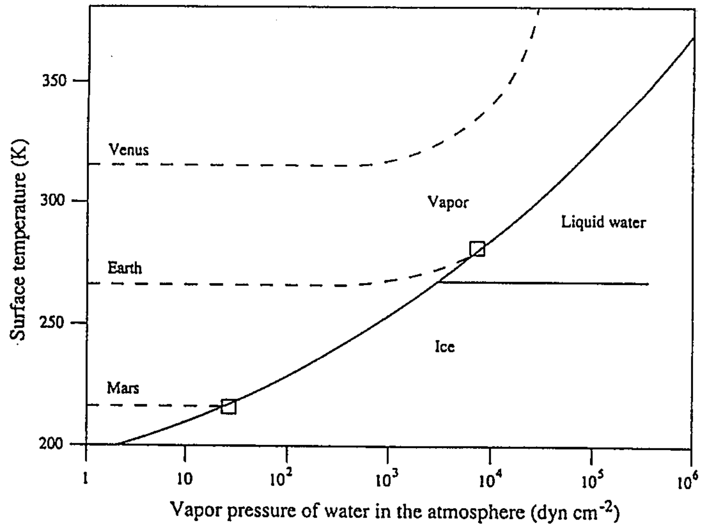
Teacher Background Information: Earth, Venus and Mars

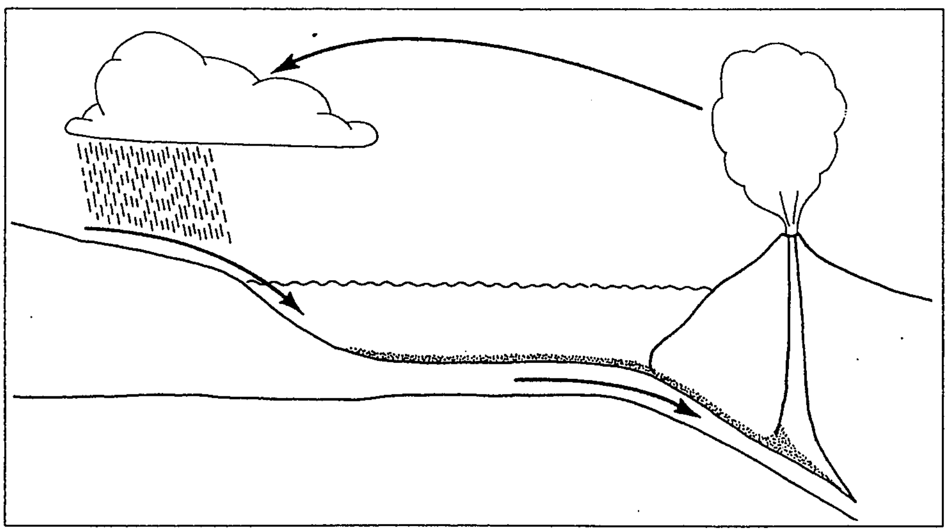
Before moving on from the natural greenhouse effect to consider the anthropogenic changes now taking place in the Earth system, it seems appropriate to consider just how the Earth got here in the first place and why life exists here and not on Venus or Mars, the two planets whose orbits are closest to the Earth. Venus orbits inside our orbit, closer to the Sun; Mars outside the orbit of the Earth, a little further from the Sun. Together with Mercury, they form a group known as the "terrestrial planets - all relatively small, rocky bodies, quite different from the huge, gaseous planets such as Jupiter and Saturn in the outer part of the solar system. Astronomers believe that all the planets formed at the same time, in the same way, from a cloud of smaller objects called "planetesimals", which collided and accreted. In the cloud of planetesimals, four clumps of rock grew bigger than any other aggregations and attracted the rest of the pieces by gravity. According to this theory, which is based on a wealth of astronomical evidence including data sent back to Earth by space probes, all three of these planets should have started out in much the same state, with the same mixture of materials and similar atmospheres. Any differences evident today should simply be a result of their different sizes and distances from the central heat source, the Sun. Today, Venus is a super-hot desert, with a thick blanket of air rich in carbon dioxide. Mars is a frozen desert, draped with only a thin atmosphere, also made almost entirely of carbon dioxide. Earth has oceans of liquid water, and an atmosphere composed chiefly of nitrogen, less than 25 percent oxygen and only a trace of carbon dioxide. *The differences all have to do with the greenhouse effect.*



The dashed lines show how the surface temperatures of Venus, Earth and Mars may have increased, due to the greenhouse effect, as water vapor and other gases accumulated in the atmosphere. On Mars and Earth the increase was terminated when water vapor pressure in the atmosphere reached the saturated vapor pressure, shown as the solid line, and freezing or condensation occurs. On Venus, temperatures are higher because it is closer to the Sun and saturation was not achieved. All gases released to the atmosphere from volcanoes on Venus remain in the atmosphere, where they produce a "runaway greenhouse effect" that has increased through time.

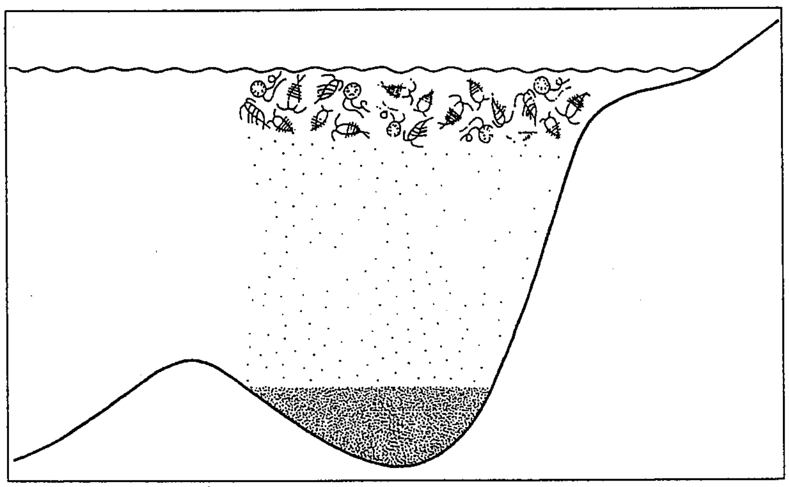
Astronomers calculate that at the time the solar system formed, about 4.5 B years ago, the Sun was about 30 percent cooler than it is today . If the Sun were turned down by that much today, the Earth would freeze. Even allowing for the greenhouse effect of the present atmosphere, the Sun would not have been warm enough to thaw the Earth until about 2 B years ago. There is clear evidence from sedimentary rocks, however, that there was liquid water on Earth 3.8 B years ago, and there are fossil traces of life from 3.5 B years ago. How did the Earth stay warm when it was young?

The obvious answer is that the greenhouse effect was stronger in the past than it is today. But what made it stronger, and why has it been reduced over time by just the right amount to stop the Earth from overheating as the Sun put out more energy? Many scientists suggest that the amount of carbon dioxide in the ancient atmosphere was responsible. There is definitely plenty of the right material around today, locked away in rocks in the form of *carbonate*. (Carbonate rocks, such as limestone, dolostone and chalk, are formed by biological and chemical precipitation of carbonaceous minerals dissolved in sea water.) The atmosphere today exerts a pressure at the surface of the Earth that is defined as 1 bar - one "atmosphere" of pressure. If all the carbonate in the Earth's crust today were converted into carbon dioxide gas, the atmosphere would exert a pressure of 60 bars - the equivalent of sixty present day atmospheres. The amount of CO_2 in the air today is just 0.035 percent of the atmosphere, or 0.00035 of a bar. Just 1 percent of the CO_2 available, half a bar or even less, would have been sufficient to keep the young Earth warm. How was so much carbon dioxide taken out of circulation and buried in the crust quickly enough to keep the Earth cool as the Sun warmed? The answer has to do with liquid water.



Carbon dioxide converted into bicarbonate is washed off the land by rain and enters the ocean where marine organisms convert it into carbonate sediments, which are then thrust into the Earth's interior and become part of the molten magma. CO_2 returns to the atmosphere by volcanic eruptions.

Scientists believe that there is a *natural negative feedback process* at work which takes carbon dioxide out of the air as the temperature rises, and puts it back if the planet cools down. This is how it works: Carbon dioxide from the atmosphere dissolves in rainwater, forming *carbonic acid*, which eats away at rocks containing calcium, silicon and oxygen (calcium silicates).This chemical action releases calcium and bicarbonate ions, which eventually reach the oceans and are used by living organisms, such as plankton, to build their chalky shells, made primarily of calcium carbonate. When the creatures die, their shells fall to the sea floor, building up layers of sediments rich in carbonate. Initially, this reduced the atmospheric concentration of CO_2 . However, geological activity carries the sea floor (thin "plates" of the Earth's crust) under the edges of the thicker continental crust that borders the oceans in a process known as " plate tectonics". The carbonate in the sea floor is pushed under the continents and deeper into the Earth, where it is heated, and melts. Under high temperature and pressure, carbon dioxide is released as new silicate rocks are formed, and finds its way up to the surface and out into the atmosphere during volcanic eruptions.



Formation of limestone from carbonaceous sediments deposited on the ocean floor.

These geological processes take a very long time to cycle carbon dioxide. Once the system was in place, however,the amount of carbon dioxide being released into the atmosphere over time became roughly constant. What happens if the temperature of the Earth changes? If the temperature falls, less water evaporates from the ocean, there is less rain, less weathering of the crustal rock, and less carbon dioxide taken out of the air. As the output from volcanic activity continues unabated, the concentration of carbon dioxide increases, warming the Earth through the greenhouse effect and increasing both evaporation and rainfall until a balance is reached. If the world warms, there is more rainfall and more weathering, which takes CO_2 out of the air, reducing the greenhouse effect. The temperature at which the balance is reached depends on the overall tectonic activity of the Earth.

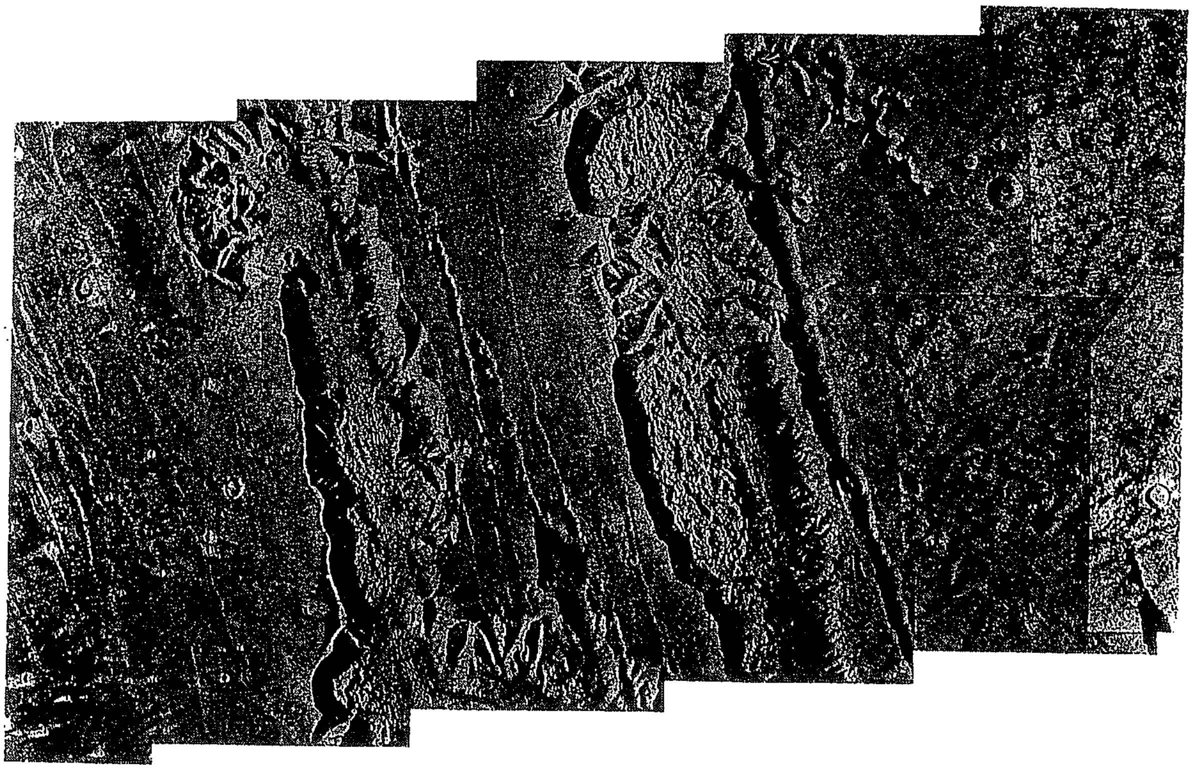
The most important point is that this is a negative feedback- increasing the temperature of the Earth as the Sun warms reduces the strength of the CO_2 greenhouse effect, and vice versa. In the case of water vapor, the opposite is true: increasing the temperature puts more water vapor into the air and strengthens the greenhouse effect further, causing the temperature to rise even more in a *positive feedback*. That seems to be what happened on Venus. The "wet" greenhouse effect got out of control and became a "runaway".

Assuming that Earth and Venus formed from the same cloud of planetesimals and that they were nearly identical at first, Venus, should also have been richly supplied with water. When the Sun was cooler, there may even have been oceans on Venus. However, the planet soon became hot enough for large amounts of water to evaporate. While water vapor remained in the atmosphere, it added to the greenhouse effect, exacerbating the problem. After being transported higher up into the atmosphere, the water molecules would have been split by sunlight into atoms of hydrogen and oxygen, thereby reducing its lifetime in the atmosphere. The hydrogen would have escaped into space due to its low atomic mass, and in a few hundred million years, all the water would have disappeared. This process will occur if the incoming solar energy is only 10 percent stronger than at the Earth's surface today; if it is 40 percent stronger, no oceans of water can exist at all on the surface, and the "runaway" greenhouse effect develops without going through a wet phase. With no oceans and no rainfall, there was no way for Venus to extract carbon dioxide from the atmosphere in large quantities, even if tectonic processes did proceed in the same way as on Earth. At present, Venus receives 90 percent more solar energy (1.9 times as much) than the Earth does. It has been left with a 93 bar atmosphere composed almost entirely of carbon dioxide and a greenhouse effect so strong that, combined with its proximity to the Sun, temperatures at the Venusian surface soar to above 500 *C. The vital difference between the two planets is that the temperature on Venus apparently passed the critical value needed to trigger a runaway greenhouse very early in its history.

	Mars	Earth	Venus
Distance to the sun (10^6 km)	228	150	108
Surface temperature (°c)	−53	16	474
Radius (km)	3390	6371	6049
Atmospheric pressure (bars)	0.007	1	92
Atmospheric mass (g)	2.4×10^{19}	5.3×10^{21}	5.3×10^{23}
Atmospheric composition (% wt.)			
CO_2	95	0.035	98
N_2	2.5	78	2
O_2	0.25	21	0
H_2O	0.10	1	0.05

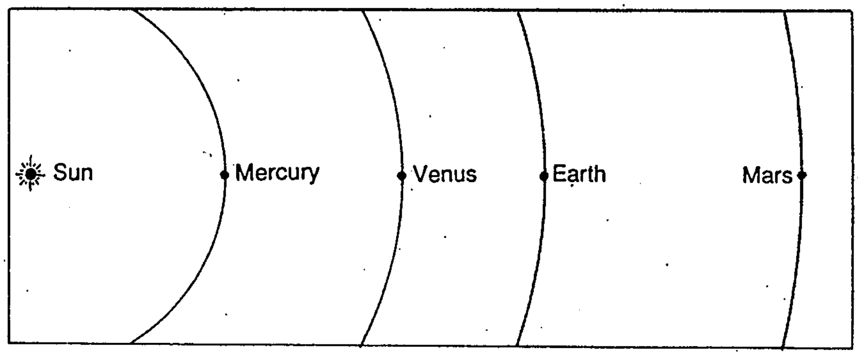
Some characteristics of the inner planets

While we can only speculate about oceans on Venus, we can actually see ancient evidence of liquid water on the surface of Mars. Mariner and Viking images reveal remarkable meandering channels, valleys and canyons, all pointing to an earlier period - or periods - when Mars' climate was less harsh than it is today and liquid water could exist on the surface. These features reveal the surface of Mars to be more Earth-like than the other planets, and indicate that water has played a major role in its geological history. Craters formed by meteorite impact support this idea. The areas surrounding many of Mars' craters give the impression that the impacts took place into a wet, plastic medium like mud. These areas, called "ejecta blankets", may have been formed by impacts striking areas of Mars' surface where there was a deep permafrost ice layer, which was heated and then melted. Such occurrences point to unmistakable evidence of dramatic changes in Mars' climate throughout its history. At present, the atmospheric pressure is low, equal to about 6 terrestrial millibars (standard atmospheric pressure on Earth = 1113.25 mb) and surface conditions are extremely cold and dry. Liquid water would not be stable at this extremely low pressure and would rapidly evaporate.



A mosaic of the Martian surface at the west end of the Valles Marineris system. These two canyons are over 30 miles wide and 1 mile deep.

Assuming that Mars shares the same heritage as Venus and Earth, it should have had proportionately the same amount of CO_2 and water as its neighboring planets. The obvious question: Where did it go? Theories point to a system of carbon dioxide cycling on Mars which worked differently from that on Earth. There is no evidence of plate tectonic activity on Mars, the process which recycles carbon dioxide on Earth and prevents it from being locked indefinitely in crustal rocks. One possibility is that volcanic lava flows buried carbonated sediments and squeezed them to depths where heat and pressure would have the same results. However, such a process would only have worked when the planet was relatively young and volcanically active. Because of Mars' smaller mass in comparison to the Earth, it could not have generated or stored sufficient heat to keep its interior in a molten state. It lost its "internal heat engine" relatively quickly and estimates are that the early volcanic activity died away less than a billion years after the planet formed. Once that happened, and as long as rainfall still occurred, carbon dioxide was removed from the atmosphere, but not replaced. As the greenhouse effect weakened, the planet cooled, and eventually froze.



The zone of life around our Sun embraces the orbits of both Earth and Mars, but not Venus.

Not far beyond the orbit of Mars, the Sun is too faint for the greenhouse effect to have provided a comfortable home for life, even on a planet as big as the Earth. What astronomers called the "habitable zone" in our solar system stretches from just inside the orbit of the Earth, to just outside the orbit of Mars. Two planets in our solar system out of nine orbit in that zone - a reasonably large proportion. A hypothetical visitor from another star, approaching our solar system from outside, could easily analyze the compositions of the atmospheres of the nine planets, using the same techniques of spectroscopy that we use to study the atmospheres of Mars and Venus from a distance. Such a visitor would immediately spot that the Earth was the odd one of the terrestrial planets. Our planet has a disequilibrium atmosphere rich in oxygen; Mars and Venus have stable carbon dioxide atmospheres in chemical equilibrium. They are dead.