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The Prospects for Life on Mars: A Pre-Viking Assessment

CARL SAGAN

Laboratory for Planetary Studies, Cornell University,
Ithaca, New York 14853

AND

JOSHUA LEDERBERG

Department of Medical Genetics, Stanford University Medical School,
Stanford, California 94305

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Mariner 9 has provided a refutation or reinterpretation of several historical claims for Martian biology, and has permitted an important further characterization of the environmental constraints on possible Martian organisms. Four classes of conceivable Martian organisms are identified, depending on the environmental temperature, T, and water activity, a_w: Class I, high T, high a_w; Class II, low T, high a_w; Class III, high T, low a_w; and Class IV, low T, low a_w. The Viking lander biology experiments are essentially oriented toward Class I organisms, although arguments are given for the conceivable presence on Mars of organisms in any of the four classes. Organisms which extract their water requirements from hydrated minerals or from ice are considered possible on Mars, and the high ultraviolet flux and low oxygen partial pressure are considered to be negligible impediments to Martian biology. Large organisms, possibly detectable by the Viking lander cameras, are not only possible on Mars; they may be favored. The surface distribution of Martian organisms and future search strategies for life on Mars are discussed.

INTRODUCTION

The Mariner 9 orbital mission to Mars obtained 7200 photographs of the entire planetary surface, hundreds of occultation profiles and infrared radiometric observations, and tens of thousands of ultraviolet and infrared spectra. Many of these data and a wide range of interpretations of geological and atmospheric phenomena on Mars have already been published. Our present task is to survey the further implications of these findings for the investigation of Martian biology in the next decade, beginning with the Viking mission.

Mariner 9 was not designed to detect life on Mars, nor did it. Only the most extraordinary contingencies would have allowed direct evidence of life to be sensed by the photographic and other instrumentation of this mission. The most important contribution to biological studies was rather in refining our knowledge of Martian habitats and thereby in specifying boundary conditions that any organisms would have to meet in order to survive on Mars at the present time. In addition, the history of Mars is now perceived to be one of surprising complexity, relieving some of the previously held constraints on the evolution of life on that planet. Finally, some historical ground-based observations that had laid claims for relevance to the problem have now been refuted or drastically reinterpreted.

MARINER 9 AND HISTORICAL CLAIMS FOR OBSERVATIONS OF MARTIAN BIOLOGY

These historical claims, and their refutation or reinterpretation, are now briefly

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summarized. A network of fine rectilinear markings reported on Mars by Schiaparelli and Lowell initiated one tradition of "evidence" for engineering constructions and an advanced civilization on the Martian surface. However, the reality of many of these markings has long been suspect (see, e.g., Antoniadi, 1930). No sign of their presence was obtained in the Mariner 4, 6, and 7 missions (Leighton *et al.*, 1969). Some smaller rectilinear features of probable tectonic origin, the long rift valley Vallis Marineris, and a few crater chains were uncovered by the Mariner 9 mission; but no Lowellian canals were found, and the locales of many of the classical rectilinear features show no hint of anomalous linear or other features (Sagan and Fox, 1975).

The Martian bright and dark areas vary their relative contrast both annually and irregularly; a biological interpretation of these changes also dates back to the 19th century and has had recent supporters (see, e.g., Slipher, 1962). The high spatial resolution and long time base of Mariner 9 have shown that such changes are almost certainly due to wind-transportable fine particulates, and no biological interpretation is required (Sagan *et al.*, 1972, 1973; Veverka *et al.*, 1974).

The apparent secular acceleration of Phobos, the innermost moon of Mars, interpreted as due to drag in the Martian atmosphere, led Shklovskii to propose an origin of Phobos as a hollow artifact of an advanced Martian civilization (Shklovskii and Sagan, 1966). High-resolution photography of Phobos by Mariner 9 has shown conclusively that it is an entirely natural and ancient satellite (Pollack *et al.*, 1972). In addition, the most recent reduction of the celestial mechanical data shows that there may be no large secular acceleration; and what secular acceleration there is can be understood in terms of body tides (Smith and Born, 1976; Pollack, 1976).

At 100m surface resolution, the Earth displays a remarkable checkerboard pattern due to human agricultural and urban constructs. Mariner 9 provided the first opportunity to examine Mars at adequate coverage and resolution to detect such a pattern on that planet, should it exist (Sagan and Wallace, 1971). No such features were found. Some peculiar geometric features were uncovered, but they are amenable to abiological interpretations, particularly when account is taken of the high Martian winds (cf. Sagan, 1975).

Thus, Mariner 9 was able to exclude four previous hypotheses on Martian biological activity. These negative results, however, leave the question of life on Mars open, as it was before the Mariner 9 mission. Some prejudgments and simple hypotheses have been excluded, but no critical tests have yet been performed.

WATER

The availability of liquid water as a solvent for indigenous molecular biology appears to be the most stringent limiting factor for possible Martian biology. However, the water need be liquid only *within* the organism. Even on Earth, organisms are known which acquire water in the vapor phase under high humidities from the air (e.g., spanish moss, lichens), or metabolically from foodstuffs (e.g., desert rodents). Growth of terrestrial microorganisms is known at least down to −15°C and the germination of spores down to −25°C (see, e.g., Packer *et al.*, 1963). The corresponding water activities a_w (numerically equivalent to relative humidities) are about 0.85 to 0.70. Unfortunately, there has been no systematic search for ultimate limits on a_w, nor any real understanding of the mechanisms that determine such limits. Less well-documented claims of growth down to −20 and −25° appear in the literature, but they cannot be accepted without critical reexamination.

From time to time, brines are invoked as possible eutectic point depressors below 0°C, but many other factors may influence the microenvironment of an organism to permit it to flourish in or on bulk ice. For example, many bacteria do not have a well-defined outer boundary. They secrete a mucopolysaccharide gum or capsule in which water should dissolve even from an ice interface, and allow the absorption of water at subzero temperatures: a kind of portable tethered antifreeze. These gummy layers on microbes are sometimes microns thick, often exceeding the diameter of the bacterium itself. Similar substances are employed by antarctic fish to maintain the fluidity of their circulatory fluids.

In addition to hypothesized environments for liquid water on Mars, discussed below, there is direct evidence for water vapor in the Martian atmosphere, water ice in the Martian polar caps, and water of crystallization in the Martian surface materials. Subsurface permafrost must also exist because the planet is outgassed and the mean temperatures are below the freezing point of water. The distribution of these various forms of water substance may be heterogeneous both in space and in time. Thus, under rather parochial assumptions about the indigenous biochemistry, the question is whether there are (T, a_w) pairs suitable for a conceivable Martian biology.

FROST

Now that extensive vulcanism is known to exist on Mars, as well as probable thermokarst terrains (Sharp *et al.*, 1971; Belcher *et al.*, 1971) a previous suggestion (Lederberg and Sagan, 1962) that there may be locales of geothermal penetration of the subsurface permafrost layer and consequent patches of subterranean liquid water appears somewhat more plausible. It has also been suggested (Sagan *et al.*, 1968; Farmer, 1976) that ice, deposited in soil interstices, may enter a temporary liquid phase due to the soil diffusion barrier. If the soil can hinder evaporation long enough for the ice to reach −10°C, that would be enough for many terrestrial microbes. And it is of course plausible that Mars-adapted microbes would extend those boundaries further (e.g., by creating low-albedo microenvironments), especially as they would not simultaneously have to be armed against drowning in higher water activities at above-zero temperatures.

Heterogeneities of water abundance with time occur on diurnal, annual, and long-term climatic change time scales. Even at equatorial latitudes, the surface temperature drops below the frost point of the atmospheric water-vapor partial pressure before dawn each Martian day. The amount of water that is actually deposited on the ground is still uncertain, but a few micrometers per night might support a steady-state biomass as thick as a cover of moss or lichens. The problem is to estimate the frost thickness that will survive temperatures up to the −10°C range; and to seek means by which colder frost can be sequestered by the postulated frost eaters, described below.

The Martian polar caps vary in extent with the seasons, reaching in winter down to about 60° latitude. This annually varying component is probably mostly frozen carbon dioxide, although some frozen water will partake of the annual cycle. Temperatures low enough to freeze carbon dioxide are certainly low enough to freeze water. The permanent polar cap is thought to have considerably larger amounts of frozen water (Murray *et al.*, 1972). A local slope of $X°$ at low latitudes is the temperature equivalent of an increment of $X°$ latitude on a smooth surface (see, e.g., Balsamo and Salisbury, 1973). Thus, a boulder at 30° latitude with a 30° slope will have the same temperature for half a Martian year as a smooth surface at 60° latitude. In addition, the temperatures within the boulder shadow are determined largely by radiation; convective heat exchange with the atmosphere and conductive heat transport in the porous surface are both very low. Permanent shadows can be significantly colder than their surroundings and the progressive buildup of frost in such shadows can be expected. At polar latitudes, much larger quantities of water substance change phase. A vertical polar organism might manage high T and high a_w simultaneously. Because the Martian year is twice as long as the terrestrial, very high temperatures can be achieved in midsummer at Martian polar latitudes, including temperatures above the freezing point of water. Thus the edge of either polar cap in midsummer is another potential habitat of interest for conceivable Martian organisms.

POSSIBLE CLEMENT EARLIER ENVIRONMENTS

The Martian polar laminae (Murray *et al.*, 1972) and particularly the sinuous dendritic channels (Sagan *et al.*, 1973; Milton, 1973; Carr, 1974; Pieri, 1976) suggest a significant climatic variability of the Martian environment. For many of the channels no plausible alternative to flowing surface liquid water has been offered; although some investigators believe that extensive surface liquid water on Mars is so unlikely that they would wish to reserve judgment on the matter. At least one specific numerical model giving climatic variations from environments more severe than the present Martian environment to Martian climates rather close to the present terrestrial climate has been proposed (Sagan *et al.*, 1973). The period for such climatic variation is of course not well determined; but the shortest of the climatic time scales calculated in the preceding reference are $\sim 10^5$ yr; the ages of some channels of intermediate size (Pieri, 1976) suggest the longest of these time scales to be $\sim 10^9$ yr. The time scale for the origin of life on Earth may have been significantly shorter than the earliest clement epoch on Mars. If such more-clement epochs existed in past Martian history, extensive liquid water would be available episodically; and it has been suggested that some subset of Martian organisms may be in cryptobiotic repose awaiting the return of wetter and warmer conditions (Sagan, 1971).

A CLASSIFICATION OF POSSIBLE MARTIAN BIOLOGIES

From the standpoint of an unreconstructed Earth chauvinist, we must strain at improbabilities in searching for congenial habitats on Mars. But to surrender the search is to give too little credit to the adaptive versatility of living organisms, a versatility whose boundaries are understood very poorly. Biological evolution has a major stochastic component, which makes biology more akin to history than to planetary physics. We will never be able to make precise predictive models in biology that will approach even the most difficult models of, e.g., planetary differentiation. We do not know, for example, how many alternative self-replicating molecular systems there might be other than nucleic acids.

In this spirit of seeking possible alternative ecological niches, we wish to offer four possible classes of Martian organisms associated with temperature/water ecological niches in the external environment (cf. Fig. 1):

Class I organisms. Organisms requiring high temperatures ($T \geqslant 240$K) and high water activities ($a_w \geqslant 0.7$). These requirements correspond to those of many known terrestrial organisms. Such organisms may flourish only during the presumed high water phase of Martian climatic variations; or they may inhabit soil interstices, which have temporary accumulations of liquid water arising from the diurnal cycle; or they may inhabit locales where the permafrost has been breached by geothermal activity, but the soil overburden keeps the vapor pressure high enough to cross the liquidus.

Class II organisms. Organisms inhabiting niches with low temperatures ($T \leqslant 240$K) and high water activities ($a_w \geqslant 0.7$). The low abundance of water vapor on Mars forces high humidities to occur at typical nighttime temperatures. It is known (Pollack *et al.*, 1970) that the hydration water of ferric oxide polyhydrates or other minerals can be in gas–mineral equilibrium with water vapor in the Martian atmosphere. The water vapor pressure must be very high within a few mean free paths of the surface. The Martian regolith can be regarded as a chemical as well as a physical buffer for water activity, which allows the kinetic persistance of favorable (T, a_w) microenvironments with appreciable departures from thermodynamic equilibrium. (See the cross-hatched region in Fig. 1.)

Class III organisms. Organisms inhabiting ecological niches of high temperature and low water activity. Such organisms are unknown on Earth, but there are no obvious physical impediments to their existence. Very deliquescent organisms

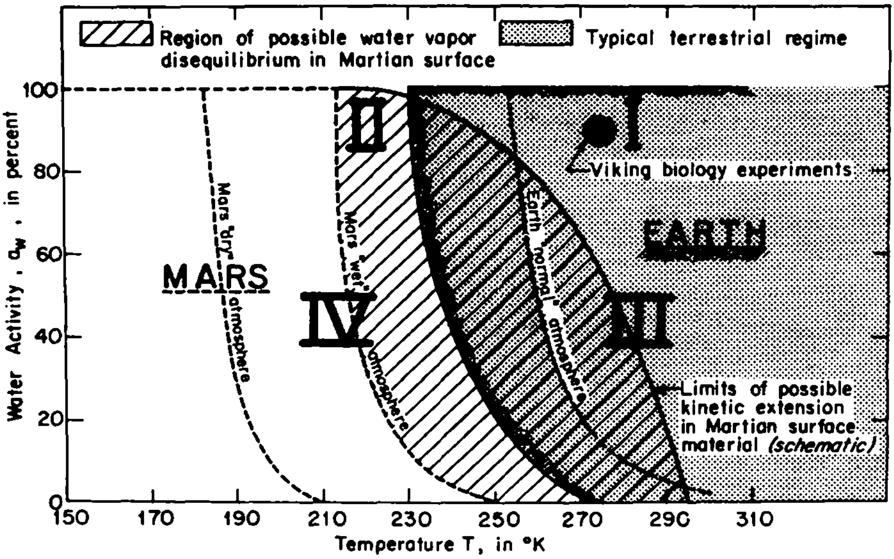

FIG. 1. A highly schematic representation of water activity/temperature space for Earth and Mars. The general provinces of Class I, II, III, and IV organisms, described in the text, are shown, as is the province of the bulk of the Viking biology experiments. The cross-hatched region shows a possible kinetic extension of the provinces of Mars on this diagram, due to departures from thermodynamic equilibrium near soil/atmosphere interfaces (cf. Farmer, 1976). The Martian province continues at high water activities to very low temperatures. Possible Martian excursion to high temperature/high water activity provinces, as, for example, in subsurface permafrost melted by internal heating, are not shown. The curve for Mars "dry" atmosphere corresponds to ~1 precipitable μm of water vapor; Mars "wet" atmosphere, to 100 μm; and Earth "normal" atmosphere, to 1 precipitable cm.

are one possibility. The metabolic concentration of rare materials, such as phosphorous or vanadium or niobium is well known among terrestrial organisms. Water substance is relatively much more available on Mars than these elements are on Earth, and concentration mechanisms are also known to exist. Indeed, the kidney function of mammals compared to fish is testimony to the remarkable evolutionary adaptations to water scarcity which are possible.

Class IV organisms. Organisms inhabiting low temperature and low water activity ecological niches. They are, by ordinary terrestrial standards, the most exotic. But technological *H. sapiens* is on occasion a Class IV organism. Martian surface minerals are known to have a bound water content ~1% (Houck *et al.*, 1973). This is probably some combination of physically and chemically bound water. The hydration bond energy corresponds to a few electron volts, or the mean energy of a solar near-ultraviolet photon which penetrates the Martian atmosphere. Class IV organisms would have to heat themselves metabolically as well as employ metabolic energy to extract moisture from surface minerals or ice. The lifetime for which such metabolic heating can be maintained varies directly with the size of the organism. Because of this argument concerning the area-to-volume ratio, there may be a strong selection pressure for Class IV Martian organisms to have large dimensions.

Class III and Class IV organisms may extract water from minerals or from ice in the arid Martian environment. Neither adaptation is known on Earth, but there has not been strong selection pressure for, and indeed there may have been evolutionary potential barriers against, their development on a wet planet. For future convenience, we propose calling organisms with such adaptations petrophages

(Greek, rock eaters) and crystophages (Greek, frost eaters), respectively.

Finally, we note that the internal environment of Class II, III, or IV organisms may be a Class I environment for parasites or commensual organisms.

ULTRAVIOLET FLUX

Except during a global dust storm, the ultraviolet flux at the surface of Mars in the 2000–3000 Å range is lethal to all terrestrial organisms. Nevertheless, this does not strike us as a significant hazard, and there are three conceivable adaptations, which have recently been discussed by Sagan and Pollack (1974). First, the organisms may carry many redundant copies, as do some terrestrial radiation-resistant species; or they may contain a genetic material which is not photolabile in near-ultraviolet light. Their genetic material might be simply nonabsorbing at these wavelengths or—if, for example, composed of many aromatic compounds—it may absorb but no bonds may be broken. Second, the efficiency of repair of ultraviolet damage to Martian genetic material may be more efficient than ours. Less than 10^{-2} of uv lesions escape terrestrial repair mechanisms (Jaggar, 1967). We cannot exclude the possibility that on Mars the number is 10^{-5} or 10^{-7}. Third, Martian organisms may be shielded from ultraviolet damage. Significant protection can be provided by tens of microns of nitrogeneous bases (Sagan, 1973a); or by a 1 cm depth of Martian surface particulates (Sagan and Pollack, 1974), a depth at which there may still be enough visible light for photosynthesis. Thus, Martian organisms may live in a surface habitat or may carry ultraviolet-absorbing shields around with them, like the exoskeletons of shellfish and insects. Such shields might also be useful for water conservation. If the shields are inorganic, they may provide an abundant fossil trace.

ATMOSPHERIC COMPOSITION

The primary constituents of the Earth's atmosphere are the products of biological activity. Oxygen is produced by green plant photosynthesis, and nitrogen by denitrifying bacteria. Even minor constituents such as carbon dioxide and methane are deeply involved in biological activities on Earth. The major constituent of the Martian atmosphere is CO_2, present in absolute abundance about 20 times the abundance of CO_2 in the terrestrial atmosphere. The carbon dioxide equivalent of the carbonates in the terrestrial sedimentary column is some 50 to 100 bars. The carbonate content of the Martian lithosphere is unknown. An upper limit to the N_2 abundance in the Martian atmosphere is $\sim 10^{-2}$ (Dalgarno and McElroy, 1970). Thus, the ratio of atmospheric N_2 to sedimentary CO_2 on the Earth is not inconsistent with the ratio of atmospheric N_2 to atmospheric CO_2 on Mars. The detectivity of N_2 in the Martian atmosphere should be greatly improved in the near future by mass spectrometers on Mars atmosphere entry probes.

Let us consider the case that the atmospheric N_2 abundance on Mars proves to be $\leqslant 10^{-2}$, or that the crustal carbonate content proves to be large. Then the N_2/CO_2 ratio would be significantly below the comparable value for the Earth. In the absence of denitrifying bacteria, nitrate nitrogen atoms would not be returned to the atmosphere as N_2. Thus a low N_2/CO_2 ratio on Mars may only indicate that denitrifying bacteria are not preeminent. This by no means excludes Martian biology, and biological exchange processes between nitrates and ammonia which do not involve gas phase N_2 can easily be envisioned. Indeed, because of the stricture for water conservation on Mars, Martian organisms may have major barriers to gas exchange, and the rarity of nitrogenous gases in the Martian atmosphere may be only a biological reflection of the underabundance of gaseous water in the present Martian atmosphere.

The mixing ratio $[O_2]/[CO_2]$ is $\sim 10^{-3}$ in the Martian atmosphere. Molecular oxygen is of course not necessary for even rather complex forms of life, as both obligate and facultative anaerobes on the Earth demonstrate. Conceivable electron transfer processes feasible for Mars, which do not involve molecular oxygen, have been discussed elsewhere (Vishniac *et al.*, 1966). Martian animals may metabolize organic material produced by Martian plants; or alternatively may live out a heterotrophic existence off carbohydrates produced by ultraviolet irradiation of the Martian atmosphere (see Hubbard *et al.*, 1971). Molecular oxygen does provide almost an order-of-magnitude improvement in the efficiency of the glycolytic pathways in terrestrial metabolism. Even if the molecular oxygen in the Martian atmosphere is not utilized for metabolism, we do not believe that the absence of aerobic metabolism on Mars excludes the presence of larger organisms.

The Viking biology experiments, with a terminal heating stage, can test the idea of Martian biological gas exchange barriers or directionally selective gas flow interfaces. Significant departures from thermodynamic equilibrium in a planetary atmosphere may be a strong indication of biological activity (Lovelock and Hitchcock, 1967; Lippincott *et al.*, 1967). However, the observed upper limits on minor constituents in the Martian atmosphere (Owen and Sagan, 1972) are far above the values required to make a significant test of departures from thermodynamic equilibrium (Lippincott *et al.*, 1967). The Viking atmospheric experiments might just conceivably perform such a confrontation.

Microbes and Macrobes

The widespread impression that if there is life on Mars it must be confined to microorganisms is a misunderstanding. Not all Martian ecological niches may be filled by primary photoautotrophs or chemoautotrophs: we saw earlier that the heat and water budgets at low Martian temperatures provide a premium for low area-to-volume ratios, and therefore a selective advantage for large organisms, which we here call macrobes. There may be other vicissitudes of the Martian environments which can be better managed by macrobes than by microbes.

Martian macrobes have the advantage that they can be detected without assumptions on their biochemistry. A lander imaging experiment, for example, can detect an unusual biogeometry even if the macrobe's metabolism is very exotic. These considerations also suggest that macrofossils may be a suitable objective of Martian landed imagery experiments, especially on a rover. Living and dead fossils are possible: living fossils being the dormant forms of macrobes which flourish during the favorable segment of the presumed Martian climatic cycle; and dead fossils being of the usual sort, of organisms which flourish at any time in these cycles. We have already mentioned the possibility of ultraviolet shields as a dominant fossil form. The hint of geological stratification in the Martian polar laminae and, for example, in the interior cliffs of Vallis Marineris suggests particular sorts of locales in searches for fossils.

Distribution of Organisms

All categories of Martian organisms discussed above, Classes I through IV, may have an essentially global distribution. Even Class I organisms, which require high temperatures and high water activities, are conceivable in the summer circumpolar regions. However, some habitats, such as underground thermal springs, may have a very limited distribution. If the only life on Mars lives in such habitats, then Martian biology is restricted to microenvironments. However, there is observational evidence that even underground springs may have a substantial distribution. The so-called chaotic terrain is most likely thermokarst produced by melting and lateral flow of subsurface permafrost (Sharp *et al.*, 1971; Belcher *et al.*, 1971). Chaotic terrain covers more than 1% of the Martian surface. Indeed, several of the major sinuous channels are discovered emanating from chaotic terrain, and there seems to be a substantial possibility of extensive underground river systems on contemporary as well as on ancient Mars.

If Martian biology is ubiquitous (Class IV organisms, for example), reproduction in place may be expected. However, there are many cases where aeolian transport of dispersules would have a high selective advantage on as windy a planet as we know Mars to be—including isolated microenvironments, and habitats which are unstable or unpredictable for relatively short periods of time. Especially to the extent that unoccupied ecological niches appear, due to climatic or tectonic activity, such aeolian dispersion may be expected. Dispersules carried easily by high Martian winds can have diameters of at least hundreds of microns (see, e.g., Sagan *et al.*, 1972). This permits aeolian transport of macrobial as well as microbial dispersules (cf., e.g., fern spores or pine tree pollen). As on Earth, macrobial dispersules can be generated in apparent extravagance and still not be a significant fraction of the biomass.

SPACECRAFT STRATEGIES

Such considerations of course affect choices of landing sites on Mars in searches for indigenous biology. If Class IV organisms exist, or if airborne dispersules are common, all places on Mars may be of almost equal value in the search for life. Alternatively, on the microenvironment hypothesis, only certain locales, occupying a small fraction of the Martian surface area, are suitable for exobiological investigations. Apart from engineering considerations, Viking landing site selection attempted to optimize these strategies. A latitude of 21° was selected for the prime and backup sites of the A mission; and a latitude of 44° was selected for the prime and backup sites of the B mission. A low-latitude site may optimize the chances of discovering Class III organisms; and a high-latitude site, the chances of finding Class II organisms. A latitude of 44° is of course not polar, and it represents a compromise which, however, hopes to take advantage of the yearly accumulation of frost.

There is some observational evidence for higher water vapor abundances at such middle latitudes (Farmer, 1976; Barker, 1976). However, any Martian latitude poleward of 23° is inaccessible to quasi-specular radar reflectivity studies. A significant fraction of potential Viking landing sites at low latitudes which appear suitable to Mariner 9 B-frame photography have distressingly low radar reflectivities (cf. Lipa and Tyler, 1976), due either to high roughness or to high porosity and consequent low bearing strength, either contingency posing serious potential problems for the Viking landings. Thus, the B-site landing decision depends on whether the arguments for liquid water at 44°N are sufficiently persuasive in a biological context to offset the additional dangers of the landing site in an engineering context. The authors of the present paper find themselves in disagreement on this vexing issue.

The prime site of the A mission is in Chryse near the confluence of several sinuous channels, where it may be possible to find dormant or possibly even contemporary Class I organisms. However, even a simple comparison with comparable landing sites on the Earth shows that more than a few landers are necessary to perform an adequate characterization of planetary biology (Sagan, 1973b).

The explicit biology experiments on the Viking 1976 landers (Klein *et al.*, 1972; Horowitz *et al.*, 1972; Levin, 1972; Oyama, 1972) are, largely for engineering reasons, mainly directed to searches for Class I microbes, either active or dormant; the one exception, which will search for Class III and IV microbes, is the pyrolytic fixation option, but this has the disadvantage of a relatively short time base. It is conceivable but unlikely that the range of conditions in these experiments will overlap the active range of organisms primarily adapted to Classes II, III, or IV. The lander cameras can detect life of any class; but only if it is macrobial, nearby, and slow-moving (Mutch *et al.*, 1972)—or leaves footprints.

Thus, while Viking 1976 represents a significant first step in the *in situ* search for a Martian biology, negative results would exclude an important subset, but only a subset, of the possible classes of Martian organisms. Whether Viking 1976 succeeds or fails, however, subsequent landed spacecraft on Mars should have a wider range of biology experiments, able to search for a broader spectrum of conceivable Martian organisms. The design of instrumentation and mission strategies to search for Martian microbiota of Classes II, III, and IV could begin even before results from Viking 1976 on microbes of Class II are fully analyzed.

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REFERENCES

ANTONIADI, E.-M. (1930). *La planète Mars.* Hermann, Paris.

BALSAMO, S. R., AND SALISBURY, J. W. (1973). Slope angle and frost formation on Mars. *Icarus* **18**, 156–163.

BARKER, E. S. (1976). Martian atmospheric water vapor observations: 1972–74 apparition. *Icarus* **28**, 247–268.

BELCHER, D., VEVERKA, J., AND SAGAN, C. (1971). Mariner photography of Mars and aerial photography of Earth: Some analogies. *Icarus* **15**, 241–252.

CARR, M. H. (1974). The role of lava erosion in the formation of lunar rilles and Martian channels. *Icarus* **22**, 1–23.

DALGARNO, A., AND MCELROY, M. B. (1970). Mars: Is nitrogen present? *Science* **170**, 167–168.

FARMER, C. B. (1976). Liquid water on Mars. *Icarus*, **28**, 279–289.

HOROWITZ, N., HUBBARD, J. S., AND HOBBY, G. L. (1972). The carbon-assimiliation experimont: The Viking Mars lander. *Icarus* **16**, 147–152.

HOUCK, J. R., POLLACK, J. B., SAGAN, C., SCHAACK, D., AND DECKER, J. A. (1973). High altitude infrared spectroscopic evidence for bound water on Mars. *Icarus* **18**, 470–480.

HUBBARD, J. S., HARDY, J. P., AND HOROWITZ, N. H. (1971). Photocatalytic production of organic compounds from CO and H_2O in a simulated Martian atmosphere. *Proc. Nat. Acad. Sci. USA* **68**, 574–578.

JAGGER, J. (1967). *Introduction to Research in Ultraviolet Photobiology.* Prentice–Hall, Englewood Cliffs, N. J.

KLEIN, H. P., LEDERBERG, J., AND RICH, A. (1972). Biological experiments: The Viking Mars lander. *Icarus* **16**, 139–146.

LEDERBERG, J., AND SAGAN, C. (1962). Microenvironments for life on Mars. *Proc. Nat. Acad. Sci. USA* **48**, 1473–1475.

LEIGHTON, R. B., HOROWITZ, N. H., MURRAY, B. C., SHARP, R. P., HERRIMAN, A. H., YOUNG, A. T., SMITH, B. A., DAVIES, M. E., AND LEOVY, C. B. (1969). Mariner 6 and 7 television pictures: Preliminary analysis. *Science* **166**, 49–67.

LEVIN, G. V. (1972). Detection of metabolically produced labelled gas: The Viking Mars lander. *Icarus* **16**, 153–166.

LIPA, B., AND TYLER, G. L., (1976). Surface slope probabilities from the spectra of weak radar echoes: Application to Mars. *Icarus*. **28**, 301–306.

LIPPINCOTT, E. R., ECK, R. V., DAYHOFF, M. O., AND SAGAN, C. (1967). Thermodynamic equilibria in planetary atmospheres. *Ap. J.* **147**, 753–766.

LOVELOCK, J. E., AND HITCHCOCK, D. R. (1967). Life detection by atmospheric analysis. *Icarus* **7**, 149–159.

MILTON, D. J. (1973). Water and processes of degradation in the Martian landscape. *J. Geophys. Res.* **78**, 4037–4048.

MURRAY, B. C., SODERBLOM, L. A., CUTTS, J. A., SHARP, R. P., MILTON, D. J., AND LEIGHTON, R. B. (1972). Geological framework of the south polar region of Mars. *Icarus* **17**, 328–345.

MUTCH, T. A., BINDER, A. B., HUCK, F. O., LEVINTHAL, E. C., MORRIS, E. C., SAGAN, C., AND YOUNG, A. T. (1972). Imaging experiment: The Viking lander. *Icarus* **16**, 92–110.

OWEN, T., AND SAGAN, C. (1972). Minor constituents in planetary atmospheres: Ultraviolet spectroscopy from the Orbiting Astronomical Observatory. *Icarus* **16**, 557–568.

OYAMA, V. I. (1972). The gas exchange experiment for life detection: The Viking Mars lander. *Icarus* **16**, 167–184.

PACKER, E., SCHER, S., AND SAGAN, C. (1963). Biological contamination of Mars. II. Cold and aridity as constraints on the survival of terrestrial microorganisms in simulated Martian environments. *Icarus* **2**, 293–316.

PIERI, D. (1976). Distribution of small channels on the Martian surface. *Icarus* **27**, 25–50.

POLLACK, J. B. (1976). The Martian satellites. In *Planetary Satellites* (J. Burns, Ed.). University of Arizona Press, Tucson. In press.

POLLACK, J. B., PITMAN, D., KHARE, B. N., AND SAGAN, C. (1970). Goethite on Mars: A laboratory study of physically and chemically bound water in ferric oxides. *J. Geophys. Res.* **75**, 7480–7490.

POLLACK, J. B., VEVERKA, J., NOLAND, M., SAGAN, C., HARTMANN, W. K., DUXBURY, T. C., BORN, G. H., MILTON, D. J., AND SMITH, B. A. (1972). Mariner 9 television observations of Phobos and Deimos. *Icarus* **17**, 394–407.

SAGAN, C. (1971). The long winter model of Martian biology: A speculation. *Icarus* **15**, 511–514.

SAGAN, C. (1973a). Landing on Mars. *Nature* (*London*) **244**, 61.

SAGAN, C. (1973b). Ultraviolet selection pressure on the earliest organisms. *J. Theoret. Biol.* **39**, 195–200.

SAGAN, C. (1975). The recognition of extraterrestrial intelligence. *Proc. Roy. Soc. London B* **189**, 143–153.

SAGAN, C., AND FOX, P. (1975). The canals of Mars: An assessment after Mariner 9. *Icarus* **25**, 602–612.

SAGAN, C., LEDERBERG, J., AND LEVINTHAL, E. C. (1968). Contamination of Mars. *Science* **159**, 1191–1196.

SAGAN, C., AND POLLACK, J. B. (1974). Differential transmission of sunlight on Mars: Biological implications. *Icarus* **21**, 490–495.

SAGAN, C., TOON, O. B., AND GIERASCH, P. J. (1973). Climatic change on Mars. *Science* **181**, 1045–1049.

SAGAN, C., VEVERKA, J., FOX, P., DUBISCH, R., FRENCH, R., GIERASCH, P., QUAM, L., LEDERBERG, J., LEVINTHAL, E., TUCKER, R., EROSS, B., AND POLLACK, J. B. (1973). Variable features on Mars. II. Mariner 9 global results. *J. Geophys. Res.* **78**, 4163–4196.

SAGAN, C., VEVERKA, J., FOX, P., DUBISCH, R., LEDERBERG, J., LEVINTHAL, E., QUAM, L., TUCKER, R., POLLACK, J. B., AND SMITH, B. A. (1972). Variable features on Mars: Preliminary Mariner 9 television results. *Icarus* **17**, 346–372.

SAGAN, C., AND WALLACE, D. (1971). A search for life on Earth at 100 meter resolution. *Icarus* **15**, 515–554.

SHARP, R. P., SODERBLOM, L. A., MURRAY, B. C., AND CUTTS, J. A. (1971). The surface of Mars. II. Uncratered terrain. *J. Geophys. Res.* **76**, 331–342.

SHKLOVSKII, I. S., AND SAGAN, C. (1966). *Intelligent Life in the Universe.* Holden–Day, San Francisco.

SLIPHER, E. C. (1962). *Mars.* Lowell Observatory Flagstaff, Ariza.

SMITH, J., AND BORN, G. (1976). Secular acceleration of Phobos and Q of Mars. *Icarus* **27**, 51–54.

VEVERKA, J., SAGAN, C., QUAM, L., TUCKER, R., AND EROSS, B. (1974). Variable features on Mars. III. Comparison of Mariner 1969 and Mariner 1971 photography. *Icarus* **21**, 317–368.

VISHNIAC, W., ATWOOD, K. C., BOCK, R. M., GAFFRON, H., JUKES, T. H., MCLAREN, A. D., SAGAN, C., AND SPINRAD, H. (1966). A model of Martian ecology. In *Biology and the Exploration of Mars* (C. S. Pittendrigh, W. Vishniac, and J. P. T. Pearman, Eds.), pp. 229–242. National Academy of Sciences–National Research Council, Washington, D.C.