EXPLORATION OF THE PLANETS: AN INVITED DISCOURSE PRESENTED BEFORE THE SIXTEENTH GENERAL ASSEMBLY OF THE INTERNATIONAL ASTRONOMICAL UNION GRENOBLE, FRANCE, AUGUST, 1976

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Until recently the entire astronomical endeavor was restricted to passive observations from the surface of the Earth. Natural experiments -- such as stellar occultations, eclipsing binaries, or supernova explosions -- might fortuitously arrange themselves, and systematic inventories were performed of information carried by reflected or emitted electromagnetic radiation. But it is only in the last twenty years that our species has been able to carry out <u>in situ</u> experiments on astronomical objects.

Radar astronomy permits a kind of experimentation on solar system objects not too distant from Earth, and has made a number of major discoveries, including the determination of the 3:2 spin/orbit coupling of Mercury, the Earth-locked retrograde rotation of Venus, and major elevation differences on Mars. Radar is the tool of choice for geomorphological mapping of cloud-enveloped Venus, and efforts now underway at the Arecibo Observatory should lead to complete mapping of one hemisphere of Venus down to 10 km resolution. The radar reflectivity of the rings of Saturn has forced a rethinking of the nature of the constituent particles in the rings; and a determination of the radar cross-section of Titan is an experiment which can resolve much of the uncertainty about the atmospheric structure and surface pressure for that enigmatic and fascinating object.

The chief means of performing planetary exploration today, and the pioneering tool for experimental astrophysics, is the space vehicle. The first significant mission beyond the Earth-Moon system was the <u>Mariner 2</u> spacecraft which flew by Venus in 1962. It measured the number density and velocity of charged particles in the solar wind, confirming deductions which had been made from the motion of knots in comet tails and selecting one of two rival theories on the nature of the solar wind. It also performed a disk-resolved microwave scan of Venus and discovered that the planet is limb-darkened at a wavelength near 1 cm. The earlier discovery in 1956 of the high microwave brightness temperature of Venus rapidly led to both thermal and non-thermal models of the microwave emission and its spectrum. The <u>Mariner 2</u>

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microwave radiometry experiment immediately eliminated a range of models of the high microwave brightness temperature of Venus in which the emission source was above the surface -- synchrotron or free-free emission in a magnetosphere or ionosphere, for example; and confirmed the notion of a very high Venus surface temperature.

Beginning a decade ago, Venus surface conditions have been explored directly by the Venera series of spacecraft, culminating in the very impressive achievements of Veneras 8, 9 and 10, each of which survived for about an hour on the Venus surface in an environment of 750 K temperatures, 90 bars pressure, and an atmosphere containing at least trace amounts of hydrochloric, hydrofluoric and sulfuric acids. There were a few of us who had deduced the high surface temperatures and pressures on Venus, on what can now be discerned as essentially correct grounds and before the Venera landings. But I do not think that the general acceptance of these unusual surface conditions -- much less that they are caused by a massive CO_2/H_2O greenhouse-effect would have occurred without direct spacecraft measurements. The most recent and most impressive spacecraft observation of Venus are the two surface photographs obtained from two different sites on Venus by Veneras 9 and 10, images which clearly initiate a new science of small scale comparative planetary geology.

One of the great virtues of spacecraft missions is that they provide -- often for the first time -- a calibration on the reliability of astronomical inference and astrophysical theory. In an 1899 issue of the Astrophysical Journal appears a paper by a graduate student at Princeton University Observatory who was permitted to use the finder telescope of the "Great Princeton Refractor" to observe the extension of the cusps of the planet Venus. He concluded that the phenomenon was due to an aerosol scattering layer above the main Venus clouds, and deduced the physical properties of such a layer. Three-quarters of a century later, the layer was observed directly as a detached limb haze by the Mariner 10 spacecraft, and the properties of this layer turned out to be extremely similar to those deduced in 1899 by the graduate student -- whose name was Henry Norris Russell and who, perhaps finding planetary astronomy too easy, went on to other activities.

The existence and properties of a synchrotron-emitting radiation belt around Jupiter followed from the radioastronomical discovery of decimeter emission, the determination of its spectrum and polarization, and the interferometric investigation of its spatial extent. From these data were derived the magnetic field strength at the Jovian cloud tops, the inclination of the magentic to rotational axes, the offset of the magnetic axis from the center of figure, and some information on the charged particle density and energy spectrum within the Jovian magnetosphere. These are exercises often pursued in a variety of similar contexts in stellar and galactic astrophysics. But a thorough checking of every link in this deductive web is difficult to perform. It will undoubtedly be a long time before we will send particles and fields experiments to the Crab Nebula or Cygnus X-1, to say nothing of

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3C273. But we do have in our solar system a small and relatively feeble representative of this class of synchrotron emission objects, Jupiter, which was examined in situ by the Pioneer 10 and 11 spacecraft. It turns out that deductions on the magnetic field strength, tilt and offset were remarkably on target, but that notions on the energy density and spectrum and the large-scale field geometry were in substantial need of revision, results which ought to be studied seriously by those concerned with where we can be confident and where we must be cautious about comparable astrophysical deductions.

Direct applications to conventional astrophysics of such in situ measurements have been only occasional so far, but that situation may change in the reasonably near future. It is possible to fly a probe which will approach within a few solar radii of the sun, and possibly penetrate the photosphere, using a thermal shield. The favored trajectory requires an initial Jupiter swingby. The scientific return intrinsic to such a mission is clearly immense, permitting a determination of the solar quadrupole moment, an important discrimination among various gravitational theories, and vital information on stellar atmospheres and stellar evolution. I think it is likely that before the end of the century we will have a wide array of direct measurements obtained from within the nearest star, employing the vehicles and technology developed for planetary exploration.

Within the last five years space vehicles have been launched successfully from the planet Earth to all the planets known to the astronomers of pretelescopic times. Spacecraft have flown by Mercury, Venus, Mars, Jupiter and (shortly) Saturn; and orbited and landed on Venus and Mars. Reliable spatial resolution of features on the surface of Mars, for example, have evolved from a few hundred kilometers in the early 1960's, to spacecraft orbital resolutions of one hundred meters by Mariner 9 in 1972, to Viking Lander resolutions better than one millimeter in 1976. This is an improvement in resolution by a factor of 10^8 in little more than a decade. A mission such as Mariner Jupiter/Saturn -- scheduled to be launched in 1977, arrive in the Jupiter system in 1979, and in the Saturn system in 1981 -- is designed to acquire some 40,000 photographs, each significantly better than the best ground-based photography of these planets and their 24 natural satellites. Comparable improvements in infrared spectroscopy, particles and fields experiments, and other investigations have been achieved or are anticipated. Future missions, not yet approved, but well within our technological capability include entry probes into Jupiter and Titan, floating stations in the Venus atmosphere, Mercury orbiters, and roving vehicles on the martian surface. Planetary astronomy has clearly arrived at a revolutionary epoch, its most exciting and promising moment since the invention of the telescope.

As an example of what is now possible I would like to describe briefly the Viking mission to Mars, being vigorously executed at the time of the IAU General Assembly at which these remarks were first presented. We have two orbiters and two landers in excellent

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working order on the surface of the planet. By the end of the nominal mission in November 1976, when the planet was in solar conjunction, more than 10^{11} bits of data had been acquired. This number makes it clear that I can touch only telegraphically on a few highlights of the mission. Figures 3 through 25 are a small collection of the more than 10,000 photographs obtained by Viking. Preliminary results by a science team of well over 100 individuals have been published in Science (27 August, 1 October, and one further issue in December 1976), and additional results should fill many pages of Icarus, the Journal of Geophysical Research, and other journals in forthcoming years.

One vital aspect of these missions is that they are adaptive and permit a reconfiguration of scientific strategy on the basis of results only recently acquired. In addition, the spacecraft themselves have a fair degree of artificial intelligence, made necessary by the 40 minute roundtrip light travel time between Earth and Mars. (Because of the longer light travel time there, expeditions to the outer solar system will require increasingly sophisticated degrees of artificial intelligence.) The adaptive and intelligence aspects of these spacecraft played a critical role in the successful landings of Viking 1 and and Viking 2 in Chryse Planitia and Utopia Planitia on July 20 and September 3, 1976, respectively. Landing sites which had been thought safe by Mariner 9 photography in 1971/1972 turned out to be rough or otherwise undesirable to Viking Orbiter photography and Arecibo radar Doppler spectroscopy. At least three unsuccessful attempts to land on the surface of Mars were made by the Mars series of spacecraft. Since these failures were of devices produced by the same design group which had brilliantly landed in so inhospitable an environment as Venus, we were forewarned that landfall on Mars might be difficult. But because of Viking's engineering design, adaptive capability, and landing site capability, and landing site certification exercises, we were able to land successfully on two spots on the planet Mars, within 40 km of the designated target, after an interplanetary voyage of over 400 million km.

The Viking instrument complement includes orbital imaging, infrared water vapor detection, and infrared thermal mapping experiments; lander imaging, meteorology, seismology, magnetic properties, radiophysics, inorganic chemistry, organic chemistry and microbiology experiments; and several experiments on both the neutral and ionized atmosphere performed on entry. In addition to Mars itself, the spacecraft are studying the natural satellites Phobos and Deimos, and have uncovered a series of strange and so far unexplained parallel rectilinear markings on the former.

Mars is revealed to be a geologically exuberant planet, with clear evidence of volcanic, impact, fluvial, mass wasting, aeolian, and possibly glacial processes. The volcanic regions of Mars (the largest volcano, Olympus Mons, is almost thirty km high) are very young; cratering statistics place an age of less than a few hundred million years for the Tharsis volcanic plateau. Other regions of Mars, the cratered plains for example, seem to be several thousands of millions of years old. The sinuous tributaried channels -- many with collapsed banks, parallel scour marks, and hydrodynamically shaped interior islands -- provide firm evidence for fluvial activity in the past. Because the present atmospheric pressure is below the triple point pressure of water, the atmospheric pressure must have been significantly higher in earlier times. _Viking_ measurements of the isotopic abundances of nitrogen and argon, and its detection of krypton and xenon, lead by a variety of independent arguments to the conclusion that the total pressure in the ancient martian past was at least tens and possibly many hundreds of times greater than the present atmospheric pressure. The martian environment must have been much more earth-like a thousand million years or more ago, a conclusion of some interest for the possibility of the origin of life in the early martian past and for studies of comparative climatology. Mars has, at least once and perhaps many times in its history, undergone massive climatic change, additional evidence for which exists in the laminated terrain in both polar caps. In comparative climatology as with many other areas in meteorology, geology and biology, the study of one planet promises to cast significant light on all, including our own.

The orbital infrared instruments on _Viking_ have provided firm evidence that extensive regions of the North polar cap are composed of frozen water and not frozen carbon dioxide. Lander meteorological data have so far confirmed the predictions of the best numerical circulation models for Mars. An important test will be provided in Spring, 1977 when much more violent weather is anticipated, including winds above the boundary layer in excess of about one hundred meters per second required to bring the stress at the surface above the threshold value for saltation. Through November, 1976 all velocities measured have been below the calculated saltation threshold and, in pleasing agreement, no signs of sand or dust carried by the winds have been detected by the lander cameras.

The character of the rock and sediment revealed by the two lander imaging systems raises interesting questions on the evolution of the surface terrain. The clear mix of highly eroded and quite fresh rocks suggests differential friability and the possibility that the landing sites have been exhumed in geologically recent times by aeolian removal of some meters of overlying debris. These two sites were purposely chosen for their blandness, a consequence of the landing safety requirements; they should be among the dullest spots on the planet. Even so, the profusion of detail is very rich, particularly in the stereo, color, and infrared images. The surface is a vivid red, attributed to a ferric oxide stain, such as goethite; and the sky is a distinct creamy orange or pink, due to particles of about one micron radius suspended there from the last dust storm.

No signs of large forms of life have been discerned in these photographs, which represent about 10^{-7} of the surface area of the planet. _Viking_ sample arms have dug trenches in the martian epilith many times in the two landing sites, to acquire fine particle samples for the x-ray fluorescence spectrometer, the gas chromatograph/mass spectrometer, and the three microbiology experiments. The atomic composition revealed by the inorganic chemistry experiment seems to imply that iron-rich clays, such as montmorillonite, are a major constituent of the fine-grained component of the martian surface material. The organic chemistry experiment has yielded entirely negative results, with a sensitivity of about 10^{-6} for very simple organic molecules and about 10^{-9} for organic molecules with three or more carbon atoms. On the other hand, two of the three microbiology experiments have yielded, by criteria established before launch, positive results.

There is no necessary discrepancy among the results of the three microbiology and one organic chemistry experiments, because the two microbiology experiments with positive results utilize radioactive carbon in the detection system, which makes them more than 1000 times more sensitive than the remaining two experiments under appropriate normalization. One of the microbiology experiments searches for the oxidation by martian surface samples of radioactively labeled organic molecules sent from Earth. The second, a kind of inverse of the first, searches for the fixation of labeled carbon in $^{14}CO_2$ and ^{14}CO into organic molecules. Great caution is needed in the interpretation of these results. For example, the ultraviolet irradiation of martian surface material, rich in physically and chemically bound water, very likely results in the production of peroxides and superoxides which are able to oxidize organic matter to carbon dioxide. The data in these experiments are very rich and some of it -- for example the cessation of such chemistry by a prior exposure of the sample to temperatures only 30°C above experimental temperature -- lean perhaps more towards biological than nonbiological explanations. Further _Viking_ experiments and ground-based laboratory simulation work promise to cast further light on this very important but so far ambiguous set of results. At the very least, we have found a nonbiological chemistry on the martian surface which duplicates many of the essential steps in animal respiration and in green plant photosynthesis. It seems likely that, whatever the final outcome, _Viking_ has provided important data relating to the origin of life.

Viking may continue working for months or years. It will be followed in the next decade by more advanced exploratory attempts -- the most cost effective of which, in my view, is a Mars roving vehicle which can wander from the safe dull places to the more dangerous but scientifically much more interesting places, which are abundant on this geologically heterogenous planet. It is clear that this moment in the history of astronomy -- the time of _Vikings_ and _Veneras_ -- represents a crucial and historically significant transitional moment from passive remote sensing of the planets to vigorous _in situ_ exploration of our companion worlds in the solar system.

This work and the Viking Project were supported by the National Aeronautics and Space Administration.

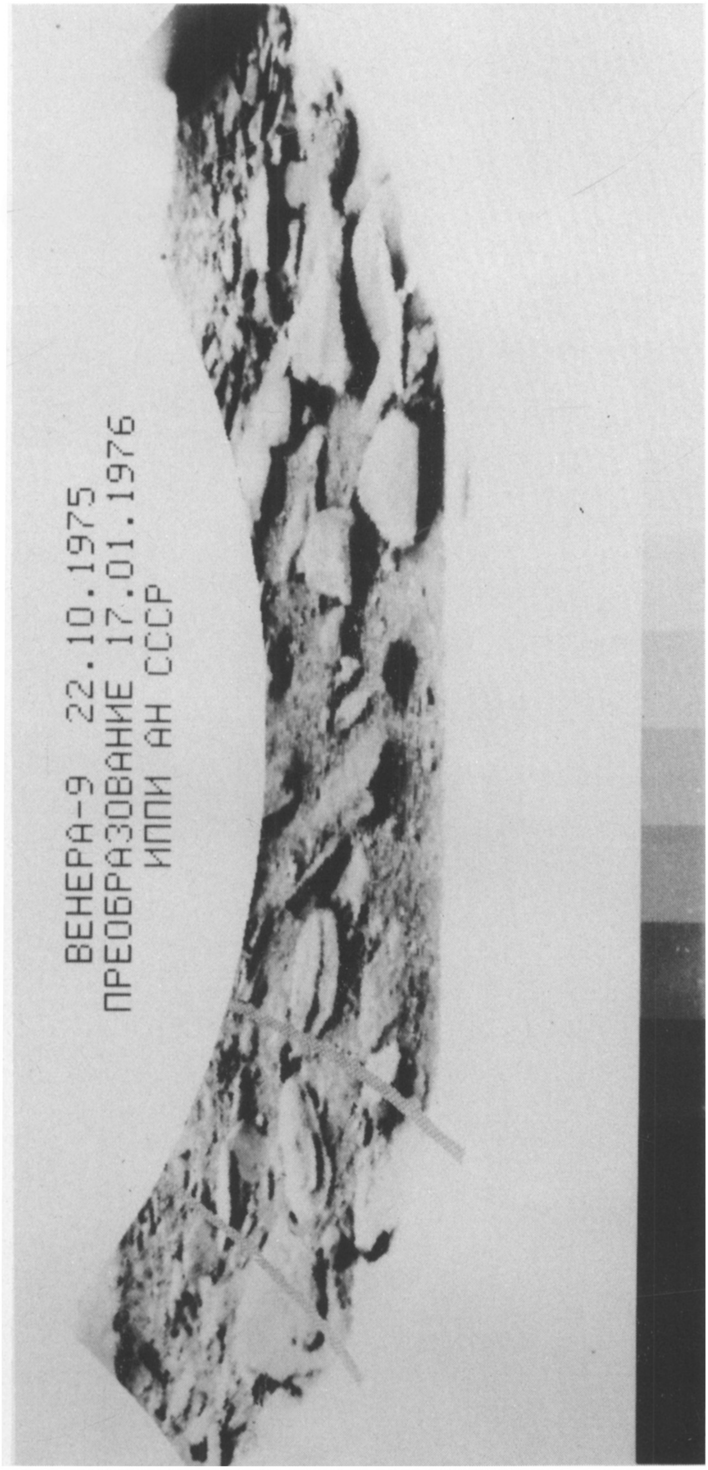

FIGURE 1. Venus from Venera 9, the first photograph ever returned from the surface of another planet. The horizon can be seen in the upper right corner. In the absence of fluvial and aeolian erosion, these rocks may have been processed by chemical weathering or by the long-term flow of a low melting-point component.

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FIGURE 2. The *Venera 10* panorama. The different appearance of the *Venera 9* and *10* landing sites and the almost complete absence of rocks in the latter indicate a heterogeneity of terrain and geological processes on Venus. Other *Venera* data and the ground-based radar observations clearly suggest a differentiated planet.

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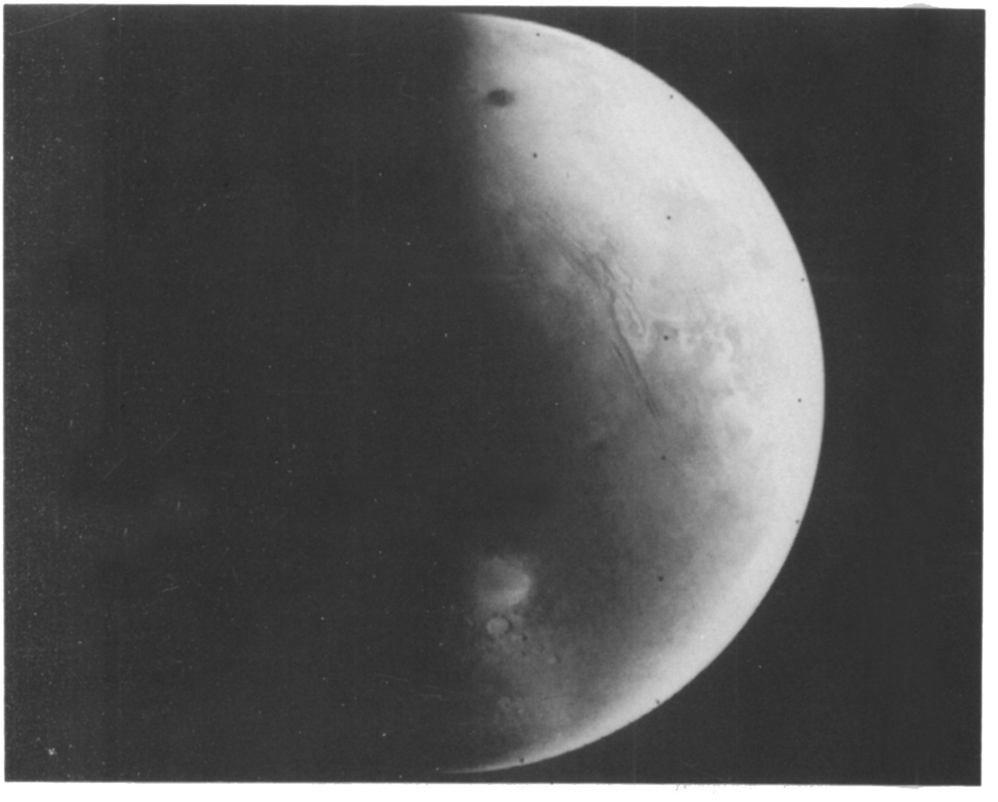

FIGURE 3. Pre-encounter photograph of Mars, taken by the Viking 1 Orbiter on the day before it was injected into Mars orbit. The photograph was obtained from a range of 360,000 kilometers. At middle right can be seen Valles Marineris, an enormous rift valley which extends for 5,000 kilometers. The dark spot at the top is Ascraeus Mons, one of the great martian volcanos in the Tharsis plateau. A number of impact craters can be seen at the bottom of the image.

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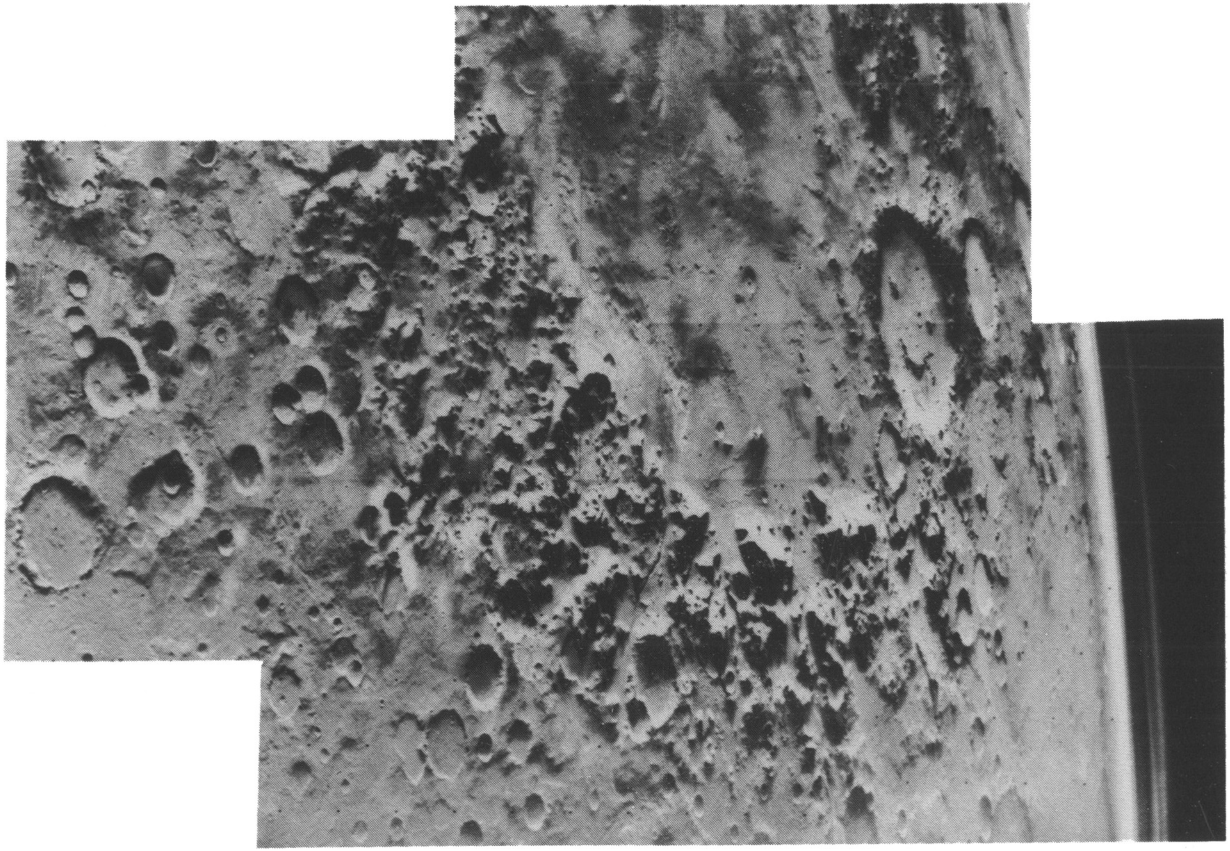

FIGURE 4. Viking 1 Orbiter oblique view of Argyre Planitia, the relatively smooth depressed plane seen at center left. Such basins are thought to be the source of some of the great martian global dust storms. A detached limb haze can be seen at the horizon.

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FIGURE 5. A view looking down the central caldera, about 120 kilometers across, of Arsia Mons, another of the great Tharsis volcanos. The production of and outgassing from such volcanos probably made major contributions to the inventory of surface volatiles on Mars. Vertical photographs such as this were taken near Viking orbital periapsis, at altitudes of about 1500 kilometers.

FIGURE 6. Viking photograph of a small section of Valles Marineris, which is typically about 100 kilometers across. The far wall has repeatedly collapsed and the canyon widened by mass wasting, and the avalanche debris can be made out at the bottom of the rift valley, several kilometers below the clifftops. Another branch of the valley system is seen at the top, and a range of other martian erosion processes are apparent in this image.

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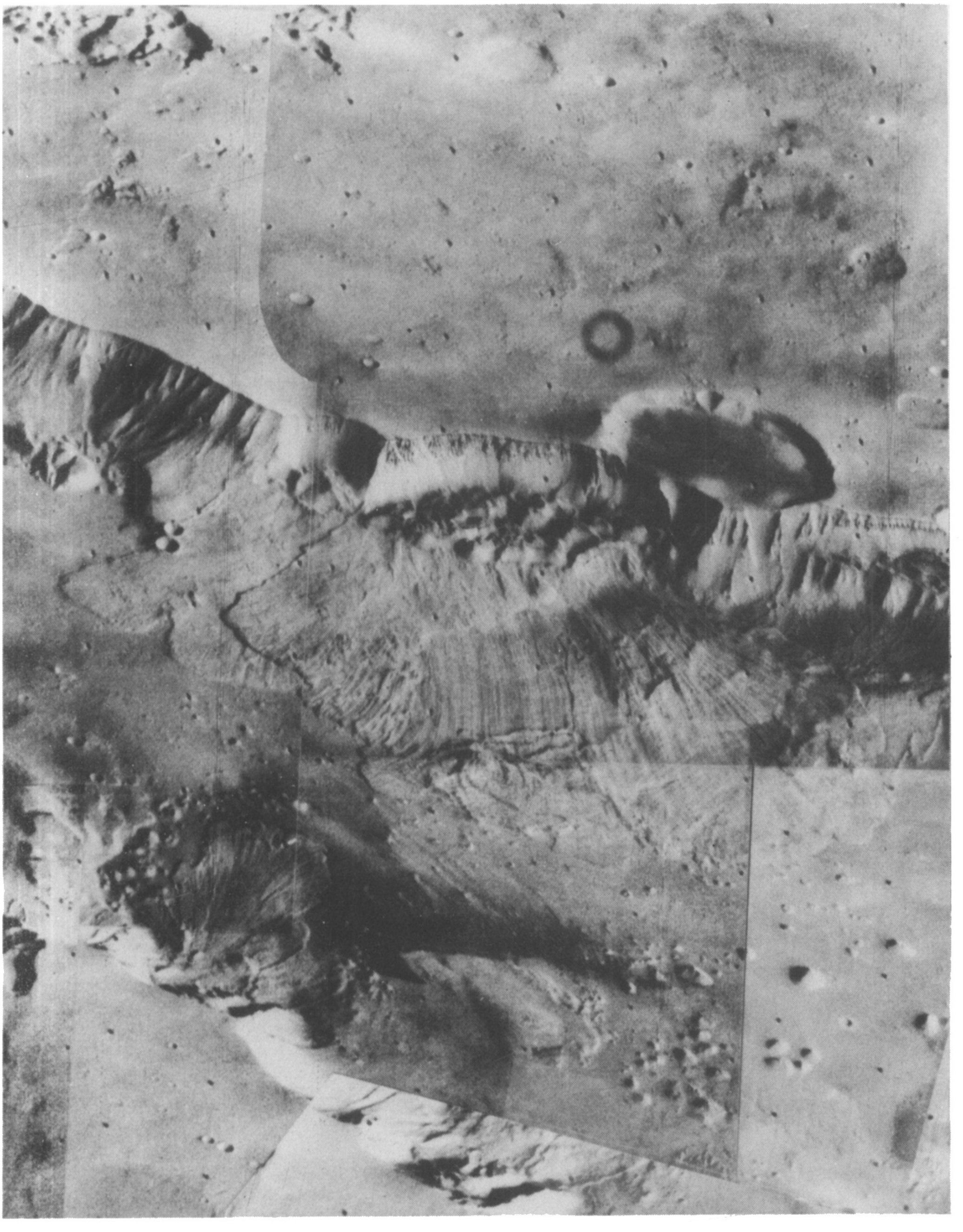

FIGURE 7. *Viking* photomosaic of a small part of the interior of Valles Marineris, showing evidence for a succession of avalanches from the periodic collapse of both canyon walls. There is evidence that avalanche debris from one side of the valley has overflowed debris from the other side.

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FIGURE 8. A fairly characteristic impact crater on Mars, displaying a lobate ejecta blanket of a sort unfamiliar from spacecraft studies of Mercury and the Moon. Such features may be produced by impact melting of subsurface permafrost, with the layer of liquid water serving as an instantaneous lubricant for the outward flow of impact debris. There is a range of other Viking evidence for abundant permafrost on Mars.

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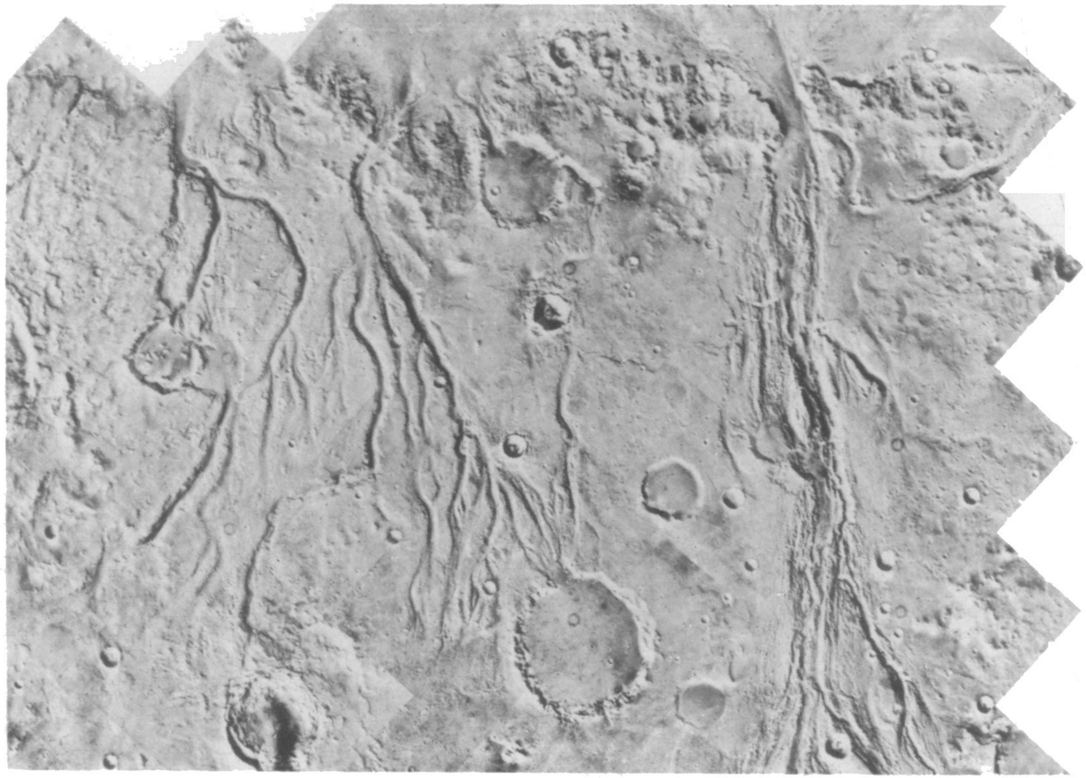

FIGURE 9. *Viking* photomosaic of a channeled region in Chryse Planitia, the general region of the *Viking 1* landing. These dendritic or tributaried sinuous channels are very likely produced by running water during a previous more clement epoch in martian history, probably about 10^9 years ago.

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FIGURE 10. A photomosaic of pictures taken on October 4, 1976 from Viking Orbiter 2 in the martian north polar ice cap. The North Pole is about 300 kilometers off the top of the picture. The mosaic exhibits details of the differentially frosted terrain characteristic of both martian polar caps. The dark sinuous breaks in the thicker polar ice exhibit an intricate array of parallel bright and dark terracings which are probably connected with climatic change on Mars.

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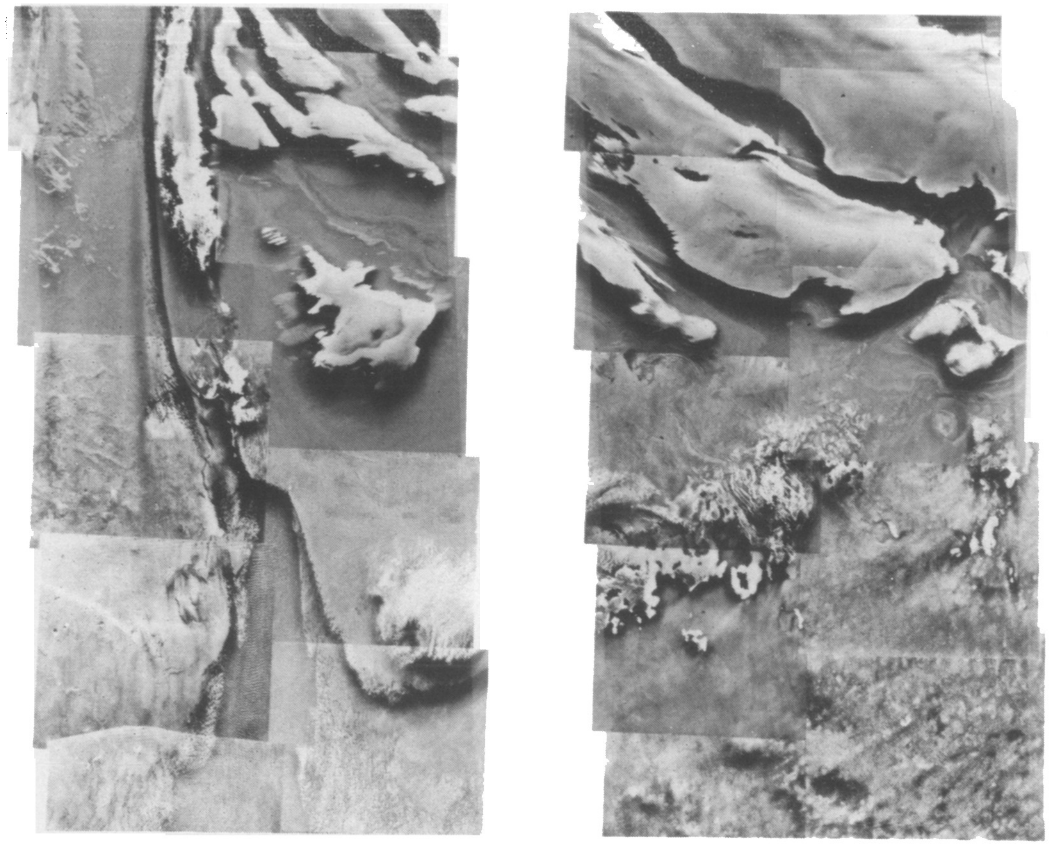

FIGURE 11. Another Viking Orbiter 2 close-up of the martian North polar cap. Patches of thick ice are separated by ice-free terraced slopes. At the left a great field of dark sand dunes can be discerned. Some of the landscape is obscured by patchy overlying condensation clouds.

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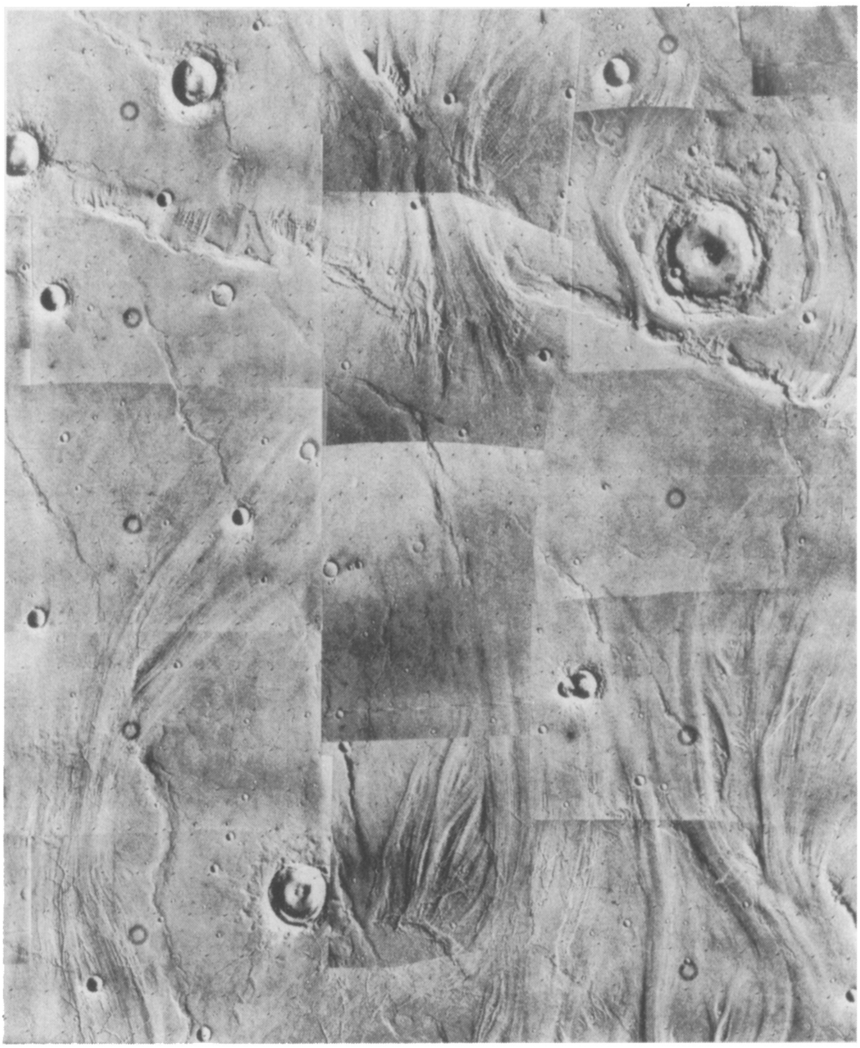

FIGURE 12. A photomosaic of a region in Chryse Planitia east of the final *Viking 1* landing site, exhibiting some details of the variety of channel systems in this region. Some of the features seen here may, however, be of lava or glacial rather than aqueous origin.

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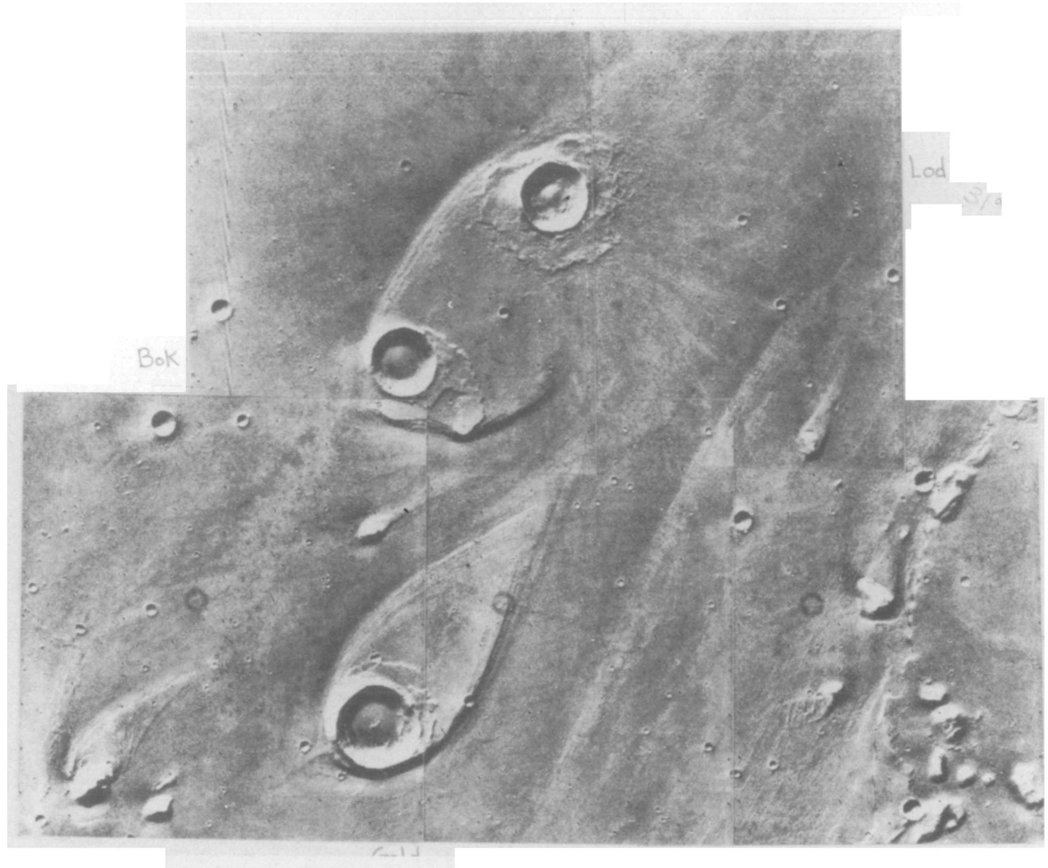

FIGURE 13. A region still further east of the final Viking 1 landing site showing the evident result of hydrodynamic streaming past positive relief obstacles in the ancient martian past. These features may be produced by great floods, but other interpretations are possible. The nomenclature noted is unofficial.

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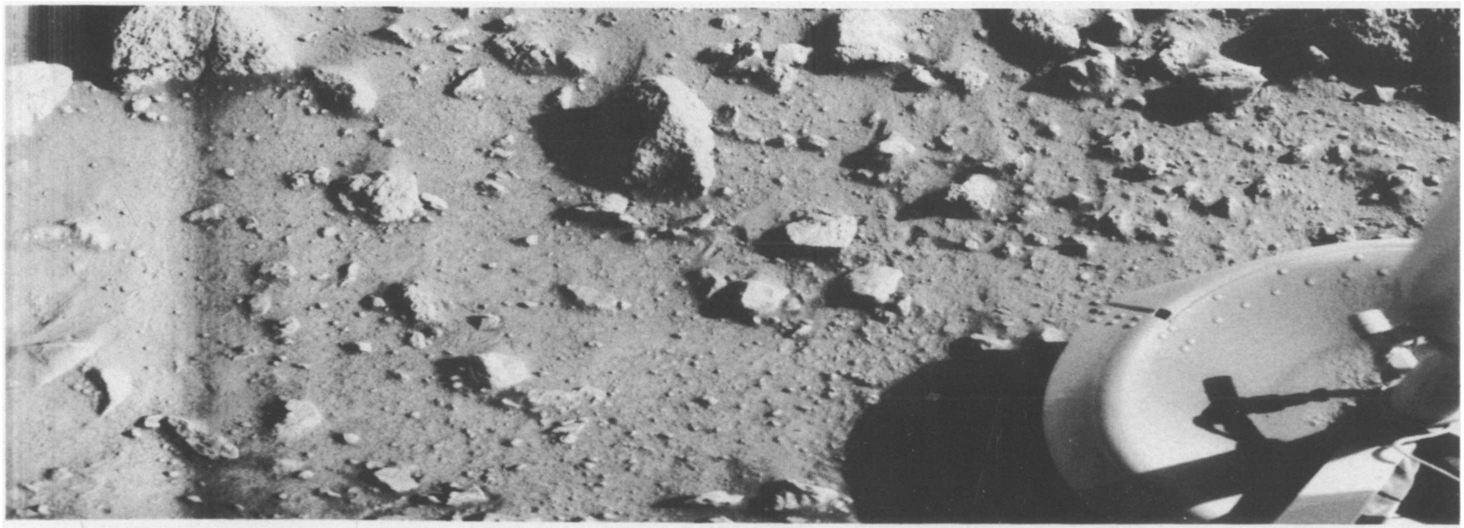

FIGURE 14. The first photograph ever taken on the surface of the planet Mars. A variety of rocks, both highly eroded and relatively uneroded, can be seen along with associated granular material. The large rock in the center is about 10 centimeters across. In the lower right corner is a portion of Viking Lander Footpad number 2 with small quantities of fine-grained sand and dust deposited near the support strut during the landing maneuvers. The bright and dark vertical streaks near the left edge of this scanning system picture are attributed to fine particles sprayed into the martian atmosphere during retrorocket firing and the impact of landing. Note that the footpad sits high above the martian surface.

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FIGURE 15. Photograph of Viking 1 Lander Footpad number 3. Only the support strut is visible. The Footpad proper is buried under several centimeters of martian surface material. A comparison with the previous photograph shows that the bearing strength of the surface material in the Viking 1 landing site is significantly variable.

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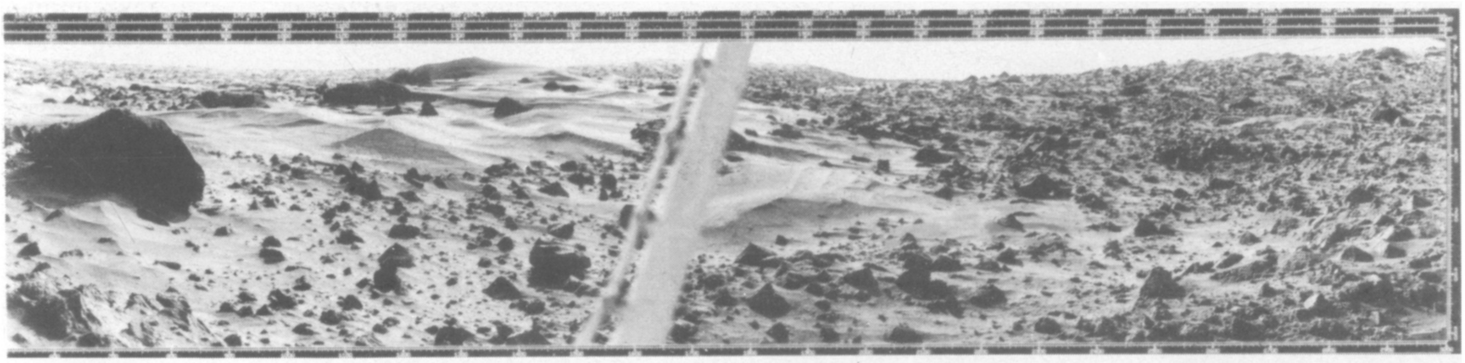

FIGURE 16. Viking 1 panorama obtained with early morning lighting, at about 7:30 a.m. martian local time. The picture is vertically bisected by the meteorology boom. The large boulder at left is about eight meters from the spacecraft and about three meters in its longest dimension. Drifts of fine-grained material and the array of small boulders indicate two quite different sorts of terrains. Many of the rocks appear modified by aeolian abrasion.

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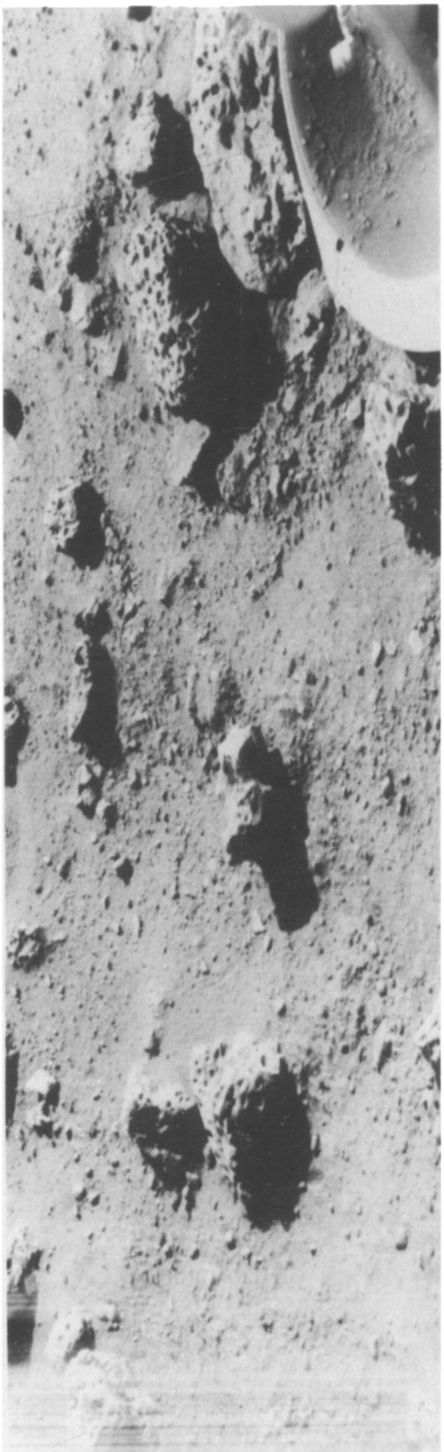

FIGURE 17. The first photograph returned from the *Viking 2* Lander on September 3, 1976, in Utopia Planitia, about 7500 kilometers northeast of the *Viking 1* landing site in Chryse Planitia 45 days earlier. Rocks here are more vesicular and more fluted than at the *Viking 1* locale and may be derived in part from volcanic processes and more highly modified by the wind. The spacecraft has probably landed on one or more rocks; photographs which display the horizon indicate an 8 degree tilt of the spacecraft to the local horizontal.

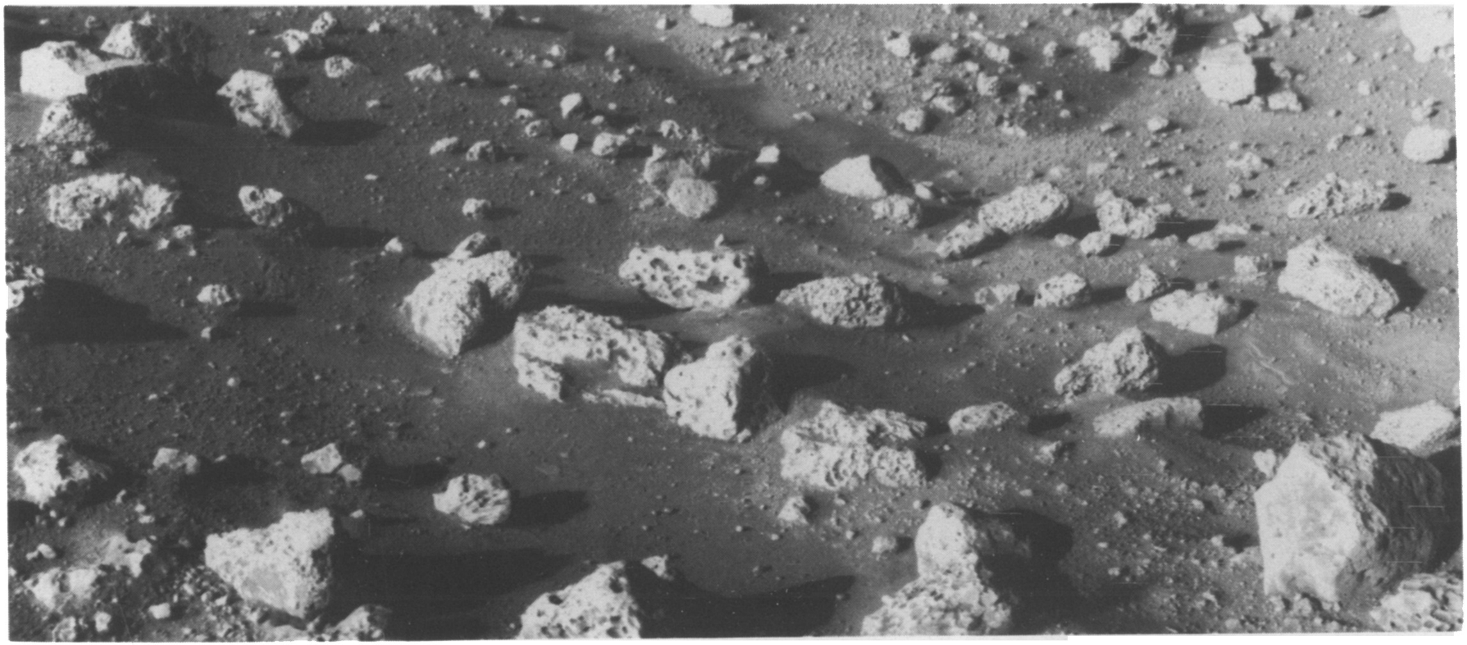

FIGURE 18. A photograph at middle distance of the terrain in the Viking 2 landing site. The rock in right foreground is about 25 centimeters across. Flat, platy surface crusts can be seen in various locales in this picture.

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FIGURE 19. A Viking 2 mosaic including the region seen in Figure 18. The landscape is boulder-strewn horizon to horizon and covered with much less windblown sediment than is the Viking 1 landing site. The picture is traversed by a trench which is part of an intricate, mutually connected, approximately polygonal network of unknown origin. The largest rock, near the center of the picture, is about two-thirds of a meter long and shows evidence of banding.

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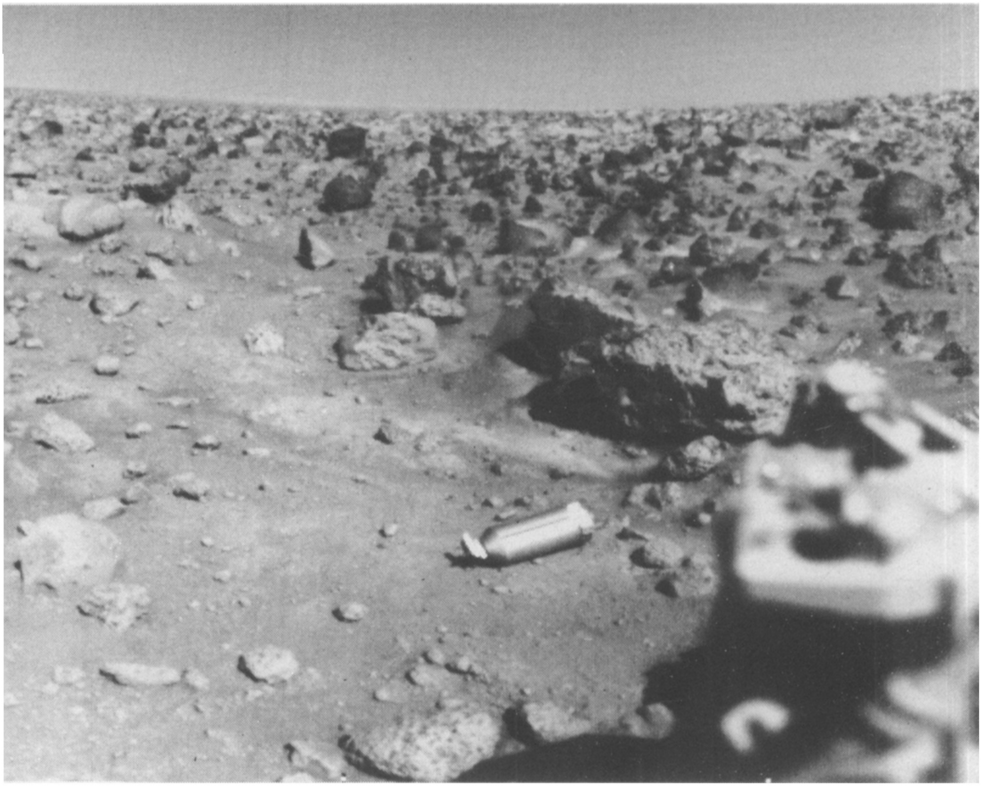

FIGURE 20. An artifact of intelligent life on Mars. On the martian surface, near the out-of-focus housing of the sample arm, is an aluminum cover which protected the head of the sample arm during its year-long voyage from Earth. The ejection of the cover is preliminary to the acquisition of surface samples.

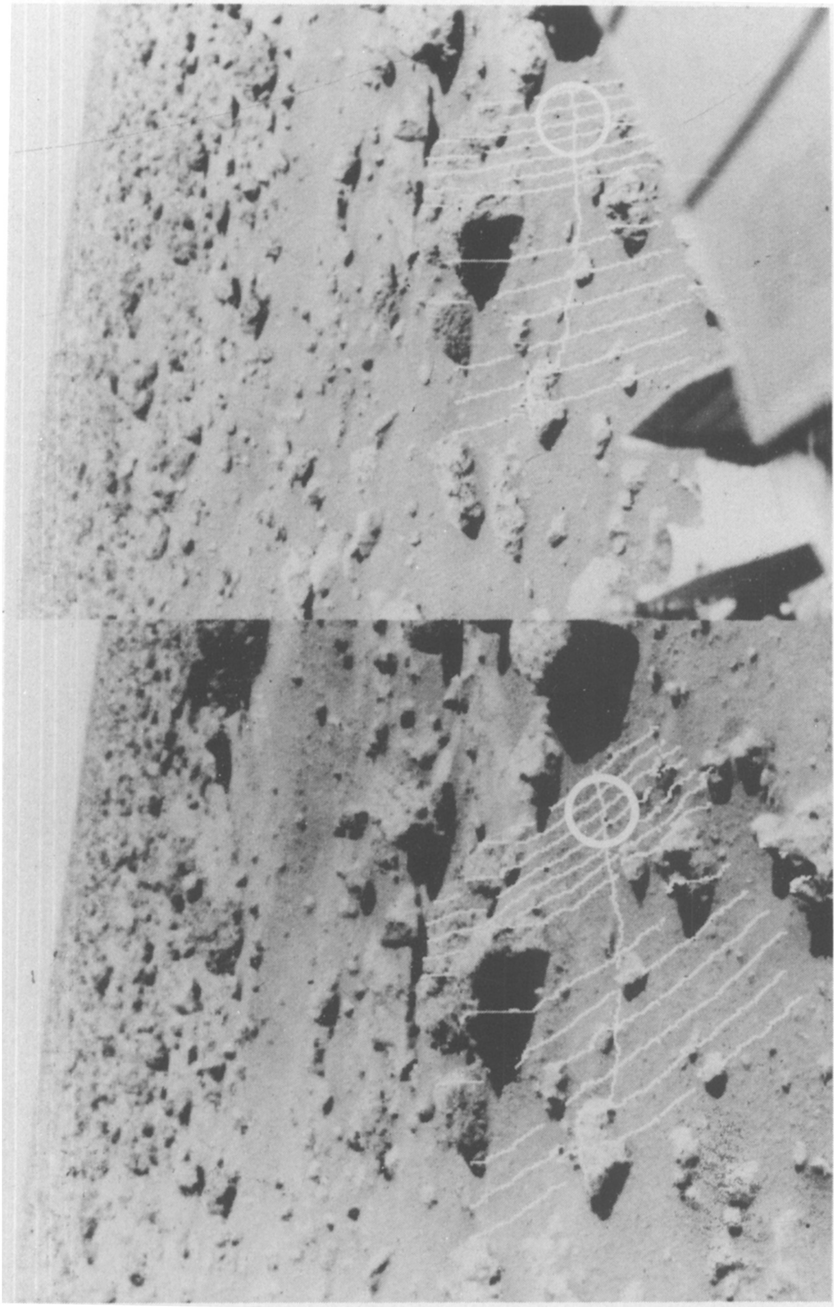

FIGURE 21. A stereo pair of photographs of the site for the first sample acquisition by the *Viking 2* Lander on September 12, 1976. The sampling target is indicated by the white circle; the computer-generated grid of white lines is a high-resolution topographic map of the relevant foreground region. This stereo mapping was necessary for both scientific and sample arm safety reasons.

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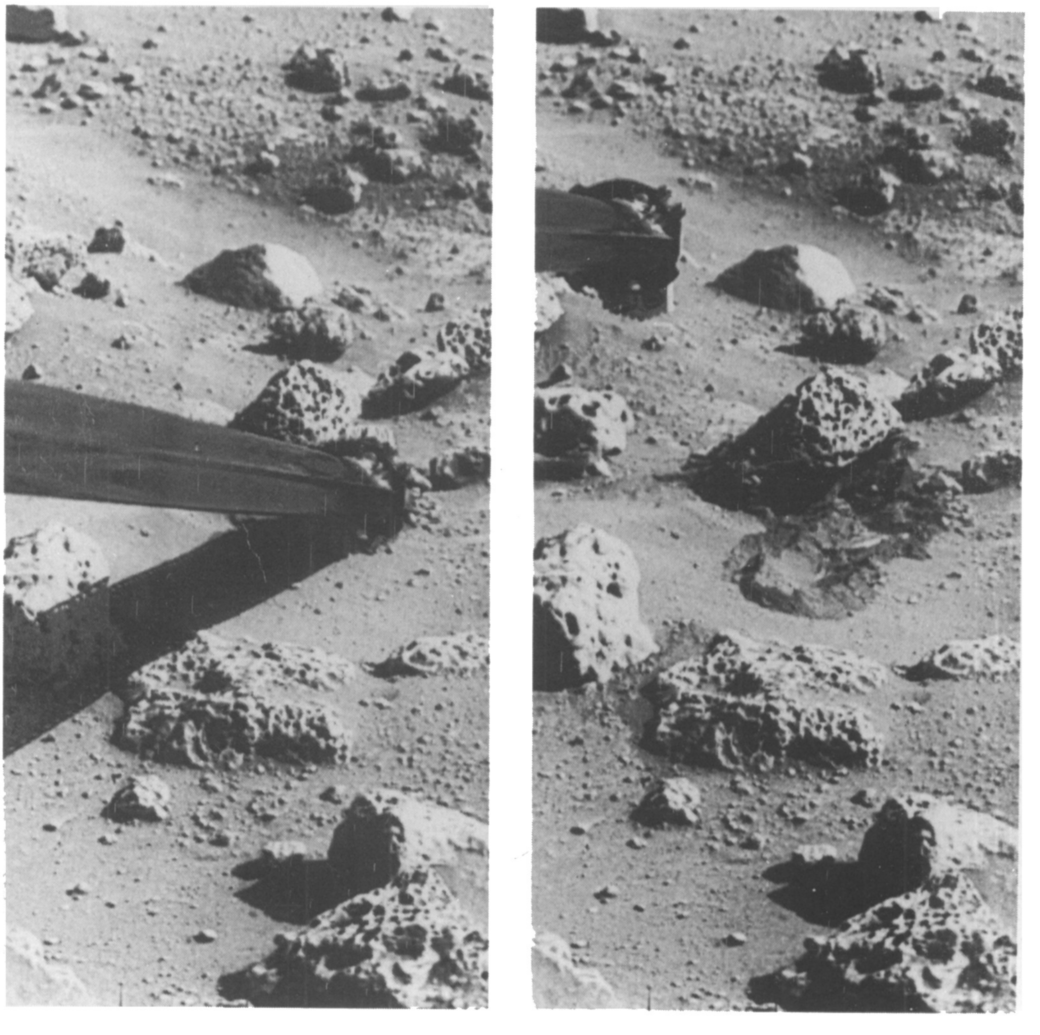

FIGURE 22. "Before" and "after" photographs of a successful rock-pushing maneuver in the *Viking 2* site on the afternoon of October 8, 1976. A rock was pushed in order to acquire surface samples which had not been recently exposed to the solar ultraviolet flux. The sample arm head can be seen above the trench it dug in the photograph at right. Separate samples were acquired for microbiology, organic chemistry and inorganic chemistry experiments from many locales in both *Viking* landing sites.

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FIGURE 23. Martian sunset at Chryse Planitia taken by Viking 1. The intensity contours in the sky are artifacts of the 6-bit intensity digitization of the camera system. This, and many other *Viking* photographs, were obtained in color. Multispectral imaging was essential for identifying the source of the martian sky brightness, approximately micron-sized, blue-absorbing particles suspended in the martian atmosphere.

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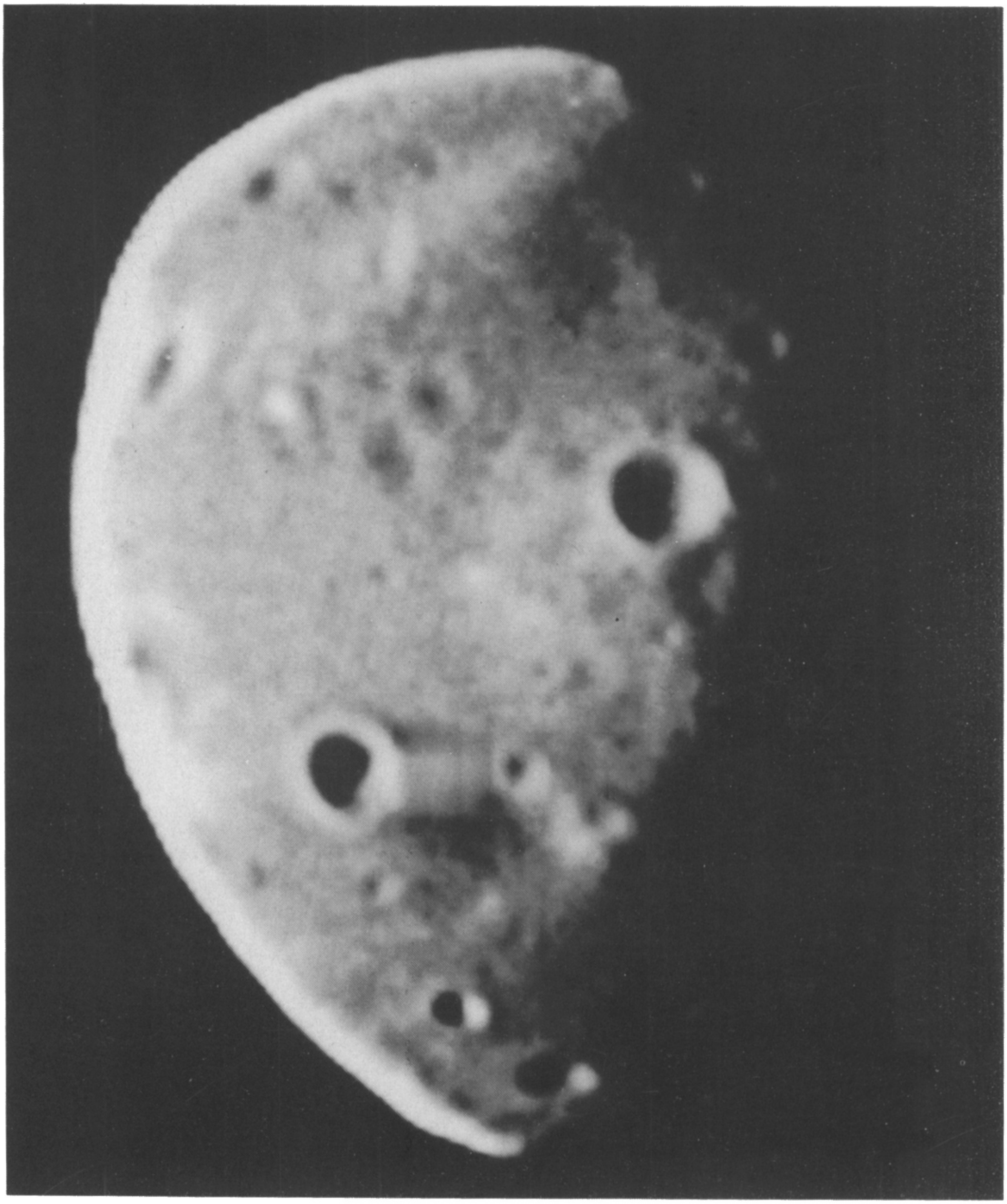

FIGURE 24. Viking photograph of Deimos, the outer natural satellite of Mars. At least a dozen impact craters are apparent, compared with the two originally discovered by Mariner 9 (and since given IAU names commemorating Voltaire and Jonathan Swift). In the next decade photographs of more than a dozen satellites in the outer solar system beyond Mars should be obtained with resolutions considerably superior to this photograph, and for far more interesting objects.

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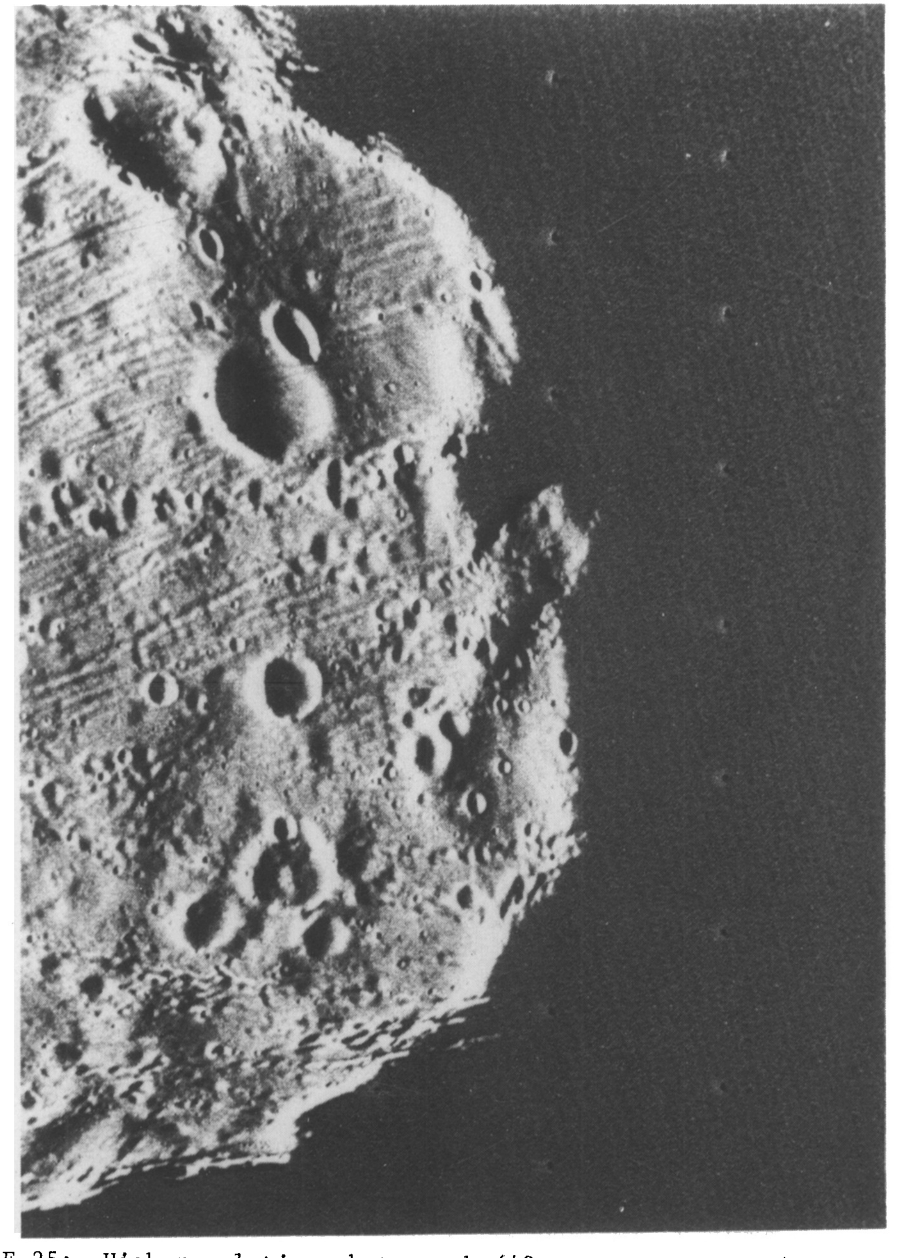

FIGURE 25: High resolution photograph (40 meter resolution) of Phobos, the inner natural satellite of Mars, obtained on September 18, 1976 by Viking Orbiter 2. The terminator is evident near the middle of the picture. This is the discovery photograph of the surface striations on Phobos, an entirely unexpected phenomenon which has so far resisted attempts at a comprehensive explanation. Closer encounter photographs, with a surface resolution better than 10 meters, are possible in the Viking extended mission.

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