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Polar Volatiles on Mars—Theory versus Observation

Excess solid carbon dioxide is probably present in the north residual cap.

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Mariner 9 produced a wealth of new information concerning processes on Mars involving solid-vapor equilibria of water and carbon dioxide (*1–3*). Interpretations of these observations in terms of theoretical models, such as that of Leighton and Murray (*4*) have been attempted. In this article we synthesize the results of the Mariner 9 mission, as they pertain to polar volatiles, and compare them with a description of the solid-vapor equilibrium relations we believe are presently active on Mars.

CO_2 Reconsidered

Leighton and Murray's (*4*) study of CO_2 and other volatiles on Mars was a simple representation of the absorption and reradiation of solar energy by solid CO_2 on Mars. In order to describe the processes taking place, an almost lunar thermal model of the martian surface was assumed, and a simplified orbit was used to facilitate computation. The model did not provide for horizontal heat transport by the atmosphere or dust, or for any interference in the polar radiation balance arising from clouds (*5*). A uniform height was assumed for the surface, and this has been contradicted by the large altitude differences discovered by ground-based radar in the late 1960's. In addition, the model range of albedos assumed was not based on actual observation. In spite of these simplifications, it was evident that the surface atmospheric pressure on Mars is limited by the polar heat balance; excess CO_2 must be accommodated in solid form at the poles rather than by an increase of CO_2 in the atmosphere.

The model predicted (i) a mean surface pressure of CO_2 similar to that actually observed by Mariner 4, about 5 millibars; (ii) a rate of recession of the seasonal polar caps comparable to that observed; (iii) a permanent north polar cap, which was also observed from the earth; and (iv) a semiannual planet-wide pressure fluctuation arising from atmospheric exchange with surface frost during the seasonal growth and disappearance of the polar caps. As a consequence, Leighton and Murray (*4*) concluded that the seasonal frost caps on Mars are composed of solid CO_2, not water-ice as had commonly been believed. The Mariner 7 spacecraft confirmed this prediction; it carried an infrared spectrometer, which directly detected characteristic absorption bands of solid CO_2 (*6*), and an infrared radiometer (*7*) which, along with the infrared spectrometer, confirmed that the brightness temperature of the frost composing the seasonal southern cap was approximately 150°K as predicted by Leighton and Murray. Further confirmation was provided by ground-based interferometric observations in 1971 (*8*).

A deficiency of the model arose from the simplified description of the orbit of Mars. The (erroneous) computation suggested a periodic variation in the average annual insolation at the two poles with a 50,000-year cycle, caused by precessions of the perihelion and spin axis. Leighton and Murray attributed the large residual cap, currently present in the north, to this supposed effect. More accurate analyses—carried out first by Kieffer (*9*) and later by ourselves and by Cuzzi (*10*)—indicate that the average annual insolation at the two poles is always identical (*11*). Inasmuch as the stability of a perennial deposit of solid CO_2 on the surface can be considered solely in terms of its annual heat balance, there is now little basis for the original Leighton-Murray explanation of north polar dominance as the site of a permanent CO_2 deposit (*12*).

Mariner 9 has increased our knowledge of the heat transport processes and circulation systems operative in the martian atmosphere. This new information suggests to Leovy (*13*) that a significant amount of heat is transported from equatorial areas to polar areas during certain seasons on Mars. Additional heat transfer also occurs during large dust storms that periodically envelop the planet. These considerations, which are based on observations, cause concern about the original Leighton-Murray model, which ignored these effects. Similarly, the polar hood, a phenomenon long observed from the earth, has been studied more completely from martian orbit in the visible, infrared, and ultraviolet wavelengths (*14*); we conclude that it may influence the oversimplified heat balance equation used in the original model.

A third possible deficiency, pointed out by Kieffer (*9*), concerns the extreme sensitivity of the equilibrium pressure and temperature to albedo values of the exposed CO_2 frost. For example, a change in albedo from .65 to .75

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results in a change in equilibrium partial pressure of CO_2 from 13.5 to 2.3 mbar (*15*, *16*). Occurrences that might, at times, change the albedo, such as dust infall on the ice surface or perhaps different textures of CO_2 frost resulting from local micrometeorological conditions, cause Kieffer to believe that the Leighton-Murray model may be inherently unstable.

Reservoir of Solid CO_2

It is most important to recognize that the only place on or within the planet where perennial solid CO_2 can now exist is on the surface near the poles, or at shallow depth (*17*) there beneath a permanent cap with a high albedo. Solid CO_2 can not survive burial beneath any low-albedo "dirt," even temporarily, since the subsurface temperature exceeds the sublimitation point of the solid and CO_2 will escape as a gas; this is the case everywhere except near the poles. In addition, any burial process (for example, eolian deposition of dust) will necessarily be slow, with individual particles warming the CO_2 around them, and sinking from solar view by subliming CO_2 into the atmosphere. Thus, a scum layer of dark (low-albedo) material may be buried beneath a topmost layer of frost, but as soon as this topmost layer is removed, the dark dust will heat up and any CO_2 beneath it will escape. Although the escape will be limited by the rate at which CO_2 can pass through the scum layer, it is unlikely that this layer could resemble a solidified, although porous medium, and the resulting rate will thus be rapid (*18*). Furthermore, McElroy (*19*) argues that the amount of CO_2 lost through atmospheric escape is probably small. There is no evidence that large amounts of CO_2 are tied up in surface materials such as carbonates (*20, 21*). Therefore, most of the CO_2 ever released from the interior of Mars is probably now in the atmosphere or included within permanent polar frost deposits. Furthermore, the discovery by Mariner 9 of extensive volcanic deposits on portions of the martian surface suggests that the total amount of CO_2 liberated to the surface probably exceeds that now present in the atmosphere (*22*). Thus, excess CO_2 in the solid form is to be expected in the polar areas.

Conversely, it would have to be considered an extraordinary accident if the total CO_2 released over the history of Mars and now available at the surface should just exactly equal that required for the formation of the observed annual caps: a small proportion less and hardly any annual caps would form at all; any larger amount would be in the form of buried solid, as is proposed here. Although the simplified model (*4*) which predicts a permanent CO_2 cap has significant deficiencies both theoretically and observationally, the seasonal caps are composed of CO_2 as predicted, excess solid CO_2 is quite likely, and a permanent deposit of solid CO_2 evidently is in equilibrium with atmospheric CO_2. Otherwise, the observed CO_2 surface pressure of about 5 mbar must be regarded as a fantastic coincidence, especially in view of the obliquity variations discovered by Ward (*23*) and the consequent hundredfold atmospheric pressure oscillations (*16*).

So, what is missing? We believe that there must be a large reservoir of solid CO_2 in gaseous equilibrium with the atmosphere (on some time scale), but buried immediately below the exposed residual water-ice cap. And we believe we have located this reservoir near the north pole.

The principal effect of such a reservoir is to average out annual and longer-term fluctuations in the polar heat balance. Heat exchange probably takes place between buried and exposed solid CO_2 through a "heat pipe" effect with gaseous CO_2 as the circulating medium, as well as by direct conduction through the water-ice cap. The temperature of the reservoir must therefore be a slowly changing function of the past polar heat balance. It is that temperature (*24*) which now regulates the pressure of the martian atmosphere. If such a reservoir exists, it might provide an answer to the difficulties concerning the stability of the exposed CO_2 cap. Short-term fluctuations in the albedo of the polar cap or in atmospheric heat transfer would be compensated by heat exchange with the large reservoir, rather than causing precipitous changes in atmospheric pressure, as might be implied by the earlier model (*4*). The characteristic response time of the reservoir to temperature variations was found to be 10^2 to 10^3 years (*16*).

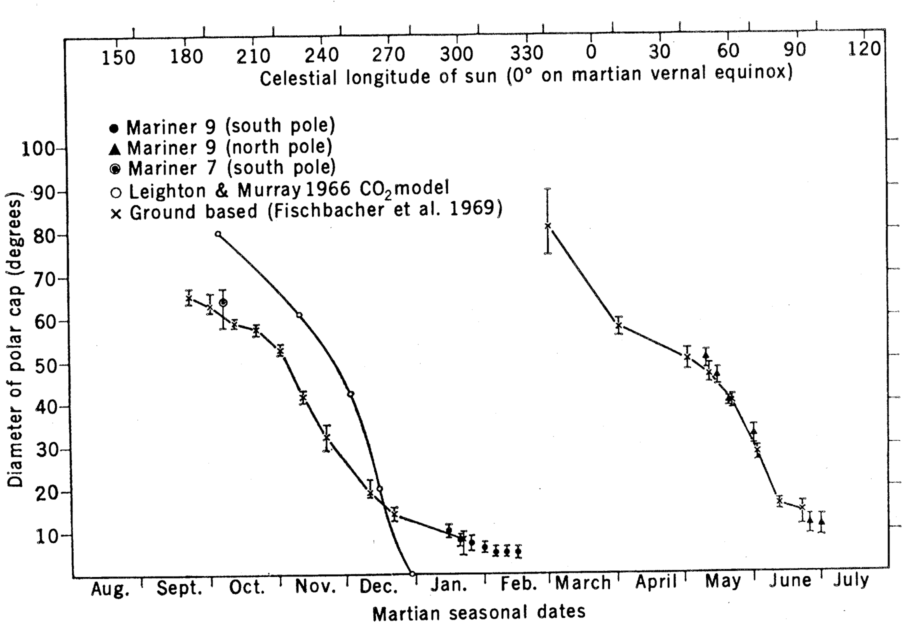

Fig. 1. Recession of the martian polar caps as a function of martian seasonal date. The error bars represent the maximum variations seen as a function of longitude. For the compilation of ground-based observations by Fischbacher *et al.* see (*25*); for Leighton and Murray see (*4*). Note the excellent agreement between the spacecraft and ground-based observations. The differences between the curves may reflect topographic control of the polar cap retreats.

Implications of Mariner 9 Observations

Thus, we are especially interested in the Mariner 9 observations for clues to the nature of the residual polar caps, and to the location and size of any subsurface solid CO_2 deposits.

The retreat of the south polar cap was monitored by Mariner 9 and the results were reported by Murray *et al.*

(*1*). As indicated in Fig. 1, the cap did not disappear entirely—contrary to the prediction of the Leighton and Murray (*4*) model of a seasonal CO_2 cap. Near the south pole a small residual cap was found which had only recently been recognized with confidence from the earth (*25*). The outline of the residual cap did not change appreciably during the peak of summer insolation in the southern hemisphere. This observation led Murray *et al.* (*1*) to postulate that the residual southern cap may be composed of water-ice rather than solid CO_2. A similar relationship in the north polar region based on observations obtained later in the mission has been described by Soderblom *et al.* (*2*). In both cases, the residual cap exhibits sharp boundaries and lies entirely within a peculiar, very smooth, layered formation which occurs only in the polar areas of Mars. Figure 2 shows a stereographic outline of the residual caps for comparison with observations of nearly a century ago. The residual caps appear to be a long-term feature of the martian landscape.

The probability that the exposed residual frosts are water-ice is reinforced by a consideration of the relative stability of solid H_2O and solid CO_2 during the maximum solar heating at the poles on Mars. The maximum surface temperatures if we consider radiative exchange only (no allowance for inward heat flow) range from 160° to 200°K for water-ice with albedo values of 0.8 to 0.6 (*26*). Inasmuch as CO_2 is the major constituent of the martian atmosphere, an exposed deposit will evaporate or condense in response to increases or decreases in the net heat balance. For example, approximately 1 meter of solid CO_2 would sublime while the residual cap is exposed during summer. Loss of water-ice, on the other hand, is limited in the higher temperature ranges (180° to 190°K) by the capacity of the cold CO_2 atmosphere to accept and transport water vapor. At lower temperatures the evaporation rate of ice itself becomes a limit. Therefore, a residual water-ice cap is much more stable than a solid CO_2 one on Mars in the summertime.

This line of inquiry suggests several other factors of interest. The temperature of the residual water-ice frost will be maintained at the condensation temperature of CO_2 (150°K) until all the CO_2 has sublimed away at the end of the seasonal recession. Only then can the water-ice begin to heat up in response to absorbed solar energy. This heating process will not be instantaneous. The rate of heating depends on the thickness of the ice, the proximity to dust and rocks, and related factors. However, if the water-ice heats up slowly enough to reach a temperature of 180° to 190°K by late in the summer, it will then begin to saturate the atmosphere immediately above it with water vapor. The polar hood phenomenon, which develops in the fall over each cap, may well involve saturated water conditions in the atmosphere above the pole (*27, 28*). Leovy (*13*) notes that an abundance of water vapor is inconsistent with simple models of atmospheric transport from equator to pole. It seems plausible to us that a residual water-ice cap at each pole could be the source for atmospheric water vapor in the fall season of each hemisphere. Similarly, the polar regions may at some seasons act as sources of atmospheric water vapor and at others as sinks. Such two-way exchanges of water between equator and pole might reduce the large amounts of water apparently lost to permanent polar deposits (*29*) and ease the difficulty encountered by Leovy.

Accordingly, the next question we wish to investigate is whether there is indeed solid CO_2 buried beneath the water-ice in the polar regions. No observational evidence of any such deposit has yet been reported. The south polar region was monitored at higher resolution and more extensively than the north. Figure 3 shows two views of a local area taken during and at the end of the martian southern summer. In the latter view, there is a considerable amount of residual frost, but also dark areas where bare ground is exposed. It is clear that the water-ice is not lying directly on top of massive CO_2 deposits in that region. A more general examination of the south polar region, as shown in Fig. 4, indicates that the white frost delineates and follows very closely the underlying terrain of the layered deposits.

The circumpolar dark bands are believed to be sloping surfaces that face the equator and separate level areas on

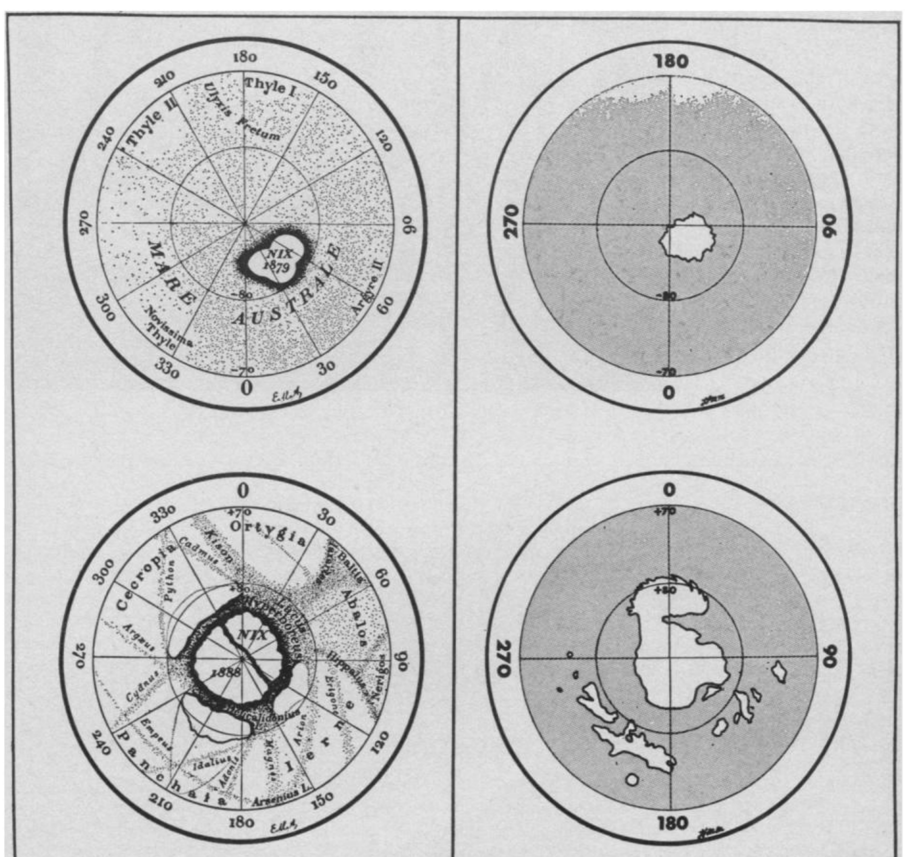

Fig. 2. Residual frost caps on Mars as seen in the 19th and 20th centuries. These stereographic projections of maps of the north and south polar caps are separated by almost 100 years. Note the latitudinal and longitudinal similarities and the close correspondence in areal extent. The 19th-century drawings by the astronomer E. M. Antoniadi, presented in Pickering (*42*), show the dates of the observations.

which the residual frost is accumulated (*1*, *30*). In 1969, Mariner 7 photographed these circumpolar features when they were covered by the seasonal CO_2 deposit. They appeared brighter then than the surrounding area because of the higher solar insolation on those slopes. For the same reason they defrosted before the Mariner 9 encounter and thus appear as dark bands in the Mariner 9 pictures.

Kliore *et al.* (*31*) report radio occultation observations which suggest to us that solid CO_2 should not be present now in the south polar regions. Figure 5 shows the planetary radii corresponding to spacecraft occultations which occurred in the polar latitudes (as viewed from the earth). It can be seen that the southern residual cap must be higher than the northern one by at least 2 kilometers. Any solid CO_2 in the south would be in contact with atmospheric CO_2 at a pressure lower by about 2 mbar than in the north (*32*). There is no reason to suppose a permanent CO_2 southern cap would be at a systematically lower temperature than the northern one. Hence, solid CO_2 deposits in the south would be out of equilibrium and would gradually be transferred to the north. A mass of CO_2 equal to that in the present atmosphere of Mars would be transferred in well under 1000 years. Thus, it seems unlikely that any significant mass of solid CO_2 could be buried beneath the south polar residual cap, and most improbable that it could be buried beneath the bare ground there because of the high subsurface temperature.

In the north polar regions, a similar appearance of the frost-coated layered terrains also places limits on the location and size of any buried CO_2 deposits over most of the residual cap. However, in one locality, indicated on Figs. 6 and 7, there is an interruption in the underlying terrain pattern sug-

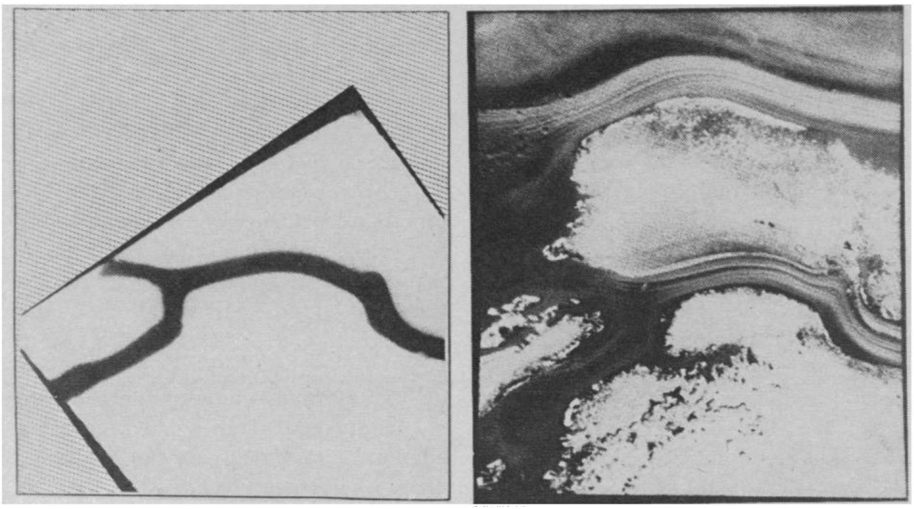

Fig. 3. High-resolution south polar frames of "the fork." The two photographs, taken 110 days apart, show a region of layered terrain and permanent polar ice near 85.4°S, 355.0°W. The dark features are bare ground. The presence of interior dark material indicates that the ice is thin enough to allow small-scale relief to show through and that it is probably water (CO_2 ice could not survive in contact with low-albedo material).

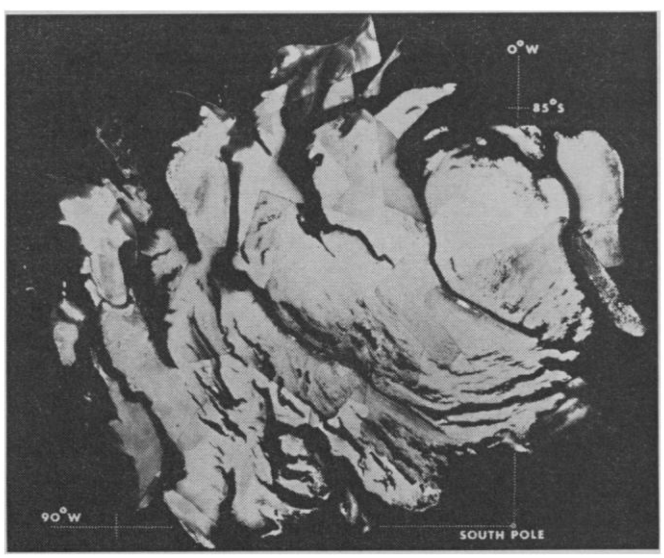

Fig. 4. Residual south polar cap of Mars, shown in a stereographic mosaic of Mariner 9 high-resolution frames taken over a period of 36 days at the end of the martian southern summer. Note the many dark regions where the bare ground (low albedo) shows through the permanent ice. The biggest, longest dark bands are equatorward slopes of layered terrain plates.

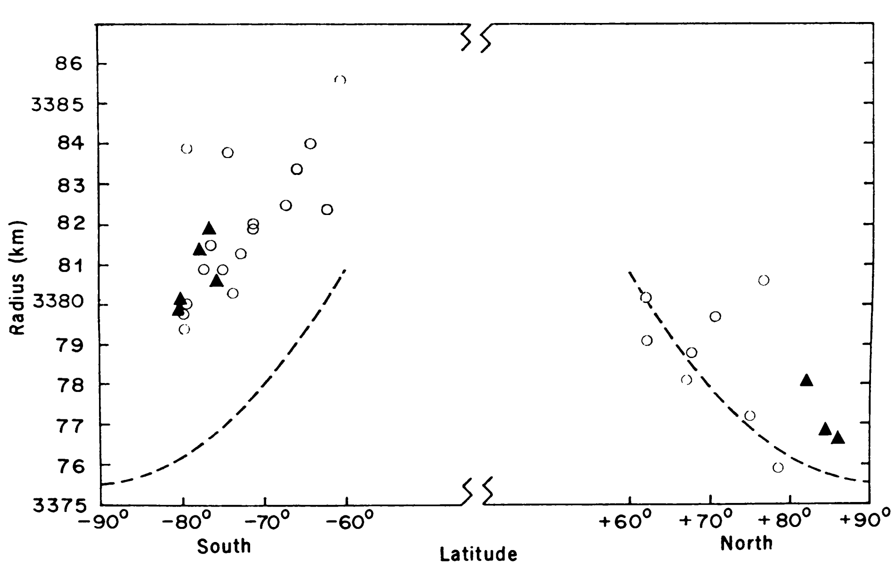

Fig. 5. Radii of Mars in polar regions, measured by the radio occultation experiment and reported by Kliore *et al.* (*31*). (Open circles) Occultation points in polar regions; (closed triangles) occultation points on layered terrains. The dashed line represents the triaxial ellipsoid which best approximates the figure of Mars. Both sets of data show that the southern points tend to be some 2 to 4 km higher than the northern points. Independent reductions of the surface pressures show the same trend, but with greater observational scatter.

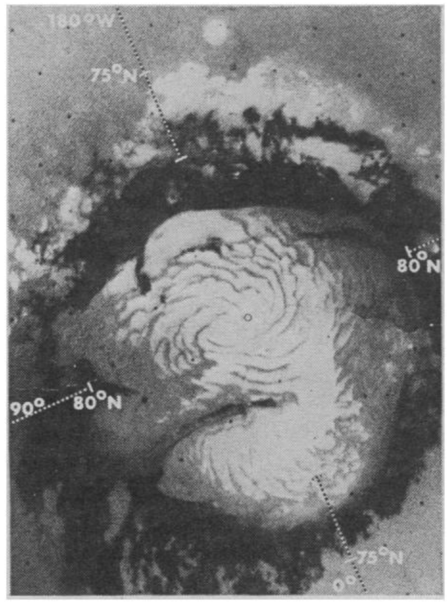

Fig. 6. Residual north polar cap of Mars. This is a stereographic mosaic of two Mariner 9 low-resolution photographs, taken 12 hours apart on 27 October 1972, on Mariner orbits 667 and 668. The three albedos are indicative of dark ground, light ground, and high-albedo ice. Except for a few outlying patches, most ice lies within two lobate forms joined at one end, above the 80th parallel. The dark arcuate features are believed to be equatorward slopes of the layered terrains. The featureless bright ice connecting the two ellipses is believed to be the area of the solid CO_2 reservoir.

gestive of a thicker deposit of frozen volatiles. We believe that this is the location of a significant accumulation of solid CO_2 buried beneath a relatively thin water-ice cover.

An important question is, how thick is the white deposit? And how can we be sure it is solid CO_2 and not water-ice? First, we think it is very unlikely that a thin deposit of CO_2 would be found on a surface sloping toward the equator. Solid CO_2 on a 5° equatorward slope experiences about the same insolation as that on a level surface 5° in latitude closer to the equator. The sharp boundary of the receding seasonal cap is evidence of the sensitivity of CO_2 to such slight insolation differences.

Water-ice is not nearly so responsive to insolation differences on a short time scale. However, the existence of the dark bands in both north and south residual caps is testimony to the preference of water for level surfaces. There is no evident reason why that pattern should change sharply in the anomalous area under consideration. Hence, we think the break in the pattern of the dark bands corresponds to the location of a thick mass of volatile.

If the white substance is thick enough to bury the local topography, just how thick must it be? The topographic relief across the dark bands in the south polar area is believed to be of the order of 300 to 500 m (*33*). If similar relief is exhibited in the north, the excess mass of frozen volatile lying on top of the layered terrain and beneath the water frost is probably at least 300 m in average thickness in order to mask the terrain configuration. On the other hand, solid CO_2 could hardly exhibit more than about 2 km in maximum relief without finding itself out of equilibrium with the atmosphere, since the same kind of redistribution which favors the north pole over the south will also limit the vertical relief of a solid CO_2 deposit. The inferred shape of the deposit is consistent with that expected for solid CO_2 responsive to slight variations in insolation (*4*) and height. Water-ice is not similarly regulated and displays a thin uniform structure in the south, for example, where it can be studied at high resolution (*34*). We cannot definitely rule out a thick deposit of water-ice, but we think it is much less likely than CO_2. A reasonable upper limit to the volume of a CO_2 deposit can be computed by using an thickness of 1 km.

We can estimate the limits on the mass of solid CO_2 contained in the thickened portion of the north residual cap as follows. The area of the thickened part, including some uncertainty, is (7 to 8.5) $\times$ 10^{14} cm^2. The thickness is 300 to 1000 m, as discussed above. Thus, the volume is (21 to 85) $\times$ 10^{18} cm^3. We use a density range of 1.0 to 1.5 g/cm^3 to allow for the possibility of some admixture of water-ice or dust buried within the CO_2 (1.0 g/cm^3) and the possibility of pure cold CO_2 (1.5 g/cm^3). Thus, the limits on the mass of CO_2 in the thickened part of the north residual cap are (21 to 127) $\times$ 10^{18} g, equivalent to 1.1 to 6.4 times the mass of CO_2 in the present atmosphere of Mars. We take a range of 2 to 5 as a reasonable estimate, recognizing that the upper limit is more sure than the lower one.

Leighton and Murray (*4*) predicted planet-wide seasonal pressure variations of the martian atmosphere of about 25 percent from peak to peak due to the transfer of solid CO_2 between the two hemispheres. So far, Mariner 9 data acquired by radio occultation and infrared and ultraviolet spectroscopy have not detected any annual pressure variation. However, the absolute accuracy of those tests may not be sufficient to rule out a small variation of the type predicted (*35*). We cannot propose any entirely satisfactory mechanism by which a solid CO_2 reservoir could stabilize the atmosphere at a constant pressure on such a short time scale. Hence, a more complicated situation (*36*) is indicated if the annual variation is really absent.

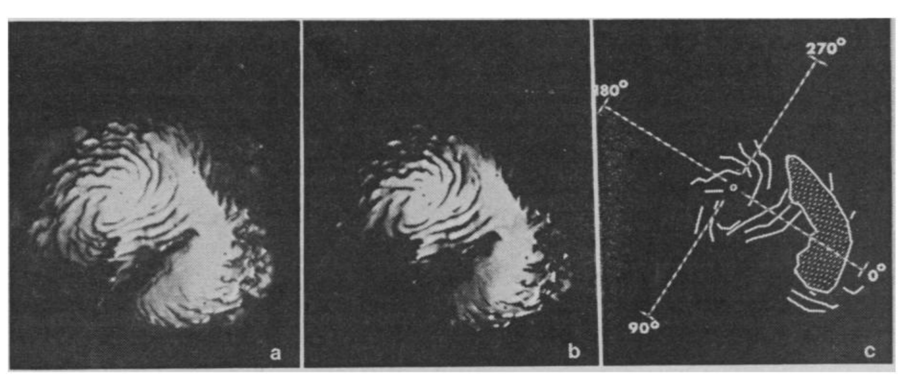

Fig. 7. The CO_2 reservoir. (a and b) Stereographic projections of the north polar caps, processed to enhance fine-scale albedo differences. Image (a) was made by isolating a range of gray levels which included light bare ground and bright ice, and then enhancing the contrast within that range. Image (b) is of the same region, with only the bright ice isolated. The faint gray markings in the center frame represent variations in brightness of less than 5 percent at high albedo, and are interpreted as photometric shading due to very slight slope differences. Thus, it is believed that the layered terrain scarps are overlain by material at least as thick as the elevation differences across the scarps. The drawing in (c) delineates the area believed to be thickened frost.

Conclusions

The residual frost caps of Mars are probably water-ice. They may be the source of the water vapor associated with seasonal polar hoods. A permanent reservoir of solid CO_2 is also probably present within the north residual cap and may comprise a mass of CO_2 some two to five times that of the present atmosphere of Mars. The martian atmospheric pressure is probably regulated by the temperature of the reservoir and not by the annual heat balance of exposed solid CO_2 (*37*). The present reservoir temperature presumably reflects a long-term average of the polar heat balance.

The question of a large permanent north polar cap is reexamined in light of the Mariner 9 data. The lower general elevation of the north polar region compared to the south and the resulting occurrence in the north of a permanent CO_2 deposit are probably responsible for the differences in size and shape of the two residual caps. The details of the processes involved are less apparent, however. It might be argued that the stability of water-ice deposits depends on both insolation and altitude. The present north and south residual caps should be symmetrically located with respect to such a hypothetical stability field. However, the offset of the south cap from the geometrical pole, the nonsymmetrical outline of the north cap, and the apparently uniform thickness of the thin, widespread water-ice all argue against control by simple solid-vapor equilibrium of water under present environmental conditions. We think that the present location of the water-ice may reflect, in part, the past location of the permanent CO_2 reservoir. The extreme stability of polar water-ice deposits increases the likelihood that past environmental conditions may be recorded there. Detailed information on elevations in the vicinity of the residual caps is needed before we can further elucidate the nature and history of the residual caps. This, along with measurements of polar infrared emission, should be given high priority in future missions to Mars.

Two conclusions follow from the limitation of the mass of solid CO_2 on Mars at present to two to five times the mass of CO_2 in the atmosphere. If all of this CO_2 was entirely sublimated into the atmosphere as a result of hypothetical astronomical or geophysical effects, the average surface pressure would increase to 15 to 30 mbar. Although such a change would have considerable significance for eolian erosion and transportation, there seems to be little possibility that a sufficiently earthlike atmosphere could result for liquid water to become an active erosional agent, as postulated by Milton (*38*). The pressure broadening required for a greenhouse effect requires at least 10 to 20 times more pressure (*39*). If liquid water was ever active in modifying the martian surface, it must have been at an earlier epoch, before the present, very stable CO_2/H_2O system developed. There can be no intermittent earthlike episodes now.

Furthermore, the present abundance of CO_2 on Mars may be an indicator of the cumulative evolution of volatiles to the surface of the planet (*40*). Thus, even the possibility of an earlier earthlike episode is dimmed. On Mars, the total CO_2 definitely outgassed has evidently been about 60 ± 20 g/cm^2. On the earth, about 70 ± 30 kg/cm^2 of CO_2 have been released to the surface (*41*). Hence, the total CO_2 devolved by Mars per unit area is about 0.1 percent of that evolved by the earth. Thus, the observational limits we place on solid CO_2 presently located under the north residual cap also may constitute considerable constraints on the total differentiation and devolatilization of the planet. If they are valid, it would seem unlikely that Mars has devolatilized at all like the earth, or ever experienced an earthlike environment on its surface.

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18. Murray *et al.* (*1*) suggested the possibility that either solid CO_2 or water-ice might be included within polar sedimentary layers that are annually covered by seasonal frost. Whereas water-ice is a possible or even likely constituent of those deposits, further reflection on the stability of solid CO_2 rules out that substance as a constituent of those layers or any other exposed rock unit. For example, even an albedo as high as .50 indicates a subsurface temperature at the pole of 169°K. For an albedo of .25 the temperature will be 187°K.
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32. This difference in height should influence the thickness and therefore the rate of recession of the seasonal CO_2 caps as well. The asymmetry between the northern and southern recessions shown in Fig. 1 between cap diameters of 50° and 15° may reflect the height differences illustrated in Fig. 5. Similarly, the correspondence between the computed and actual recessions might be improved if the prominent height differences were included.
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34. There is much poorer Mariner 9 coverage of the northern residual cap than of the

southern one because of orbit, lifetime, and seasonal constraints (*2*). There is virtually no useful high-resolution coverage of the thickened area of the north polar cap.
35. Improved limits on the presence or absence of planet-wide seasonal pressure fluctuations probably can be obtained from refined analyses of the results from (i) the Mariner 9 radio occultation and ultraviolet and infrared spectroscopy experiments, and (ii) the Soviet Mars 2 and Mars 3 orbital experiments (as well as Mars 4, 5, 6, and 7 experiments now under way). Direct measurements of surface pressure from future U.S. and Soviet landers, as well as further measurements from orbit, could provide sufficiently long-term, precise pressure observations to permit a decisive determination of how the seasonal variation in the mass of the frost caps interacts with the atmosphere. This information, in turn, has important implications for transport of heat, dust, and water vapor by the atmosphere.
36. For example, pressure buffering of the seasonal CO_2 cycle in excess of that calculated by Leighton and Murray (*4*) might arise through additional semiannual heat exchange by direct conductive transfer of heat into and out of thick water-ice deposits in the residual cap. Water-ice might be a much more effective seasonal heat reservoir than solid CO_2 because of its great stability. Alternatively, Fanale and Cannon (*21*) suggest buffering by a large reservoir of adsorbed CO_2 in the martian regolith.
37. G. Briggs (personal communication) has proposed an extreme but interesting extension of our concept of a CO_2 reservoir capped with water-ice. Briggs wondered if the water-ice could effectively and indefinitely seal off the solid CO_2 from atmospheric interaction. We do not think this is likely for reasons based on long-term climatic changes on Mars. Obliquity variations occur on Mars (*23*) which will cause extreme short-term variations in the insolation received at the poles—so large, in fact, that the equilibrium pressure regime for CO_2 (solid) varies by nearly two orders of magnitude on a 50,000-year time scale. We believe that this is too rapid and too major a variation to allow isolation. Similarly, if we assume that the meteorite flux at Mars is equal to or ten times larger than the rate of the moon, we estimate impact rates at the polar regions that would produce at least one 100-m crater in 1000 years. This would effectively break any water-ice seal of the CO_2 reservoir.
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40. We exclude any hypothetical early martian episode when enormous quantities of the substance were somehow lost through escape or surface combination. Furthermore, the present earthlike abundance of CO_2 in the atmosphere of Venus argues for the persistence of CO_2 in the gaseous phase. If the maximum ad hoc estimates of Fanale and Cannon (*21*) for adsorbed CO_2 in the regolith were correct, the total CO_2 budget of Mars would be increased to approximately 2 percent of that of the earth—still a small fraction. Furthermore, this CO_2 would not be accessible to become part of the atmosphere under current conditions; the atmospheric equilibria would be virtually unchanged, and our limits on past atmospheric history would still apply.
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Food Production and the Energy Crisis

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By 1975 the world population is expected to reach 4 billion humans (*1*). As it continues to grow, there is increasing concern about ways to prevent wholesale starvation (*2*). Concurrently, an energy crisis (due to shortages and high prices) is expected as finite reserves of fossil fuels are rapidly depleted (*3, 4*). The energy crisis is expected to have a significant impact on food production technology in the United States and the "green revolution," because both systems of crop production depend upon large energy inputs.

Both the U.S. type of agriculture and the "green revolution" type of agriculture have been eminently successful in increasing crop yields through improved technology. The ratio of persons not on farms to each farm worker in the United States increased from 10 in 1930 to 48 persons in 1971 (*5, 6*). This has lead to great social change as numbers of unemployed, untrained farm laborers migrated to our cities (*7*). In addition, the costs to the natural environment have been great, as is reflected in depleted soils, pollution, disruption of natural plant and animal populations, and natural resource shortages. One nonrenewable resource fast being depleted is fossil fuel—the most important element in the impressive yields and quality of agriculture in the United States. Energy is used in mechanized agricultural production for machinery, transport, irrigation, fertlizers, pesticides, and other management tools. Fossil fuel inputs have, in fact, become so integral and indispensable to modern agriculture that the anticipated energy crisis will have a significant impact upon food production in all parts of the world which have adopted or are adopting the Western system.

As agriculturalists, we feel that a careful analysis is needed to measure energy inputs in U.S. and green revolution style crop production techniques. Our approach is to select a single crop, corn (maize), which typifies the energy inputs for crops in general, and to make a detailed analysis of its production energy inputs. With the data on input and output for corn as a model, an examination is then made of energy needs for a world food supply that depends on modern energy intensive agriculture. Using corn as an example, we consider alternatives in crop production technology which might reduce energy inputs in food production. Other than recognizing the high costs of U.S. energy intensive agriculture, we make no effort to examine any of the projected economic, sociological, or political "trade-offs" in the United States or other countries when the energy crisis upsets the world community (*8*).

Energy Resources

As fossil fuel resources decline, the costs of obtaining fuels both from domestic and foreign sources will rapidly increase. If current use patterns continue, fuel costs are expected to double or triple in a decade (*4*) and to increase nearly fivefold by the turn of the century (*9, 10*). When energy resources become expensive, significant changes in agriculture will take place.

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