still cold.

Step 2. We need the volume inside the collapsed bottle. It is easiest to measure this indirectly. Measure the volume the crushed bottle displaces in the graduated cylinder. This includes both the volume of the air and the plastic.

Crushed volume displaced = _________

Open the bottle and let inflate. You will hear air rush in. Cap bottle so water will not get in. Measure the volume that it now displaces. This again includes both plastic and air.

Filled volume displaced = _________

These volumes include both the bottle and the air so you will need to do some calculations to get volume of air in crushed bottle.

The change in volume when the air rushed in is

Change = **Filled volume displaced - Crushed volume displaced**

__________ = _______________ - _____________________

The actual crushed volume is

Crushed volume = **filled volume - change**

_______________ = __________________ - _____________________.

The ratio of the volumes is

ratio = **filled volume** / **crushed volume**

____________ = ___________________/__________________________

Step 3. Wait for the other bottle that you capped to heat up to room temperature. It should feel full when you squeeze it. The air cannot expand because the volume stays constant. The air pressure is now higher inside than out. Soft drink bottles are designed to withstand inside pressure but collapse if the pressure inside is low.

Weigh the bottle on the scale and record the result. Your scale probably gives grams so we record it as mass

Filled mass = ________________________

Uncap the bottle. You will hear the high-pressure air rush out. The air is now back to room pressure. Weight the bottle with cap back on.

Vented mass = ________________

The masses include both air and plastic. We eliminate the plastic by using the difference of the masses.

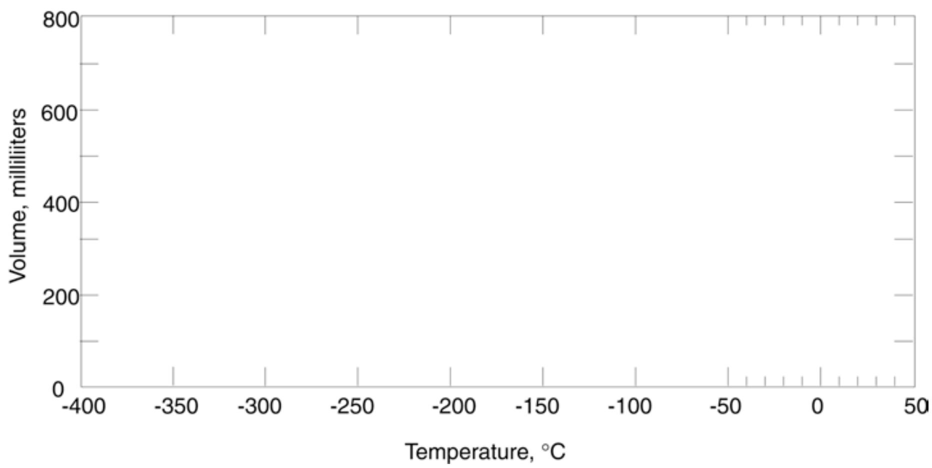
The density (with "weights" in units of mass) is

density = (filled mass - vented mass) / (ratio - 1) / (filled volume)

________ = (________ - __________) (________ - 1) / _______________

You now have the density of the air in grams per milliliter or equivalently grams per cubic centimeter. You can multiply by 1000 to get kilograms per cubic meter or 10,000 to get specific weight as newtons per cubic meter.

Determining absolute temperature scale



Measure your room temperature and record _________________

Plot (filled volume, room temperature) and (freezer volume, freezer temperature) on graph. Connect points and draw line through zero volume. This intercept gives you an estimate of absolute zero.

Measuring scale height of atmosphere

Fill bottle at the top of a hill or up on a mountain. Cap them and return to your lab at low elevation. Record Hill elevation _____________ and Lab elevation ______________. You can get these from a topographic map.

The actual crushed volume is as before

Crushed volume = **filled volume - change**

_______________ = __________________ - _____________________.

The ratio of the volumes is

ratio = **crushed volume / filled volume**

____________ = ___________________/__________________________

The scale height of the atmosphere is approximately **(elevation difference) / (1 – ratio)**

___________________ / __________________________