Reports

Ice Caps on Venus?

Abstract. *The data on Venus obtained by Mariner V and Venera 4 are interpreted as evidence of giant polar ice caps holding the water that must have come out of the volcanoes with the observed carbon dioxide, on the assumption that Earth and Venus are of similar composition and volcanic history. The measurements by Venera 4 of the equatorial surface temperature indicate that the microwave readings were high, so that the polar ice caps may be allowed to exist in the face of the 10-centimeter readings of polar temperature. Life seems to be distinctly possible at the edges of the ice sheets.*

The correspondence of the large amount of carbon dioxide found in the atmosphere of Venus by the Russian Venera 4 (*1*) with the total CO_2 on Earth suggests that Earth and Venus may have very similar overall compositions. The total amount of limestone on Earth (*2*) is equivalent to 9.2×10^{22} g of CO_2, which would amount to 18 atm of pressure if it were all present as gas; this figure agrees well with the Venera-4 result for the atmosphere of Venus. This similarity leads us to ask, Why doesn't Venus form $CaCo_3$? Where is Venus's water? These same questions were asked many years ago (*3*).

If Rubey's excellent argument (*2*), for the gradual simultaneous liberation of terrestrial CO_2 and H_2O by volcanic action, applies to Venus we need to understand where the water has gone. We can readily see that oceans cannot have formed, since they would have caused $CaCO_3$ to precipitate and would have lowered the pressure of CO_2 below that observed, unless they covered the entire planet as was suggested (*3*); in this case the rock-weathering essential to liberation of the requisite calcium could not have occurred. This possibility seems to be ruled out by the high equatorial surface temperature of 280°C reported for the dark side. The water cannot be in the atmosphere, since the Venera-4 measurements gave 20 atm as the surface pressure, of which more than 90 percent was carbon dioxide at least at the altitudes of 23 and 26 km. If the water found on Earth were in the atmosphere of Venus, the pressure at the surface would have to be 500 atm, with the temperature much higher—at least above the critical temperature for steam, 374°C.

There are various possibilities to consider, but let us first review the facts for Earth (*3*). The ratio of H_2O to CO_2 (the sum of all forms of surface compounds of CO_2, as well as the gas itself) is large: 18:1 by mass. So we must discover what could be different about Venus in its disposal of and reaction to steam issuing from its depths over the billions of years.

Let us begin with the water-gas reaction

$$CH_4 + 2H_2O = CO_2 + 4H_2$$

which occurs (in analogous form) for all forms of organic compounds at temperatures of hundreds of degrees Celsius such as have been reported on the surface of Venus. The hydrogen formed might escape from the planet; thus we would remove two water molecules for each molecule of CO_2 made, so that the ratio might be reduced substantially. But Earth has had the same experience, presumably, and still has a 17-fold excess of water. Since H_2O molecules cannot escape from Venus at any appreciable rate, it seems very unlikely that the water has disappeared; Gold has made this point (*4*). Photolysis to make hydrogen, which escapes, and oxygen, which is reduced by surface rock, would require intimate contact with at least 30 km of rock and thus require Venus to differ drastically from Earth in volcanic history. We are left seriously perplexed as to why Venus should be so different.

One possibility seems worth consideration in the light of the Russian data (if one assumes the two planets to be similar in composition and history)—ice caps at the poles. The thought is that the water may be trapped in this way in great caps perhaps 5 km or more in thickness. Is it reasonable that a planet rotating as slowly as Venus appears to do (*5*)—once every 243 days—and lying 30 percent closer to Sun than does Earth should have polar caps, especially when the mid-latitude temperatures are so high? The angle of inclination of the axis of rotation, relative to the normal to the ecliptic, is small (*5*), so that there are no seasons. Can Venus have polar areas cold enough to store the vast quantities of ice needed to keep her seas dry and thus to prevent formation of limestone? Sagan (*6*) has discussed the question most recently, just before the advent of the Venera-4 data; he concluded on the basis of the microwave data that the equatorial surface temperature might be 700°K; the polar temperatures, 470° ± 95°K. Since the equatorial temperature found by Venera 4 was lower at 550°K, ice seems to be a possibility.

Clark and Kuz'min (*7*) measured the surface temperatures from 10.6-cm microwave radiation with a two-element interferometer, obtaining 630° ± 70°K at the equatorial antisolar point and about 25-percent lower temperatures at the poles. The lower equatorial reading by Venera 4 seems to bring 273°K at the poles within the range of possibilities, because the great thickness of the atmosphere through which the polar-surface emissions would have to have traveled—some 2.5 times the equatorial thickness on the average (if the ice caps run to 30-deg latitude), and even thicker if the edge of the ice cap is at higher latitudes—seems to make clear observance of surface microwave emissions on Earth difficult because of scattering and absorption by the equivalent of some 460 m of liquid carbon dioxide. On my model, snow would be common over the polar regions.

Let us consider the problem of the circulation of the atmosphere of Venus and try to understand further the consequent patterns of heat flow from the sunlit mid-latitude regions to the poles and the dark side. First let us suppose that the planet does not rotate at all. Then the day lasts one Venus year (225 Earth days), with Sun rising in the west. In fact, as I have said, there is evidence of east-to-west rotation of Venus with about the same period; thus the day is about halved to about 120 terrestrial days, again with the western sunrise and eastern sunset; the solar constant will be 3.8 cal cm^{-2} min^{-1} at the equator, with an albedo (*8*) of about 0.7. If we suppose the CO_2 content to be 20 atm (460 mole/cm^2), the time constant for solar heating at the equator, with perfect vertical mixing, will be about 4700 minutes per degree Celsius—a very sluggish rate.

This very readily explains the hot dark side as found, because even after a night lasting 60 terrestrial days the law of radiative loss limits the night cooling. The calculated cooling, with perfect vertical stirring, would be only 5°K for a perfect black body at 235°K [the cloud-top temperature reported (*8*)].

The equatorial atmosphere thus is very hot and stays hot throughout the night, the source of heat being the visible sunlight which apparently is transmitted to the ground and absorbed there. The hot surface in turn heats the air and causes vigorous local vertical mixing up to the cloud tops, whereas on Earth the temperature gradient becomes positive, establishing the stratosphere in a stable state. Thus we can understand the little evidence of water spectroscopically observable from outside. The total water content of the stratosphere of Venus may well be less than Earth's 5 to 10 mg/cm^2. The pressure is about the same as on Earth, with CO_2 being the main gaseous component, but the mechanism of supply of water to the stratosphere—thunderstorms—may well be less efficient on Venus. Venera 4 reported (*1*) 280°C on the dark-side surface at the equator, with a nearly constant vertical gradient of about 10°C/km, so the radar altimeter reading of 26 km at 40°±10°C and a pressure of 0.684 atm showed excellent vertical mixing to extend to 26 km, and quite probably on to the cloud tops. The observed lapse rate agrees well with that expected for an all-CO_2 atmosphere: 10.4°K/km at 26 km and 8.4°K/km at the surface. Thus the cloud top, where the temperature is 240°K [as observed radiometrically (*8*)], should occur at the altitude of 33 km and at a total pressure of 0.2 atm. Of course these are extrapolations, since the highest altitude measured was 26 km, but these data appear to rule out CO_2 clouds and leave water as the leading possibility (*3*). At −40°C the vapor pressure of liquid CO_2 is 10 atm. Both oxygen (0.4 to 0.8 percent) and water (0.1 to 0.7 percent) were reported.

What should we expect the temperatures at the poles to be in the light of the above? Does it follow that the poles cannot have ice when the equatorial atmosphere is so hot? The Mariner-II data (*8*, *9*) for the 2-cm microwave emissions from Venus were obtained by scanning of the planet more or less along vertical sections perpendicular to the ecliptic. The sweeps were made with a scanning beam spread of about 10 percent of the planetary cross section. Since the spacecraft was essentially in the equatorial plane of the planet, the most direct view was of the equatorial latitudes, with the minimum path through the atmosphere. The path length through the atmosphere for polar caps extending from 30-deg latitude averages about three times that for the equatorial view, so that the equivalent of some 60 atm would have to be traversed; it seems very probable in this case that scattering and absorption would have reduced the intensity seriously. The polar regions may be subject to continuous snowfall. For these reasons it seems that these observations may not directly contradict my theory.

I suggest that ice caps are indeed possible since the planet Venus rotates very slowly (*5*). Mintz (*11*) has calculated the wind velocity at the edge of the daylight zone on Venus, assuming that it always presents the same side to Sun (counterclockwise rotation, with 224-day period), to be only 0.32 km/hour; he assumed a surface pressure of 50 atm and a surface temperature of 400°K. Further calculations of the heat flow to the polar regions, from the observed data, are planned.

In a careful analysis of the evolution and nature of the atmosphere of Venus (*12*), Dayhoff, Eck, Lippincott, and Sagan quote a measurement by Moroz (*13*) of the carbon monoxide content at 10^{-6} by volume. If this is assumed to be correct and is taken together with our assumptions of similarity in both composition and volcanic history, the observed oxygen could not have been produced by photodissociation of carbon dioxide since every oxygen molecule would have to be accompanied by two carbon monoxide molecules; the arguments expounded by Marshall and Berkner (*14*), that the oxygen on Earth must derive from photosynthesis in plants, then may apply.

The data on Venus seem to fit the Rubey model for Earth and bolster the thesis that Earth and Venus were made of very similar material, with about the same amount of carbon, probably as primeval organic compounds as well as carbides, carbonates, graphite, and such. These substances are converted to CO_2 and emitted as volcanic gases together with excess water which, I suggest, condenses in the polar regions as ice caps.

At the edge of the glaciers, melting occurs and streams (*4*) run into the hot equatorial desert and evaporate. Small oceans and freshwater lakes also may form.

Evaporation from these bodies continually replenishes the clouds which we take to be water, and over the polar areas there may be much snow.

It seems that any forms of life that can live in high concentrations of carbon dioxide may well exist on Venus in the semipolar regions where the temperatures may well be mild enough. The 0.4 to 0.8 percent of oxygen (between 33 and 66 percent of the amount in our atmosphere) reported by Venera 4 (*1*) is most suggestive, especially in view of the reported low abundance of carbon monoxide (*12*).

W. F. LIBBY

Department of Chemistry and
Institute of Geophysics and Planetary Physics, University of California, Los Angeles 90024

References and Notes

1. Tass, "Automatic interplanetary station Venera 4," in *Pravda*, 22 Oct. 1967; in *Izvestia*, 31 Oct. 1967.
2. W. W. Rubey, "Geologic history of sea water," in *The Origin and Evolution of Atmospheres and Oceans*, P. J. Brancazio and A. G. W. Cameron, Eds. (Wiley, New York, 1964) pp. 1–63.
3. D. H. Mentzel and F. L. Whipple, *Pub. Astron. Soc. Pacific* **67**, 161 (1955).
4. T. Gold, "Outgassing processes on the Moon and Venus," in *The Origin and Evolution of Atmospheres and Oceans*, P. J. Brancazio and A. G. W. Cameron, Eds. (Wiley, New York, 1964).
5. V. R. Eshleman, *Science* **158**, 585 (1967).
6. C. Sagan, *Nature* **216**, 1198 (1967).
7. B. G. Clark and A. D. Kuz'min, *Astrophys. J.* **142**, 23 (1965).
8. W. R. Koenig, F. W. Murray, C. M. Michaux, H. A. Hyatt, "Handbook of the physical properties of the planet Venus," *NASA SP-3029* (U.S. Government Printing Office, Washington, D.C., 1967).
9. F. L. Barath, A. H. Barrett, J. Copeland, D. E. Jones, A. E. Lilley, *Astron. J.* **69**, 49 (1964).
10. J. B. Pollack and C. Sagan, *Astrophys. J.* **150**, 327 (1967).
11. Y. Mintz, *Icarus* **1**, 172 (1962).
12. M. O. Dayhoff, R. V. Eck, E. R. Lippincott, C. Sagan, *Science* **155**, 556 (1967).
13. V. I. Moroz, *Soviet Astron. AJ English Transl.* **8**, 566 (1965).
14. L. Marshall and L. Berkner, in *The Origin and Evolution of Atmospheres and Oceans*, P. J. Brancazio and A. G. W. Cameron, Eds. (Wiley, New York, 1964), pp. 102–26.
15. Aided by the U.S. Air Force (grant AFOSR-1255-68) and by NASA (grant 237-62).

11 December 1967