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Venus & Mars

In the 1960s and 1970s, observations of Mars and Venus showed that planets that seemed much like our Earth could have frightfully different atmospheres. The greenhouse effect had made Venus a furnace, while lack of atmosphere had locked Mars in a deep freeze. This was visible evidence that climate can be delicately balanced, so that a planet’s atmosphere could flip from a livable state to a deadly one.

A planet is not a lump in the laboratory that scientists can subject to different pressures and radiations, comparing how it reacts to this or that. We have only one Earth, and that makes climate science difficult. To be sure, we can learn a lot by studying how past climates were different from the present one. And observing how the climate changes in reaction to humanity’s “large scale geophysical experiment” of emitting greenhouse gases may teach us a great deal. But these are limited comparisons—different breeds of cat, but still cats. Fortunately our solar system contains wholly other species, planets with radically different atmospheres.

Until the 1950s, science fiction writers gave about as accurate a picture of the nearest planets as scientists themselves held. The writers, after all, read up on the science. Mars seemed much like Earth, although its atmosphere was certainly far colder and dryer. Strange life might crawl over the Red Planet’s sands under an indigo sky brushed with wispy clouds. Perhaps it had once been a bit warmer and wetter, but everyone assumed that planetary atmospheres (including our Earth’s) were naturally stable, their composition held fixed within rough limits by simple geochemical processes. As for Venus, visitors might expect something even more Earth-like, a steam bath under perpetual clouds. Some scientists suspected that the atmosphere was largely carbon dioxide gas (CO₂), but even so, abundant life was not ruled out.

Could study of these strange atmospheres provide, by comparison, insights into Earth’s weather and climate? With this ambitious hope Harry Wexler, head of the U.S. Weather Bureau, instigated a “Project on Planetary Atmospheres” in 1948. Several leading scientists joined the interdisciplinary effort. But the other planets were so unlike Earth, and information about their atmospheres was so minimal, that the scientists could reach no general conclusions about climate. The project was mostly canceled in 1952.¹

Telescopic observations continued, benefitting from improved photographic techniques. By the mid 1950s, scientists, if not science fiction writers, knew that the atmosphere of Mars was unbreathable—mainly CO₂, very tenuous and very cold, occasionally stirred up with yellowish dust storms. If Mars had features resembling “canals” they were not full of water, for water could

¹ Doel (1996), pp. 57-67.

not exist as a liquid on the planet's surface.¹ The Mariner 4 spacecraft of 1965, sending back blurry pictures that showed a surface scarred with craters like the Moon, confirmed that the planet was an unlikely abode of life. As for Venus, radio observations published in 1958 showed an amazingly hot temperature, upwards of 600°K, around the melting point of lead. "It was very disappointing to many people," one of the discoverers recalled, "who were reluctant to give up the idea of a sister planet and perhaps even the possibility of life." Some astronomers worked up arguments that the radio measurements were misleading, representing something in the upper atmosphere, so that life might still exist on Venus. The matter was settled in 1962 when the spacecraft Mariner II flew past and showed unequivocally that the heat radiation came from the hot surface.²

Already back in 1940, Rupert Wildt had made a rough calculation of the greenhouse effect from the large amount of CO₂ that others had found in telescope studies of Venus, predicting the effect could raise the surface temperature above the boiling point of water. But raising it as high as 600°K seemed impossible.³ Nobody mounted a serious attack on the problem (after all, very few people were doing any kind of planetary astronomy in those decades). Finally in 1960 a young doctoral student, Carl Sagan, took up the problem and got a solution that made his name known among astronomers. Using what he later recalled as "embarrassingly crude" methods, taking data from tables designed for steam boiler engineering, he confirmed that Venus could indeed be a greenhouse effect furnace.⁴ The atmosphere would have to be almost totally opaque, and this "very efficient greenhouse effect" couldn't all be due to CO₂. He pointed to absorption by water vapor as the likely culprit.

Sagan, a science fiction fan from his early years, was among those who had dreamed of a living sister planet of swamp and ocean, but now he had to admit that "Venus is a hot, dry, sandy... and probably lifeless planet." Most significantly, the situation was self-perpetuating. The surface was so hot that whatever water the planet possessed remained in the atmosphere as vapor, helping maintain the extreme greenhouse effect condition. It was later found that Sagan was mistaken, for Venus's atmosphere has little water. In 1967 the Soviet Union's spacecraft Venera 4 penetrated Venus's atmosphere and found it was mostly CO₂; in 1978 the American Pioneer spacecraft proved it was almost entirely CO₂. If the greenhouse effect there is strong anyway, that is because Venus has a much denser CO₂ atmosphere than astronomers of the time thought. But mistakes in science can be as useful as valid results, when they stimulate further work and point in the right

¹ Kuiper and Middlehurst (1961), pp. 386-88, 438.

² The first observation was in 1956 by Mayer, McCullough, and Sloanaker. Mayer (1983), p. 271.

³ The actual temperature is around 750°K. Wildt predicted roughly 400, "higher than the terrestrial boiling-point." Wildt (1940); something other than CO₂ would be necessary to get to 600 according to Kuiper in Kuiper (1952), ch. 12.

⁴ Sagan, interview by Ron Doel, Aug. 27, 1991, AIP, tape 4 side 1.

direction.¹

The discovery that Venus's atmosphere had a composition, and probably a history, very different from Earth's prompted scientists to abandon their old assumption that planetary atmospheres were fixed forever by simple chemistry. A few researchers tried putting a feedback between temperature and water vapor into a simple system of equations; the results were strange. In 1969, Andrew Ingersoll reported "singularities," mathematical points where the numbers went out of bounds. That signaled "a profound change in the physical system which the model represents."² Ingersoll pointed at CO₂ as the key ingredient. Sagan had estimated that Venus had started out with roughly the same amount of CO₂ as Earth. On our planet, most of the carbon has always been locked up in minerals and buried in sediments. The surface of Venus, by contrast, was so hot and dry that carbon-bearing compounds evaporated rather than remaining in the rocks. Thus its atmosphere was filled with a huge quantity of the greenhouse gas.

Had the surface of Venus always been hot enough to melt lead, or had it once had the temperate climate that scientists had long assumed? In a 1971 paper, James Pollack argued that Venus might once have had oceans like Earth's. Perhaps the water had gradually evaporated and the greenhouse effect of the additional vapor made the atmosphere ever hotter, until CO₂ evaporated from heated minerals and the planet transformed into its present hellish state. No robot could survive on Venus long enough to sample its rocks, so into the 21st century the question of whether Venus was once hospitable to life remained a subject of research and speculation. One lesson from Venus was clear: the climate of a planet much like Earth could settle into a radically different state.³

If the starting conditions had been only a little different, could such a "runaway greenhouse" have turned Earth too into a furnace? In the late 1970s Michael Hart pursued the idea with a state-of-the-art computer model, and concluded that the balance was exceedingly delicate. Hardly any planets in the universe, he said, orbited in the narrow "habitable zone" around a star where life could flourish. For our solar system, the orbits in which a planet would be too close to the Sun—so that at some point the planet would suffer a runaway greenhouse effect from which it

¹ Sagan (1960b); Sagan (1960a), "efficient" p. vii, "lifeless" p. 20; see also Sagan (1961); arguments against a waterless Venus were developed by Gold (1964); see Davidson (1999), pp. 101-106.

² Ingersoll (1969), p.1191.

³ Rasool and de Bergh (1970) calculated that water would always have boiled on Venus, but Pollack (1971) was the first to deploy enough computer power to calculate a reasonable "runaway greenhouse" atmosphere. The ever prescient Tommy Gold had already speculated in a 1963 symposium about a "runaway process" when water boiled away, Gold (1964), p. 250. Others continued to speculate about a Venus that had once had a "clement" climate, e.g., Wang et al. (1976). The question may have been settled at last in 2024 by an analysis of the Venerian atmosphere that concluded, "the planet has never been liquid-water habitable," Constantinou et al. (2024).

could never recover—were separated by only a 5% gap from orbits in which the planet would be so far away that runaway glaciation would freeze an ocean solid. Earth was apparently a lucky place.

Hart's calculations were riddled with untested assumptions, and many scientists denied our situation was so extremely precarious. He defended his ideas energetically among his colleagues, and also in public, including an appearance on television in "Walter Cronkite's Universe." Later calculations showed his critics were right — a Venus-type runaway on our planet is scarcely possible, even if we burned all available fossil fuels. Nevertheless, the specter of humanity somehow triggering utter annihilation would haunt discussions of global warming.¹

The atmosphere of Venus was filled not only with CO₂ but also with an opaque haze. Its nature was unknown, and in the 1960s scientists could only say that the haze was probably caused by some kind of tiny particles.² "The clouds on Venus had long been a mystery," as one expert recalled, "in which stratospheric aerosols now appeared to play a key role. The unraveling of the precise role of aerosols in the Venus atmosphere would certainly benefit studies of chemical contamination of Earth's atmosphere."³ In the early 1970s, ground-based telescope observations produced extraordinarily precise data on the optical properties of these aerosols, and at last they were identified. The haze was from sulfur compounds.⁴

The greenhouse effect of the sulfates could be calculated, and by the late 1970s, NASA climate modeler James Hansen stated confidently that the sulfates together with CO₂ "are responsible for the basic climatic state on Venus." Hansen had originally become interested in the greenhouse effect when, in response to Sagan's primitive calculations, he tried to derive a better explanation of why the planet's atmosphere was so hot. Now Hansen's findings about sulfate aerosols strengthened his belief that these particles could make a serious difference for Earth's climate as well. Sulfates were emitted by volcanoes and, increasingly, by human industry, so Venus had

¹ Hart (1979). More accurate calculations in the 1990 found that for our Sun, a considerably larger zone should be habitable despite the gradually increasing brightness of the Sun itself.

² Mayer (1961), p. 458.

³ Newell (1980), ch. 20. Newell also says that "study of the role of halogens in the atmosphere of Venus... led to the suspicion that chlorine produced in Earth's stratosphere from the exhausts of Space Shuttle launches or from Freon used at the ground in aerosol sprays might dangerously deplete the ozone layer."

⁴ The first publication was Sill (1972). The idea that sulfuric acid was "the most probable constituent of the Venus clouds" was independently suggested by Louise Young, whose husband credited her in his publication, Young (1973), p. 564. Young relied especially on measurements by Hansen, who had also identified the acid but was dissuaded from publishing the idea: Hansen, interview by Weart, Oct. 2000, AIP; Hansen's contribution to the identification was noted by Prather (2002). Confirmation from an infrared telescope carried in an aircraft was reported by Pollack et al. (1975).

things to tell us about climate change at home.¹ (CO₂ was by far the largest factor in warming Venus, and the effect of sulfates would be debated for decades. It turned out that the greenhouse effect of sulfate clouds reflecting heat back to the surface of Venus was outweighed by cooling due to their reflection of incoming sunlight.)

And then there was Mars. That planet too inspired important new thinking about Earth's atmosphere, even before spacecraft paid a visit. In the 1960s, NASA asked some scientists to think about ways to detect life on Mars. A few of them noticed that life on Earth makes its presence blatantly evident by driving the atmosphere far from chemical equilibrium. In particular, the abundant oxygen in the air would swiftly drain away, by combining with surface minerals, except the oxygen is renewed by a daily emission from plants. Telescopic studies found practically no oxygen in the Red Planet's atmosphere. Overall the Martian atmosphere showed no signs of any chemical disequilibrium. Biochemist James Lovelock dismayed his peers by arguing that this showed any search for life there would be fruitless. The sterile atmosphere of Mars, so strikingly different from Earth's, helped Lovelock, and eventually others, to recognize that life plays a central role in determining the nature of our own planet's atmosphere.²

In 1971 the spacecraft Mariner 9, a marvelous jewel of engineering, settled into orbit around Mars and saw... nothing. A great dust storm was shrouding the entire planet. Such storms are rare for Mars, and this one was no misfortune for the observers, but great good luck. They immediately saw that the dust had profoundly altered the Martian climate, warming the planet by tens of degrees. The dust settled after a few months, but its lesson was clear. Haze could warm an atmosphere. More generally, anyone studying the climate of *any* planet would have to take dust very seriously. In particular, it seemed that on Mars the temporary warming had reinforced a pattern of winds that had kept the dust stirred up. It was a striking demonstration that feedbacks in a planet's atmospheric system could flip weather patterns into a drastically different state. That was no longer speculation but an actual event in full view of scientists—as of 1975 it was “the only global climatic change whose cause is known that man has ever scientifically observed.”³

Crude speculations about just such radical instabilities in Earth's own climate had been published independently by two scientists a few years before, about the same time as Ingersoll's calculation of the Venus greenhouse runaway.⁴ Pursuing such thoughts before Mariner arrived at Mars, Carl

¹ He thought “a great deal stands to be gained” by studying other planets' climates alongside Earth's. Hansen et al. (1978), p. 1067. For these matters and NASA contributions in general see Conway (2008).

² Hitchcock and Lovelock (1967); see Lovelock (2000), pp. 228ff.; the absence of detectable oxygen on Mars was long considered no definitive argument against the presence of vegetation, and in the early 1960s, NASA's ideas on detecting life through atmospheric analysis centered on a search for complex organic molecules. Dick (1998), pp. 48, 175.

³ Observations: Hanel et al. (1972); Feedbacks: Leovy et al. (1973); “observed”: Toon et al. (1975), p. 495.

⁴ Budyko (1968); Sellers (1969).

Sagan had made a bold prediction. He suggested that the Red Planet's atmosphere could settle in either of two stable climate states. Besides the current "ice age" there was another possible state, more clement, which might even support life. The prediction seemed to be validated by crisp images of the surface that Mariner beamed home after the dust cleared. The canals some astronomers had imagined were nowhere to be seen, but geologists did see strong signs that vast water floods had ripped the planet in the far past. It was a deadly blow to the old, comforting belief that planets had naturally stable climates, reinforcing the "runaway greenhouse" speculations about Venus that were emerging around the same time.

Calculations by Sagan and his collaborators now suggested that the planet's climate system was balanced so that it could have been flipped from a state with oceans to the present frigid desert, or even back and forth between the two states, by relatively minor changes — changes in its orbit, or in the strength of the Sun's radiation, or in the reflection of sunlight off the polar icecap. These were also, as the authors remarked, "fashionable variables in theories of climatic change on Earth." (Not until 2004 did direct observations on the surface of Mars prove that the planet had indeed once carried standing water, although only much farther in the past than Sagan guessed.)

The speculations recently published about Earth's climate had suggested possibilities as spectacular as anything proposed for Mars. A small change could start a warming in which Earth's polar ice caps would shrink, lowering the planet's reflectivity and pushing the warming further into a self-sustaining climate shift. Much the same thing could perhaps happen on Mars, releasing the CO₂ frozen at its poles, starting a greenhouse effect process that would melt the water ice buried in the soil. In fact some kind of drastic climate shift *had* happened on Mars, if the evidence of ancient floods and lakes was correct. Perhaps storms that deposited dust on the polar caps and darkened them had pushed the planet into its warm phase. Or perhaps (according to an idea published much later) clouds of CO₂ ice had exerted a different kind of greenhouse effect. In any case even this supposedly "dead" planet gave evidence of climate instability.¹

Studies of Mars stimulated interest in a puzzle concerning a third planet, like yet unlike our own world, that gave an additional reason to believe that CO₂ plays a crucial role in temperature regulation. That planet was Earth itself as it was several billion years ago. Sagan and a colleague pointed out in 1972 what became known as the "faint young Sun paradox." Astrophysical calculations show that the Sun changes as it burns its hydrogen fuel, gradually getting brighter. Three billion years ago, if the atmosphere was like the present, the seas should have been permanently frozen. But geological evidence showed there was liquid water. Sagan suggested this was thanks to the greenhouse effect of ammonia gas, but further geological studies found such an atmosphere unlikely. In 1979 another group produced a model whereby a very high concentration of CO₂ provided the necessary warmth. (More recent measurements, however, raised doubts about such a high early CO₂ level, and discussion of the paradox has continued.

¹ Prediction (hoping that Martian life was only hibernating through the winter of a 50,000-year cycle): Sagan (1971); Sagan et al. (1973), quotes pp. 1045, 1048. CO₂ ice: Forget and Pierrehumbert (1997).

Besides CO₂, extra methane or other gases and/or changes in clouds seem to be needed, and there may be other factors.¹⁾

In later years, spacecraft probed the exotic weather of Venus and Mars in great detail. These observations left open the possibility that in their younger days both planets had been more Earth-like, perhaps with oceans and even primordial life. (Mars also played a bit part in the drama of climate change denial in the early 21st century. An Internet myth asserted that Mars was getting warmer, which supposedly implied that Earth's warming was part of a natural solar-system cycle. The actual scientific literature, however, contained no claim that any planet except our own was getting warmer.) Meanwhile computer models of atmospheres were improving, and Earth's two neighbors, plus more exotic planets such as Jupiter, occasionally served as testbeds to probe the limits of the modelers' methods. If a set of equations gave plausible results for such utterly different atmospheres, that gave more confidence in their applications on Earth. For example, computer models and observations converged to confirm that wide variations in temperature on Mars were connected with feedback effects from occasional planet-wide dust storms.² But the main lesson was a larger one. The idea that feedbacks involving the greenhouse effect could have huge consequences for a planet's climate was not a mere speculative theory. It was an observation of real events.

Related:

Simple Models of Climate

¹ Also called the "faint young Sun" problem. Sagan and Mullen (1972); Owen et al. (1979); Feulner (2012); on self-stabilization of such a system see Walker et al. (1981).

² According to O.B. Toon, a radiative transfer model developed by Sagan and J. Pollack was influential for atmospheric studies in general. Davidson (1999), p. 244; Martian storms: Fenton (2009).