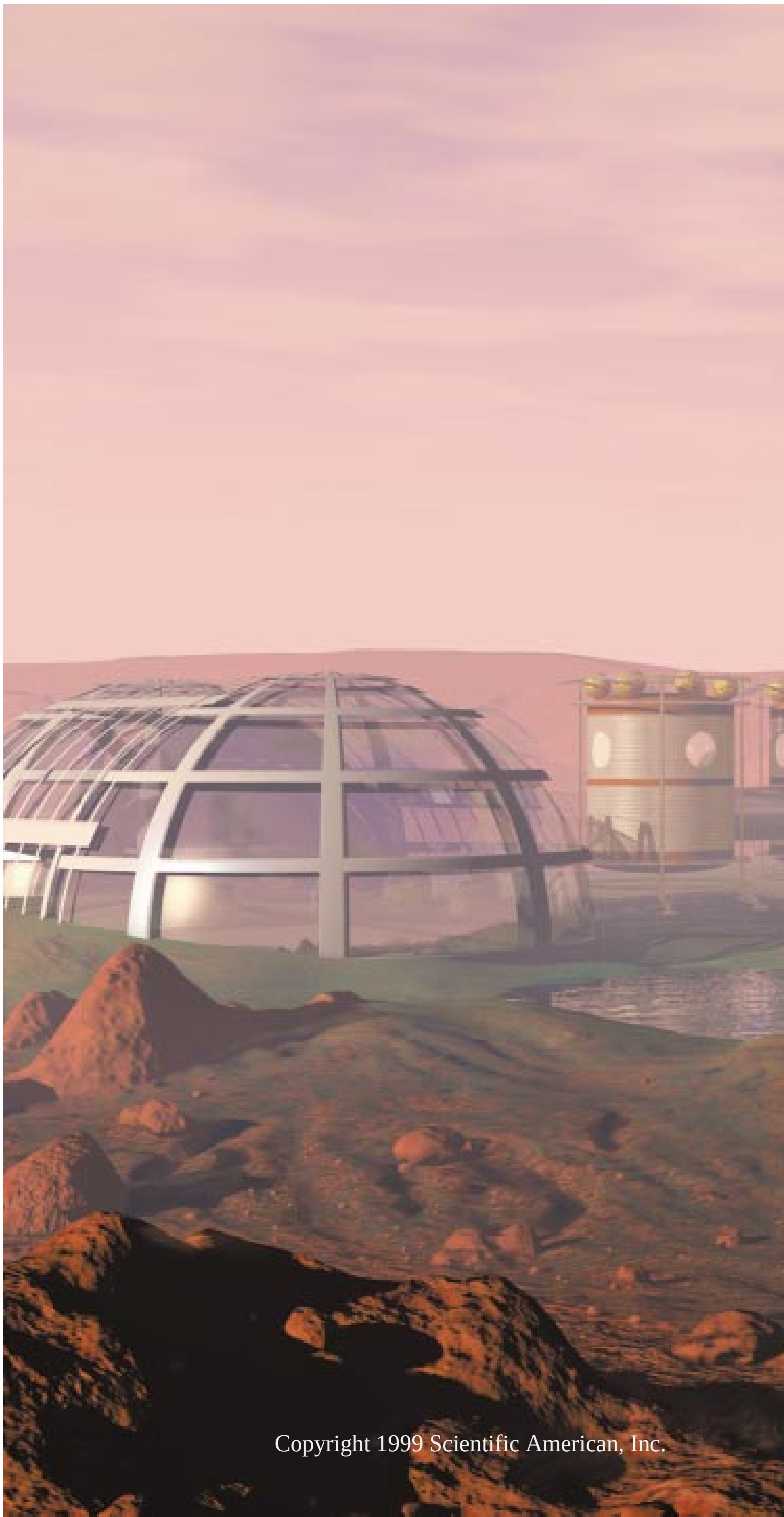
Bringing Life to Mars

by Christopher P. McKay

Climate models suggest that human beings could transform the Red Planet into a more Earth-like world using current technologies

Four billion years ago Mars was a warm and wet planet, possibly teeming with life. Spacecraft orbiting Mars have returned images of canyons and flood valleys—features that suggest that liquid water once flowed on the planet's surface. Today, however, Mars is a cold, dry, desertlike world with a thin atmosphere. In the absence of liquid water—the quintessential ingredient for life—no known organism could survive on the Red Planet.

More than 20 years ago the Mariner and Viking missions failed to find evidence that life exists on Mars's surface, although all the chemical elements needed for life were present. That result inspired biologists Maurice Averner and Robert D. MacElroy of the National Aeronautics and Space Administration Ames Research Center to consider seriously whether Mars's environment could be made hospitable to colonization by Earth-based life-forms. Since then, several scientists, using climate models and ecological theory, have concluded that the answer is probably yes: With today's technology, we could transform the climate on the planet Mars, making it suitable once more for life. Such an experiment would



ALFRED T. KAMAJIAN

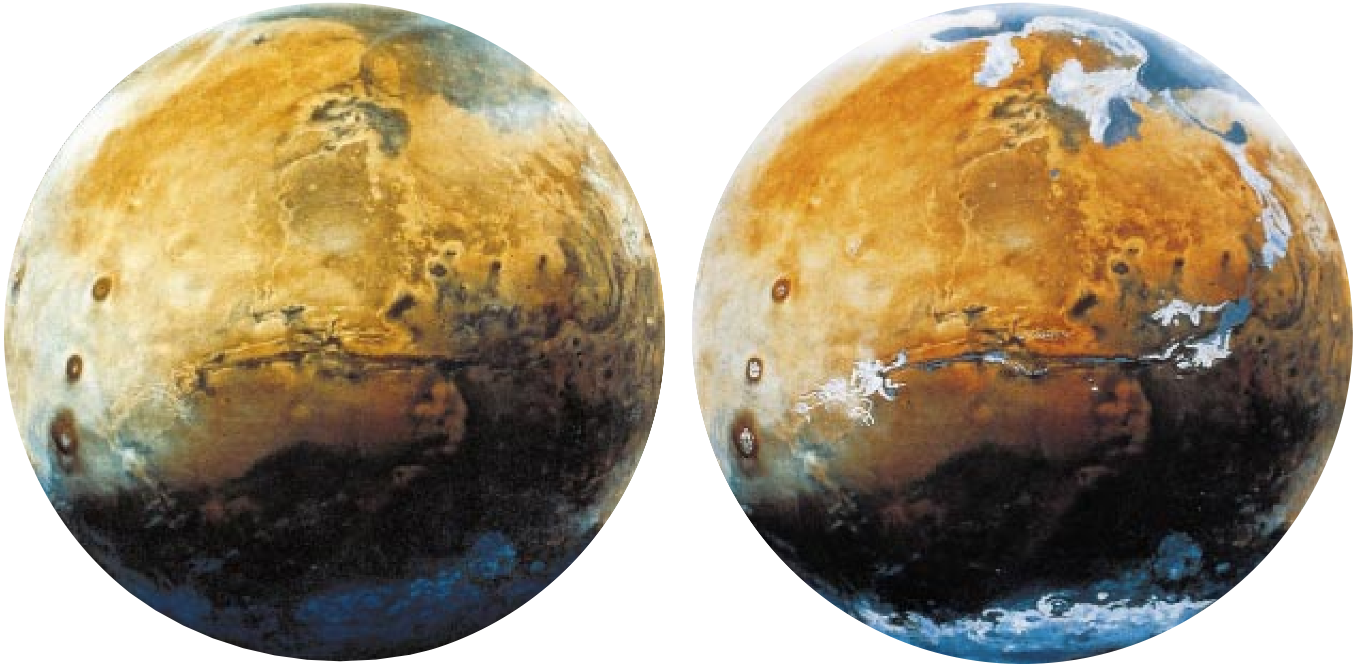
GREENING OF MARS is portrayed in this artist's conception of a Martian landscape after the planet has been warmed to Earth-like temperatures. A mobile soil-processing unit (*in foreground*) generates greenhouse gases that trap solar energy and trigger the creation of a thick carbon dioxide atmosphere. Plants imported from Earth could grow on the surface, but humans could not breathe the air and would need to carry oxygen tanks.

allow us to examine, on a grand scale, how biospheres grow and evolve. And it would give us the opportunity to spread and study life beyond Earth.

Why Mars?

Many of the key physical properties of Mars are remarkably similar to those of Earth [*see table on page 54*]. On both planets the length of day is about 24 hours—an important consideration for plants that have adapted to photosynthesize when the sun shines. Mars also experiences seasons, as the planet's axis is tilted to a similar degree as Earth's. Because Mars is farther from the sun, a Martian year is almost twice the length of an Earth year, but plants should be able to adapt to such a difference. One unalterable difference between Earth and Mars is gravity: Martian gravity is about one third that of Earth's. How life would adapt to reduced gravity is unknown. It is likely, however, that microbes and plants would adjust easily to Martian gravity, and some animals might cope just as well.

Other planets and moons in our solar system also might be considered potential sites for life, including Venus, Titan and Europa. Each of these bodies, however, possesses some basic physical parameter that is inconsistent with habitability. Titan and Europa—satellites of Saturn and Jupiter, respectively—are too far



RED PLANET TURNS BLUE in this series of images showing how Mars might change if its surface were warmed by human effort. Rising temperatures would release the carbon dioxide and water currently frozen in the planet's polar caps (*above*). The water would collect primarily in the lowlands of the northern hemisphere, forming a large ocean. In the final stage of warming (*far right*), Mars would have the same amount of liquid water that it apparently possessed billions of years ago.

from the sun. Venus is too close, and its extremely dense atmosphere makes the planet much too hot for life. Furthermore, the planet rotates so slowly that its day is equal to about four months on Earth, which might make life difficult for plants. The technology needed to alter these physical parameters is well beyond the current scope of human capability.

Mars is currently too cold, too dry and its carbon dioxide atmosphere too thin to support life. But these parameters are interrelated, and all three can be altered by a combination of human intervention and biological changes. The key is carbon dioxide. If we were to envelop Mars in a thicker carbon dioxide atmosphere, with a surface pressure one to two times that of air at sea level on Earth, the planet would naturally warm above the freezing point of water. Adding a bit of nitrogen to the atmosphere would help satisfy the metabolic needs of plants and microbes. And the small amount of oxygen that would be produced from the photochemical degradation of carbon dioxide could create a rudimentary but effective ozone shield for the rejuvenated planet. This carbon dioxide atmosphere would support plant and microbial life but would not contain enough oxygen for animals.

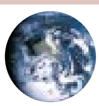
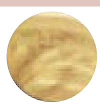
Although humans would need to carry a supply of breathable air with them, a carbon dioxide Mars would still be a much kinder, gentler place than today's Mars. The higher temperatures and atmospheric pressure would make bulky space suits and pressure domes unnecessary. And the natural growth of plants would allow the cultivation of farms and forests on Mars's surface, thus providing food for human colonists or visitors.

To make Mars suitable for animals and humans, its atmosphere would have to be made more similar to Earth's, which is composed primarily of nitrogen, with oxygen levels close to 20 percent and carbon dioxide levels less than 1 percent. The process of generating such an Earth-like, oxygen-rich environment—also called terraforming—would be much more difficult than simply thickening Mars's atmosphere. But to make Mars habitable, generating a carbon dioxide atmosphere—a process that biologist Robert Haynes of York University has dubbed ecopoiesis—would be the logical first step.

Does Mars possess the essential volatiles—carbon dioxide, nitrogen and water—needed to create a habitable environment? Ferrying these raw materials from Earth would be impractical. For example, the amount of nitrogen needed to create a breathable atmosphere on Mars is more than a million billion tons. The space shuttle can carry only about 25 tons into low-Earth orbit. Thus, if Mars does not have the necessary amount of nitrogen, it is not within near-term capabilities of humans to bring it there.

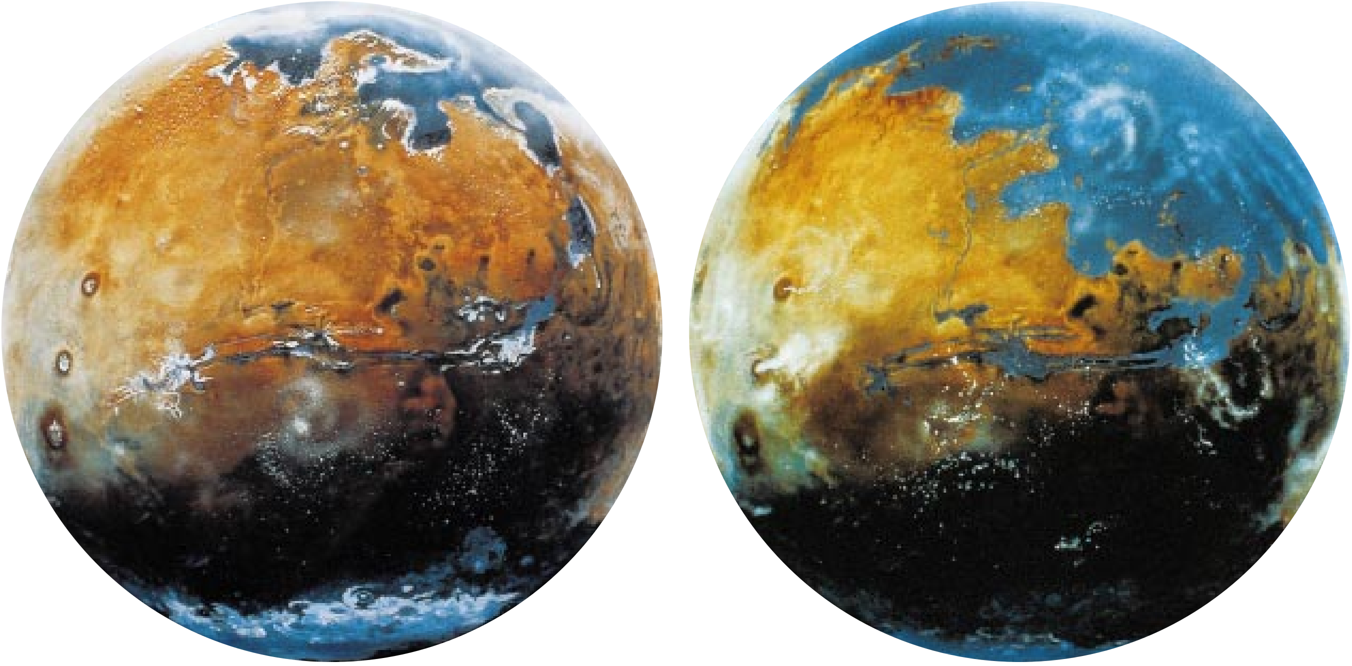
Unfortunately, we do not yet know how much of each of these key ingredients Mars has hidden below its surface. We do know

Comparing Earth, Mars and Venus

	 EARTH	 MARS	 VENUS
Gravity (g's)	1	0.38	0.91
Length of day	24 hours	24 hours 37 minutes	117 days
Length of year	365 days	687 days	225 days
Axis tilt (degrees)	23.5	25.2	2.6
Average sunlight reaching the planet (watts per square meter)	345	147	655
Average surface temperature (degrees Celsius)	15	–60	460
Surface pressure (atmospheres)	1	0.008	95
Most abundant gases in atmosphere	Nitrogen, oxygen	Carbon dioxide	Carbon dioxide

NASA

CHRISTOPHER P. MC KAY



MICHAEL CARROLL

that the thin Martian atmosphere currently contains only small amounts of carbon dioxide, nitrogen and water vapor. But at one time Mars must have had a much thicker atmosphere. Researchers have used a variety of methods to estimate how much carbon dioxide, nitrogen and water would have been present in the early Martian atmosphere. These methods—which include measuring the ratio of nitrogen isotopes and estimating the volume of water needed to etch the Martian flood channels—yield widely different estimates of the amount of volatiles once present on the planet.

Fortunately, the range of estimates overlaps the amounts of volatiles needed to produce a breathable atmosphere and a substantial ocean [*see table below*]. It is possible that some of these volatiles have left the planet permanently, flowing out into space because of Mars's low gravity. If, however, Mars once had enough of the volatiles needed to make a biosphere, it probably still has them locked up in the subsurface. Water could be frozen as ground ice, and nitrogen could be contained in nitrates in the Martian soil. Carbon dioxide could be frozen in Mars's polar caps as well as in the soil.

Turning up the Heat

If Mars does have the essential ingredients, the first step in transforming the environment is to warm the planet. Heating the Martian surface would release the carbon dioxide, nitrogen and water vapor into the atmosphere. The energy needed for such massive heating would have to come from the sun. Compared with sunlight, human energy sources are small. For example, sunlight delivers more energy to Mars in 30 minutes than the energy that would be released by the explosion of all the nuclear warheads of the U.S. and Russia. So trapping the energy from sunlight and using it to warm the planet is really the only practical option for generating a life-friendly Mars.

Through the years, scientists have proposed and considered several methods of using sunlight to heat Mars. Some researchers suggested spreading dark soot on the polar caps to help them absorb more sunlight and melt their stores of frozen carbon dioxide. Other researchers proposed putting large mirrors in orbit around Mars to reflect sunlight onto the polar regions. But the technologies needed for these methods have never been demonstrated. The space mirror, for example, would have to be the size of the state of Texas to increase the amount of sunlight hitting Mars by just 2 percent.

Perhaps the most practical approach to warming Mars would involve using "super-greenhouse" gases to trap solar energy on the planet. This method was first suggested by British atmospheric scientist James Lovelock, who is best known for the Gaia hypothesis that the presence of life maintains the habitability of Earth. Lovelock's idea for heating Mars involved pumping gases such as methane, nitrous oxide, ammonia and perfluorocarbons (PFCs) into the Martian atmosphere. These super-greenhouse gases can trap solar energy with thousands of times the efficiency of carbon dioxide, the most abundant greenhouse gas on Mars and Earth. Even small amounts of the super-greenhouse gases can warm a planet; in fact, many scientists believe that the production of these gases is contributing to global warming here on Earth.

Computer calculations performed by myself, Owen B. Toon and James F. Kasting suggest that if Mars's atmosphere contained just a few parts per million of the super-greenhouse gases, the average temperature at the planet's surface would

The Essential Ingredients for Life on Mars

	Carbon dioxide surface pressure (atmospheres)	Nitrogen surface pressure (atmospheres)	Water ocean depth* (meters)
Amount needed for plant and microbe habitability	2	0.01	500
Amount needed for breathable atmosphere	0.2	0.3	500
Amount in the present Mars atmosphere	0.01	0.00027	0.000001
Range of estimates for amount on Mars at planet's formation	0.1–20	0.002–0.3	6–1,000

**Amount of water is measured in terms of the depth of an ocean covering the entire surface of Mars.*

CHRISTOPHER P. MCKAY

A Futile Effort?

Billions of years ago Mars had a thick carbon dioxide atmosphere and temperatures warm enough for liquid water. Why then did it become uninhabitable? And if we restored a more hospitable Martian climate, would the planet once again revert to its current barren state?

The answers lie in carbon recycling. Atmospheric carbon dioxide reacts with liquid water to form carbonic acid. This acid weathers rocks, ultimately producing calcium carbonate. As this mineral accumulates in the oceans and lake basins, carbon is effectively removed from the atmosphere.

On Earth, carbonates are recycled by plate tectonics. Subduction of oceanic plates under continental plates carries the sediments deep underground, where temperatures greater than 1,000 degrees Celsius convert the carbonates back to carbon dioxide. Mars, however, is a one-plate planet with a single thick crust. Because Mars had no plate tectonics to recycle carbonates, it gradually lost its atmospheric carbon dioxide. As the atmospheric pressure dropped, the planet's surface chilled, and its liquid water froze.

If Mars were warmed and its thick carbon dioxide atmosphere restored by human effort, it is very likely that carbonate formation would again deplete the atmosphere. After a few hundred million years,

rise from –60 to –40 degrees Celsius (–76 to –40 degrees Fahrenheit). This warming could be enough to trigger the release of carbon dioxide from the polar caps and soil into the atmosphere. Carbon dioxide would then augment the greenhouse effect even further, driving the release of more carbon dioxide and water vapor into the atmosphere. Such positive feedback would be sufficient to create a thick, warm atmosphere—the carbon dioxide Mars.

Where would the greenhouse gases come from? Although PFCs at a concentration of a few parts per million would do the job, the mass of material needed to warm Mars would be much too large to import from Earth. Instead the greenhouse gases would have to be produced locally, on Mars—chemically at first and eventually biologically, with the help of microorganisms. The gases must be easily synthesized from elements likely to be abundant on Mars and must persist in the Martian atmosphere for a relatively long time. PFCs such as CF_4 and C_2F_6, and other compounds such as SF_6, would be good choices because they absorb thermal radiation efficiently and would have long lifetimes in the Martian atmosphere, on the order of hundreds of years. Furthermore, the elements making up these compounds—carbon, fluorine and sulfur—are all abundant on Mars.

To generate enough greenhouse gases, we would need to distribute hundreds of small PFC factories across the Martian surface. Powered by solar energy, each of these Volkswagen-size machines would harvest the desired elements from Martian soil, generate PFCs and pump these gases into the atmosphere.

The Matter of Time

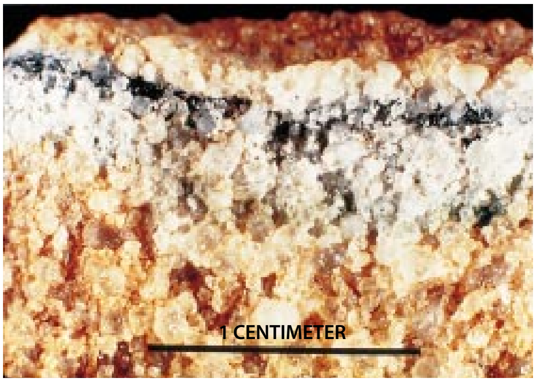
How long would it take to generate a thick carbon dioxide atmosphere? The atmospheric PFCs would have to heat the planet enough to melt the carbon dioxide and water frozen in the polar caps and to evaporate nitrogen from the soil. But how much energy is needed to raise the temperature of Mars? According to our calculations, defrosting Mars would require an energy input of five megajoules per square centimeter of planetary surface. This amount of energy is equivalent to about 10 years' worth of Martian sunlight.

Trapping this energy would vaporize the frozen carbon dioxide, generating enough gas to create a thick atmosphere. If enough carbon dioxide were generated to provide a pressure twice that of Earth's atmosphere, the average Martian surface temperature would rise to an Earth-like 15 degrees C. At this stage, the bulk of the planet's water is likely to still be frozen deep underground, where temperatures would remain much lower. Melting the reservoirs of subsurface ice would require an additional 25 megajoules per square centimeter of surface, equivalent to 50 years of Martian sunlight.

Thus, if every photon of sunlight reaching Mars were captured with 100 percent efficiency, the planet could be warmed in a decade and fully thawed in 60 years. Of course, in reality no process is 100 percent efficient. If greenhouse gases can trap sunlight with an efficiency of 10 percent, using PFCs could generate a thick carbon dioxide atmosphere in about 100 years and lead to a water-rich planet in about 600 years. These numbers are encouraging. If the answers had turned out to be millions of years, we would have to abandon our plans to turn Mars into a second home for life.

For even quicker results, the greenhouse gas effect could be amplified by coupling it with other methods, such as the deployment of huge orbital mirrors or the spreading of dark material on the planet's surface, according to calculations by Robert Zubrin. But changing Mars slowly makes sense for a number of reasons. Transforming the climate of


NASA/CHRISTOPHER P. McKAY



E. IMRE FRIEDMANN

LIFE FROM ANTARCTICA could be transplanted to Mars in the early stages of the planet's transformation. The Linnaeus Terrace in Antarctica (*left*) is one of the coldest and driest places on Earth. But lichens and algae live just below the surface of sandstone rocks in the area (*above*). These organisms might also thrive on Mars.

Mars would once again lose its capacity to support life.

But 100 million years is a long time. In fact, Earth might not be habitable for much longer than that. As the sun continues to brighten, Earth will succumb to a runaway greenhouse effect. The oceans will evaporate, creating Venus-like conditions unsuitable for life. So our second planetary home might last almost as long as our first. —*C.P.M.*

Mars over decades and centuries—as with greenhouse gases—would be financially feasible. NASA's Mars program could easily absorb the cost of shipping half a dozen PFC factories to the planet every year. Furthermore, working with longer timescales would also allow life on Mars to adapt and evolve and interact with the environment—as has been the case on Earth for billions of years. Finally, slowing the process of environmental evolution gives us ample opportunity to study the coupled biological and physical changes as they occur. Learning how biospheres are built is part of the scientific return for the investment in bringing Mars to life.

Plants and bacteria can thrive on this warm, wet, carbon dioxide–rich Mars. But producing an oxygen-rich atmosphere capable of supporting animals—and humans—is much more difficult. Thermodynamic calculations indicate that conversion of the carbon dioxide in Mars's thick atmosphere to oxygen would require about 80 megajoules of energy per square centimeter, or about 170 years of Martian sunlight. And the only mechanism that could transform the entire atmosphere is a planetwide biological process: the photosynthesis done by plants, which take in carbon dioxide and expel oxygen.

On Earth, the efficiency with which plants produce oxygen from sunlight is only a hundredth of 1 percent. With this efficiency, converting Martian carbon dioxide to oxygen would take more than a million years. Although this may sound like a long time, keep in mind that the same process on Earth took over two billion years. Of course, as plants consume the atmospheric carbon dioxide, the greenhouse effect would lessen, and Mars would once again become cold. To keep the surface temperatures warm with an atmosphere that contained mostly nitrogen and oxygen and only 1 percent carbon dioxide, the concentrations of supergreenhouse gases would have to be maintained at a few parts per million. Such quantities of greenhouse gases would be harmless to living things.

Future Martians

If Mars is currently a planet bereft of life, the Martians of the future would have to be imported from Earth. The dry valleys of Antarctica—the coldest, driest and most Mars-like place on Earth—harbor some ideal candidates for the first generation of Martians. High in the mountains, where the air temperature rarely rises above freezing, E. Imre Friedmann of Florida State University has found lichens and algae that live a few millimeters below the surface of porous sandstone rocks. When sunlight warms these rocks, enough snow melts into the sandstone to provide the moisture the microbes need to survive. Similar microorganisms that can grow without oxygen might be able to survive in their little "rock greenhouses" even in the early stages of Mars's transformation, when the planet would still be very cold.

As Mars warms, different types of plants could be introduced. James M. Graham of the University of Wisconsin likens the gradual greening of Mars to hiking down a mountainside on Earth. As one descends to lower elevations, the temperature rises and the scenery grows more lush. On Mars, the bare rock would give way to the hardy plants that thrive on Earth's tundra, and eventually the Martian landscape would blossom into the equivalent of an alpine meadow or a pine forest. The plants would generate oxygen, and eventually insects, worms and other simple animals that can tolerate high concentrations of carbon dioxide and low levels of oxygen could roam the planet.

Introducing life to Mars would be of great scientific merit and could well be relevant to understanding how to sustain the biosphere of Earth. But would such a program be desirable? What are the ethical considerations surrounding such a drastic alteration of another planet's environment?

First we must assume that Mars is currently lifeless—an assumption that must be certified to a high level of confidence before we transfer life from Earth. If Mars did harbor living organisms beneath its surface, we might consider altering the environment to allow that native life to emerge and spread across the planet. If, however, Mars has no life and we believe that life in itself has intrinsic worth, then a Mars replete with life could be considered of more value than today's Mars, beautiful but lifeless.

On Earth, environmental change almost always produces some negative effects. Would this also happen on Mars? Although we can monitor Mars as it evolves, we will not really be able to control or predict the paths that the biota and the environment will follow. The Earth's biosphere is so complex that unintended changes that adversely affect some life-forms are to be expected. But on Mars, in all likelihood, no life-forms currently exist. Thus, any biological expansion would be considered an improvement. If spreading life is the objective, making Mars habitable might allow humans to make a purely positive contribution for once. SA

EDWARD BELL

MELTING THE POLAR CAPS on Mars would probably require at least 100 years of warming. Another 500 years would be needed to melt the planet's underground ice.

Christopher P. McKay received his doctorate in astrophysics from the University of Colorado in 1982 and has been a research scientist with the space science division of the NASA Ames Research Center ever since. The year McKay entered graduate school, the Viking spacecraft landed on Mars, an event that aroused his continuing interest in planetary science and the origins of life. Today McKay helps to plan future Mars missions, and he regularly journeys to the dry valleys of Antarctica to study life in cold, dry conditions.