During the long years of the Global Atmospheric Research Program (GARP), NASA’s space science organization had been busily exploring what space scientists call the terrestrial planets, Mercury, Venus, and Mars. These three, unlike the giant outer planets, are made of rock and metal, in roughly the same amounts as Earth. At the beginning of the space age, there was a great deal of expectation within the scientific community that at least the nearer two, Venus and Mars, would be climatically like Earth. Indeed, most scientists of the late 1950s assumed that an annual “wave of darkening” across the face of Mars represented the bloom of plant life of some form in a Martian spring.¹

The 1960s proved shocking to the scientific community, as the Mariner spacecraft built by the Jet Propulsion Laboratory (JPL) proved that these worlds were radically unlike Earth. Despite having developed out of the same material, and in Earth’s and Venus’s cases, with only a small difference in orbital distance and thus solar intensity, they had each evolved in very different directions. Only Earth had apparent life; by the late 1970s, the others were judged not merely dead worlds but ones incapable of hosting any kind of life. This forced the community to think
very hard about the relationship between atmospheric chemistry and climate. This work on planetary climates caused NASA scientists to become involved in a brewing debate over whether humans were changing Earth’s climate.

James R. Fleming links the modern theory of greenhouse warming to the work of Guy S. Callendar, who demonstrated a gradual increase of carbon dioxide in the Earth’s atmosphere and made important new measurements of the infrared spectra of a number of gases, including water vapor and carbon dioxide, and Gilbert Plass, who made new measurements of carbon dioxide’s spectral characteristics and built the first modern infrared radiative transfer computer code. Their work, published between 1939 and 1958, revived and put into its modern form the hypothesis that human emissions of carbon dioxide might cause the Earth to warm.\(^2\) Spencer Weart traces the subsequent evolution of global warming theory through the work of Roger Revelle, Hans Suess, Charles Keeling, and more recent hypotheses of abrupt climate change.\(^3\)

With the exception of Plass, whose work spanned Earth and planetary atmospheres, these scientists were all Earth scientists. They were interested in the climate dynamics of Earth. But NASA, as the space agency, had little direct interest in fostering Earth science during the 1960s. Its meteorological satellite program was an applications program aimed at fostering better weather forecasting by the Weather Bureau. It was not aimed at making NASA itself an Earth science powerhouse. But NASA gradually became one during the 1970s and 1980s, with its institutional interests centered around the very large question of global climate change.

NASA, however, came to an institutional interest in climate studies via a somewhat different route than had Earth scientists. Astronomers were also interested in the atmospheres and climates of other planets, and in fact the Weather Bureau’s Harry Wexler had let a contract to Seymour Hess shortly after World War II to use the Lowell Observatory’s telescopes to try to understand the general circulations of the Mars and Venus atmospheres. Wexler hoped these would provide clues to the general circulation of Earth’s atmosphere, which could not yet be seen from a suitably large distance to make large-scale sense of. This effort didn’t succeed, as even the largest telescopes could not see enough detail.\(^4\)

It was from NASA’s interest in fostering planetary astronomy that it reached an interest in studying Earth’s climate. By 1970, it was already clear that humans were altering the chemistry of Earth’s atmosphere. And the late 1970s nearly saw the end of American planetary science. This would help bring the space agency back to Earth.
The Venusian Atmosphere

Two years after the first Television-Infrared Observations Satellite (TIROS) weather satellite went into Earth orbit, NASA’s JPL had succeeded in sending a spacecraft to visit Earth’s twin planet, Venus. Of the nine major planets in the solar system, Venus was known to be the closest in mass to the Earth, and it had long been suspected of having conditions on its surface similar to those of Earth’s Carboniferous period (345–280 million years before present). Very high temperatures and sea levels, and a nearly planetary-scale tropical climate, marked the Carboniferous. Life was so abundant and rich that most of the world’s major coal beds were laid down during this period. Venus was expected by many to be a somewhat warmer version of this period, although there were a handful of indications that this wasn’t true. As late as 1955, reputable scientists could still publish arguments that Venus was covered by a worldwide ocean. This idea did not survive the very first mission to Venus, however. Venus turned out to be extraordinarily hot. By the end of the decade, it was believed instead to have been the victim of a runaway greenhouse effect that had left its surface the temperature of molten lead—even though the planet surface received less energy from the Sun than did Earth.

In a series of meetings held at California Institute of Technology in late 1960 and early 1961, the Space Science Board (SSB) of the National Academy of Sciences had discussed the state of knowledge of the atmospheres of Venus and Mars. Will Kellogg of RAND Corporation served as chairman, and a familiar group of astronomers, atmospheric scientists, and remote sensing specialists had gathered, Lewis Kaplan, Yale Mintz, and Carl Sagan among them. With the space age just beginning and the possibility of gaining a closer perspective on, and thus better measurements of, these planets, the collected scientists hoped to provide a scientific strategy for answering some of the outstanding questions about them. A key question about Venus regarded its surface temperature. In June 1956, scientist Cornell Mayer at the Naval Research Laboratory (NRL) had announced radiotelescope measurements of Venus that showed the planet radiating strongly in the microwave region. They argued that this implied Venus’s surface temperature averaged 600 degrees K, a clear refutation of the Earthlike Venus consensus.

In 1960, while still a student, Carl Sagan had made one of the first attempts at explaining how Venus could maintain a surface temperature of more than 600 degrees K. Using the known radiative characteristics of various gases, he constructed a model atmosphere for Venus composed primarily of carbon dioxide, including small amounts of water vapor to explain the Venusian atmosphere’s ap-
parent absorptivity in the far infrared. To achieve the high temperatures, Sagan calculated that Venus’s atmosphere needed to have a carbon dioxide abundance equivalent to 3 to 4 times the mass of Earth’s entire atmosphere; assuming that the ratio between nitrogen (the dominant gas in Earth’s atmosphere) and carbon dioxide remained the same, Venus’s atmosphere would be about 300 times as dense as the Earth’s. This was a radically different concept of Venus, and left it, in Sagan’s words “a hot, dry, sandy, windy, cloudy, and probably lifeless planet.”

Sagan’s model, however, had not been widely accepted within the scientific community. It was criticized, for example, because under the gas pressures represented within the mainstream scientific literature, carbon dioxide did not display sufficient infrared opacity. Sagan, however, had used values drawn from boiler and steam engineering literature representing much higher pressures, where carbon dioxide displayed strong “pressure broadening” of its infrared absorption lines. He argued that carbon dioxide could reach 99 percent infrared opacity under these conditions, sufficient to produce extreme surface temperatures.

Another model of the Venus atmosphere was presented at this meeting, the aeolosphere. In this model, the Sun’s energy was deposited high in the atmosphere, and intense winds carried heat to the surface. The strong winds kept the surface permanently shrouded in dust. This dust also served as a strong infrared absorber, keeping the surface perpetually hot. In this model, virtually no light at all would reach the planet’s surface, rendering it extraordinarily hot and dark.

Spacecraft measurements might be able to distinguish between these measurements by examining the microwave emissions of the planet, and JPL’s Mariner R spacecraft, which was scheduled for launch in 1962, would carry a microwave spectrometer to test these hypotheses.

It was also possible that the surface was not as hot as NRL’s observers had thought, although Kellogg and Sagan considered this lingering hope “for low temperatures and a habitable surface . . . rather dim.” It was possible that the microwave radiation that Mayer had detected was not from the planet’s surface but from a highly energetic ionosphere. This hot atmosphere/cold surface model might permit the surface to remain at a more reasonable temperature.

The notion of a habitable Venus was dispelled by the earliest spacecraft-based measurements. In 1962, the United States achieved its first successful planetary mission with the Mariner 2 mission to Venus. This was a flyby mission, with the vehicle passing about 35,400 kilometers from Venus during mid-December. Mariner 2 carried both infrared and microwave radiometers for examining the planet. The microwave radiometer, whose experiment team included Alan Barrett from MIT, provided the telling surface measurement. The instrument had been de-
signed to enable selection between the hot surface/cold atmosphere model and the cold surface/hot atmosphere model by scanning across the planet disk. If the microwave radiation intensity increased toward the limb of Venus, the thin crescent of atmosphere between the planet surface and space, this would indicate that the atmosphere was the source of the radiation, not the surface. Similarly, if the limb darkened, or showed less microwave intensity than the surface, then the source would be a hot surface. The Mariner data clearly indicated that the second case was true. Venus had a very hot surface.

This left open the important question of why it did, and a number of theoretically inclined researchers tackled this question during the decade. In 1969, for example, Andrew P. Ingersoll of the California Institute of Technology proposed that a water vapor–induced runaway greenhouse effect had occurred on Venus. On Earth, atmospheric water vapor remained in equilibrium with surfaces of liquid water because, given the current composition of the atmosphere, incident solar flux was insufficient to cause continually increasing evaporation. Instead, the colder upper atmosphere forced water that evaporated from the surface to precipitate back out, maintaining a stable, if delicate, balance. On Venus, where incident top-of-the-atmosphere solar flux was considerably higher than on Earth,
this had not happened. In his calculations, water vapor outgassing from the young planet had never condensed as it largely had on Earth, producing a greenhouse effect that continually increased in intensity.\textsuperscript{13} James Pollack, Carl Sagan’s first graduate student and head of Ames Research Center’s atmospheric modeling group, made similar calculations the same year.

Researchers at the Goddard Institute for Space Studies (GISS) in New York added carbon dioxide to the evolution of the Venusian greenhouse the following year. They started from an assumption that the amount of carbon dioxide in the Venusian atmosphere was approximately the same amount held in the Earth’s crust in the form of carbonate minerals. The formation of these minerals, however, is temperature dependent and also requires the presence of water. In the absence of liquid water, which their model of Venus’s climate evolution indicated had never been possible, nearly all of the carbon dioxide outgassed by the young planet would remain in the atmosphere instead of being deposited in rock. This would maintain the greenhouse effect as water vapor disintegrated in the upper atmosphere under solar bombardment and the hydrogen escaped into space. Over billions of years, hydrogen escape would gradually remove all of the water vapor from the atmosphere, leaving the dense carbon dioxide atmosphere behind.\textsuperscript{14}

There were also alternative theses to the greenhouse model. One of these was Richard Goody’s deep convective model. Goody had argued the majority of Venus’s atmospheric energy was deposited in the high cloud layer on the sunward side of the planet and was carried to the planet’s night side by large-scale zonal currents. There, of course, radiatively cooling air masses would descend, bring energy into the lower atmosphere, and eventually return to the day side. Many scientists believed that even the very thick carbon dioxide atmosphere of Venus could not have sufficient infrared opacity to generate Venus’s high surface temperature through the classical greenhouse effect alone; very little solar energy was thought to reach the surface through the cloud layers, and hence this small amount would have to be entirely retained by the atmosphere to maintain the high surface temperature. That did not seem possible, and Goody’s dynamical model was designed to overcome the limitations of Sagan’s simple radiative model.\textsuperscript{15}

These theoretical studies were also stimulated by the increasing tempo of spacecraft operations at Venus. In 1967, the American probe Mariner 5 had made a flyby of Venus. This spacecraft was not equipped for extensive atmospheric investigation, although it did confirm the very high surface temperature via radio occultation. More detailed investigation of the predicted extreme surface condi-
tions was carried out by the Soviet Union with a series of atmospheric entry probes and landers beginning the same year. The first of these was Venera 4, which successfully entered the Venusian atmosphere on 18 October, the same day as the Mariner 5 flyby. It released thermometers, gas analyzers, a barometer, and an atmospheric density probe. These showed that the atmosphere was more than 90 percent carbon dioxide. The temperature and pressure reached 535 degrees K and 18 atmospheres before the probe failed. Initially, the Soviet mission scientists had thought the probe had reached the surface; Sagan and Pollack later demonstrated that it had not, instead failing while still descending on its parachute. Yet it was judged a highly successful mission, and a nearly continuous series of Venera spacecraft followed: two more atmosphere entry probes in 1969, the first successful Venus lander in 1970, a second lander in 1972, and still more in 1975, 1978, 1981, and 1984. The last pair carried two French constant-level balloons as well, designed to float in the cloud system.

The composition of the Venus clouds was finally figured out in 1972, based not on spacecraft data but on ground-based observations. The key measurement was of the index of refraction of the clouds’ primary constituent. This was hardly a new quantity. Every optically transparent substance has an index of refraction, but as astronomer Ronald Schorn reports in his history of planetary astronomy, no one had thought to check the clouds’ index against those of known substances. Two persons finally suggested the answer nearly simultaneously late in 1972: Godfrey T. Sill and Louise G. D. Young. They proposed droplets of sulfuric acid as the most likely culprits. Sulfate aerosols were common products of volcanic eruptions on Earth, providing an obvious mechanism by which they might have been injected into the Venusian atmosphere. In 1974, James Pollack at the Ames Research Center obtained measurements of the near-infrared spectra of the clouds using a Learjet aircraft equipped with an infrared telescope. Comparison of these reflected spectra to laboratory spectra of strong solutions of sulfuric acid provided confirmation. The Venus cloud sheet was sulfuric acid.

The Soviet 1972 lander provided important new data on both the atmosphere and surface. A photometer aboard Venera 8 demonstrated that sunlight equivalent to an overcast day on Earth reached the Venusian surface through the thick cloud mantle, making photography feasible. The amount of light was only 2 to 3 percent of the total received at the top of the atmosphere, but this suggested that the greenhouse model of the atmosphere was roughly valid. Further, the wind measurements made during the lander descent showed very high-velocity winds in the upper atmosphere that flowed from the sunlit side to the dark side. Onboard measurements demonstrated that the cloud layers—there appeared to be three
layers in the Soviet data—extended far deeper into the atmosphere than previously believed. And, finally, the probe found that the atmosphere was essentially adiabatic from the surface to 50 kilometers.

Pollack’s group at Ames used the availability of a new supercomputer at Ames, the ILLIAC IV, to construct a numerical model of Venus’s general circulation during 1974 and 1975. This was based on Yale Mintz’s general circulation model of the Earth’s atmosphere modified with a new radiative transfer scheme based on one developed by Andrew Lacis and James Hansen at GISS. There were several striking results from their calculation. The first was that the cloud layer absorbed a substantial part of the incoming solar radiation, leading to substantial heating of the surrounding atmosphere on the sunward side of the planet (as predicted by Goody and others). Much more solar energy was deposited in their model cloud layers than at the surface, in opposition to the way energy is deposited on Earth. High-altitude zonal winds carried energy to the night side of the planet, as expected.

Another surprising finding was that the sulfate aerosol clouds were also strong absorbers in the thermal infrared spectrum, and therefore enhanced the overall planetary greenhouse effect. This appeared to resolve some problems with the greenhouse model caused by insufficient infrared opacity several critics had pointed out. Further, the cloud absorption in both the visible and infrared rendered the thick cloud layers essentially adiabatic and isothermal. And a shear zone, a region in which horizontal wind speeds changed dramatically, appeared at the base of the lowest model cloud layer. Both the adiabatic cloud region and the shear zone were consistent with the measurements made by the Venera probes.20

In 1975, NASA gained new start approval for a dual-spacecraft mission named Pioneer Venus. Based at Ames Research Center, this mission had two goals: radar mapping of the surface of Venus, and examination of the chemical and thermal characteristics of the atmosphere by a set of entry probes. The concept for the mission came from Richard Goody, who had recruited to his cause Donald Hunten, Nelson Spencer from the Goddard Space Flight Center, and Vern Suomi; in 1969, the four had prepared a mission plan titled A Venus Multiple Entry-Probe Direct-Impact Mission. It had not been well-received by NASA, as the four were quite critical of the way the Venus program was currently being carried out by the agency. Goody had appended a note to the report that argued that the agency’s Venus missions were not being designed to investigate specific scientific questions, a comment virtually guaranteed to alienate NASA management (and that of JPL, which was responsible for the Mariner missions). Goody wanted measure-
ments from within the Venusian atmosphere to compare to his circulation model, and NASA did not seem interested in providing them.21

But the leaders of both the Goddard Space Flight Center and Ames Research Center, who would compete to carry it out, found it in their interests to pursue the project. Their advocacy kept the concept alive, aided by an Ames demonstration in 1971 that a high-speed entry was possible with existing technologies. The Soviet Venera plans then motivated NASA leadership to take the proposal seriously, forming a Pioneer Venus Science Steering Group in January 1972. NASA sought new start approval from Congress for fiscal year 1974 in anticipation of a 1977 set of launches; the delay of approval to fiscal year 1975 set the effort back to a 1978 launch.22

The two Pioneer Venus spacecraft were known as the Orbiter and the Bus. The Orbiter’s job was radar mapping of the planet’s surface, although it also carried instruments designed to investigate the upper atmosphere, above the cloud layers. The key instruments needed to investigate the lower atmosphere and the Venusian greenhouse effect were housed by the Bus. It carried three small probes and a large probe, each of which had instruments to measure solar and infrared flux in the local atmosphere, temperature, pressure, and the optical properties of particulates. The large probe also carried a gas chromatograph, to measure the abundance of various atmospheric gases, and a neutral mass spectrometer. Finally, the Bus itself was designed to enter the atmosphere carrying a second neutral mass spectrometer. Only the large probe had a parachute to slow its descent. The small probes and the Bus free-fell during entry. The small probes had heat shields to permit them to descend all the way to the surface, while the Bus was expected to burn up at an altitude of 80 kilometers or so, above the cloud layers.

All five entry spacecraft entered the atmosphere on 9 December 1978. The large probe and all three small probes descended through the atmosphere, impacting the surface eventually at about 32 kilometers per hour. The instrumentation also functioned relatively well, although the important heat flux instruments failed (oddly simultaneously) at 12 kilometers altitude. They also displayed behavior that made their data unreliable, so the data could not be used to detail the energy fluxes within the atmosphere. However, the temperature, pressure, and wind profiles of the atmosphere made by the probes corroborated those made by the preceding Soviet landers, clearly showing very similar adiabatic conditions, shear zones, and cloud structure. The data was also generally in keeping with Pollack’s model of the atmosphere. One major difference between the modeled atmosphere and the measured one, however, appeared in the convective stability of the lower atmosphere. Pollack’s model had shown a relatively rapid overturning
of the lower atmosphere, as had some others. The data from the probes showed the lower atmosphere to be convectively stable, with very low wind velocities. The extremely dense lower atmosphere transported heat so efficiently that it maintained uniform surface temperatures even without high velocities; in the absence of sharp surface temperature gradients, there was no mechanism to drive strong convection.  

By the end of the first two decades of space exploration, Venus had been transformed from a potentially habitable planet into an extraordinarily uninhabitable one. Most, and perhaps all, of its carbon dioxide had wound up in its atmosphere, unlike Earth’s, where the majority had been sequestered away in sedimentary rock. The perpetual yellow haze that had been visible to Earth-bound astronomers had turned out to be a sulfuric acid cloud sheet that simultaneously reflected away most of the incoming solar energy and enhanced the infrared greenhouse effect that kept the planet so hot. Finally, the atmosphere’s circulation appeared radically different, with enough energy being deposited within the cloud sheet to produce high-velocity zonal circulation that carried heat to the planet’s perpetual dark side, while the deep atmosphere was relatively quiet. Venus had evolved along a far different route than had Earth, despite its similar size and overall composition.

**THE MARTIAN ATMOSPHERE**

Mars, even more than Venus, had been seen as a potential abode of life prior to the space age. In 1877, Italian astronomer Giovanni Virginio Schiaparelli had reported the existence of canali on Mars, leading to a series of speculations about liquid water on Mars and the existence of an old, and perhaps superior civilization, on the planet. This line of thought had reached its peak with the work of American astronomer Percival Lowell. Working largely during the 1890s, Lowell contended in both the scientific and the popular press that an “annual wave of darkening” on Mars represented the seasonal growth patterns of irrigated agriculture—and thus evidence of an inhabited, and civilized, planet. While most of the scientific community had not accepted that the canali were evidence of life, they were seen as evidence of liquid water and therefore also of Earthlike conditions. Things turned out to be a bit more complicated than that.

In 1963, Hyron Spinrad, a recent PhD graduate of the University of California, Berkeley, completed a seminal study of the atmospheric radiation of Mars using the 100-inch reflecting telescope at Mount Wilson that undermined the case for liquid water on Mars. On the night of 12–13 April, Spinrad obtained a near-infra-
red spectrum of Mars that showed that there was, in fact, water in the Martian atmosphere, but the amount was tiny. Initially, he estimated the amount as having been 5 to 10 microns of precipitable water, to put it in conventional Earthly meteorological terms. This was a controversial finding, as the spectra appeared at the limit of detectability. They were also too faint to reproduce, so his plates could not be seen by others without traveling to California. Since other astronomers could not examine his evidence, it was easy for them to disbelieve his result.

Spinrad’s plate also displayed absorption lines for carbon dioxide. This was entirely unexpected. The carbon dioxide absorption bands are relatively weak, and Spinrad’s ability to detect them at all meant that there was a great deal of the gas in the Martian atmosphere—more than in Earth’s, in fact. Finally, it occurred to Spinrad to wonder whether carbon dioxide was the primary gas in the Martian atmosphere, as it was in Venus’s (but not, of course, Earth’s). If that turned out to be the case, then his measurement suggested a surface pressure of only 35 millibars, well below the figure generally accepted at the time. By comparison, the average sea level pressure on Earth is 1013 millibars; the lowest pressures at sea level occur in the middle of hurricanes and typhoons, but had never been seen below 870 millibars.

His findings were extremely important to NASA, whose engineers needed to know Martian atmospheric pressure and density accurately for the design of atmospheric entry and landing systems, so the head of NASA’s astronomy program called a meeting in Washington to try to come up with a consensus answer. Instead, estimates ranged from 8 to 100 millibars—although the 8 millibars estimate was a half-joke made by Lewis Kaplan, based on the remote possibility that the Martian atmosphere was entirely carbon dioxide.

The issue of Martian atmospheric pressure was largely settled in 1965, by the first spacecraft to reach Mars successfully. This was JPL’s Mariner 4, which flew by the planet on 15 July 1965 at a distance of about 9600 kilometers. Mariner 4 carried a camera but no atmospheric sensors; nonetheless, it provided important information about the Martian atmosphere. The photographs sent back showed an unexpectedly crater-pocked, desert-like Mars, effectively discrediting the vision of a planet inhabited by advanced sentient life and finally debunking the Martian canali. Mars lacked even the flora expected to be the cause of the “wave of darkening.” This Moonlike surface proved that Mars had a very thin atmosphere. A thick atmosphere would have burned up incoming meteorites. And the craters’ existence also showed that Mars no longer had a significant hydrologic cycle. On Earth, craters are buried by erosional processes led by liquid water; on Mars, they clearly lasted for billions of years.
But Mariner’s science team also used the vehicle’s radio to obtain a better measurement of atmospheric pressure. Shortly before launch, a JPL engineer proposed using the radio transmissions for an occultation experiment. As the spacecraft passed behind Mars from Earth’s perspective, its radio signal would be altered by the Martian atmosphere in ways that were detectable from Earth and that would provide information on the atmosphere’s temperature and pressure. His proposal caused some anguish for JPL and Mariner management, as it meant not transmitting imagery, the mission’s primary objective, during the experiment. But they agreed to it, and the resulting findings clarified the status of the Martian atmosphere considerably. The atmospheric density was about 1 percent of Earth’s,
with a surface temperature of about 180 degrees K and a pressure between 4 and 7 millibars.\textsuperscript{27} This was, roughly, the same as the estimate Lewis Kaplan had half-jokingly made several years earlier—and stunningly low.

Two more Mariner flyby missions visited Mars in 1969. Mariners 6 and 7, equipped with identical cameras but no atmospheric instruments, flew past the planet in July and August of that year, returning additional photographs of a dead, and heavily cratered, surface. At the same time, several different astronomy groups confirmed the 1963 detection of water vapor in the Martian atmosphere, again using infrared spectroscopy. They also were able to demonstrate that the water vapor content varied with latitude and season. This helped lead a JPL group under Crofton “Barney” Farmer to design a spacecraft-based instrument to provide more detailed measurements from Mars orbit; this became the Mars Atmospheric Water Detector and would fly on the 1976 Viking mission.\textsuperscript{28}

The Mars exploration effort achieved its first orbiting spacecraft in 1971, with Mariner 9 (its twin, Mariner 8, made its home on the bottom of the Atlantic Ocean). As Mariner 9 approached the planet, ground-based astronomers detected a brilliant cloud that rapidly spread to cover the Noachis region. In two weeks, it covered the entire visible disk of the planet. The spacecraft went into orbit 13 November, and the images it returned showed a completely featureless Mars. The dust storm had covered the entire planet. Mariner 9 had been intended to map the planet photographically in preparation for a 1976 landing attempt by the Viking project; the vast dust storm seemed to make that impossible. The only visible features were Nix Olympica and three other peaks that protruded above the storm. This revealed to the camera team that they were the largest volcanoes in the solar system by far, dwarfing anything on Earth, but it did not help them accomplish their primary mission.\textsuperscript{29}

Mariner 9 also carried a copy of Rudy Hanel’s Infrared Interferometer Spectrometer (IRIS) instrument, developed originally for the Nimbus meteorological satellite series. Initially intended to produce atmospheric temperature profiles, it could also generate other useful information. Hanel’s team used the data to determine the abundance and distribution of water vapor in the Martian atmosphere, finding 10 to 20 precipitable microns over most of the planet. They also found a seasonal change, in which water vapor disappeared from the south polar region and reappeared in the north polar region. And they prepared detailed analyses of the spectral characteristics of Martian carbon dioxide, which differed from Earthly characteristics slightly due to the very low pressure. IRIS could also provide surface temperature measurements through the extremely dry Martian atmosphere. Hanel’s group at Goddard used the surface temperatures to help
them construct a pressure map for Mars; they also were able to construct topographic maps for several regions of Mars by using surface pressure measurements to estimate altitudes.30

The IRIS data also sparked a great deal of interest in the radiative properties of the suspended dust in the Martian atmosphere, particularly within Pollack’s group at the Ames Research Center. The temperature profiles produced by the instrument showed that the dust had the effect of absorbing sunlight and heating the atmospheric layer around it, while simultaneously, the lack of energy reaching the Mars surface caused it to cool rapidly. The atmosphere adjacent to the surface therefore cooled as well. This had led to a temperature profile that was essentially flat between the dust layer and the surface—put in meteorological terms, the lapse rate was nearly zero. The very high daily surface temperature range (a product of the very dry, thin atmosphere) also narrowed, from about 75 degrees C to 35 degrees C. Finally, because the heat distribution in the atmosphere changed, the circulation also changed. A lofting effect attributed to solar heating of the dust-laden atmosphere resulted in the dust being transported as high as 50 kilometers.31 On Earth, this altitude represented the boundary between the top of the stratosphere and the thermosphere, where even extreme volcanic events had never been known to deposit particulate matter. These data showed a Martian atmosphere whose behavior was extraordinarily strange, and very unlike Earth’s. It also eventually led to the famous nuclear winter hypothesis.32

Mariner 9 is perhaps best known for its revelations about the Martian surface, however, not the atmosphere. After the planetary dust storm finally ended in late December, the imaging team began to produce the photographic map of the planet that was their primary goal. In the process, they found that the images from the previous flyby missions had been highly misleading. While Mars certainly had Moonlike cratering, it also had vast volcanoes, and still more interestingly, vast chasms and canyons.33 To the geologists on the imaging science team, many of these looked like the natural drainage structures on Earth—extensive dendritic patterns, outwash plains, and deltas. There was no visible water to have made them, but the signs of past water were unmistakable, unless reasoning by Earth-analogy, which was all that was available to the geologists, was itself misleading.

The science team ruled out other substances relatively quickly. A surface pressure 5 times Earth’s would have been necessary to allow liquid carbon dioxide to carve such channels, and Mars did not have it. While wind also causes erosion, Earth winds did not cut winding, tributary-laden channels the way water did. Imagery of the Tharsis region clearly showed braided channeling, a common feature of outwash plains on Earth. Further, many of the river channels appeared
to come from regions of chaotic terrain that seemed similar to glacial regions on Earth, where subsurface heating had led to the collapse of permafrost-laden terrain. Hence the imaging teams concluded that Mars had once had extensive surface water that had since gone missing. The fascinating scientific questions then became, what happened to it? And, how could Mars, with its thin wisp of an atmosphere, have once had a climate capable of supporting liquid water on the surface?
Mariner 9 ran out of maneuvering fuel and was shut down 27 October 1972, having radically altered the scientific community's beliefs about Mars. The science teams turned to evaluating the reams of data it had sent them. One important line of research that emerged was the effort to conceive of a Martian climate that could have hosted an oceanic surface. One of the first papers to appear on this came from Carl Sagan. In a 1972 paper, Sagan had argued that Mars had two stable climates, one warm, with a surface pressure approaching Earth's, and its current cold age. Then in early 1973, he and two of his students, Brian Toon and P. J. Gierasch, published a paper in *Science* that reported on a study they had done of the effects of orbital obliquity, solar luminosity, and polar cap albedo on Martian climate.\(^\text{35}\)

Using a general circulation model of the Martian atmosphere that had been adapted from Yale Mintz's Earthly general circulation model, for the 1973 paper they examined poleward heat transport in the present atmosphere as a means of estimating the overall stability of the present climate. Then, assuming varying amounts of carbon dioxide in the polar caps, at the time thought to be primarily carbon dioxide with a lesser amount of water ice, they had evaluated the effect of larger amounts of atmospheric carbon dioxide on Martian surface temperatures. An all-carbon dioxide atmosphere of 40 millibar surface pressure seemed enough to permit water at the equator; if much larger amounts of carbon dioxide had been available in the remote past, as the giant Martian volcanoes suggested was possible, a water-enhanced greenhouse effect of 30 degrees K could have permitted average equatorial temperatures to exceed water's freezing point.

They then turned to an examination of what could have caused the transfer of sufficient carbon dioxide from the polar caps to the atmosphere and back, starting with orbital variations. Their circulation model indicated that a 15 percent increase in energy absorbed at one pole was necessary to create the necessary conditions. They turned to orbital mechanics for their answer. A Czech scientist, Mitrofan Milankovitch, had argued in a series of papers prior to World War II that Earth's ice ages had been driven by very slow, small changes in the Earth's orbit. His work had not received wide acceptance prior to the 1970s, however. This is partly because the four large glaciations believed to have happened during the past 20 million years were not enough—Milankovitch's analysis suggested that there should have been many more.\(^\text{36}\) But Sagan and his colleagues, who were astronomers, not Earth scientists, chose to apply Milankovitch's reasoning to Mars.

The two major components of orbital climate forcing are distance from the Sun and obliquity (the wobble of the spin axis). Planetary orbits are not perfectly
circular; instead, they are elliptical and vary slowly. Sagan’s analysis of the Martian orbit found it too stable and circular for distance from the Sun to have changed enough to produce the necessary alterations in insolation. The observed obliquity, however, was quite sufficient to raise polar temperatures and produce the necessary outgassing of whatever carbon dioxide was present.\(^{37}\) This would occur on a cycle of about a hundred thousand years. Hence Sagan’s team concluded that “the atmospheric pressure on Mars has been both much larger and much smaller than present values during a considerable portion of Martian history.”\(^{38}\) Current models of solar luminosity changes suggested that the Sun was at its long-term minimum intensity; if correct, its gradual increase over the next several million years could also produce a warmer Mars. Finally, decreasing the albedos of the poles (making them darker and more absorptive) also appeared capable of producing such changes. In fact, their model was most sensitive to albedo change. Only a 4 percent reduction in polar albedo was necessary to produce the same effect as a 15 percent increase of insolation. There were, then, at least three ways to construct a warmer, wetter, and possibly living Mars that were physically realistic.

The three were arguing that only relatively small changes were necessary to bring about a radical shift in Martian climate. This was a direct attack on a long-held belief that the planets, once their catastrophic period of formation was over, were basically stable. Mars not only had changed since its formation, it would change again. Humans had the misfortune to have evolved when Mars (and Earth) were in cold modes (at least Sagan thought it a misfortune, as he would not get to witness a habitable Mars), but a warmer Mars would occur, eventually. Stability of planetary climates could no longer be assumed.

The final Mars mission of the decade was Viking, which consisted of two orbiter/lander pairs. The orbiters were modified Mariners, designed and built by JPL, while the landers were the responsibility of Langley Research Center, which also managed the overall program. The first landing had been scheduled for 4 July 1976, but was postponed when the chosen landing site proved unsuitable; the actual first landing was on 20 July, at a site on the Chryse plain. The landers drew the most attention by far, as they returned the first surface images of Mars and because they were equipped primarily to look for life in the Martian soil. This they did not find. Instead, they found no evidence of organic compounds in the soil. Very high levels of ultraviolet radiation reached the surface of Mars, and this appeared to have destroyed whatever organic matter had once existed. The Martian environment appeared to be self-sterilizing.\(^{39}\)

The orbiter data, however, painted a somewhat more positive picture of Mars,
at least for those willing to satisfy themselves with a Mars that might once have harbored a warmer, wetter past. Barney Farmer, a British infrared spectroscopist who had been hired to establish a spectroscopy lab at JPL in 1966, had designed an infrared-based instrument for the Viking orbiters called the Mars Atmospheric Water Detector. Over the four-year life of the first orbiter, this provided a detailed examination of the variations of water in the atmosphere. A clear pattern emerged from this data. The Martian atmosphere was nearly saturated over the summer-time pole but dried almost completely during the winter season. Yet the relationship between the polar cap and water vapor content was not absolute—water vapor appeared to be generated outside the polar regions as well. Writing in the *Journal of Geophysical Research*, Farmer and his colleague Peter Doms argued that the data suggested water ice was bound within the surface material of Mars through all latitudes poleward of 40 degrees. If true, Mars had vastly more water than had been supposed on the basis of the extent of the polar caps, and certainly more than the tiny amount in the atmosphere. But if the regolith planet-wide held water ice, then Martian oceans during the planet’s warm periods became conceivable, and it would certainly explain where the water that had formed the surface features went. It was still there, frozen into the subsurface. To optimists like Sagan, oceans’ worth of water meant a Mars that might well have had life in the past, and could have it again when the planet returned to its warmer self.

In the time span of a decade, then, Mars in the human imagination went from a living world to a Moonlike dead one, and thence finally to one that might once have had (and might again) have life. The possibility of life was critically dependent on the Martian climate, which had turned out to be currently inhospitable to life as 1970s scientists understood it to be, but good observational evidence suggested had not always been so. This effort to understand Mars drew scientists to make broad analogies to the planet they thought they understood better, Earth, and to construct rather speculative arguments on very limited data. Farmer’s argument regarding the ice content of the Martian regolith, while physically plausible, was based on a chain of inferences, not direct measurement; he would not be shown to be correct until 2002, long after he had retired. Similarly, Sagan’s model of Martian climate change was based on a good deal of calculation and extrapolation, and on very little data. Actual measurements that suggested that his vision of cyclic changes in the Martian climate might be correct did not appear until 2004, when new surface data from a pair of geological robot landers clearly showed layered sedimentary deposits. The timescale, however, remained unmeasured, and the consensus as of 2005, several years after Sagan’s death, was that Mars’s warm period had been confined to its first billion years.41
Sagan’s willingness to engage in what were to many scientists improvable speculations made him highly controversial. But space science itself was increasingly controversial during the decade because of how it was being conducted. The effort to understand the Martian surface, and the related climate that could explain it, caused the Mariner and Viking science teams to engage in interdisciplinary research. Farmer, for example, was by training a spectroscopist originally interested in trying to measure the Sun’s infrared spectrum. Water in the Earth’s atmosphere made that difficult, and he had had to develop expertise in the infrared signature of water vapor to accomplish his measurements. This, of course, had made him an obvious person to make measurements of Martian water vapor. But he had gone far beyond that, establishing an argument regarding the distribution of water ice in the Martian subsurface.

This was problematic, because the scientific disciplines provide the social infrastructure for the sciences: physicists determined what methodologies were acceptable in physics, established standards of evidence for physics, edited the physics journals, and operated the all-important peer review system for physics, as did geologists for geology, astronomers for astronomy, and meteorologists for meteorology. While the boundaries were permeable to a degree, with physicists colonizing all of these other fields during the period, this was a one-way exchange—meteorologists did not switch to physics. Understanding the complexity of the terrestrial planets’ atmospheres seemed to require collaborative research between members of very different disciplines. The mechanisms of science, particularly peer review, did not handle this well. The controversy remained subdued and relatively minor as long as the planetary scientists only studied other planets—no one else much cared what planetary scientists had to say about cold, dead Mars. But this changed when they began to turn their insights, and instruments, on the Earth.

RECKONING WITH THE EARTH

In 1972, Sagan and George Mullen had published a short paper in *Science* that encompassed the climate histories of both Earth and Mars. Their motivation was a thorny problem deriving from stellar astronomy and fusion physics. Specialists in both these fields believed the Sun had been substantially dimmer when it had first formed four and a half billion years ago. Known as the Faint Early Sun hypothesis, this meant that Earth should have been a frozen ball of ice for most of its history. But the geological evidence available in the 1970s was that it had never been one. This required explanation. By the end of the decade, the expla-
nation had become highly controversial. The brilliant independent scientist James E. Lovelock extended Sagan’s reasoning about the Earth’s physical climate into an argument that life itself was responsible for the Earth’s comfortable climate.

Sagan and Mullen began their analysis of the Earth’s past climate with a discussion of the greenhouse effect that maintains Earth’s current average surface temperature about $30$ degrees K higher than it would be in the absence of an atmosphere. They then turned to the Faint Early Sun hypothesis, reviewing the various estimates of the Sun’s evolution, which ranged from luminosity changes of $30$ to $60$ percent. They chose $30$ percent to be conservative, and then ran the Sun backward to evaluate the effect on surface temperatures. Average temperatures in their simple radiative model dropped below the freezing point of seawater $2.3$ billion years ago. The geologic evidence available in the 1970s was relatively clear, however, that the Earth was largely ice-free as far back as $3.2$ billion years, and life clearly existed in the form of algal mats called stromatolites at $2.8$ billion years. (In this paper, Sagan accepted some rather controversial microfossils as extending life back to $3.2$ billion years as well.) There was thus a substantial conflict between what should have happened and what had actually happened, and their purpose was to explain it.

They believed that only a much stronger greenhouse effect than the current Earth’s atmosphere provides was necessary to keep the Earth from freezing under the faint early Sun. The two therefore sought an atmospheric composition that was more in keeping with the Earth’s climate history. They needed a gas that was a strong absorber in the mid-infrared, as the carbon dioxide bands were relatively saturated—they accepted as true Syukuro Manabe’s calculation that doubling the carbon dioxide content of the Earth’s atmosphere, in the absence of any other feedback processes, would result in a $2$ degrees C increase in average surface temperature. This was not enough to counter a $30$ percent dimmer Sun.

The molecule they found most suitable was ammonia. In the presence of oxygen, this gas is highly reactive and would not last the necessary billion or so years, but the early Earth’s atmosphere had no oxygen. There was some evidence from oceanic clay minerals that ammonia had been a minor constituent of the Earth’s atmosphere in its youth; there was also evidence from a very famous experiment by chemists Stanley Miller and Harold Urey that showed an ammonia-bearing atmosphere was necessary for the formation of amino acids, the basic constituents of living organisms. They thus postulated that Earth’s early atmosphere was a mixture of carbon dioxide, water vapor, and ammonia, with additional minor greenhouse contributions from methane and hydrogen sulfide. Their model re-
quired that small amounts of ammonia remained in the atmosphere up to the Precambrian-Cambrian boundary (570 million years before present), but this they found plausible even with the evolution of small amounts of atmospheric oxygen somewhere between 1 and 2 billion years ago. The origin of photosynthetic life in the early Cambrian, and subsequent production of the modern oxygenated atmosphere, would then have resulted in the removal of the ammonia. They concluded that “the evolution of green plants could have significantly cooled off Earth.”

British chemist James E. Lovelock, one of the handful of scientists in the late twentieth century able to make a living as an independent consultant, then expanded on this argument to contend that life itself was responsible for Earth’s comfortable climate. Lovelock had started serving as a consultant at JPL in the early 1960s, working with a group of scientists on the question of life detection on other planets, specifically Mars. In his popular book *Gaia: A New Look at Life on Earth*, he recounts that he wound up at odds with his research group fairly quickly. They wanted to look for signs of life in the soil (on Earth, of course, soil teems with living things), but Lovelock disagreed with that approach. He thought that the most obvious place to look for telltale signs of life was in the atmosphere. His key insight was that a planet with abundant life would have an atmosphere in a state of extreme chemical disequilibrium. In other words, it would contain chemicals that would long ago have been stripped out by reactions with the solid surface or have been destroyed in reactions with other gases. This led him to reinterpret the history of Earth’s atmosphere, and the climate that it regulates.

Lovelock began from an idea that the most general function of living organisms was to reduce entropy. Entropy, a thermodynamic quantity that had to continually increase generally, but could be reduced locally with the consumption of energy, cannot be directly measured. And in any case, living processes were not the only natural processes known to reduce entropy. Hence this was not a useful formulation of the problem. Instead, he started to look at living processes as factories, which reduce the entropy of the materials going into them while increasing the entropy of their surroundings via their waste products. Waste products were the key. Just as factories deposit some of their waste in the atmosphere, so did living things. Lovelock, early on working with Dian Hitchcock and later Lynn Margulis, started looking at the gaseous waste products produced by life: oxygen, carbon dioxide, nitrogen, ammonia, and methane.

When Lovelock was writing, the Earth’s atmosphere consisted of 21 percent oxygen, by volume, 78 percent nitrogen, with the remaining 1 percent made up of various trace gases. Carbon dioxide, for example, was 0.03 percent of the atmo-
sphere’s volume. Yet in terms of chemical equilibrium, this was highly improbable. Over the Earth’s billions of years of existence, oxygen, a highly reactive gas, would have been extracted by chemical weathering of surface material and be, as it was on Venus and Mars, undetectable. Similarly, the most chemically stable form of nitrogen was in the form of nitrate ions in the oceans, not as a noble gas in the atmosphere. Hence in a chemically stable version of the Earth, the atmosphere would be mostly carbon dioxide, as were the atmospheres of Mars and Venus, and contain neither nitrogen nor oxygen.\textsuperscript{45}

Lovelock was not the first to recognize the unstable nature of the Earth’s atmosphere. Rather, he was building on a minority view in geochemistry. In the majority view, the Earth’s unlikely atmosphere was explained as a product of planetary outgassing, with the oxygen provided by the photodissociation of water vapor in the upper atmosphere. The resulting hydrogen, as it had on Venus, would then escape into space, leaving oxygen free in the atmosphere. Yet this view did not comport with evidence available by the late 1960s regarding the dissociation rate of water in the upper atmosphere, or with the rates of consumption of oxygen in the weathering processes. Nor did it square with the interplanetary view. Lacking both a magnetic field and an ozone layer, Venus experienced much larger high-energy fluxes at the top of its atmosphere than Earth did, which would lead to a higher dissociation rate and more rapid hydrogen escape and oxygen production. And, of course, whatever water Venus had once had was gone. But there was no measurable residual oxygen. Hence the majority view no longer explained the available evidence.

Lovelock credits Swedish chemist Lars Gullen Sillen as being the first to question the control mechanism for oxygen, nitrogen, and carbon dioxide.\textsuperscript{46} But Lovelock extended Sillen’s point to argue that life itself maintained the relative abundances of these gases. Photosynthetic plants consumed carbon dioxide and released oxygen, while animal life consumed oxygen and released carbon dioxide. The trace amounts of methane in the atmosphere, about a billion tons, were already well-known to be a mostly biological byproduct.\textsuperscript{47} The presence of these gases was, for Lovelock, the ultimate proof of life, and in a 1965 article for Nature, he set out his argument that the atmosphere was the place to search for Martian life.\textsuperscript{48}

But in the process of thinking about how to find life, he began to reconceive the Earth as a single, self-regulating organism. After a 1969 presentation in Boston, he began working with Lynn Margulis, then Sagan’s wife, to refine and flesh out the idea. They eventually published two important articles in 1973 and 1974 in which they described their hypothesis. They started out by telling a story about
the Earth’s climatic evolution that began with Sagan and Mullen’s model of the Earth under the faint early Sun.  

Sagan and Mullen had argued that the early Earth had needed ammonia in its atmosphere to compensate for the much dimmer early Sun. Margulis and Lovelock looked at the problem of the faint early Sun somewhat differently, however, asking how the Earth’s temperature had remained essentially constant during 3 billion years of gradual solar intensity increase. Their reading of the geologic evidence suggested that the Earth had not varied in globally averaged temperature by more than 10 degrees C in the past 3.5 billion years. During that time, solar luminosity had increased by 40 to 60 percent. Yet a virtually unchanging climate seemed highly unlikely given what was known about the solar system at the time. Following Sagan and Mullen, Manabe, and Rasool and De Bergh, they accepted that only a 10 percent change in solar luminosity was necessary to provoke either a runaway greenhouse effect and evaporation of the oceans, or alternatively bring about an iceball Earth. But that had not happened. Instead, despite the slowly warming Sun, the Earth’s temperature had remained effectively constant. This is what Lovelock and Margulis sought to explain.

They began their story with the need for an early ammonia-laden atmosphere to keep Earth largely ice-free, and then presented evidence for the very early evolution of life. The 1960s and early 1970s had seen a number of important discoveries of microfossils in some of the most ancient rocks still accessible on the Earth’s surface, extending the history of life back to about 3 billion years. More important, these discoveries had expanded the variety of early life. The discovered fossils were prokaryotes (blue-green algae), and these displayed what Margulis and Lovelock called “metabolic versatility.” They existed via a wide variety of different metabolic processes, and as a result generated a variety of different waste products. They were also widespread, and certain types formed large structures—the stromatolites Sagan had mentioned. These were distributed globally by the late Precambrian, and had been in existence for about 1.2 billion years. One of the most common metabolic cycles for prokaryotes on the present Earth results in the production of oxygen from carbon dioxide; Margulis and Lovelock argued that these vast stromatolite beds were the likely source of the oxygen that gradually became present in the Earth’s atmosphere during the Precambrian.  

The transition from an anoxic, ammonia and carbon dioxide atmosphere to the present oxygen-rich one should have destabilized the Earth’s climate by dramatically reducing the atmosphere’s greenhouse capacity, but it had not. This led them to argue for active control of climate. They used the metaphor of a planetary engineer, whose employer had assigned him a planet and directed him
to maintain a specific set of temperature and acidity specifications for several billion years. Then they reviewed the tools available to the engineer for temperature control: control of the planet’s radiation balance, its surface emissivity, the composition of its atmosphere, and the distribution of suspended particulates. As seemed to be the case with Mars, small changes in planetary albedo could effect sizeable changes in temperature. The engineer could change this by, for ex-
ample, darkening the polar regions, something Harry Wexler had studied briefly during the 1950s. Similarly, organisms could impact albedo by changing their colors, by changing the color of the sediments they trapped and fixed, and even by altering the color of snow and ice. The same was true of surface emissivity. The global distribution of stromatolites would have allowed them to alter the Earth’s overall emissivity through changes in their surface porosity and composition, for example.

Organisms also altered the chemical composition of the Earth’s atmosphere, impacting its radiative qualities. Nearly all organisms either consumed or produced carbon dioxide. Ammonia, the gas Sagan and Mullen had proposed as maintaining the Earth’s warmth under the faint early Sun, was also a “very active product of microbial metabolism.” It was a waste product of many organisms, and was also consumed by nearly all bacteria and fungi. Hence, while the amount of it in the current atmosphere was vanishingly small, this was because virtually all of the billion or so tons produced each year by biologic processes were also being consumed. To Margulis and Lovelock, microbial consumption explained the near-disappearance of ammonia from the early atmosphere; ammonia-fixing microbes would have thrived on the young Earth, and as they drew down the atmospheric reservoir of ammonia would have been increasingly pressured into environments where they would be in contact with ammonia producers. This would have had a large radiative impact on the Earth’s atmosphere, as under the faint early Sun removal of ammonia at too high a rate would have sent the Earth into an iceball mode from which it could not recover. Indeed, their reading of the Earth’s chemical history suggested a crisis for its thermal equilibrium in the late Precambrian, but the geologic record did not seem to contain evidence of one.\(^5\) They took this as evidence of active control of the climate by biologic actors, postulating that selection pressures on local populations produced a response to the cooling Earth that eventually counteracted it.

The need for an active control agent led the two to conceive of the Earth as a single organism they named Gaia, for the Earth goddess of the ancient Greeks (also known as Ge, from which derived the names for geology and geography).\(^5\) Greek philosophy had been based on the notion of a balance of nature, which was essentially what their vision of a self-regulating Earth implied. This naming was the first source of controversy for their hypothesis, because it imbued the Earth with a quasi-religious mysticism that did not comport well with the belief systems of most of their scientist peers—particularly physical scientists. Their metaphor of a planetary engineer, while intended to help simplify the explanation, was not
well-received either. It implied a conscious regulator, which was not what they were arguing. In the same article they deployed this metaphor in, they also explained that Neodarwinian mechanisms of selection were the means by which planetary control was maintained.\(^\text{53}\) This did not protect them from vocal criticism by their biologist peers, who eventually forced them to reformulate the hypothesis with more care toward the details of the current evolutionary synthesis.

In their seminal 1974 *Icarus* article, Margulis and Lovelock commented that “probably a planet is either lifeless or it teems with life. We suspect that on a planetary scale sparse life is an unstable state implying recent birth or imminent death.”\(^\text{54}\) The combination of living processes and evolutionary ones was so powerful, in their view, that organisms could remake a planetary environment to facilitate their own spread. Hence over the eons of deep time, life would take over a planet, make it more suitable, and eventually be found everywhere. In this view of life, there were no marginal environments. Life would be found in any local environment of an inhabited planet—or nowhere. This did not bode well for NASA’s dreams of finding life on Mars, or anywhere else in the solar system. If life existed at all off Gaia, it would be readily apparent from its impact on the composition of the Martian or Venusian atmospheres. Radiotelescopes, and telescope-aided infrared spectroscopy, were all one needed.

Stripping away the mysticism inherent in the Gaia label, the two were presenting a view of the Earth that could be grasped by systems engineers, a profession that specialized in (nonliving) feedback control systems. In his 1979 popular exegesis of the Gaia hypothesis, Lovelock devoted a chapter to cybernetic theory, the mathematical basis for feedback systems. For Earth scientists, Margulis and Lovelock were presenting a view of the world that required examination of complex, interlocking feedback loops. Some of these feedback loops, such as the hydrologic cycle that was of great interest to meteorologists, were primarily physical. At least in the 1970s, evapotranspiration was perceived as only a minor participant in the water cycle. Other obvious cycles, such as the carbon cycle, were both physical and biological. Understanding them required the very interdisciplinary research that the American scientific community did not consider serious science, and was not set up to foster. In fact, they expressed the hope that their hypothesis would change that particular scientific dynamic.\(^\text{55}\)

Taken in a larger view, Lovelock and Margulis were arguing that the Earth’s climate had been fundamentally altered by the evolution of life. Living things affected the chemistry of the atmosphere, altering its composition. Changing the atmosphere’s chemistry affected its radiative characteristics, and over geologic
time, these biogenic changes had produced the Earth’s current comfortable climate. Life, they were arguing, had achieved the ability to make planetary-scale changes eons ago. This early life, however, had done so unwittingly. They did not weigh in on whether humans had achieved this ability as well, but in these papers did not need to. Lovelock, in fact, had already demonstrated that human emissions of chlorofluorocarbons (CFCs) had changed the composition of Earth’s atmosphere, but he did not yet perceive the consequences. And Charles David Keeling, by the early 1970s, had conclusively demonstrated that human emissions of carbon dioxide were also changing the composition of the atmosphere. As carbon dioxide was a greenhouse gas, humans had clearly achieved the power to change the Earth’s climate.

NASA Chief Scientist Homer Newell remarked in his 1980 memoir that space science had proven to be integrative. Planetary science had drawn on many scientific disciplines to develop new knowledge about the other planets during the 1960s and 1970s. At the same time, that knowledge had informed thinking about the Earth and its processes. The Earth is, at least from the standpoint of planetary scientists, just one of the several terrestrial planets in the solar system; its processes are not governed by different rules. Planetary research had also forced the scientific community to begin placing Earth in the context of its sister rocky planets Mars and Venus, and begin to think about why it had turned out so differently from what they believed was a similar beginning. This was one thread of the increasing interest in Earth’s climate within the scientific community; Earth was a great deal closer than the other terrestrial planets, and due to the presence of water and life, it was also a good deal more complex.

The question of climatic evolution was, at one remove, a question of chemistry. On Mars and Venus, non-biologic chemical processes had produced very different outcomes; on Earth, however, the biosphere clearly played a substantial role in making the Earth chemically different from the other terrestrial planets. What the biosphere’s role was could not be quantified, at least during the 1970s. But the mere claim that the Earth’s climate was actively, if not consciously, regulated by life itself was highly influential. It caused great controversy in the scientific community, which was not prepared to accept that the thin green layer on the planet’s surface could have such great impact.

It also caused great controversy in the public arena, but for a slightly different reason. Humans had achieved the power to fundamentally alter the conditions of
life on Earth. The consequences of this ability were not yet known, and were not yet knowable, given the state of knowledge of the early 1970s. But recognition that humans might alter the atmosphere’s chemistry enough to change the Earth’s climate produced rapid demands by scientists and by political activists alike to figure out what those consequences might be.