Goldilocks and the Three Planets

By CALVIN W. JOHNSON, Ph.D., Assistant Professor, Department of Physics, San Diego State University

Reprinted with the author's permission from: http://physics.sdsu.edu/~johnson/writing/climate.html

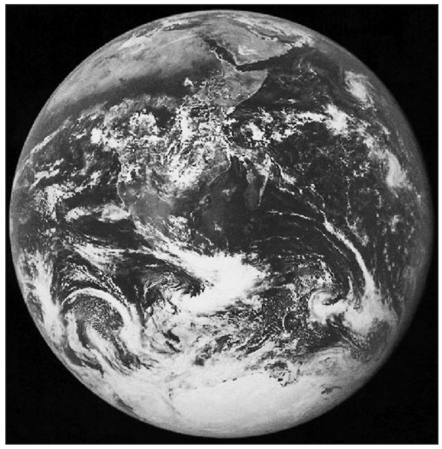
I've become acutely aware of climate since moving to Louisiana. The summers here are steamy and the winters fickle. Because Louisiana houses often lack sufficient insulation (due to some combination of poverty and optimism) thermostats work hard to moderate the temperature, running either the air conditioner or the heater constantly—sometimes both in the same day. Of course, compared to other locales, such as Alaska or the Sahara, Louisiana has a very mild climate.

Compared to other cosmic locales, the Earth itself has a very hospitable climate. Our neighboring planets, Venus and Mars, range the extremes in temperatures: the surface of Venus, at a temperature of 900º F, is hot enough to melt lead, while during Martian nights the temperature drops to 220º F below zero.

Is Earth's favorable climate an accident?

Earth's temperature is comfortably in-between: "just right," like the bowl of porridge that Goldilocks ate. Thus planetary astronomers talk about the "Goldilocks problem": is Earth's favorable climate an accident, or maybe an act of God? Is Venus just hot because it's closer to the Sun, and Mars cold because it's farther away?

The answer is no. The more you study any science, such as astronomy, the more you find that the universe is far from random. There are very deep reasons for the differences in climate among the terrestrial, or Earth-like, planets (as opposed to the Jupiter-like gas giants in the outer solar system), and I mean that literally. Beauty is only skin deep, but climate is not.



View of Africa and Saudi Arabia from Apollo 17. NASA

There are three layers to the answer to the Goldilocks problem. The first layer is like insulation, which keeps planets warm (and would keep my townhouse warm if it had any): the infamous greenhouse effect.

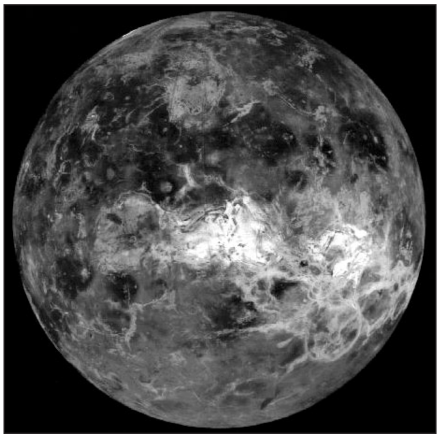
From all the debate about the greenhouse effect, it's easy to get the impression that the greenhouse effect is a great evil. But that's not true. The greenhouse effect makes Earth cozy. Without the greenhouse effect the Earth would be frozen, more than 60º F colder. I could use my cross-country skis in Louisiana, but that would be a high price to pay. The great bugaboo that has everyone worried, global warming, is actually a very small enhancement to the Earth's overall greenhouse effect. (We should worry about global warming, but let me save that for later.)

We receive energy from our Sun in the form of light. The Sun is a ball of very hot gas, heated by thermonuclear reactions at its core. All hot objects emit electromagnetic radiation, which includes radio waves, visible light, and X-rays, as well as ultraviolet and infrared radiation. The kind of radiation emitted depends on the temperature (the higher the temperature, the shorter the wavelength). For example, a piece of hot metal glows different colors at different temperatures. At "moderate" temperatures, metal glows a dull red; then, as it gets hotter, it will be orange in color, and then a brilliant yellow-white—about the same as the surface of the Sun, roughly 9000º F. If you could heat the metal even hotter, it would glow a bluish white, and eventually it would emit energy primarily in the ultraviolet.

But all objects emit electromagnetic radiation, even relatively cold objects like rocks and people. Objects at room temperature emit infrared radiation, which is how some night-vision scopes see.

So the greenhouse effect works like this: the Sun, being very hot, emits visible light. The light from the Sun passes through the Earth's atmosphere, which is transparent to visible light (that's why our eyes evolved to be sensitive to this kind of electromagnetic radiation), and warms the surface of the Earth, which in turn reradiates the energy, now as infrared radiation, because the Earth's surface isn't as hot as the Sun.

But the Earth's atmosphere, while transparent to visible light, is not transparent to infrared light. So the heat energy, in the form of infrared radiation, stays trapped in the Earth's atmosphere, and the Earth is much warmer than it would be without the greenhouse effect.



Hemispheric view of Venus produced by Magellan. **NASA**

Only a few types of gases in the atmosphere, the greenhouse gases, are opaque to infrared radiation. For example, nitrogen and oxygen, the major components of our atmosphere, are not greenhouse gases. The most important greenhouse gases are water vapor, methane, and carbon dioxide (CO_2). It's the CO_2 that worries people when it comes to global warming. Carbon dioxide makes up only about 330 parts per million of our atmosphere, but that has nearly doubled since the beginning of the industrial revolution because of burning fossil fuels. The whole debate about global warming is exactly how much carbon dioxide one has to add in order to change world temperatures; but no one disputes that, eventually, too much carbon dioxide will increase the temperature.

What about Venus and Mars? Unlike Earth's atmosphere, their atmospheres are about 95% CO_2. But it's not the percentage of CO_2, it's the total amount in the atmosphere. Venus has a very thick atmosphere: at the surface, the atmospheric pressure is ninety times that at Earth's surface! You'd have to dive nearly three thousand feet into the ocean to feel the same kind of pressure. So the Venusian atmosphere is set into overdrive as far as the greenhouse effect is concerned, cooking its surface. The Martian atmosphere, in contrast, although nearly pure CO_2, is very thin: less than 1% the pressure of Earth's. Mars barely has any greenhouse effect—it's only warmed about 10° F above what it would be without an atmosphere. Earth, of course, with a moderate greenhouse effect, is "just right."

So the first step in understanding the climates of Venus, Earth, and Mars, is the relative amounts of greenhouse gases in their atmospheres: Venus has too much, Mars too little, and Earth just the right amount (in fact, water vapor, which is one percent of our atmosphere, dominates most of our greenhouse effect—but additional CO_2 can dramatically change the amount of greenhouse effect).

The climates of the terrestrial planets are different because of dramatic differences in their atmospheric composition. But why do Venus, Earth, and Mars have such different atmospheres? In particular, why are there such huge differences in the amount of CO_2 in their atmospheres? To answer that, we must look at something called the carbon cycle. The carbon cycle acts as a huge, planetary thermostat: when working properly, it cools a planet when it gets too warm, and heats it up when it gets too cold.

On Earth, atmospheric CO_2 is absorbed by precipitation—by rain—and forms a very weak solution of carbonic acid, a very mild form of acid rain. This acid rain falls on surface rocks, many of which contain calcium, and the carbonic acid dissolves a tiny bit of the calcium. Eventually the water, containing both carbonic acid and calcium ions, washes down to the ocean. In our oceans tiny plants and animals, plankton, incorporate the calcium and carbonic acid into shells of calcium carbonate. When the animals die, their calcium carbonate exoskeletons drift to the ocean floor. When enough of these carbonate deposits build up, they form carbonate rocks, such as limestone, which are composed of the skeletons of trillions of dead plankton. In short, the action of water removes CO_2 from the atmosphere and puts it into the crust of the Earth. The Earth has roughly the same amount of CO_2 as does Venus, but it is nearly all locked up in the crust as carbonate sediments.

Life may be an integral part of Earth's climate.

(The fact that plankton play a role in precipitating carbonates out of water is used to bolster the so-called Gaia hypothesis, the idea that life is an integral part of Earth's climate. Other scientists dispute the necessity of life to the carbon cycle, for even without plankton, calcium carbonate at sufficiently high concentration would precipitate out of ocean water.)

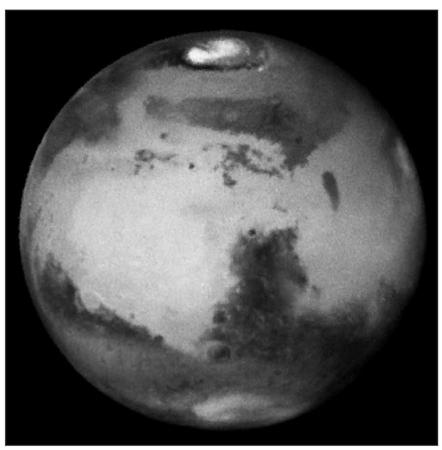
While most of the Earth's CO_2 is locked in her crust, it doesn't stay there forever. The action of plate tectonics, the motion of the Earth's surface, can subduct carbonate sediments; that is, as chunks of the Earth's crust gets pushed together, some of the rocks get pushed deeper into the interior, where they are subjected to heat and pressure. Such heat and pressure initially changes limestone to marble. But under even greater heat and pressure, the CO_2 is released from the rock, and makes it way back to the surface where it is emitted into the atmosphere through volcanic action. Hence volcanoes are a source of CO_2.

This is the complete carbon cycle: rainwater removes CO_2 from the atmosphere and puts it in the crust, and volcanic action releases CO_2 from the crust and puts it back in the atmosphere.

What happens on Venus? Venus has no water! Early in its history Venus may have had water, but it is too close to the Sun to retain it. When water molecules rise high in an atmosphere, ultraviolet radiation splits the water molecules into their component gases, oxygen and hydrogen, and the lighter hydrogen molecules escape into space. While Earth's lower atmosphere is about one percent water vapor (although it seems much higher in the humid Louisiana summers), the upper atmosphere, where ultraviolet radiation can penetrate, is very dry: a cold trap, a combination of pressure and temperature, prevents water vapor from rising high in the Earth's atmosphere. Venus has a cold trap, too, but because Venus is closer to the Sun its cold trap is much higher in the atmosphere and Venusian water molecules rise high enough to be broken apart by ultraviolet radiation.

Therefore the carbon cycle is incomplete on Venus: without water, CO_2 cannot be removed from the atmosphere. Venus does have volcanoes, however. Radar mappings of Venus by interplanetary probes indicate volcano-like mountains, and there is other evidence for volcanoes as well. The atmosphere of Venus is full of sulfur dioxide and sulfur particulates. Sulfur and sulfur dioxide is highly reactive and cannot remain long in an atmosphere; therefore something (volcanoes) must be regularly replenishing the sulfur. This theory is bolstered by data from interplanetary probes, which have detected large fluctuations in the sulfur content of the Venusian atmosphere, as well as radio signals reminiscent of lightning—and lightning is often found in volcanic plumes.

And Mars? The carbon cycle is also broken on Mars, but opposite to Venus. Mars has no active volcanoes to replenish the CO_2 in its atmosphere. We know Mars once had running water—we can still see billion-year-old river beds where water once ran—and the water may still be there, locked up in the ice caps and in permafrost beneath the surface. And it seems likely that Mars has CO_2 still locked up in its crust, deposited there billions of years ago by the action of water. If you could release that CO_2 you could warm up Mars again. Indeed, this is a major premise of science fiction stories about terraforming Mars; an excellent example is Kim Stanley Robinson's Mars trilogy.



Late spring on Mars (centered on roughly 305 degrees longitude). NASA

A fully active carbon cycle acts as a thermostat, regulating a planet's climate. In your thermostat at home, two strips of dissimilar metals bend one way or the other depending on the temperature. If it gets cold in your house, the metal strip bends one way and switches on the heater; if it gets warm, it bends in the opposite direction and switches on the air conditioning. The carbon cycle has similar negative feedback. Suppose the Earth gets too warm. Then more water will evaporate from the oceans, and the additional precipitation will remove CO_2 from the atmosphere, moderating the greenhouse effect and cooling the planet. If the planet cools too much, less water will evaporate and there will be less precipitation to remove CO_2; the CO_2 will build up, warming the planet.

This carbon cycle thermostat helps to explain a mystery about Earth's long term climate. Computer models of our Sun show that it has gotten progressively brighter over its five-billion-year lifetime, by about twenty-five percent. Since a mere two percent change in the Sun's luminosity would (all other things being equal) plunge the Earth into a deep ice age, one might expect the surface to have only recently defrosted. But two hundred million years ago the Earth was in fact warmer than it is today. So all things were not equal. (For one thing, continental drift affects climate; the formation of deep oceans tends to cool the planet, whereas shallow oceans warm it.) The carbon cycle explains how the Earth's climate can compensate for changes in the Sun's luminosity. It seems likely that the

Earth's atmosphere had somewhat more CO_2 half a billion years ago than today; as the Sun slowly grew brighter, the carbon cycle deposited more CO_2 in the crust, keeping the temperature "just right."

The carbon cycle is a crude and slow thermostat, however. It takes millions of years to compensate, enough for slow changes in the Sun, but not enough to immediately correct for humans dumping tons of extra CO_2 every year. So don't be complacent about global warming—the carbon cycle won't protect us!

The story is not quite finished. We've learned that Venus is too hot because it has a runaway greenhouse effect, caused by a broken carbon cycle, from too little water; Mars is too cold because its carbon cycle is also broken, lacking active volcanoes, and therefore it has too small a greenhouse effect. Earth is lucky, with a fully functioning carbon cycle and therefore a moderate and moderated greenhouse effect.

But why do Earth and Venus have active volcanoes, and Mars none? We know that Mars once had volcanoes. In fact Olympus Mons on Mars is the largest volcano, albeit extinct for billions of years, in the solar system. You could fit the entire state of Rhode Island in the caldera of Olympus Mons. But no Martian volcanoes are active today. To understand why, we must delve deep into the interior of the planets.

The interior of the Earth is hot. Part of this heat is generated by the natural decay of radioactive elements in the rocks, and part of the heat is left over from the formation of the Earth five billion years ago—when gravity pulled together bits of gas and dust to form our planet. And there are three ways a planet can lose heat from its interior. The first is simple conduction. If you stick a poker into a fire and hang onto it, heat will slowly travel up the poker to your hand and burn you. This is the main way small planets and moons lose heat, for the smaller the object the faster it cools. Imagine baking potatoes of different sizes. When you take them out, the bigger one cools much slower than the small one. (This is the physics error in the original Goldilocks tale: you'd expect Papa Bear's porridge to be too hot, but Baby's would be too cool and Mama's, in between in size, would be just right.) And so this is what happened to Mars. With only about one-eighth the mass of the Earth, Mars is a small potato and cooled so rapidly it lost its heat to power volcanoes. Jupiter, on the other hand, as the largest planet in the solar system, is still immensely hot in its gaseous interior: in fact Jupiter radiates 1.7 times as much thermal energy as it receives from the Sun.

There are two other ways to transport heat from the interior of a planet to its surface, both of which can produce volcanoes. One is convection. You can, with care, produce convection on your stove top. Take some soup—thick tomato or some sort of cream soup might work well—and heat it slowly. Don't bring it to a boil; but if you get the temperature right, you will see soup upwelling from the bottom. Hot soup expands and becomes lighter, and floats to the top, while cold material on the top is denser and sinks, forming a cyclic pattern.

Convection drives plate tectonics: the source of continental drift, building of mountain ranges, earthquakes, and some kinds of volcanoes. If you drive up interstate highway 5 from California to British Columbia, you'll see a string of volcanoes: Lassen, Shasta, Hood, St. Helens, Rainier, Baker. Convective patterns driven by heat transport in the interior of the Earth push one crustal plate under another (subduction) and the friction heats up the magma necessary for volcanic action—which in turn releases CO_2 into the atmosphere.

Not all volcanoes arise from plate tectonics. Sometimes a little "worm" of hot rock will force its way up through the crust, forming what is known as a shield volcano, with long, gentle slopes. The Hawaiian Islands are formed from shield volcanoes. This process is called advection. The volcanoes on Venus, and the ex-volcanoes on Mars, were all formed by advection.

Venus is the same size as Earth, and so its interior stays hot enough to support vulcanism. Exactly why Venus lacks plate tectonics is not clear. Perhaps its crust is too thick and brittle; or perhaps water is necessary to "lubricate" the action of plate tectonics. But in contrast, Mars, being so much smaller than Venus and Earth, lost its interior heat too quickly to support volcanoes for long.

So now we can solve the Goldilocks problem. Venus is too close to the Sun to retain water, which breaks its carbon cycle, leading to an overabundance of greenhouse gases and a well-cooked surface. Mars is too small to have a hot interior, and thus no volcanoes to pump greenhouse gases into its atmosphere, and so is cold due to lack of insulation. We Earthlings are lucky: our planet has water and volcanoes and a regulated climate.

If only the summers in Louisiana were a little more regulated.... ■

Calvin W. Johnson is Assistant Professor at San Diego State University.