How Climate Evolved on the Terrestrial Planets

Planets with temperate, earthlike climates were once thought to be rare in our galaxy. Mathematical models now suggest that if planets do exist outside the solar system, many of them might be habitable

by James F. Kasting, Owen B. Toon and James B. Pollack

Why is Mars too cold for life, Venus too hot and the earth just right? At first glance the answer to this question, the so-called Goldilocks problem of climatology, may seem simple. Common sense suggests that the earth, with a livable mean temperature of 15 degrees Celsius, just happened to form at the right distance from the sun, whereas Mars (–60 degrees C.) and Venus (460 degrees C.) did not; as a result only on the earth does one find the liquid surface water that is crucial for life.

Yet happenstance is not the complete explanation for the temperatures of these terrestrial, or rocky, planets. We propose that the three neighbors, all of which formed when large numbers of bodies known as planetesimals collided, were once alike in many ways. They had similar minerals on their surfaces and similar gases in their atmospheres (including carbon dioxide and water vapor), and they were all temperate enough to maintain liquid water on much of the surface. They acquired dramatically different climates largely because they differed in their ability to cycle carbon dioxide between the crust and the atmosphere. Carbon dioxide, like water vapor and certain other substances, is a "greenhouse" gas: it allows sunlight to pass through it, but it absorbs infrared radiation (heat) that rises from the planet and reradiates part of this heat back to the surface.

More specifically, calculations by our group at the National Aeronautics and Space Administration and by other investigators suggest that the earth has always had a moderate climate primarily because its cycling mechanism increases the amount of carbon dioxide in the atmosphere when the surface of the planet cools and reduces the amount when the ground temperature rises. Mars is now frozen because it has lost the ability to cycle the gas back into its atmosphere, and Venus is a hothouse because it developed the opposite problem: it has no way of removing carbon dioxide from its atmosphere. (Mercury, the other terrestrial planet, has no atmosphere; its temperature is controlled exclusively by the sun.)

The Faint-Young-Sun Paradox

Our interest in the role of carbon dioxide in the evolution of the earth, Mars and Venus had its roots in another cosmological puzzle relating to the origin of the earth: the faint-

VENUS, EARTH AND MARS (*left to right*), shown roughly to scale, may each have been temperate enough in their early history to support life-giving, fluid water on their suryoung-sun paradox. Virtually every model of stellar evolution indicates that the sun was between 25 and 30 percent dimmer when the solar system formed some 4.6 billion years ago than it is today. Since then the solar luminosity, or intensity, has apparently increased approximately linearly with time.

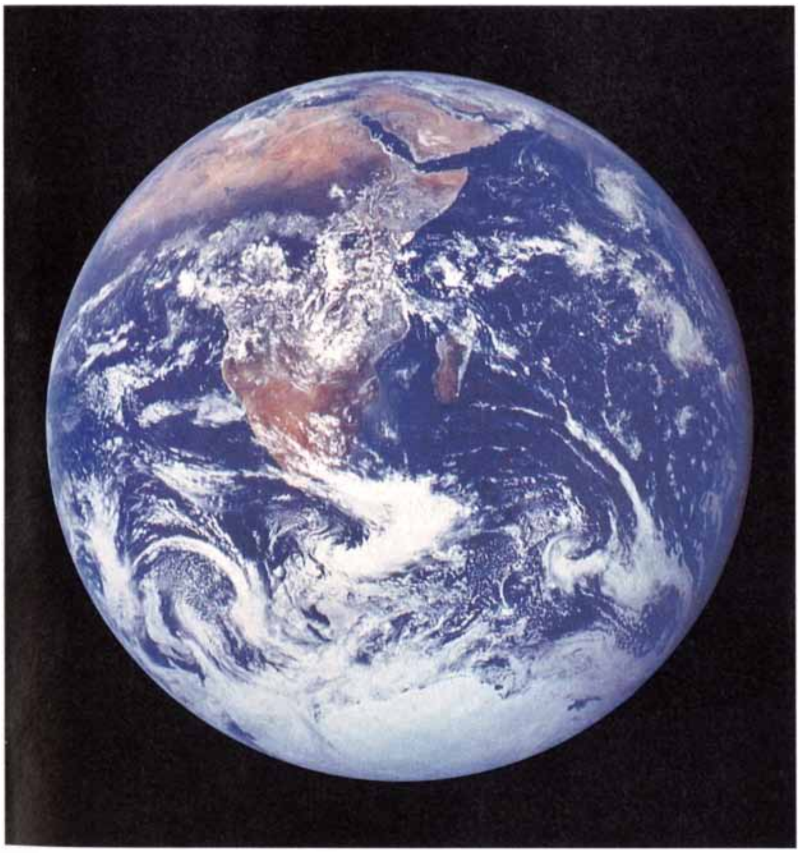
The paradox arises, as Carl Sagan and George H. Mullen of Cornell University pointed out about 15 years ago, when one realizes that if the earth's early atmosphere was the same as it is now, a weak sun would have resulted in an ice-covered earth until about two billion years ago. Yet the planet did not freeze. In fact, evidence from sedimentary rocks indicates that the earth has had liquid oceans since at least 3.8 billion years ago, when the geological record begins. Moreover, life has been present for at least the past 3.5 billion years, demonstrating that the earth's surface has never been entirely frozen during that time. (Water can remain fluid as long as the temperature is between zero and 374 degrees C.; it boils and evaporates at 100 degrees C. at sea level today but will stay liquid at higher temperatures if the atmospheric pressure is increased.)

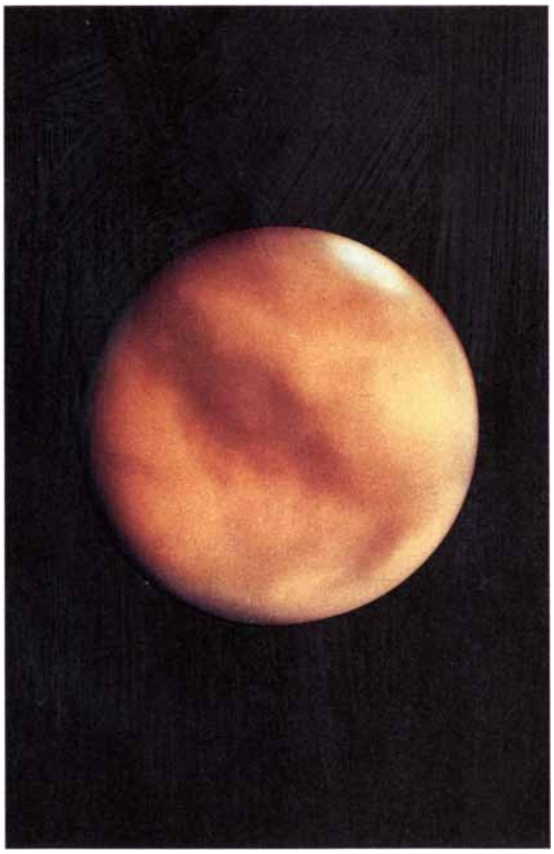
Sagan and Mullen realized that the paradox disappears if one assumes the earth's atmosphere has changed in the course of time. For instance, if the young planet had fewer clouds than it has today, less of the sunlight that impinged on the earth would have been reflected back into space, and the planet would have been correspondingly warmer. Some 30 percent of the sunlight that currently reaches the top of the atmosphere is returned to space, most of it by clouds. A chillier earth might well have had fewer clouds but the geological record suggests the early earth was actually warmer than today's. Parts of the planet are covered with glaciers now, but there is no evidence of similar glaciation before about 2.7 billion years ago.

A more probable explanation is that the greenhouse effect was more pronounced in the distant past. Sagan and Mullen suggested that ammonia (NH_3), an efficient absorber of infrared, could have warmed the climate if the gas represented just 100 out of every million molecules of the air. Subsequent studies have shown, however, that the sun would have rapidly converted ammonia into the nongreenhouse gases nitrogen and hydrogen unless it was continually resupplied to the atmosphere from the planet's surface.

Other investigations have focused on carbon dioxide, which sunlight does not readily decompose. Carbon dioxide is certainly abundant here; the amount now stored in the planet in carbonate rocks would exert a pressure of about 60 bars if it were released into the atmosphere. (One bar is equal to 14.5 pounds per square inch, the pressure at sea level. Today the earth's atmosphere contains about .0003 bar of carbon dioxide.) If just a few tenths of a bar of the stored carbon dioxide was originally present as a gas, its additional greenhouse warming would have compensated for the reduced sunlight.

The notion that higher carbon dioxide levels could have protected the early earth from freezing soon gave rise to a related idea: if the carbon dioxide level declined at a rate that precisely counteracted the increase in solar luminosity with time,





faces. Computer models suggest that differing abilities to cycle carbon dioxide between the atmosphere and the land—and not solely the planets' distance from the sun—helped Venus to lose its water and Mars to freeze, while the earth remained habitable.

the decline might account for the fact that the earth's temperature has always remained within reasonable limits. One investigator, Michael H. Hart of NASA, undertook to calculate such a compensatory rate.

Hart managed to work out a solution in which the levels of the gas declined approximately logarithmically with time, but his most interesting finding was that very few of his calculations succeeded. In other words, if the composition of the atmosphere had at any time changed at a rate different from his precise solution, the planet would have become unable to support life. If the carbon dioxide level had declined too slowly, the earth would have become a hothouse; if it had declined too quickly, the oceans would have frozen.

Hart did similar calculations for cases in which the distance between the earth and the sun was varied by small amounts. He found that if the earth had formed 5 percent closer to the sun, the atmosphere would have become so hot that the oceans would have evaporated, a condition known as a runaway greenhouse. Conversely, the planet would have encountered runaway glaciation if it had formed as little as 1 percent farther from the sun. Only in the relatively narrow range of orbits between .95 astronomical unit and 1.01 A.U. could one or the other of these climatic catastrophes be avoided. (One A.U. is the distance between the sun and the earth, or 149.6 million kilometers.) Hart termed this narrow band of orbital distances the continuously habitable zone (CHZ).

Hart's conclusions were unsettling because they suggested that the earth must have beaten extraordinary odds in avoiding the fate of Mars or Venus. Only within the past few years have investigators discovered the flaw in his hypothesis. A mathematical model developed by James C. G. Walker and Paul B. Hays of the University of Michigan and by one of us (Kasting) suggests that the changes in carbon dioxide concentration did not arise by sheer luck. Rather, carbon dioxide levels have probably fluctuated in response to changes in surface temperature. When the temperature goes up, atmospheric carbon dioxide levels decline, cooling the surface; when the surface cools, the abundance of atmospheric carbon dioxide increases and warms the surface. The existence of such a negative-feedback loop means that the earth probably has never been in danger of undergoing either the runaway greenhouse or the runaway glaciation postulated by Hart.

The Carbonate-Silicate Cycle

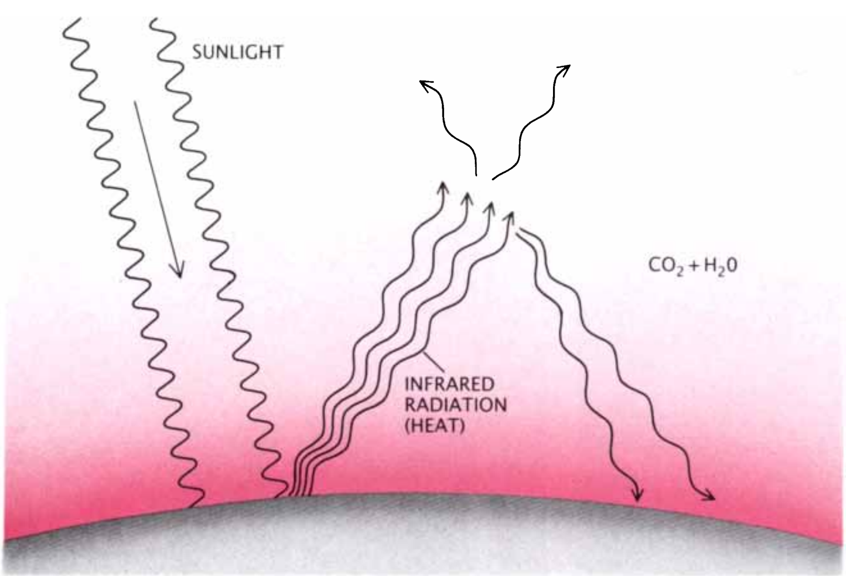
The proposed feedback system is mediated by the carbonate-silicate geochemical cycle, which accounts for about 80 percent of the carbon dioxide exchanged between the solid earth and its atmosphere over a time scale in excess of 500,000 years. The cycle begins when carbon dioxide in the atmosphere dissolves in rainwater, forming carbonic acid (H_2CO_3). The rain weathers, or erodes, rocks that contain calcium-silicate minerals (compounds of calcium, silicon and oxygen). In the process the carbonic acid reacts chemically with the rocks, releasing calcium and bicarbonate ions (Ca^{++} and HCO_3^-) into the groundwater. The water transports the ions to streams, rivers and ultimately the ocean.

In the sea, plankton and other organisms incorporate the ions into shells of calcium carbonate ($CaCO_3$). When the organisms die, they settle to the bottom of the ocean, forming carbonate sediments. As the millenniums pass, the sea floor spreads, carrying these sediments to the margins of the continents. There the sea floor slides under the landmasses and turns downward toward the interior of the planet.

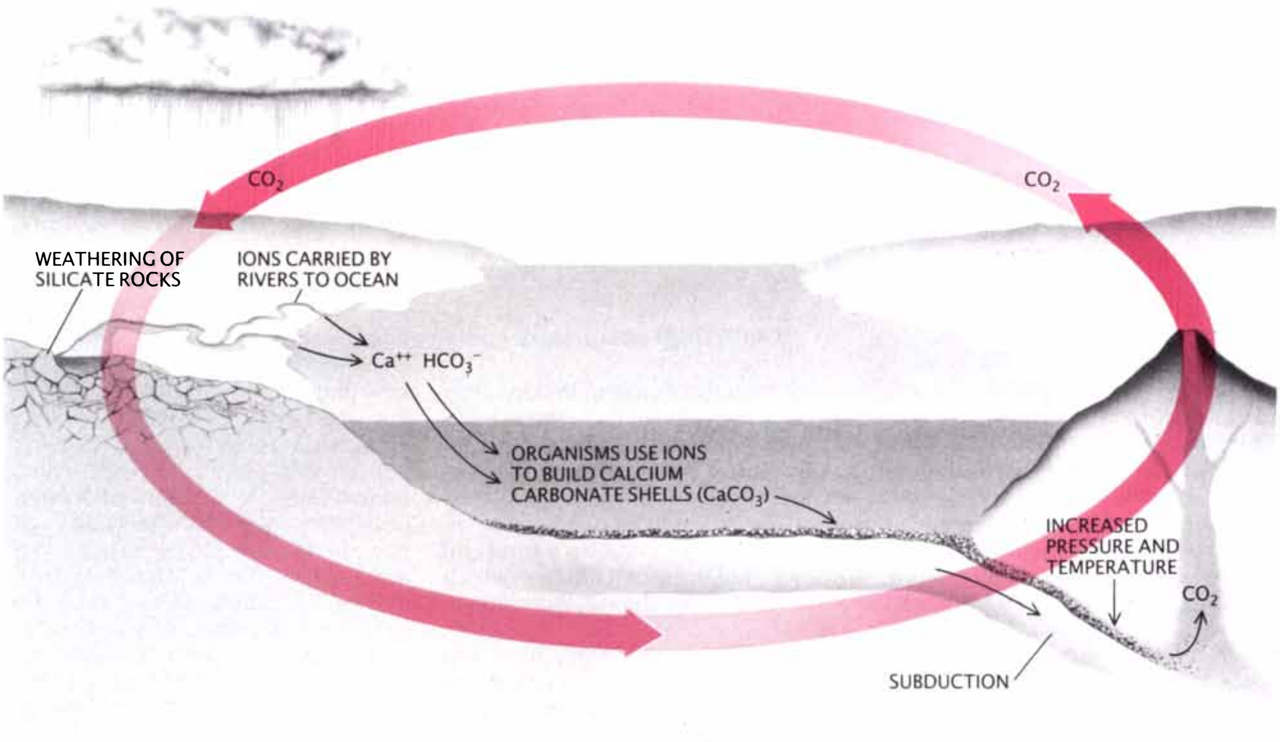
As the sediment is subducted and subjected to rising temperature and pressure, calcium carbonate reacts with silica (quartz), re-forming silicate rocks (a process known as carbonate metamorphism) and releasing gaseous carbon dioxide. The gas then reenters the atmosphere by way of midocean ridges or, more violently, through volcanic eruptions near the margins of tectonic plates.

Walker and his colleagues recognized that changes in the surface temperature in the course of time should affect the amount of carbon dioxide that leaves the environment and in turn the amount of greenhouse warming. Suppose the temperature of the surface were to fall for some reason, such as a decrease in the sun's output. When ocean temperatures fall, less water vapor evaporates into the atmosphere, and so there is less rain and therefore less weathering. Under such a circumstance the rate at which carbon dioxide leaves the atmosphere declines—but there is no change in the rate at which carbon dioxide is regenerated by carbonate metamorphism and "outgassed" into the environment. The net result is an accumulation of the gas in the atmosphere, an increase in greenhouse warming and in turn the restoration of higher surface temperatures.

Conversely, if the surface temperature were to increase for some reason, the rate of evaporation of the oceans would increase and with it the amount of rainfall. There would



GREENHOUSE EFFECT occurs when certain gases, notably carbon dioxide and water vapor, warm the surface of a planet. Such gases allow light from the sun to reach the planet, but they intercept the infrared rays (heat) that the planet radiates into space and reradiate much of this energy toward the surface. The gases raise the earth's surface temperature some 35 degrees Celsius above what it would be if they were absent.



CARBONATE-SILICATE geochemical cycle, which operates on a time scale in excess of 500,000 years, removes carbon dioxide from the atmosphere, stores it in carbonate rocks and then returns it to the air. Carbonates form when carbon dioxide dissolves in rain and reacts chemically with rocks that contain calcium-silicate minerals (compounds composed of calcium, silicon and oxygen). Such reactions release calcium and bicarbonate ions (Ca^{++} and HCO_3^-) into groundwater, which transports the ions to streams, rivers and the ocean. In the ocean, plankton and other organisms use the ions to construct shells of calcium carbonate ($CaCO_3$); they then deposit the shells in sediments on the sea floor when they die. Slowly the sea floor spreads; eventually it slips under the continents and turns downward, carrying the sediment with it. Exposed to increased temperature and pressure, the sediment gives off carbon dioxide gas, which then reenters the atmosphere primarily by way of volcanic eruptions.

be an increase in the weathering of silicate rocks and hence in the removal of carbon dioxide from the environment. The greenhouse warming would then decrease.

The feedback is perhaps easiest to visualize if one considers an extreme case. If the oceans ever froze over completely, rainfall would come to a virtual halt and carbon dioxide would build up in the atmosphere. Current rates of gas release would supply the atmosphere with a bar of carbon dioxide in 20 million years, a geologically insignificant amount of time. This amount would raise the surface temperature by about 50 degrees C.—more than enough to melt the ice and restore equable climatic conditions.

Role of the Biota

Because living organisms play an important role in the exchange of carbon dioxide with the atmosphere, some investigators have suggested that the biota are primarily responsible for modulating the climate of the earth. James E. Lovelock of the Coombe Mill Experimental Station in Cornwall and Lynn Margulis of Boston University are the main proponents of this point of view, which they call the Gaia hypothesis, after the Greek goddess of the earth. They maintain that the decrease in atmospheric carbon dioxide over the course of history has been a direct consequence of biological intervention and that without living organisms the earth's climate could well have gone the way of Mars or Venus.

The biota are certainly important. The fraction of carbon dioxide (roughly 20 percent) that does not take part in the carbonate-silicate cycle is removed from the atmosphere by photosynthetic plants. When such organisms die, they deposit organic carbon in sediments. Carbon dioxide is regenerated when tectonic processes elevate sedimentary rocks and form mountains, enabling carbon in the rocks to react with atmospheric oxygen in rainwater.

Living organisms also affect the carbonate-silicate cycle. We have discussed the role of oceanic plankton in forming carbonate sediments, but land plants may actually have a more important function. When the plants decay, oxidation of their remains enhances the abundance of carbon dioxide in the soil. As a result the concentrations of carbon dioxide in typical soils today are probably higher than they were before the appearance of vascular plants some 400 million years ago. This elevation speeds the conversion of silicate minerals into carbonate sediments.

All of this having been said, we nonetheless suggest that the fundamental controls on atmospheric carbon dioxide levels are physical rather than biological. We would argue, for example, that if the shelled organisms that now deposit calcium carbonate on the sea floor did not exist, the concentration of calcium and bicarbonate ions in seawater would rise. Once the ion concentrations reached a critical level, calcium carbonate would form without the intervention of organisms. Such must have been the case before about 600 million years ago, when the shell makers first appeared.

Similarly, calculations show that the decrease in silicate weathering caused by a complete disappearance of land plants could be offset by a temperature increase of about 10 degrees C.—a change that could be accomplished by the negative-feedback loop of the carbonate-silicate cycle. The increased greenhouse warming would produce a climate similar to that of 100 million years ago during the mid-Cretaceous period: warm, but nonetheless well suited for many forms of life, including the dinosaurs. Hence there is good reason to believe the earth would still have remained habitable even if it had never been inhabited. The carbonate-silicate cycle, acting alone, would have provided the necessary buffering mechanism.

One might well wonder whether water vapor, which today provides most of the 35 degrees C. of the earth's greenhouse warming, could have been responsible for the ability of the planet to remain temperate in the course of its evolution. The answer is no. The amount of water in the atmosphere does not counteract changes in the surface temperature. Rather it amplifies them: the abundance of water in the atmosphere increases when the surface temperature rises and decreases when the surface temperature falls. It follows, then, that only an overall decline in carbon dioxide levels can account for the fact that as the sun became brighter over the eons, the surface temperature of the earth did not rise in parallel but remained within a livable range.

Buffering Fails on Mars

The cycling of carbon dioxide may have kept the earth's climate within reasonable bounds as the planet evolved, but if a similar process ever existed on Mars, it failed to do the same for that planet. Today the atmosphere there consists entirely of just .006 bar of carbon dioxide, which provides a greenhouse warming of only about 6 degrees C.

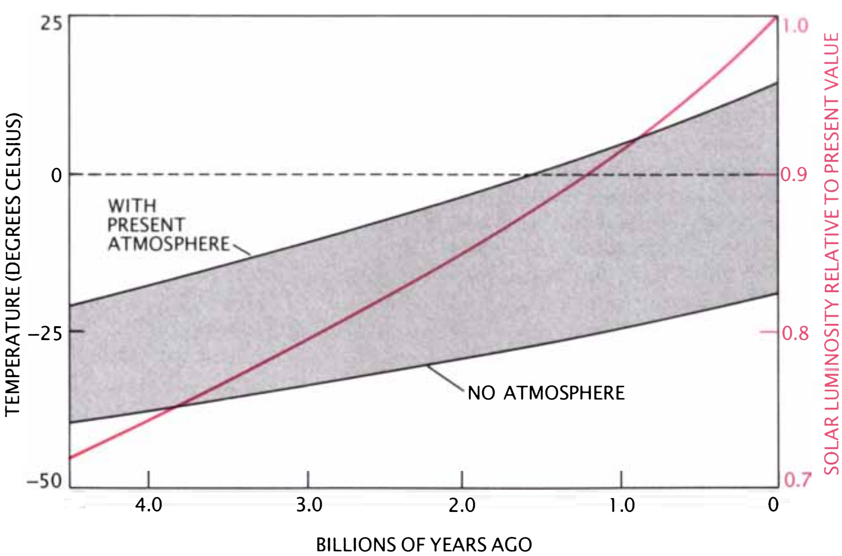
Is it possible that Mars was cold from the start and that its climate has undergone little change in the past 4.6 billion years? That is unlikely. Photographs made by NASA's Mariner and Viking spacecraft show that the Martian surface is cut by many channels that were almost certainly formed by running water. Although some of the channels could have been formed in a cold climate by the sudden release of water from great depths, the valley networks that crisscross the oldest terrain on Mars are thought to have required warmer temperatures for their genesis. The planet also had a higher rate of erosion during the first billion years of its history than it does today, according to estimates made by Peter H. Schultz of Brown University. This finding too suggests that the planet was once warm enough to support liquid water.

Geologists do not know exactly how hot Mars was, but the surface may well have been warmed by the greenhouse effect of a dense carbon dioxide atmosphere. Our calculations indicate that an atmosphere of between one and five bars of carbon dioxide would have kept parts of the Martian surface above freezing early in the planet's history. The lower figure applies to conditions at the Martian equator when the planet is closest to the sun; the higher figure is an average that applies to the entire planet.

It is within the realm of possibility that Mars once had that much carbon dioxide, even though these amounts are some 150 to 800 times more than is present in the atmosphere now. If Mars, whose mass is about a tenth of the earth's, once possessed a proportional amount of carbon dioxide, the planet would have had a total carbon dioxide endowment equivalent to about 10 bars. (To arrive at this figure one must take into account the smaller surface area and surface gravity of Mars compared with the earth.)

We suggest that Mars had an adequate supply of carbon dioxide but cooled off because its recycling mechanism ran down. We think the planet once had an effective recycling system since, if it had lacked one, the weathering of rocks would have removed all the atmospheric carbon dioxide within about 10 million years. Yet the atmosphere apparently retained abundant amounts of the gas for considerably longer. The valley networks provide the clue: the ones on the old southern highlands can be dated by counting the number of meteorite craters that overlie them. On this basis workers have concluded that the networks persisted until near the end of the period of the heaviest meteoritic bombardment—about 3.8 billion years ago.

The recycling system probably removed carbon dioxide from the atmosphere by the same weathering

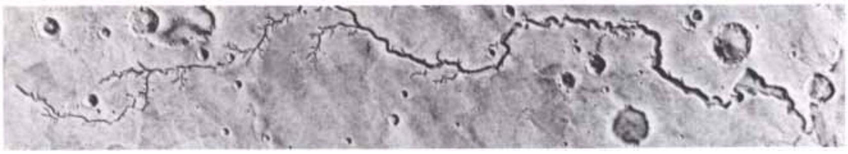


CLIMATE-MODEL CALCULATIONS indicate that the earth would have been frozen during the first part of its history if its atmospheric composition was the same as it is today. The reason is that the sun was up to 30 percent fainter in the past (*colored curve*). The top curve shows the surface temperature calculated by a "one-dimensional" (globally averaged) climate model, assuming a constant concentration of atmospheric carbon dioxide. (Many of the calculations discussed in the text are also based on a one-dimensional model.) The bottom curve shows the surface temperature of an airless earth. The shaded region between the curves represents the magnitude of the greenhouse effect. Actually carbon dioxide levels were probably higher in the past, and the surface temperature of the earth was higher than is shown here. The solar-luminosity curve is based on a calculation by Douglas O. Gough of the University of Cambridge.

process as on the earth. The mechanism that returned the gas to the environment may have been rather different, however, because a planet as small as Mars may never have developed plate tectonics. One possibility is that lava emitted by volcanoes on the Martian surface could have covered carbonate sediments and then gradually buried them to a depth at which pressure and heat would cause them to release gaseous carbon dioxide. Computer models indicate that such a process could have been sufficient to recycle carbonates for up to a billion years after the planet formed.

Mars apparently cooled down not because it received less sunlight than the earth but because it was smaller. Mars had less internal heat when it formed, and its high surface-to-volume ratio meant that it lost such heat at a higher rate. Eventually the interior became so cold that Mars could no longer free carbon dioxide from carbonate rocks. Any carbon dioxide that left the atmosphere through weathering remained locked in the ground. The Martian atmosphere became thin and the climate approached its present frigid state. If the planet had been the size of the earth, the chances are good that it would have had enough internal heat to continue recycling carbon dioxide and thus to counteract the low level of sunlight it received.

This scenario predicts that Mars now has substantial amounts of carbonate rocks buried in its crust. So far earth-based spectroscopic searches have not discovered such materials. On the other hand, James L. Gooding of NASA has recently detected small amounts of calcium carbonate in the so-called SNC (Shergotty, Nakhala and Chassigny) meteorites—which are fragments of rock that are thought to have originated at the Martian surface. The forthcoming Mars Observer Mission, scheduled for 1992, will carry out a more extensive search for carbonates and should provide important new evidence relating to our theory of how Mars froze.



SURFACE OF MARS is carved by many channels whose presence suggests that the planet was once warm enough to maintain liquid water. Typical "runoff" channels, like Nirgal Vallis (*top*), look different from rivers on the earth because their tributaries are short and sparse; they probably derive from the sapping, or leaching, of groundwater. Other, highly branched structures (*bottom*) found in ancient terrains appear to be valley networks; sapping or precipitation and runoff could have formed them. The fact that the networks are overlain by craters implies they developed before the end of the period of heavy bombardment by meteorites about 3.8 billion years ago. Certain "outflow" channels (not shown) could have formed in a cold climate by other processes.

How Venus Dried Out

Whereas Mars has a vast supply of water (albeit frozen), Venus today is almost completely dehydrated. What little water there is resides in the atmosphere as vapor or as a component of the dense sulfuric acid clouds that surround the planet. Climatologists have advanced two major theories to explain why Venus is so dry.

John S. Lewis of the University of Arizona and his colleagues have suggested that Venus never had much water—that the region of the solar nebula where Venus formed was too hot to allow for the formation of hydrated minerals. A serious problem with this theory is that it does not consider the role of gravity. According to dynamical models developed by George W. Wetherill of the Carnegie Institution of Washington, developing planets not only sweep up planetesimals that cross their orbits but also perturb the orbits of such bodies and scatter them throughout the inner solar system. During the later stages of their growth, the "proto" earth and Venus were massive enough to have actually exchanged planetesimals. Because the ones derived from the earth would have been rich in water, Venus would have received a substantial endowment of the fluid.

As this objection suggests, the alternative theory is that Venus originally had plenty of water—perhaps as much as the earth—but lost it when the life-giving substance found its way to the upper atmosphere. There sunlight tore apart the water molecules and liberated hydrogen atoms, which escaped into space. (Only water in the upper atmosphere is subject to hydrogen escape; at low altitudes hydrogen atoms, which are light, are held in the atmosphere by the drag exerted by background gases, such as carbon dioxide.)

Variations on this alternative theory differ in whether they allow water to remain fluid on the surface for any length of time. The classical explanation, the runaway-greenhouse theory, holds that Venus never retained any water on its surface. The concept of the runaway greenhouse was suggested as early as 1955 by Fred Hoyle of the University of Cambridge, but many of the details were worked out in the late 1960's by Andrew P. Ingersoll of the California Institute of Technology and one of us (Pollack).

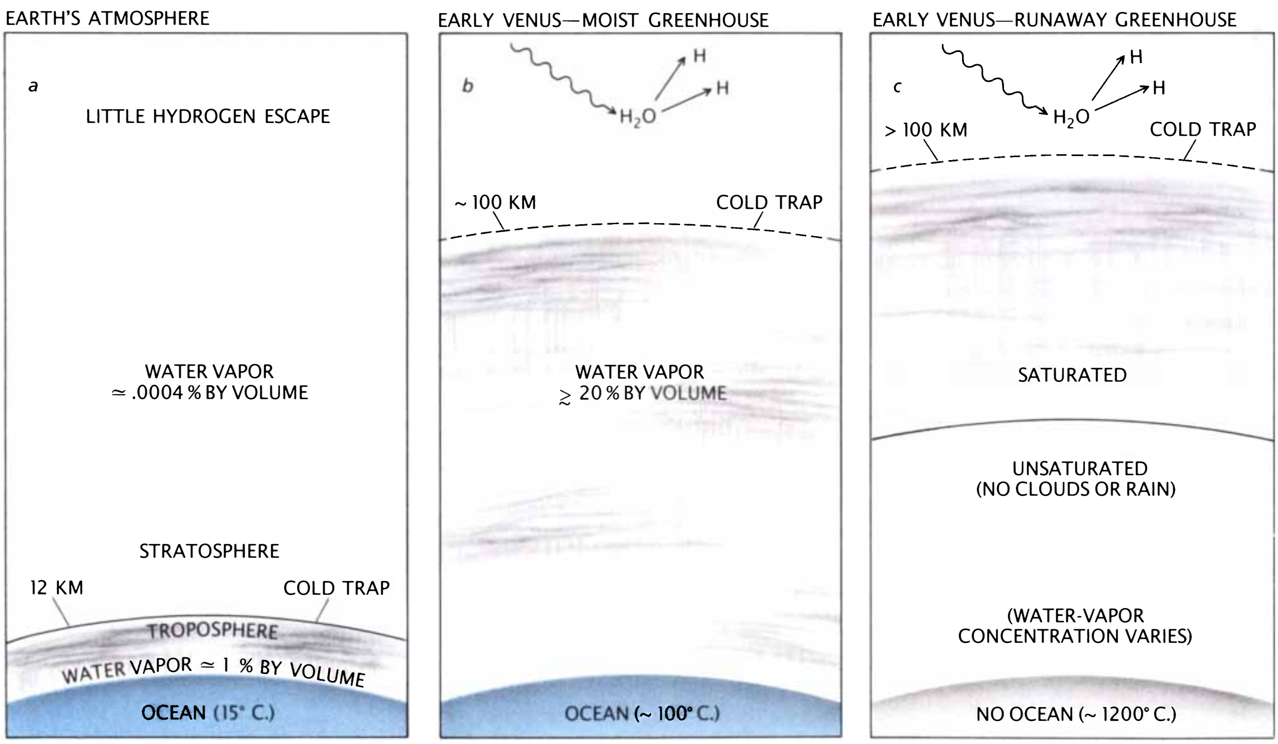
According to these workers, surface water cannot remain liquid if there is more than a critical amount of sunlight incident on a planet. If the solar flux at the orbit of Venus exceeded that critical value from the start, any water released from the interior would have vaporized instantly. At least in the lower, hotter part of the atmosphere, this vapor would not have condensed out as rain, and so no oceans would have formed.

Water would have been lost from the atmosphere because in such a hot, wet environment air would cool unusually slowly as it rose. Consequently the atmospheric "cold trap" would be pushed up to a high altitude (about 100 kilometers). The cold trap is the region where cold temperature and a high ambient pressure combine to hold the saturation point to a minimum. Normally the relative concentration of water vapor (the fraction of atmospheric volume represented by the vapor) in the cold trap is much less than the concentration in the atmosphere below it, and water condenses out instead of rising. In an elevated cold trap, however, the relative concentration of water vapor would be similar to that in the atmosphere closer to the surface. Under this condition the cold trap would allow a significant amount of water to pass into the upper reaches, where it would be subject to "photodissociation" and hydrogen escape. Such escape could potentially have eliminated the equivalent of an ocean in less than 30 million years.

In the earth's present atmosphere, in contrast, the cold trap is found at rather low altitudes (between nine and 17 kilometers), at the boundary between the troposphere and the stratosphere. When water vapor from lower altitudes rises to the cold trap, almost all of it condenses out, with the result that our stratosphere is extremely dry and little hydrogen escapes.

We calculate that the solar flux necessary to trigger a runaway greenhouse is about 1.4 times the amount of sunlight that currently impinges on the earth—if the planet in question has a fully saturated atmosphere that is free of clouds. This is approximately equal to the estimated solar flux at the orbit of Venus early in the history of the solar system, suggesting that Venus was on the brink of a runaway greenhouse. Nevertheless, if clouds were present and able to reflect a substantial fraction of the incident sunlight, it is likely that a runaway greenhouse could have been avoided on the very early Venus, allowing oceans to exist for a time.

Such oceans would not have been spared indefinitely. As an alternative to the runaway-greenhouse theory we propose that Venus once had oceans but lost them because its atmosphere was what we call a moist greenhouse: a condition in which the relative concentration of water vapor near the ground accounts for more than 20 percent or so of the volume. For a one-bar atmosphere like that of the earth, this concentration can be reached when the surface temperature rises above about 70 degrees C. (If Venus had an ocean and rain, most of its carbon dioxide would have been buried in carbonate rocks, and



TENDENCY OF WATER VAPOR to escape from the earth is minimal; the same cannot be said for early Venus. On the earth (*a*) water in the troposphere is blocked from entering the stratosphere by a cold trap: the region where cold temperature and relatively high ambient pressure combine to minimize the concentration of water vapor. When vapor reaches the trap, most of it condenses out. On early Venus the lower atmosphere, though warm by the earth's standards, may have been cool enough for water to condense and form an ocean. The sea would in time have been lost, however, to a "moist greenhouse" (*b*): a condition that arises when a high surface temperature enables water vapor to constitute more than about 20 percent of the lower atmosphere. The cold trap then moves to a high altitude and becomes inefficient at preventing water vapor from rising into the upper atmosphere. Although some vapor condenses out as rain, the steam at the top dissociates and its constituent hydrogen atoms escape into space. Venus might have been so hot that a runaway greenhouse (*c*) developed instead: all the water released by the planet turned to steam instantly, and no ocean formed. The water essentially traversed a one-way route: up and away.

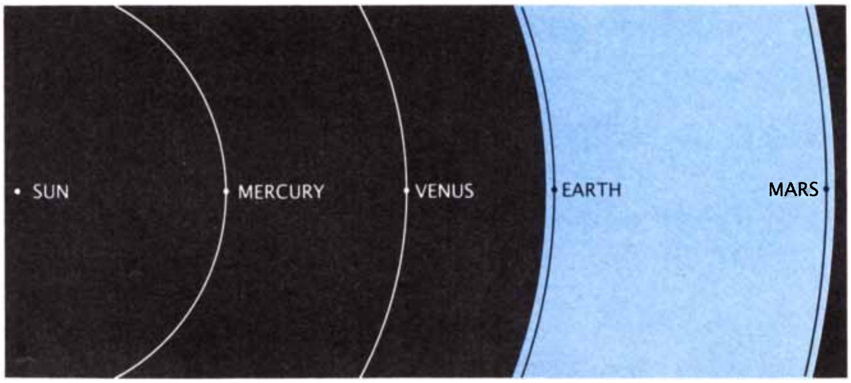
a one-bar atmosphere would have been possible.)

Our climate simulations indicate that a moist greenhouse should arise when the solar flux striking a cloud-free atmosphere is at least 1.1 times the amount of light incident on the earth. When the water-vapor concentration near the ground surpasses 20 percent, water condensation (which generates heat) warms the atmosphere significantly and, as in the runaway-greenhouse condition, causes the cold trap to rise. Water can then make its way into the upper atmosphere. An ocean could exist on a planet with a solar flux of between 1.1 and 1.4 times that of the earth, but it would be depleted by hydrogen escape within a few hundred million years.

In our view the moist-greenhouse theory does a better job than the runaway-greenhouse theory of explaining why Venus has almost no liquid water today. Because weathering would suppress the atmospheric carbon dioxide levels in a moist greenhouse, the total gas pressure of the atmosphere would be lower than in a runaway greenhouse. As a result it would take a small amount of water vapor to constitute 20 percent of the total gas volume, and so a greater fraction of the final water supply would reach the upper atmosphere. For example, if the atmosphere consisted of one bar of water vapor and one bar of carbon dioxide, the water would constitute 50 percent of the volume and much of it would escape. In contrast, if there were 99 bars of carbon dioxide, the one bar of water would constitute just 1 percent of the volume and would remain in the planet's atmosphere.

Regardless of whether the early atmosphere of Venus was in a runaway- or moist-greenhouse state, the planet would eventually have evolved to its present hot, dry condition. Once the oceans disappeared carbonate formation should have ceased, causing carbon dioxide to accumulate in the atmosphere. Consequently the planet's 93-bar atmosphere is now mostly carbon dioxide. Sulfur gases, which were initially scarce because they dissolve readily in water, also accumulated and formed the sulfuric acid clouds that are now a major feature of the Venusian environment.

It is the carbon dioxide, not the distance of Venus from the sun, that today accounts for its high surface temperature. Venus receives 1.9 times more solar radiation than the earth, but its sulfuric acid clouds reflect about 80 percent of that sunlight, so that Venus actually absorbs significantly less solar energy than the earth. Without the greenhouse effect Venus would be colder than the earth and only slightly warmer than Mars.



CONTINUOUSLY HABITABLE ZONE (*light blue*) is the region of space where a planet could theoretically maintain an earthlike climate long enough for life to proliferate. An early estimate suggested that the zone was rather narrow, extending from about .95 astronomical unit to 1.01 A.U., from just inside to just outside the earth's orbit. Newer work suggests that the outer edge may lie as far out as 1.5 A.U.—past the orbit of Mars.

The Continuously Habitable Zone

The finding that a planet with a solar flux 1.1 times the earth's would lose its water by photodissociation is consistent with Hart's calculation that the inner boundary of the continuously habitable zone lies at about .95 A.U. This agreement is somewhat coincidental, however, because we base our estimate on hydrogen-escape rates, whereas he came to his estimate by other means. Of course, a planet at the inner limit would not be habitable for long. The sun is currently increasing in luminosity by about 1 percent every 100 million years. Hence the earth itself may have difficulty maintaining its water starting about a billion years from now. This disaster may be postponed for sometime by a decrease in atmospheric carbon dioxide mediated by the carbonate-silicate cycle. Such a decline might itself prove harmful to the biota, however, because many plants would not be able to carry out photosynthesis if they received significantly less carbon dioxide than they get today. (Astute readers might note at this point that carbon dioxide levels are currently rising in the atmosphere owing to the burning of fossil fuel. In fact, such activity cannot continue for more than a few hundred years before the planet's reserves of coal and oil are eliminated. After the brief warming period carbon dioxide levels will again begin to fall.)

The outer edge of the CHZ must lie considerably farther out than Hart imagined—perhaps as far as 1.5 A.U., which would place the boundary somewhat beyond the orbit of Mars. We limit the outer boundary at this distance because it seems unlikely that a terrestrial planet could form farther out.

Much the same negative-feedback mechanism that has helped to stabilize the earth's climate for the past 4.5 billion years would presumably operate on a planet of similar size farther from the sun. The only reason Mars froze is that it was too small to continue recycling carbon dioxide. An earth-size planet at the orbit of Mars should, according to our theory, have several bars of carbon dioxide in its atmosphere and a mean surface temperature above the freezing point. This atmosphere would not be breathable by human beings, but it would be perfectly capable of supporting some form of life.

When Hart first determined that the CHZ was extraordinarily narrow, his conclusion implied that the chance of finding earthlike planets around other stars was rather slim, even if other planetary systems were themselves abundant. Our calculations point to the opposite conclusion. If other planetary systems exist, as in all likelihood they do, then there is a good probability of finding habitable planets. Whether or not any of them are in fact inhabited is, of course, an open question, but it is one that can no longer be dismissed on the assumption that the earth is climatologically unique. Perhaps on one such planet there is even an extraterrestrial version of the story of Goldilocks.