What the exploration of Mars tells us about Earth

The fabulous success of the Viking mission to Mars has thrown new light on questions such as plate tectonics, climatic changes and the early history of atmospheres and life on Earth.

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The success of the Viking missions has a special significance for the student of planetary evolution who considers such questions as: How did the atmosphere and oceans originate on Earth? What circumstances created the benign environments at the surface of Earth so that the first synthesis of living organisms could take place three to four billion years ago? What do continental drift, earthquakes, and other surface tectonic and volcanic activity indicate about the interior and its evolution? What stimulates a long-term climatic change—such as an ice age? It is interesting that the experiments being performed by Viking[1] touch on each of these questions and that data from Mars will contribute significantly to scientific progress in these fields. In essence we are trying to understand why Earth and Mars evolved so differently (see figure 1).

While the greater popular fascination rests with the origin and evolution of life and the fluid envelope on which it depends, a more logical cause-to-effect progression through these four questions would be:

- What is the thermal and compositional evolution of a terrestrial planet interior? What factors influence it, and what are its surface manifestations?
- What is the origin of ocean and atmospheres, and how does it depend on outgassing from the interior?
- What primitive oceanic and atmospheric environment led to the origin of life on Earth?
- How has this fluid environment subsequently evolved, and why? What are the evidences for and causes of climatic change on Earth and Mars?

Let us examine each of these questions in turn, with emphasis on the enlightenments afforded by the Viking findings.

Internal evolution and surface tectonics

The surface of Earth has been shaped by thermal convection in the mantle, its interactions with the lithosphere and the separation of the crust. The direct evidence for major changes in the shape of Earth's surface, clarified in recent years, is plate tectonics: Motion of a few centimeters per year of the rigid segments or "plates" of the lithosphere is the mode by which continents are moved, resulting in the opening of ocean basins and, at the margins, the formation of mountain ranges. The average heat flow out of the Earth, combined with the rate of postglacial response, indicates a ratio of heat sources to viscosity (Rayleigh number, in fluid dynamicists' jargon) some orders of magnitude in excess of the minimum necessary for convection to prevail.

This convection is severely modified from simple laboratory examples, not only by the greater scale of the system but also by severe temperature dependence of material properties, highly non-uniform partitioning of radioactive heat sources upon differentiation, variation of material properties with relatively slight volatile content, phase transitions and other factors. The current plate-tectonic pattern of the Earth is the consequence of a complex thermal and compositional evolution that evidently has far from run its course, since estimates of crustal uranium, thorium, and potassium content[2] do not account for more than a third of the 60–80 ergs/cm^2/sec average heat flow out of the Earth.

Among the examples of inhomogeneity that have attracted considerable attention are "hot spots," regions of marked volcanism that appear to be much slower-moving relative to the mantle than are the tectonic plates. Over 100 such hot spots have been identified,[3] among them Hawaii, Yellowstone, and Iceland. Volcanism is plausibly, though not necessarily, associated with an upward stream of solid-state convection. It is characteristic of any flow that features of the system necessarily move about at rates slower than the material velocities; hence the meaningful question is whether the hot spots are fixed on geological time scales of some hundreds of millions of years. If they are, then they are probably associated with fixed "plumes" dependent on inhomogeneities in the mantle, because solutions for convection with contained heat sources always obtain a shifting about of the flow pattern to remove the heat from all regions. The terrestrial evidence on this problem is still unclear. Sea-floor remanent magnetism indicates that hot spots have moved at rates of 1–2 centimeters/year with respect to each other over the last 60 million years or so,[4] but trends in the ratios of radiogenic lead and other isotopic data indicate that source regions of ocean island basalts have remained separated from each other for durations on the order of two billion years.[5]

It would be good to test these ideas by looking at another planet that has volcanism but not plate tectonics. Photography of the Martian surface by Mariner 9 and Viking orbiters has revealed significant differences from Earth. Mountain ranges are virtually absent on Mars, yet there are volcanoes about five times larger than any on Earth. Mars also has a canyon that stretches for more than 2000 miles. Half of Mars's surface is

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heavily cratered, the other half being relatively smooth, but sprinkled with volcanoes, including one 30-km high (figure 2).

Comparisons and deductions

Study of these features on Mars and comparison with Earth, Moon and Mercury leads to the following deductions about Mars in particular and terrestrial planets in general:

▸ Convective and magmatic mechanisms on Mars have not been vigorous enough to break the lithosphere sufficiently to produce plate tectonics for at least a billion years.

▸ The large volcanoes on top of a high plateau could well result from a combination of fixed plumes and no plate motions on Mars: The volcanic material merely piles up in one region, rather than being strung out relative to the lithospheric plate (like the Hawaiian island chain). On the Moon, which also lacks plate tectonics, volcanism also appears to have come from a few vents,[6] but in this case a combination of thicker lithosphere and lower silica content (resulting in lower viscosity) led to lower volume flows ponding in the basins as maria.

▸ The giant canyon may be an example of "unsuccessful" initiation of continental drift on Mars: a consequence of a heat excess leading to tensile stress in the lithosphere. On Earth, the Red Sea and the African Rift Valley are examples of recent and incipient tension features leading to new plate-motion configuration, and there are many cases in the geologic record of failed rifts.[3]

▸ From gravimetric and altimetric data, the mean crustal thickness must be at least 50 km (for a crust–mantle density differential of 0.5 gm/cm^3), more than thrice the mean for Earth.[7]

The tectonic and volcanic differences discussed here are relatively recent and superficial manifestations of a more fundamental feature of terrestrial planets—their thermal and compositional evolution.[8] Given that the main energy source for convection and magmatism is the radioactive decay of uranium, thorium and potassium (more than a few hundred million years after formation); that the rate of this heat generation decreases with time (by a factor of four since solar system origin), and that these radioactive elements differentiate upward, then the inevitable end state of a planet is one of compositionally stratified quiescence.

What we have learned about Mars, Mercury, the Moon and Earth indicates that the degree to which a planet has approached this end state is an inverse function of size. The Moon is the "deadest" of the terrestrial bodies; it essentially ceased volcanic activity three billion years ago. We are not sure when Mars ceased major volcanic activity, because of the difficulty of cratering chronology: One-third to three billion years ago covers the range of estimates. This more rapid evolution of smaller bodies appears to be more than just the cooling consequent upon their higher area-to-mass ratio; the Moon, as well as Mars, has been much more efficient than Earth in differentiating a crust, and hence in moving radioactive heat sources upward. While variations in origin circumstances—initial temperature profile, complement of volatiles and radioactive elements, and so on—play some role, better understanding of how thermal and compositional evolution interact is needed to explain these differences in planetary state.[8]

Atmospheres and oceans

Most geologists agree that the current atmosphere and oceans of the Earth were exhaled from the interior through vol-

PHOTO: J. T. SCOTT

Contrasting planets. While water, vegetation and life are abundant on Earth, Mars at Chryse looks dry and sterile. Is this scene typical of Mars? If so, why is there such a difference between two neighboring planets? Figure 1 canic activity. In a classical paper written in 1951, William Rubey[9] examined thoroughly the evidence then available: "It is clear ...", he wrote, "that the more volatile materials—water, carbon dioxide, chlorine, nitrogen and sulfur—are much too abundant in the present atmosphere, hydrosphere, biosphere, and in ancient sediments, to be explained, like the commoner rock-forming oxides as the product of rock weathering alone." An inventory of these "volatiles" present today in and near the surface of the Earth (Table 1) speaks to the problem. Including the fraction that is buried in sedimentary rocks, we have, on an average, 330 000 gm/cm^2 of H_2O, about 80 000 gm/cm^2 of CO_2 buried as carbonate in the sediments (less than 1 gm/cm^2 is in the atmosphere), 7000 gm/cm^2 of Cl mainly in the form of NaCl in the oceans, 1000 gm/cm^2 of nitrogen mainly in the atmosphere, and 500 gm/cm^2 of S as sulphates in the oceans and sediments. According to Rubey and others only a very minute fraction of these, 1% or so, could be supplied by the weathering of crystalline rocks.

Where did these volatiles come from? Two hypotheses could be advanced. The first would presume that these volatiles are leftovers of all the gases that surrounded Earth when the planet had just accreted, 4.5 billion years ago. However, this hypothesis becomes immediately untenable when one compares the total amounts of the volatile elements present on the Earth with what Earth should have had if it accreted out of the material of the solar nebula. Table 2 shows that volatile elements, ranging from hydrogen to xenon, are missing from the Earth by a very large factor.[10-12] Note that the deficiency factors are particularly high for the inert gases, which do not combine chemically. These arguments were advanced as far back as 1949 by Harrison Brown and Hans Suess[13] to argue that Earth either lost all the volatiles soon after its formation or accreted out of material that was already deficient in these volatiles. The latter explanation is indicated by similar deficiency factors in meteorites, which must have come from small parent bodies.[14]

The second hypothesis presumes that the atmosphere and oceans have been exuded from Earth's interior through gases escaping from volcanoes, fumaroles and geysers. This hypothesis is favored mainly on the grounds that outgassing is occurring today and, more importantly, the relative composition of gases being exuded matches the composition of the "excess" volatiles. Another argument in favor of outgassing as the source of the current atmosphere is the fact that today's atmosphere contains as much as 10 gm/cm^2 (1%) of Ar^{40}. This element is extremely rare in the cosmos and is largely produced within the planet by the radioactive decay of K^{40} with a half life of 1.23×10^9 years. Calculations by a number of authors, especially Karl Turekian and Sidney Clark,[11,15] indicate that for a reasonable distribution of potassium, the atmospheric Ar^{40} can be explained by continuous degassing of Earth's outer layers. The argument therefore goes that if Ar^{40}, which we know is produced in the interior, has been exhaled, why not the other volatiles?

Although the hypothesis of an internal origin of the atmosphere and oceans is now widely accepted in principle, several major unanswered questions remain about the mechanism that led to today's conditions.

First, were all the volatiles that currently make up the atmosphere, hydrosphere, and the biosphere exhaled "suddenly" in the very early history of the planet, to be recycled ever since by the volcanic and other crustal activity? Or have they "grown" slowly as a function of time?

Second, was the composition of the early outgassing and the early atmosphere similar to that of today?

And third, what determines the rate of

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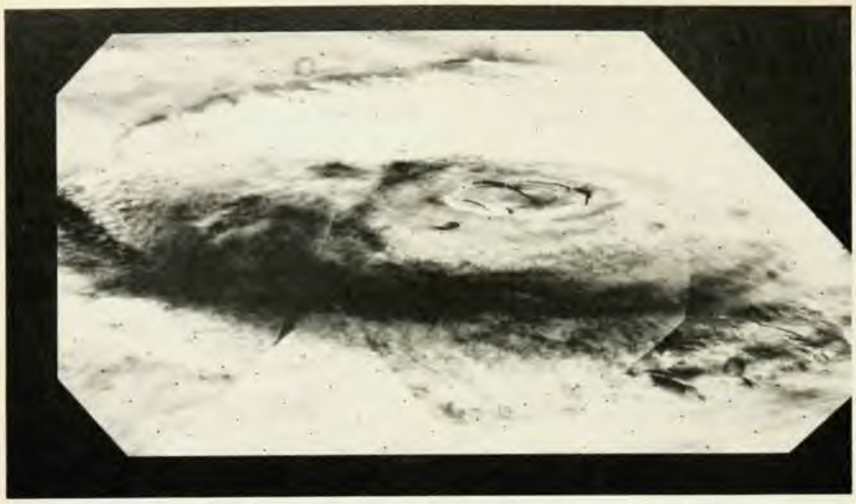


Olympus Mons, partly hooded by clouds. The summit caldera is 24 km high and 80 km across, and the full diameter is 600 km. NASA photograph no. 76-H-628. Figure 2

outgassing on a planet at any particular time? The obvious factors are the size of the planet, the extent of differentiation and the intensity of internal convection; the latter two in turn depend on the thermal evolution, starting from initial temperature, composition and radioactive heat sources.

Evidence from other objects

During the last decade a number of discoveries about the state of other objects in the solar system have given significant new insights into the problem of atmospheric evolution.

For example, careful and exhaustive analyses of a variety of meteorites have shown that even the most primitive (that is, the least affected by heat or shock), type I carbonaceous chondrites are deficient in heavy rare gases relative to the composition of the Sun by large factors. In fact, the deficiency factors in the ordinary chondrites[14] appear to be the same as on Earth (about 10^6). Since chondritic meteorites are the most plausible samples of the primordial material from which the terrestrial planets were formed, Earth and its neighbors apparently accumulated out of solid material that was already deficient in volatiles. Although hydrogen and helium make up the bulk of Jupiter and Saturn, solutions for their internal structures that account for their densities and shapes indicate that they must have rocky or icy cores at least ten Earth masses in size.[16]

The various kinds of meteorite have also been used as cosmothermometers and cosmobarometers to derive temperature and pressure conditions in the primitive solar nebula. John Larimer[17] infers a temperature range of 350–500K and a pressure range of 10^{-6} to 10^{-4} bar for formation of ordinary chondrites.

Spacecraft measurements of the terrestrial planets require that all of them, including the Moon, have been differentiated to some degree. Many theorists are now suggesting that the differentiation takes place very early in the history of the planet, during the terminal phases of planetary formation. Direct evidence of differentiation within the first 200 million years is given for the Moon and meteorites by radioisotopic ages. For Earth, the evidence rests on the plausible assumption that the upper-mantle ratio of uranium to lead would have increased markedly[18]; these elements tend respectively to move upward and downward on differentiation.

The atmospheres of Mars and Venus are largely CO_2. Mercury has a remarkably slight atmosphere (less than 10^{-11} of Earth's) and the Moon even less, although it may still be degassing Ar^{40} from its interior.

Accurate mass spectrometry of the Martian atmosphere performed by Viking has revealed the presence of N_2, Ne, Ar^{36}, Kr and Xe. Abundances of these gases on Mars[19,20] (Table 3), when compared with those in the meteorites and on Earth, can now be used to reflect on the outgassing history of both Earth and Mars.

These new findings suggest the following model of the evolution of the atmosphere and oceans. The terrestrial planets (and the cores of the major planets) formed from the solid condensed material in the solar nebula. The temperature of this nebula varied from perhaps 1000 K near the center to 100 K near the rim. Correspondingly there were many types of condensed material, but for simplicity we will group them into two classes: high-temperature and low-temperature condensates. The "rocky" material would contain large amounts of oxides and silicates rich in calcium, aluminum and titanium, along with metallic iron and magnesium silicate material, while the "icy" material would contain in addition large amounts of volatiles such as carbon dioxide, methane, water, nitrogen and rare gases. Therefore Earth, and by inference, the other terrestrial planets, started accreting in a hot solar nebula using material made up of high-temperature condensates. This protoearth was sufficiently heated by impacts for iron to melt (starting at the Fe–FeS eutectic, approximately 1000°C[21]), thus causing liquid iron and nickel to sink to the center, with release of further gravitational energy.

The separation of the core from the mantle probably took place *before* the entire planet completely accumulated. Evidence thereof is the disequilibrium between the core and the upper mantle.[22] With the passage of time the mantle cooled, and so did the solar nebula. It is hypothesized by some (for example, Edward Anders[23]) that Earth did not acquire its outermost layers until after this cooling and that the material was mainly low-temperature condensates rich in volatiles, resembling the composition of ordinary chondrites. Subsequently the upper layers of Earth were reheated by radioactive decay of K^{40}, U^{238}, U^{235}, and Th^{232}. Most of the volatiles trapped in the low-temperature condensate were then circulated to the surface and outgassed by volcanic activity.

A comparison of the relative amounts of carbon, hydrogen, nitrogen and rare gases present in the atmosphere, oceans, crust and upper mantle of Earth, compared with those in ordinary chondrites, shows a reasonable similarity (Table 4). As for the rare gases, the agreement seems to be better for ordinary chondrites than carbonaceous chondrites. Furthermore, when one compares the total absolute amounts of these elements on Earth with estimates of the concentration of these gases in ordinary chondrites, it appears that all the volatiles listed in Table 4 could be the result of complete outgassing of the upper 100 km of Earth.[24] There is thus a range of interpretations, from the foregoing inhomogeneous hypothesis, where the upper 100 km (5% by mass) is all that Earth has of the low-temperature condensates, which have been completely degassed, to one where volatiles were acquired throughout the accretion of the Earth, and have been only partially outgassed. The principal unknown is the rate of cooling of the nebula compared to the rate of accretion. Dynamical con-

Table 1. Volatiles on the surface of the Earth

	gm/cm^2
H_2O	330 000
CO_2	80 000
Cl	7 000
N_2	1 000
S	500
Ar, F, H, B, etc.	30

siderations indicate about 10^8 years for the latter,[26] but the former depends on ill-understood properties of the early Sun. Relevant terrestrial evidence is the extent to which outgassing was skewed to the early stages of evolution, which is also debatable.[27]

Evolution of the Martian atmosphere

Now, what about Mars? The recent measurements of the abundances of nitrogen and rare gases in the Martian atmosphere make it possible to discuss the processes that may have occurred on that planet in context of the mechanisms of planetary formation. According to nearly all models of the primitive solar nebula in the inner part of the solar system, Mars should contain relatively more of low-temperature condensates than Earth does. This supposition is based on the fact that Mars is located at 1.5 AU from the Sun and Earth at 1.0 AU. Furthermore, the decompressed density of Mars is more than ten percent less than that of Earth, which virtually requires that iron and nickel on Mars be less abundant than on Earth.[28] But the relatively high amount of low-temperature condensates does not necessarily mean that there should be large amounts of volatiles in the atmosphere. The amounts present at or near the surface would depend on the extent and rate of volcanic activity that has taken place on Mars. Table 5 shows the volatile inventory in the atmosphere of Mars as measured by Vikings 1 and 2, those that we expect from degassing of an 0.5-km-thick layer of ordinary chondrite material, and the differences.[24] A number of authors[29,30] have argued that these differences could be accounted for if some of the volatiles are present in the regolith of Mars or have escaped from the planet.

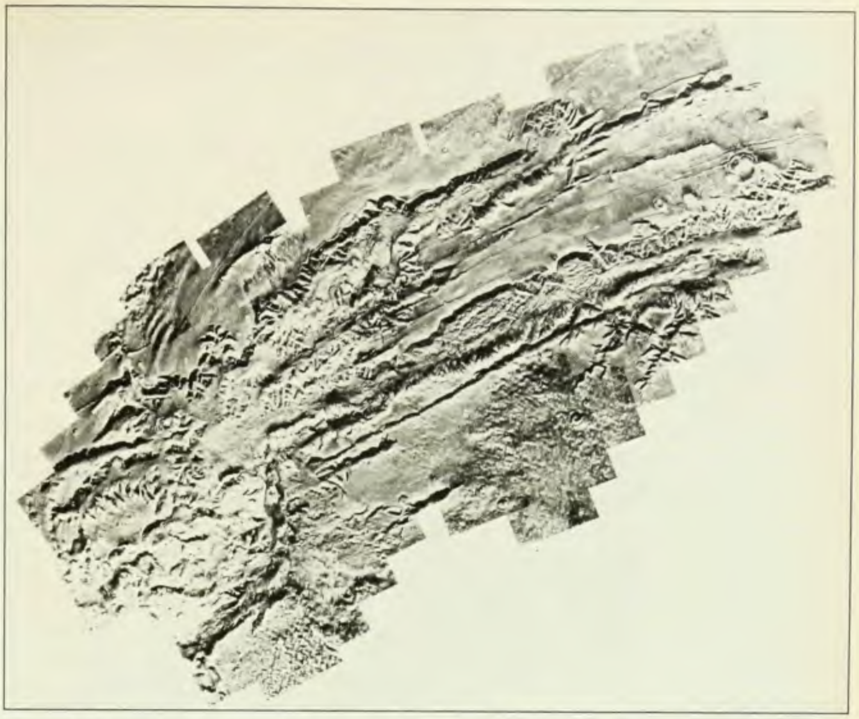
What conclusions might we draw from these and other Viking results about Mars and Earth?

▶ The relative abundances of the volatile elements on Mars could be about the same as on Earth and in ordinary chondrites; this fact argues in favor of the hypothesis that the outer layers of at least two of the terrestrial planets had a high concentration of low-temperature condensates.

▶ The current atmospheres and oceans of Earth, and the volatiles of Mars are a result of internal degassing.

▶ It is extremely implausible that Mars accumulated less than one percent of the low-temperature condensates of Earth; hence its degassing activity must have been much less than on Earth.

▶ If Mars originally had the same N^{15}/N^{14} ratio as Earth, the current 1.75-fold enrichment observed by Viking[19] could be generated in a period of 3 billion years by more rapid escape of the lighter isotope.[30] It follows that most of the outgassing on Mars took place during the first billion years.



A mosaic of part of Valles Marineris (Mariner Valleys), the huge complex of equatorial canyons on Mars. Evidence for landslides and faulting is abundant. The region shown in this photograph (NASA photograph no. 76-H-726) is about 1000 km across. Figure 3

▶ Viking observed Ar^{40}/Ar^{36} ratios on Mars to be about ten times higher than on Earth.[20] However, the problem of Ar^{40} in the atmosphere is decoupled from those of other rare gases because it is continuously produced by the radioactive decay of K^{40}. The amount of Ar^{40} in the Martian atmosphere corresponds to total outgassing to a depth of 6 km from a potassium content of 2000 ppm (the upper limit measured by Viking being 2500 ppm). This thickness is quite different from that calculated from other volatiles, namely 0.5 km, thus implying a different mechanism for the outgassing of Ar^{40} relative to other gases of the atmosphere.

▶ Earth and Mars differ in area/mass ratio by a factor of 2.7. However, the proportion of ocean and atmosphere outgassed differs by a factor well over 100. The relationship is obviously not linear. The most evident way in which the cooling effect of area/mass ratio affects outgassing is through the thickness of the *lithosphere*, the outer layer, which is

Table 2. Comparison of the compositions of the Earth and solar system

Element	Whole Earth[a]	Solar system[b]	Deficiency factor $\left(\log \frac{\text{solar system}}{\text{Earth}}\right)$
	atoms per 10^4 atoms of silicon		
H	250	3.2×10^8	6.1
He	3.5×10^{-7}	2.2×10^7	13.8
C	10	118 000	4.1
N	0.2	37 400	5.3
O	35 000	215 000	0.8
Ne^{20}	1.3×10^{-6}	34 400	10.4
Na	460	600	≈0
Mg	8900	10 610	≈0
Al	940	850	≈0
Si	(10 000)	(10 000)	0
Ar^{36}	2.5×10^{-6}	1 172	8.6
Kr^{84}	5.3×10^{-8}	0.26	6.7
Xe^{132}	2.0×10^{-8}	0.01	5.7

a. After B. Mason (ref. 10) and K. K. Turekian and S. P. Clark (ref. 11).
b. After A. G. W. Cameron (ref. 12).

mechanically strong because it is cold (to be carefully distinguished from *crust*, the layer of lower-density rock).

Manifestations of a lithosphere on Mars much thicker than on Earth include: a much rougher gravity field;[31] the great stresses necessary for static support of Olympus Mons (more than 500 bars for a lithosphere of less than 200 km thickness[32]); the great size and wide spacing between volcanoes; the large scale of tensile features, such as the great equatorial rift (figure 3), and the absence of plate tectonics.

Causative factors affecting lithospheric thickness and thence outgassing rate, are: abundancies of radioactive heat sources U, Th, K; the degree of upward differentiation of these heat sources into the crust; the abundance of volatiles, which can act to reduce melting temperatures by as much as 400°C, and the surface temperature. The principal unknown in extrapolating from Mars and Earth to Venus is the third of these, the volatile abundance.

The origin of life

An important finding of the Viking project is that the surface of Mars (at least at the two locations so far studied), does not contain organic molecules at the detectable limit of about 1 part per billion[33] (one part per million for a few light molecules such as methane). This result was obviously disappointing to exobiologists, partly because the experiments designed to detect metabolic activity in Mars were not unanimously negative, but ambiguous. We know that the relatively "sterile" soil of Earth's antarctic is populated by at least a factor of a hundred more organic molecules than on Mars, and that even some meteorites contain more organic matter than does the Martian surface.

What circumstances led to this intriguing situation on Mars? What are the implications for our concept of the origin of life on Earth? The ideas of Alexander Oparin and J. B. S. Haldane have many followers: They assume that the first organic compounds on Earth were synthesized in a reducing atmosphere through the action of solar ultraviolet radiation penetrating down to the lower depths. Slowly these molecules accumulated in the oceans, where they joined together to form the more intricate amino acids and subsequently the long chains of proteins, nucleic acids, and so on. Chemical evolution of life thus began on Earth about 3.5 billion years ago. These ideas appeared to be confirmed in the laboratory by a dramatic experiment of Stanley Miller in 1951, when amino acids were produced from CH_4, H_2O and NH_3 by an electric spark discharge. Similar synthesis using ultraviolet radiation was also achieved later.

Table 3. Composition of Martian atmosphere (by volume)

CO_2	95%
N_2	2.6%
Ar^{40}	1.6%
O_2	0.15%
Ar^{36}	5 ppm
Kr	0.3 ppm
Xe	0.08 ppm
N^{14}/N^{15}	≈160
Ar^{40}/Ar^{36}	≈3000

Data from refs. 19 and 20.

If this is how the chemical evolution of life began on Earth, a number of important questions should be answered:

▶ If Earth's early atmosphere was reducing in nature, what was its composition, how did it come about, how long did it survive, and how did it change to its present state?

▶ What was the extent and the pH of the oceans when the organic molecules began to accumulate?

▶ If the solar ultraviolet light was the main source of energy for the synthesis of organic molecules, which energy range was responsible for the synthesis, and how were these molecules subsequently protected from destruction by the very same ultraviolet radiation?

It is of course difficult to answer these questions when most evidence of what occurred at that time has disappeared; the main reason for the loss of the evidence is that biological activity itself has greatly changed those aspects of Earth's environment most relevant to the origin of life. This is why one main objective of the current space program is to determine the conditions existing on other planets, so that a coherent story of the development of a planet and of life on its surface can eventually be told.

Before we discuss the Viking results and their implications on these questions, it is important to mention a different and challenging suggestion made by Anders *et al.*[34] about the origin of organic compounds on Earth. Two recent discoveries have prompted these ideas. First, meteorites of the class known as Type I carbonaceous chondrites have been found to contain relatively large amounts of organic matter. Second, a variety of organic molecules has been detected in interstellar space. Anders and his colleagues argue that metastable hydrocarbons such as $C_{20}H_{42}$ could be synthesized in the solar nebula by catalytic reaction of CO and H_2 (the Fisher–Tropsch synthesis). With the inclusion of NH_3 and suitable catalysts, the origin of most of the organic molecules discovered in meteorites and in interstellar space could be explained. The argument then is that most of the prebiotic organic matter was delivered to Earth by meteoritic-size bodies (1 to 100 cm), which would survive atmospheric entry. Water erosion would subsequently bring these molecules into the oceans or lakes, and the chemical evolution of life could then proceed.

This thesis has important implications because it resolves the difficulty of having a reducing atmosphere in the beginning and it does not involve the dangerous penetration of the solar ultraviolet down to the surface layers, which could at once be destructive as well as constructive for the complex organic molecules.

Table 4. Volatiles on Earth, carbonaceous and ordinary chondrites

	H	C	N	Ne^{20}	Ar^{36}	Kr^{84}	Xe^{132}
	Concentrations in gm/cm²						
a Atmosphere, hydrosphere, crust, upper mantle	35 800	52 800	1955	1.3×10^{-2}	4.1×10^{-2}	3.5×10^{-3}	4.3×10^{-3}
b Carbonaceous chondrites (C 1)	34 300	(52 800)	4990	3.1×10^{-4}	2×10^{-3}	5.9×10^{-5}	7.6×10^{-5}
c Ordinary chondrites (LL)	24 200	(52 800)	3010	5.3×10^{-3}	3.6×10^{-2}	5.2×10^{-4}	6.4×10^{-4}
	Atom ratios						
Atom ratios, row a/row b	1.0	(1)	0.4	37	20	33	15
Atom ratios, row a/row c	0.7	(1)	0.67	2.1	1.08	3.8	1.8

Data normalized to carbon

Table from reference 24; data in row a from ref. 11, data in row b from ref. 25.

Hydrogen-content data in row c taken as 0.05% by weight (Geiss, private communication).

The Martian environment

Let us now examine more of the Viking results. Among the newly established facts are:

▶ organic molecules are very scarce on Mars at the two different locations

▶ the surface material is highly oxidizing

▶ water in the liquid phase has, at times, existed on Mars, but not as abundantly as on Earth and certainly not for the same length of time. Although this conclusion had already been reached from the orbital photographs of Mariner 9, some of the Viking pictures, such as the one in figure 4, are particularly striking.

▶ Water vapor is moderately abundant

in the summer hemisphere, in confirmation of the difficult telescopic measurements over the past decade.

- Mariner 9 confirmed what had been known for some time, that ultraviolet radiation down to 2000 Å reaches the surface.

Photochemical calculations based on these last two facts, and laboratory simulations, had already revealed that the surface environment must be highly oxidizing.[35] The fundamental point is very simple: 2000 Å photons dissociate H_2O into H and OH. The latter is probably the strongest oxidant in existence. Further reactions lead to HO_2 and H_2O_2, both of which readily freeze out at Martian surface temperatures. Hunten had pointed out that methane would be rapidly eliminated from the atmosphere by reaction with OH, and R. L. Huguenin had shown that the surface material itself would slowly be oxidized.[35] But by the time these studies were published it was too late to change the design of the Viking biology instruments. Peroxides in the soil do not explain all the results that these instruments obtained, but they go a good part of the way.

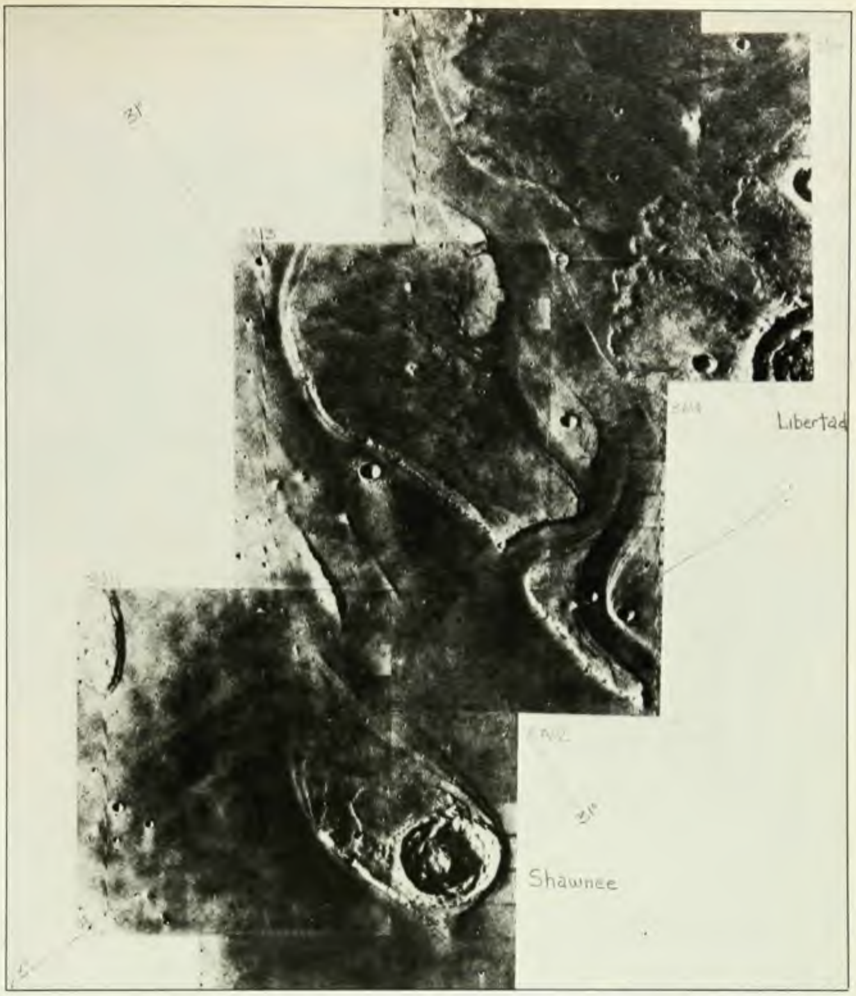
When we compare Earth and Mars, it is tempting to suppose that the Martian atmosphere may always have been highly oxidizing and therefore, highly unfavorable to the synthesis of prebiotic organic compounds. But this is not required by the observations: an early atmosphere of CH_4 and H_2O could have been converted to the present one by processes we see operating today, photolysis of water, oxidation of organics, and escape of hydrogen. The case for early reducing atmospheres in general is much less clear than it once seemed.

We can also infer that the present amount of gas in Mars's atmosphere is near the optimum for destruction of organic matter. The surface, the water vapor, and the short-wave ultraviolet are all present together. Growth of oxygen and ozone, which could shield the lower atmosphere, is also inhibited by the oxidants from water vapor photolysis.

Nevertheless, the balance between creation and destruction of complex organic molecules by solar radiation appears to be delicate. The destruction has not received enough attention in the past, and its prevalence on Mars tells us that we should consider its role on the primitive Earth.

We assume that a considerably thicker atmosphere gives a much more benign environment. Reservoirs of liquid water make a planet even more favorable for the preservation, accumulation and onward evolution of the organic matter. Earth probably acquired relatively large amounts early in its history, while Mars, being much colder, has most of its water tied up in the frozen state either at the poles or in the subsurface layers.

If, instead, the organic matter was delivered by chondritic material, the outer layers of Mars should be about as rich in original organic matter as Earth is. However, because the outgassing activity on Mars has been at least 100 times less efficient than on Earth, the chance of it arriving at the surface are 100 times smaller.



Meandering, intertwining channels flowing northward were vividly photographed by Viking in the Chryse region. Each frame is about 45 km across. NASA photograph no. 76-H-481. Figure 4

Climatic changes on Earth and Mars

Recent events have made us very aware of the major economic and social impacts of a seemingly small change of global weather patterns. A change in mean temperature of 1°C over a large part of the world would have enormous effects on agricultural productivity, both directly and through change in length of the frost-free growing season. Rainfall is even more critical. We know that much larger changes have occurred in the past; the latest ice age was at its peak only 18 000 years ago, and ended a mere 9000 years ago. In a sense, we are still in an ice age, with huge ice caps on Greenland and Antarctica. If they too were to melt, the resulting 30-meter rise of sea level might be more disastrous than the return of continental ice sheets.[36] Short-term changes, hurricanes, droughts, floods, and the like, are all too familiar.

In trying to understand the climatic system, we are faced with a complicated, nonlinear problem involving solar heat input, planetary radiation by atmosphere and surfaces, cloudiness, oceanic heat balance and circulation, and ice and snow. Clouds and snow cover affect the albedo of the planet and therefore the fraction of solar radiation that enters the system. It may be that the system has two (or more) metastable states, even if the external inputs remain the same. If so, it might be triggered from one state to another by seemingly minor changes. There is concern about the long-term increase of atmospheric CO_2 from the burning of fuel, and the (perhaps compensating) effect of haze and smoke.

Among the influences on the solar input are dynamical changes in Earth's motion: precession of the axis, changes in obliquity, and variation of orbital eccentricity. Since 1930, these "Milankovitch cycles" have been sought in the climatic record. Perhaps the hardest part of the problem has been to provide an accurate, uniform time base for the paleoclimatic data. A

Part of the residual north polar cap of Mars. The bright areas are water ice, and the terraces are presumably due to some geological cycle. NASA photograph no. 76-H-915. Figure 5

major step forward has come from the availability of deep-sea drill cores. Two such carefully chosen cores from the South Indian Ocean have given a record extending back 450 000 years.[37] They show periodicities of 21 000, 41 000, and 100 000 years, which are identified with cycles of precession, obliquity and eccentricity, respectively. The prominence of the last is surprising, for changes of eccentricity give an extremely small change of energy input.

What can Mars teach us about these problems? Any source of data is welcome in such a complicated situation. William Ward[38] has shown that both the obliquity and the eccentricity are subject to large changes (14.9 degrees to 35.5 degrees and 0.005 to 0.141). Dominant periods range from 95 000 to 2 million years. But we also need indicators of past climate. Mars has no seas; and even if it had, we would have difficulties obtaining cores. There is a tantalizing observation of layered structures in the polar regions, first photographed by Mariner and clearly seen in some Viking pictures (figure 5). We do not know the mechanism of formation of these terraces, but it is tempting to identify them with one or more of the Milankovitch–Ward cycles.

Major changes of climate have taken place at some time in the past, for it is obvious from many of the orbital photographs that liquid water in abundance has flowed across the surface (figure 4). Although these changes may be related to the astronomical cycles, there is evidence that the fluvial episode occurred in the remote past. Whenever it was, the atmospheric pressure must have been greater, for liquid water is not stable under present conditions. It is tempting to conclude that Mars is in an ice age, with CO_2 and H_2O locked up in polar caps (figure 5). The actual amounts that can be inferred from observations tend to be rather small, but there is no doubt that permanent water-ice caps and temporary CO_2-ice caps do exist. It is not hard to imagine the possibility of a runaway warming effect, in which CO_2 is released to the atmosphere, which thereby becomes so dense that it transfers heat from low to high latitudes and causes the permanent caps to disappear entirely.[39]

So far, we have discussed direct comparisons of Earth and Mars. There is another approach, especially useful when data are limited: Formulate models of

Table 5. Martian volatile inventory derived by degassing from ordinary chondrites

	H	C	N	Ne^{20}	Ar^{36}	Kr^{84}	Xe^{132}
					gm/cm²		
Mars atmosphere observed	—	5.0	0.50	$<10^{-4}$	1.0×10^{-4}	$\approx 6 \times 10^{-6}$	$\approx 2 \times 10^{-6}$
Ordinary chondrite	66	145	8.3	10^{-5}	(1.0×10^{-4})	2×10^{-6}	$\approx 3 \times 10^{-6}$
Volatiles escaped or on the surface	66	140	7.8	—	—	—	—

Table from ref. 24.
Data normalized to Ar^{36}.

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the system and test them against what observations can be obtained. One class, important in meteorology, is the global circulation model, a numerical simulation of the atmosphere that runs on a large computer. It is equally applicable to Mars, which is a much simpler case than Earth, and some studies have already been made. Once the Viking orbiters and landers have gathered meteorological data over a whole Martian year, we will be in a good position to test and refine our global circulation models.

There is also a lot of interest in models of atmospheric chemistry, particularly with respect to the effects of pollution. When it comes to detailed measurement, and even more to prediction, our own stratosphere is almost as inaccessible as Mars. We worry about reduction of our own ozone abundance by one or a few per cent; on Mars we predict and observe an order-of-magnitude reduction, due to a hundred parts per million of water vapor. (On Venus there is an even larger effect, due principally to the presence of chlorine, the same ingredient that causes us to worry about release of chlorofluoromethanes at home.) Our planetary neighbors offer real examples of pollution and climate change at work.

At this point we must close our rather personal account, which has not begun to do justice even to the early results from the fabulously successful Viking and other planetary missions. We have omitted whole areas, and the flood of data and interpretations is still continuing. However, we chose these few examples to illustrate that the comparative study of Earth and other planets, all in the same context, has begun.

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