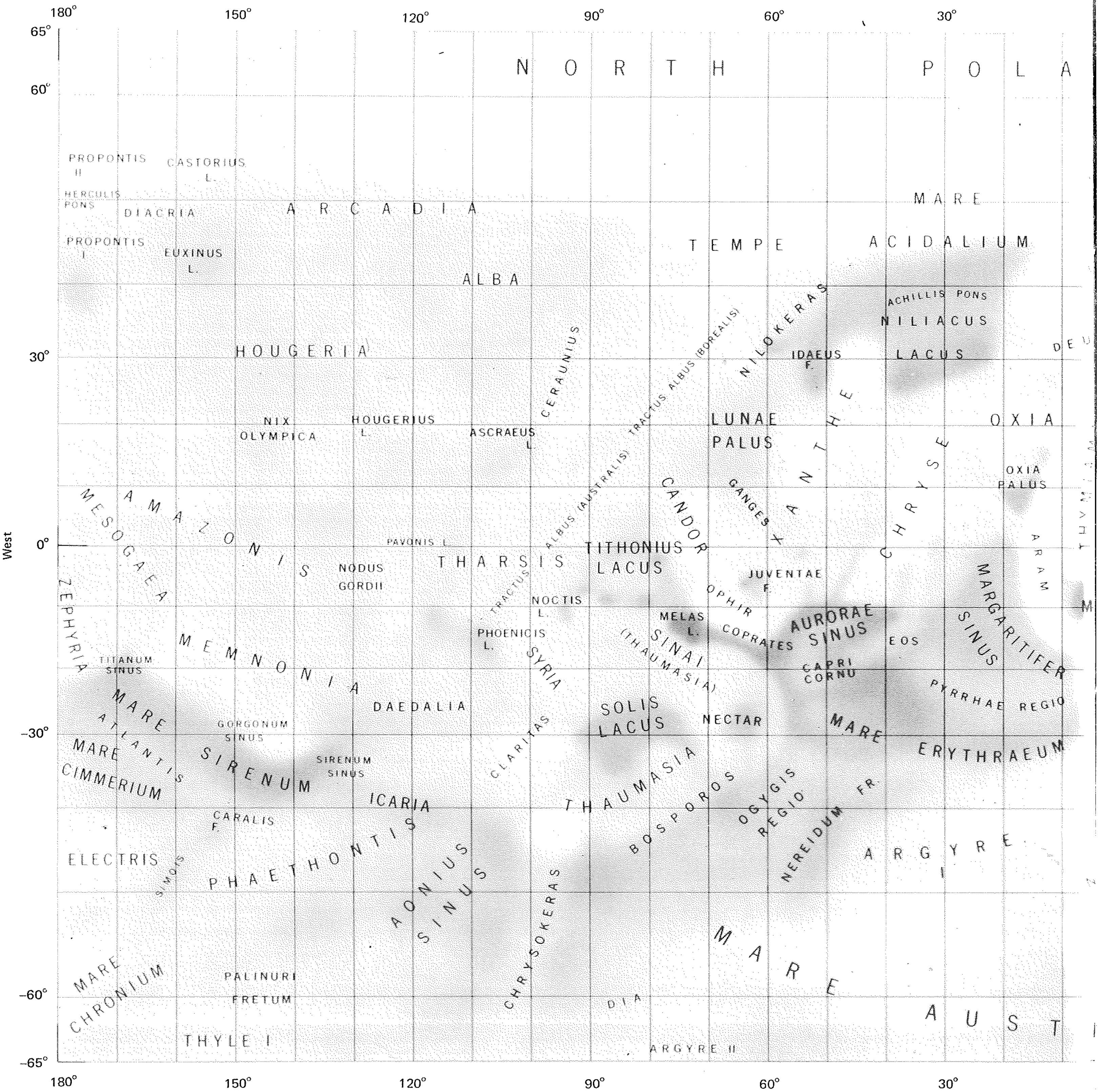
THE NEW MARS

The Discoveries of Mariner 9

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION



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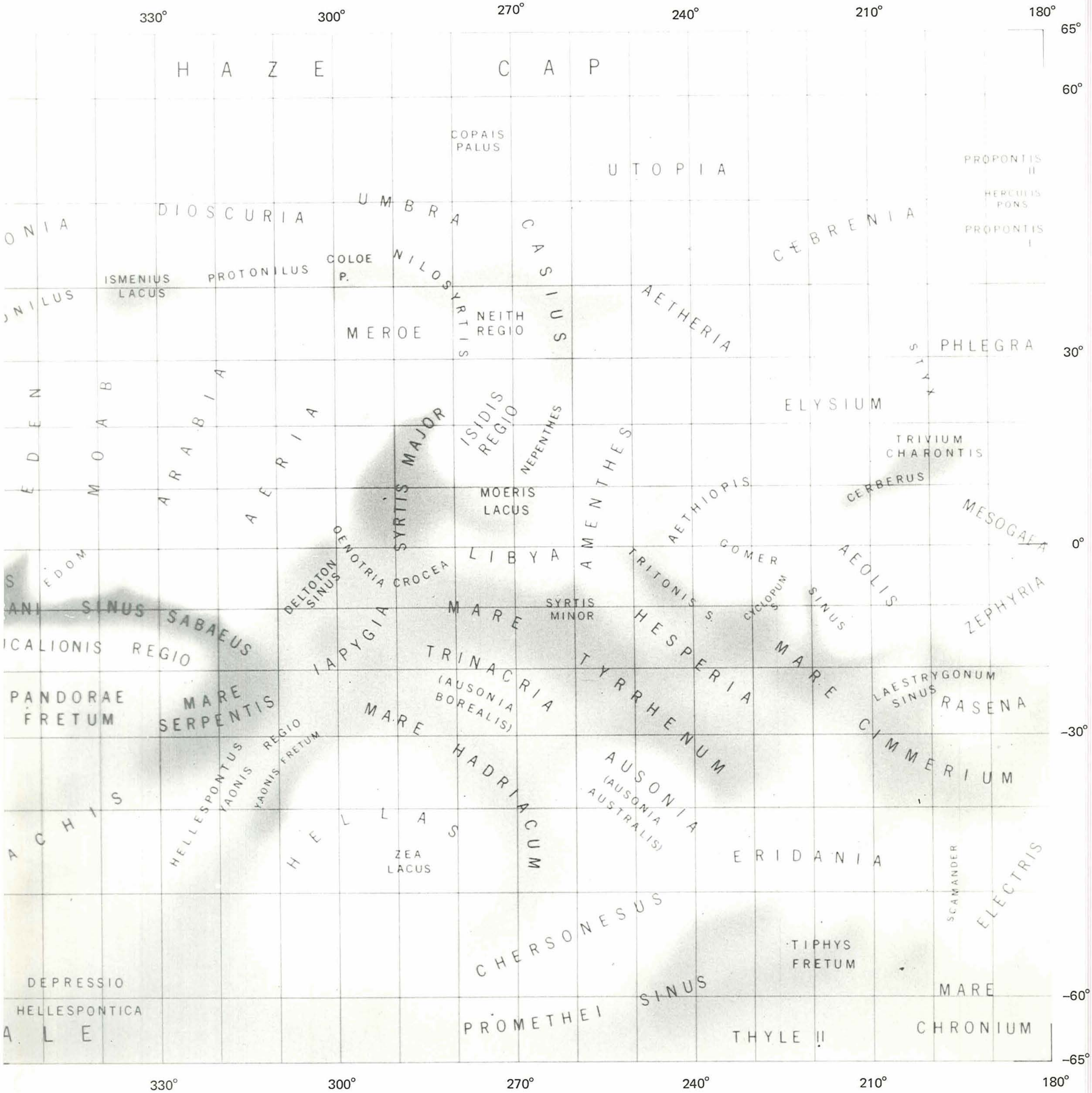

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THE NEW MARS

The Martian map forming the front endpaper is an example of one of the best representations of the surface of Mars shortly before the Mariner 9 mission. It shows the dark and light markings due to regions of different albedo, or reflectivity. These regions have long been visible from Earth. The classical names given by 19th- and 20th-century astronomers are shown on the map. The map shows no geologic structure because none could be detected from Earth.

The Martian map forming the rear endpaper is the product of the Mariner 9 mission and shows the abundant, varied geologic structures of the planet, including craters, volcanoes, and riverlike channels. Selected examples illustrate the names assigned to these structures in 1973 by the International Astronomical Union. These names do not replace the classical names, but refer to *structures* instead of the albedo features indicated on earlier maps. In coming years the International Astronomical Union will make further selections and possible modifications of names for the newly revealed Martian features.

NASA SP-337

THE NEW MARS

The Discoveries of Mariner 9

WILLIAM K. HARTMANN AND ODELL RAPER

With the cooperation of
the Mariner 9 Science Experiment Team

Prepared for the NASA Office of Space Science

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Foreword

Mars, our planetary neighbor that gleams redly in the night sky, has intrigued man ever since he first began to study the heavens. The first telescopes brought exciting images of white polar caps that expanded and contracted with the seasons. In the 19th century, telescopes employed at the limits of useful resolution introduced the controversial "canals," with their radical implication, at least to Percival Lowell, of an advanced civilization struggling to survive in an increasingly arid world. In 1965 Mariner 4, the first flyby spacecraft, returned 22 images that in their limited field of view suggested that Mars might be a cratered, moonlike, dead planet. The 1969 flyby missions added rich detail and complexity. Then the 11-month scrutiny of Mars by Mariner 9—by all odds the most productive planetary mission that has ever been flown—provided us with a revolutionary new concept of the red planet.

We now perceive that Mars is an active, evolving planet. In some areas it is characterized by gigantic volcanoes, bigger than any on Earth, and in other areas by immense canyons of totally unprecedented length and depth. It is a world etched by wind erosion and patterned by eolian deposits in some places it seems to have been dissected by a fluid erosion of undetermined nature. The scientific achievements of the Mariner 9 mission have been enormous, establishing new benchmarks in our understanding of the solar system.

It would be shortsighted to think of this voyage of planetary exploration, for all its productivity, as providing no more than additional data about one distant world. We are discovering that knowing more about Mars gives us insight about more than Mars. To learn about neighboring planets leads to improved understanding of the entire solar system, including the planet Earth. This is because planetary exploration provides a vast new laboratory in which scientists in many disciplines can create and test conceptions of the origin and evolution of the solar system and the dynamic processes that have affected all planets. Theories can be derived, compared with known effects of known processes, modified, verified, or discarded. From distant planets we are gaining significant new understanding of such down-to-earth subjects as volcanism, plate tectonics, seismic instability, magnetic-field generation, and the dynamics of planetary atmosphere. From these studies and from the future exploration of Mars and other planets will come the answers that our children and grandchildren will need to keep Earth a comfortable abode in space for man.

JOHN E. NAUGLE
Associate Administrator for Space Science
National Aeronautics and Space Administration

JANUARY 14, 1974

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WILLIAM K. HARTMANN
Planetary Science Institute
ODELL RAPER
Jet Propulsion Laboratory

Mariner 9 Science Experiment Team

Television

*Masursky, H.
- Arthur, D.
- Batson, R.
- Borgeson, W.
- Carr, M.
- McCauley, J.
- Milton, D.
- Soderblom, L.
- Wildey, R.
- Wilhelms, D.

†Lederberg, J.
- Levinthal, E.
- Pollack, J.
- Sagan, C.
- Veverka, J.

†de Vaucouleurs, G.
- Young, A.

†Briggs, G.
- Shipley, E.

*Smith, B.
- Cutts, J.
- Davies, M.
- Hartmann, W.
- Leighton, R.
- Leovy, C.
- Murray, B.
- Sharp, R.

Infrared Interferometer Spectrometer

†Hanel, R.
- Conrath, B.
- Hovis, W.
- Kunde, V.
- Levin, G.
- Lowman, P.
- Pearl, J.
- Prabhakara, C.
- Schlachman, B.

Infrared Radiometer

†Neugebauer, G.
- Chase, S.
- Kieffer, H.
- Miner, E.
- Munch, G.

Ultraviolet Spectrometer

†Barth, C.
- Hord, C.
- Lane, A.
- Stewart, I.

Celestial Mechanics

†Lorell, J.
- Anderson, J.
- Martin, W.
- Sjogren, W.

†Shapiro, I.
- Reasenberg, R.

S-Band Occultation

†Kliore, A.
- Cain, D.
- Fjeldbo, G.
- Rasool, S.
- Seidel, B.

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* Team leaders.

† Principal investigator. (The coinvestigators are indented beneath each principal investigator.)

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CHAPTER I

Mars Before Mariner

In questions of science the authority of a thousand is not worth the humble reasoning of a single individual.

—Attributed to Galileo

One is permitted to say crazy things at least two times a year.

—Schiaparelli, quoted by Flammarion

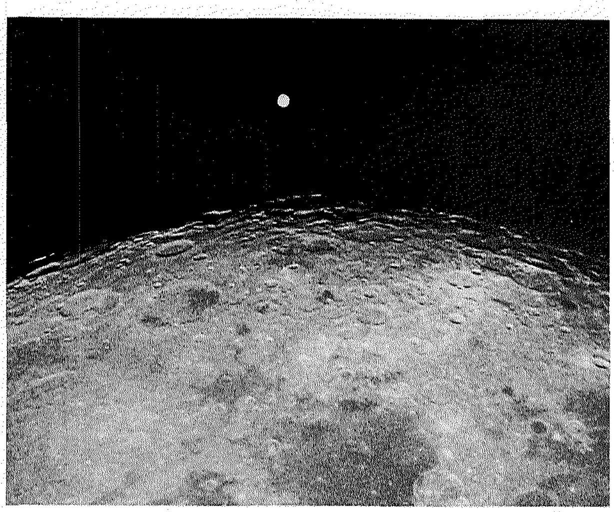
Those of us who grew up reading Wells or Burroughs or Bradbury or Clarke—or other writers of sufficient imagination to allow their characters to travel to or from Mars—have always known that Mars was a special target. Mars was said to be the planet where we might find life. Yet as we studied the concrete observational data in the last few decades, the supporting evidence for life on Mars seemed ever more elusive. By the mid-sixties the prospects seemed dim indeed. Telescopic observations showed the present state of Mars to be drier and more severe than the optimistic estimates of the early writers, who in turn based their settings on the estimates of still earlier scientists.

In 1971 and 1972, Mariner 9 revolutionized our conceptions. Before we can see how this came about, we have to understand how, through continually refined limits imposed by observations, we reached the pre-Mariner conception of Mars.

The first telescopic observations of Mars are believed to be those of Galileo, who, in 1610, wrote that he had detected the disk and phases of Mars, showing that it was a sensibly spherical body illuminated by the Sun. Lacking photography, early observers could record the appearance of the Martian surface only by carefully made sketches. The first of these was produced by the Italian scholar Francisco Fontana in 1636. Unfortunately, Fontana's telescope was too poor to show true details of the surface although he, too, recorded the phases. It was not until October 13, 1659, that the Dutch physicist Christiaan Huygens produced what Percival Lowell later called "the first drawing of Mars worthy of the name ever made by man." For the first time this showed one of Mars' characteristic dusky markings, probably the dark triangular region now known as Syrtis Major. The early observers assumed that the dark markings on Mars (and even on the Moon) were bodies of water and referred to them as "*maria*" (the Latin word for "seas").

During the rest of the 1600's, Renaissance scientists such as Cassini, Hooke, and others from all over Europe produced numerous observations of Mars. By 1666 Cassini and others deduced a rotation period of close to 24 hours—the same as Earth's—by following the motion of the spots and other markings. It was found that bright white caps marked the two poles and that the caps alternated in growing to a maximum size, depending on which hemisphere of Mars was experiencing winter. During Martian summer, the caps shrunk or disappeared.

By the early 1700's the drawings of Mars began to approach the quality of modern drawings. Finer patterns of dusky markings were recorded, having shapes that can still be identified today. A 1719 drawing by Maraldi shows a dark



Mars passing near the Moon. This photograph illustrates the difficulty of observing details on Mars from Earth. The planet appears no larger than a modest-sized lunar crater. (Lowell Observatory)

band that appeared to border the bright polar cap, a phenomenon later given much attention. Maraldi also noted changes that he thought might involve clouds.

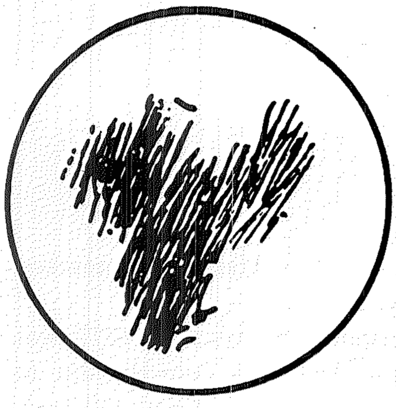
In the late 1700's, the English astronomer William Herschel speculated that the dark band near the polar cap, which came to be known as the "polar melt band," was the product of melting ice or snow that composed the caps. Herschel noted that the caps could not be too thick because they nearly disappear in summer. Herschel also observed bright, changeable patches, which he took to be "clouds and vapors floating in the atmosphere of the planet." From his observations of the polar caps he deduced the inclination of Mars' axis to its orbital plane. Finally, Herschel and the German observer Schroeter in the 1780's and 1790's began to record narrow streaky markings such as a curving "tail" on Syrtis Major.

It is interesting to note the conception of Mars that was transmitted by astronomers to other intellectuals of the early 1800's. Mars was a planet with oceans and lakes, dry reddish land, clouds, polar snows, a day of some 24 hours—in short, it was a planet much like Earth. In view of the momentous import attached by us moderns to the search for life in the universe, it may come as some surprise to realize that Herschel and other scientists of his time almost casually assumed that Mars and other planetary bodies were inhabited. This was before Darwin gave us the idea of the long struggle toward sentient life; thus scientists of the 19th century inherited the idea of "the plurality of worlds," with a Mars already teeming with creatures and a reasonably pleasant environment well suited for them.

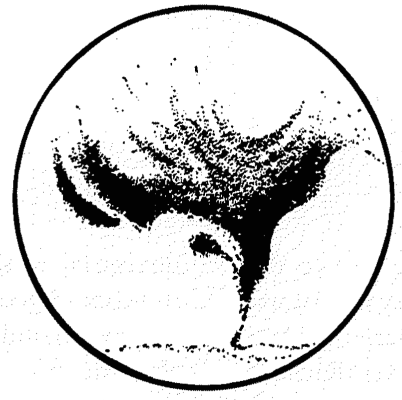
In 1840 the Germans Wilhelm Beer and Johann Mädler published the first global charts of Mars. Other maps followed. While many features are easily recognizable today, some areas show systematic differences that undoubtedly reflect long-term changes. In 1863 Father Pietro Angelo Secchi in Rome published the first known color sketches.

About 1867 the physicists Pierre Jules Janssen and Sir William Huggins made the first attempt to detect oxygen and water vapor in the Martian atmosphere by searching for telltale absorptions in the planet's spectrum, but the attempt was inconclusive.

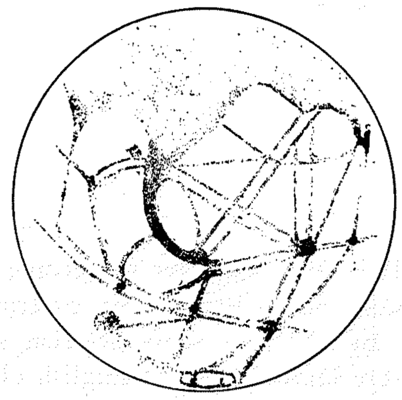
In 1869, Father Secchi referred to some of the streaklike Martian markings as *"canali,"* a term probably chosen to maintain the convention that dark areas were named after bodies of water.



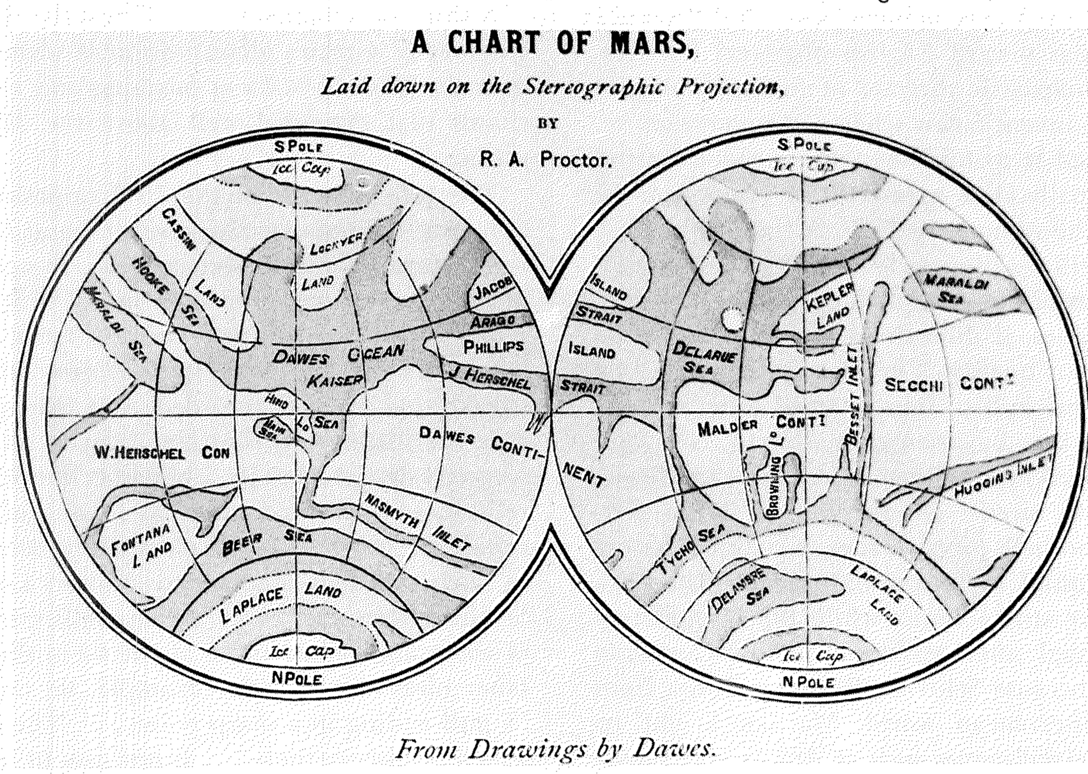
One of the earliest known sketches of Mars. It was drawn by Christian Huygens on November 28, 1659. The northward-extending marking is believed to be Syrtis Major.



Drawing of Mars by W. R. Dawes during the 1864–65 opposition. Syrtis Major extends toward the north, and the north polar hood is indicated.



Mars as drawn by Giovanni Schiaparelli on June 4, 1888. Syrtis Major extends north just below and to the left of center. Schiaparelli's system of *"canali,"* including many double canals, can be contrasted with the streaky markings shown by Dawes in the previous drawing.



R. A. Proctor's map of Mars, published in 1871. South is at the top, a convention adopted by users of (inverting) astronomical telescopes. Syrtis Major is centered in the left hemisphere, bearing the now-discarded title "Kaiser Sea."

This term was later to become the key to the most famous astronomical controversy in history.

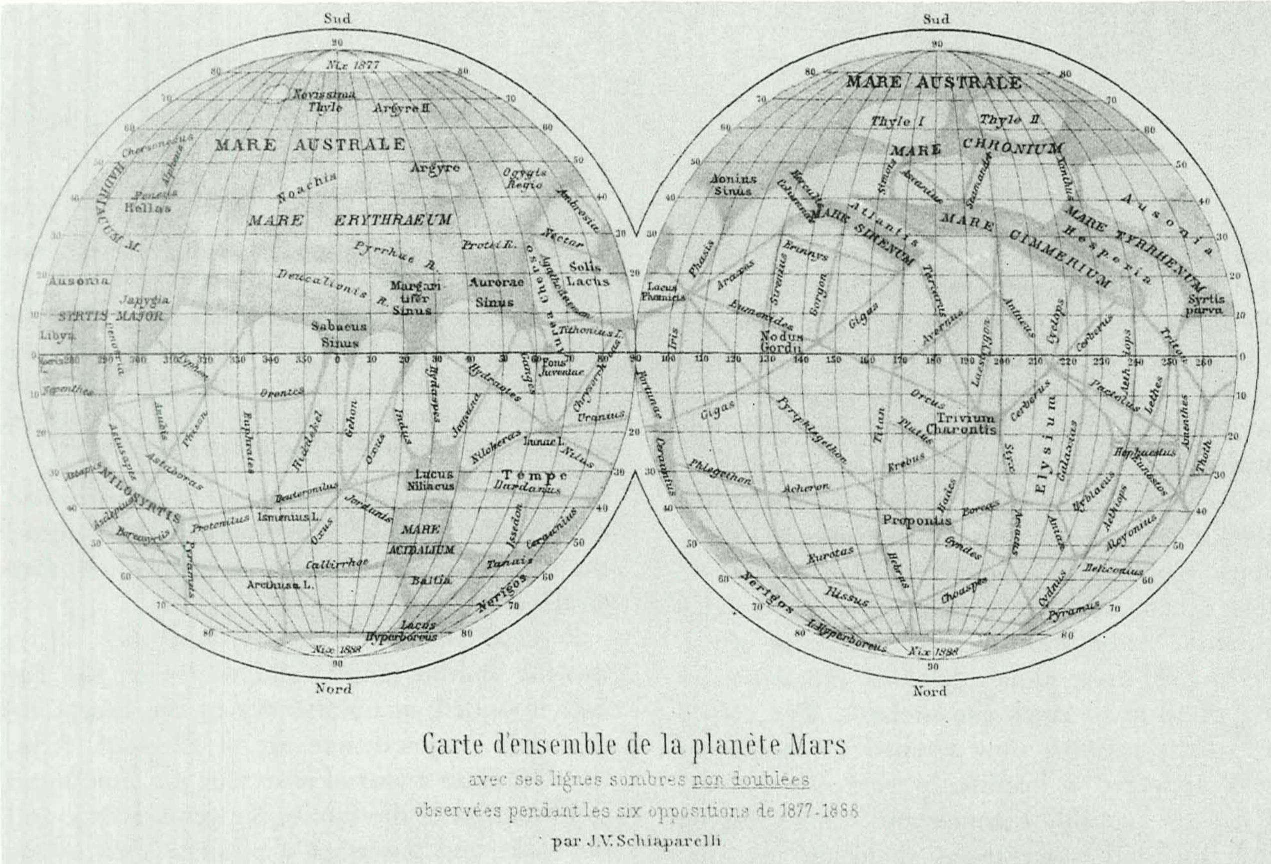
By 1871, so many Martian surface features were known that the English observer Richard Proctor produced a map with names attached to them. Proctor's proposed nomenclature was somewhat confusing, using the names of famous observers for all features. "Dawes' Ocean" and "Kaiser Sea," for example, were designations covering the most famous dark marking, now known as Syrtis Major.

A banner year for Martian studies was 1877. The confusion over nomenclature and Proctor's alleged bias toward English observers led Giovanni Schiaparelli, director of an observatory in Milan, to invent a new scheme of nomenclature. He applied it to his observations made during the unusually close approach—or opposition—of Mars in the summer of 1877. A classical scholar, Schiaparelli took names from historic and mythical sources of the classical Mediterranean world. These names, if difficult to grasp readily, have a marvelous quality. The most prominent dark area became Syrtis Major, named after a Mediterranean bay. Egyptian gods (Thoth, Isis, Anubis), biblical lands (Eden, Hiddekel), the Greek muses and sirens (Aonius Sinus, Mare Sirenum), and hell (Styx, Hades, Trivium Charontis) all found their way onto Mars. The dark areas were still oceanic, while the bright areas were named after terrestrial lands. Curiously enough, because Schiaparelli chose names from the Mediterranean world, Martian bright regions received names such as Arabia and Libya, thus by chance being named for arid, windblown, volcanic terrestrial deserts; Mariner 9 later revealed that these are among the closest terrestrial analogs to their Martian namesakes, in terms of geology.

The second outstanding event of 1877 was also the first major American contribution to the story of Mars. At the U.S. Naval Observatory, Asaph Hall discovered that Mars had two satellites, which he named "Phobos" and "Deimos" (fear and terror) after the horses that drew the chariot of the god of war. From their faintness it was clear that the two moons were only a few miles or tens of miles across—mere chunks of rock.

A third development in 1877 was the English observer N. Green's identification of white spots near the limb of Mars as morning and evening clouds that extended well above the Martian surface.

The fourth result of the 1877 opposition of Mars was the popularization of the most famous —or notorious—bit of Martian lore. In accounts of his observations published in 1878, Schiaparelli casually used Father Secchi's term *canale* (singular) and *canali* (plural) to refer to streaks that he had recorded. But Schiaparelli gave the idea a new character. (He is often incorrectly described as its originator, but Schiaparelli himself pointed out that "many of these *canali* are not new and have already been seen by such excellent observers as Kaiser, Lockyer, Secchi, Green, etc. . . .") Schiaparelli saw more of them and talked more about them than the other observers had. For example, he wrote of "a gulf ending in a sharp point. . . . The *canale* which originates there . . . is not easy to see and some uncertainty may arise concerning it." What an understatement! Schiaparelli's prediction of some uncertainty was to stretch into a



Schiaparelli's map of Mars, based on observations in 1877–88. This map shows the nomenclature introduced by Schiaparelli and since adopted by other observers. Syrtis Major is at the extreme left; south is at the top. The map shows the system of linear "canali" popularized by Schiaparelli.

60-year argument between observers who saw what they took to be "canals" and observers who could make out nothing of the sort.

In the following year, 1879, Mars was again in place for observation, and Schiaparelli, looking for one of the canals he had mapped in 1877, was astonished to see two parallel canals in its place. This doubling phenomenon came to be known as "gemination" in the literature of the late 1800's. No one else had seen any canals, let alone double ones. As Percival Lowell later wrote,

> For nine years [Schiaparelli] labored thus alone, having his visions all to himself. It was not until 1886 that anyone but he saw the canals. In April of that year Perrotin at Nice first did so. . . . Perrotin was on the point of abandoning the search for good, when, on the 15th of the month, he suddenly detected one of the canals, the Phison. His assistant, N. Thillon, saw it immediately afterward. After this they managed to make out some others, some single, some double, substantially as Schiaparelli had drawn them. . . .

Observers from Italy, France, England, and the United States also claimed to see canals in 1886.

Here, then, was a strange new Mars, with networks of fine streaks crossing the bright areas, which had come to be known as deserts, and passing also through the dark regions. It seems that the more the observers studied the canals, the narrower and straighter the canals became. The canals were supposed, then, to be barely within the resolving power of the best telescopes under the best conditions; they appeared only during moments of superseeing.

Once the canals were widely reported, they quickly became the center of observers' discussions. What could be their explanation? In the 1890's many attempts were made to answer this question. Abbé Moreaux and a geologist associate in 1890 made globes that they inflated, causing pressure to crack the surfaces. The resulting crack patterns they likened to canals. In 1892 appeared a mammoth work, *La Planète Mars*, by Camille Flammarion, who gathered and discussed observations spanning 3½ centuries, including those of canals. In the same year the American observer W. H. Pickering first detected and defined Martian oases, which were small round dark spots said to lie at the junctions of the canals.

Among other observers straining to see the canals was E. E. Barnard, at Lick Observatory. Barnard, whom the late astronomer G. P. Kuiper called one of the most acute observers of all time, had a telescope with about twice the aperture of Schiaparelli's. On September 11, 1894, Barnard reported his efforts in a letter to Simon Newcomb:

> I have been watching and drawing the surface of Mars. It is wonderfully full of detail. There is certainly no question about there being mountains and large greatly elevated plateaus. To save my soul I can't believe in the canals as Schiaparelli draws them. I see details where he has drawn none. I see details where some of his canals are, but they are not straight lines *at all*. When best seen these details are very irregular and broken up—that is, some of the regions of his canals; I verily believe—for all the verifications—that the canals as depicted by Schiaparelli are a fallacy and that they will be so proved before many favorable oppositions are past.

Barnard's skepticism was soon to be drowned out by the flood of attention directed toward the canals by other observers, particularly Percival Lowell.

Percival Lowell, traveler, member of a wealthy Boston family, and writer on the Far East, founded an observatory in the exceptionally clear, high-altitude air of Flagstaff, Ariz., in 1894. After a year of observing, he announced confirmation of the canals, the geminations, and the oases, and published a popular book, *Mars*. Lowell, an excellent writer, described both his observations and his interpretation of them with an extraordinary hypothesis. As for the canals, he stated,

> Singular as each line looks to be by itself, it is the systematic network of the whole that is most amazing. Each line not only goes with wonderful directness from one point to another, but at this latter spot it contrives to meet, exactly, another line which has come with like directness from quite another direction.

While most observers would question whether this is really a description of Mars, it is undeniably a fine description of Lowell's drawings of Mars, by the artist himself. In a bit of interobservatory one-up-manship, Lowell claimed four times as many canals as were recorded on Schiaparelli's charts, a result he attributed to the superb Flagstaff observing conditions.

Lowell went on to picture the planet as a dying, drying world late in its evolution because of its smaller size and faster cooling rate. Little water was left on the once humid surface, he said, and so it followed that—

> If . . . the planet possesses inhabitants, there is but one course open to them in order to support life. Irrigation, and upon as vast a scale as possible, must be the all-engrossing Martian pursuit. So much is directly deductible from what we have learned at Flagstaff of the physical condition of the planet. . . .

To illustrate the way Lowell built up his argument, it might be noted that these words appear on the last page of the chapter before the discussion of canals. In succeeding chapters the once innocuous term *canali* becomes the physical interpretation; the linear markings are irrigation canals constructed by intelligent beings to bring water from the poles to the more temperate equator. The idea was admittedly straightforward. Lowell ridiculed alternate ideas that had been put forward:

> Snow caps of solid carbonic acid gas (CO_2), a planet cracked in a positively monomaniacal manner . . . hypotheses each more astounding than its predecessor. . . .

So the Victorians passed to the 20th century the possibility of a Mars with dwindling water and a civilization attempting to save itself by building irrigation systems. People discussed means of communicating with the Martians and began to conceive of Earth as viewed from a cosmic vantage point. Tennyson wrote,

> Hesper—Venus—were we native to that
> splendour or in Mars
> We should see the Globe we groan in,
> fairest of their evening stars.
>
> Could we dream of wars and carnage, craft
> and madness, lust and spite,
> Roaring London, raving Paris,
> in that point of peaceful light?

While British physicist George Johnstone Stoney was attempting to defend the idea that the polar caps might be frozen CO_2 (dry ice) in 1898, British novelist H. G. Wells published *The War of the Worlds,* in which Martians send expeditionary forces in capsules to land on Earth and decimate its population. (The Martians were finally defeated not by man's technology but by infection with terrestrial bacteria.) Thus while the most cautious scientists debated in the journals, the man in the street read of canal networks and invaders from Mars, and the seeds of a hundred grade B monster movies were sown.

While the study of Mars in the 1890's provides one of the best illustrations of the transmission of science to the public through various entertaining but rather distorting filters, this is not to say that there was not a legitimate scientific puzzle of great excitement. What was Mars like? Could it sustain life? Were the canals real? There was great excitement but there were few solid empirical facts.

Lowell defended artificial canals in two books published in 1906 and 1908. In 1907, Alfred Russell Wallace, who had conceived of Darwinian evolution independently of Darwin, published a book attacking Lowell's ideas. He stated that cracks must form on any planet with a hot, stable core and a cooling crust, thus forming an apparent "canal" network. Remarking on the very low, subfreezing temperature expected on Mars, Wallace concluded that no water vapor can exist and that "Mars . . . is absolutely uninhabitable."

In 1909 Camille Flammarion published the second volume of his encyclopedia of Martian observations, containing 426 drawings and 16 maps from the period 1890 to 1901. Flammarion struggled to make sense out of the mass of different impressions of the planet.

Flammarion and his contributors discussed all of the problems then current. For example, E. W. Maunder, of the Greenwich Observatory, calculated the atmospheric structure on the basis of gravity and relative mass of Mars. Because of the lower gravity, the Martian atmosphere would be more extended and have only about 40 percent the surface pressure of Earth's atmosphere, even if it had the same mass. If the Martian atmosphere were less massive in proportion to the planetary mass it would have about 14 percent the surface pressure, resembling Earth's atmosphere at nearly 50 000 feet. Because of the distance of Mars from the Sun, Maunder estimated temperatures as low as −135° Celsius (−211° Fahrenheit). At best, Maunder thought a day on Mars could be no more attractive than a day on a 20 000-foot mountain in Spitsbergen. Maunder's Mars was clearly not so hospitable as Lowell's

W. H. Pickering, using Lowell's telescope, reported that the dark areas generally appeared depressed when seen at the sunrise or sunset line and concluded,

> Perhaps we are on the eve of constructing an orographic map of the planet, but these observations are very difficult and one must not expect too great precision. . . . There are hills and valleys and consequently the dark regions do not represent the surface of an ocean.

Louis Jewell at Johns Hopkins reported a new attempt to get spectroscopic evidence for oxygen and water vapor on Mars. Jewell concluded that the upper limit that could be set for oxygen was one-fourth that of Earth's atmosphere and for water vapor, an amount considerably greater than that of Earth.

As for the question of life on Mars, Schiaparelli himself contributed a discussion to Flammarion's book. Schiaparelli and others had noted that if the polar caps were frozen water, the fact that they melted in summer indicated a much warmer climate than Maunder had hypothesized. As Flammarion paraphrased,

> Everything leads one to think that the climate of Mars is the same as that of our high mountains —very warm in the full sunlight of the day, very cold during the night. No clouds in general, no rains, just some sky and some snow.

Schiaparelli took a middle road on the question of life:

> Geometric design [of the canals] lead[s] one to believe the work was done by intelligent beings . . . [yet] the bodies in Saturn's ring definitely were not turned out on a lathe. . . . Geometric forms are the simple and necessary consequences of the laws which govern the physical and physiological world.
>
> It would be easier to satisfy oneself [as to the appearance. geminations, and variability of the canals and associated features] by introducing the action of organic forces. Here the field of hypotheses grows larger and infinite combinations present themselves. Changes in vegetation . . . generations of small animals. . . . Let us hope and continue to study.

Clearly the discussion had gone as far as it could (or farther) without substantial new scientific information. So strongly had Lowell emphasized the advantages of excellent atmospheric conditions and optics, that opinion was heavily swayed by the reports of observers with big telescopes in good locations. G. E. Hale and his associates turned the 60-inch telescope of Mount Wilson toward Mars on November 3, 1909, during a period of excellent conditions when 800-power magnification could be used. They reported "not a trace of geometrical structure on the planet, nor any narrow straight canals." This observation was widely quoted by observers who could not confirm the straight, Lowellian canals.

A similar result was later reported by the French observer E. M. Antoniadi, who described his impression at a 32¾-inch telescope on September 20, 1909:

> At the first glance . . . [I] thought [I] was dreaming and scanning Mars from his outer satellite. The planet revealed a prodigious and bewildering amount of sharp or diffused natural, irregular, detail, all steadily; and it was at once obvious that the geometrical network of single or double canals discovered by Schiaparelli was a gross illusion. Such detail could not be drawn; hence only its coarser markings were recorded in the note-book.

Such reports marked the beginning of a reversal in the discussions. Nonetheless, it was later pointed out in rebuttal that the Hale and Antoniadi observations were made at a midsummer season on Mars (Martian effective date July 23 for Hale) when canals were not usually prominent. Observers who detected canals reported that they were most prominent during late spring (Martian dates April 1 to June 15 for the northern hemisphere).

In 1913, E. W. Maunder published his famous "English schoolboy experiment" in which a classroom of some 200 pupils unaware of the elements of the controversy sketched from their seats at various distances a set of Martian drawings which contained no linear canals, but in their place "a few dots or irregular markings . . . here and there." The closest pupils drew the spots; the farthest could not see any of the fine markings, but the intermediate students made out systems of nonexistent straight lines. This supported a growing suspicion that Mars contained a variety of surface detail just on the limits of resolution from Earth, so that observers in the best moments of seeing mistakenly perceived lines instead of the actual poorly alined splotches and shadings.

During the 1924 and 1926 appearances of Mars, the American observer Trumpler, using the 36-inch Lick telescope, wrote,

> [Canals] vary greatly in visibility, width, and definition. . . . Practically every step of transition between . . . broad bands and the finest most difficult canals is represented. The canals . . . do not appear quite sharp, but rather as diffuse hazy shadings.

This again was quite a different description than that given by Lowell, who had popularized the canals as finely etched straight lines.

During the same years, W. H. Wright of Lick and E. C. and V. M. Slipher of Lowell obtained the first good series of photographs in various colors. These showed that just as on Earth, red light penetrated farthest through the atmosphere, while blue light was reflected or scattered from the atmosphere, hazes, and clouds. Photographs through blue filters did not show the surface features of Mars, but rather showed a hazy surface with occasional cloud features. Martian dark markings showed most clearly with the reddest filters but were sometimes obscured by yellowish clouds assumed to be blowing dust.

At the same time Nicholson and Pettit at Mount Wilson and Coblentz and Lampland at Lowell got the first good measurements of the thermal radiation of Mars, giving the following temperatures:

South polar cap	−70° Celsius (−94° Fahrenheit)
Sunset	−13° Celsius (9° Fahrenheit)
Noon (subsolar)	10° Celsius (50° Fahrenheit)

The mean temperature on Mars, on the basis of such measurements, was interpreted to be –40° Celsius (–40° Fahrenheit), as opposed to a terrestrial mean temperature of about 15° Celsius (59° Fahrenheit).

In 1930 the French observer E. M. Antoniadi published a compendium of Martian observational data, *La Planète Mars,* which contained a new detailed map and stressed that in regions where earlier observers had reported canals, he himself, using the largest refracting telescope in Europe, had seen only irregular patchy arrays of spots and splotches that merely seemed linear under poorer conditions. This became the most definitive word on canals, as far as Earth-based telescopic observation was concerned.

There remained, of course, the question of the cause of the large-scale, variable dark markings on Mars. Because of their seasonal variations and reputed greenish color, the hypothesis of Martian vegetation remained attractive. What was needed to confirm or refute this idea was more discriminating observational tests. In 1938, the Canadian astronomer Peter M. Millman began a spectroscopic study of the markings by noting,

> . . . so much nonsense has been written about the planet in various branches of literary endeavor, that it is easy to forget that Mars is still the object of serious scientific investigation. . . .

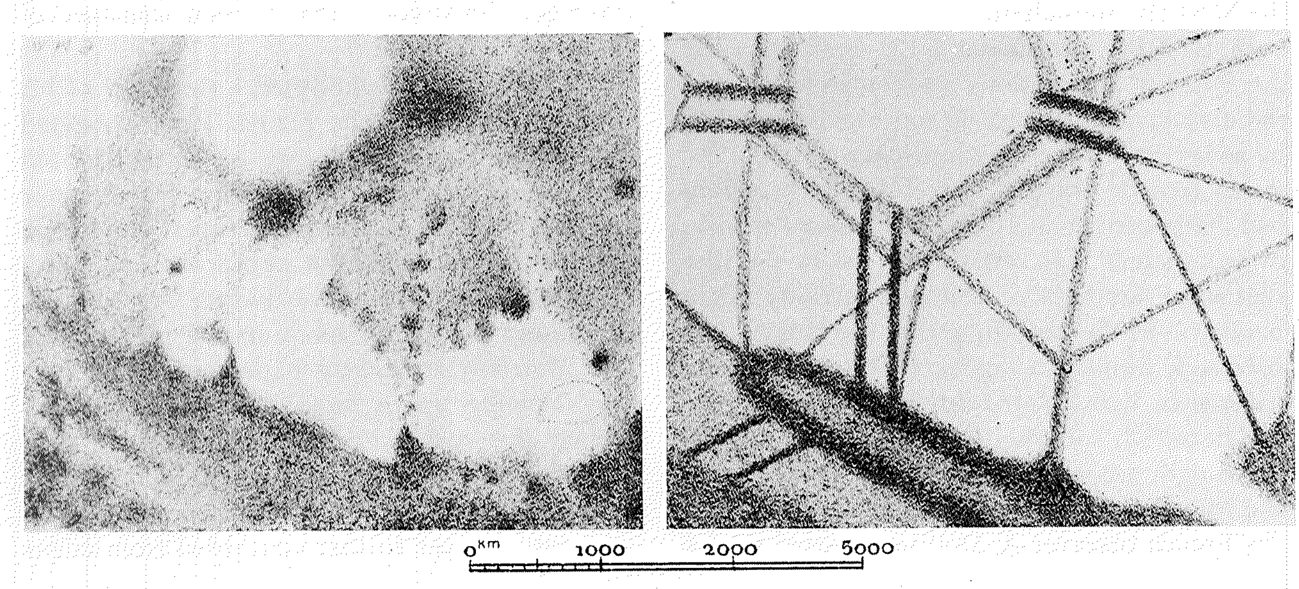
Millman considered the spectrum of the light reflected from the dark areas separately from that of the light reflected from the bright regions. Just as Wright's photographs in 1924 had shown the dark markings to be most pronounced in red light, Millman found that the greatest contrast in his photographic spectra appeared at red wavelengths near 6000 angstroms. On the other hand, he noted that all leafy vegetation on Earth is bright rather than dark at red wavelengths because of chlorophyll's transparency in red and resultant multiple scattering of red light. This difference between Earth's plants and Martian dark areas was a substantial argument against the dark markings being vegetated areas.

More data came from the oppositions of 1934, 1937, and 1941, during which W. S. Adams and T. Dunham, using the 100-inch reflector on Mount Wilson, were able to reduce still further the limits for oxygen and water vapor on Mars. After finding no O_2 or H_2O absorptions in the best spectra yet obtained, they concluded that the oxygen content was less than 1 percent the quantity above Earth's surface and that the water vapor content of the Martian atmosphere was similarly low. Not only the temperature but also the atmospheric conditions were more hostile than had once been assumed.

It is interesting to note the steady drift away from the conception of a habitable Mars. Near 1800, Herschel had assumed a fertile, inhabited planet. By 1900 the conception was that the Martians had to struggle against arid environment for their existence, if they existed at all. By 1940, evidence was beginning to accumulate against vigorous plant life, not to mention intelligent creatures.

Nonetheless, the peculiarity of the markings on Mars (as compared with those on the Moon, for example) could not easily be dismissed. They changed both seasonally and sporadically. Even the "canals" were still a subject of discussion. For example, Edison Pettit of Mount Wilson, who had never seen "canals" during his observations of Mars with large telescopes, finally reported them during a series of observations with a 6-inch refracting telescope, undertaken for his own education. One morning in 1939 a linear feature became visible, followed in seconds by another. Pettit attributed the visibility of canals to moments of superseeing, which came only rarely. His report to some extent reopened the debate about the canal question; there was the nagging suspicion that

A proposed solution to the problem of the "canals." In the left drawing, E. M. Antoniadi shows markings under the very best observing conditions in the region south of Elysium (bright oval, top). On the right, the same region is shown as drawn by earlier observers under poorer conditions when dark "nuclei" and color boundaries are seen as streaks.



unusual linear features or alinements did exist in some form on Mars, and might be variable in their prominence because of seasonal or nonseasonal real changes on the surface of Mars.

In the 1940's, G. P. Kuiper at the McDonald Observatory took advantage of newly developed infrared detectors to study parts of the spectrum even redder than had been studied before. In these infrared regions, carbon dioxide, water vapor, and other gases have diagnostic absorptions. In 1947, for the first time, Kuiper identified one of the Martian gases, carbon dioxide. Some other gases such as nitrogen, which composes 78 percent of Earth's atmosphere (by volume), could not be ruled out because they exhibit no spectral absorption bands in the region of the spectrum studied. Oxygen was virtually absent and water vapor very scarce. In view of the uncertainty about such potentially major constituents as nitrogen, it was difficult to estimate the total surface pressure of the Martian atmosphere.

In 1950 the astronomer E. J. Öpik reviewed the current observations and emphasized that the dark markings must be continually renewed by some mechanism, because photographic and visual records proved that certain dark regions had disappeared only to reappear several months or years later. This revived interest in the idea that some low form of biological activity might be involved in renewing the markings; dark bare rock would not regenerate by itself if once covered by light-colored dust.

The search for specific rock or soil materials that might account for the known properties of the Martian surface was advanced in 1950 when the French observer A. Dollfus reported that of many soil samples, the only one that matched the color, brightness, and polarimetric qualities of the bright areas on Mars was a sample of powdered limonite, a hydrated iron oxide formed in arid regions on Earth. A powdery or dusty texture was required and was consistent with the yellowish hazes said to be "dust storms." Other rock types such as red sandstone and various volcanic ashes did not match the data as well. This observation supported the longstanding theory that the reddish color of Mars was due to oxidation of iron-bearing surface minerals, as occurs in the orangish deserts of Earth.

In 1951 the French observer Gerard de Vaucouleurs published the most recent technical book-length monograph on Mars, which was subsequently translated into an English edition in 1954, *Physics of the Planet Mars.* This contained not only a review of observations through 1952 but also material on the theoretical meteorology, climatology, and internal structure of Mars.

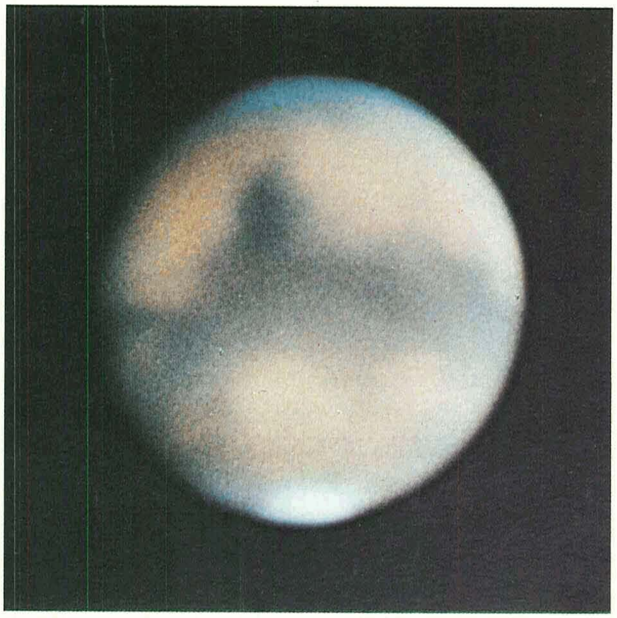
In 1952, Kuiper published a summary of his infrared studies of the planet. He interpreted his spectra of the polar caps as solving the old problem of whether the caps were frozen water or frozen CO_2—i.e., dry ice. Kuiper found that his spectra matched the appearance of water frost, and not dry ice. Concluding that the caps contained water ice, he proposed a model of the Martian atmosphere with floating ice crystals, ranging up to some 10 or 15 kilometers above the surface, responsible for the well-known bluish hazes that partly obscure the planet. Yellowish hazes were taken to be blowing dust. Kuiper further concluded from colors and spectral features that "the bright regions of Mars are composed of igneous rock, similar to felsitic rhyolite," a brownish rock that matched the spectra better than red soils or volcanic ash samples. Taking into account the emphasis by Öpik and others on the variability of the dark regions, Kuiper discussed the possibility that lichens—a symbiotic plant combining fungi and algae and frequently found on bare rock in a wide range of climates including Antarctica—were responsible for the dark markings. Kuiper proposed that lichens might account for the color and regenerative properties, although they do not display as strong a seasonal variation as found on Mars.

In 1954, W. M. Sinton and J. Strong, using the 200-inch telescope on Mount Palomar, obtained new radiometer measurements of temperatures on Mars. These included—

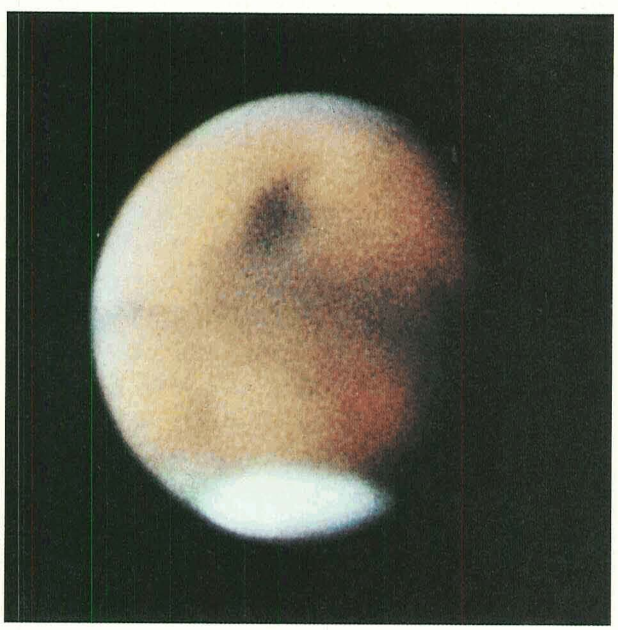
Sunrise on equator	−60° Celsius (−76° Fahrenheit)
Noon on equator	25° Celsius (77° Fahrenheit)
Yellow cloud	−25° Celsius (−1° Fahrenheit)

The year 1954 also saw publication in five astrononomical and geological journals of a new theoretical interpretation of the Martian markings, which, in the light of Mariner 9 knowledge, was one of the most accurate of the pre-Mariner general planetary models for the surface of Mars. Dean B. McLaughlin, of the University of Michigan, started by considering the general shape of the large dark masses. Instead of being roughly circular, as are the lunar maria (lava flows filling circular impact craters), the Martian markings are elongated, often with curving branches or streaky extensions lying at an angle to the equator. The pattern suggested to McLaughlin the trade wind patterns of Earth. Perhaps the markings were deposits of dark windblown dust, McLaughlin suggested. He next considered the common pointed extensions of Martian dark areas named "carets" by Lowell. Examples are the forks of the "forked bay," Sinus Meridiani. The tips of these, he reasoned, must be sources of dark powdery material that was then blown by prevailing winds and deposited in the characteristic funnel-shaped fans. McLaughin assumed that the sources were active volcanoes and that the dark windblown material was volcanic ash. The markings, then, were due to ash deposits maintained in certain patterns by the stable prevailing winds. The regenerative power of the dark markings was attributed to the eruption of volcanoes, at the tips of pointed markings, and their variability was attributed to local changes in deposition patterns due to wind shifts.

In 1955, Kuiper reviewed the available evidence on the surface markings and concluded that the dark areas were probably ultimately caused by ancient lavas, as on the Moon, but possibly covered in part by primitive plants. Kuiper argued against McLaughlin's notion of active volcanism as the essential cause of the changes because terrestrial volcanoes emit large amounts of water; volcanism at the rate required by McLaughlin would produce orders of magnitude more water on Mars than the amount observed in the spectroscopic results. Such arguments caused McLaughlin's hypothesis to lose favor in the 1950's. Instead, most



Two modern terrestrial photographs of Mars showing the face of the planet illustrated in some of the early drawings in this chapter. Syrtis Major is the darkest marking. The bright, pale oval area due south of Syrtis Major is the "desert" Hellas. The south polar cap and north polar haze are visible. (Lunar and Planetary Laboratory, University of Arizona)



observers agreed at that time with Kuiper's conclusion:

> The hypothesis of plant life . . . appears still the most satisfactory explanation of the various shades of dark markings and their complex seasonal and secular changes.

We will not continue to detail the myriad of new observational material that poured in after the beginning of the space age in 1957. This information will be presented in the topical chapters that follow. However, we will discuss two types of research that directly attacked the old question of life on Mars.

The profound ramifications of the hypothesis of plant life on Mars—i.e., the implication that life arises on any planet where conditions are clement, and could evolve to intelligence—of course led to many attempts to confirm or refute the idea. Clearly, proof of life on Mars would be one of the great discoveries of history.

The first type of research on this problem was directly observational. It was known that certain carbon-hydrogen molecular bonds in vegetation, particularly in chlorophyll, give rise to spectral absorptions far in the infrared, near wavelengths of 3.4 to 3.5 micrometers. After observations in 1956, the American observer W. M. Sinton announced confirmation of three of these absorption bands in the spectrum of Mars. This report, contained in a paper titled "Spectroscopic Evidence for Vegetation on Mars," caused a flurry of excitement. However, a few years later, Sinton, along with astronomers D. Rea and B. O'Leary, was able to identify two of the three bands as caused not by molecules on Mars but by molecules of heavy water (a rare form of H_2O containing an atom of

An early conception of the Martian landscape, as painted about 1946 by Chesley Bonestell, 2½ decades before Mariner 9. The orangish desert and distant dust cloud are consistent with modern views, but the green tones of the foreground are inconsistent with recent measurements. (From *The Conquest of Space* by Willy Ley and Chesley Bonestell. © 1947 by Chesley Bonestell. Reprinted by permission of The Viking Press, Inc.)

deuterium in place of one hydrogen atom) in Earth's atmosphere. By coincidence, the heavy water absorption bands happen to overlap the spectral positions of the sought-for Martian C–H bands. The third band that had been reported was so weak that its existence was questionable from the start. Thus, by the early 1960's, there appeared to be no spectroscopic evidence of complex organic materials on Mars.

A second type of research dealing with life on Mars was experimental. H. Strughold and his colleagues at the U.S. Air Force Aerospace Medical Division began experiments around 1957 to find out if simple terrestrial organisms could survive in the Martian environment. Of course, the test environment was a simulation of the Martian environment as it was conceived in 1957. Because the estimates of surface pressure declined markedly during the following decade, the experiments had to be repeated. In general, the results stayed the same: terrestrial microorganisms and spores could survive at least in a dormant state on Mars; growth and reproduction depended on the availability of moisture, ultraviolet light incidence, and similar environmental factors. Native Martian life forms, however, might conceivably have evolved by natural selection to a condition where they could flourish in the present Martian environment.

Quotations from several workers during this period sum up the prevalent attitudes. The biologist N. H. Horowitz in 1966 wrote,

> . . . if we admit the possibility that Mars once had a more favorable climate . . . we cannot exclude the possibility that Martian life succeeded in adapting itself to the changing conditions and remains there still.

In 1968, the chemist W. F. Libby, known for developing the radiocarbon method for archeological dating, commented,

> Intelligent life as we know it can hardly be expected on the surface of . . . Mars . . . for two reasons—the extreme swing of temperature and the killing nature of unfiltered sunlight. So the possibility of life . . . would appear to be restricted to subterranean forms requiring no atmosphere and no sunlight. Our studies of meteoritic matter show that considerable quantities of organic matter, presumably primeval, exist, and we can think therefore of anaerobic bacteria living off of this matter. . . . Anaerobic subterranean life may be chemically possible on . . . Mars.

Finally, NASA biologists C. Ponnamperuma and H. P. Klein reviewed the knowledge of Mars as recently as 1970 and concluded,

> . . . it seems clear that the limiting factor for life on [Mars] is likely to be the unavailability of water. Temperature fluctuations, low atmospheric pressures, lack of atmospheric oxygen . . . and increased radiation (even in the ultraviolet region), are all secondary to this point.
>
> Future [experiments], particularly on the Mariner 1971 orbiting spacecraft, will survey the planet for local sources of water. . . .

New observations by substantially new techniques were now needed to go beyond the level of theorizing that had led observers closer to, but had not really produced, a complete understanding of the processes occurring on Mars. Investigation by spacecraft was to provide a quantum jump forward and shed new light on the key question of water and its behavior on the surface of Mars.

CHAPTER II

Summary of the Changing Face of Mars

A vast collection of facsimiles and information has been amassed.

—Earl C. Slipher, 1962

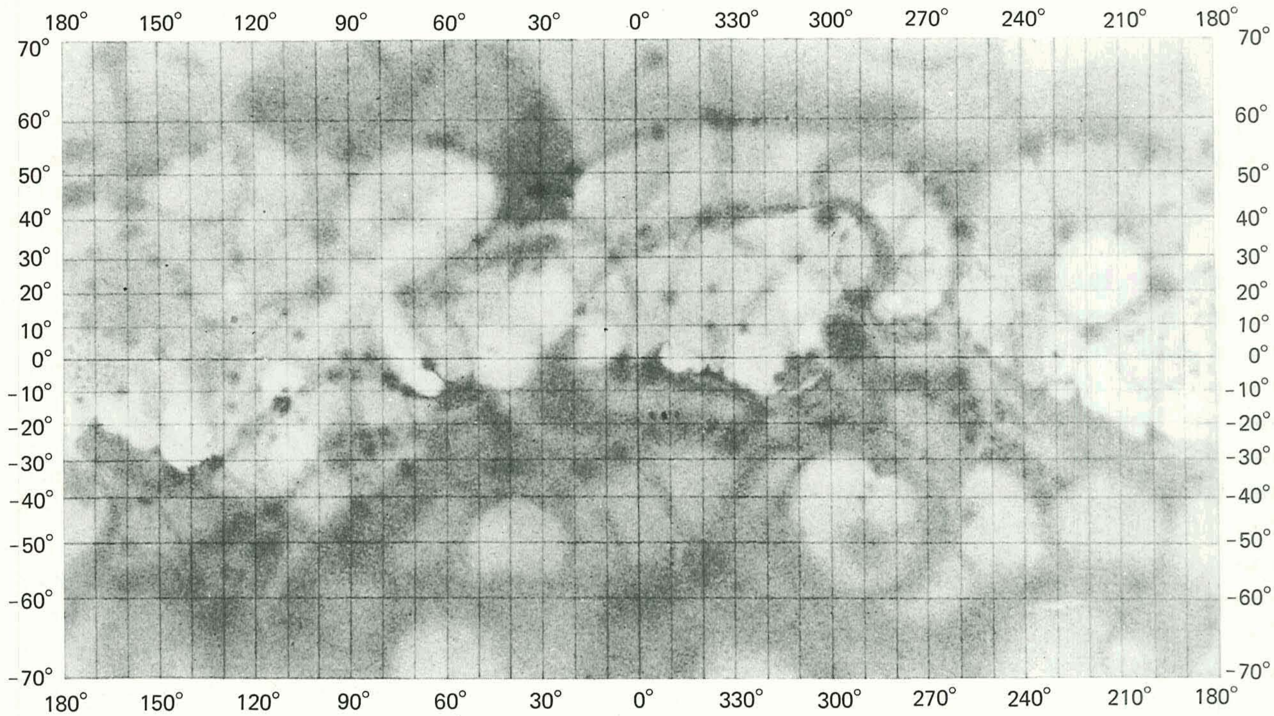
Before beginning a systematic topical review of the findings of the Mariner 9 mission, we must pause to summarize what was known of the peculiar, changing markings observed during the hundreds of years of data collecting described in chapter I. We will present this in the form of a discussion of four types of markings and their seasonal changes. We also take this opportunity to present several classical and recent maps of Mars as constructed by Earth-based observers without the benefit of spacecraft data. This material summarizes pre-Mariner knowledge on the basis of which the Mariner missions to Mars were conceived and planned. The four categories of markings—those which greet the observer who first looks at the planet with a large telescope—are polar caps, dark areas, bright areas, and clouds.

POLAR CAPS

At the end of summer on either hemisphere of Mars, a vast, whitish, diffuse haze forms over the polar region, extending as far as latitude 40° to 50°. The nature of these clouds was uncertain prior to Mariner 9. When this veil finally disappears at the end of winter, a brilliant white polar cap is exposed. Slowly it begins to shrink, and its rate of shrinkage increases as spring proceeds. By midspring on Mars, the cap begins to break into various sections, divided by dark rifts. Isolated patches may appear near the edge. Finally the summer cap shrinks to a small residual patch. Prior to Mariner 9 it was widely but incorrectly believed that the south cap disappeared entirely during summer, although de Vaucouleurs in 1954 noted that neither cap vanished. In late summer the polar haze forms again, first as patchy diffuse clouds, later merging into a uniform polar haze. The new cycle thus begins and repeats the old cycle with small variations from year to year. One of the main unresolved research questions about the cap concerns its composition. Clearly it is some frost or snowlike material, but in spite of Kuiper's 1952 assertion that the cap surface showed spectral features of water frost, later results suggested a large amount of frozen CO_2, or a mixture, the relative abundance of which was a key question for Mariner 9 in order to progress toward an understanding of the past availability of water on the surface of Mars.

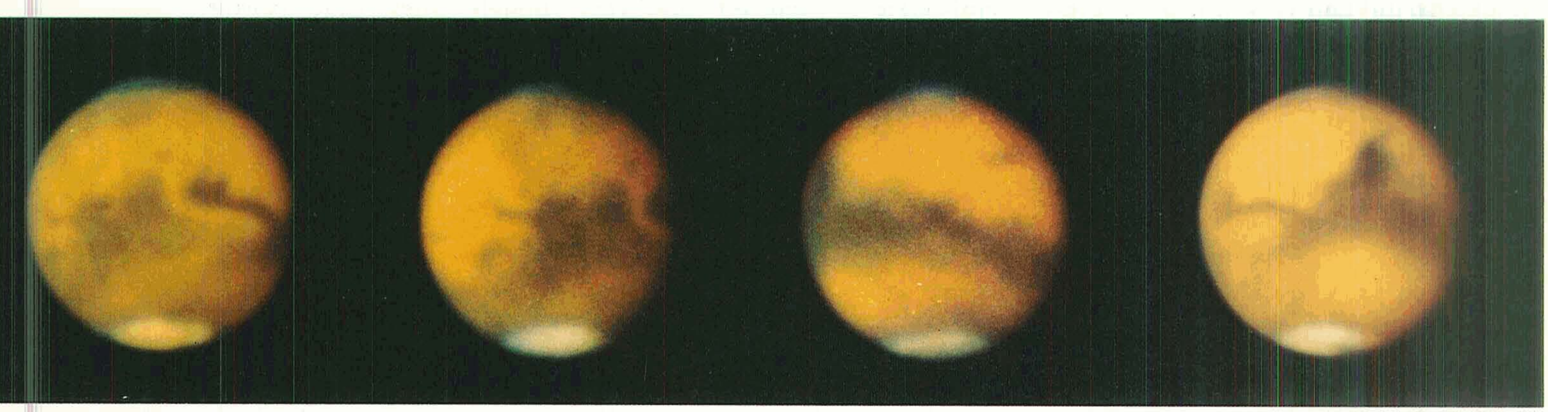
DARK AREAS

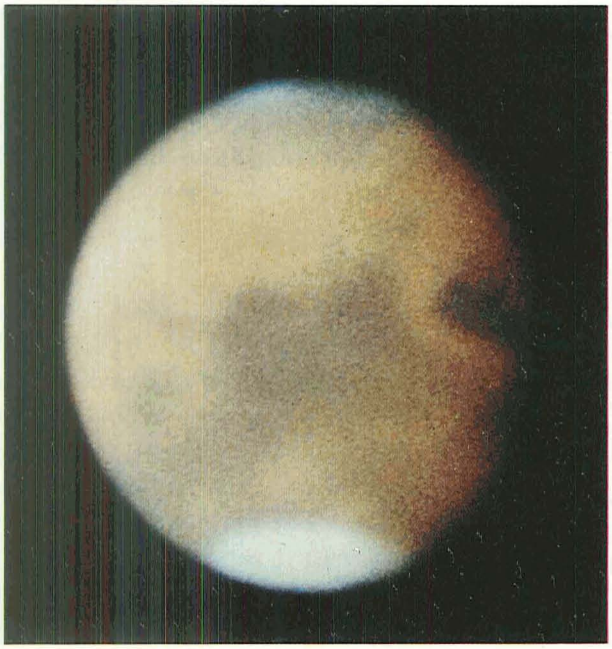
The dark areas are called "maria" (singular, "mare"), the Latin word for seas, because the earliest observers thought they were oceans. Smaller dark areas are referred to as lakes (lacus), bays, etc. Although visual observers of the past usually described the dark areas as greenish or bluish in color, spectroscopic observations in the last decades—such as those by the French observer A. Dollfus and by T. McCord of MIT—have shown that they are merely less red than the bright areas. That is, they are brownish, or perhaps occasionally gray.



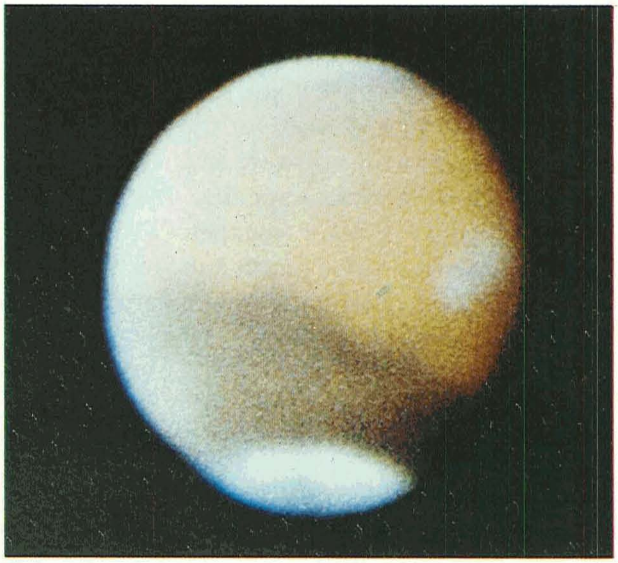
Map of Mars by the French observer E. M. Antoniadi, drawn in 1925. This map emphasizes the patchy nature of the dark markings and the spotty "nuclei" of which they are composed as seen visually from Earth under the best conditions.

Four faces of Mars as recorded in composite photographs, prepared by combining single-color images made with red, green, and blue filters. (Lowell Observatory International Planetary Patrol)





Region of Mare Erythraeum, photographed in 1971. (Lunar and Planetary Laboratory, University of Arizona)



A bright cloud is visible at right, having formed in the Martian evening over the Tharsis area. A bright south polar cap is visible in this July 7, 1971, photograph, along with a bright south polar cap and some north polar haze. (Lunar and Planetary Laboratory, University of Arizona)

The subjective greenish tone may be a color-contrast effect caused by the markings being placed on an orangish background. Changes in the markings included sporadic changes in shape or darkness, and seasonal changes. One example of a sporadic change is the darkening and spreading since 1909 of a curved region (called a "canal" complex by some) east of Syrtis Major known as Thoth-Nepenthes. Another example is the changeability of the Solis Lacus region, which occasionally disappears only to re-form at some later date. Many such changes have been documented in a photographic atlas by E. C. Slipher of Lowell Observatory. Seasonal changes are just as remarkable. During the Martian winter, the markings are faint. As the polar cap begins to retreat in spring, a dark band is reported nearby, which then spreads toward the equator. Markings darken dramatically and become more clear and well defined. This phenomenon is called the "wave of darkening." De Vaucouleurs has reported a rate of 2.0 kilometers per hour (1.2 miles per hour) for the general wave, with considerably slower rates in certain dark "arteries," such as Hellespontus. That the darkening spreads from the polar cap as the cap itself diminishes was, of course, responsible for the early belief that some material from the cap itself was responsible for darkening. This led at once to the hypothesis that the mysterious material was water or water vapor, and that the darkening was a result of its action on vegetation. A counter argument is that even the earliest advocates of vegetation recognized a color change that accompanied the wave of darkening, and this change was from a grayish (or reportedly greenish) winter color to a brown or chocolate color in spring and summer—opposite from the terrestrial vegetation color changes. The obvious research question prior to the Mariner 9 mission concerned the exact nature of the dark material and the cause of the changes.

BRIGHT AREAS

Because these areas were thought by the first observers to be land, and because Mars is known to be dry, these areas acquired the name "desert"—a name certainly more fitting than the appellation "maria" for the dark regions. Although there has been a tendency to think of these areas as passive backdrop for the variable dark markings (perhaps the psychological response from sketching the dark markings on blank white paper), the bright areas have detail of their own. The Elysium area, for example, is often noticeably lighter than other areas. Yellowish dust veils seem to be associated with light areas, particularly Hellas. Recently, spectrophotometric observers such as P. Boyce of Lowell Observatory and T. McCord of MIT have reported that when the relative brightness of neighboring bright and dark areas changes, as in the case of Arabia and Syrtis Major the bright area may brighten rather than the dark area growing darker. Similarly, these observers report a common midafternoon brightening of the bright areas, suggesting that winds rise in the afternoon and stir up dust clouds. Some of these observations suggest, but do not prove, that the bright areas have significant amounts of fine mobile surface dust that can be easily stirred by winds. The Mariner 9 mission was designed to allow photographic resolution of fine detail in the bright areas and to detect changes in brightness of markings.

CLOUDS

The relative permanence of the background markings on Mars makes it easy to detect clouds that temporarily obscure these markings. Such clouds have traditionally been divided into three categories: yellow clouds, white clouds, and bluish clouds and hazes. The yellow clouds have a relatively straightforward interpretation. Their color, their association to some extent with bright areas, and polarimetric observations by the French observer A. Dollfus and others all indicate that they are composed of fine yellowish dust particles, some micrometers (1 micrometer = 0.0001 centimeter) in diameter, raised from the surface of Mars by winds. White clouds have been thought to be condensation products; hypotheses include high cirruslike clouds of water ice crystals or frozen CO_2 crystals. Such clouds are sometimes associated with white patches that remain fixed, apparently lie on the ground, and are believed to be frost deposits. White clouds and frosts are often observed along the sunrise or sunset lines, but occur elsewhere. We will see that Mariner 9 gathered definitive new evidence on the nature of these clouds. Bluish clouds and hazes are a more controversial topic. Discrete blue clouds—so named because they were detected on photographs made with blue filters—are usually coincident with what visual observers call white clouds. However, an additional phenomenon is present because photographs in blue light almost always show a nearly blank haze obscuring the surface markings. On occasion, however, blue photographs show the markings almost as clearly as photographs made with red filters. For some years, many observers believed this so-called "blue clearing" occurred only at opposition, when Mars was in its full phase opposite in direction from the Sun; hence it was suggested that the blue clearing might be related to the phase of Mars. Other observers have discounted this relationship as an effect of observational selection. Slipher's photometric catalog shows examples of blue clearing far from opposition. It has been hypothesized that the surface markings of Mars are intrinsically low in contrast in blue light, accounting for the puzzling "blue haze" without actually invoking an atmospheric haze. However, this hypothesis does not account for a blue clearing, in which most of the markings of a whole hemisphere can become visible in blue light. Alternately, the blue haze might be caused by the finest dust particles—of diameter less than half a micrometer—which because of their small size cause Rayleigh scattering and remain suspended in the atmosphere for months. The usual objection to this theory is that the clearings occur too fast to correspond to settling of such fine particles. Still another hypothesis discussed by S. L. Hess, G. P. Kuiper, and others is that the blue haze is formed by small crystals of frozen water or CO_2. Melting or subliming these could produce sudden clearings. The atmospheric nature of the blue haze is especially indicated by 1954 photographs in which, during partial clearings, crude zonal bands formed parallel to the equator, typical of global atmospheric circulation patterns. Slipher proposed that because these bands are less pronounced in the Martian afternoon, afternoon winds disrupted them. This idea is carried further by D. T. Thompson of Lowell Observatory, who proposes that part of the blue clearing is caused by the brightening of bright areas, usually in the Martian afternoon and following different behavior patterns in different parts of the planet. Mariner 9 was designed to carry out spectroscopic analysis, temperature sensing, and photography to clarify the nature of the blue hazes and other cloud phenomena.

CHAPTER III

Early Mariners and the Profile of the Mariner 9 Mission

. . . man has imagined that Mars, of all the planets, most closely resembles Earth. . . . Mariner 4 abruptly reversed these visions and suggested that Mars, heavily cratered and lacking Earth's dense atmosphere . . . more closely resembled the Moon. The Mariner 6 and 7 flights have finally revealed a unique Martian character, distinctly different from that of either the Earth or the Moon.

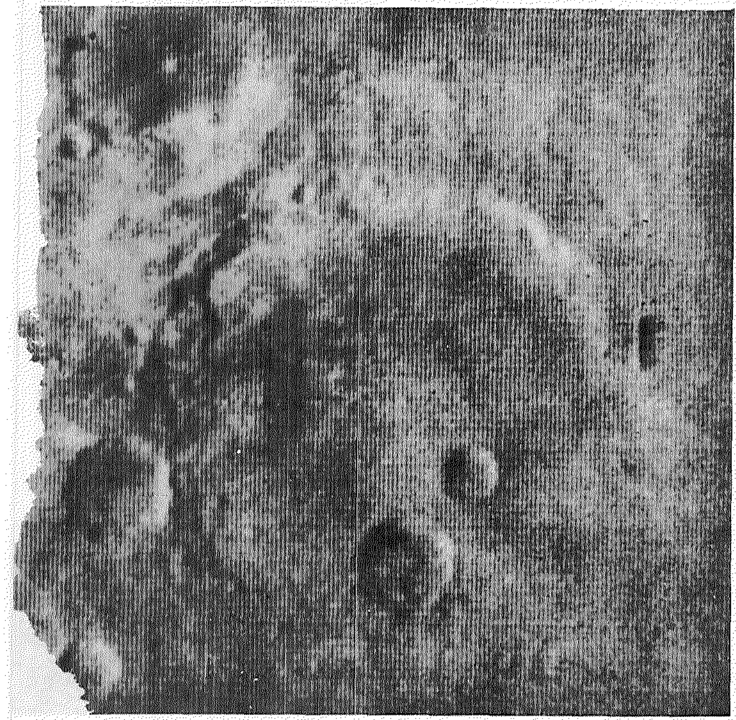
[These missions] have raised many new questions whose answers await the discoveries of future missions.

—S. A. Collins, 1971

On November 28, 1964, an Atlas/Agena rocket was launched from Cape Kennedy, carrying atop its second stage a spacecraft designated as "Mariner 4," which was destined to end the era of Martian studies limited exclusively to Earth-based observations. Unlike its sister ship Mariner 3, which had suffered a catastrophic failure 23 days earlier when the protective shroud failed to separate from the spacecraft after launch, Mariner 4 was successfully deployed on its planned course to Mars. The spacecraft payload consisted of an array of instruments for measuring particles and fields, which were operative throughout the interplanetary journey, and a single television camera for photographing the surface of the planet during encounter. In addition, an occultation experiment was planned, using the onboard radio. To perform this experiment, the spacecraft was intentionally targeted to pass behind Mars immediately after the flyby, thus allowing radio signals to pass through the Martian ionosphere and atmosphere. The changes in frequency, phase, and amplitude of the radio signals resulting from refraction by the atmosphere could then be studied and used to deduce atmospheric pressures, temperatures, and densities.

On July 15, 1965, at 18 minutes and 33 seconds past midnight Greenwich mean time, Mariner 4 shuttered man's first closeup picture of Mars. As the spacecraft flew by, 20 additional pictures of the planet's surface were shuttered, the last two falling completely beyond the terminator (sunset line) on the dark side. Following the planned occultation, playback of the taped pictures and other information began; because of the necessarily low data rate capability at the tremendous distance involved (more than 300 million kilometers), the first transmission of all the recorded data was not completed until 9½ days later, on July 24. However, by the time the first few pictures were received, it was already apparent that Mars was a different planet than that which hundreds of years of ground-based observations had led us to expect.

The most significant fact revealed by the Mariner 4 pictures was the distinctly lunar appearance of the Martian surface: in the 19 frames, several hundred craters were identified. Until that time, only a few scientists had considered the possibility that Mars might be heavily cratered, and their predictions were largely ignored. In addition, data from the occultation experiment yielded a 5- to 10-millibar surface pressure —much lower than predicted from most previous Earth-based observations—and an average mo-


The first photographic mission to Mars, by Mariner 4, returned photographs of craters, such as this crater in the region of Atlantis.

lecular weight of 40, indicative of an atmosphere primarily composed of carbon dioxide. No significant changes in the particles and fields measurements were observed in the vicinity of the planet.

As Mariner 4 continued in its orbit around the Sun, scientists began a painstaking analysis of the data it had collected and transmitted to Earth. In terms of information theory, the amount of information contained in each of the Mariner pictures was nearly 20 times that of the best Earth-based photographs of the planet, but this was still really not very much data: one ordinary snapshot, taken through a good lens, contains about 25 times as many information bits as the entire set of Mariner 4 pictures. In addition, the Mariner 4 pictures, although showing finer detail than ever before seen, showed only a very limited area of the planet, making planetwide generalizations extremely speculative.

Therefore, shortly after the successful Mariner 4 flyby, NASA authorized a second, more ambitious Mariner mission to Mars. Accordingly, two spacecraft with improved two-camera imaging systems and more complex science payloads were designed and built for a Mars flyby in late July and early August 1969. Designated Mariners 6 and 7,[1] both spacecraft were successfully launched and deployed on their proper trajectories. These trajectories were planned so that, although launched more than a month apart (on February 24 and March 27, 1969, respectively), the two spacecraft would encounter Mars 5 days apart.

Each spacecraft carried both a camera with a wide-angle lens and a camera with a telephoto lens. The telephoto lens covered a field of view one-tenth the size of that covered by the wide-angle lens, with a corresponding increase in angular resolution. In addition to the cameras, each spacecraft carried an ultraviolet spectrometer, an infrared spectrometer, and an infrared radiometer. In a complementary fashion, the spectrometers were capable of detecting and measur-

[1] Mariner 5, a single-launch mission, successfully flew by Venus in 1967. The first two Mariners were also Venus probes launched in 1962: Mariner 1 veered off course at launch and had to be destroyed by the range safety officer, but Mariner 2 successfully completed the mission.

ing many of the atomic, ionic, and molecular species potentially present in the atmosphere of Mars, including those considered to have biological significance. The radiometer was designed to measure surface temperatures and was boresighted with the imaging system, thus covering the same areas as the television pictures.

Two new features of the Mariner 6 and 7 spacecraft enhanced their capability over Mariner 4. The first of these, a two-degree-of-freedom scan platform, allowed the instruments to be pointed, extending the range over which the planet could be seen during encounter. The second innovation was an experimental high-rate telemetry system which, when used in conjunction with the then recently completed 64-meter antenna at Goldstone, Calif., provided a telemetry capability of 16 200 bits per second, 2000 times greater than Mariner 4. To take maximum advantage of these capabilities, the Mariner 6 and 7 encounters were planned in two phases, designated "far encounter" and "near encounter," with pictures being taken as early as 3 days before flyby and played back at intervals coincident with the Goldstone viewing periods. These far-encounter pictures would allow Martian coverage to provide a "missing link" in resolution between Earth-based and near-encounter Mariner pictures.

On July 29, Mariner 6 began photographing Mars. Late the following day it flew by the planet after having taken 50 far-encounter and 25 near-encounter pictures. Three days later, on August 2, Mariner 7 began its operations, successfully acquiring 91 far-encounter and 33 near-encounter pictures before passing beyond Mars on August 4. After their flybys, both Mariners passed behind Mars, providing four new occultation data points for subsequent analysis.

For the most part, the vastly improved Mariner 6 and 7 pictures tended to strengthen the somewhat tenuous conclusion derived from Mariner 4 results that lunarlike craters were widely scattered on Mars, although they also revealed that the Martian craters were more heavily modified by erosion processes than were those on the Moon. In addition, a few of the near-encounter photographs yielded evidence of two distinctly different types of terrain: the floor of Hellas, near the south polar cap, was apparently devoid of craters or any other terrain features, and a jumbled, broken type of terrain, unlike any known terrestrial or lunar topography, was observed in the near-equatorial region of Aurorae Sinus. The occultation results were consistent with the earlier results of Mariner 4, with surface pressures at the four occultation points ranging between 4 and 7 millibars. Data from the spectrometers confirmed the prediction, based on the Mariner 4 occultation experiment, that the Martian atmosphere was primarily CO_2, with only trace amounts of other gases being observed. Finally, the radiometer data revealed that the temperature of the south polar cap was consistent with the temperature of frozen carbon dioxide.

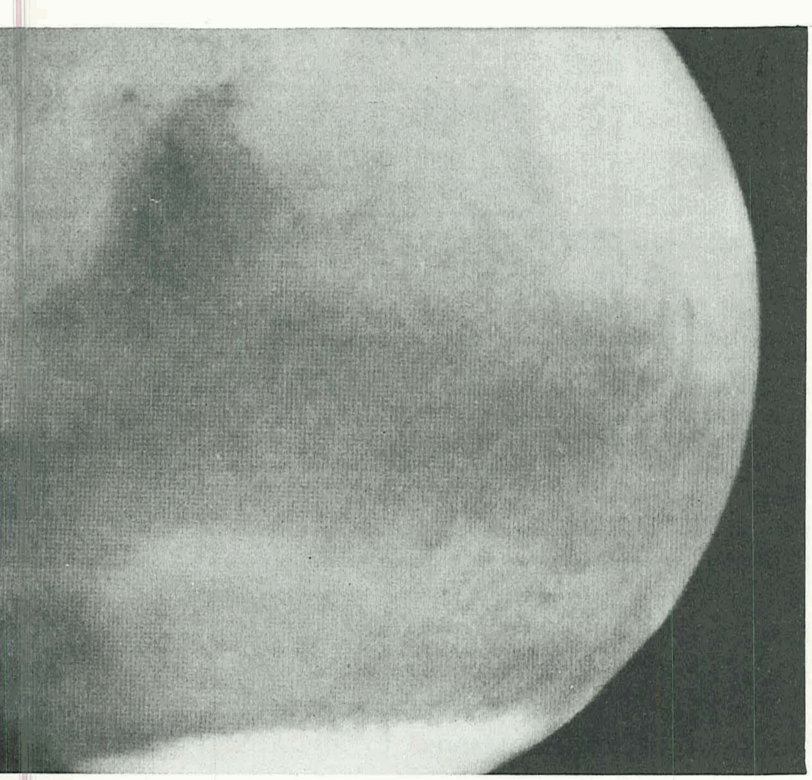
Even as the analyses of these data began, many of the same scientists involved in the task were already hard at work in planning for the next encounter with Mars. While Mariners 4, 6, and 7 had all been successful in fulfilling their mission objectives, each had provided only a brief and tantalizing glimpse of the planet's surface. Clearly, scores of such flybys would be needed to resolve the many mysteries still remaining. The alternative, as envisioned by NASA and the scientists and engineers who were planning the new mission, was to place an advanced Mariner in permanent orbit around Mars.

The events that led to the first successful placement of a spacecraft into orbit around another planet actually began in September 1968, when NASA authorized the Mariner-Mars 1971 Project with the objectives of mapping the planet and observing its dynamic characteristics over a period of 90 days. Six experiments, all of them similar to those of the 1969 Mariners, were chosen to form the science payload: television, ultraviolet spectroscopy, infrared spectroscopy, infrared radiometry, occultation, and celestial mechanics. The scientists selected by NASA formed several teams, representing the different experiments, with each team specifying the requirements of its investigation to the project scientists and engineers charged with designing the spacecraft and the mission. Eleven principal investigators, five of whom were keyed to the television experiment, were selected to represent these experiment teams in the mission-planning phase of the project, meeting with key project personnel to determine, from an almost infinite number of alternatives, the best trajectories and operating sequences.

The chosen plan specified that two identical spacecraft be launched to perform separate, but complementary, missions. The first was to be placed in an 11.98-hour orbit with an 80° inclination to the Mars equator and a periapsis (closest approach) altitude of about 1250 kilometers. This flight was intended primarily as a mapping and polar reconnaissance mission, returning about 5400 pictures and spectral data during the 90 days.

The second spacecraft was to be placed in a 20.5-hour orbit (five-sixths the rotational period of Mars) with a 50° inclination and 850-kilometer periapsis. The orbit period was chosen to permit repeated coverage of the same areas of Mars to study variable surface features. The 50° inclination and 850-kilometer periapsis allowed high-resolution coverage of the midlatitudes where these features could be observed to the best advantage. About 3000 pictures and spectral data were expected from this mission.

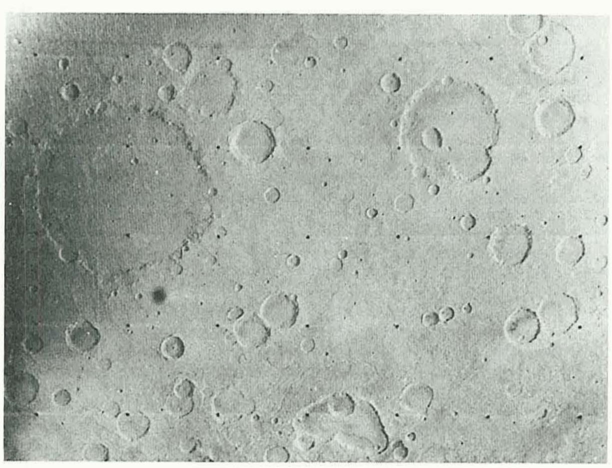
The sequencing of events for each of the two missions was carefully planned to insure that each experiment had ample opportunity to pursue its major goals. The primary objectives of the ultraviolet spectroscopy experiment were to study the composition, structure, and dynamics of the upper atmospheric regions of Mars, to measure the atmospheric surface pressure over most of the planet, and to search for localized concentrations of ozone. The instrument itself, which was much the same as that used on Mariners 6 and 7, consisted of a two-element telescope that focused ultraviolet light into a simple, rugged spectrometer, where it was dispersed into a spectrum by a diffraction grating and focused through two exit slits onto separate photomultiplier tube detectors. The cathode materials for the detectors were selected so that each was sensitive in a different bandpass of the ultraviolet, one responding in the 145- to 350-nanometer region and the other in the region from 110 to 190 nanometers. The spectral sweep through these regions was accomplished once every 3 seconds by rotating the diffraction grating.



A closeup view of Syrtis Major. This photograph was taken by the Mariner 6 telephoto camera on July 29, 1969. The darkest, triangular marking is Syrtis Major; the light oval to the south is Hellas. The south polar cap is at the edge of the frame at the bottom.

A mosaic of three black-and-white views of Mars by Mariner 7 taken with different color filters in August 1971 produces this color view of a portion of the Martian disk. (Jet Propulsion Laboratory)

Mariner 6 wide-angle view of the cratered terrain of Mars. The region is Deucalionis Regio, photographed July 31, 1969.



Mariner 6 telephoto frame, taken July 31, 1969, showing "chaotic terrain" in lower center.

Following the Mariner 4 mission, U.S. Geological Survey artist Don Davis, consulting with J. McCauley and other Survey astrogeologists, made this painting showing craters, sand dunes, volcanic flows, and other hypothesized features of the Martian surface, based on analyses through 1969. *(U.S. Geological Survey)*

Like the ultraviolet spectrometer, the infrared radiometer chosen for Mariner 1971 was nearly the same as its predecessor on Mariners 6 and 7. Using refractive optics, infrared radiation was focused onto two thermopile detectors through separate filters, each covering a different wavelength band (8 to 12 and 18 to 25 micrometers). The source of radiation was alternated by a digitally stepped mirror between Mars, the 4° Kelvin background of deep space, and an internal surface of known temperature (measured by a thermistor). Martian surface temperatures could thus be derived by comparing Mars with the two sources corresponding to known temperatures. From these data, information could be gained concerning the thermal properties of the surface materials, irregularities in cooling rates, or the existence of "hot spots" indicative of internal heat sources.

Among the major goals of the infrared spectroscopy experiment were the detection and measurement of the minor constituents in the Martian atmosphere, including the total water vapor content, and the temperature of the atmosphere as a function of height. Information could also be obtained for the temperature, composition, and thermal properties of the surface similar to that obtained by the infrared radiometer experiment. The interferometer spectrometer chosen for the experiment had not previously been used on interplanetary missions, but similar instruments had been flown on Earth-orbiting Nimbus satellites. In essence, it used a beamsplitter to divide the incoming radiation into two approximately equal components that were then reflected from two mirrors, recombined at the beamsplitter, and focused on a detector. To obtain a scan containing spectral information, one reflecting mirror was moved with respect to the other, causing the two beams to travel unequal distances before recombining, and resulting in an interference pattern between the two beams as the various wavelength components went in and out of phase. This interference pattern—called an interferogram—was detected and recorded for subsequent conversion to an actual spectrum by a complicated mathematical procedure known as a Fourier transformation.

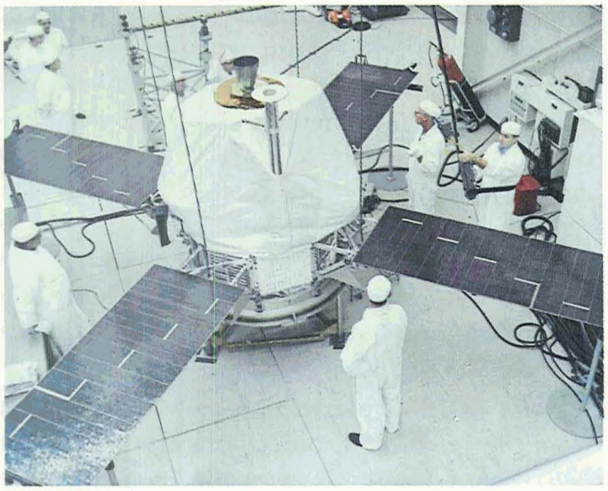
As on the previous Mariners, the S-band occultation experiment was based on analysis of the distortion of the radio signals passing through the Martian atmosphere. However, with the multiplicity of occultations provided by an orbiter, information could be obtained on the shape of the planet as well as variations in the properties of the atmosphere with latitude, season, and time of Martian day. Like the S-band occultation studies, no specific instrument was needed for the celestial mechanics experiment except the spacecraft radio. Through tracking observations of the motions of the spacecraft, celestial mechanics information could be obtained that would help to determine the size, shape, distance, and position of Mars and to detect any large concentrations of mass (mascons) on the planet.

The two spacecraft designed to accomplish this formidable set of objectives were similar to Mariners 6 and 7, the most obvious difference being the large engines needed to place them in orbit around Mars. Like all their predecessors, they were inertially stabilized with their solar panels always facing the Sun and with their roll position controlled by a star tracker pointed at Canopus. The solar panels were designed to supply 350 to 500 watts of power to the spacecraft continuously during the missions, excepting those periods during propulsion maneuvers when the panels were turned away from the Sun and the spacecraft battery supplied power.

The experimental high-rate telemetry system, used with great success by Mariners 6 and 7, became the standard system for Mariners 8 and 9. However, it was anticipated that lower data rates would be necessary late in the missions to compensate for the loss in signal strength due to the increasing distance between Mars and Earth and the slowly degrading pointing alinement between the spacecraft's fixed antennas and the 64-meter antenna at Goldstone. Thus, in addition to the 16 200-bit-per-second rate, rates of 8100, 4050, 2025, and 1012 bits per second were designed into the Mariner 8 and 9 telemetry system.

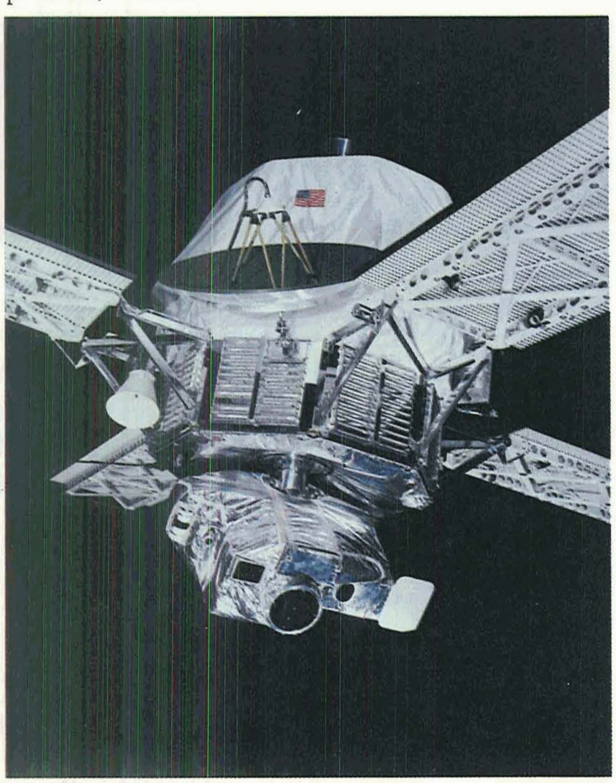
As the design of the spacecraft and the mission proceeded, the ground-support facilities were also being designed and organized. These

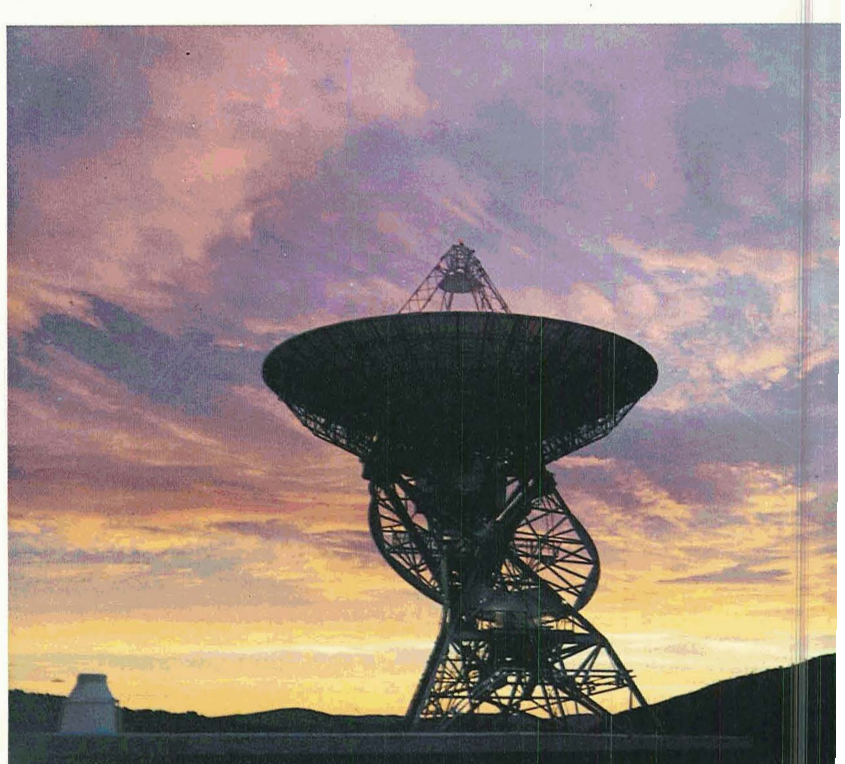
Launch of Mariner 9 from Kennedy Space Center, May 30, 1971.



Mariner spacecraft being readied for launch. White shroud protects spacecraft mechanisms. Television cameras and other instruments are out of sight at the bottom. Solar panels are extended, and technicians indicate the scale of the spacecraft. (Jet Propulsion Laboratory)

Mariner spacecraft ready for flight, showing television camera and other instruments mounted on scanning platform, bottom.





Goldstone tracking antenna, which received radio signals from Mariner 9. From Goldstone the signals were relayed to viewing monitors in the Jet Propulsion Laboratory where scientists made copies and conducted analysis.

facilities included tracking systems and computer equipment to process the transmitted data. Mission planners decided to maintain an "adaptive operational capability" throughout the orbital missions—meaning that the mission plan could be changed on short notice if required by unexpected events or unanticipated discoveries. As will be seen, this adaptive mode became crucial to the success of Mariner 9.

In contrast to the modest data rates of the nonimaging experiments, the high data rate of the television cameras and the need to process the pictures rapidly on the ground made ground support for the television experiment quite formidable. Ground-support activities for television were therefore divided into two areas: termed "real-time" and "non-real-time" processing.

Real-time processing involved three versions of each incoming image for distribution to the science teams within 24 hours. Each version was produced by computer processing the television data, which were transmitted as a set of numbers representing light values for dots making up the image—as in a newspaper's Teletype photographs. The first of these, called a "shading-corrected" version, represented a first-approximation removal of camera-induced intensity gradients across the raw picture. The second was a "contrast-enhanced" version of the first, accomplished by linearly expanding the range of luminance represented by the picture—similar to increasing the contrast on a home television set. The third, a "high-pass filter" version, was designed to enhance contrast of fine details at the expense of gross contrast differences.

While many special processes were available to aid non-real-time studies by the television experimenters, the ultimate requirement for non-real-time processing, because of the mapping nature of the mission, was complete geometric correction, photometric correction, removal of errors or omissions due to the telemetry, and removal of residual ("ghost") images. These decalibrated pictures were then to be enhanced, orthographically rectified, scaled, and assembled into large maps of the Martian surface.

Early in 1971, Mariners 8 and 9 were moved from the Jet Propulsion Laboratory to the Kennedy Space Center in preparation for launch. Following a systematic sequence of events during which each spacecraft was armed, fueled, enshrouded, and mated to its launch vehicle, Mariner 8 was launched on May 9. The elation felt by those who had labored over Mariner 8 for more than 2 years as they watched it disappear, on course, into the night sky was to be short lived. A malfunction in the guidance system of the Centaur stage caused the vehicle to tumble, prematurely separating the payload and cutting off the engine. Lacking orbital velocity, Mariner 8 fell into the sea some 350 miles northwest of Puerto Rico.

That the loss of Mariner 8 did not preclude accomplishment of many Mariner objectives is a tribute not only to the concept of a backup spacecraft, but also to the project personnel who immediately set about redesigning the Mariner 9 mission to incorporate the major goals of both missions. The newly chosen orbital parameters included an 11.98-hour orbital period with a 65° inclination and a periapsis altitude of 1250 kilometers. Being 17/35 of a Martian mean solar day, the new orbital period meant that after 17 Martian days and 35 spacecraft revolutions, the track on the surface of Mars would begin to repeat itself under essentially the same solar illumination conditions, allowing areas to be restudied in a search for variable features. The minimum periapsis altitude of 1250 kilometers was chosen from mapping consideration to insure that, when two consecutive wide-angle pictures were taken looking straight down at periapsis, there would be some overlap. Any gaps between pictures taken near periapsis on successive orbits could be filled in on the subsequent 17-day cycles. The 65° orbit inclination was a compromise between the higher inclination, preferred for mapping and polar observations, and the lower inclination, which was more favorable for studying variable features and time-of-day (diurnal) effects in equatorial regions.

Mariner 9 was successfully launched on May 30, 1971, and 6 days later a trajectory correction was made so accurately that no other corrections were necessary for the entire 167-day trip to Mars. After traveling 394 million kilometers, the spacecraft arrived at the planet within 50 kilometers of the target point, a feat virtually indescribable by any earthly analogy. As Mariner 9 made this precise journey, planning for the new mission continued. The new plan was destined to be so successful that Mariner 9 would eventually achieve every objective of both former missions, returning over 7000 pictures and completely mapping the surface of Mars.

CHAPTER IV

Mars Encounter and the Great Dust Storm of 1971

Besides the permanent spots, I have often noticed occasional changes in partial bright belts. . . . [*These may be due to*] *clouds and vapors floating in the atmosphere of the planet.*

—William Herschel, approximately 1784, quoted by S. Gladstone

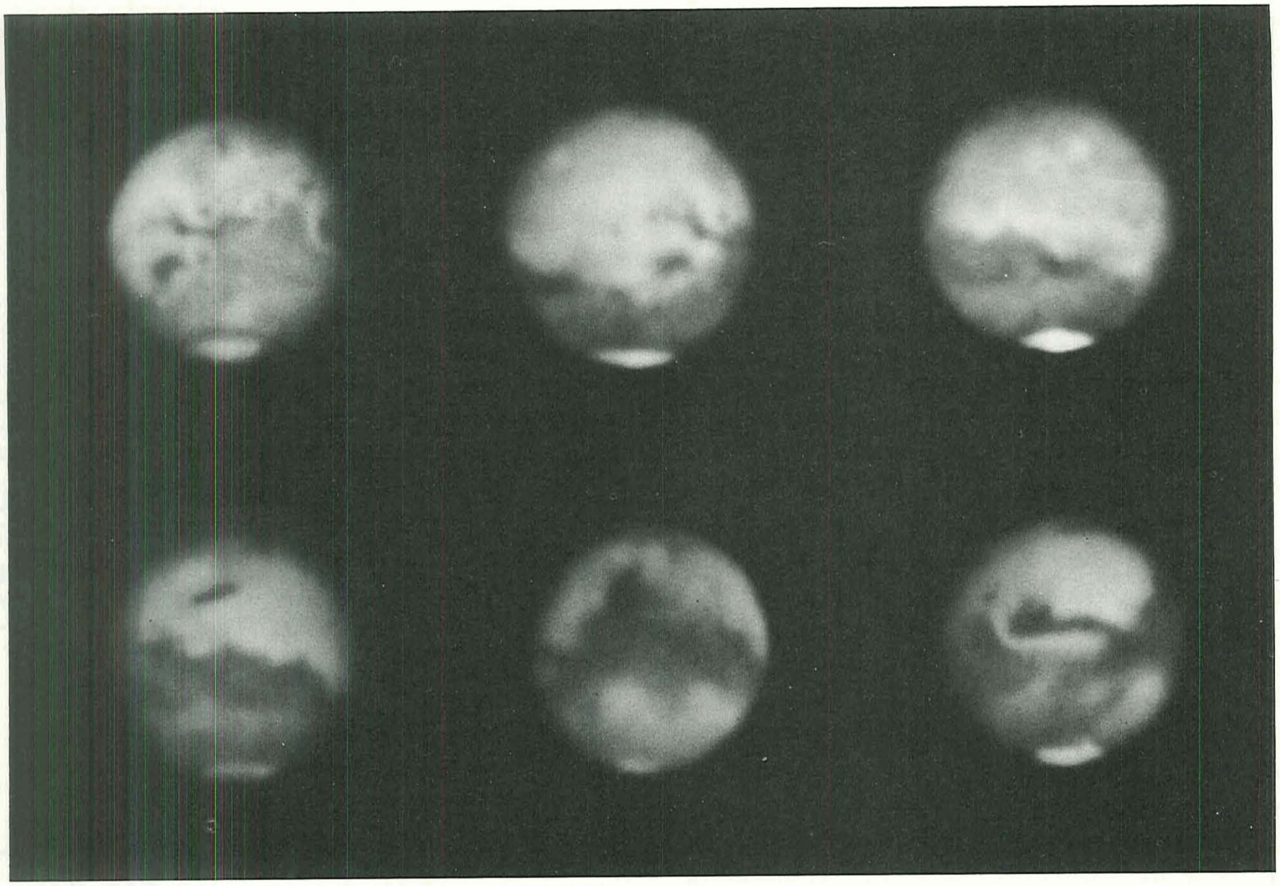
During prelaunch planning, it was determined that Mariner 9 would arrive at Mars during rapid shrinking of the south polar cap, when markings in the southern hemisphere would be rapidly darkening. The adaptive mission was therefore designed on the basis of anticipated early detection of interesting surface features.

However, on September 22, 1971, nearly 4 months after launch and nearly 2 months before Mars encounter, a brilliant whitish cloud appeared within a space of a few hours over the Noachis region and spread in the next days to become one of the greatest and most widespread Martian dust storms ever recorded.

The storm was first photographed in South Africa by G. Roberts at the Republic Observatory. As tracked by observers at New Mexico State University Observatory and Lowell Observatory in Flagstaff, Ariz., it spread from an initial streaklike core about 2400 kilometers in length and expanded slowly for 2 days. On September 24 the storm began to expand more rapidly, especially to the west. By September 27 a large area stretching from the east edge of Hellas west across Noachis was obscured, and the storm cloud was encroaching on Syrtis Major to the north. University of Arizona photographs on September 28 showed a new cloud developing in Eos, a region later found to be part of the great canyon of Mars. Flagstaff astronomer Peter Boyce subsequently reported that the contrast of features as far away from the storm core as Syrtis Major and Mare Cimmerium had faded in contrast in blue light some days before the dust cloud was first seen, indicating that Martian dust had been injected into the atmosphere before the discrete cloud became visible from Earth. By the end of September the contrast of markings had been reduced substantially around most of the planet.

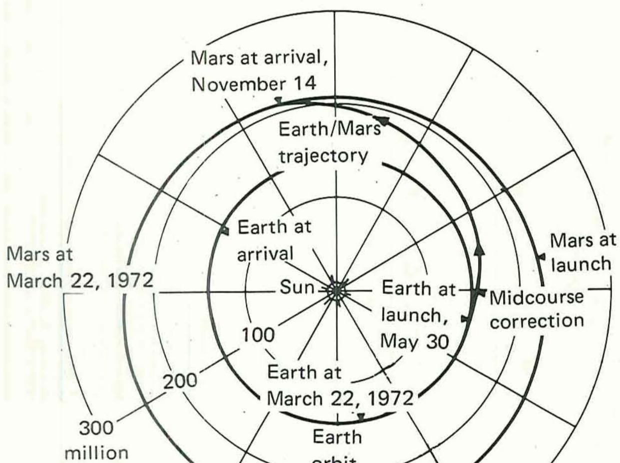
On October 7, 16 days after the storm's onset, the principal bright cloud was still expanding to the west along the bright corridor of Hesperia, between the dark regions of Mare Cimmerium and Mare Tyrrhenum. The original cloud and isolated yellowish clouds in other areas had now coalesced almost entirely around the planet. A zone approximately 12 000 kilometers long had been obscured in only 16 days. This corresponds to an average advance rate of 30 to 40 kilometers per hour (20 to 30 miles per hour), but this speed is not necessarily that of the surface winds. Even red photographs from Earth showed virtually no detail during most of October. Prospects were dim for successful mapping following Mariner 9's encounter with Mars on November 14.

In retrospect, team members realized that a major dust storm should not have been totally unexpected. In fact, the possibility of such a storm occurring coincident with the Mariner 1971 mission was postulated by Lowell Observatory astronomer C. Capen in February 1971 be-

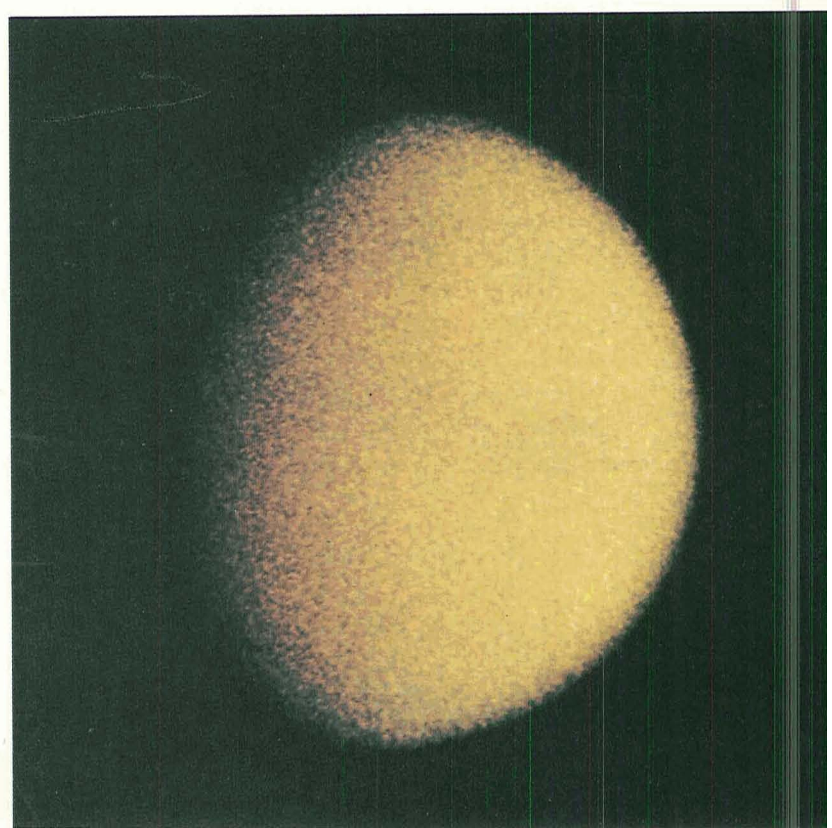


These images of Mars during summer 1971 show the clarity of its atmosphere before the great dust storm set in. From top left, dates are July 18, August 16, August 12, August 7, September 3, and August 27. (Lunar and Planetary Laboratory, University of Arizona)

The orbit of Mariner 9 between Earth and Mars.



Earth-based color photograph of Mars at the height of the dust storm, showing total obscuration of all surface detail including polar cap (Lunar and Planetary Laboratory, University of Arizona)

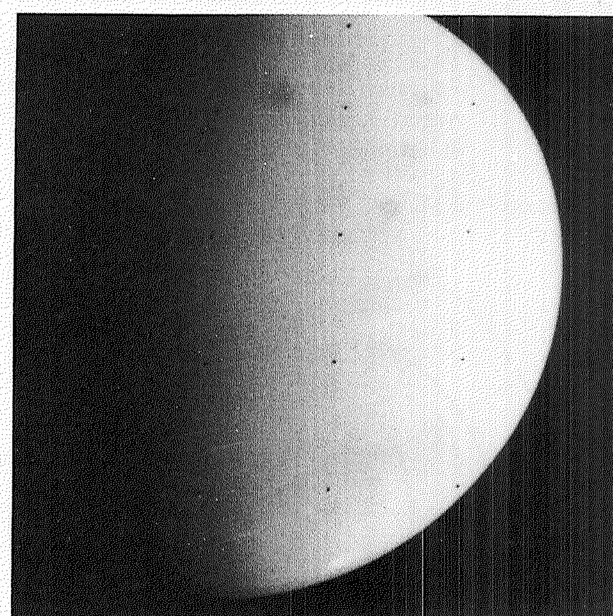


fore Mariner 9 was launched. Since 1892, during each opposition of Mars that coincided with Mars' closest approach to the Sun, terrestrial observers had noted substantial dust storms. They were noted in 1892, 1909, 1924–25, 1939, and 1956. As early as 1909, the French observer Antoniadi had pointed out that the most intense storms occurred near Mars' perihelion passage. It was later reasoned that because the radiation received from the Sun at perihelion is more than 20 percent stronger than the average radiation, the surface and lower atmosphere would be heated to substantially higher temperatures than normal, causing instabilities in the atmosphere. In arid regions on Earth, similar instabilities give rise to "dust devils"—swirling columns of air that entrain dust and debris and lift them into the air. Some theorists proposed that this might be the mechanism for lifting Martian dust and maintaining dust clouds.

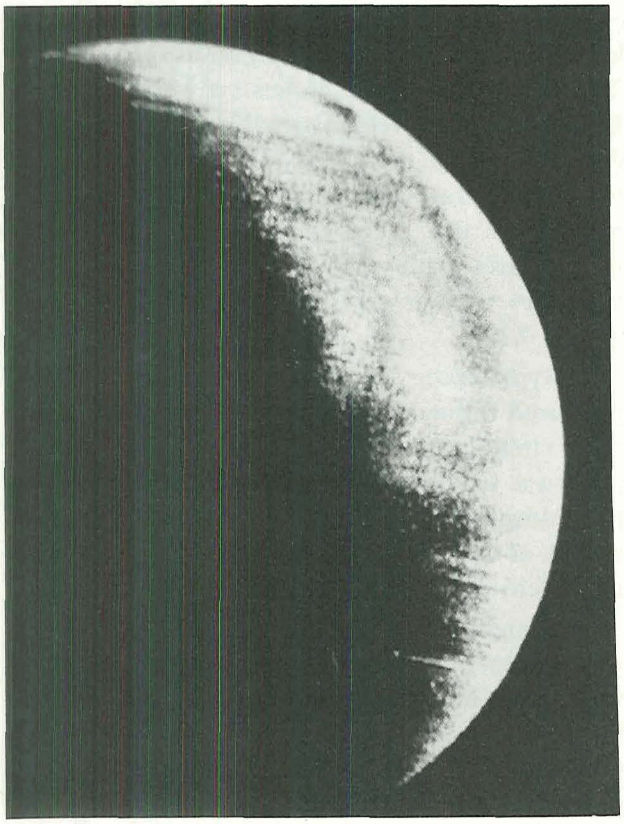
Such dust clouds might be self-perpetuating by a feedback effect proposed by the Soviet meteorologist G. S. Golitsyn, who suggests that once the dust cloud is formed, its absorption of sunlight cools the surface underneath it, causing atmospheric temperature instabilities that then increase the local wind, stirring up more dust. Once the storm has spread, as long as Mars is near perihelion, any local clearing would allow more heat to reach the surface causing new atmospheric winds and restirring the surface dust. The American meteorologists P. Gierasch and R. Goody have recently published detailed calculations supporting such a model of Martian dust storms.

On November 4, Mariner 9 team members reviewed the progress of the storm and concluded that it would still obscure Mars at the time of encounter. While some experiments such as the radio-occultation experiment would not be adversely affected by the dust storm, the television experiment would be severely affected. The question was how much detail was visible on the surface. From Earth, only the polar regions were dimly visible.

On November 8, the first pictures of Mars came back from Mariner 9. These were merely calibration pictures, to test the television system. The diameter of Mars was about 25 picture elements, large enough to show some detail under normal conditions. Even the processed versions of these pictures showed no detail except for the phase. One scientist jokingly speculated



One of Mariner 9's first photographs of Mars, a far-encounter photograph made during approach to Mars on November 12–13, 1971. The three dusky spots toward the top were later revealed to be summits of enormous volcanic mountains protruding through the dust pall.



The Soviets photograph Mars. This image of the crescent Mars during the dust storm was obtained by one of the Soviet spacecraft that orbited the planet.

that the spacecraft must have been sent by mistake to Venus, which is perennially obscured by clouds.

Three days before the scheduled orbital insertion maneuver, a series of preorbital science data-gathering sequences began. Originally scientists had hoped that these far-encounter pictures of the whole planetary disk would show the configuration of global-scale surface features, such as dark areas and "canals." Such pictures would help fill the gap between the low-resolution views obtained from Mariner 4, 6, and 7, and later Mariner 9 mapping frames. Instead, the first preorbital science picture showed a nearly blank disk with a faint south polar bright area and several small dark spots. Working with classical maps, television team members were able to demonstrate that one of the spots coincided with Nix Olympica, a small dark area often seen to be occupied by bright clouds or frost deposits (hence Schiaparelli's name, "snows of Olympus"). From radar measurements it was known that the general longitudinal region of Nix Olympica was one of the highest areas on the planet; Nix Olympica itself was now revealed as a high mountain protruding through the dust pall. Nix Olympica was thus the first Martian surface feature, other than the polar cap, identified by Mariner 9 photography.

The second and third preorbital science pictures were received on November 12 and 13. These, too, showed the Nix Olympica dark spot and also three nearby dark spots protruding through the dust in the Martian region named Tharsis. There was a hint that each dark spot contained a crater.

At the same time, on November 13, the Soviet Union announced that its two spacecraft, also approaching Mars, would attempt to land instrumented packages on the surface of Mars. The timing of these landings, and hence the anticipated surface condition, were not announced.

On November 14, 1971 (universal time), Mariner 9's rocket motor was fired for 15 minutes and 23 seconds, successfully slowing the spacecraft and putting it into orbit around Mars. The initial orbital parameters were—

Orbital period . . 12 hours, 34 minutes, 1 second
Inclination to Mars equator . . . . 64.4°
Minimum altitude (periapsis) . . 1398 kilometers

The initial orbital period was intentionally made longer than the desired 11.98 hours, because the spacecraft arrived at Mars more than 2 hours too early for optimal coincidence between its periapsis pass and the Goldstone viewing period. The longer period effectively delayed periapsis by some 36 minutes on each pass, allowing Goldstone to "catch up" on the fourth pass after insertion. At that time, a trim maneuver was made, changing the period and periapsis altitude to—

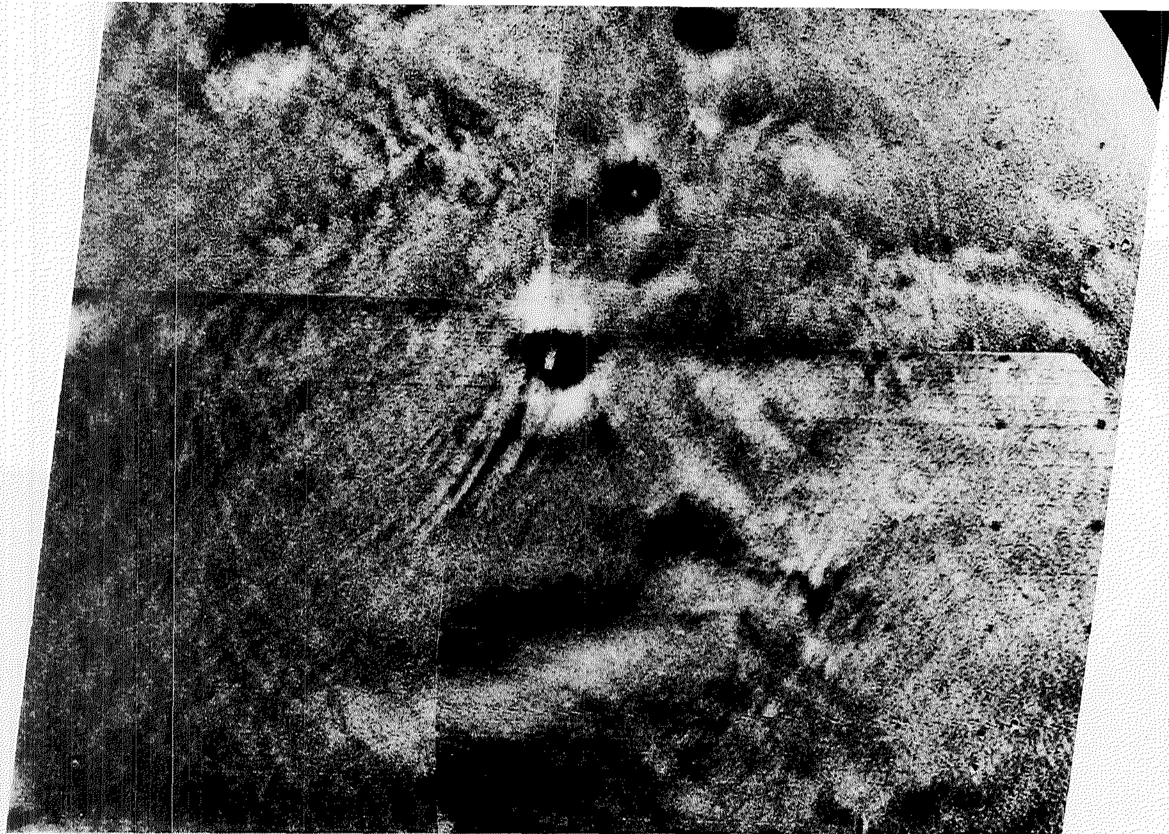
Orbital period
11 hours, 58 minutes, 14 seconds
Minimum altitude (periapsis) . . 1387 kilometers

Computer enhancement of the November 14 pictures revealed volcanic craters in the summits of the four mountains that protruded through the dust storm and a 1000-kilometer-long curved "wake" in the cloud pattern extending behind one of the mountain tops. This unexpected information led to the discovery that Nix Olympica and the three nearby dark mountains were enormous volcanoes and that extraordinarily strong winds were still stirring the Martian dust clouds.

As early as 1954, de Vaucouleurs had shown that isolated yellowish dust clouds typically had velocities as high as 60 to 90 kilometers per hour during the day of their formation, and generally slowed to velocities of 5 to 30 kilometers per hour after a few days. Velocities of winds in major dust storms, however, were uncertain. C. Sagan, J. Veverka, and P. Gierasch estimated in 1971 that windspeeds of up to 250 kilometers per hour are likely to exist on Mars. The velocity of sound is less on Mars than on Earth, and this velocity corresponds to mach 0.4 (40 percent the speed of sound). From lee wave cloud structures observed near Martian mountains and craters by Mariner 9, experimenters were later able to directly deduce wind velocities as high as 180 kilometers per hour (mach 0.28).

Early mapping sequences of photographs only produced frame after frame of nearly featureless dust cloud expanses. Therefore, the mission plan was changed and more flexible targeting procedures were adapted, to allow repeat photographs of areas of interest and to allow study of the satellites Phobos and Deimos.

Although the television imaging experiment was hampered, other experiments could get valid and interesting data. For example, the infrared interferometer spectrometer and S-band occultation data gave the temperature as a function of altitude in the atmosphere. Under normal nonstorm conditions, the ground surface would be warmer than the air because the surface absorbs the sunlight; the temperature would decrease vertically 4° Kelvin for each kilometer (2.2° Fahrenheit per 1000 feet). However, during the storm, dust in the atmosphere was warmer than usual and the surface cooler than usual because the airborne dust absorbed much of the available sunlight. Measures during the height of the storm showed a nearly isothermal lower atmosphere; i.e., with air temperature constant at all heights. At the same time, the infrared radiometer data indicated that the range of daily surface temperatures was very



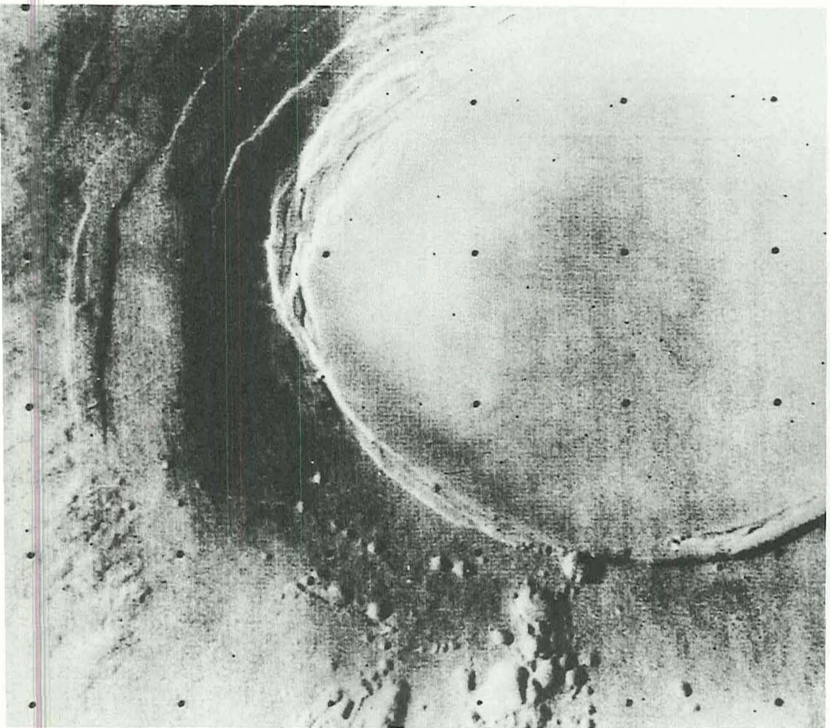
This view taken November 13, 1971, is a mosaic of four frames printed with high contrast and showing the four dark volcanic peaks, the mottled appearance of the swirling dust, and a "wake" of parallel streaks extending southwest from the southern volcano, named Arsia Mons. This is thought to be a product of the wind driving clouds past the mountain.

much reduced as a result of the dust storm. Temperature excursions from −84° Celsius (−119° Fahrenheit) just before sunrise at the equator to +10° Celsius (+50° Fahrenheit) near midday were expected on the basis of Mariner 6 and 7 data. The actual excursions went from about −75° Celsius (−103° Fahrenheit) to about −35° Celsius (−31° Fahrenheit). On the second orbit the radiometer measured the temperature of one of the four dark spots (later found to be extinct volcanic mountains) and found it to be much warmer than its surroundings and closer to the temperature expected for a dust-free planet.

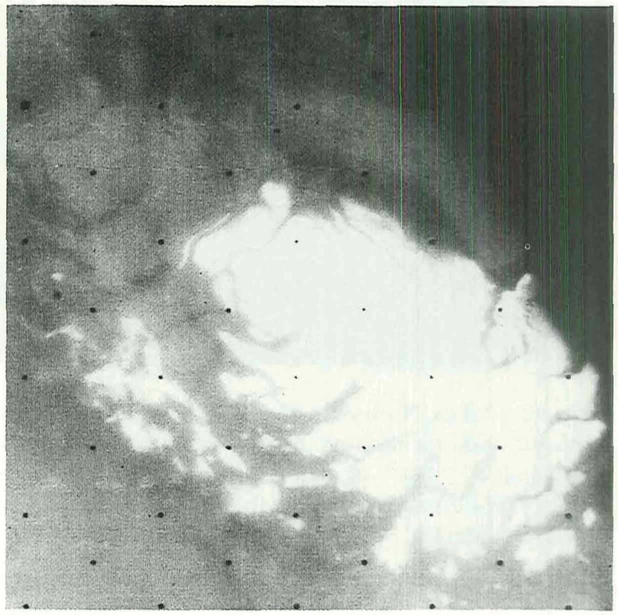
By November 17, craters in certain regions began to appear on television pictures as light-colored circular patches, apparently because of longer lines of sight through bright dust in the craters. In the same way, an irregular bright streak appeared, running along the dark "canal" Coprates, through Aurorae Sinus into Eos, the region of the chaotic terrain discovered by Mariners 6 and 7. Radar measurements had already shown a depression of several kilometers in depth in this region; the evidence thus pointed to an enormous canyon running the 3000-kilometer distance from Coprates to Eos and having a width of 100 to 200 kilometers.

By November 21, crater rims and central peaks had been discerned dimly through the dust clouds, and unexpected families of streaks had been discerned in the Hellaspontus-Noachis region. These streaks were later identified as deposits of material blown out of or around craters that disturbed the local airflow pattern. By November 28, highly detailed B camera pictures of the summit calderas on Nix Olympica and nearby volcanoes had been received.

During this period and later, a number of high-resolution pictures of the limb, or horizon, were also taken. These showed the atmosphere in profile and revealed layers of dust in the



As the dust cleared, the tops of the four volcanic mountains became clearer. This photograph, taken on November 29, shows the large crater in the summit of the southernmost volcano, named Arsia Mons after a nearby classical feature seen from Earth. The crater diameter is about 140 kilometers.



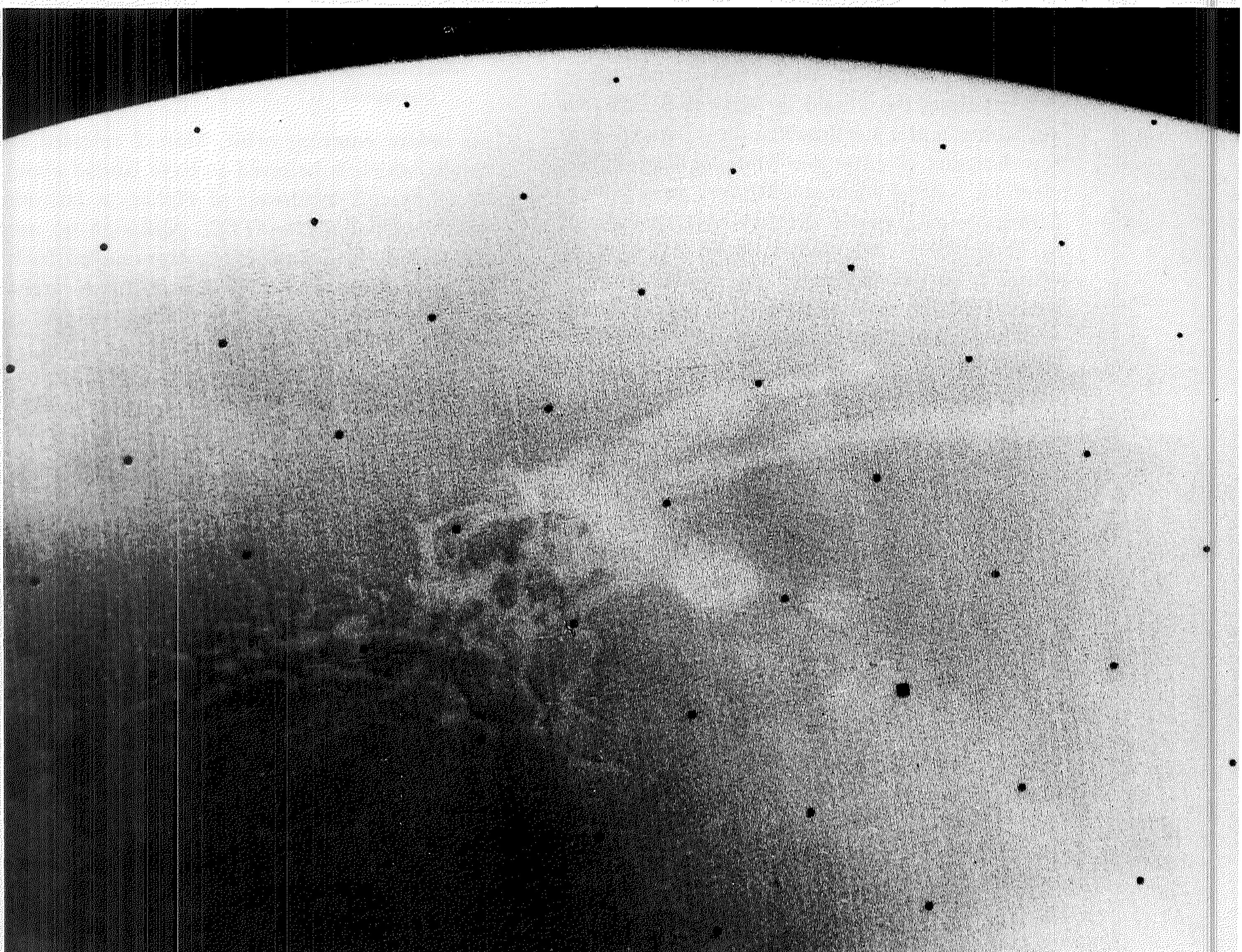
The south polar cap is visible through the dust pall in this photograph taken on December 2.

atmosphere at heights of 30 kilometers, 50 kilometers, and more. In late November and the first half of December, the dust pall seemed to be clearing. However, in mid-December, the rate of clearing slowed to a standstill and did not begin again in earnest until the last week of December.

Following the first orbital trim of Mariner 9, tracking data revealed that the orbital period was not constant, but varied sinusoidally with a period associated with the movement of the periapsis point around the planet. This variation was ultimately attributed to an equatorial irregularity in the gravitational field of Mars. (See ch. XI.) Because the average period of the orbit did not correspond to the desired 11.98-hour period, synchronization with Goldstone was slowly being lost. To maintain the necessary Goldstone-periapsis coincidence, a second trim maneuver was made on December 30, 1971. During the maneuver, the periapsis altitude was also raised to improve picture overlap for the beginning of planetary mapping. The new orbital parameters were—

Orbital period
11 hours, 59 minutes, 28 seconds
Inclination to Mars equator .... 64.4°
Minimum altitude (periapsis). . 1650 kilometers

While the dust storm had a significant effect on the Mariner 9 mission, its persistence through late November had a disastrous effect on the mission of the two Mars probes, Mars 2 and

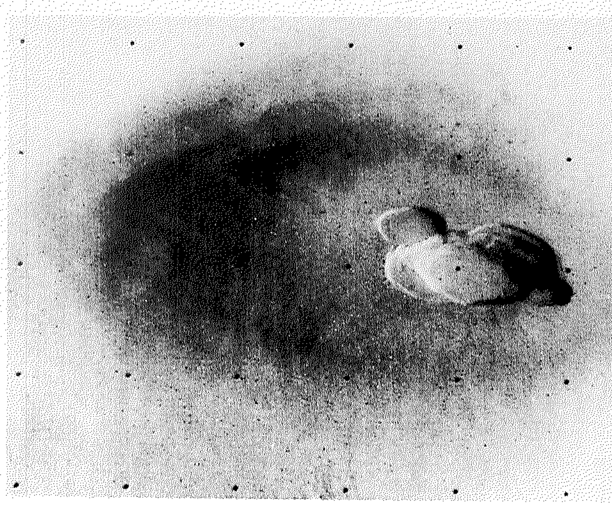


This view toward the horizon taken on December 17 shows the west end of the canyon system emerging from the dust. In the lower left, some shadows can be seen in the branching latticework of canyons. (Black dots are reseau marks allowing geometric calibration of photographs.)

Mars 3, launched by the Soviet Union on May 19 and 29, respectively. Each probe, weighing 4650 kilograms (somewhat over 10 000 pounds—nearly eight times the weight of Mariner 9), carried an orbiter and a sterilized landing package that was designed to enter the Martian atmosphere, eject its conical heat shield, and parachute a hemispherical capsule through the atmosphere to about 20 to 30 meters above the surface, where it would land with the assistance of a braking rocket. Each orbiter also contained instruments for remote sensing of Mars. Mars 2 entered a highly elliptical orbit on November 27. Its parameters were—

Orbital period	18 hours
Inclination to Mars equator	48.9°
Minimum altitude (periapsis)	1380 kilometers
Maximum altitude (apoapsis)	24 900 kilometers

Complex crater on the summit of "north spot" volcano, renamed Ascraeus Mons, appears in this photograph taken December 17. The darkest parts of the rim are most free of dust; lower flanks of the mountain are obscured by bright dust clouds.



Just before entering orbit, Mars 2 released its capsule, which is believed to have landed about 500 kilometers southwest of Hellas, at latitude −44.2° and longitude 313.2°. Although no useful scientific information was transmitted back, this became the first manmade object to arrive on Mars. Perhaps the dust and high winds interfered with the landing procedure.

Mars 3 ejected its lander and entered an even more elliptical orbit 5 days later on December 2. The orbit parameters were—

Orbital period	12 days, 16 hours
Inclination to equator	60°
Minimum altitude (periapsis)	1530 kilometers
Maximum altitude (apoapsis)	190 000 kilometers

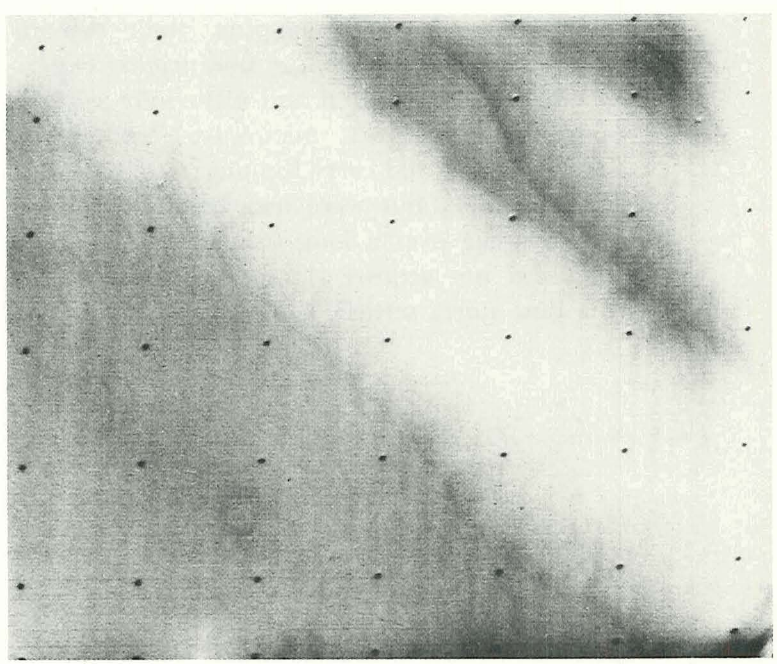
The Mars 3 lander successfully landed on Mars and within 1½ minutes was activated by its time sequencer. It began to transmit a television picture of the Martian surface to the orbiter, which would relay the picture to Earth. After 20 seconds—having transmitted only part of one frame—it suddenly ceased transmitting. In spite of intensive attempts to process this fractional frame of the Martian surface, no recognizable detail has been found by Soviet analysts. It may be that a picture of a Martian dust storm is indeed a featureless gray frame!

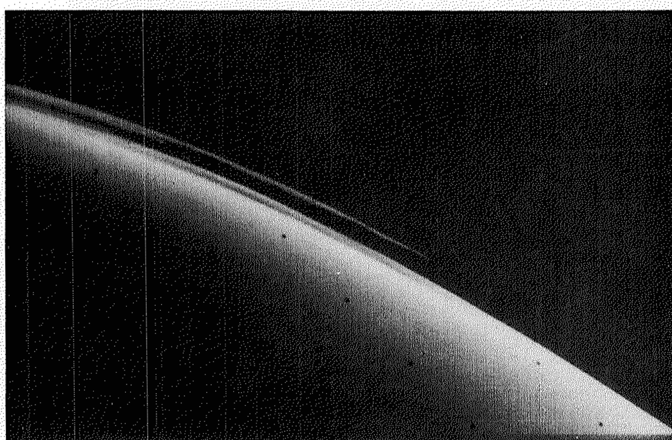
Various hypotheses have been suggested to explain why the Mars 3 lander stopped transmitting. Did it get covered with dust, or did the

Artist's conception of swirling dust being raised during the early phases of a Martian dust storm. Artist Ludek Pesek collaborated with some members of the Mariner 9 team during preparation of this 1972 Mars painting for the National Geographic. (Painting by Ludek Pesek, © 1973, National Geographic Society)

parachute (which was supposed to jet out of the way) come down on top of the lander? Was it damaged on impact, even though it was designed to withstand a 200-mile-per-hour crash? If the suggestion of extremely high wind velocities during the dust storm is correct, it seems plausible that the lander may have been blown over, or been damaged by blowing dust. According to Soviet scientists, there was no possibility that the parachute landed on top of the lander. They verified that it landed slowly at least in the vertical velocity component, and postulated that the two most likely failure modes were an uncompensated high horizontal velocity or sinkage through Martian quicksand. The Mars 3 lander presumably still lies near its landing site at latitude −45° and longitude 158°,

Bright clouds lying in faulted valleys of the Valles Marineris canyon complex. The crests of the cliffs bordering the valley can barely be discerned at the edges of the bright dust clouds. (Mariner 9 telephoto view taken December 19.)





On March 1, 1972, even after most of the dust storm had cleared, bands of haze could be seen lying along the curving Martian horizon.

in a moderately light region between Electris and Phaethontis, not far from the northern limit of the southern polar cap. Perhaps one day, like Surveyor 3, these pioneering devices will be recovered and returned to Earth for placement in some future museum.

The Soviet scientists later reported that because Mariner 9 was designed to do extensive orbital imagery and mapping, their orbiters were designed to emphasize nonimaging experiments, such as infrared and ultraviolet sensing, magnetometry, and microwave radiometry. Their orbiters did carry limited imaging equipment as well, but were not designed to carry out imaging over a long time duration; hence they did not acquire significant imagery after the dust storm settled. Conceivably, had it not been for the dust storm, we would now have photographs from the Martian surface, additional surface analysis, and more useful material from orbit.

On the other hand, the storm was in many ways a blessing in disguise. It gave scientists a chance to study not only the "normal" Mars but also the unusual storm environment. Measurements made by ultraviolet, infrared, and other instruments revealed a number of characteristics of the dust storm. Dust was stirred to heights greater than 30 kilometers (97 000 feet) above the surface during midstorm. The particles causing measured effects ranged in size from roughly 2 to 15 micrometers in diameter. Experimenters using the infrared interferometer spectrometer concluded from spectral features that the dust had a relatively high silicon content, about 60 percent, indicating that substantial geochemical differentiation has occurred on Mars. This would indicate that the interior of Mars has at least partially melted, a conclusion consistent with the presence of large volcanoes. Television experimenters noted several examples of localized dust storms during the general clearing after the main storm. One incident appeared to have been initiated by rapid southern movement of cold air following a cold front identified by characteristic cloud patterns. In these localized storms, dust was rapidly carried to heights of 15 to 20 kilometers, indicating strong convective motion of the air, probably triggered by the warming of dusty air masses due to absorption of sunlight.

CHAPTER V

The Classical Markings: Toward an Explanation

Why are the maria shaped and oriented as they are?

The absence of appreciable liquid water greatly simplifies the problem. . . . The chief agent of erosion, in all probability, is windblown sand. And winds are the chief, practically the only, agent for transportation and sedimentation.

—DEAN B. MCLAUGHLIN, 1954

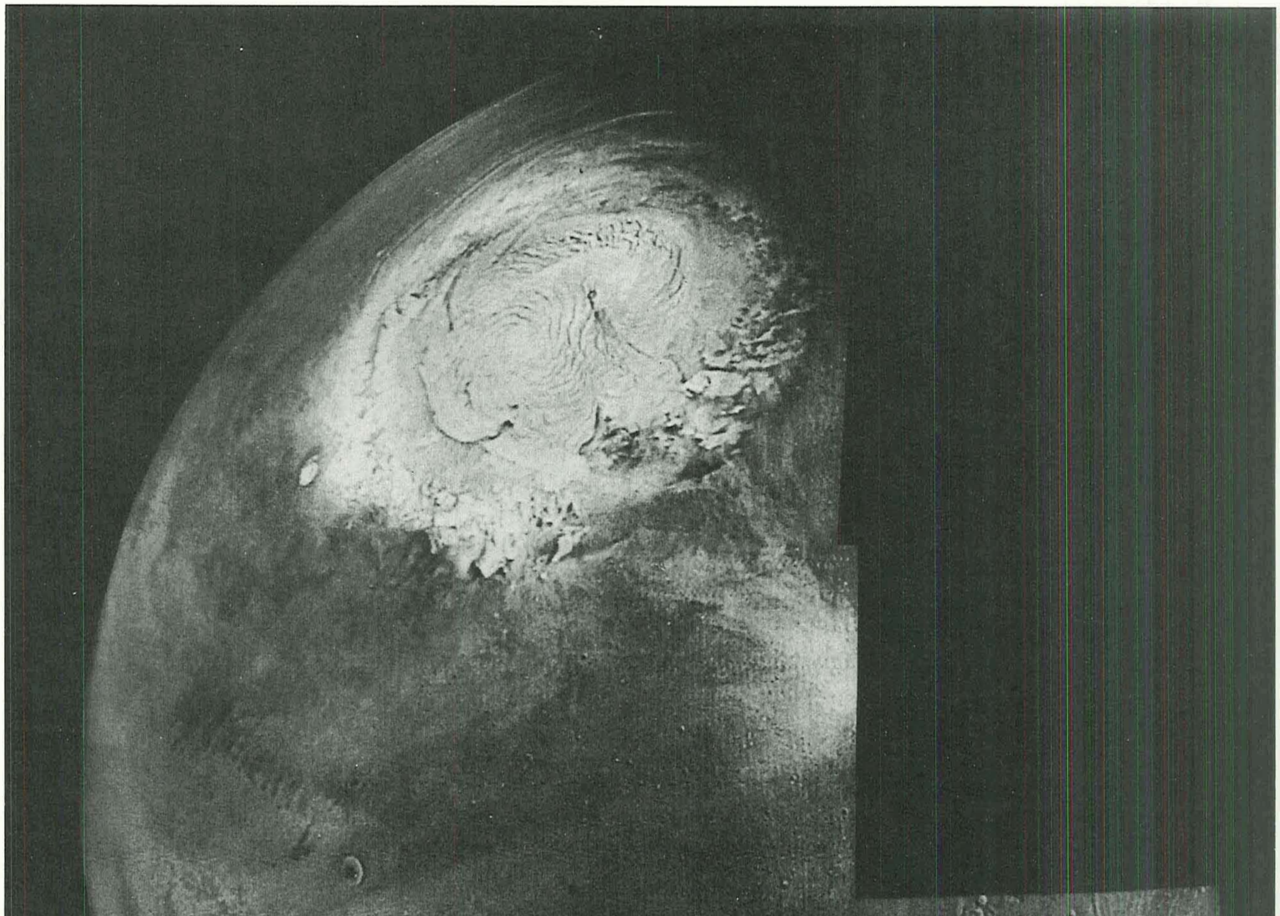
If we agree with [Öpik's 1950 suggestion that the maria must be continually renewed], then the problem is reduced to the identification of the formative activity.

—DEAN B. MCLAUGHLIN, 1955

Once the dust storm cleared and the normal mapping of the planet began, a natural early question concerned the nature of the light and the dark markings seen by Earth-based observers. Years of telescopic observation had produced no satisfactory identification of the dark material, with hypotheses ranging from substantial vegetation through lichen-spotted lava outcrops to windblown deposits of volcanic ash. Mariners 6 and 7 in 1969 had shown the markings clearly in global far-encounter photographs, but detailed high-resolution frames with resolution down to 4 kilometers had produced no firm diagnostic information as to their ultimate cause. Instead, puzzling "chaotic terrain" and cratered areas seemed to cross the boundaries of classical dark markings, suggesting that the markings were not correlated with underlying geologic structure. Mariners 6 and 7 also showed small dark patches in some craters, but with resolution insufficient to distinguish crater-floor lava flows—such as appear in lunar craters—from aeolian deposits or vegetation patches. The markings, as possible candidates for vegetated areas, thus remained the most exciting Martian mystery.

Because of the dust storm, Mariner 9's pre-orbital far-encounter photographs did not yield global views of the dark markings. Very late in the mission, a few composite pictures of most of the disk of Mars were made from apoapsis (the farthest point of the orbit from the planet), but, unfortunately, several of these happen to show the hemisphere most devoid of dark markings. Therefore little opportunity exists to compare Earth-based and space observations of maria, oases, "canals," and large-scale changes that might appear following a major dust storm.

Thus the frames from the normal mapping sequences and certain specially targeted high-resolution pictures of dark spots are the best Mariner 9 data concerning the classical Martian markings. Much of the computer processing that has been applied so far to these photographs has not been ideal for emphasizing the kind of broad, dusky shadings found on classical Earth-based maps, however. Thus it is important to consider the nature of the processing before studying the markings. The processing usually applied is designed to emphasize small-scale detail, such as fractures, crater-rim shadows, and surface texture in different geologic provinces. This processing is analogous to a process of photographic printing in which very-high-contrast printing paper is used, with "dodg-



Much of the northern hemisphere of Mars is shown in this composite of several Mariner 9 frames taken late in the mission. Although the polar cap (*top*) and several volcanoes (*bottom*) can be seen, this global view does not reveal the nature of the dark markings.

ing" applied to reduce large-scale regional contrast; the resulting print shows very high contrast among small details but may not show the original high contrast between dark and light land regions, or the rapid falloff of sunlight toward the sunrise or sunset line. For this reason, and because of variations in original exposures on the spacecraft, care must be taken in comparing different Mariner frames, because the processed images tend to have the same general background tonality, regardless of whether the original frame showed a dark region, a lighter "desert," or the intensely bright polar cap.

Because the mapping frames each cover only a very small region of Mars, their best application to the study of the large-scale markings is through mosaics of wide-angle A camera frames. Such mosaics have been prepared by the Jet Propulsion Laboratory. These include computer-produced mosaics, handmade mosaics of selected regions, and a mosaic on a 5-foot-diameter globe, covering the whole planet. At the same time, the U.S. Geological Survey Center for Astrogeology and Lowell Observatory have produced a number of airbrush renderings of physical structure and classical markings based on the Mariner 9 mapping.

In addition to these methods for enhancing large-scale markings, special processing was carried out by Stanford University's Artificial Intelligence Laboratory and by the Jet Propulsion Laboratory. These processes included rectification (computerized reprocessing of pictures to remove effects of oblique viewing angle), calibration of intensities on different photographs, and differencing (a technique of comparing pictures to detect any changes from one frame to a later frame).

Streaks within Syrtis Major, near 283°, +13°. (1409–211522)

What can be learned from these materials about the cause of the classical markings of Mars? The Mariner A camera photographs and mosaics have too low a resolution to solve the puzzle of their origin, but they give intriguing clues. One of the most interesting examples is the region of Syrtis Major—the first dark marking ever recorded on Mars by human observers. Syrtis Major is now resolved not into a single dark patch, but into a series of dark streaks, similar to streaks photographed in other areas of Mars. Almost every streak emanates from a small cra-

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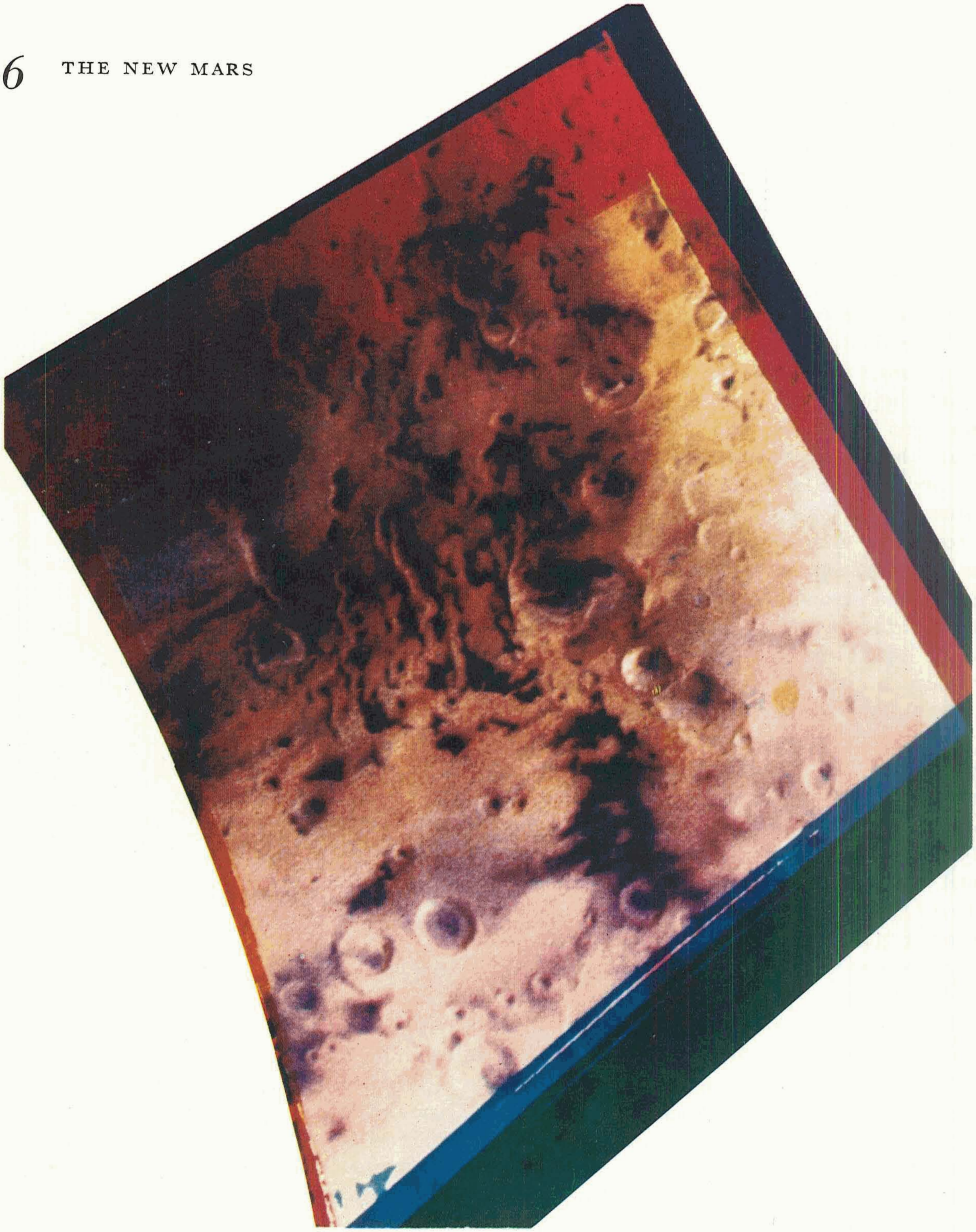
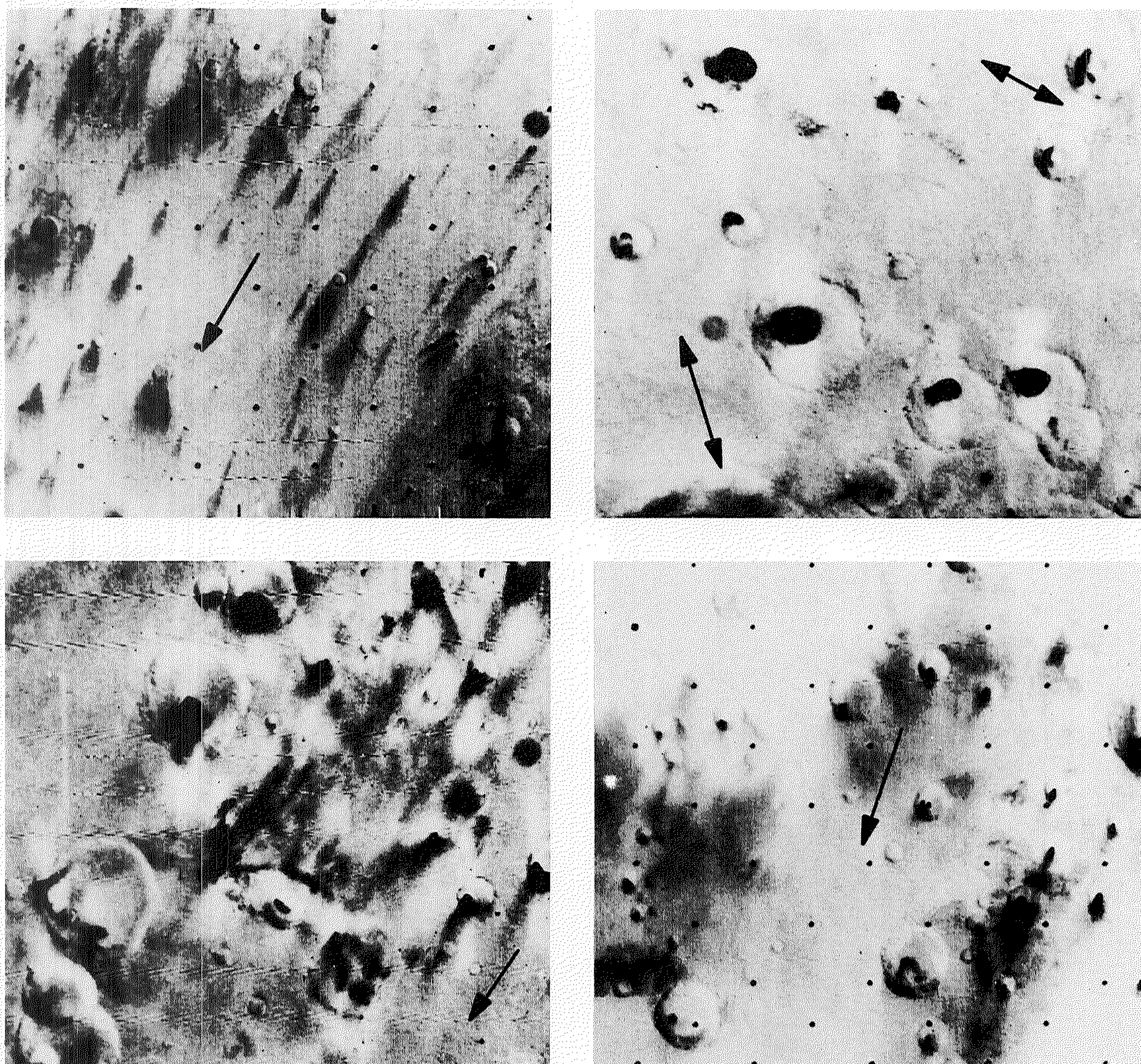
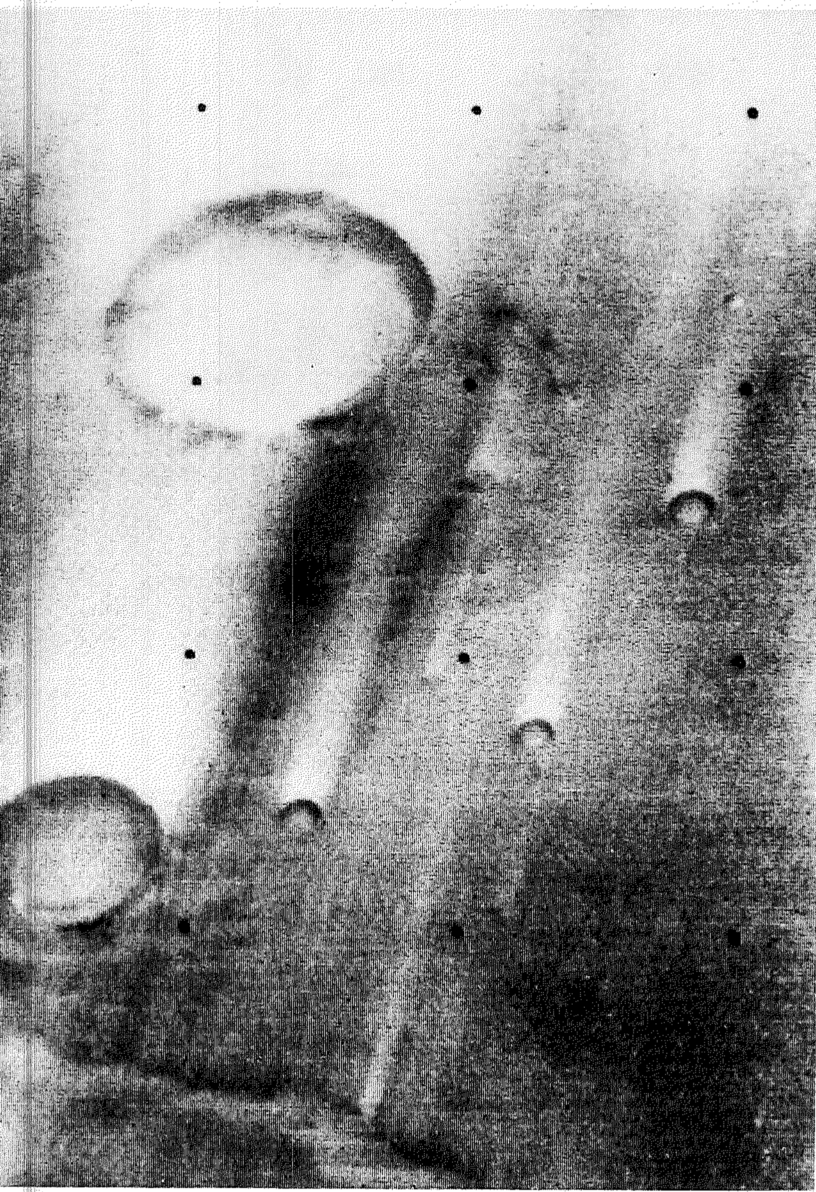


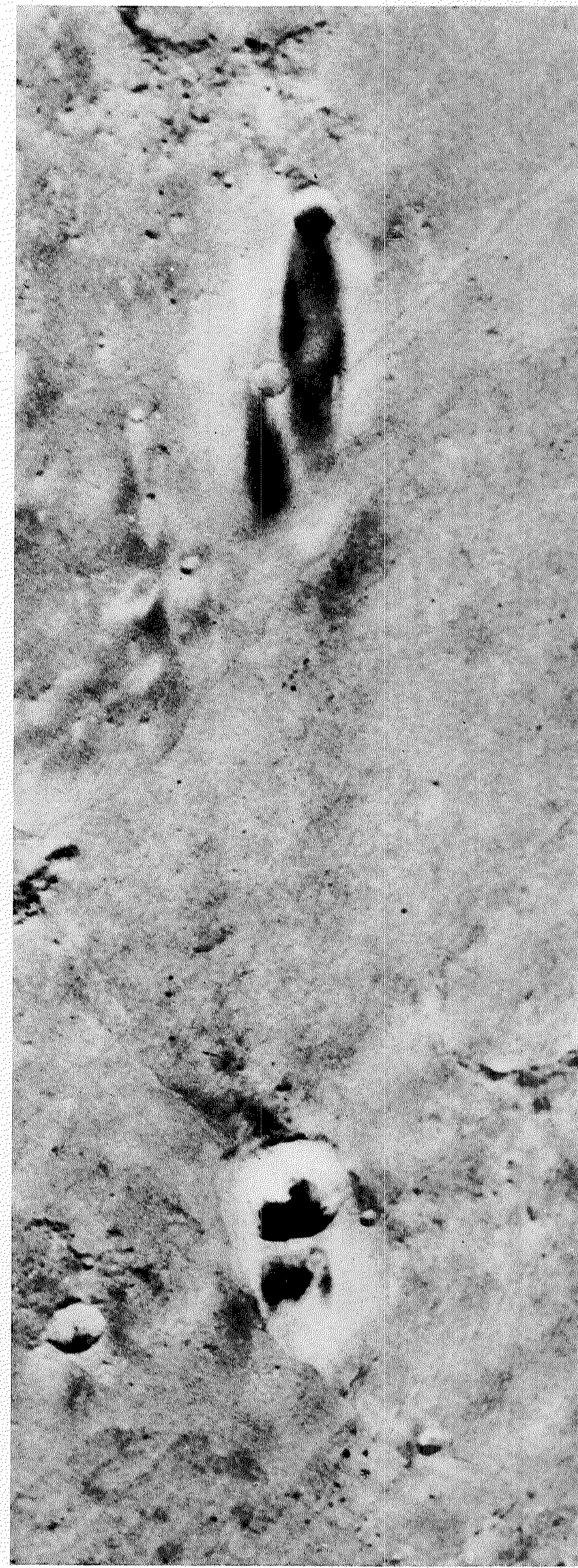
Patchy dark markings on Mars. Red, green, and blue filter photographs are combined to give this color view of the surface. Precise color reconstruction is difficult because of differences in lighting and viewing geometry between the original frames. (Jet Propulsion Laboratory)



Examples of dark streaks and patches associated with craters. Arrows show inferred wind directions.



Bright windblown streaks emanating from craters near the east edge of Syrtis Major are seen in this Mariner 9 telephoto view taken near 294°, +4°. (1409–195521)



Dark streaks emanating from large craters are prominent in this mosaic stretching about 1200 kilometers across Mesogaea, near 195°, +5°.

ter. The most pronounced concentration lies on the inward-facing slopes of an enormous eroded basin centered east of Syrtis Major. What causes the streaks? They are evidently associated with strong winds, because in the southern hemisphere the direction of the streak (away from crater) is generally the direction of spreading of the 1971 dust storm. Furthermore, even prior to the Mariner 9 mission, in a meteorological analysis by P. Gierasch and C. Sagan, strong winds had been predicted in steeply sloping areas such as Syrtis Major. Terrestrial experience in arid regions shows that wind deposition patterns often create long leeward or windward alinements of dunes or other disturbances in regions with strong prevailing winds.

These lines of evidence point to the conclusion that the dark streaks in the Syrtis Major area are the result of deposition by strong winds, whose patterns are disturbed by craters and other topographic irregularities. One would expect the resulting deposition patterns to vary from year to year and perhaps seasonally, because of changes in airflow patterns; indeed, as long ago as 1930 the French observer Antoniadi noted that the eastern edge of Syrtis Major—the region of streaks lying on a steep slope—varied considerably from year to year by shifting back and forth in position. This east-west shift corresponds to motion up and down the slope, while the west edge of Syrtis Major, which is more stable in position, does not lie on as steep a slope. Confirmation that these changes involve patterns of streaks comes from the discovery during the Mariner 9 mission of changes among the dark streaks in Syrtis Major.

Another suggestion that changes in streaks and splotches combine to produce large-scale changes, as seen from Earth, comes from the discovery that the densest groupings of streaks in some areas, such as Syrtis Major and Solis Lacus, correspond approximately to the positions of the classical, variable, dark areas.

The strongest bit of evidence in favor of the dark markings being related to deposition patterns comes from a few high-resolution B camera pictures in which certain dark spots in the floors of craters can be identified as immense dune fields, obviously formed by depositional effects. These pictures, incidentally, confirm a prediction by F. Gifford in 1964 that sand dunes should be found on Mars and predictions by astronomers E. Öpik, W. Hartmann, C. Chapman, J. Pollack, and C. Sagan, based on Mariner 4 results, that deposition must be occurring in Martian craters.

Analysis of the geometry of these dune fields might be expected to give us new information on the winds and dust transport of Mars. The most famous study of this subject is a 1941 book by the English naturalist R. A. Bagnold, who observed dune formations in Africa and elsewhere. His work, often cited in Martian studies, showed the complexity and variability of dune fields, and the difficulty of predicting deposition patterns from wind and topography, or vice versa. Recently, an experimental approach has been taken by scientists at NASA Ames Research Center, where sand was blown in a wind tunnel across model craters under conditions simulating the Martian surface. It

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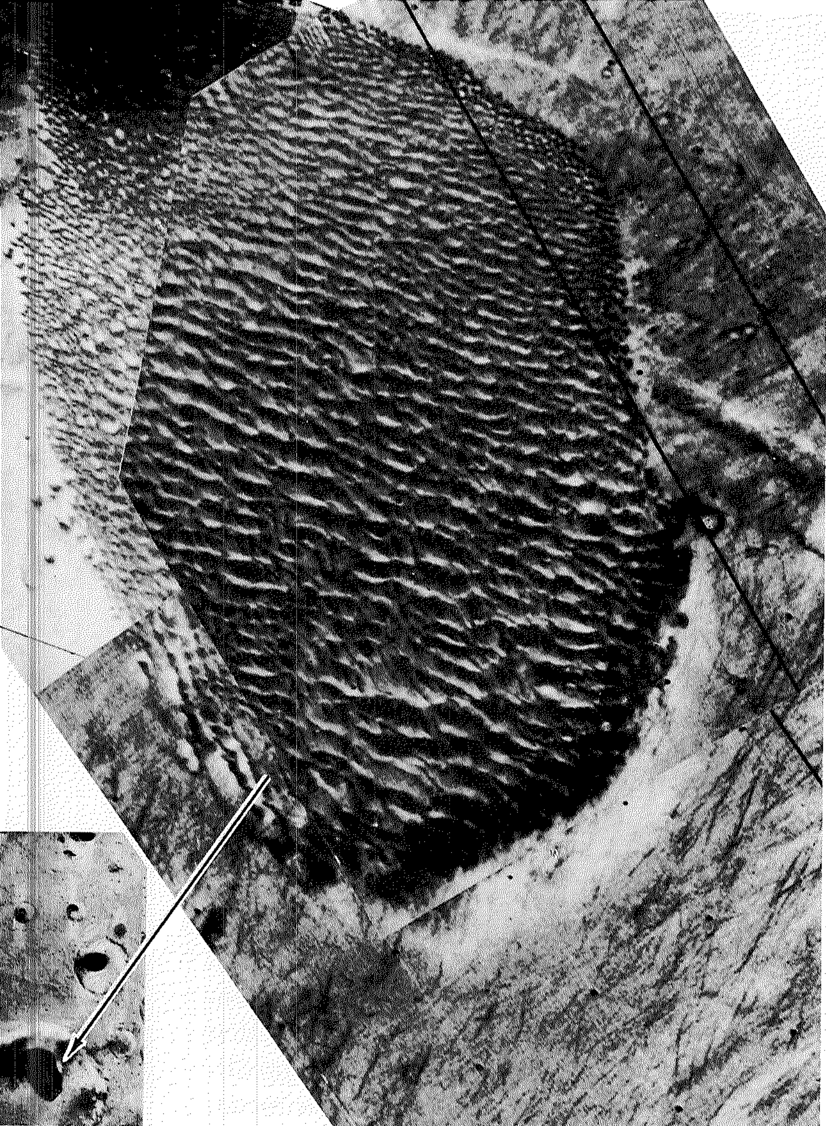
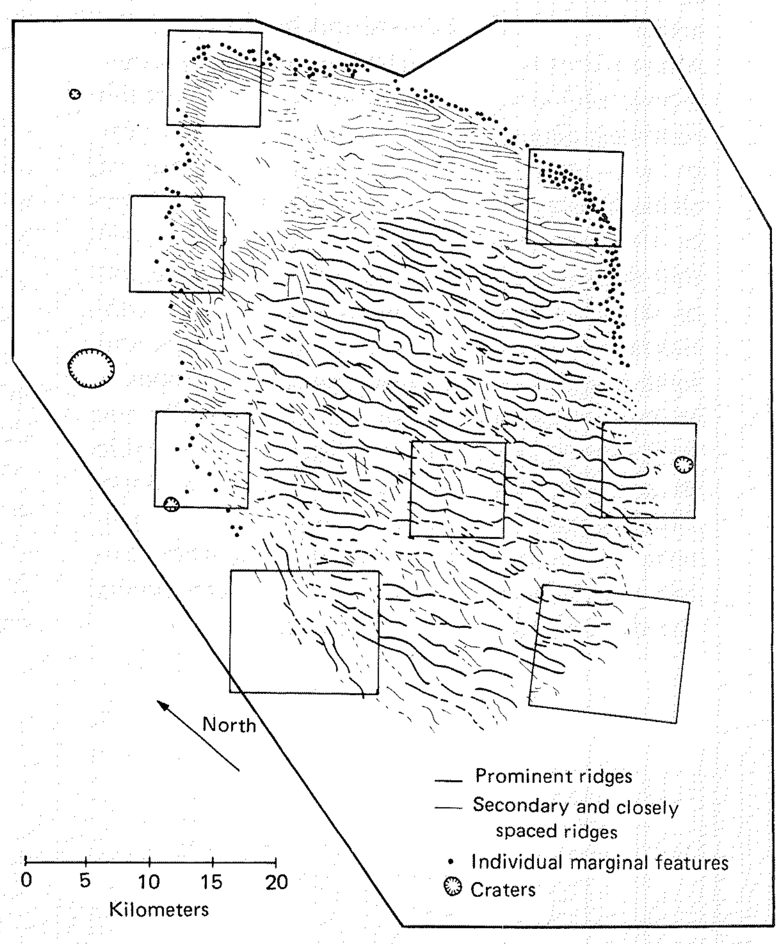
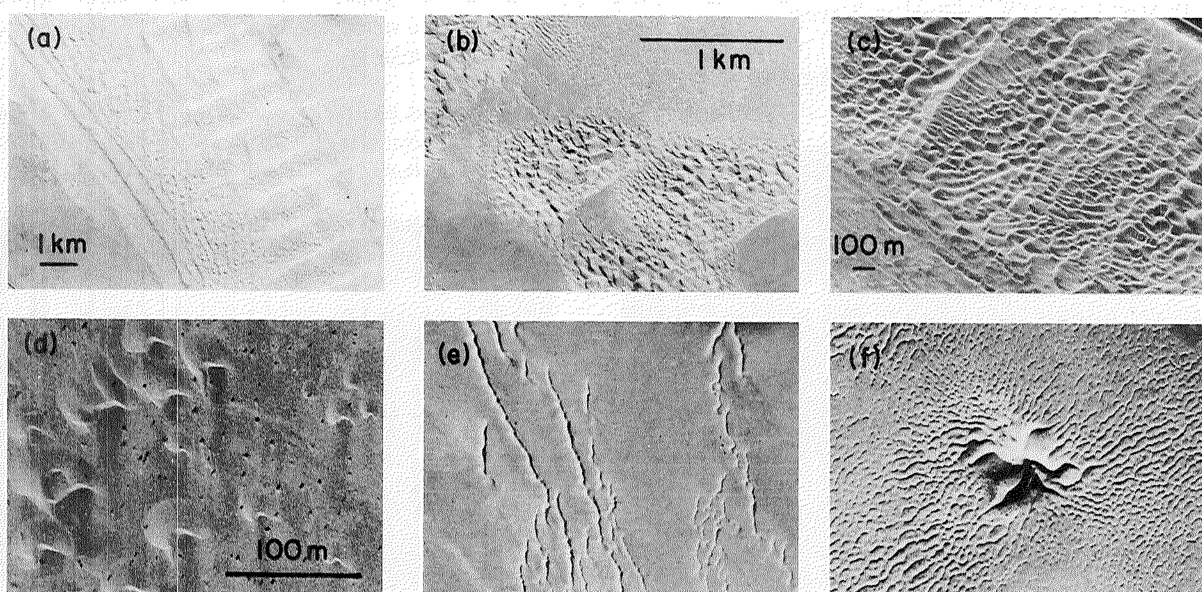


A dune field, measuring about 35 by 50 kilometers, occupies the floor of a large crater in Hellespontus (inset and arrow). The dune field is identical with the dark patch on the crater floor.



Sketch map of the above dune field showing orientation and scale. Boxes show regions singled out for study by Mariner scientists.

Dunelike features in a dark patch occupying a crater some tens of kilometers in diameter at 166°, —74°. (1348–212624)



Examples of terrestrial dunes. (*a–d*) Increasing resolution in the Algodones dunes of southern California. The low-resolution view (*a*) has several times better resolution than the Mariner 9 telephoto views. (*e–f*) Ridge and pyramid dune forms in the Sahara. (U.S. Air Force, R. S. U. Smith, and H. T. U. Smith)

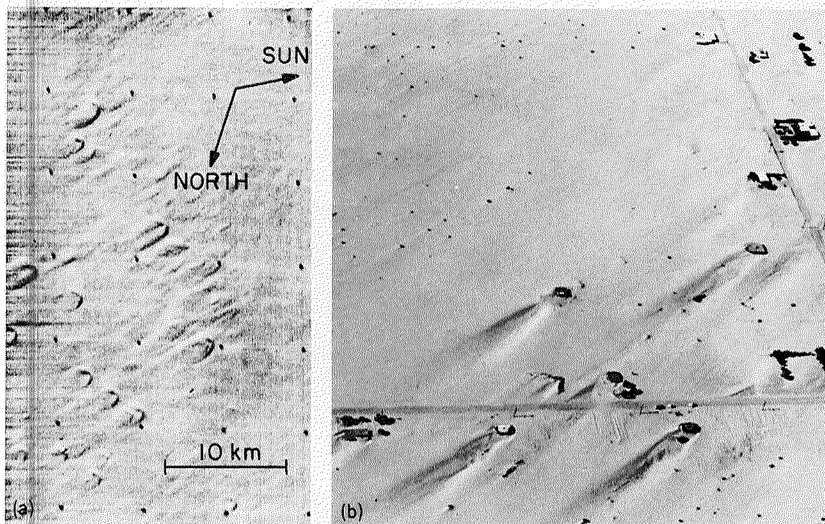
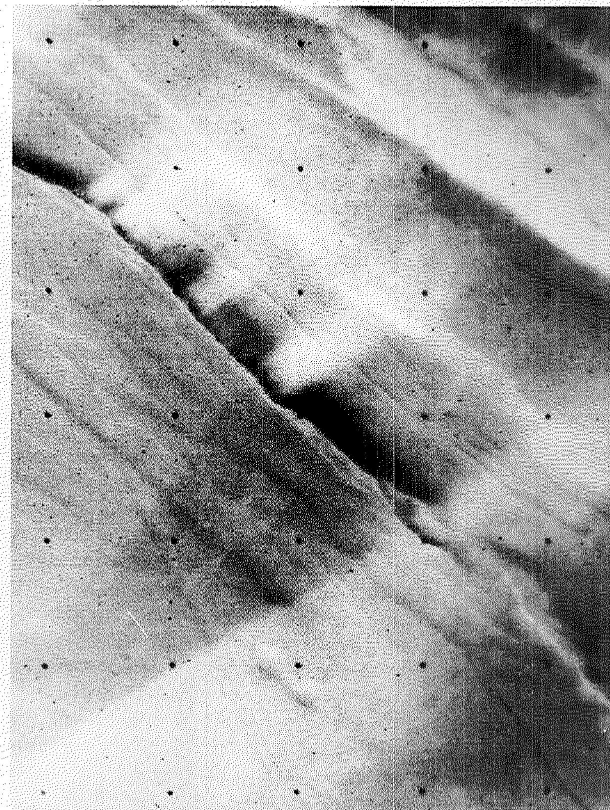


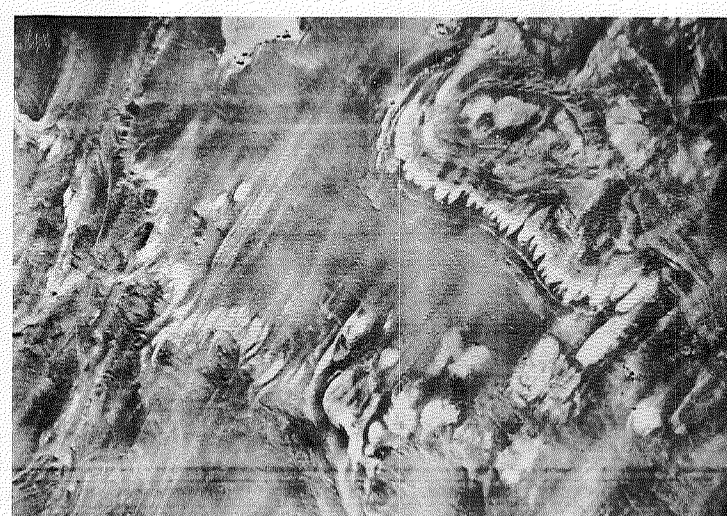
Illustration (*a*) shows the lighting and scale of the Amazonis-Memnonia elongated depressions, and (*b*) shows a much smaller example of similar features in the Coachella Valley of southern California, where houses and other buildings have produced wind shadows and elongated depressions in windblown sand. (4254–55 and J. F. McCauley, U.S. Geological Survey)

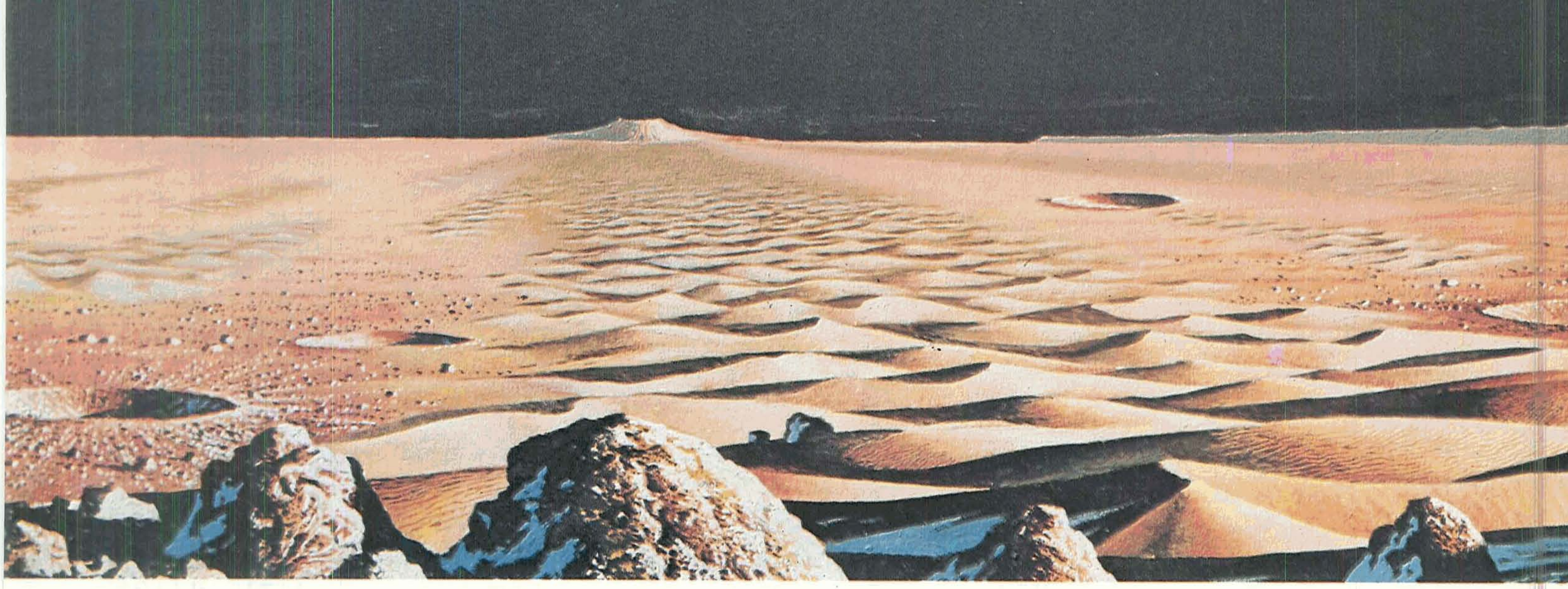
Field of bright streaks, each emanating from a crater in the Hesperia region at 241°, −23°. (4155–84)



Field of bright streaks traversing faulted terrain in southern Tharsis near 108°, −9°. Unlike most streaks, these do not emanate from craters; many appear to emanate from small irregularities on the crests of faulted cliffs. (1348–225134)

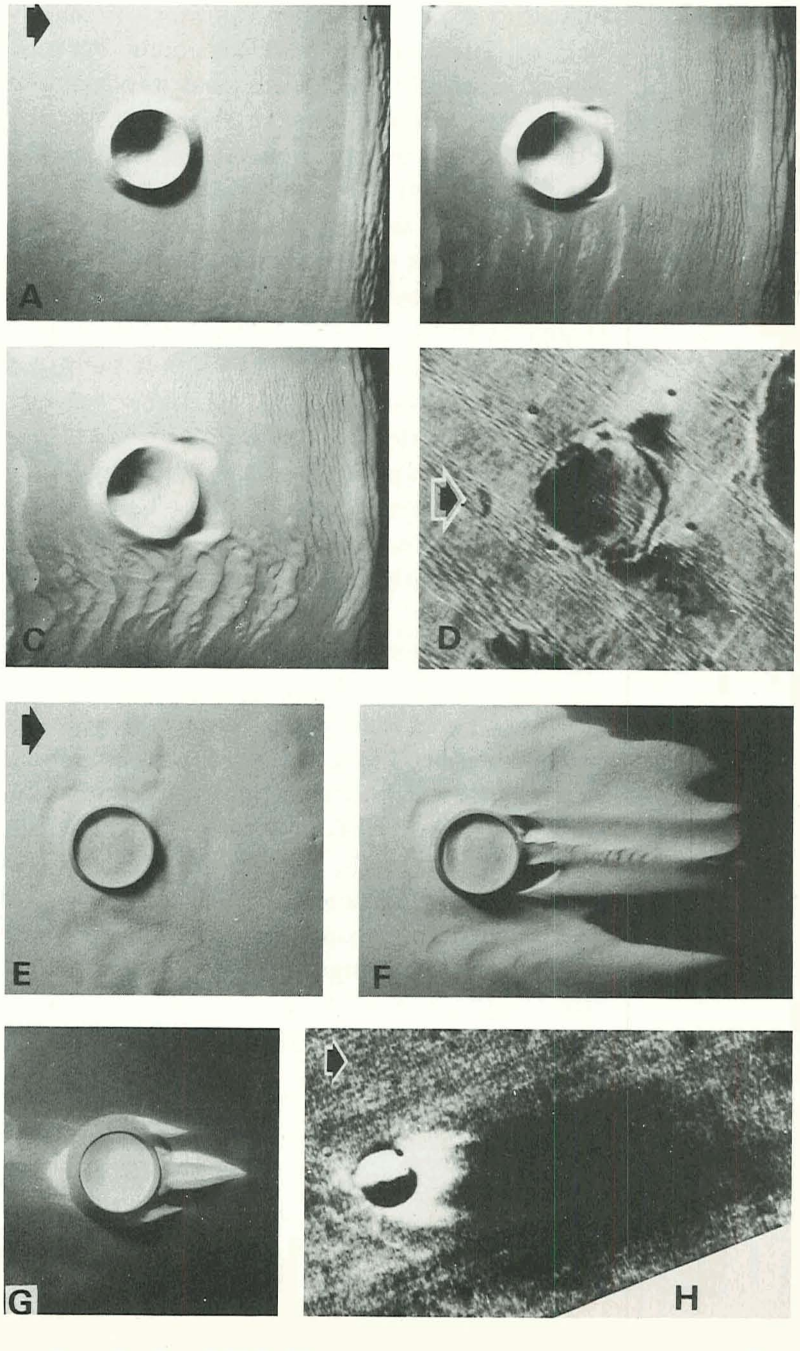
Ragged edges among terrestrial sand deposits caused by fluted cliffs and windblown deposits. High-altitude view over central Peru. (U.S. Geological Survey)





Artist's conception of a dark streak or "tail" emanating from a distant obstacle that interrupts the wind flow. The streak is interpreted by the artist as an alinement of dunes. (Don Davis, Morrison Planetarium)

Streaks and patches in a region, about 500 kilometers top to bottom, corresponding to the position of the "canal" Hiddekel, near 348°, +9°. The northeast-southwest orientation of the streaks approximates that of the "canal" as shown on old maps, but it is uncertain whether the area, photographed shortly after the 1971 dust storm, has the same appearance that it presented to Lowell, Schiaparelli, and other early observers. (4168–72)



Simulation of Martian windblown streaks near craters in wind tunnel tests at Ames Research Center, NASA. Photographs *D* and *H* are of Martian craters. Additional photographs are of wind tunnel test models showing evolution as sand is blown across the crater. Photographs *C* and *G* show simulations of the Martian observed features.

was found that the observed streaks and accumulated deposits on crater floors and on leeward rims can be reproduced vividly. This work again supports the assertion that the streaks, splotches, and dune fields are depositions or scourings of dust.

These discoveries provide only a general kind of solution to the mystery of the Martian markings: they are related to, or a product of, deposition of fine material carried about by high winds, especially the winds that produce the major dust storms. Thus Mariner 9 has provided much of the solution—or perhaps the entire solution—to the mystery of the Martian markings. This solution accounts for the changes in the markings observed from Earth from year to year, because the patterns are expected to change as the winds shift. At the same time, it accounts for the long-term stability of the markings, because Mars, as Earth, probably has relatively stable patterns of prevailing winds. These assertions are supported by the preliminary evidence, which suggests correlations between the sites of dark streaks and the orientation of local steep slopes with respect to the local wind direction.

A number of specifics of the problem are not yet solved, however. For example, not only dark streaks but also light streaks have been revealed by Mariner 9. These follow a pattern similar to the dark streaks, emanating from craters, but raise the necessity of accounting for both dark and light materials. Mariner 9 photographs showed many instances of dark streaks and patches changing shape, but no instance where bright streaks change. However, new bright streaks appeared in the 2-year interval between Mariner 6 and 7 and Mariner 9 photographs. One hypothesis concerning these facts is that Martian materials are sorted by particle size. (It is well known that fine powders of rock material are usually lighter in tone than coarse powders or the unpowdered rock itself.) According to this hypothesis, the dark and bright markings of Mars might not be much different in mineralogy, only different in mean particle size, and whether local streaks or splotches were darker or lighter than the background would depend on whether the deposited particles were finer or coarser than the background. As Sagan and Pollack noted in 1969, the physics of windblown dust on Mars dictates that winds of a certain minimum speed are required to lift any particles, but still higher winds will lift both finer and coarser particles as well. The fines might be responsible for the light streaks, which change only rarely because the necessary high-speed winds are rare.

This particle-size hypothesis is difficult to prove, however, in view of rather crude evidence of differences in the spectroscopic and radar tests of the dark and bright markings. These differences, particularly in color and spectral absorption characteristics, could be due to mineralogical differences. Such a suggestion is consistent with the Mariner 9 infrared spectroscopic indications that Mars has undergone at least partial melting and differentiation into silica-rich and silica-poor rocks. The former are usually lighter in color and the latter, darker. Similar differentiation has occurred to varying degrees on Earth and the Moon. Thus, might Martian markings result from uneven distribution of light (silica-rich) and dark (silica-poor) rock powders.

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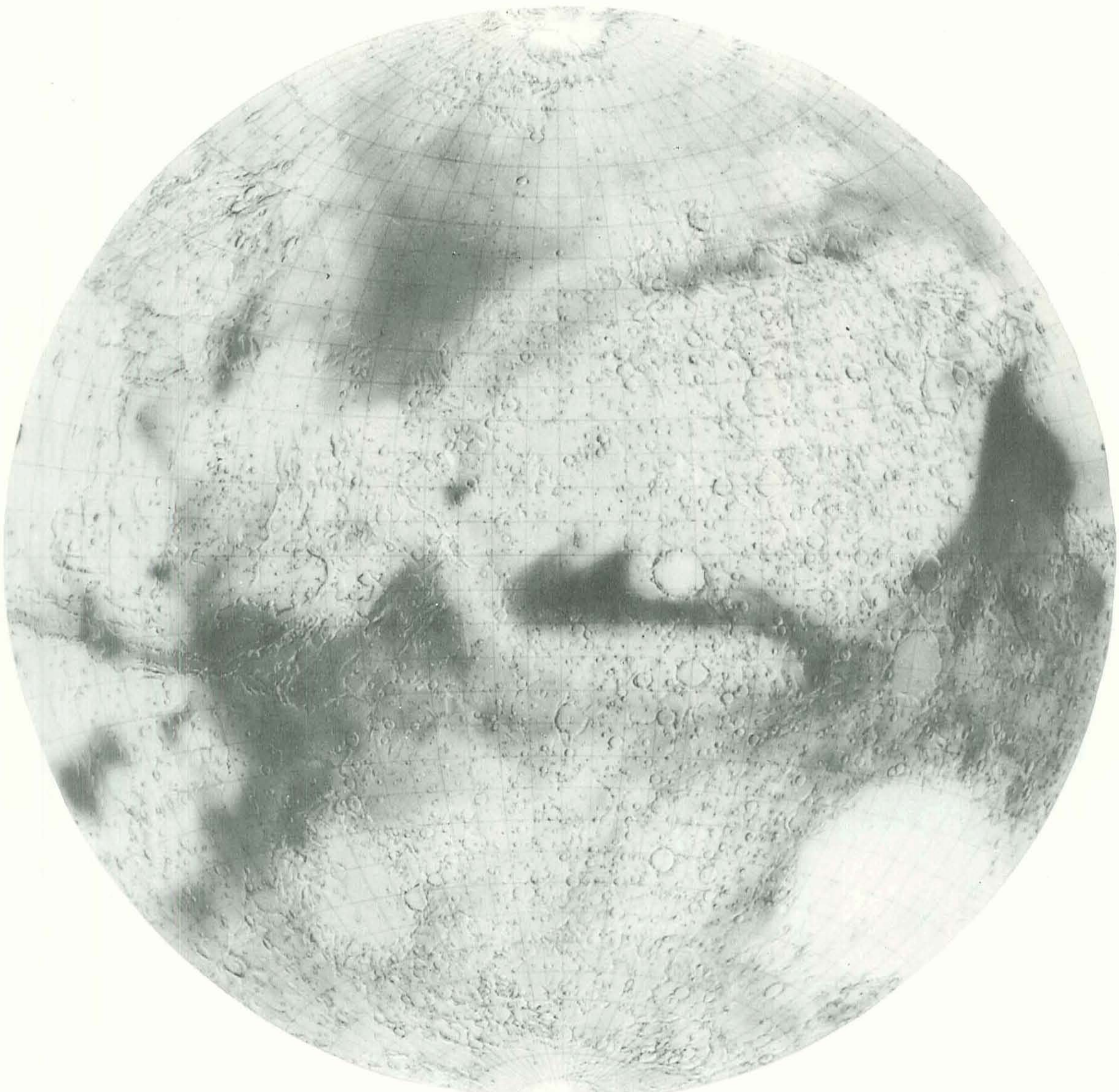
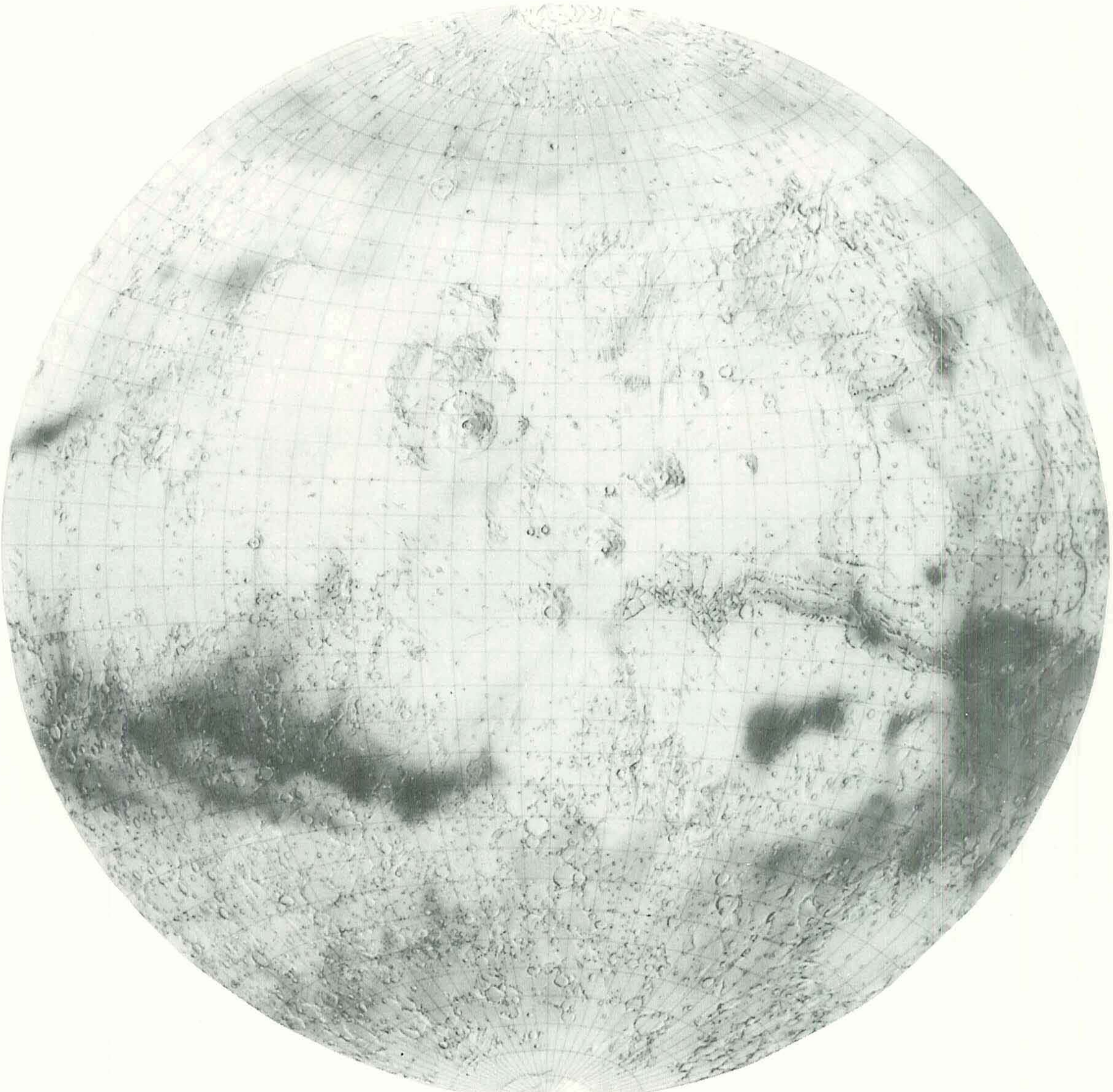
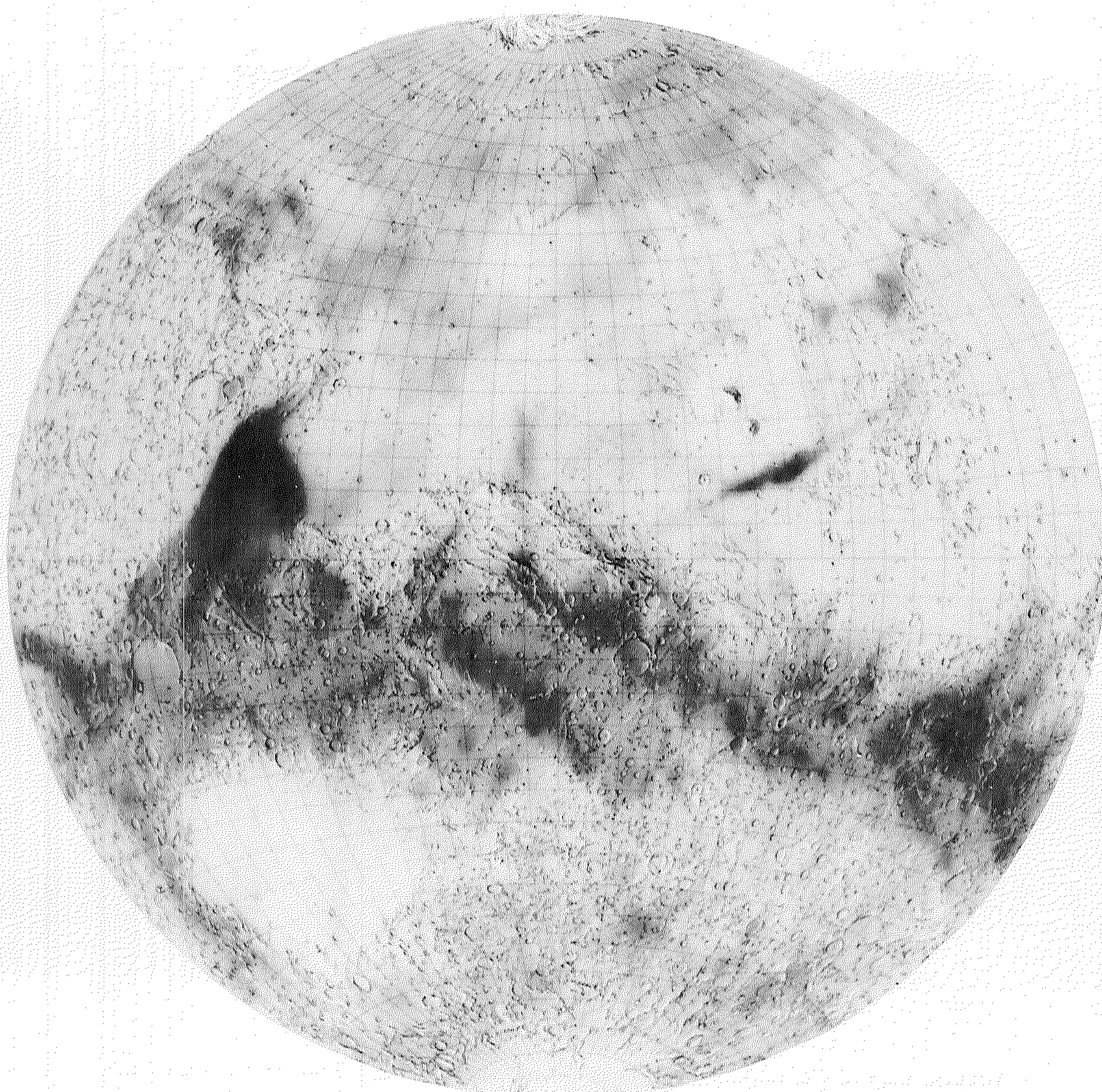
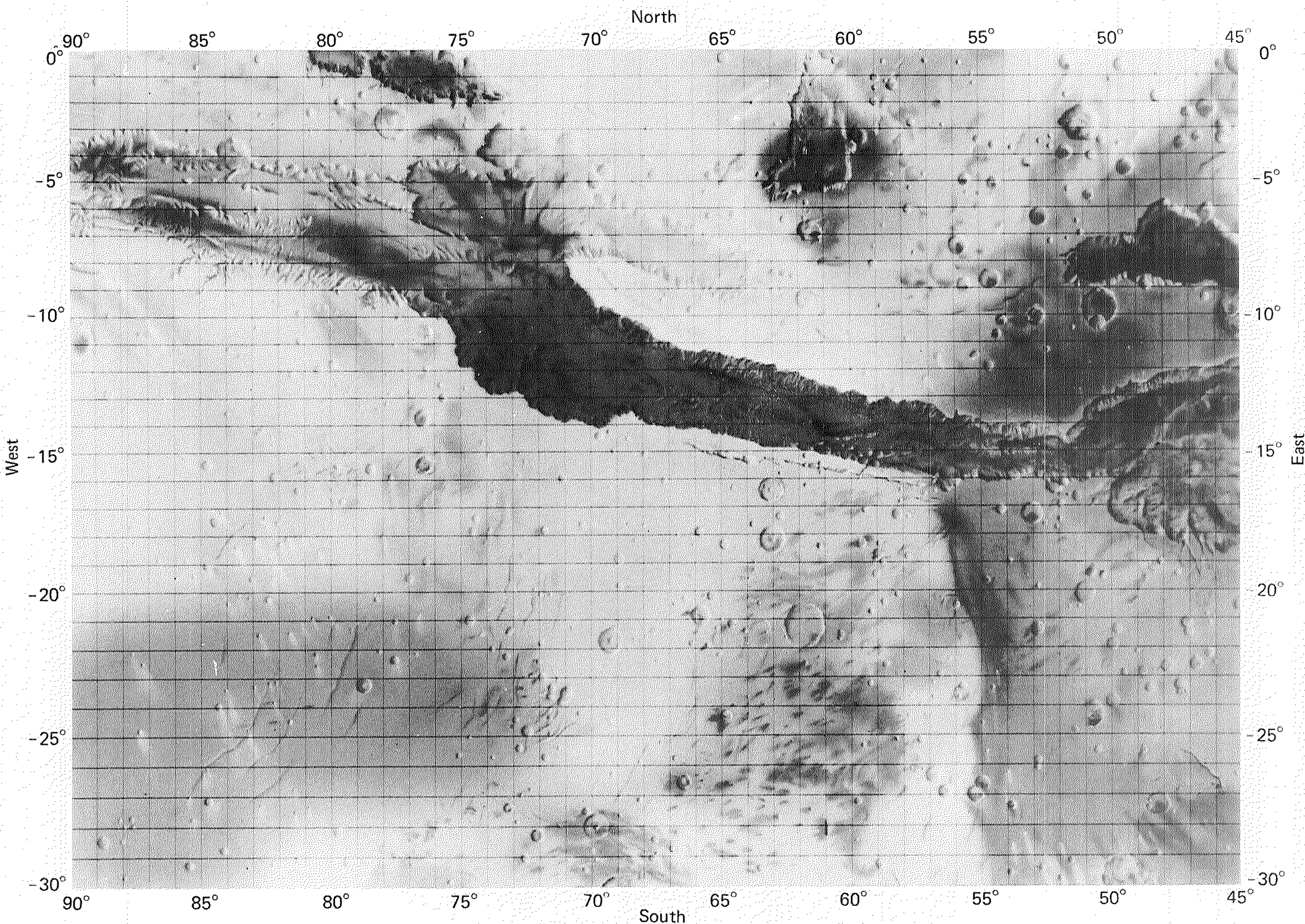


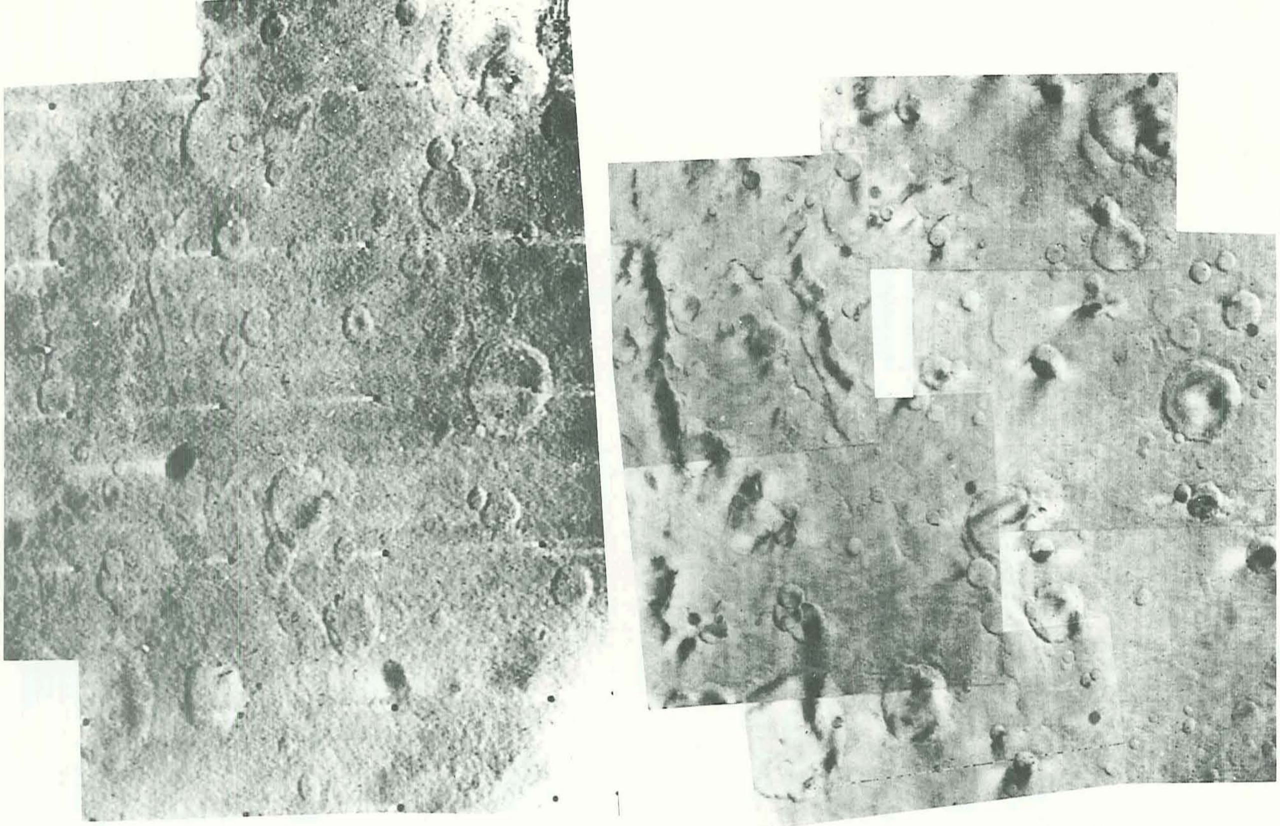
Airbrush drawings of three faces of Mars, showing the classical markings superimposed on physical relief detected by Mariner 9, appear on this and the following two pages. No high degree of correlation is found between markings and terrain type. Compare with earlier maps in this book. (Lowell Observatory)





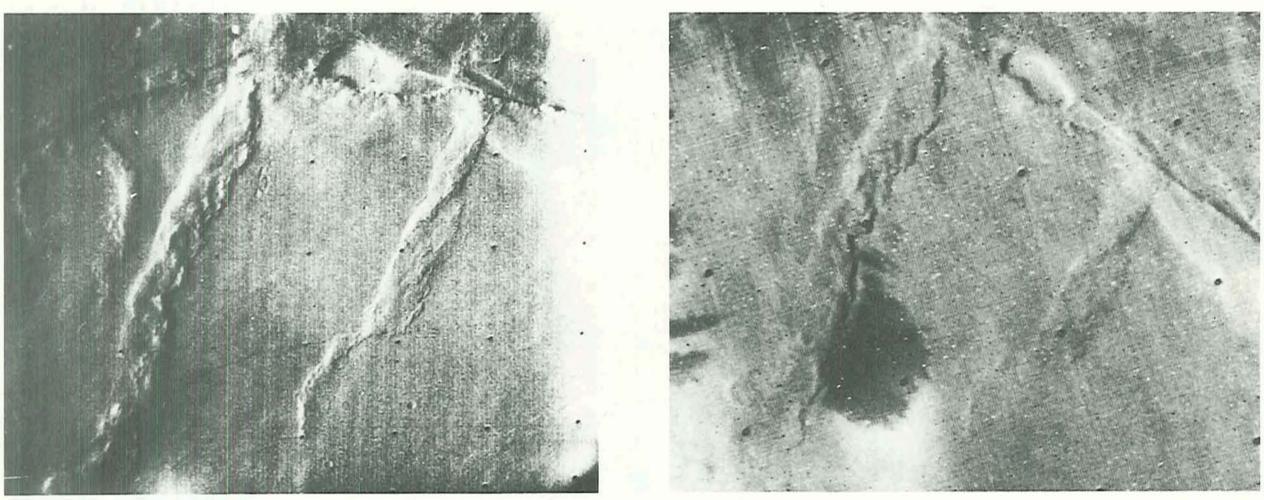


Airbrush map of Coprates area showing classical dark "canal." This dark feature coincides with the recently discovered canyon called Coprates Chasma. (James Roth and G. de Vaucouleurs, University of Texas)

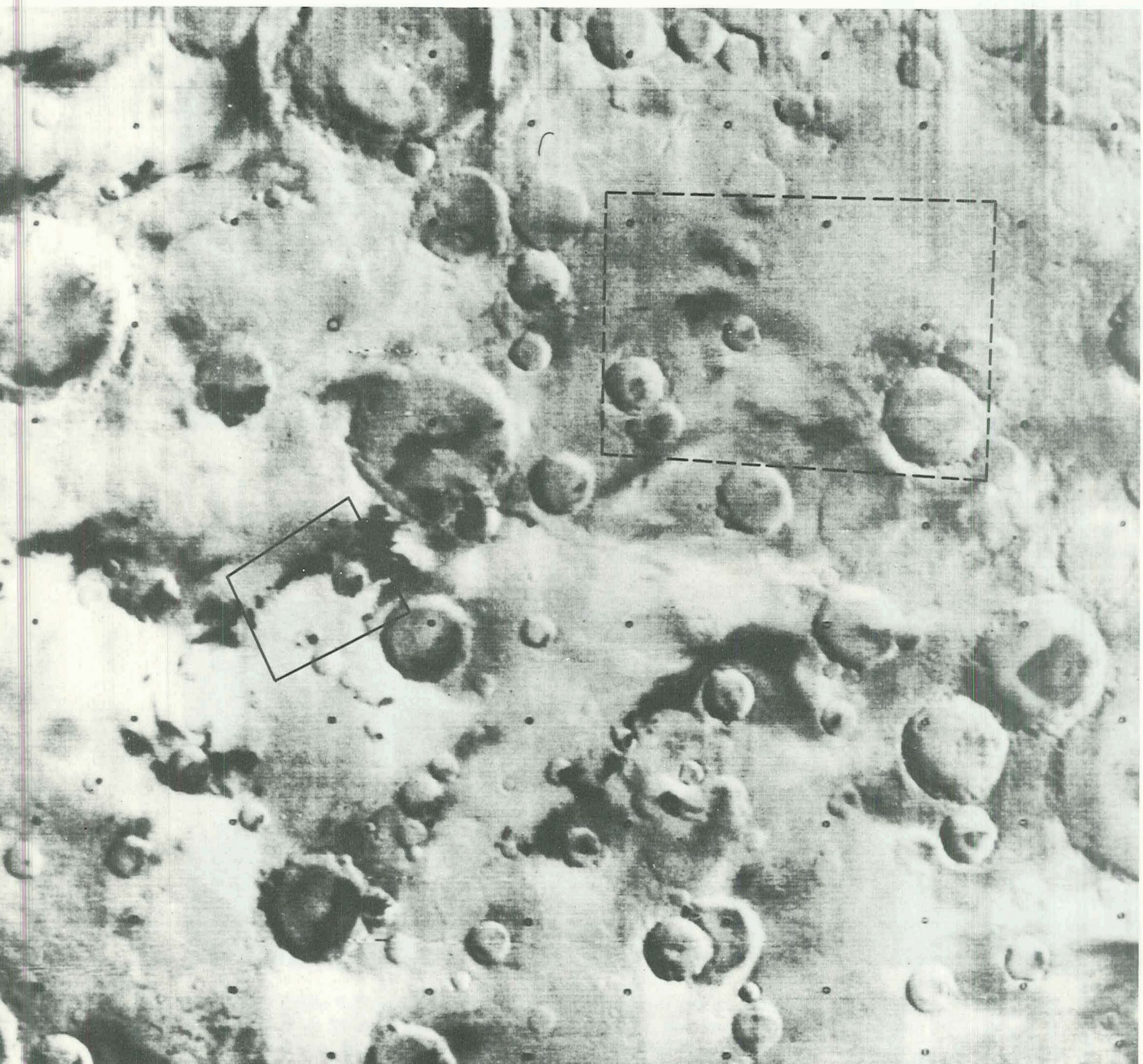


August 4, 1969 January 8, 1972

The search for changes in Martian markings. Here, a frame from Mariner 7 in 1969 is compared with the same region shown in a mosaic of Mariner 9 frames. Several dark spots and streaks have developed in the intervening 2½ years.



Detection of changes on the surface of Mars. This pair of Mariner 9 telephoto pictures shows the summit of the volcano Pavonis Mons on two occasions 77 days apart. Most of the development of the large dark spot east of the ridge occurred in a 20-day period between orbits 154 and 195 of Mariner 9. The hypothesis of deposition of windblown dust, which accounts for variations in many dark patches, has been questioned in this case because of the high altitude and low atmospheric pressure at this location. (4096–80, 4267–42)



Region in Promethei Sinus (269°, −71°) where variable dark patches were noted by Mariner analysts. This wide-angle view covers an area about 750 kilometers across. Boxes show areas studied in detail; variable features in the small box are shown in the next picture. (4211–9)

Telephoto view of variable features in Promethei Sinus, centered at 253°, −70°. Features lettered *A* to *F* have ragged edges, characteristic of windblown deposits. Feature *A* was observed to change shape dramatically, as shown below. (Photograph width is about 80 kilometers.)

Changes on Mars. The spade-shaped marking developed between the taking of the left and middle photographs. The marking is *A* in the above picture. This sequence shows a technique for detecting and portraying changes developed at Stanford's Artificial Intelligence Laboratory. The differences in brightness between elements of the left and middle pictures are displayed at the right. Regions where no change has occurred are neutral gray; regions of variation appear bright or dark. (Stanford University)

Low-altitude aerial view of terrestrial dunes and windblown deposits in northwest Mexico showing ragged forms developed by interaction with local topography of different reflectivity. (W. Hartmann)

A third hypothesis combines the other two. According to this idea, there is no intrinsic difference in petrology between the large and small particles that must exist in the Martian dust. However, because of their greater ratio of surface area to volume, the small particles may become more oxidized, changing their color to a brighter and redder hue, and resulting in a superficially different petrology. Thus spectral and superficial petrologic differences between bright and dark regions might be due to secondary differences in geochemical behavior caused by the different particle sizes rather than to differences in underlying rock type.

Another unresolved problem is the nature of the classical "canals" and "oases." With the exception of the extraordinary canyon that appears to coincide with the rather stubby "canal" Coprates, no other clear-cut features have been found to account for the system of canals reported by many observers. While one of the Mariner 6 frames shows a patchy streak running out of the east fork of the "forked bay" region (Meridiani Sinus) of the well-known canals called Gehon and Hiddekel, a mosaic of Mariner 9 frames in this region shows a little detail but occasional dark streaks and patches. Similarly, neither the near-global Mariner 9 frames taken near apoapsis nor the Mariner 6 and 7 global far-encounter frames show any trace of a canal network. Clearly the canals are not the kind of artificial network once hypothesized, but the answer to their nature is not yet certain. Given the variability of markings and the evidence for variable subaerial deposition of dust splotches and streaks, and given the seasonal and other variations in canals reported by early observers, one suspects that the appearance of Mars presented to Mariner 9 immediately after the greatest dust storm on record may not be the nominal appearance of Mars. We cannot be so hasty as to say that no alinements of spots or streaks will ever be found by spacecraft photography. Thus, future orbital photography of Mars will be studied with great interest, but the best present evidence concurs with the best telescopic reports, which indicate that the "canals" are merely rough alinements among a myriad of nearly subtelescopic splotches and patches.

The oases, or small dark spots visible from Earth, appear to have various causes. While Nix Olympica, for example, is the site of a towering volcano, Juventae Fons (fountain of youth) is found to be a striking irregular depression apparently caused by collapse and related to the nearby Coprates canyon and the chaotic terrain discovered in Mariner 6 and 7 photographs.

Whereas these data rule out the idea that "canals" and "oases" are artificial water-carrying networks, Mariner 9 has forced us to be very cautious when discussing water on Mars because one of the mission's most surprising results was discovery of evidence for existence of rivers at some unknown time in the past. We will consider the implications of this in a later chapter.

The shapes of markings and the theoretical wind patterns are not the only support for the hypothesis that the classical markings are related to windblown dust. Mariner 9 investigators have also detected and analyzed changes in the patterns that are consistent with variations in windblown dust deposits. One obvious experiment was a comparison of Mariner 9 pictures with pictures from earlier Mariner missions. These comparisons showed, in some areas, changes in the distribution or shape of dark and light streaks and splotches. Further study also revealed that changes took place *during* the Mariner 9 mission. In regions such as Promethei Sinus, Telephoto pictures showed changes of several kilometers in the size of dark markings over a period of several days. New dark patches were observed to develop during the mission, even on the summit of one of the volcanoes. The latter example came as a surprise because the volcano protruded above much of the denser dust storm. Nonetheless, in all these instances of change, the pattern of markings and their ragged edges are similar to patterns found on Earth in nature and in the laboratory when thin veneers of dust are moved by wind. In the case of Mars, it is uncertain whether the development of dark patches is due to deposition of dark material or removal of light material; dark markings seem to be more variable than bright streaks and patches.

In summary, the Mariner 9 mission has given the first firm evidence that the shapes and variations of markings observed on Mars for hundreds of years have something to do with the transport and deposition of fine, windblown material. Whereas these data rule out an interpretation based *solely* on advanced forms of plant-life as an explanation for the markings, they do not rule out the possibility that primitive life-forms might have existed in the past or might still exist. Indeed, we will see that the discovery of riverlike channels raises intriguing possibilities about the past biological environment on the planet of Mars.

CHAPTER VI

The Ancient Cratered Terrain

There is no reason to believe that the Earth and Moon were singled out for meteoritic bombardment in preference to the other bodies. Mars lies even closer to the belt of asteroids . . . hence its chances for asteroidal collisions would presumably be higher. . . . Distributed widely over both the ocher deserts and the green maria are round dark spots, the oases, which conceivably could mark large craters. . . .
—R. B. BALDWIN, 1949

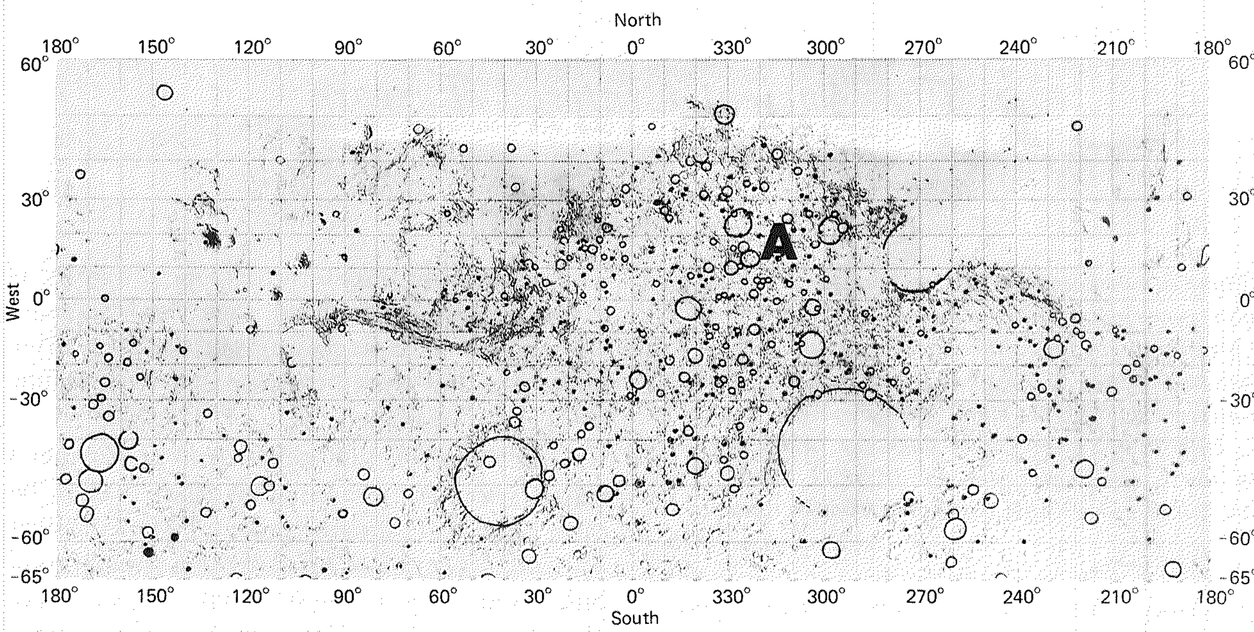
The round oases found on Mars could be impact craters caused by collisions with small asteroids.
—ATTRIBUTED TO C. W. TOMBAUGH, 1950

Now, with respect to the possibility of collisions with asteroids, Mars is in an especially favorable (or unfavorable, according to the viewpoint) position. . . . It seems really worthwhile looking for meteor craters and meteor impacts on Mars!
—E. J. ÖPIK, 1950

These quotations constitute the first known pre-Mariner predictions of cratering on Mars. In the 1950's, in the absence of interplanetary flight, these speculations could not lead to any productive observations; except for some theoretical treatment by Öpik, they were largely ignored. It thus came as an undue surprise to Mariner 4 investigators when, in July of 1965, the first few closeup photographs of Mars showed not mountains, erosion patterns, or other signs of active geology, but rather a lunar-like, cratered landscape. Similarly, Mariners 6 and 7 in 1969 showed heavily cratered terrain, with only hints of other types of surface structure, such as the "chaotic terrain" whose true nature remained mysterious. The discovery of a surface nearly saturated with eroded craters led many analysts to picture Mars as even drier, less active, and more lunarlike than pre-Mariner models of the planet.

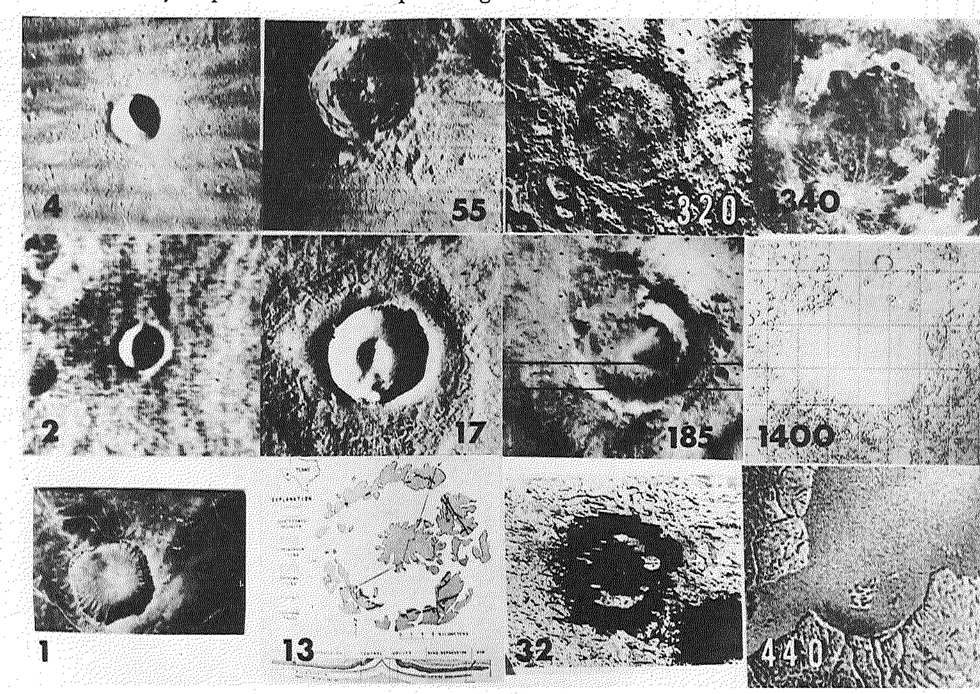
After the 1971 dust storm cleared, Mariner 9 began systematic mapping of Mars and it became clear that all three previous Mariners had, by coincidence, spent most of their photographic budgets on only the most heavily cratered parts of Mars. Much of Mars was sparsely cratered and characterized by extensive plains, spectacular canyons, riverlike valleys, layered sediments, lava flows, mammoth volcanic mountains, or the so-called chaotic terrain. The moonlike Mars that had been pictured had been only an all-too-simple generalization.

The best simple picture of Mars is that of a globe divided into two hemispheres by a great circle running at about a 50° inclination to the equator. The hemisphere centered in the south is heavily cratered, with maximum concentration of craters near the dusky regions Sinus Sabaeus and Mare Serpentis and in the desert Arabia. The hemisphere centered in the great volcanic region near Tharsis has only sparse cratering, the ancient crust having been obliterated and replaced by vast lava flows, volcanic cones, and other disturbances. This second hemisphere contains much of the evidence of recent geological activity on Mars—evidence that had escaped detection until Mariner 9. Superimposed on these two hemispheres are more complex variations such as a deficiency of craters in the immediate polar regions, sheets of "laminated



Map showing topographic features discovered by Mariner 9 with all craters larger than 64 kilometers in diameter marked. Craters larger than 90 kilometers are marked with open circles; craters between 64 and 90 kilometers in diameter are marked with black dots. The global asymmetry of Mars is apparent, with northern latitudes and the volcanic region around Tharsis (*left*) deficient in craters. The region marked *A* is the vicinity of Arabia, one of the few bright and heavily cratered areas.

Comparison of crater types on the Moon (top row), Mars (middle row), and Earth (bottom row). Diameters are given in kilometers. From the left the columns show bowl-shaped craters, craters with central peaks, craters with central rings of mountains, and large basins. The terrestrial craters, from left, are the Arizona meteorite crater, Sierra Madera in Texas, Clearwater Lake crater in Canada, and a portion of Hudson's Bay suspected to have impact origin.



terrain" in northern and southern latitudes, a belt of channellike furrows in the equatorial regions, mysterious arroyolike valleys resembling dry riverbeds, and other still more localized structures. We will treat these indicators of varied geologic activity in later topical chapters.

The cratered terrain is believed to contain the oldest structures on Mars and is perhaps the simplest terrain to interpret because it has been the least modified since Mars formed. This statement is based on the belief that most craters in this region are ancient impact craters, dating back to the early period not long after Mars formed, when the solar system was being swept clean of abundant meteoritic debris, which collided with planets and cratered their surfaces. Evidence in support of this belief comes not only from the craters' abundance but also from their similarity to known impact craters on Earth and on the Moon, and from the similarity between their size distribution and that which would result from the fall of known interplanetary bodies onto the surface of Mars. The best-known example of an ancient, crater-saturated surface is the ancient lunar uplands, which Apollo rock samples show to be more than 4 billion years old. Hence the question arises as to whether the Martian cratered terrain is as old and as uncomplicated as the lunar uplands.

Before such a question can be answered, one must note that many volcanic craters are scattered among the impact craters. Hence we must distinguish volcanic from impact craters. Because the volcano near Arsia Silva has a summit caldera about 140 kilometers in diameter, volcanic craters this large cannot be excluded in other parts of Mars; some smaller examples are recognizable among scattered features of the cratered terrain. Usually such volcanic craters are recognizable by their positions on the summits of volcanic cones or their association with lava flows, rows of pit craters, faults, or other signs of volcanism.

Once assured that the volcanic craters can be distinguished from the other craters of the cratered terrain, Mariner 9 analysts were able to pursue the interpretation of this most ancient part of Mars. Because these regions had been photographed in part by Mariners 4, 6, and 7, some interpretation had already been published by scientists such as E. Öpik, C. R. Chapman, A. Binder, A. Marcus, G. McGill, D. Wise, and others, as well as Mariner 9 team members. One consensus was that erosional effects and regional variations were important; hence the history has been more complicated than the history of the lunar cratered surfaces. Invoking some degree of erosion was necessary to account for the worndown appearance of the Martian craters. Mariner 9 data support this view and suggest that the oldest craters have been at least partly filled with loose material, perhaps eroded and transported by the wind.

Mariner 9's complete mapping of Martian craters allows interpretation of the relative ages of different areas. The longer a surface has been in existence, the more meteorites will have fallen on it, and the more craters it will display. This is the basis for the statement that the heavily cratered areas are ancient. Mariner 9 data show that the most cratered regions of Mars are also the rarest, unlike the situation on the Moon. This suggests that, as on Earth, the crust has been so disrupted by the planet's evolution that few primeval areas have survived. Thus even the oldest, most stable regions of Mars are more complex and altered than the lunar uplands.

If the exact rate of formation of craters on Mars were known, one could easily calculate the time required to form the observed number of craters on Mars; that is, the age of the Martian surface. Such a "crater retention age" would be dependent on the size of the crater because multikilometer craters would date back much farther than the quickly eroded 100-meter craters. Unfortunately, no exact measurement of the Martian cratering rate is available, although the problem is being studied theoretically by researchers such as G. Wetherill and J. Williams. Using rough estimates and comparative data such as the dates of lunar rock samples, Mariner 9 researchers have estimated the age of the heavily cratered regions on Mars as some billions of years, whereas the same kinds of data give ages as low as 100 million years for some structures in the sparsely cratered regions of Mars. The latter age is comparable to the age and active lifetime of major tectonic or mountain-building areas on Earth.

Among the largest craterlike features are the enormous basins of Hellas, Argyre I, and Moeris Lacus. At least the first two have been recognized from Earth as bright, circular patches, although their identification as giant impact basins was not possible until the Mariner missions. Indeed, the last decade saw considerable debate as to whether these bright areas were high or low regions. According to Mariner 9 photographs and altitude contours mapped by the infrared and ultraviolet spectrometers and radio-occultation experiment, the Hellas basin measures about 2200 kilometers in diameter in the east-west direction and 1800 kilometers north to south and has a nearly featureless floor at least 2 to 3 kilometers deeper than its rim. The paucity of detail in the floor of Hellas, the obscuration of the detail as late as 50 days after the general clearing of the dust storm, and Earth-based observations of erratic brightenings of Hellas all suggest that the depressed floor of Hellas is mantled with dust that is easily stirred by the high winds and unusually high atmospheric pressures existing at that low level.

The basin known as Argyre I, though smaller than Hellas, is less degraded and shows characteristics of an impact basin more clearly than Hellas. These characteristics, such as a rugged rim and a surrounding field of radiating fractures, have long been recognized in well-preserved impact basins on the Moon; in most Martian basins they appear to have been degraded by the more active atmospheric environment of Mars. Argyre I was shown as a particularly bright spot on maps as old as Proctor's 1871 map.

The basin of Moeris Lacus is of special interest because its western inner wall is the site of the sloping terrain containing the shifting edge of the famous dark marking Syrtis Major. Earth-based radar showed some years ago that Syrtis Major lies on a slope, leading to some speculation about a possible crater rampart there. Mariner 9 photographs proved that the cause of this topography was the remnant rim of a large circular basin. Only the western and southern rims of Moeris Lacus are intact, the

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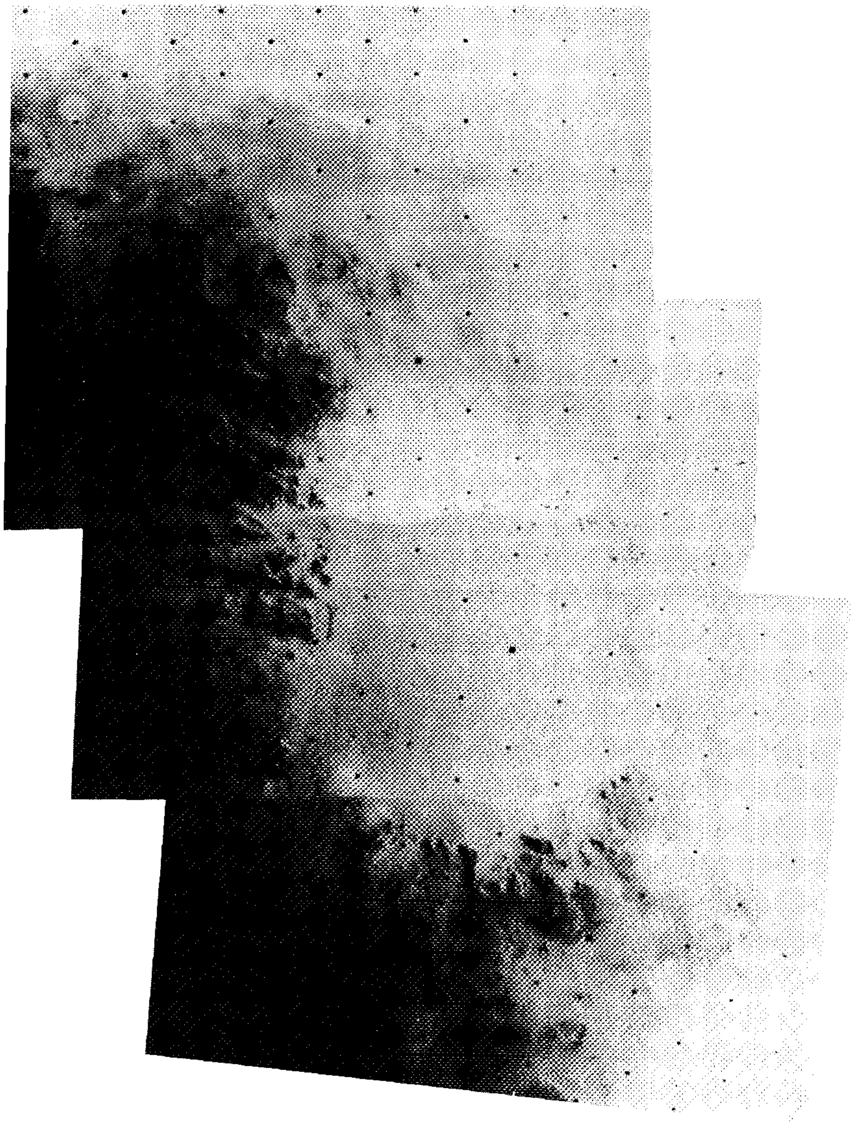
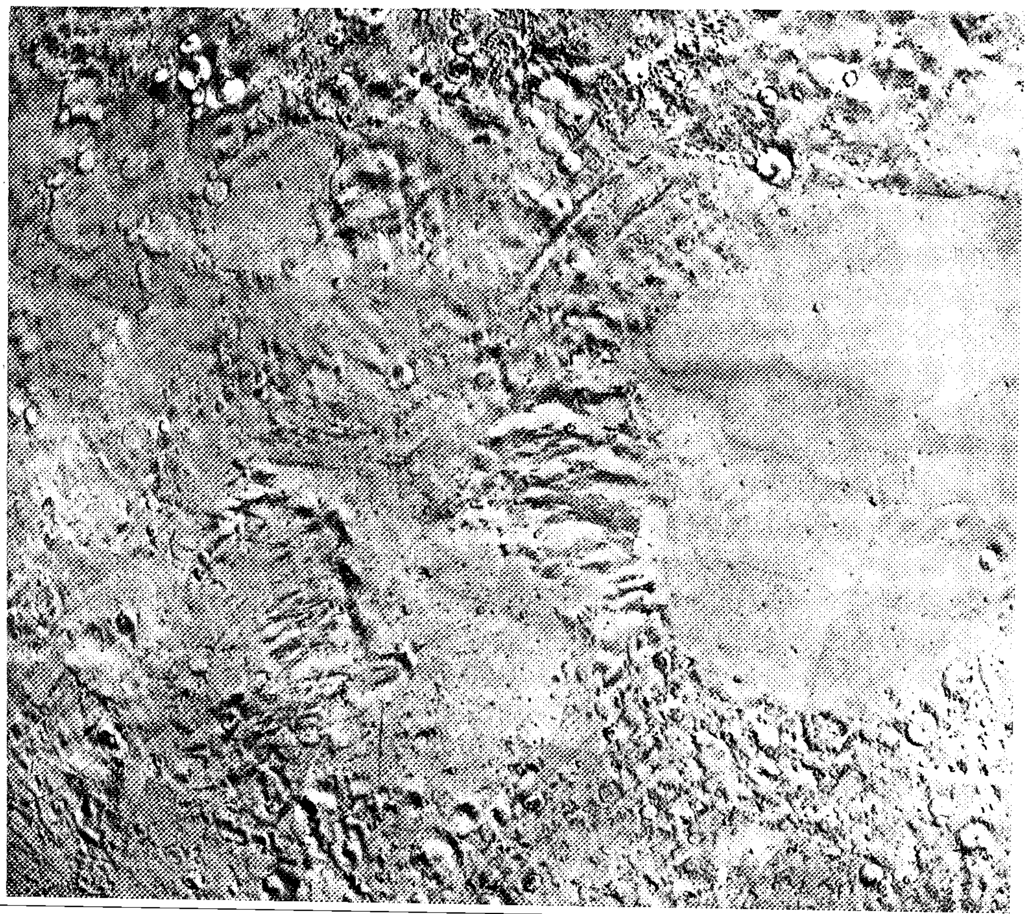
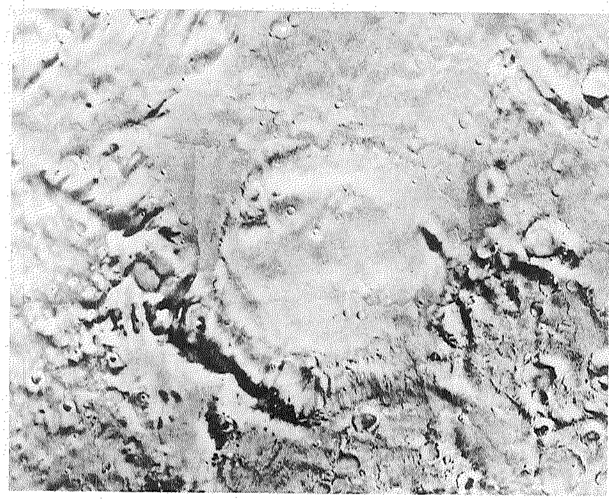


Mosaic of photographs showing the Argyre I basin. These show the original light and dark tones, with sunlight from the right (east), and washed-out detail in regions of high lighting angle as well as in the basin interior where there is probably airborne dust. Argyre I has long been noted on Earth-based maps as a bright spot roughly 1000 kilometers in diameter.

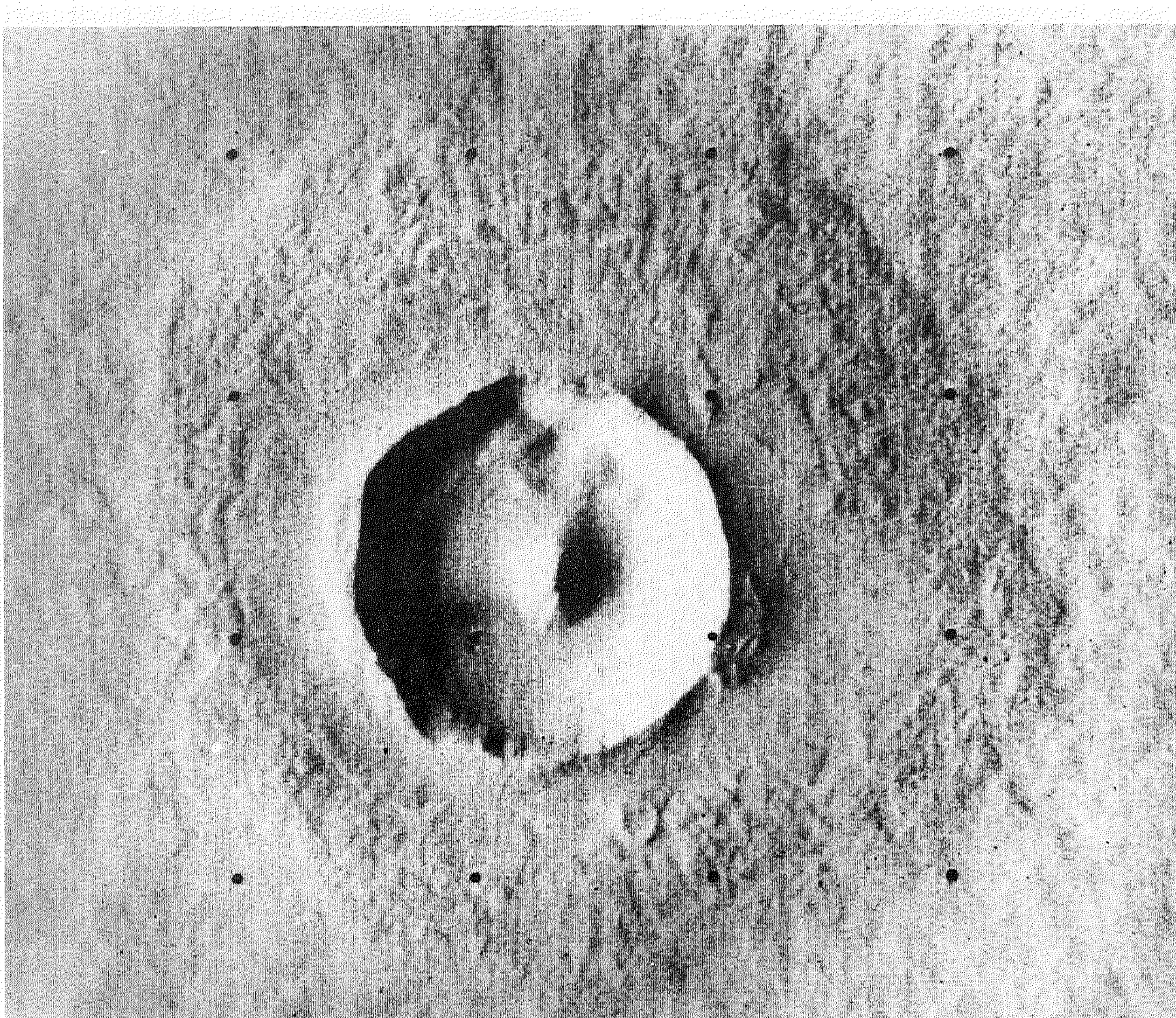


Region of Moeris Lacus basin (right of center, featureless circular floor) and Syrtis Major (left of center, dark streaks). The most prominent streaks in Syrtis Major correspond to the rim and wall structure of the Moeris Lacus basin, perhaps being initiated by topography in that region.



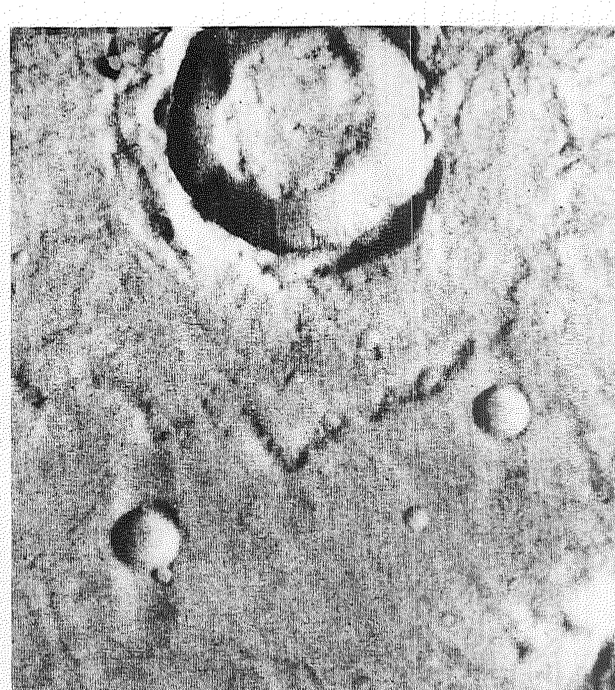
Edom, long observed as a bright spot on Earth-based maps, is here resolved into a large shallow crater occupying the central third of this mosaic. The crater has been named Schiaparelli, after the famous observer of Mars. The dark markings at the left are part of the eastern "prong" of the fork-shaped Meridiani Sinus.

This 185-kilometer-diameter crater on Mars shows an inner ring of peaks and concentric ridge structure on its rim. Beyond the rim are radial striations. Such a structure is believed to be produced by the mechanics of the impact process when large meteorites strike planetary surfaces. The crater resembles a similar structure on the Moon, named Schrödinger, discovered in the late 1960's in Lunar Orbiter photography. (406–192722)



Martian crater near 260°, +38° with well-formed central peak and radially striated ejecta blanket. The hummocky exterior ejecta blanket is believed to be a deposit of fragmental material thrown out of the crater during its formation. (1433–210033)

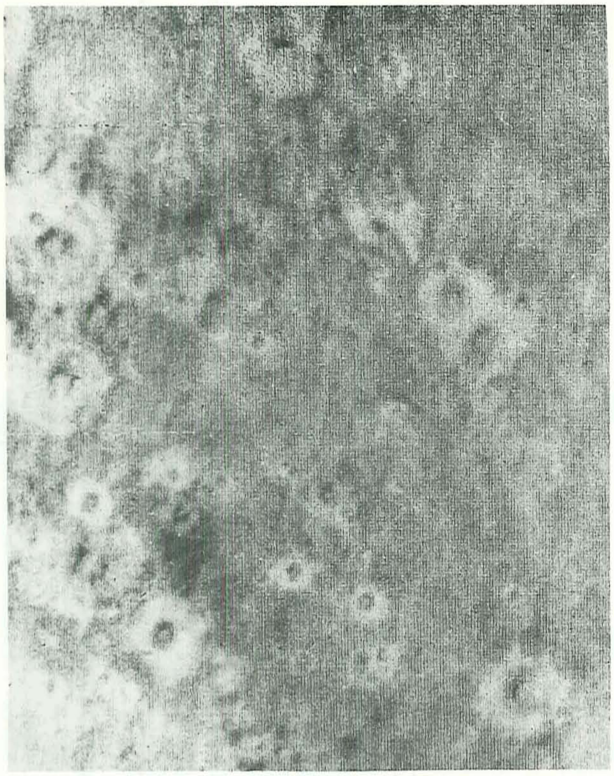
Martian crater near 330°, +30° displaying central hills and hummocky radial outer rim structure. (1419–153055)



Example of a possibly exhumed ejecta blanket surrounding a crater. Instead of feathering out into the surroundings as is normal, this ejecta blanket appears to stand out above the surroundings, possibly as a result of erosion of surrounding loose material. (1590–121733)

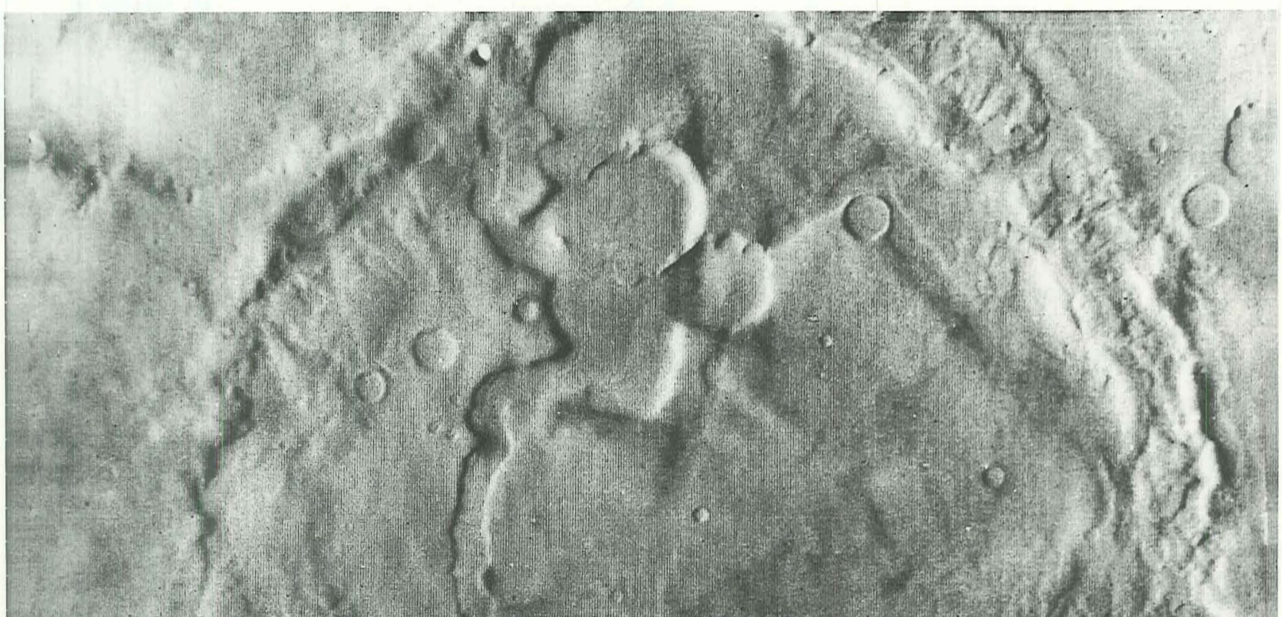
eastern and northern edges grading out into a broad expanse of Martian "desert."

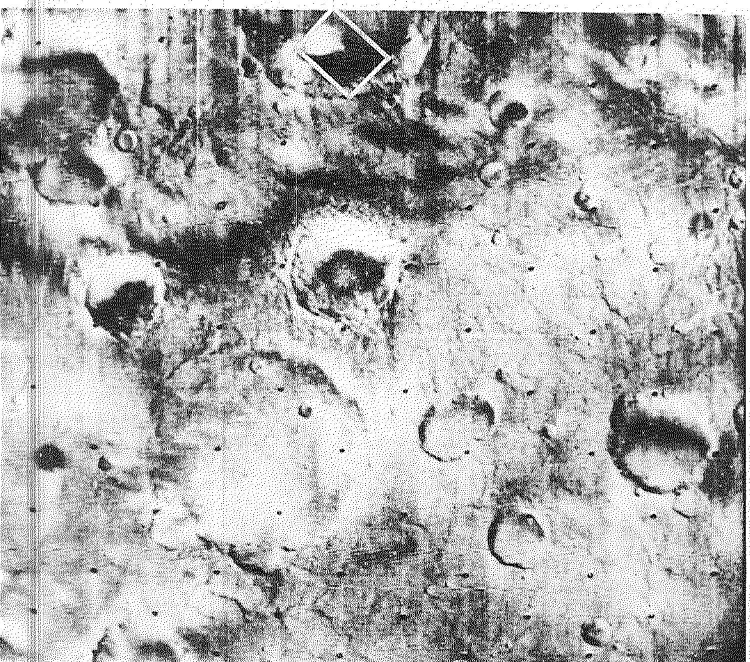
Although these basins are the only craterlike features large enough to be distinguished (but not identified) from Earth, certain smaller craters apparently affect the pattern of markings sufficiently that their immediate regions were given names by pre-Mariner telescopic observers. Two of these craters, each about 470 kilometers (290 miles) in diameter, occupy the regions of Iapygia and Edom. Iapygia was shown on Flammarion's map as long ago as 1909 as a circular spot slightly brighter than its dark background (just south of Syrtis Major) and coinciding with what we now know to be the crater floor. Edom has long been recorded by telescopic observers as one of the brightest desert patches, just east of the forked bay of Meridiani Sinus. By extension of the evidence for dust clouds in Hellas, one suspects that these craters may be the sites of dust deposits stirred by winds, creating brighter-than-background clouds recorded by Earth-based observers. Old maps show numerous such bright

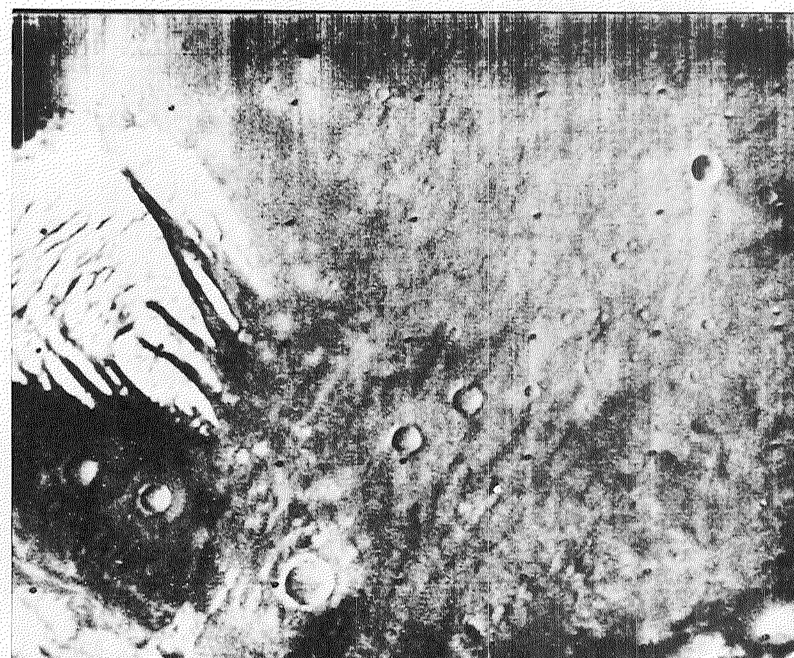


Unusual pattern of bright ejecta blankets surrounding craters near 31°, +60°. The explanation might involve ejection of underlying light material on dark surface material, or possible deposition of frost or other light material on rough ejecta blanket surfaces. (7270–195648)

A highly eroded Martian crater near 325°, +37° with a sinuous arroyolike channel winding across its floor. This and similar craters testify to various processes smoothing, eroding, and obliterating the ancient craters on Mars. (1419–154957)







Enigmatic bright formation in a Martian crater. The wide-angle frame (*left*) shows the location of the feature in the floor of a crater at top edge, center. The telephoto view (*right*) shows the bright structure at the left edge of the frame. The feature resembles a windblown bright deposit with ragged edges, but it is of unusually high reflectivity.

patches, which may represent dust activity in craters.

Do the myriad of smaller craters on Mars have any bearing on the markings seen from Earth? Mariner 9 photographs showed that many craters display dark patches deposited on their floors. In general, such dark patches are too small to be resolved from Earth, but it is of interest to recall that late pre-Mariner French observers such as Lyot, Focas, and Dollfus, observing visually under excellent conditions with resolutions corresponding to as little as 56 kilometers (35 miles) on Mars (under full-disk illumination), stated that the dark markings were composed of "innumerable small spots" (Dollfus) or "dark nuclei" (Focas). Because the craters appear in the bright areas of Arabia and Moab as well as in dark areas, one cannot ascribe all of the classical dark markings to crater effects alone, but a case can be made from the association of the dark areas and craters that the craters do influence the markings seen from Earth.

The smallest craters so far resolved on Mars by Mariner 9 measure some hundreds of meters in diameter, and there is every reason to believe that still smaller examples exist. However, craters as small as a few kilometers and less are much scarcer on Mars than on the Moon; erosional effects must have obliterated them during short intervals of past geologic time. In fact, positive proof of the effectiveness of Martian erosion exists among these small craters because they are only about one one-hundredth as abundant on Mars as they are on the surfaces of the Martian satellites Phobos and Deimos, which orbit above the Martian atmosphere. Because Phobos, Deimos, and Mars must all be subjected to nearly the same rate of bombardment, the deficiency of craters on the surface of Mars must be due to obliterative processes.

In spite of the evidence for effects of past erosion on the smaller Martian craters, a curious fact noted during the Mariner 6 and 7 missions and confirmed by Mariner 9 is that the smallest craters are often sharply rimmed and bowl-shaped whereas the larger craters are often degraded. Craters of intermediate size often show radial blankets of ejecta standing in relief, as if exhumed or preserved during erosion by wind. If erosion and cratering were both continuing at a constant rate, one would instead expect the most noticeable erosive degradation on the smallest-scale craters. This situation has led to the hypothesis by some Mariner 9 analysts that the rate of erosion on Mars is less in the recent past than it was earlier. Together with the Mariner 9 observations of what appear to be dry riverbeds, this state suggests that the environment on Mars was once more Earth-like than it is now. We will consider this possibility in later chapters.

In summary, the ancient cratered terrain of Mars is a natural recording surface on which meteoritic impacts have left their records. Some local regions are older than others, allowing analysts to construct at least a crude model of ancient Martian history.

CHAPTER VII

The Volcanic Regions

Quite possibly cones as large as Mounts Rainier and Shasta have been missed!

—DEAN B. MCLAUGHLIN, 1954

The above quotation reflects McLaughlin's reappraisal of the traditional views that there are no large mountains on Mars. Early observers had searched the edges of the planet for fixed protuberances or shadows that might mark high mountain masses. Their failure to find them led to the view that major mountain chains did not exist on Mars. A common belief grew that high mountains and ranges were altogether excluded, although broad regional elevation differences were not ruled out.

Therefore, enormous volcanic peaks were not among the expected landforms. Some observers thought the dark areas might mark lava flows, as on the Moon. Also, because of the abundance of small volcanic craters, crater chains, and volcanic cones on Earth and the Moon, few pre-Mariner analysts would have ruled out their presence on Mars. Nonetheless, such landforms were not widely discussed.

McLaughlin departed from traditionalists by asserting that volcanism was an active agent on Mars and was the ultimate source of the materials in the dark markings, which he took to be volcanic ash. By considering the sizes and shadows of cones like Mounts Rainier and Shasta, he estimated that, if present on Mars, they would not have been discovered from Earth. Most other observers did not concur with the extent of the volcanism proposed by McLaughlin, although many agreed that the dark markings might be volcanic materials, such as lava. It was pointed out that the present atmosphere lacks the gases that should be produced by active volcanoes.

Whereas Mariner 9 did not confirm the essence of McLaughlin's volcanic thesis that volcanoes located at the pointed tips of dark markings erupted clouds of dark ash to renew the markings, it did confirm decisively his proposition that previously undetected large cones might exist.

Even while the 1971 dust storm raged at its height, Mariner 9 photographed the tips of four large volcanic mountains protruding through the pall. Each contained summit calderas whose volcanic origins were unmistakably indicated by complex coalescence of small craters, by chains of pit craters, by concentric fractures, and by other features.

As the dust settled, the flanks of these cones emerged covered with streams of frozen lava descending the slopes in radial patterns reminiscent of those on the slopes of the Hawaiian volcano Mauna Loa and other terrestrial volcanoes. Soon traces across these volcanoes became available from instruments such as the ultraviolet spectrometer, whose spectra indicated the altitude of the surface. Olympus Mons, the peak near Nix Olympica, had an astonishing height: the summit was at first estimated to be 27 kilometers above the planetary base level, defined as the level where the atmospheric pressure was 6.1 millibars. This meant that the mountain, whose

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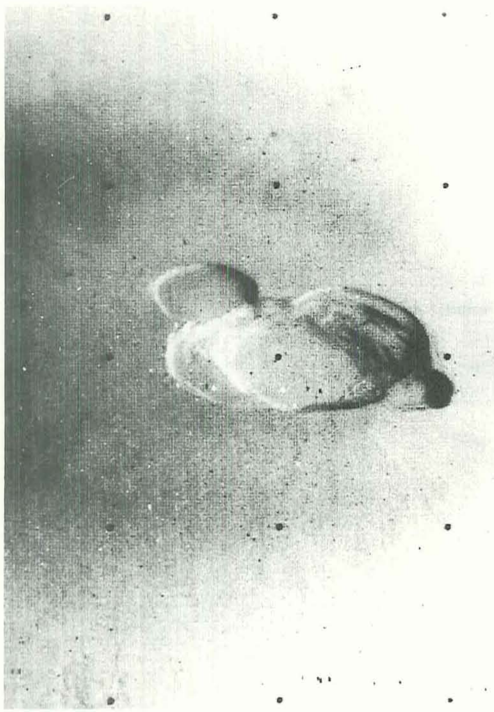
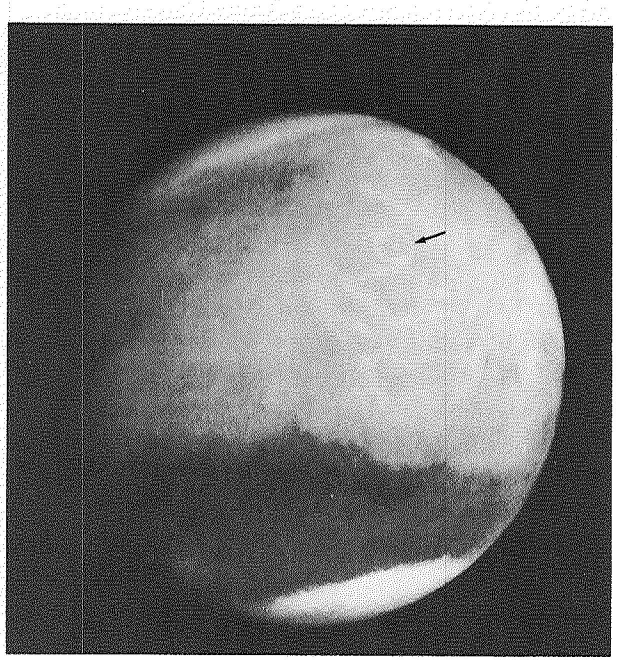
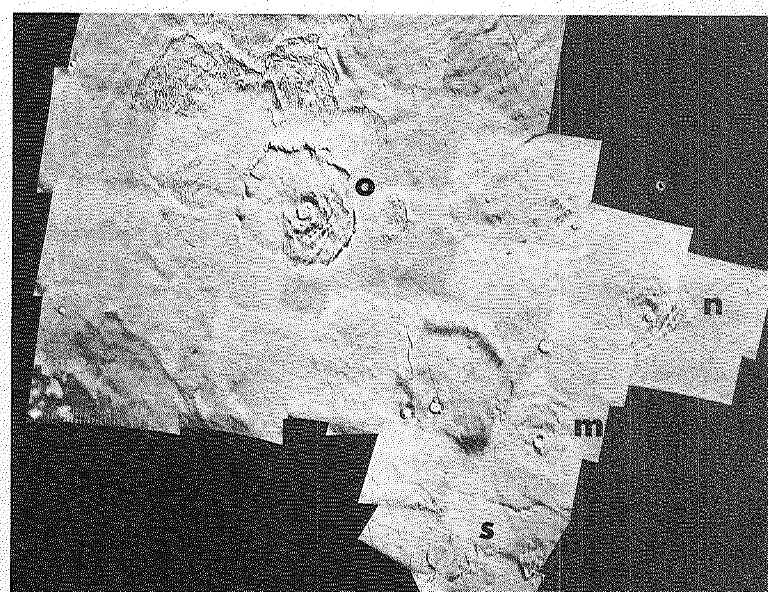


The summit of Ascraeus Mons volcano protrudes from the Martian dust pall.

Example of a terrestrial volcano and caldera protruding from a cloud blanket, showing superficial similarity to the Martian case above. (Fernandina volcano, Galapagos Islands) (U.S. Air Force; U.S. Geological Survey)



Bright, volcanic regions of Mars as shown by Mariner 7 on August 4, 1969. The bright ring (arrow) was revealed by Mariner 9 to be a bright cliff or haze at the base of the volcano Olympus Mons. Other bright mottled markings include cloud formations.



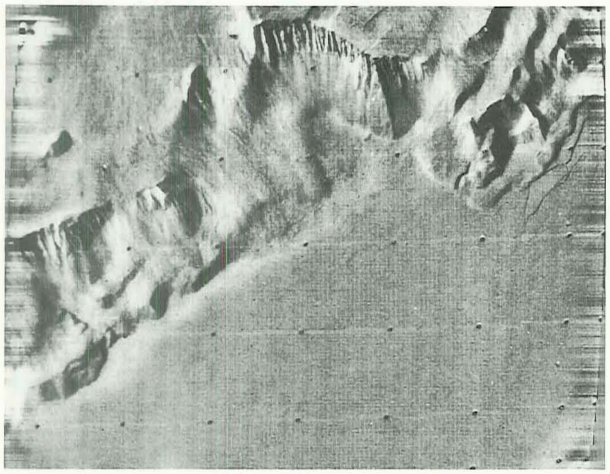
Mosaic of Mariner 9 photographs showing the four large volcanoes of the Tharsis complex: Olympus Mons (*o*), Ascraeus Mons (*n*), Pavonis Mons (*m*), and Arsia Mons (*s*). The Tharsis dome reaches its highest elevations in this area. (Jet Propulsion Laboratory)

Mosaic of Mariner 9 photographs showing Olympus Mons and the nearby fractured or "grooved" terrain. (Jet Propulsion Laboratory) base is about as big as the whole State of Missouri, towered some 88 000 feet above other features on Mars, compared with Mount Everest's 29 000 feet above sea level, 42 000 feet above the mean ocean floor, and 65 000 feet above the greatest ocean depths. At first, many analysts believed that there must be some calibration error in the ultraviolet spectroscopy data. However, recent analyses by various other techniques, such as photogrammetry, converge on a height of about 24 kilometers, or about 78 000 feet above the 6.1-millibar reference level. This puts the summit of Olympus Mons about 100 000 feet higher than the lowest places on Mars. Mars thus has about half again the total 65 000-foot relief of Earth.

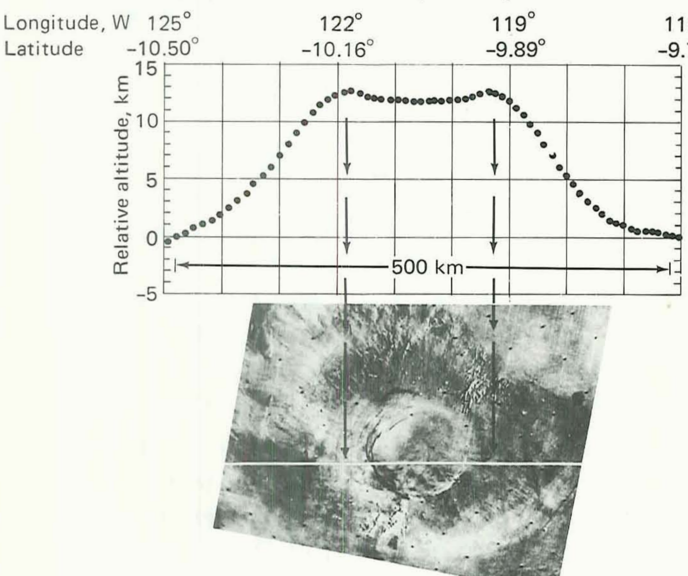
Nix Olympica, as it turned out, had been aptly named. When Schiaparelli back in 1877 named this small dark spot, he was struck by its frequent transformation into a bright, cloudlike patch. Perhaps conceiving it as a sometimes snow-covered peak, he named it "Nix Olympica," meaning "snows of Olympus." So the highest mountain on Mars is associated with the home of the Greek gods. Because the classical names apply in principle only to the bright and dark patches seen from Earth, the actual volcanic peaks received their own new names from a committee of the International Astronomical Union in 1973; the mountain near Nix Olympica was thus named Olympus Mons.

How has the mountain reached such a height? Most of the height is due to the buildup of repeated outpourings of lava, as evidenced by the flows descending the conical slopes away from the summit caldera. Part of the elevation of the lower reaches may be due to uplifted, fractured blocks because such fractured blocks are exposed on the lip of the cliffs defining the edge of Olympus Mons. In addition, the whole mountain is sitting on the summit of a broad uplifted dome or ridge known on classical maps as the Tharsis area and distinguished on Mariner 9 photographs by radiating fractures. The Tharsis dome is about 2500 kilometers in diameter and stands about 4 to 8 kilometers above the Martian reference level of 6.1-millibar atmospheric pressure. Thus, about one-sixth to one-third of the 24 kilometers of the summit altitude of Olympus Mons is due to very broad crustal deformation.

Olympus Mons and the other major nearby volcanoes on the Tharsis dome have been compared by Mariner 9 geologists with large volcanoes on Earth. They resemble a type of structure known as a shield volcano. A typical shield volcano on Earth is Mauna Loa in Hawaii, which is approximately 120 kilometers in diameter at its sea-floor base, has a cluster of summit calderas ranging up to several kilometers in diameter, and stands about 9 kilometers above the sea floor. The Martian shield volcanoes reach much larger sizes. Small examples on the Tharsis dome include shields 180 to 200 kilometers across with large central craters up to 60 kilometers in diameter. The three large volcanoes that accompanied Olympus Mons in protruding above the 1971 dust storm average about 400 kilometers in diameter. The middle of these stands about 11 kilometers above the surrounding plains of the Tharsis dome according to ultraviolet spectroscopy measurements. Geologic analysis reveals an aureole of fractured terrain surrounding Olympus Mons as far as



Telephoto view of the face of the cliff around the base of Olympus Mons volcano. (4265–44)



Example of a preliminary altitude profile derived for the volcano Arsia Mons from infrared radiometer measurements using thermal data and simplifying assumptions to derive local slopes. Uncertainty on the vertical scale is 50 percent.

Mariner 9 mosaic showing the volcano Ascraeus Mons (bottom) and associated fractured or "grooved" terrain. (Jet Propulsion Laboratory globe)

1400 kilometers from the center. The summit calderas of Olympus Mons, Ascraeus Mons, Pavonis Mons, and Arsia Mons are, respectively, about 65, 50, 45, and 140 kilometers in diameter.

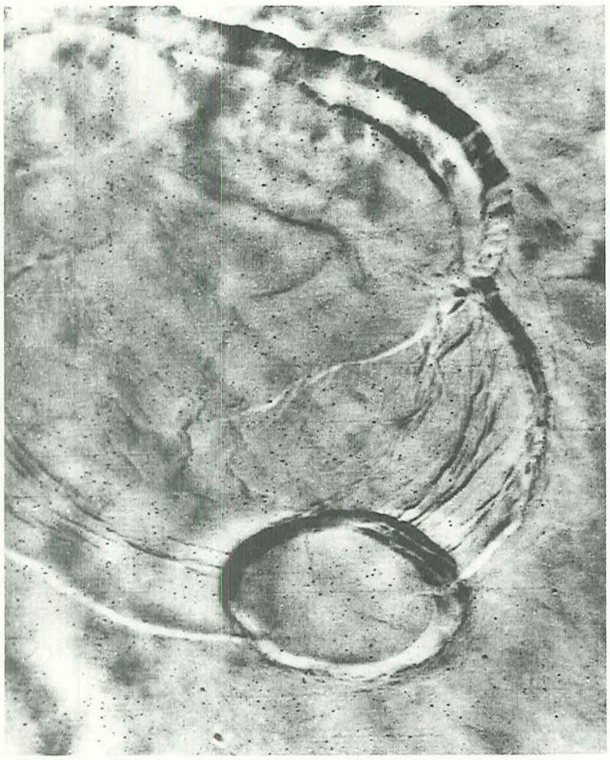
One possible explanation of the unusually large size of the Martian volcanoes reflects on recent geological theory about Earth. On Earth, it has been established that "plates," or discrete units in the crust, move with respect to each other, giving rise to the phenomenon known as continental drift. The Hawaiian Islands, for example, are believed to have been sliding over a "hot spot," or ascending hot plume in Earth's mantle, which provides the source of the volcanic lavas. Thus instead of producing one enormous Olympus Mons-sized volcano in the central Pacific, this plume produced the string of Hawaiian Islands and a string of still older extinct volcanoes and islands extending to the northwest from Hawaii. The explanation of the Martian volcanoes, according to this hypothesis, is that the Martian crust is not as active as Earth's, lacks significant motion among its crustal units, and hence allows a volcano to reside over a given magma source long enough for an enormous volcanic pile to accumulate. Supporting evidence for this idea would help to confirm the plate tectonic model of Earth's crust. This is one example of how the exploration of Mars by Mariner 9 has begun to illuminate large-scale problems of geology on Earth.

The association of the most prominent Martian volcanoes with the broad, domed Tharsis area prompts the search for other such associations. One other clear example is found in the region of Elysium, a circular, bright area about 1800 kilometers in diameter. This area was discovered to be a broad dome by radar altimetry studies from Earth in the midsixties. Ultraviolet spectroscopy altimetry from Mariner 9 confirms that the dome rises about 3 to 5 kilometers above its surroundings. Mariner 9 photographs reveal large volcanic cones on its summit. Hence the association of Martian volcanoes and broad domes is not a random one.

Other Martian volcanoes are scattered around the planet. One example occupies a relatively uncratered plain in the midst of the cratered terrain. Because of a set of radiating ridges that reach out petallike as far as 200 kilometers from the center, this volcano earned the nickname "dandelion." Its 15-kilometer central caldera is surrounded by a ring fracture about 45 kilometers in diameter and is connected by a channel to a similar-sized depression 35 kilometers to the southwest.

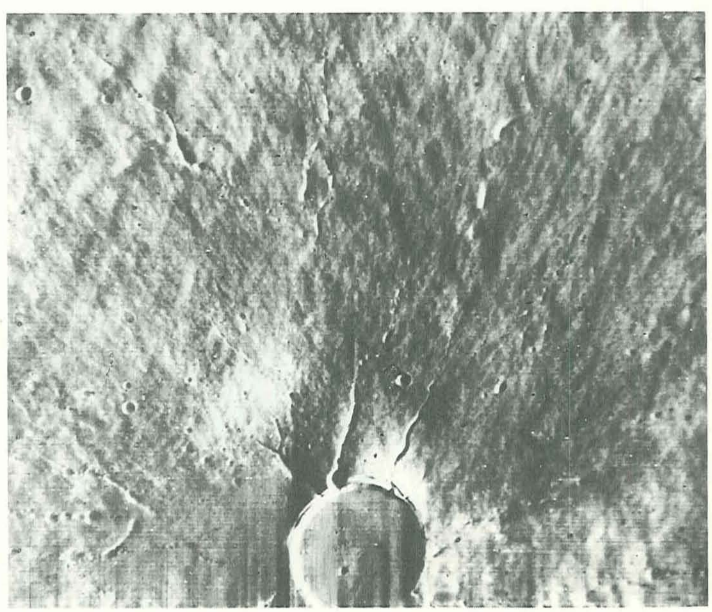
Surrounding most volcanic mountains of Mars are sparsely cratered plains that, as photographed with the high-resolution B camera, reveal the telltale characteristics of lava flows. These include flowfront scarps and lobate outlines, the same characteristics that allowed identification of the lava flows on the lunar mare plains prior to the Apollo landings.

The fact that the volcanoes, domed areas, and lava flows on Mars are sparsely cratered indicates that they are considerably younger than the more heavily cratered parts of Mars. If we knew exactly how many impact craters form per century in a square kilometer on Mars, we could date these structures. Only rough estimates of the cratering rates are now available, however. Mariner 9 analysts have suggested that these

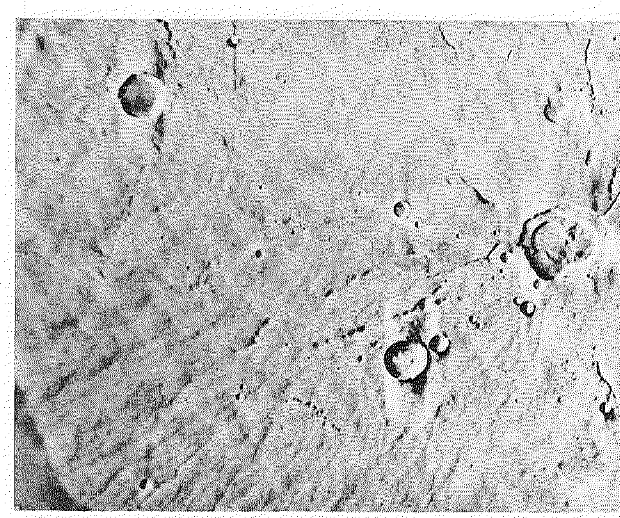


Summit caldera in the volcano Olympus Mons showing multiple fractures. (1406–164237)

Summit caldera in Kilauea volcano, in Hawaii, showing multiple fractures and smaller collapse pits analogous to those found in the Olympus Mons caldera. (U.S. Geological Survey)

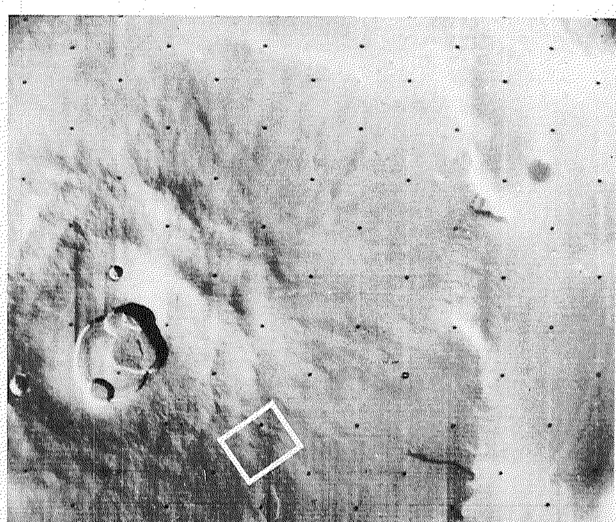


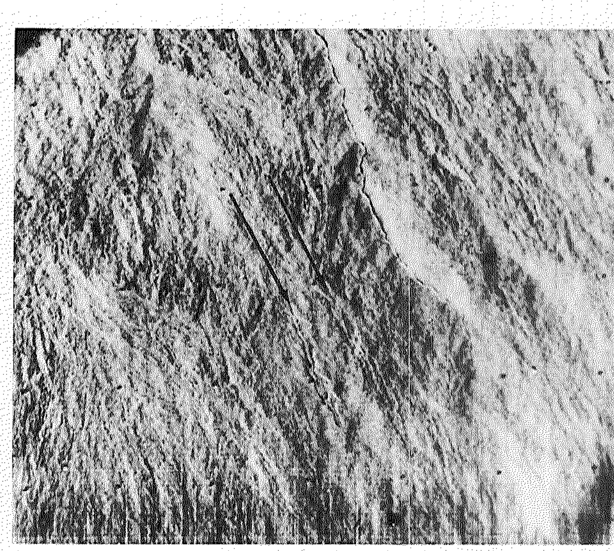
Summit of shield volcano in central Elysium dome showing summit caldera, radial lava channels, and fine striations from lava flows on flanks. (4298–39)

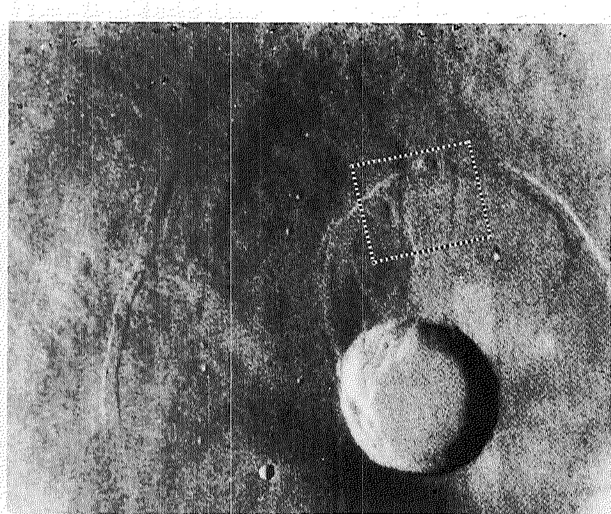


Volcanic pits on the surface of the domed volcano in the Elysium complex (210°, +31°) showing the 9-kilometer multiple-collapse caldera, radiating grooves, and crater chains. (4292–59)

Wide-angle (*left*) and telephoto (*right*) views of the flanks of Olympus Mons, showing the striated surface of the volcano. Arrows on lower picture show two long narrow lava flows running downslope, parallel to a narrow fissure. The width of the lower frame is about 55 kilometers. (Telephoto, 4133–96)





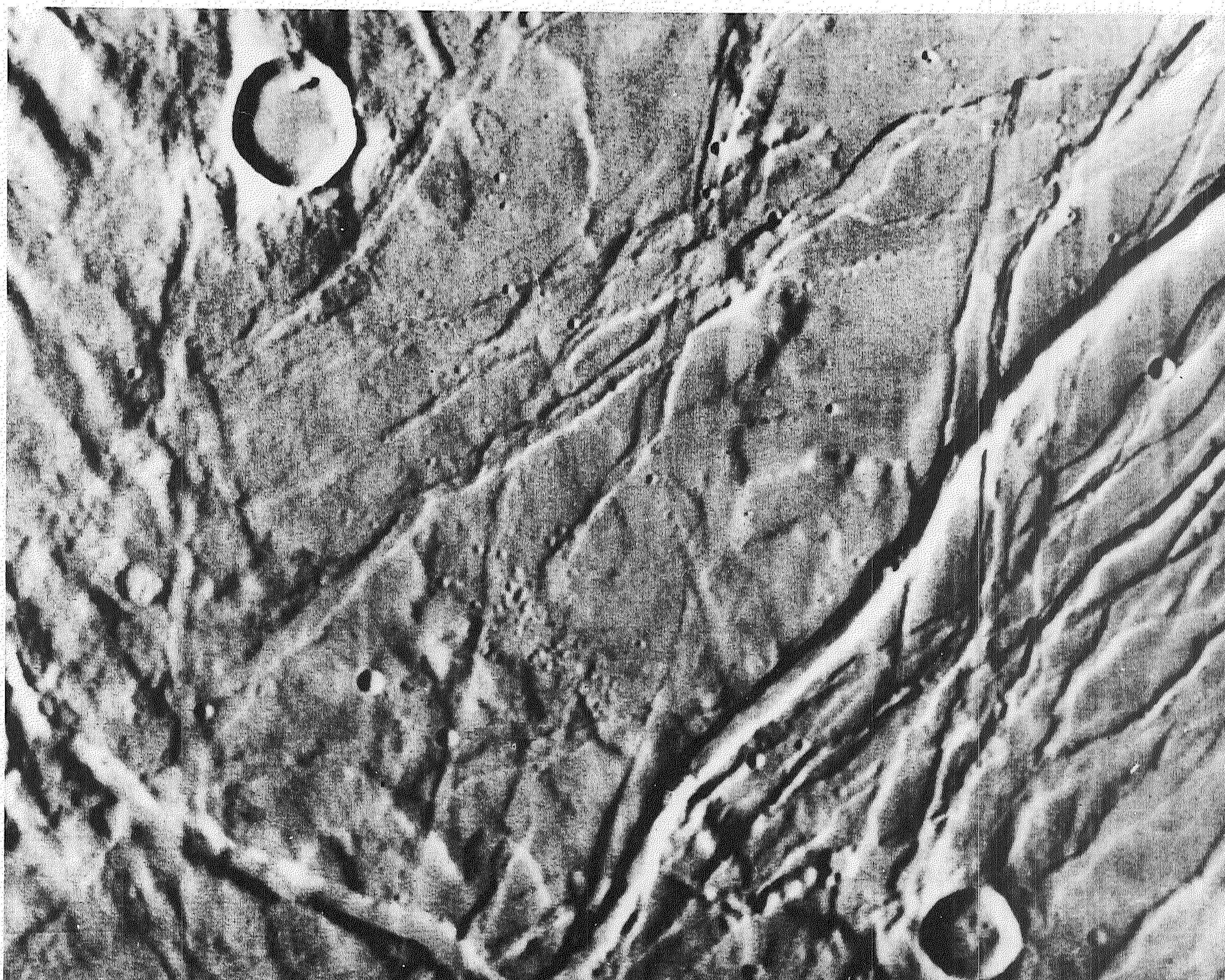


Ridges associated with summit caldera on the volcano Pavonis Mons. The telephoto view to the right shows the sinuous structure of the ridges, which resemble sites of extruded lavas found on the Moon.

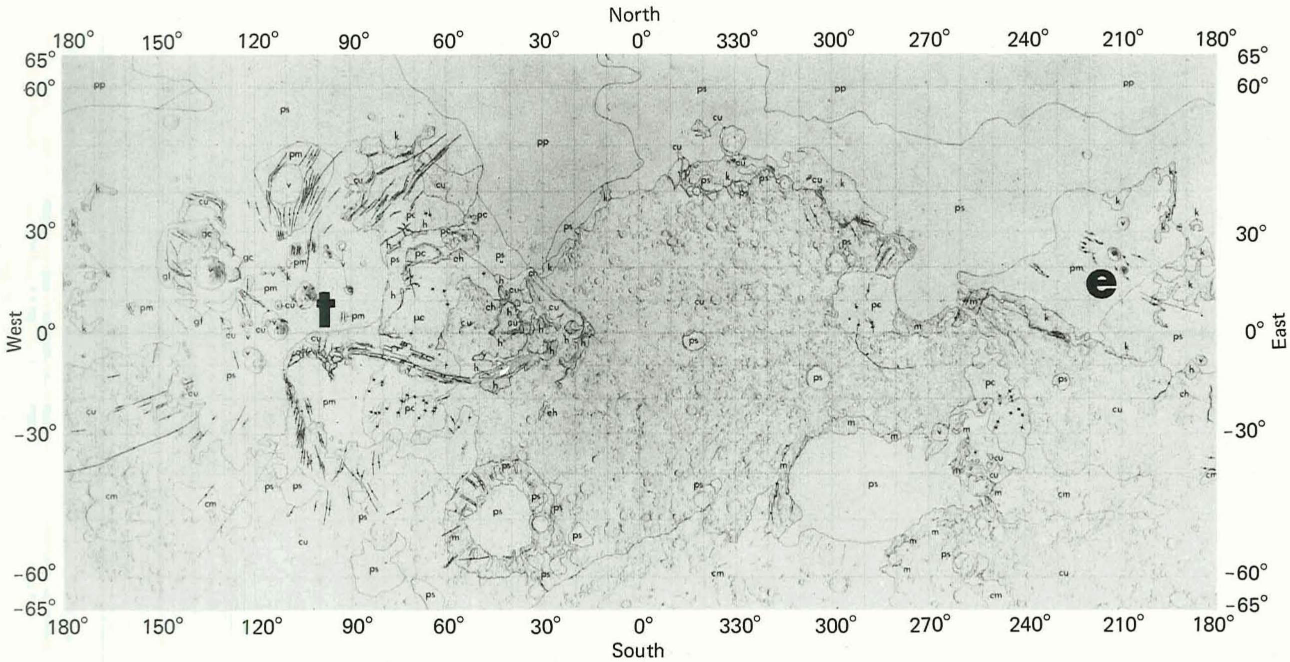
units can be dated in terms of hundreds of millions of years—about a tenth the age of the planet—and that the shield volcanoes such as Nix Olympica are the youngest of the structures. Some analysts have suggested that Mars is becoming more active, and has perhaps only in the geologically recent past heated up to a point promoting active volcanism.

Another type of structure associated with the volcanoes, domed areas, and lava flows is a pattern of fractures, faults, and other disturbances of the crust. Such tectonic structures form a vast radial pattern of fractures centered on the Tharsis volcanic dome and covering about a third of the planet. These radially alined fractures show an unusual degree of symmetry for a global phenomenon, and they point accusingly back to the center of focus of the disturbance that caused them. Because their center lies at the central highest point of the Tharsis dome, they strongly suggest that the same forces responsible for the uplift were responsible for shattering the crust in a radial pattern. Mars provides a second smaller example in the Elysium volcanic dome, which is also surrounded by a radial fracture pattern.

Among the radial fractures associated with Martian volcanic domes, by far the most spectacular is the set forming the great Coprates canyon complex, recently renamed the Valles Marineris. Prior to the Mariner 9 mission, Coprates was a name associated with an unremarkable, stubby, canal-like dark marking extending from the very dark patch Aurorae Sinus and forming one border of the "eye of Mars." the Solis Lacus region. (See maps in ch. II.)



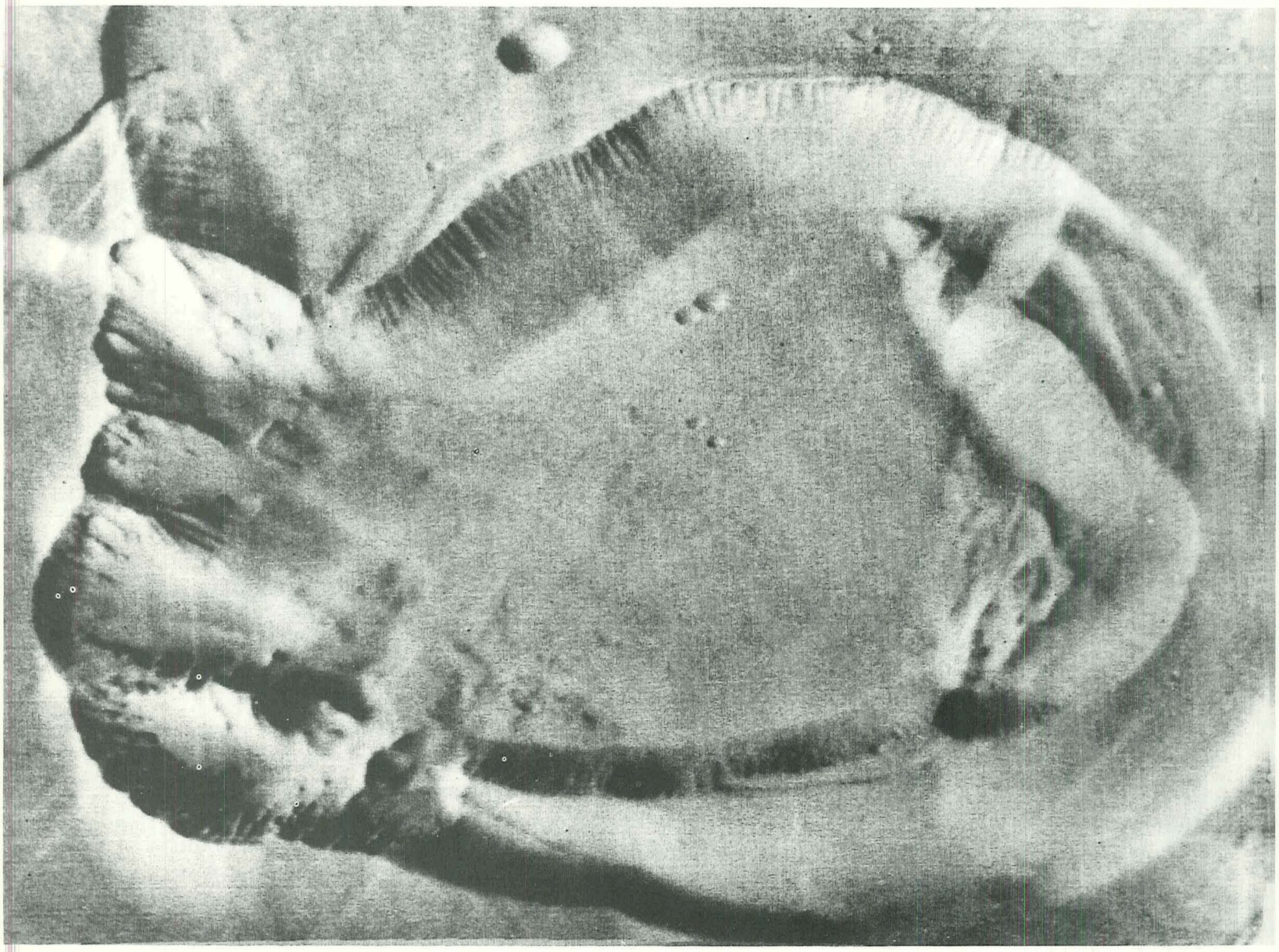
Fractured and faulted terrain about 2000 kilometers northeast of the Tharsis volcanic dome at 82°, +31°. (1434–180111)



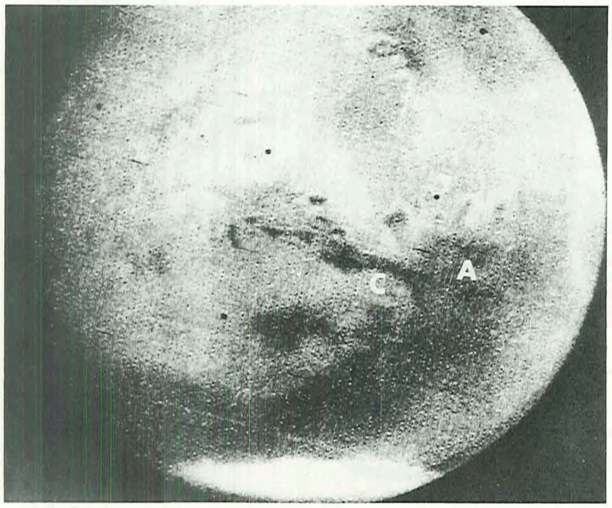
Geologic map of Mars indicating Tharsis (*t*) and Elysium (*e*) volcanic domed regions and associated radial fractures. Small letters show various geologic provinces, explained in chapter 11.

The "chaotic terrain," or jumbled craggy lowlands discovered by Mariners 6 and 7, lie at the east end of Aurorae Sinus, on a line with Coprates. As the 1971 dust storm cleared, Coprates became apparent not in its usual guise of a dark streak, but as a straight, bright, cloudlike band. As the atmosphere cleared, it became evident that this was a dust cloud lying in a deep valley. Finally the dust settled out of even this lowest part of the atmosphere, and the Vallis Marineris was revealed. The canyon can be traced in nearly linear band for 4000 kilometers from its latticelike, fractured western end to the very low, chaotic terrain at its east end, a distance of more than one-sixth of the planetary circumference. Numerous branching tributary canyons enter it. At its widest points it approaches 200 kilometers in width and its depth reaches as much as 6 kilometers (nearly 20 000 feet) below its rim, according to ultraviolet-spectroscopy-measured altitudes. For comparison, the Grand Canyon is only about 150 kilometers long, 6 to 28 kilometers in width, and about 2 kilometers (less than 7000 feet) in

(Continued on page 91)

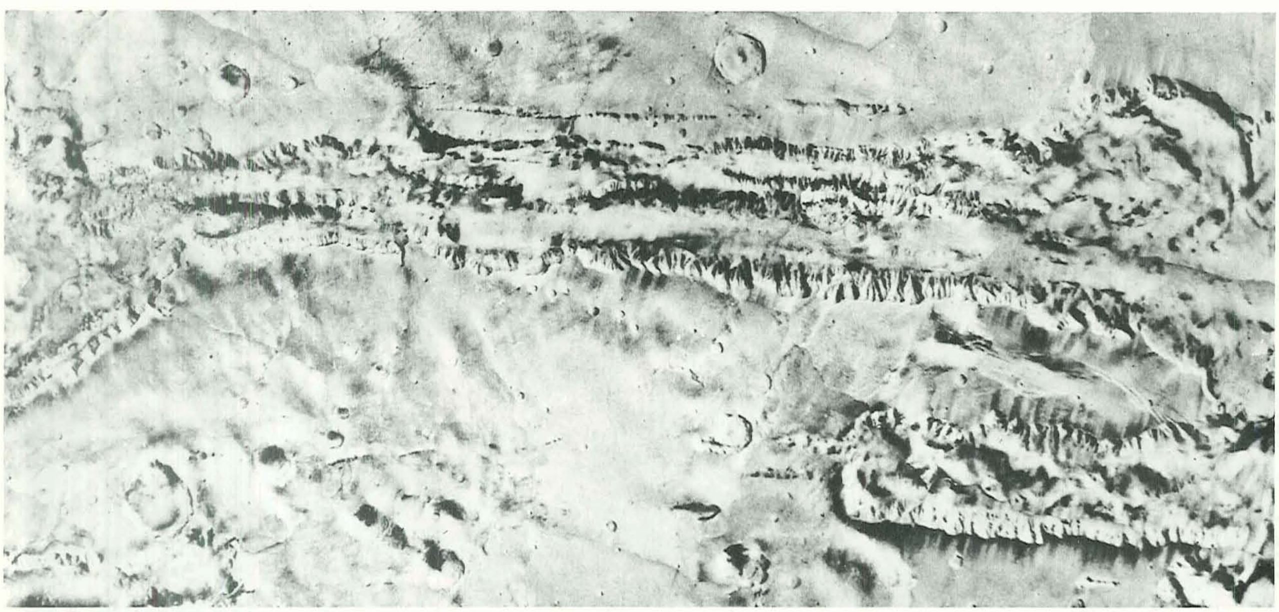


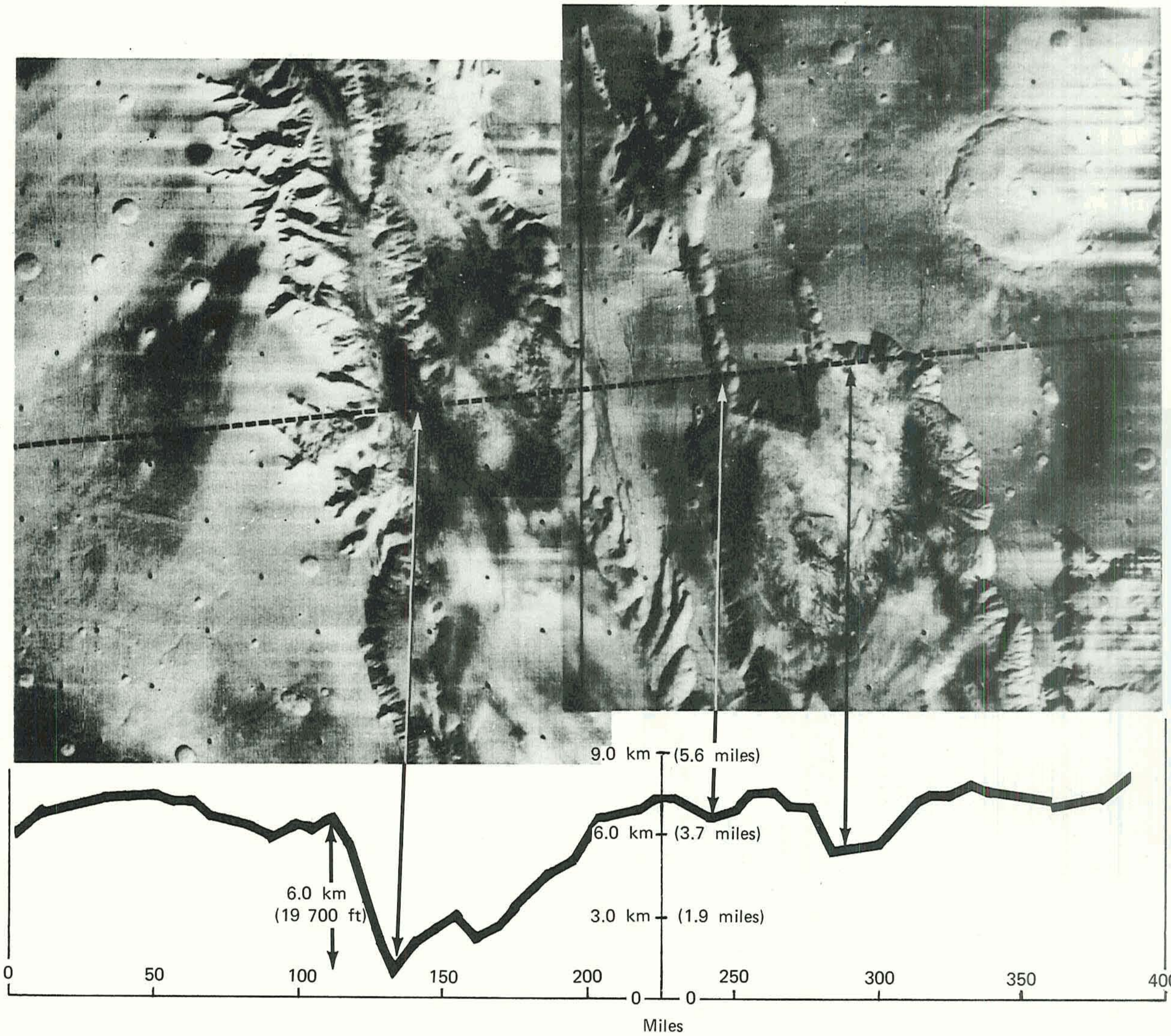
Caldera of a volcano located east of Ascraeus Mons at 91°, +14°. Rim displays upper fluted cliffs and lower talus slopes, as well as evidence of multiple collapse. The caldera diameter is approximately 60 kilometers. (1434–174452)



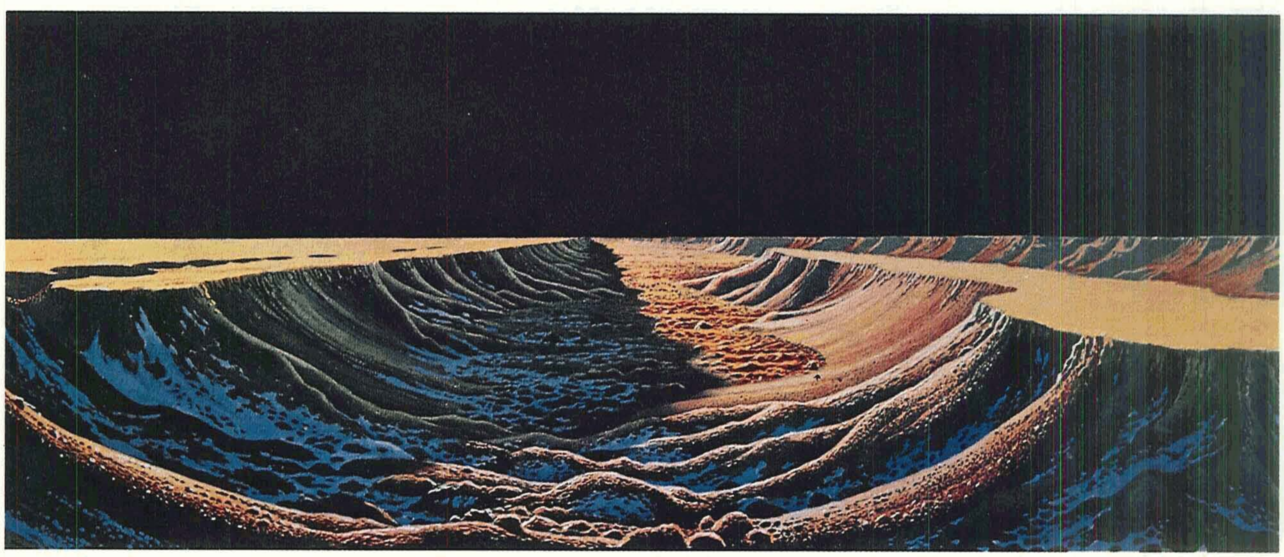
This view of Mars by Mariner 7 shows the dark stubby "canal," Coprates (*C*) extending from the dark region Aurorae Sinus (*A*). Mariner 9 revealed a great linear system of canyons, named Valles Marineris, in this area. The straightest portion of the canyon, apparently containing dark deposits (*C*), has been named Coprates Chasma.

Mosaic of the linear portions of Coprates Chasma. (Jet Propulsion Laboratory)

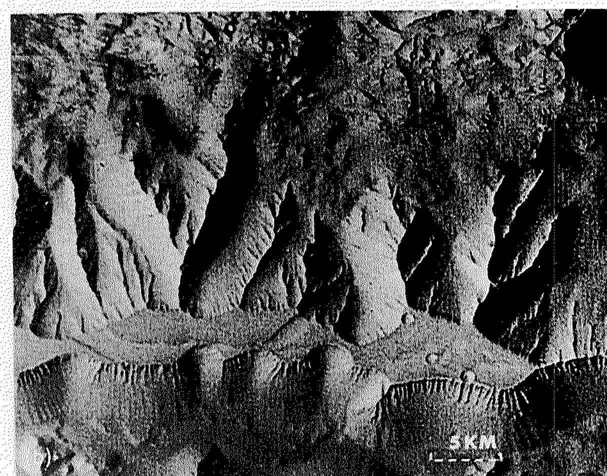




Elevation and horizontal dimensions in the Valles Marineris as mapped by the ultraviolet spectrometer pressure-mapping technique. (See also ch. XI.)



Artist's conception of a view along one of the canyons in the Valles Marineris complex. (Don Davis, Morrison Planetarium)

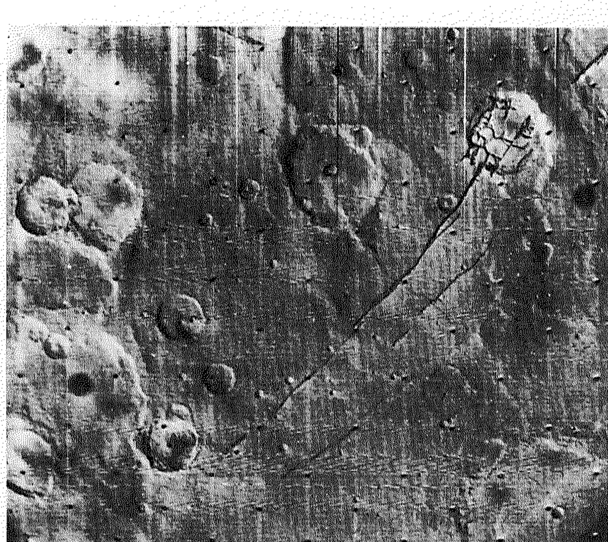


(*a*) A portion of the Valles Marineris, at 84°, −8°, showing the dendritic pattern of tributary canyons. (4144–87) (*b*) Detail from left side of (*a*), showing a plateau in the central part of the canyon. (4191–42)

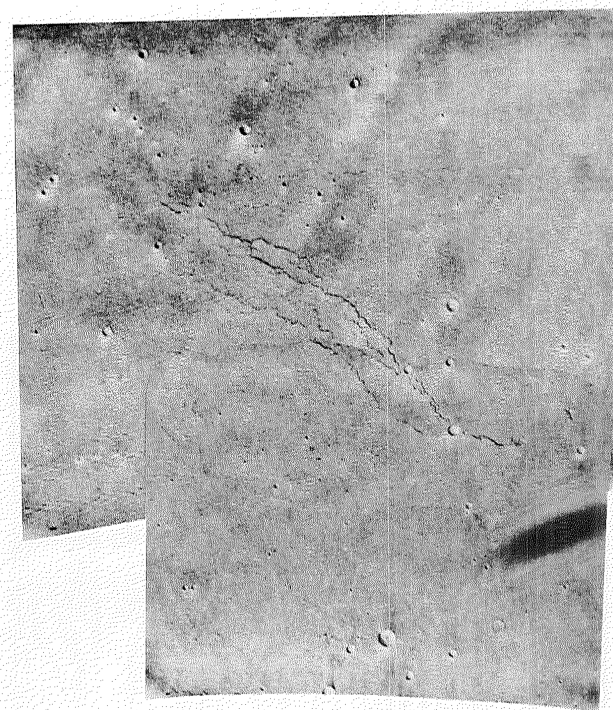
depth: the Grand Canyon of Earth would be only a tributary canyon to the grand canyon of Mars.

Whereas our first reaction is to compare the Martian canyon with our own Grand Canyon, the actual comparison suggests that the two are different species because they are an order of magnitude apart in dimension. Whereas the Grand Canyon has been cut by a river, the Vallis Marineris appears to be a tectonic rift in the Martian crust. It is thus more similar to the Red Sea (length: about 3000 kilometers including termination grabens, or fractured valleys; width: up to 400 kilometers; depth below rim: up to 2 kilometers) or the east African rift valley. These features are caused by updoming of the basement rocks and associated lateral fracturing of the crust to form long rift valleys, or grabens. The agents behind such terrestrial uplifts are believed to be slowly moving currents in the mantle below Earth's crust. In the case of the Vallis Marineris, the central axis is alined toward the center of the Tharsis dome, and the floor slopes downhill away from the dome center.

Just as the nature of the individual Martian volcanoes has shed light on the plate tectonics of Earth, so the large domes and radial faults that form their background also clarify terrestrial geology. Geologists analyzing the Mariner 9 material, including not only the photographs but also gravitational and altimetry data, have proposed that these patterns reflect activity in the

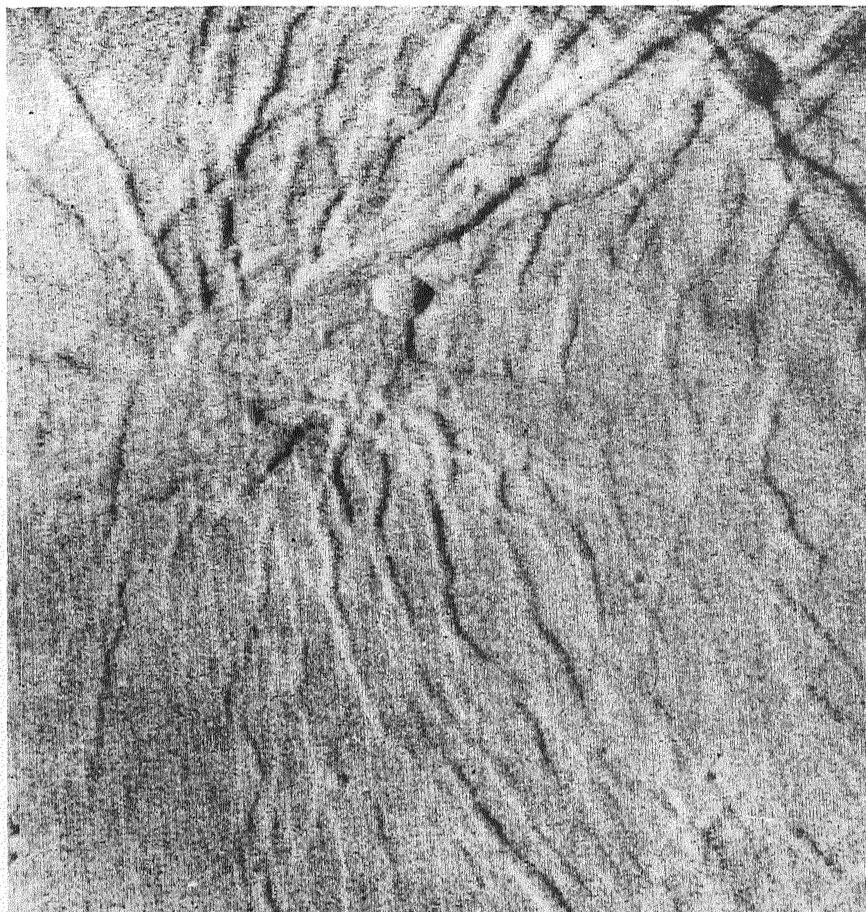


Fracture in Mare Sirenum. This frame shows nearly 500 kilometers of the fracture, the total length of which approaches 1800 kilometers. Adjacent fractures in crater floor (upper right) are unexplained but may relate to volcanism or interaction with permafrost layer in the crater floor. (4174–27)



Fractures in a sparsely cratered plain at 137°, +20°. Dark spot at lower right is the shadow of Phobos; i.e., the site of a solar eclipse. (See ch. XII.) The length of the fracture is approximately 480 kilometers. (211–4622B)

Arcuate ridge (near 84°, −24°) south of Valles Marineris complex. Several kilometers wide, the ridge resembles sites of lava extrusion on the Moon. (211–4644)



The "elephant skin" fracture complex near the west end of the Valles Marineris canyon complex, near 109°, −17°.

mantle and crust of Mars. They believe that horizontal motions in the Martian crust are not as great as in Earth's crust because Mars does not display the crumpled and folded mountain belts, such as the Rockies, Andes, and Himalayas, that mark terrestrial sites where crustal plates collide. On the other hand, the Martian patterns suggest a sort of incipient plate tectonics in which ascending hot currents in the Martian mantle disrupt the crust and cause volcanism, but perhaps do not last long enough to cause full-fledged horizontal drifting of crustal blocks.

The beauty of the Martian evidence is that Mars has no oceans to mask the deepest rifts in its crust. Thus Mars presents a plain display of the results of forces that terrestrial geologists have speculated about and glimpsed with great difficulty by means of complex deep-sea experiments. One of the main results of the Mariner 9 mission—unexpectedly—is thus likely to be a tying together of many loose ends left in terrestrial geology by the revolution of the last decade, when, in the face of new evidence, the view of continents as fixed, near-permanent rock units gave way to a view of changing, colliding crustal blocks driven by forces deep in Earth's mantle.

CHAPTER VIII

Channels and the Evidence for Ancient Rivers

. . . there must be rivers on Mars. . . . The mere existence of continents and oceans on Mars proves the action of forces of upheaval and of depression. There must be volcanic eruptions and earthquakes, modeling and remodeling the crust of Mars. Thus there must be mountains and hills, valleys and ravines, watersheds and watercourses.

—R. A. PROCTOR, 1871

. . . spectrographic results and the . . . indications derived from the polar caps . . . agree in pointing to a much higher degree of dryness in the bright equatorial regions of Mars than in the most arid terrestrial deserts.

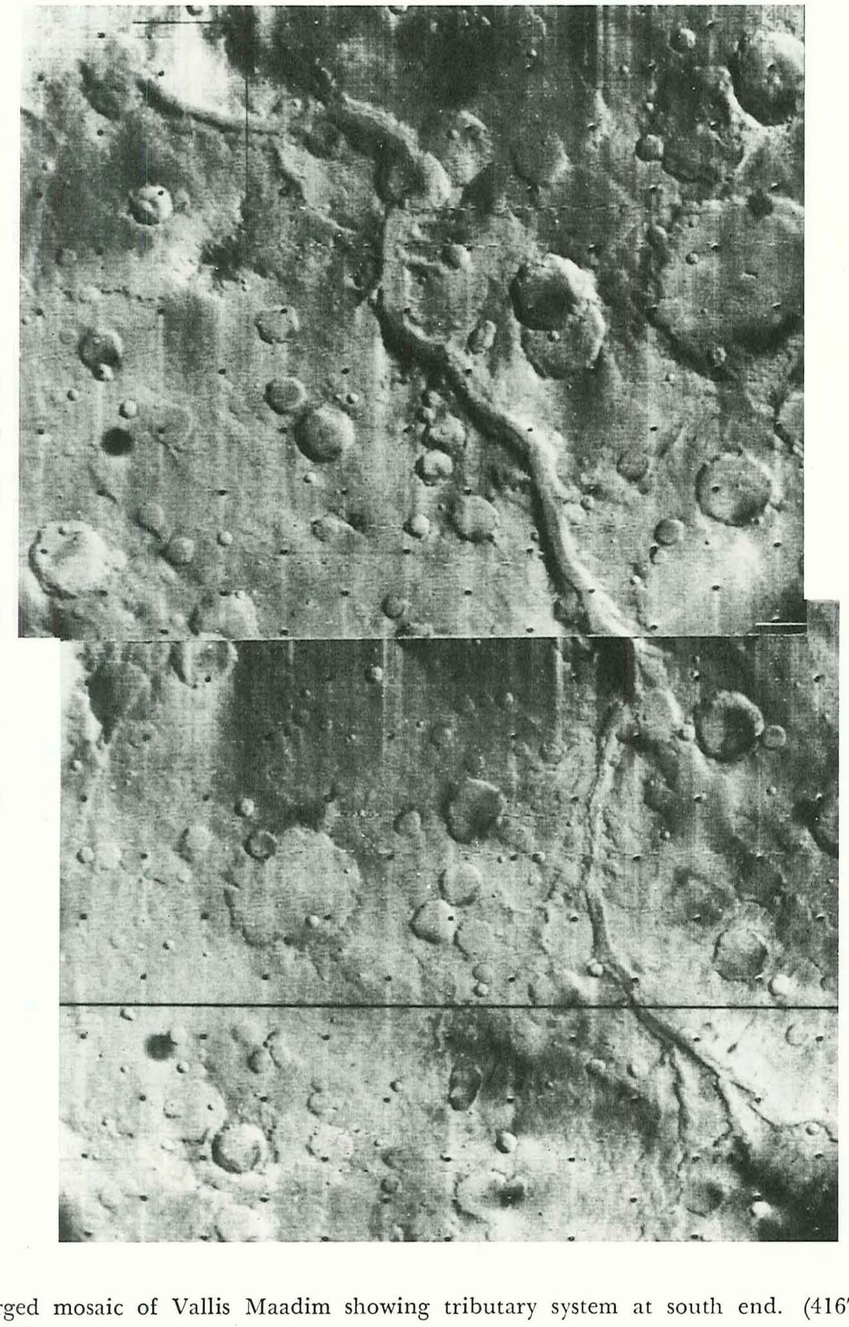
This extreme desiccation is in excellent agreement with the whole body of observations. . . .

—G. DE VAUCOULEURS, 1954

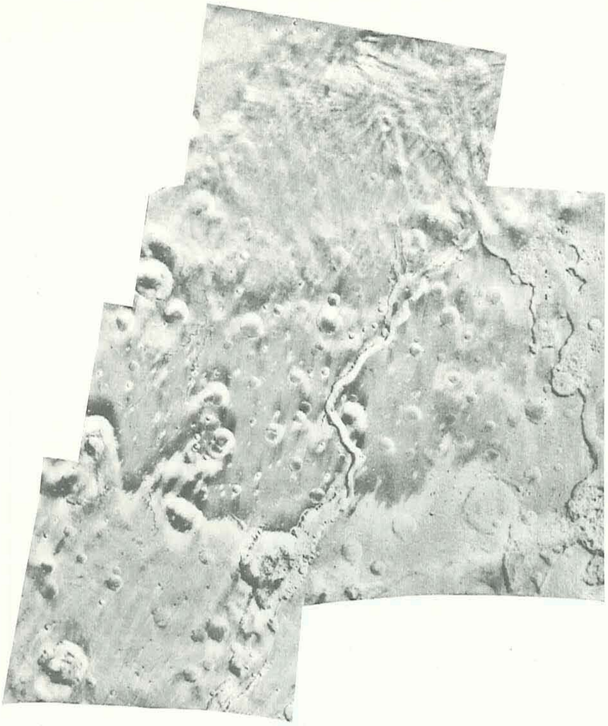
In terms of fitting Mariner 9's new information to pre-Mariner 9 information, the most astonishing discovery was that of widespread channels that bear every conceivable resemblance to dry riverbeds. They are not the linear "canals" that were once shown on maps nor do they coincide with them except in a few instances; rather, they are prominent, meander sinuously, and include short branching tributary systems. The idea that these really are riverbeds seems at first glance to fly in the face of all information about the current state of Martian climatology. As for present-day conditions, de Vaucouleurs was right in the introductory quotation. For example, the total amount of water vapor in the Martian atmosphere is so small that if all the water on a typical day precipitated in the form of rain, it would make a layer only 0.002 to 0.005 centimeter deep according to Earth-based and Mariner 9 infrared interferometer spectrometer data. Furthermore, if water did accumulate by some means, the pressure of the air is so low and the temperature so cold that in most regions of Mars it would spontaneously boil away or freeze. This behavior would occur in all regions having elevation higher than the Martian reference level, which has an atmospheric pressure of 6.1 millibars.

This particular pressure, whether on Mars or elsewhere, is the so-called triple-point pressure; it is the minimum pressure at which liquid water can exist in equilibrium with its gaseous vapor. Thus at lower pressures it boils or freezes, depending on the temperature; at higher pressures it can exist as a liquid in equilibrium, but it evaporates if the atmosphere is dry enough. At exactly 6.105 millibars and 273.01° Kelvin (32° Fahrenheit), the three phases of water—gas, liquid, and solid—can all exist together in equilibrium; hence the name "triple point."

Locations on Mars at elevations below the reference level at 6.1 millibars—i.e., locations with greater atmospheric pressure—could have liquid water that would not spontaneously boil. Nonetheless, temperatures above 273° Kelvin would be required for liquid water, and such temperatures exist only on the warmest afternoons in summer near the equator. If liquid water does occur, evaporation could be rapid, depending on the local temperature and water vapor pressure in the atmosphere. According to calculations by physical chemist C. B. Farmer, the evaporation rate under summer afternoon

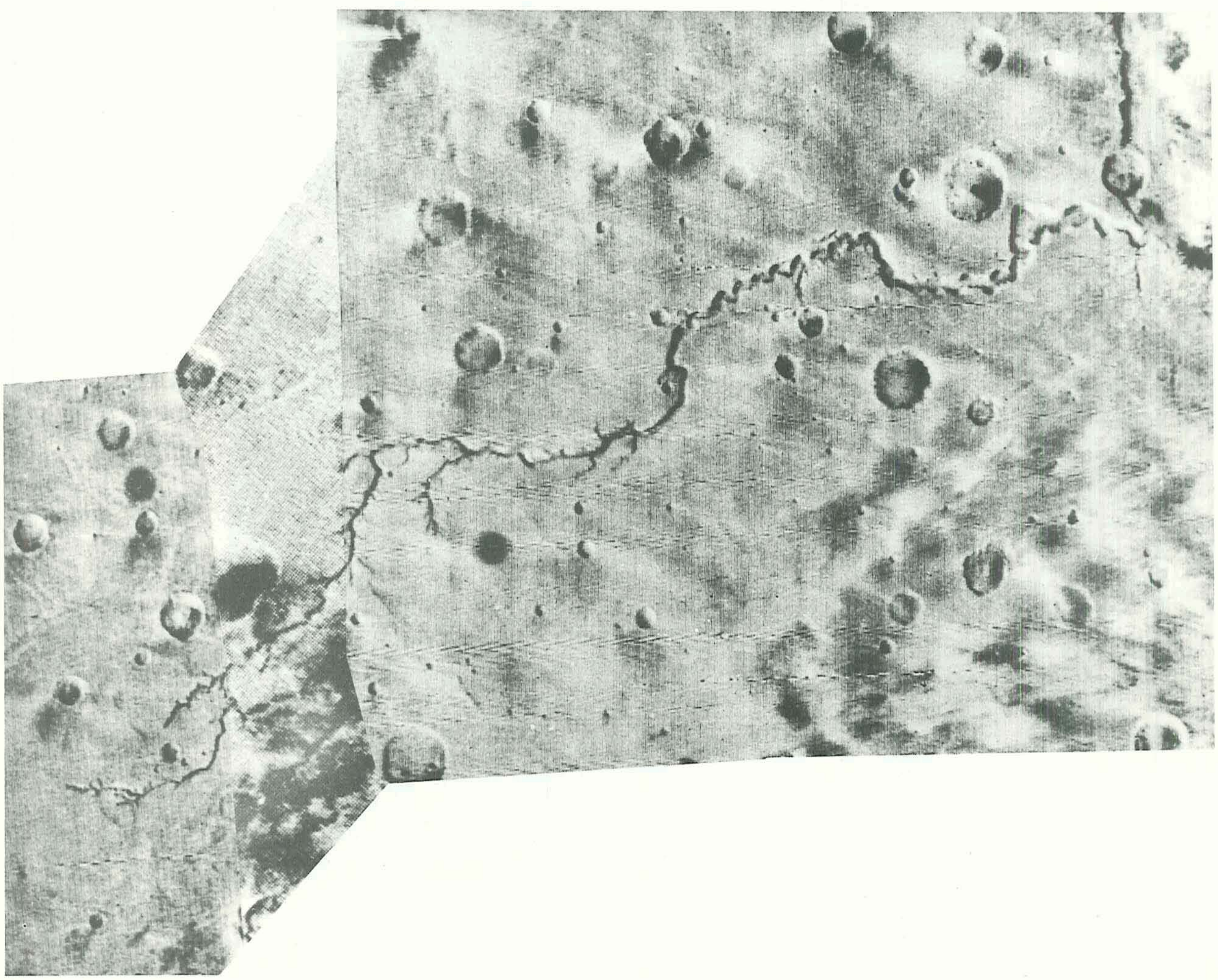


Enlarged mosaic of Vallis Maadim showing tributary system at south end. (4167–18, 4167–24)

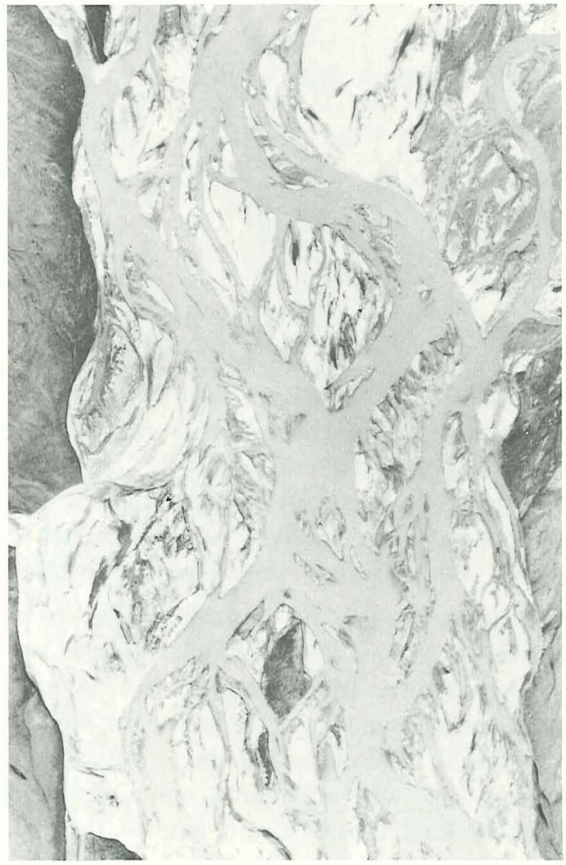


Channel in Xanthe-Chryse area near 45°, —5° named Vallis Shalbatana. Downhill slope is north (*top*) toward low region of Mare Acidaleum. Note finer sinuous channels, left. The length of the channel is about 1200 kilometers. (Jet Propulsion Laboratory mosaic, 211-4646)

Enlarged mosaic of Vallis Nirgal in Mare Erythraeum showing details of the tributary system and central meandering portion.



Telephoto view of braided channels associated with Vallis Mangala, in the Amazonis region near 150°, —6°. Such deposits are normally attributed to sediments dropped during meandering stream flow. North is at top; each frame measures about 30 by 40 kilometers. (4258–35; 4258–39)



Terrestrial example of braided deposits in the Sagavanirtok River, Alaska. Note truncated downstream ends of bars (flow toward top). Compare with Martian example at left. The width is 2 kilometers. (U.S. Navy photograph BAR 2830955, U.S. Geological Survey)

Martian temperatures would be about 2 centimeters per hour. A foot-deep rivulet might evaporate between dawn and dusk even in those parts of Mars where liquid water is favored.

So the proposition of rivers on Mars was greeted with skepticism on two counts: it seems to require a miracle to get large volumes of water on the surface of Mars and it seems to require another miracle to keep the water there long enough to erode a river channel.

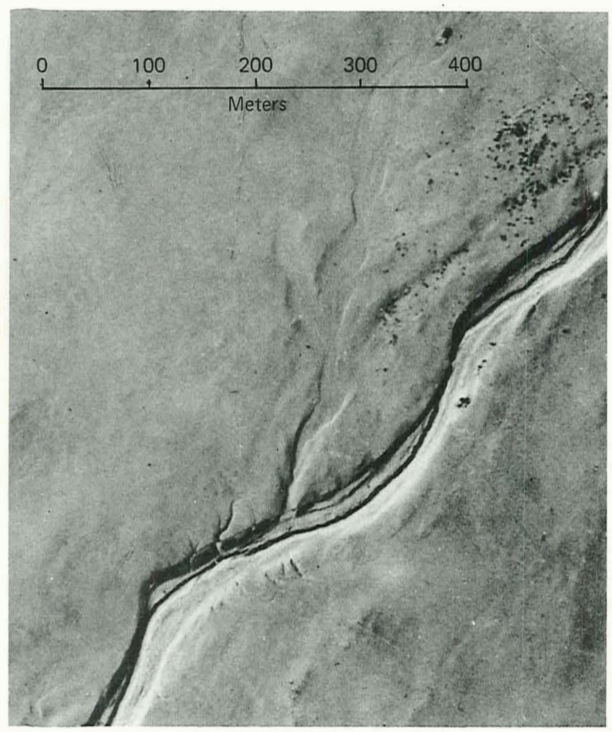
Faced with this dilemma, the initial reaction of Mariner 9 scientists was to consider the alternatives. Could lava flows cut the channels? The braided deposits in their floors suggested that the fluid carried sediments unlike lavas, and the channels were not limited to highly volcanic terrains. Could the channels be cut by some liquid other than water? No suggestions were forthcoming on what such an abundant liquid could be; liquid carbon dioxide, for example, would require five times the atmospheric pressure that exists at Earth's surface. Could they be cut by some sort of exotic fluidized suspension of dust particles in the wind? In terrestrial volcanic eruptions of a certain type, the hot volcanic gases can trap fine ash particles creating a fluidlike mass that flows down mountainsides and spreads across plains. Such a mass—known as a *nuee ardente*—was responsible for destroying the city of St. Pierre, Martinique, with the loss of 30 000 lives in 1902. Such systems, however, are not known to erode winding riverlike systems with tributaries. In view of the low atmospheric pressures on Mars and the lack of good terrestrial analogs, the hypothesis of windcut "river channels" seemed unsupportable.

The more careful the scrutiny of the channels, the stronger the conviction became that they were similar to dry arroyos cut by sediment-carrying waters in terrestrial arid regions. For example, the major channel crossing the Amazonis area, west of Tharsis, contains a complex of braided channels and bars of the type that develop when sediments build deposits in meandering rivers and subsequent meanders of the flowing channel then cut across the already formed bars. Named Vallis, this channel as a whole is about 350 kilometers in length and consists of a complex of individual channels. Geomorphologists studying the orientation of the streamlined and truncated bars in the channel suggest that the flow direction was from south to north. A similar situation applies in the channel complex of the Chryse region, east of Tharsis. The flow direction appears to run about 1200 kilometers from the chaotic terrain at the east end of the Vallis Marineris toward the broad featureless plains near Mare Acidalium. This is consistent with the altimetry data in the area, which show that the latter regions are lower than the former, although such evidence is not conclusive because crustal deformation might have altered the topography since the channels formed. The geomorphological analysis of the channels indicates that they were cut by a high-density, low-viscosity, sediment-carrying true liquid confined to the channel. Water appears to be the only acceptable possibility.

With flowing water as the only viable hypothesis to account for the channels, and with no evident contemporary source of surface water, analysts turned to consideration of conditions in the past history of Mars. In addition to the mere existence of the channels, there are several other indications that the past climatology of Mars might have been more conducive to river formation than the present climatology. First, subtleties of impact crater distribution and morphology suggest greater rates of erosion and deposition in the past than at present. The few examples of craters superimposed on channels indicate that they formed in the past but not in the extremely distant past. Also, the low temperatures prevailing on Mars now mean that large amounts of water would, if they existed, be mostly frozen somewhere on the planet. "Somewhere" could mean in the permanent polar caps, in mixed layers of dust and ice deposited in the polar regions (which are observed to contain layered terrains—see later chapters), buried widespread ice deposits resembling permafrost deposits in terrestrial tundra, or other unknown forms of ice deposits. In support of this, spectrophotometric data from Earth-based observers such as T. McCord, A. Binder, J. Houck, and others have led to suggestions of water frosts mixed with Martian surface soils, perhaps to about 1 percent by weight. Also, theoretical work such as that of F. Fanale suggests abundant water should be available on Mars.

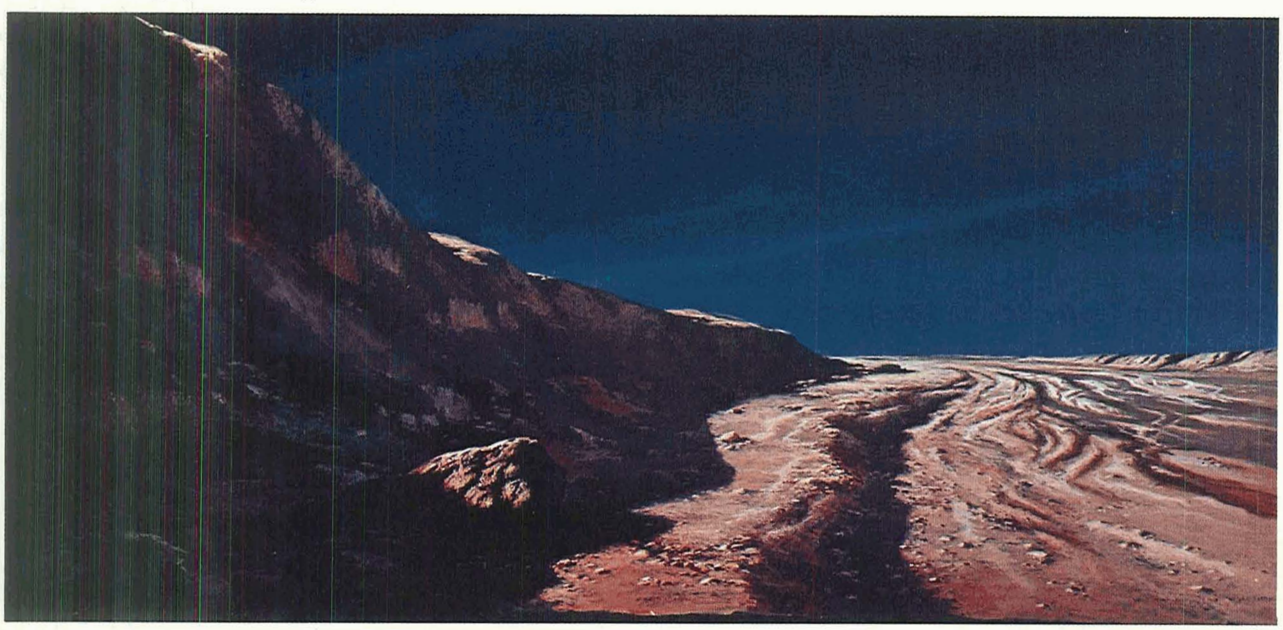
The permafrost hypothesis is supported by the existence of the Martian chaotic terrain, which

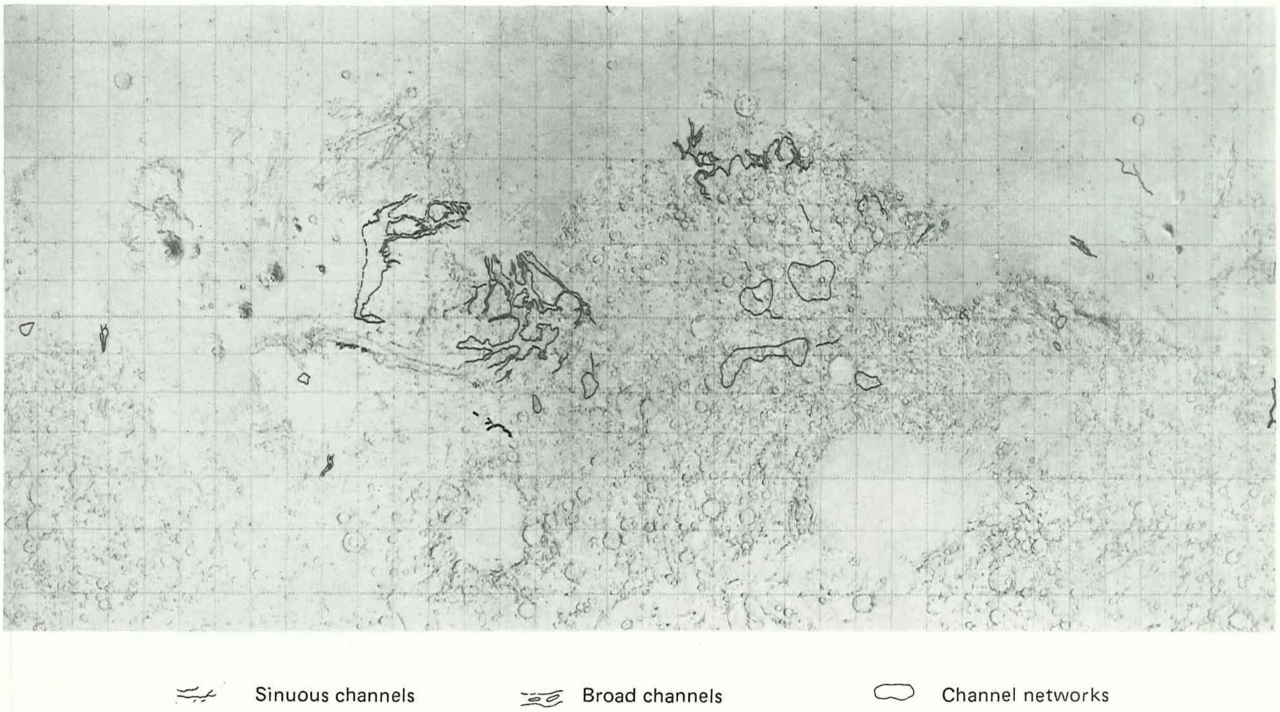
Tributaries to a channel in Moab, near 339°, +31°. The width of the channel is about 5 kilometers. (1417-221824)



Terrestrial example of a channel cut in an extremely dry region in the coastal desert of Peru. Typical of arroyos in arid regions is the stubby tributary system and multiple channel pattern on the arroyo floor. (U.S. Geological Survey)

Artist's conception of the appearance of a Martian channel showing braided deposits. (Ludek Pesek, © 1973, National Geographic Society)



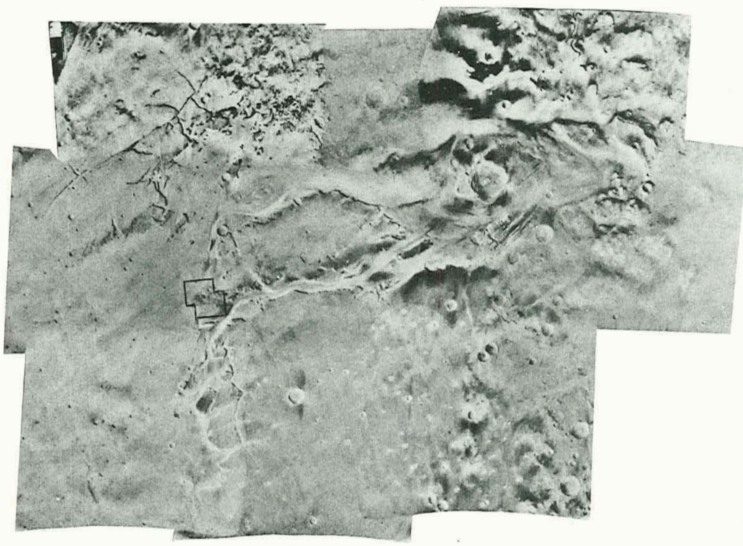


Distribution of channels on Mars showing classification into three general types.

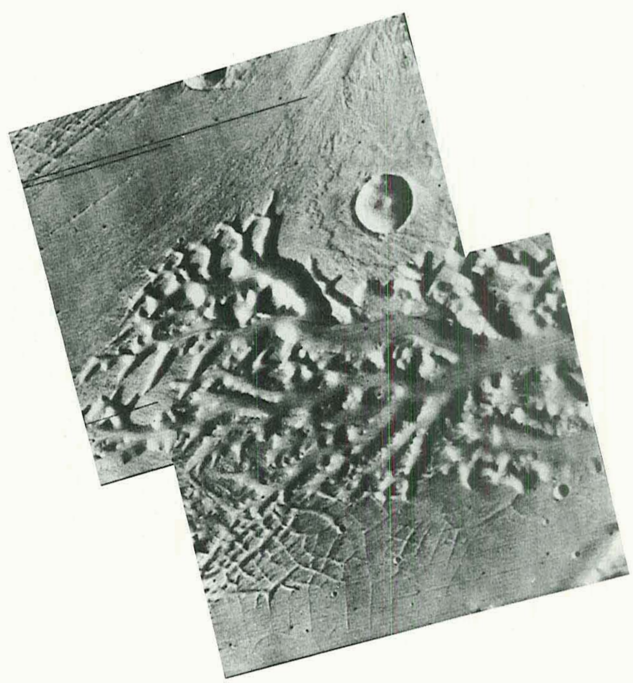
resembles collapsed, rugged terrain produced when deposits of subsurface ice melt by some source of heat, such as local volcanic or geothermal activity, or seasonal or secular climatic warming. Such collapsed areas appear on a much smaller scale in arctic regions of Earth and are known as thermokarst topography—from the term "karst," referring to a collapsed pit. This explanation of chaotic terrain, which was first suggested by geologists R. Sharp, L. Soderblom, B. Murray, and J. Cutts in their analysis of Mariner 6 and 7 photographs, is further strongly supported by the fact that the Martian "river channels" frequently appear to emanate from the regions of chaotic terrain. One is led to speculate that under some warming condition in the past, underground permafrost melted, causing collapse of surface layers and release of a flood of water that rushed over the surface, cutting channels through loose, windblown deposits.

Mariner 9 geologists and geomorphologists who have studied the structures at the edges and "sources" of the channels have pointed to fractured and slumped terrain that suggests not only stream cutting and collapse from below but an additional process known as ground-water sap-

Gullied slopes on a volcano in Alba, near 116°, +45°. The dendritic pattern is similar to erosion patterns on alluvial slopes in arid terrestrial regions. The frame width is about 60 kilometers. (4182–96)



Channel complex in Lunae Palus, near 65°, +22°. Flow direction is east (*right*) toward the Mare Acidalium area. Note isolated fractures and chaotic terrain in northwest. Box marks location of additional fractured terrain shown in telephoto view below. (Jet Propulsion Laboratory mosaic 211–4653)



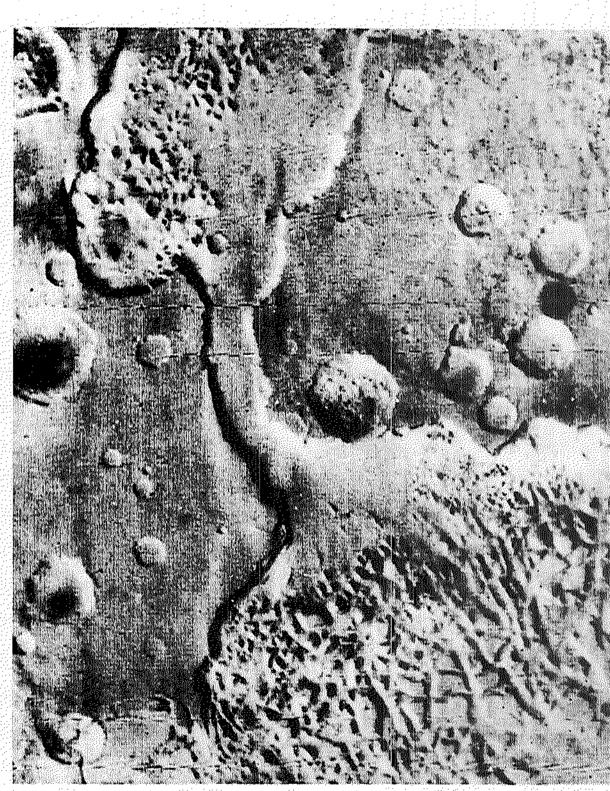
Dendritic canyon and fracture system near west end of Lunae Palus channel, near 73°, +22°. The pattern suggests extension of the canyon along fractures widened by removal of material. Note ejecta blanket of crater, upper right, which has withstood erosion. The frame width is about 50 kilometers. (4297–8, 4297–12) ping. This occurs when ground water seeps directly toward and out of the exposed valley walls, causing slumping of the ground. Thus the channel expands by having its walls cut back, instead of only downward. A variant of this process, perhaps more applicable to contemporary Mars, is ground *ice* sapping. In this process, a permafrost layer of underground ice, exposed by any mechanism such as river channeling or faulting, begins to sublime or melt. This releases entrained gravel and causes a void; the associated cliff face collapses, exposing new ice. If the rubble is continually removed by wind or water, the process continues and the cliff or channel wall continues to retreat. It has been suggested that large areas of Mars have been denuded and reduced to low elevation by this process, which may have widened channels or chaotic terrain since the rivers last contained liquid water. An example of a region where this may have occurred is the west-facing cliff face bordering the channel at the east edge of the Tharsis region.

The shape of several other Martian channels supports the idea that they are enlarged by ground water or ice sapping. For example, several of the "small" tributary canyons to the great Vallis Marineris are similar in size and appearance to the Grand Canyon of the Colorado River. Each has stubby side canyons ending at steep headwalls. The Grand Canyon is known to involve ground-water sapping by artesian springs that undermine the headwalls; a similar process may cause the similar forms on Mars. A long narrow channel of quite different form occurs on Mars in the Rasena region. In its lower reaches it resembles the sinuous rilles of the Moon, believed to be the channels of lava flows that have formed not so much by excavation as by processes involving the solidification of lava at the walls of the flow. In its upper reaches, the Rasena channel has tributaries like those of other Martian channels and distinctly unlike any lava flow features. The tributary system again suggests water flow (unlike volcanic flows that generally have a discrete source), but the analogy to molten lava/solid rock interfaces again suggests liquid water running through ice layers, with associated ground ice sapping.

Mariner 9 geologists have noted that many Martian channel systems seem immature and discordant with their local terrain, suggesting sporadic catastrophic flooding rather than gradual, smooth evolution. On Earth, such channels may arise in arid regions where infrequent major floods accompany local downpours. Another example is the most violent known flood, produced during the prehistoric catastrophic discharge of Lake Missoula, whose ice dam broke, releasing a torrent 70 times the average discharge rate of the Amazon River. This torrent produced the Mars-like erosional landform known as the Channel Scablands in the State of Washington.

Clearly we have passed from the realm of direct photographic discovery to a realm of difficult interpretation by analogy and inference. Mariner 9 analysts believe they have located important pieces of the channel puzzle—flowing water, past warmer climates and greater atmospheric pressure, ground ice or permafrost, removal of debris by water or wind, and sporadic flow—but the pieces have not yet fallen into place to produce a satisfying picture.

Association of Vallis Simud channels and chaotic terrain, near Chryse, centered near 35°, −4°. The frame height is about 1250 kilometers. The lower part of the frame includes the east end of the Valles Marineris complex. (Jet Propulsion Laboratory globe)



Detail of channel near Chryse near 32°, −3°, showing association with chaotic terrain. The frame height is about 480 kilometers. (7350–165312)

The clues go far beyond the striking suggestion that Mars was more Earth-like in the past. They raise the questions of the cause of the changes of climate, of whether there was one or more changes, and of whether the changes were long-term slow changes or sudden catastrophic changes. These questions have stimulated much theorizing about Mars. For example, studies of the small uneroded craters, in contrast to the large eroded craters, suggests a geologically sudden transition from past erosive conditions to present less erosive conditions on Mars. More exciting is the fact that these questions may reflect on ancient terrestrial conditions.

An approach to the problem lies in the origin and atmospheric behavior of the water on Mars and Earth. How did the atmospheres and water content of Earth and Mars originate? It is widely believed that a massive primitive atmosphere of gases such as hydrogen, methane, and ammonia must have been left after planet formation. This atmosphere is believed to have dwindled over a

Association of channels, fractures, and chaotic terrain along contact between cratered regions (bottom) and northern plains (top), near 295°, +33°. Note fractured crater floor, lower right. The frame width is approximately 1260 kilometers. (Jet Propulsion Laboratory globe)

These gullied slopes, on the flanks of the volcano Alba Patera, at 116°, +45°, form the best-developed dendritic drainage system on Mars. Such patterns resemble erosion on alluvial slopes in arid terrestrial regions. The frame width is about 60 kilometers. (4182–96) period of time because the light hydrogen atoms easily escape, but simultaneously the atmosphere was replaced by gases exhaled from the planetary interior through volcanoes. The most common of such gases on Earth are water vapor and carbon dioxide, according to chemical analysis of volcanic gases. On Earth, the water vapor has ended up in liquid oceans, polar caps, and the air; and much of the carbon dioxide has been dissolved in the oceans and found its way into carbonate rocks. These observations suggest a possible explanation for the great amount of carbon dioxide in the Martian atmosphere and at the same time suggest that there ought to be water somewhere on Mars if the atmosphere was so produced. Where is this water now, and what is its relation to the channels?

One line of reasoning advanced by some Mariner 9 analysts is that the youthful volcanoes of Mars, such as Olympus Mons, indicate that the interior is becoming more active (perhaps as heat from radioactivity builds up, as on Earth) and that volcanoes are now building a new atmosphere through their exhalations. Conceivably, bursts of volcanic activity might add enough water vapor to cause precipitation and eventual channel formation. Subsequently the water might be trapped in the form of ice at the polar caps or in underground permafrost. Between volcanic eruptions (the current condition) there would be no appreciable liquid water available.

Another line of reasoning, proposed by other Mariner 9 scientists, involves the possibility of releasing all the frozen materials in both polar caps at once. Even prior to the Mariner 9 mission and the discovery of the riverlike channels, C. Sagan speculated in 1971 about the possible consequences if both caps should simultaneously melt, perhaps because of changes in the Martian seasonal patterns due to Martian precession. Early studies suggested that the atmospheric pressure and temperature would then rise because of the release of frozen CO_2. Recent studies suggest that the pressure might reach 0.1 to 1.0 bar, compared to 1.0 bar on Earth. If much water were so released, it could thus exist in liquid state for appreciable periods.

Spurred by Mariner 9 discoveries, recent studies have focused on possible sources of past climatological variation that might allow melting of both caps. These can be divided into two groups: variations that would affect only Mars and variations that would affect the other planets including Earth.

In the first group were discoveries by dynamicists working with the Mariner team of several periodic variations in the Martian orbit. These would cause changes in the input of solar energy on Mars, but it seems doubtful that these changes could be large enough to radically affect the Martian climate, and they appear to occur on too short a time scale to explain Martian features. For example, variations in Martian eccentricity affect the temperature with 95 000-example of another change would be a deposit of dust on the polar caps causing the polar reflectivity to remain low for many decades. In this case the absorption of sunlight by the caps would be increased and the caps might sublime or melt, increasing the atmospheric pressure.

However, because the caps receive a fresh deposit of snow or frost every year, such a mechanism seems doubtful.

The second group of possible variations involves changes in the radiation output of the Sun. Recent astronomical discoveries, such as neutrino studies described by A. Cameron and others, suggest that the Sun may have radiated more heat in the past. If the radiation flux were high enough (about 15 percent higher than at present), the caps would melt, increasing the atmospheric pressure, which in turn would increase the polar temperature and cause a geologically quick conversion of Mars to a planet having a different climate with much higher atmospheric pressure and conditions allowing liquid water.

The most important consequence of this last model is that it would affect Earth. The hypothetical increased solar radiation in the past would have caused Earth to be warmer, more humid, and cloudier. Because the hypothesis is based on a model of cyclical solar variation having a period of several hundred million years, it would predict that both Earth and Mars were warmer some few hundred million years ago. Some Mariner 9 scientists have speculated that the recent ice ages of Earth and the possibly warmer conditions that favored the ascendancy of cold-blooded reptiles on Earth during the Triassic and Jurassic periods about 200 million years ago might reflect such solar variations.

This speculation demonstrates the fresh look at long-lived terrestrial mysteries stimulated by the discoveries on Mars. Clearly it would be a profound triumph of space exploration if the first global reconnaissance of Mars could not only explain Martian phenomena but also lead to new understanding of the ice ages and biologic revolutions of Earth, problems that have remained unsolved after a century of scientific sleuthing.

A second profound effect of the climatological studies stemming from the discovery of Martian channels is that they raise the possibility of gross instabilities in planetary climatology and geology. Modern terrestrial geology is based on the principle of uniformitarianism—the principle that past geology can be interpreted on the basis of processes continuing today. This principle, almost universally assumed, has been developed primarily from the fossil stratigraphic geologic record, which extends only back to the Cambrian period, some 500 million years ago—about a tenth the history of Earth. The Martian studies suggest a somewhat different viewpoint: as we push farther back into ancient planetary histories, we must be prepared to meet with conditions substantially different from the present conditions. This idea, if confirmed, could alter our philosophic approach to terrestrial geology.

The discovery of riverlike channels on Mars has led to a study of the possibilities for past water, and this in turn has led to consideration of the polar caps and atmosphere. The stage is now set for a more careful analysis of the polar regions where more clues may be found about the nature of past climatic, erosional, and depositional processes. We will describe the search for these clues in the next two chapters.

CHAPTER IX

Polar Caps and Layered Terrain

Before the discovery that water exists on Mars, it was perhaps somewhat bold to pronounce that these [polar] spots [are] ice fields around the Martian poles, resembling those which exist around the poles of the Earth. Sir William Herschel, indeed, with that confidence which he always showed when he had a trustworthy analogy to guide him, came to this conclusion on the strength of the correspondence between the changes of the two spots and the progress of the Martian seasons.

—R. A. Proctor, 1871

Snow caps of solid carbonic acid gas . . . hypotheses each more astounding than its predecessor. . . .

—Percival Lowell, 1895

The conclusion is that the Mars polar caps are not composed of CO_2 and are almost certainly composed of H_2O frost at low temperature (much lower than 0° C).

—G. P. Kuiper, 1952

Insofar as frost preservation is a function of vapor-pressure relationships, it is consistent with the conclusion, now strongly supported by infrared radiometer and infrared spectrometer observations, that the Martian polar caps are composed primarily of CO_2.

—R. Sharp, B. Murray, R. Leighton, L. Soderblom, and J. Cutts, 1971

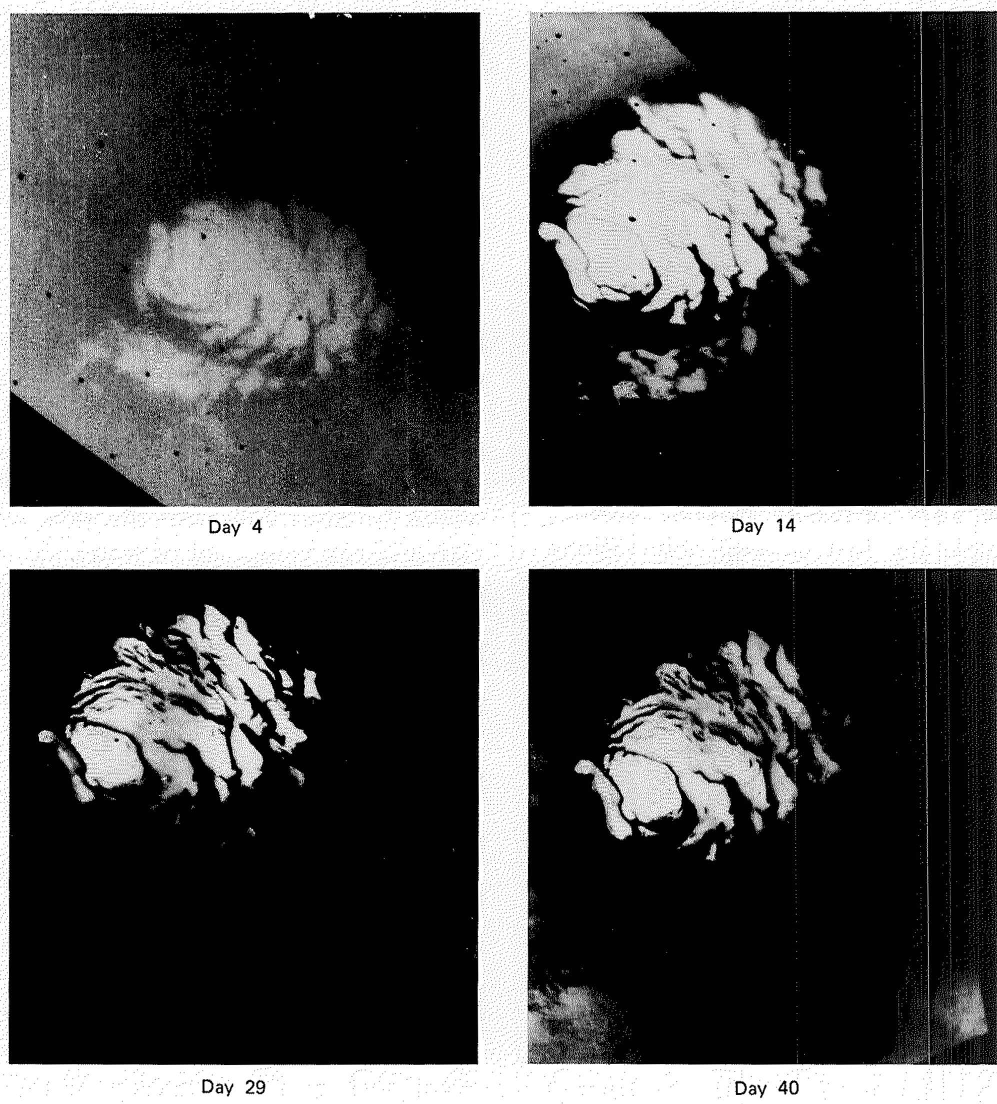
For the beginning telescopic observer, the first and perhaps only discernible features on Mars are the polar caps. They are by far the most prominent features on the planet and were recorded in some of the first drawings of Mars by Cassini in 1666. Herschel, at the beginning of the 19th century, was the first to note that the caps varied in size in a rhythmical sense with the Martian seasons. This observation, coming at a time when the existence of life on Mars was widely accepted in the scientific community, was immediately interpreted in terms of an Earth analogy as evidence of the existence of water on Mars. Water ice and snow were obviously responsible for the polar caps on Earth, and it was at least intuitively clear that these caps, if viewed remotely, would appear to advance and recede in accordance with the seasons. It was therefore natural to assume that the appearances and disappearances of the Martian caps were associated with the freezing and thawing of liquid water. As was indicated in chapter I, Lowell eventually postulated that the reason for the existence of "canals" on Mars was to transport this water from the melting caps to the arid midlatitudes for purposes of irrigation.

In 1830, W. Beer and J. H. Mädler reported the presence of a dark band around the receding north cap, but this phenomenon received little further attention until Lowell observed a similar band around the waning southern cap in 1894. Lowell described the band as "deep blue" in color—referring to it as a "badge of blue ribbon about the melting cap." Other observers described the band variously as brown or black, and some called it an optical illusion, thus creating another Martian controversy.

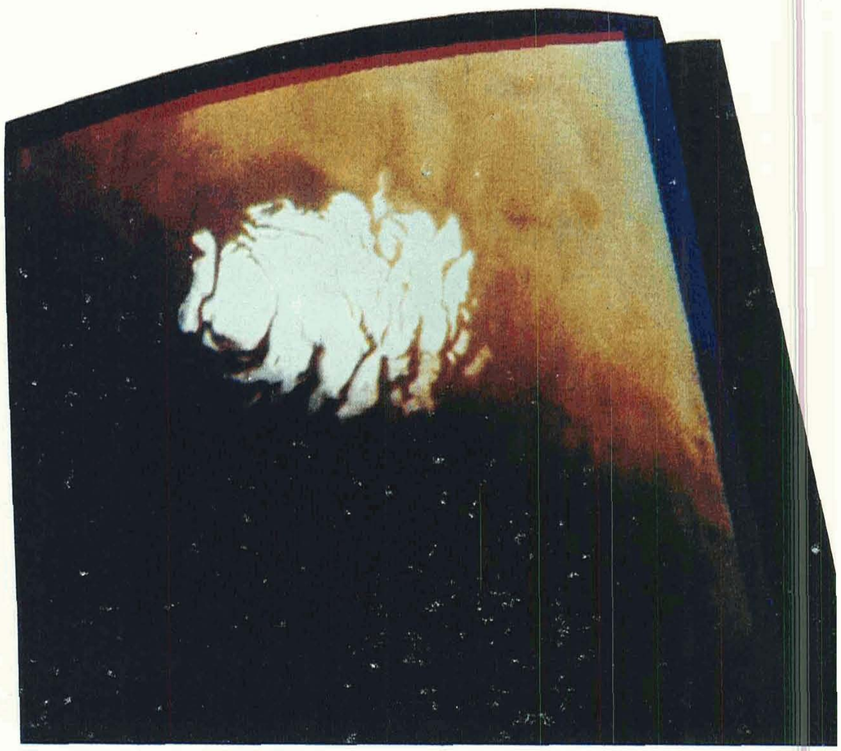
At about the same time, an additional controversy arose as a result of independent suggestions by A. C. Ranyard and G. J. Stoney that the caps were composed of solid carbon dioxide. The early proponents of this view were few in number, largely because of the lack of information concerning the atmosphere and surface of Mars and the consequent tendency to interpret all observations in terms of Earth analogies. It was not until 50 years later that astrophysical studies were undertaken to discern the true nature of the polar caps, first by Kuiper in 1948 and later by Dollfus in 1950. Both experiments were based on the reflective properties of the cap material, and in each case the experimenters concluded the material was water ice. Whereas Mariner 4 did not view the polar cap in 1965, the occultation data showed the atmosphere to be essentially carbon dioxide at a few millibars pressure, and this led to strong new arguments by Murray, Leighton, and Leovy as well as others that the caps were primarily carbon dioxide. Mariner 7 made the first closeup observations of the south polar cap in 1969, and whereas the temperatures measured by both the infrared instruments were consistent with a frozen carbon dioxide cap, the data were insufficient to settle the question. Mariner 7 seemed to dim the prospects for a polar "melt band"; no dark area of any kind was observed around the receding cap.

Mariner 9 photographed the south polar region of Mars from November 1971 until March 1972. The time at which the spacecraft arrived corresponded to early summer in the southern hemisphere of Mars, and the polar cap was in the late stages of its retreat. In contrast to pictures taken by Mariner 7, the first Mariner 9 pictures showed the cap edge to be sharply defined, with very few isolated frost patches outside the cap or "windows" in the cap. This implied that the cap's boundaries were determined by underlying terrain that was relatively smooth and free from topographical irregularities. These boundaries continued to retreat for about 3 weeks after Mariner 9's arrival, but changed very little during the remainder of the mission.

Earth-based observations had never unambiguously established the presence of a residual cap in the southern hemisphere of Mars, and the observation of a stable cap remnant during the 1972 opposition was a significant result of the Mariner 9 mission. Calculations made by Mariner 9 scientists studying the cap suggested the evaporation rate of solid carbon dioxide might be too high during the Martian southern summer to permit a residual cap of this material to survive. On the other hand, the vapor pressure of water ice at the polar temperatures would be quite low, and the slow evaporation rate of a cap composed of water ice would permit it to survive indefinitely. Thus the Mariner 9 experimenters proposed that the primary cap, which comes and goes with the seasons, is mostly carbon dioxide, but that the residual cap left each year is possibly water ice. If this view is correct, it goes a long way toward answering the question raised in the preceding chapter as to the location of the "missing" water on Mars: it may be locked in residual ice caps that do not melt now, but may have melted under warmer conditions in the geologic past. Some experimenters suggested the water ice caps may have originally formed because of a large atmospheric influx of water vapor during some past epochal event such as the formation of the large volcanoes mentioned in the previous chapter as possible sources for water vapor. The persistence of the caps through the Martian spring and summer, during the time when entrained water is being released by the subliming carbon dioxide,



Four views of the shrinking south polar cap showing the development of a residual cap during 37 days of Mariner 9 photography. The first view shows the cap shrouded in dust from the 1971 dust storm. By day 14 this dust has cleared, but the cap's outline, about 300 by 350 kilometers, changes little thereafter. (P12803)

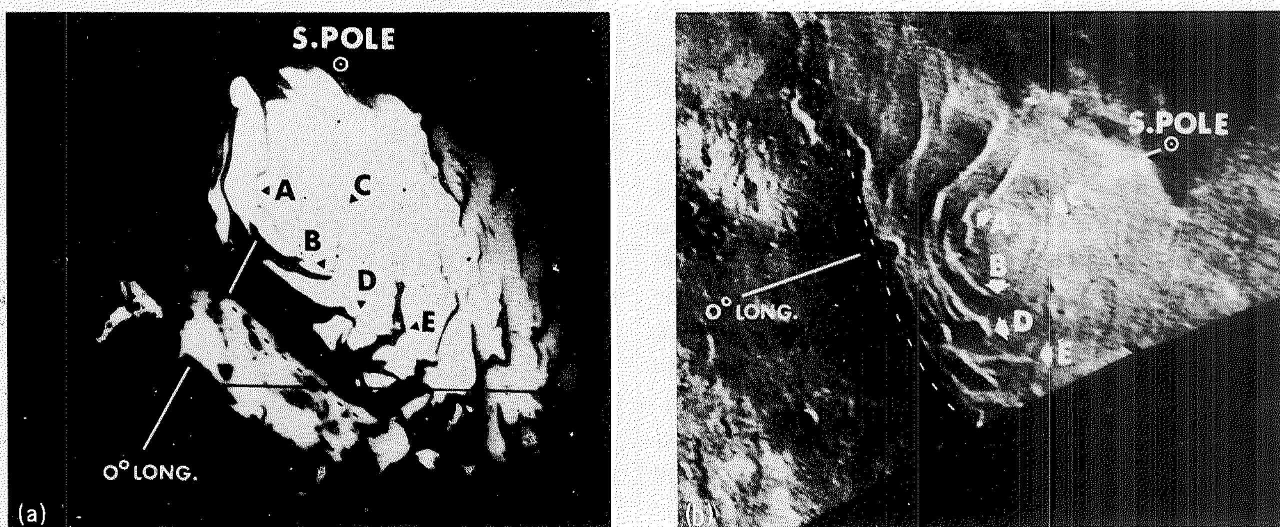


The south polar cap of Mars in color, in a reconstructed view using photography with different color filters. The terminator, or sunset line, slants across the bottom of the picture. (Jet Propulsion Laboratory Image Processing Laboratory 211–4641)

may also imply they are slowly growing through a process of accretion of this water vapor from the atmosphere. This growth process may in turn be modified or reversed by long-term cyclic changes in conditions on Mars associated with precession of both its own spin axis and its perihelion, or point of closest approach to the Sun, during the planet's orbit. Although these ideas are still unproven, they indicate that we are probably close to a final answer to the long-debated question of the composition of the Martian polar caps. Future research will be directed in earnest toward the Martian polar caps, which have emerged as a result of the Mariner 9 mission as key features in the Martian environment.

In 1969, during the Mariner 7 photography, the south polar cap was in a very extended early spring stage. The arrival time and orbital parameters selected for Mariner 9 were nearly ideal for high-resolution frostfree coverage of the region that had been frost covered. Special interest attached to this region because Mariner 7 had shown hints of an unusual type of sparsely cratered terrain there. Mariner 9 photographs more than justified this interest. The early Mariner 9 pictures revealed a vast area of terrain in the region of and encompassing the pole with a relatively smooth, uncratered surface, ending in a graceful, sinuous staircase of slopes descending to the apparently more ancient terrain below. The layers were stacked like saucers of various sizes, and their edges defined curving contours around the residual cap. The descriptive term "layered" was adopted for this terrain, and subsequent mapping proved it to exist at both the north and south poles, but to be unique to the polar regions.

The presence of the layered terrain on Mars was an intriguing discovery, perhaps comparable in significance to the subsequent discoveries of riverlike channels and the great crustal disturbances of the volcanic province. What caused the layered structure? What were the layers composed of? How was the material transported and deposited? Could the Martian dust storms be involved? Considering these questions, some members of the Mariner 9 television team drew the initial conclusion that formation of the laminated terrain involved either water or carbon dioxide, or both, because the phenomenon was

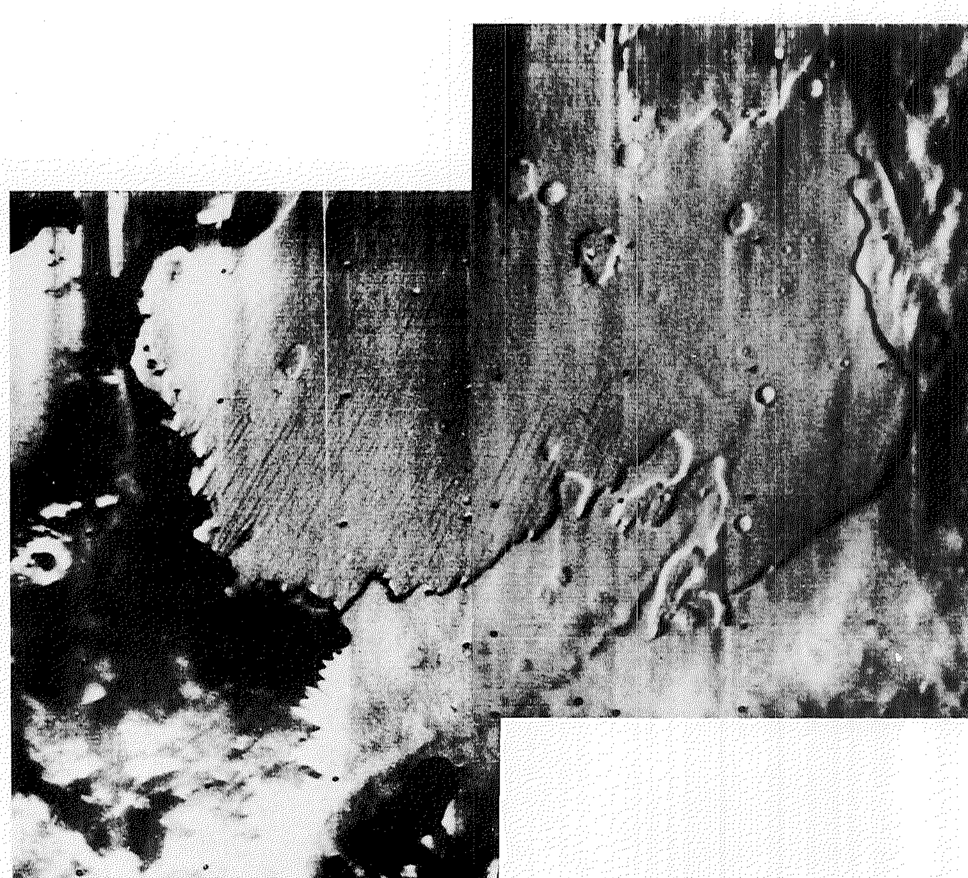


Comparison of features in residual southern cap (*a*) with the same features in the snow-covered cap photographed by Mariner 7 in 1969 (*b*). Although (*b*) shows a region entirely snow covered, it has been printed with darker tone to show features within the cap itself. The arcuate features, labeled *A* to *E,* may be ridges related to stratified deposits near the pole.

restricted to the polar region where volatiles were regularly condensed and evaporated. They suggested that fine dust and volcanic ash, circulated by the frequent dust storms, could easily be entrained by volatiles condensing there and accumulated into stratified deposits; subsequent evaporation of the volatiles would then leave a deposit much like sedimentary rock on Earth. Alternatively, the water ice or carbon dioxide ice might still be present as a part of the layers. Partial erosion due to ice evaporation might then explain the observed rounded edges. Finally, one of the cyclic changes previously mentioned in connection with Mars' orbit occurs with a period of 95 000 years, and this periodic modification of the Martian seasons was postulated as being responsible for the layered nature of the deposits and their resultant thickness.

Other Mariner investigators disagreed with the postulate that the 95 000-year cycle was responsible for layer formation, arguing that the observed thicknesses of the individual layers represented amounts of material far in excess of that which could be transported and deposited in the polar regions in such a geologically short period. An additional periodicity occurs in Mars' orbit with a 2-million-year cycle, and these

Laminated terrain in the south polar region near 229°, −75°. Laminations descend from smooth, striated uplands (*center*) to low, sinuous features (*right*). (The light comes from the left.) The thinnest laminations are believed to be about 30 meters thick. Depth of area in this photograph is about 50 kilometers. Striations in center of frame are interpreted as wind erosion features from strong prevailing winds. (4213–21)



Raised and pitted layer near 325°, −66°. Width of smooth plateau is about 70 kilometers. Striations on its surface are attributed to erosion by strong prevailing winds. (The light comes from the left.) (P–12752)

Oval, laminated tableland near the south pole, 84°, −82°. The stratified area appears to overlie older, pitted terrain that emerges at the bottom. Sunlight comes from 10° above the horizon at the left. The frame dimension is about 47 by 60 kilometers. (P–12925)

Possible terrestrial analog of Martian laminated terrain. Freezing conditions in Kelso dunes, southern California, led to wind etching of stratified layers within the dunes. Width between main dark bands is about 2 meters. (Robert P. Sharp)

investigators considered this period to be more compatible with the time necessary to form the observed layers. They proposed that the variation in insolation at perihelion associated with the 2-million-year cycle modulates the occurrence of global-scale dust storms, and that this modulation is responsible for layer formation.

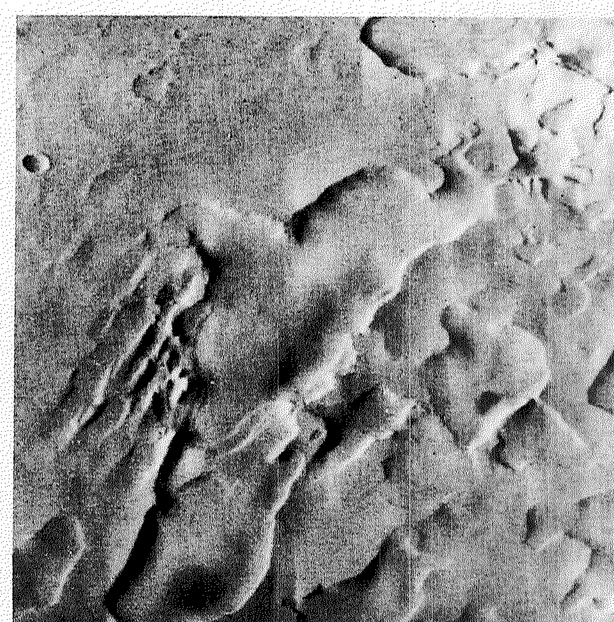
An entirely different hypothesis concerning layer formation was proposed by one Mariner scientist, based on the triple point of carbon dioxide. He proposed that a process much like glacier formation on Earth could occur in the carbon dioxide deposits at the Martian poles once the deposits became heavy enough. Under the proper conditions, liquid carbon dioxide could be formed at the bottom, flow out, and subsequently refreeze.

These ideas, whereas they might account for the formation of layers, left a number of other mysteries unanswered. For example, the edges of the layered deposits tended to define contour-like arcs not only with different sizes but with apparently different centers. Why did the arcs of different radii seem to have different centers? One early published analysis by Mariner 9 investigators suggested that Mars undergoes polar wandering—a phenomenon known on Earth—by which the polar position, and hence the point of symmetry for layered deposits, changes. This might cause each cyclic layer to be deposited with a different center.

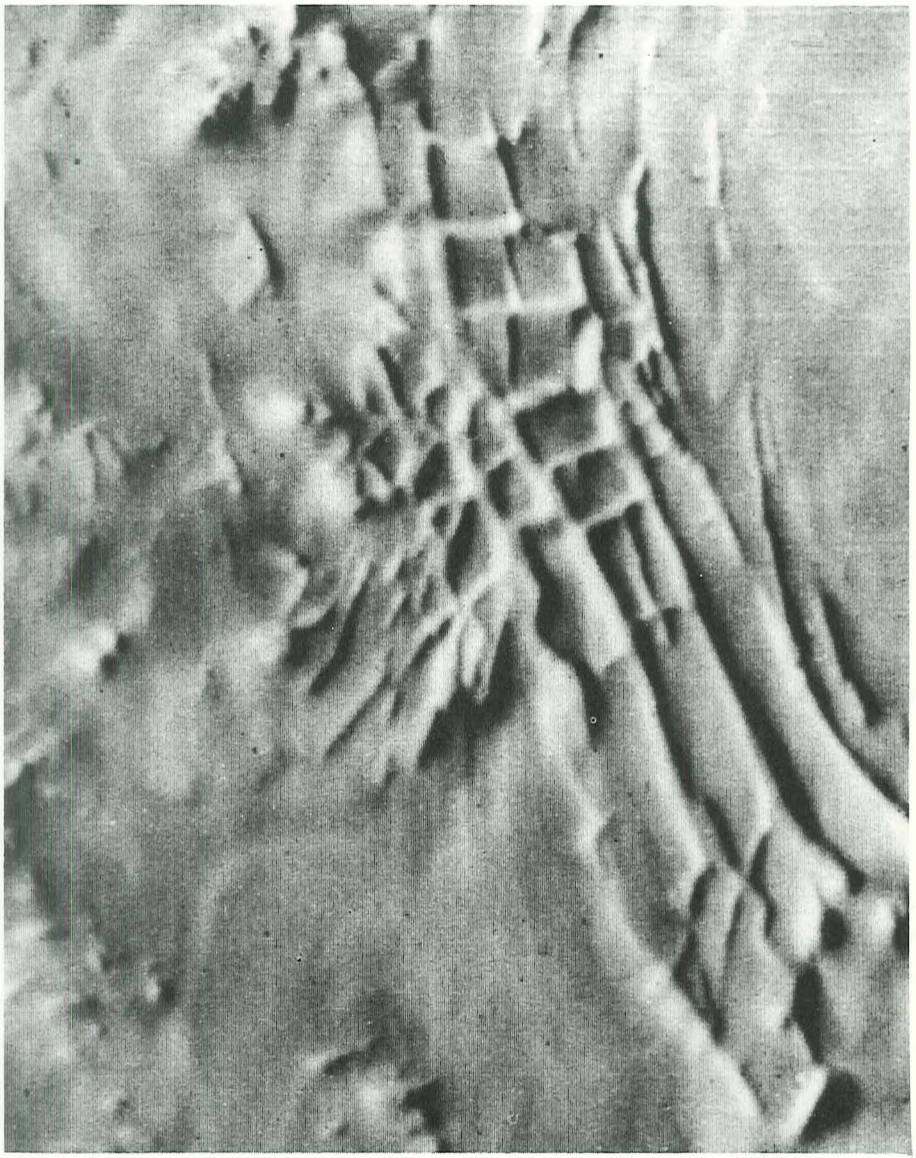
Whereas the ultimate origin of the polar layered terrain is less than certain, the processes modifying these units have been clarified by studies of television photographs and theoretical analysis of Martian winds near the poles. The surfaces of these units are frequently scoured with fine parallel striations a few hundred meters in width and many kilometers long. The units are also pitted with irregular depressions, or "etch pits," many kilometers in diameter. Study of the striations revealed that they were generally oriented nearly radially to the pole, but with a spiral pattern centered at the pole. These patterns are similar to theoretically predicted patterns for Martian polar winds, and it is believed that they represent wind erosion patterns. Similarly, the irregular pits are interpreted by many observers as deflation basins, excavated when loose material at some point in one of the layered units is blown out by the wind. Similar deflation basins appear in terrestrial deserts.

What were the relations between these various polar terrain units? Although absolute ages of the distinctive types are not certain, the absence of craters on the surface of the layered terrain indicates it is quite young compared to other Martian structures. Counts of craters suggest the polar surfaces are as young as or younger than the large volcanoes. In several photographs it is apparent that the escarpments forming borders of layers were only partially obscuring the features of the underlying terrain. The underlying terrain could additionally be separated into two types, the first being characterized as "etch pitted" and the second as the cratered terrain relatively common to Mars. While the layered terrain obviously overlaid both the cratered and etch-pitted terrain, there were similar indications that the etch-pitted areas overlaid the cratered terrain. Thus the relative ages of the observed terrain ap-

Channellike escarpments in the south polar area near 154°, −74°. Picture width is about 420 kilometers; south pole is out of the frame to the left. (1697–170347)



Irregular pits in south polar terrain near 93°, −77°. These may be old craters and other irregular features being etched or deflated by wind removal of deposits. Fresh crater at upper left is about 4 kilometers in diameter. (1589–134624)



Unusual rectilinear structure associated with south polar pitted terrain, near 64°, —80°. Informally dubbed the "Inca City," it is probably the result of wind deflation of deposits from underlying (faulted?) rough terrain. Individual "cells" are about 4 to 5 kilometers in width. (1417–160341) peared to increase in the order of layered, etch-pitted, and cratered. Subsequent analysis showed that the etch-pitted areas were divided into "blankets" that could also be differentiated in terms of their age.

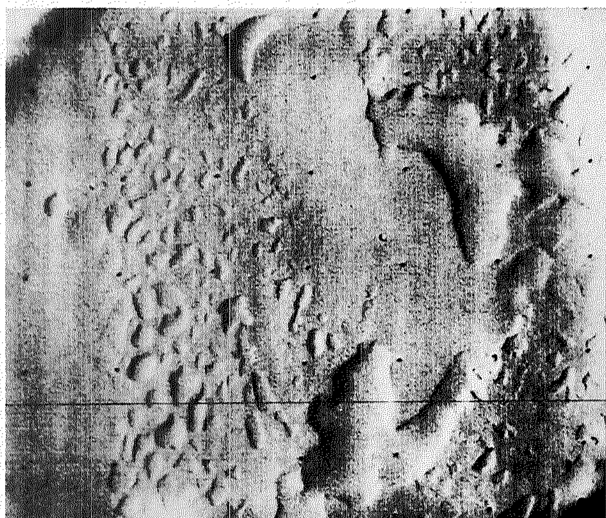
Some Mariner analysts, noting the relationships between the etch-pitted and layered units, concluded that they may indicate an episodic history in the polar regions, alternating between periods of erosion (etch pits) and deposition (layers) by the polar winds. It was speculated that such episodic behavior might be associated with the cyclic perturbations in the Martian orbit, previously described.

Throughout most of the standard mission of Mariner 9, the north polar cap was shrouded by the darkness of winter and the haze of the polar hood. Also, while the south cap was clearly visible throughout this part of the mission, most of the seasonal deposition had disappeared before the spacecraft arrived. The decision to extend the Mariner 9 mission was thus a welcome one to the scientists involved because it afforded them the opportunity to monitor the north cap at intervals throughout its recession and to make detailed comparisons between the two polar regions. Unfortunately, it was not possible to plan the extended mission of Mariner 9 as a simple, continuous extension of the standard mission. Shortly after the standard mission ended in March, the changing geometry between the orbits of the spacecraft and planet caused Mariner 9 to pass into the shadow of Mars during each revolution, obstructing the spacecraft's view of the Sun. Because the solar panels were unilluminated and incapable of generating power during these periods, it was decided to keep the science instruments inactive until June, when the orbital geometries would no longer cause solar occultation of the spacecraft by the planet. Additional science data acquisition was then possible until Mars began its passage behind the Sun relative to Earth in early September. This is called superior conjunction, and the proximity of the Sun to the telemetry beam made radio communication between the spacecraft and Earth impossible during this period because of interference from the solar corona. After superior conjunction, additional data could be gathered, but it was anticipated that this period would be short because of the rapidly diminishing amount of attitude-control gas on the spacecraft. Because the spacecraft used this gas to maintain its fixed position in space, its final depletion would ultimately terminate the mission.

Intentional maneuvering of the spacecraft or the scan platform accelerated the loss rate of the spacecraft's attitude-control gas. To minimize this, the television teams planned the imaging sequences carefully for the extended mission, attempting to get the maximum amount of information possible from a minimum number of pictures. In the north polar region, the strategy adopted was to initially map the entire areas with wide-angle pictures, and then continue monitoring the cap's recession from high altitude with single frames. Using the information contained in the mapping coverage, the remaining frames could then be critically targeted to get as much information as possible about the terrain types and the relationships between them.

At the beginning of the extended mission in

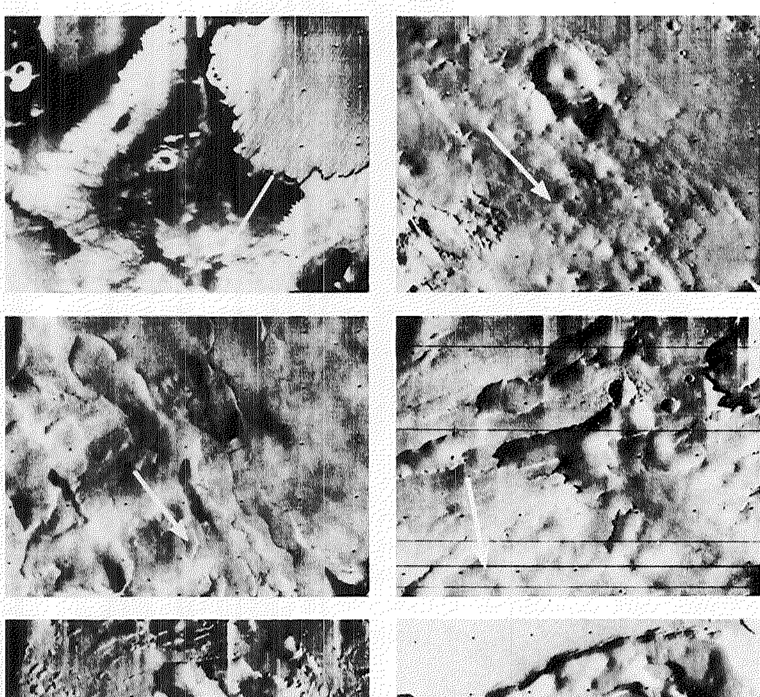
(Continued on page 122)

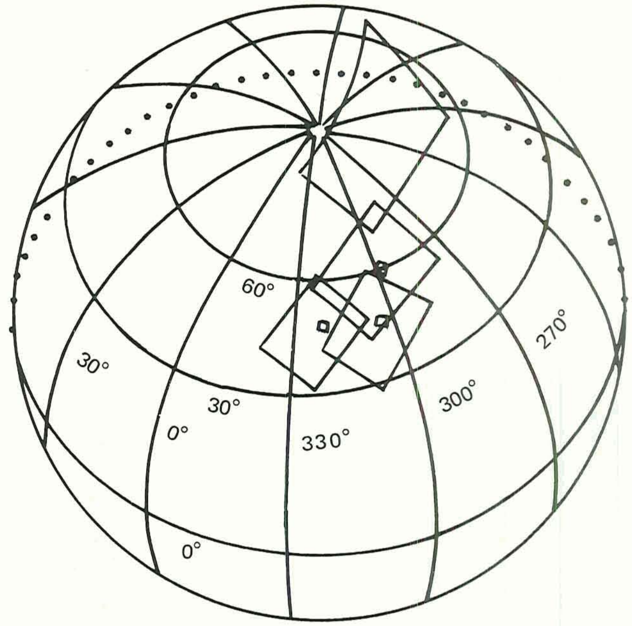


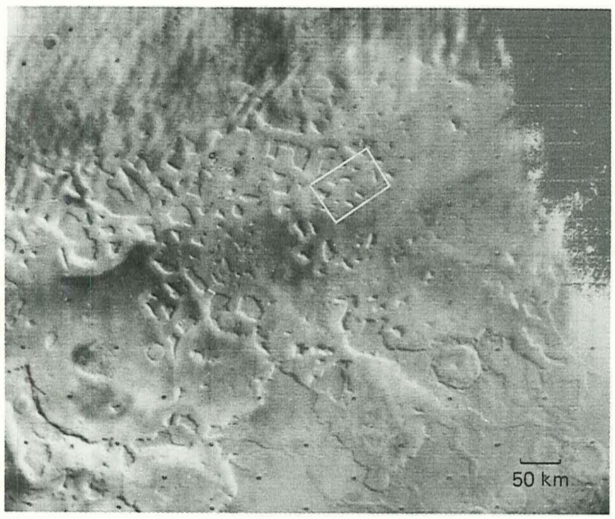
Pitted terrain near 67°, −74°. Pits appear to lie in an extensive sedimentary blanket, probably of windblown deposits. Pits are believed to be enlarged by wind excavation, eventually coalescing to produce rugged terrain. The smallest pits in this photograph are about 1 to 2 kilometers in diameter. (4132–21)

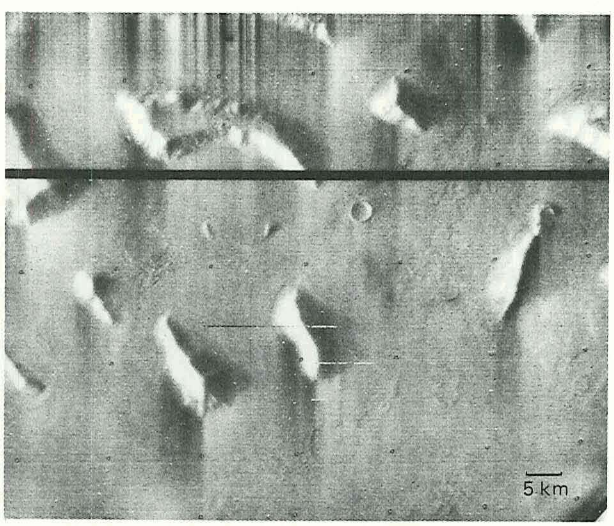
Spiral wind motions confirmed in cloud structure near edge of north polar cap. Note frost-rimmed crater (*top*), near featureless plains close to cap, and cratered terrain near bottom. (4295–71, 4295–67)

Pitted and striated terrain with indication of local prevailing wind direction (arrows), based on deposition patterns and theoretical analysis. Striations are generally alined with wind.

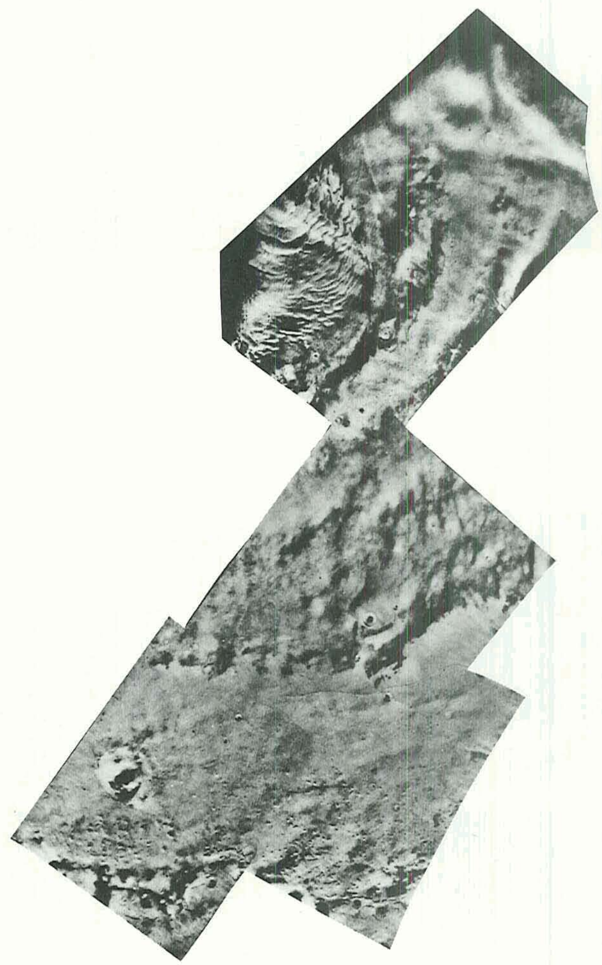




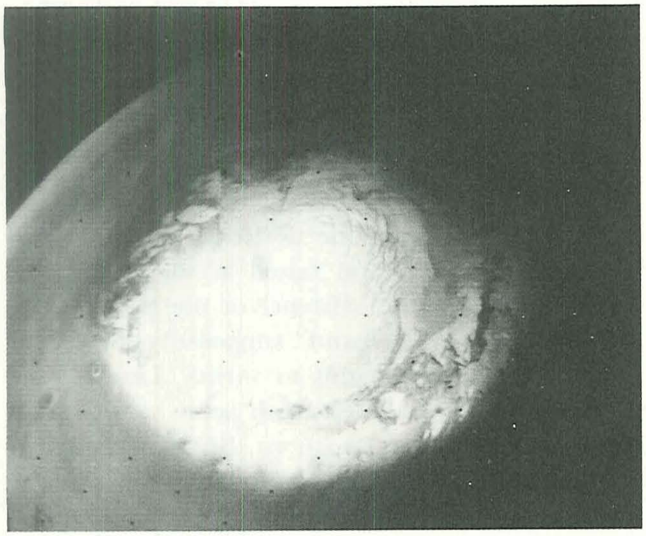




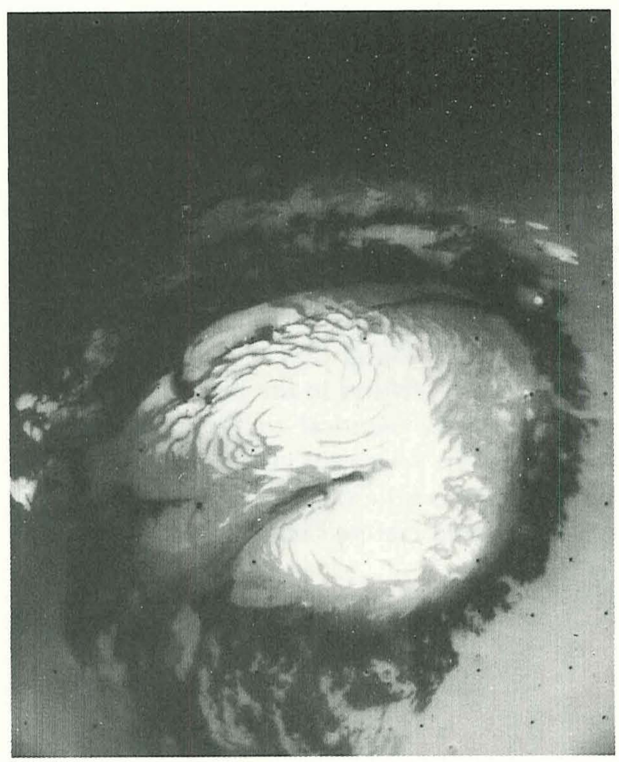
"Fretted" terrain, near 333°, +44°, characterized by isolated hills believed to originate by recession of scarps due to ice evaporation. At top is a wide-angle view, and at bottom is a telephoto view of the boxed region in the top photograph. (4212–69, 4212–72)



Mosaic of north polar latitudes showing relation of different terrain units. Top shows residual cap (*left*) and polar haze. Middle shows relatively featureless plains with dark deposits. At bottom can be seen craters and isolated hills, or "fretted" units.



North polar cap showing craters and other interior detail during retreat. (4296–102)



North polar cap showing formation of residual permanent cap with spiral lanes and surrounding dark annulus, possibly related to the "melt band" long reported by Earth-based observers. (4297–46)

June, the north cap had already begun its recession. Thus Mariner 9 began monitoring the cap when it was about 85 percent of its original size and continued to monitor it until it had receded to a perennial cap similar to that found in the south. The rate at which the cap receded conformed closely to that predicted from Earth-based observations and the Leighton-Murray calculations based on carbon dioxide sublimation. The abrupt halt in this retreat and the relative stability of the remaining portion of the cap again suggested that this permanent residue might be water ice. Temperatures measured by the infrared radiometer tend to support this hypothesis. In some of the high-altitude pictures taken during the early stages of recession, the outline of the cap appeared to be polygonal; this shape seemed to be maintained during the cap's retreat, with all sides receding at roughly the same rate. It was suggested that the outline might be controlled by regional topography, which had been modified by the loading of the polar region with thick deposits. On a smaller scale, it was apparent that local topography controlled the persistence or loss of frost at the edge of the retreating cap.

The terrain features in the north polar region were essentially identical to those observed in the south. The relatively smooth, layered plains with their graceful escarpments, overlaying both etch-pitted and cratered terrain, were characteristic of both polar regions. Perhaps the major difference between the two regions, inferred from occultation measurements and spectrometer data, lay in the relative abundances of the polar deposits and their possible influence on the observed shape of Mars.

A final feature of the north polar cap brings us back to a problem raised at the beginning of this chapter: the existence or nonexistence of a dark polar "melt band" supposedly surrounding the cap as it begins to shrink. Late in the Mariner 9 mission, afer north polar haze cleared and the north cap began to shrink, Mariner 9 sent back several excellent photographs of the north cap and its surroundings, and these photographs showed a terrain of low albedo surrounding the cap. This terrain, when viewed from the Earth, could easily have been interpreted by early observers as a "melt band" following the receding cap. However, it appears to be a fixed surface feature, not a band of temporarily moist soil.

As we have pursued the Martian volatiles, particularly water, to their possible reservoir in the Martian polar caps, it has become clear that we must consider the Martian atmosphere and its important roles as transport medium for volatiles, modifier of the surface material, and repository for clouds and hazes. This topic will be taken up in the next chapter.

CHAPTER X

The Atmosphere

I believe it will be possible in the future to foretell, with something approaching the certainty of our esteemed weather bureaus' prognostications, not indeed what the weather will be on Mars—for, as we have seen, it is more than doubtful whether Mars has what we call a weather to prognosticate—but the aspect of the planet at any given time.

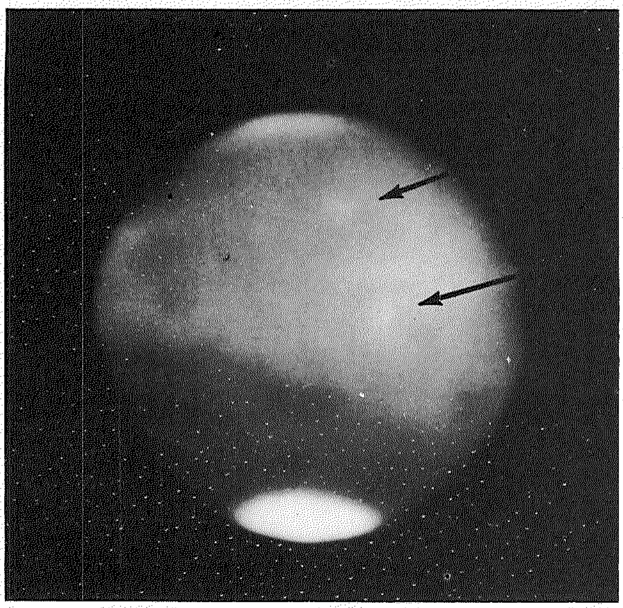
—PERCIVAL LOWELL, 1895

When Herschel and the other scientists of the early 1800's were providing Mars with a population through hypothesis, they did not fail to endow the planet with an atmosphere much like that of Earth. This was an assumed necessity, because life as we know it is markedly dependent in many ways on the specific constituents of our atmosphere, as well as the relative abundances. Liquid water is a fundamental necessity to the life process on Earth, and while the presence of water vapor in the atmosphere does not necessarily signify the existence of liquid water on the surface, the absence of water vapor is a positive indication that no liquid water is present. With the exception of some lower life forms called anaerobes, free molecular oxygen is also required to sustain Earth's living organisms. Thus it was no coincidence that the first crude attempt by Janssen and Huggins at spectroscopic analysis of the Martian atmosphere was performed primarily to determine the presence or absence of molecular oxygen and water vapor.

A more indirect but equally necessary atmospheric function for sustaining terrestrial life is the screening out of the Sun's lethal ultraviolet radiation. In the case of Earth, this function is performed by the ozone layer in the stratosphere: the ozone completely absorbs all of the short-wavelength radiation and dissipates it in a dissociation-recombination process that ultimately converts the ultraviolet light into other harmless forms of energy. In the absence of an ozone layer or its equivalent for shielding the surface, life forms on other planets would have to have evolved within themselves some protection mechanism, or be perennially restricted to an existence that avoided direct contact with sunlight.

In addition to deriving protection and sustenance from the atmosphere, life forms may also contribute to its content. For example, the ammonia, methane, and other small hydrocarbon molecules present as trace constituents in Earth's atmosphere are all there as a result of present or past life processes. Thus, a great deal of excitement was generated among those present at a press conference shortly after Mariner 7 had flown by Mars when it was announced that preliminary analysis of the data from the infrared spectrometer experiment revealed two small spectral features attributable to methane and ammonia. However, subsequent analysis did not support the initial conclusions: the spectra containing the two features had been recorded in the vicinity of the south polar cap and were ultimately identified as two seldom-seen absorption bands of solid carbon dioxide.

Whereas the biological implications that can be inferred from atmospheric studies have a strong popular appeal, they represent only a

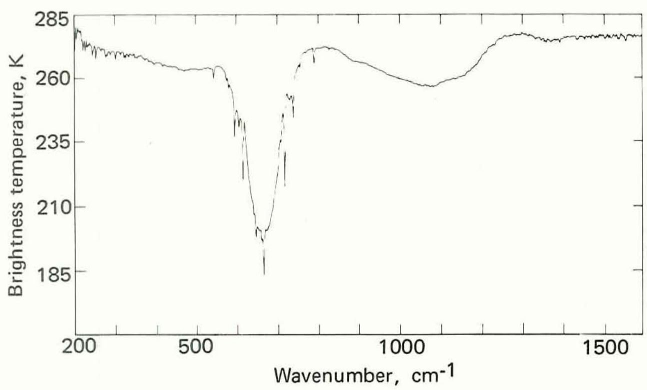


Photographs from Earth in blue light show Martian atmospheric features such as clouds and hazes. This example shows two bright clouds near the positions of the volcanoes Olympus Mons (top) and Arsia Mons (bottom). (August 12, 1971; University of Arizona Lunar and Planetary Laboratory)

small fraction of the total information such studies provide with regard to the planet itself. The atmosphere, after all, provides the surface environment and affects surface processes. An accurate knowledge of the present state of a planet's atmosphere, including the types of species present and their abundances, atmospheric temperature profiles, the photochemical processes occurring, and the formation and movement of clouds and dust storms, is of inestimable value to scientists who are attempting to deduce the past and future history of the planet and explain any periodic or sporadic changes occurring on the surface. For example, the water vapor content in the Martian atmosphere was known from pre-Mariner 9 measurements to be quite low, and this seems unlike the atmosphere that would accompany a planet with features appearing to be riverbeds. If these features imply the presence of liquid water in the past, where is it now? If it has been photochemically dissociated to hydrogen and oxygen, what has been the fate of these species? Hydrogen, because of its low atomic weight, would ultimately escape from the planet's gravitational field, and its escape rate was actually measured by Mariner 9.

By monitoring the strong emission line at 1216 nanometers, the ultraviolet spectroscopy experimenters were able to measure the atomic hydrogen concentration in the upper atmosphere of Mars and calculate the rate at which it was escaping from the planet. The value found for the escape rate was 2×10^8 atoms per second per square centimeter through an imaginary surface at the top of the atmosphere. If the only source for hydrogen atoms on Mars is water, this represents a loss of water from Mars of about 1 million gallons per day. If Mars has lost water at this rate since its formation, the total water that has escaped would be sufficient to cover the entire surface of the planet to a depth of 5 meters! Projecting this escape rate into the future, an amount equivalent to the total water vapor now present in the atmosphere will be lost in less than 100 000 years.

Does this imply we have begun our closeup observations of Mars only to learn that the planet



Martian spectrum obtained by Mariner 9 infrared spectrometer on December 29, 1971, during final clearing of the dust storm. Dips are caused by absorptions due to dust particles. Shape of absorption dips can be related to particle size, indicating airborne dust particles about 2 to 20 micrometers in diameter. Other spectra revealed data on atmospheric pressure and composition.

is in the final stages of dehydration as suggested by Lowell? Probably not. There is unquestionably water ice stored in the polar caps and in the form of permafrost, and the volcanoes may provide an additional source of water vapor to the atmosphere. Also, the assumption that water vapor is the sole source of atomic hydrogen in the Martian atmosphere is based on the lack of evidence to the contrary, rather than positive evidence that such is the case. Two alternate but unlikely sources of hydrogen atoms have been suggested: the thermalization of solar-wind protons (hydrogen ions) in the upper atmosphere or the presence on the planet of a continuous source of molecular hydrogen, a molecule neither spectrometer would have been able to detect. One factor arguing mildly against the water vapor hypothesis for the source of escaping hydrogen—again assuming the hydrogen atom escape rate has been constant throughout the history of Mars—is the amount of oxygen that would have been produced in the photolytic process. The present concentration of molecular oxygen in the atmosphere is only a few millionths of the amount that would have been generated. However, it is possible that a great deal of this oxygen could have been used up in surface oxidation; astrophysicist Michael McElroy has also suggested a possible mechanism for the escape of atomic oxygen through recombination reactions of the major ions in Mars' ionosphere.

The ionospheric region of an atmosphere is characterized by the presence of charged species, or ions, that are produced as a result of interactions between the neutral atmospheric species and high-energy photons and electrons from the Sun. The base of the region is defined by the depth to which these photons and electrons can penetrate; and the top, called the exosphere, is considered to be that region above which collisions between particles no longer occur because of the extremely low densities. Thus, particles passing outward through the ionosphere with sufficient velocity to overcome the gravitational forces of the planet will probably escape the planet permanently. The highly energetic processes continuously occurring in the ionosphere cause temperatures higher than those in any other region of the atmosphere; at the exosphere, temperatures begin to fall off rapidly. This ionospheric environment was probed by various Mariner instruments.

Using a combination of data from the ultraviolet spectrometer, occultation results, and laboratory experiments, the Mariner 9 ultraviolet spectroscopy investigators were able to construct a model of the Martian ionosphere consistent with the hypothesis that all of the species present except atomic hydrogen are there as a direct or indirect result of the impingement of solar ultraviolet photons and electrons upon a pure CO_2 atmosphere. In their model, the temperature in the Martian ionosphere is in the region of 300° to 350° Kelvin, and the neutral species present, in order of their abundance, in addition to carbon dioxide, are atomic oxygen, carbon monoxide, and molecular oxygen. The primary ions present are O_2^+, CO_2^+, and O^+, in that order. (These represent, respectively, an oxygen molecule, a carbon dioxide molecule, and an oxygen atom, each of which has lost an electron.) At first glance, the relative abundances of molecular oxygen O_2 and the corresponding ion O_2^+ may seem inconsistent because O_2 is the least abundant neutral species and O_2^+ the most abundant ion. However, most of the O_2^+ is formed by a fast reaction between CO_2^+ and atomic oxygen; there is no direct dependence on the O_2 concentration. When either of the two major ions (O_2^+ or CO_2^+) recombines with an electron without a third particle present to absorb the energy released in the reaction, the recombined molecule wlil immediately dissociate into neutral particles with excess kinetic energy; these are the reactions that McElroy proposes to account for the loss of the oxygen initially produced by the photolysis of water vapor in the lower atmosphere of Mars.

That sufficient water vapor exists in the Martian lower atmosphere to account for the hydrogen atom escape rate was confirmed by the infrared interferometer, which continuously monitored the water vapor content throughout the Mariner 9 mission. The infrared investigators found that the water vapor in the midlatitudinal regions remained fairly constant at 10 to 20 precipitable micrometers (the depth of the liquid layer that would result if all the water could be precipitated on the surface), while the concentration in the polar regions showed a strong seasonal effect. During the midsummer season in the southern hemisphere, the water vapor abundance in the south polar region was about the same as that in the midlatitudes, but no water vapor was observed in the north polar area. As the Martian seasons progressed to late spring in the northern hemisphere, 20 to 30 precipitable micrometers were detected over the north polar cap region, while the measurable water vapor in the southern polar area declined to zero. These measurements are consistent with the theory that at least some water vapor is frozen and trapped as water ice in the polar caps and seasonally transported between them. The total abundance of water vapor over the planet as determined by the infrared interferometer was considerably less than that measured from Earth in previous oppositions. The infrared investigators have suggested this may be due to adsorption of the vapor onto the dust particles during the planetwide dust storm. The data tend to support this hypothesis because the total abundance was observed to decrease as the dust settled and then increase once again as the surface warmed up.

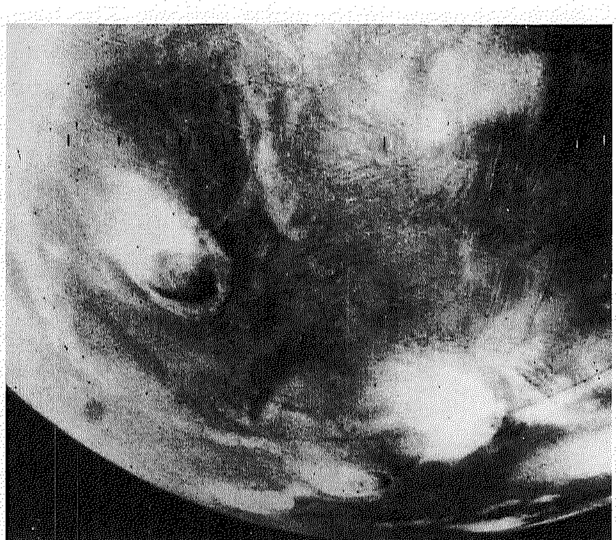
In addition to water vapor, Mariner 9 also detected ozone in the lower atmosphere of Mars. Ozone had previously been seen by the ultraviolet spectrometer on Mariner 7 in the region of the south polar cap, and in view of its biological significance as an ultraviolet shield, specific modifications were made to the Mariner 9 spectrometer to enhance its capabilities for detection and characterization of the molecule. As a result of these modifications and the extended viewing period provided by the orbiter, the ultraviolet investigators were able to show conclusively that ozone does exist on Mars, but mostly in the polar regions and with a marked seasonal variation in its concentration. They concluded that in early summer, there is no ozone in the atmosphere anywhere in the hemisphere associated with the season. In later summer and early fall, ozone began to appear both over the polar cap and in association with the formation of the polar "hood," a cloud cover associated with the polar cap. In winter, the entire polar region from 45° latitude to the pole is covered by the polar hood, and it was at this time that the maximum amount of ozone was observed over the polar cap. As the season progressed, less and less ozone was detected until by early summer ozone had once again disappeared from the entire polar region.

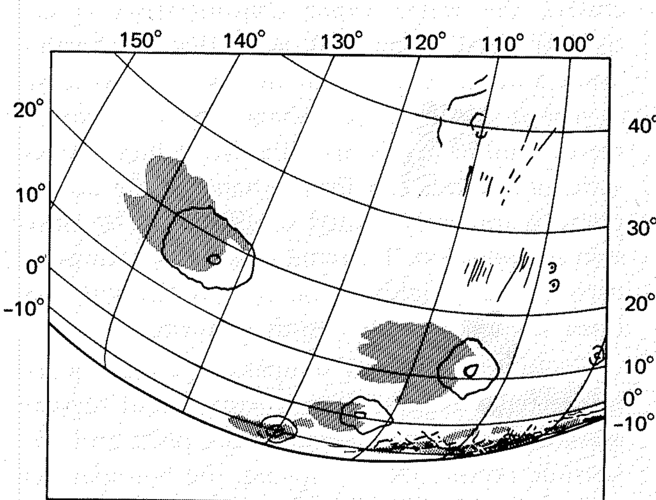
It is quite probable that the seasonal variation observed in the ozone concentration is directly associated with the water vapor variation, which peaks as the ozone declines. From laboratory photochemical studies, ozone is known to be destroyed rapidly by reaction with the products of water photolysis, and it is a reasonable assumption that this process, or a closely associated one, is responsible for the cyclic behavior of ozone in the polar regions. The formation of ozone in the midlatitudes would thus be precluded by the relatively continuous amount of water vapor present there, and ozone is not, in fact, observed in these regions.

Among the most striking observations of the lower atmosphere of Mars were television pictures of the Martian clouds. Pressures and temperatures in the lower Mars atmosphere correspond to those at heights of 30 to 40 kilometer in Earth's atmosphere, and cloud formations at these altitudes on Earth are relatively rare. Nonetheless, clouds do occasionally occur on Mars, and their nature has long puzzled and fascinated planetary scientists.

Both carbon dioxide and water vapor can freeze out under favorable conditions in the Martian atmosphere. Although, as previously discussed, the water vapor concentration is extremely small compared with that in Earth's lower atmosphere, it is about 100 times as large as that in Earth's stratosphere, and the average relative humidity is actually fairly high. Thus water ice clouds can form whenever the atmosphere is intensely cooled by lifting or by emission of radiation. Extreme cooling, to temperatures in the neighborhood of 146° Kelvin, can cause carbon dioxide clouds to form.

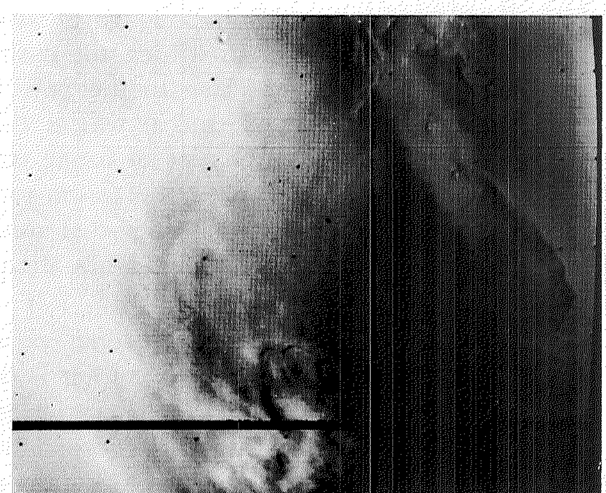
Cooling to very low temperatures takes place in the polar regions during winter, and regular seasonal brightening between the poles and 45° latitude occurs. During spring, the boundary of these polar bright regions is sharp and it retreats slowly and regularly toward the pole. Mariner 7 observed the south polar region during Martian spring in 1969 and showed that the region below 60° south latitude was covered by a surface cap





Detailed view and map of bright clouds leeward of volcanic mountains in the Tharsis-Olympus Mons area. On the sketch map, bright clouds are shown by stippled areas. This photograph was made during orbit number 676, late in the extended mission. (4298–82)

Bright clouds or fog on lower west slopes of the volcano Ascraeus Mons at about 4 p.m. local time. (4296–62)

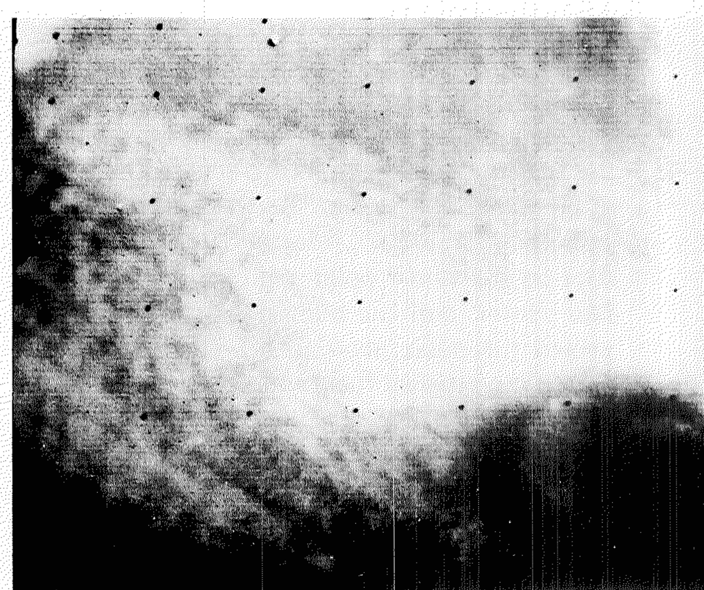


Bright clouds or fog on lower west slopes of Olympus Mons at about 2 p.m. local time. Puffy clouds about 10 to 20 kilometers in diameter lie above the caldera. (4296–58) apparently composed of carbon dioxide ice or snow. On the other hand, during autumn and winter the polar brightenings appear diffuse and show large day-to-day fluctuations, suggesting that the polar regions are covered by a hood of clouds at this season. Between mid-February and mid-March 1972, Mariner 9 acquired daily data in the north polar region; the season was late winter, and the television investigators expected the polar hood to be active. The hood more than satisfied their expectations; it did consist of clouds, and daily observations of their structure and behavior provided a great deal of information on atmospheric motions.

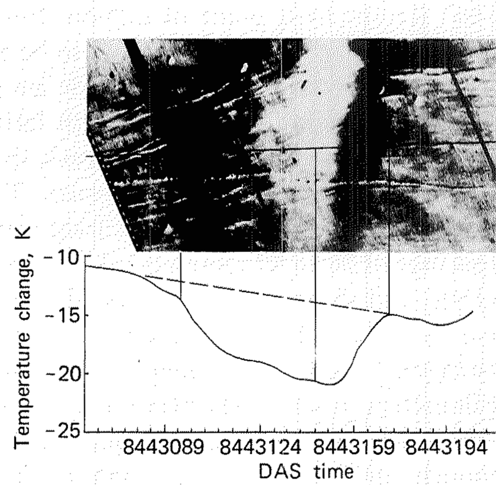
Most of the clouds observed could be divided into two general classes. From 55° up to 70° north latitude (the highest latitude regularly viewed during the interval), clouds were diffuse and structureless. They appeared to be close to the surface and were not thick enough to obscure scattered patches of surface frost. Infrared radiometer and spectrometer data showed that the temperatures in this region were close to the 146° Kelvin frost point of carbon dioxide, and this part of the hood was inferred to be a groundfog or thick haze of carbon dioxide ice particles. Between 45° and 55° or 60° north latitude, depending on the day-to-day variations, spectacular cloud waves were usually observed. Two types of waves were seen: relatively long waves, with spacings of 30 to 40 kilometers between adjacent crests, and shorter wavelets spaced about 5 kilometers apart. The long wave clouds were usually between 7 and 15 kilometers high, and 2 or 3 kilometers thick; they were closely associated with large topographical obstacles and were obviously produced by deflection of the airflow over the obstacle. Waves of this type are common in Earth's atmosphere downwind from large mountain ranges such as the Sierras or the Andes. They are known as lee waves, or mountain waves, and are formed as air, forced to rise over a range, becomes cooler and therefore denser than its surroundings. The excess density causes the air to accelerate downward toward its starting level, but under favorable conditions it will overshoot and will oscillate about its original height as it flows downstream from the obstacle. On Earth, the number of such downstream oscillations seldom exceeds five or six, but in the Martian polar hood a dozen or more oscillations downwind from the generating obstacle appeared to be the norm. The clouds therefore were clear indicators of the wind direction, which was in general from the west with daily variations over the range southwest to northwest.

These same clouds also gave good indications of the windspeed. Very persistent long waves such as these require surface westerly winds, probably in the range of 10 to 40 meters per second (22 to 88 miles per hour) of 60 meters per second (133 miles per hour) or more near the cloud level. Winds in a planetary atmosphere are driven by differences in temperature in the horizontal direction. Under the influence of planetary rotation, which is nearly as rapid for Mars as for Earth, the winds aloft will tend to aline themselves with contours of constant temperature at each height and will be inversely proportional to the contour spacing. Thus, the temperature drop between tropical and polar latitudes causes prevailing west winds that increase with height on Mars as on Earth. Temperatures derived by the infrared investigators

Brightening around eastern base of cliffs surrounding Olympus Mons at about 10 a.m. local time. Brightening may be due to local topographically controlled fog although photometric properties of soil on the cliff face might be a factor. Such brightening of the cliff may contribute to the bright ring around Olympus Mons that puzzled analysts of Mariner 6 and 7 photographs. (See Mariner 7 view of this bright ring on p. 78.) (4288–91)



Telephoto view of cloud structure on the volcano Ascraeus Mons (caldera lies at lower right). Patchy structure is believed to be the result of convective structure, as occurs in cumulus clouds on Earth. (4298–78)



Radiometric temperature tracing across a bright cloud in the region Alba, 100.8°, +42.3°. The temperature of the cloud is about 7 K lower than that of the surroundings. (Local time is 16.3^h; base temperature is 202 K.)

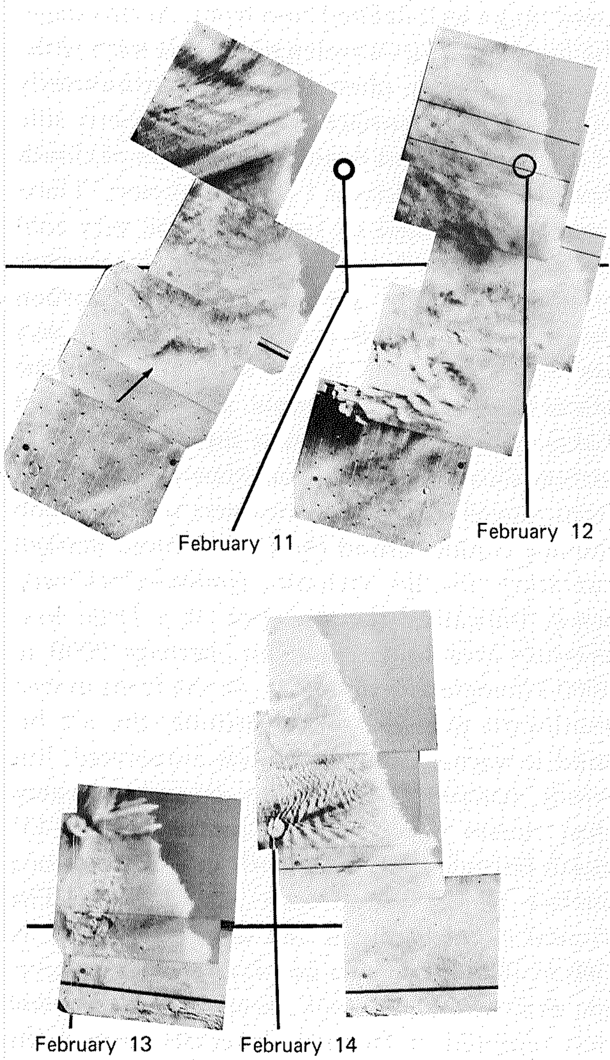
showed that the temperature drop between 40° and 60° north latitude was extremely large, about 50° Celsius, so that the strong west winds inferred from the cloud structure and the temperature distribution were quite consistent with each other.

The small cloud wavelets that were observed usually appeared to be much closer to the surface. They may also have been formed by flow over topography, but there is no obvious relationship between these waves and surface features, and it is more likely that they are formed by overturning air at the interface between a slow-moving layer of air and a relatively rapidly moving higher one. Temperatures in the 45° to 55° north latitude zone were high enough that both the long wave clouds and the shorter cloud wavelets should have been made of water ice rather than carbon dioxide ice, and the infrared data showed that water ice was present in the region.

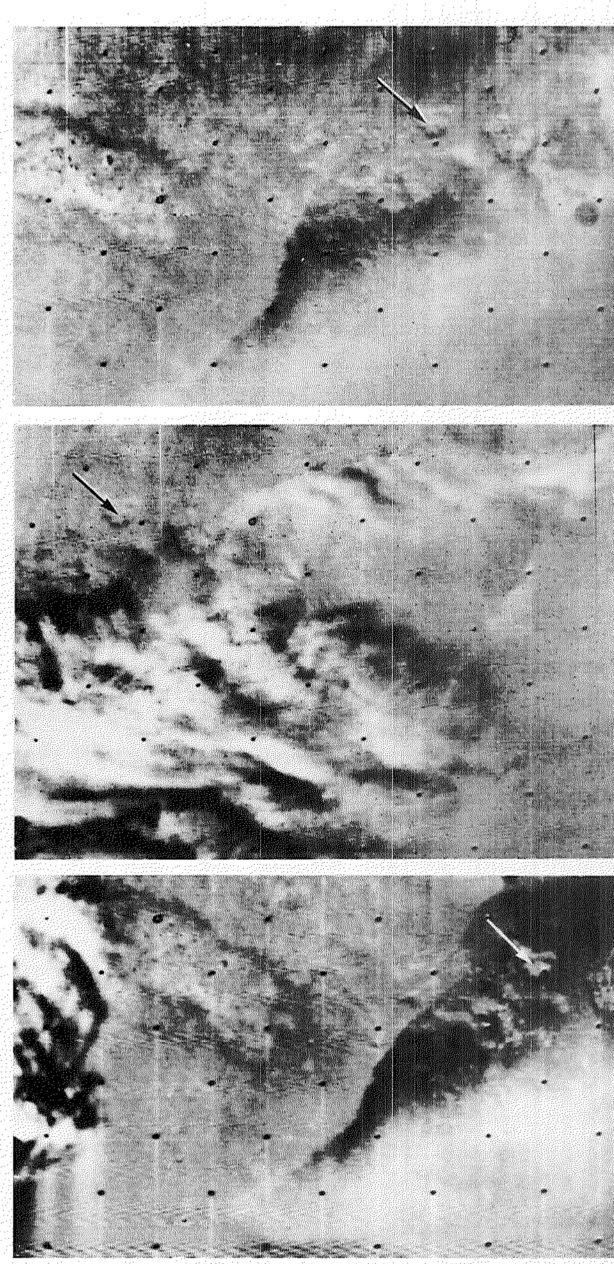
Day-to-day variations in northern clouds revealed fronts and large-scale storm systems like those that occur at middle and high latitudes on Earth. According to one of the investigators on the television experiment, a typical sequence of events was the following. The edge of the cloud pattern began north of its usual position, and was quite diffuse. Evidently, relatively warm air had been displaced unusually far north. Then the lee-wave activity began to intensify along the edge of the hood, and one or more broad bands of bright wave clouds formed, oriented from southwest to northeast, parallel to the wind. The most prominent band narrowed and began to move southeastward as the zone of strong temperature contrast became organized into a well-defined cold front. At this stage, the low-level short-wavelength clouds were widespread, and they often indicated northwesterly winds near the surface. On the northern side of the frontal cloud band, regular lines of clouds developed in the lowest 1 or 2 kilometers. These clouds were caused by heating of the very cold air as it moved southeastward over warmer ground and were probably made of carbon dioxide ice. (Clouds formed in a similar way are responsible for heavy snowfalls in some places on Earth, for example, around the Great Lakes, and it is possible that these clouds cause carbon dioxide snowfalls on Mars.) As the cold front moved southward, streamers in the carbon dioxide clouds behind the front showed marked curvature in the cyclonic (counterclockwise) sense, indicating the presence of a large low-pressure area in the cold air, perhaps 2000 to 4000 kilometers in diameter. As the front moved southward past 45° north latitude, the air behind it warmed and the clouds evaporated, but winds remained strong. On several occasions dust storms were observed in the 35° to 45° north latitude zone, apparently due to the strong surface winds behind such a cold front. The frontal cloud bands moved southeastward from 500 to 1000 kilometers per day. The entire process described above took about 2 or 3 days and was repeated at frequent intervals around the polar periphery.

Storm systems in terrestrial middle latitudes behave in a similar fashion, although they are a little longer lived and smaller in size than those on Mars appear to be. These storm systems are very effective in transferring heat and moisture to the polar regions. On Mars, this heat transfer

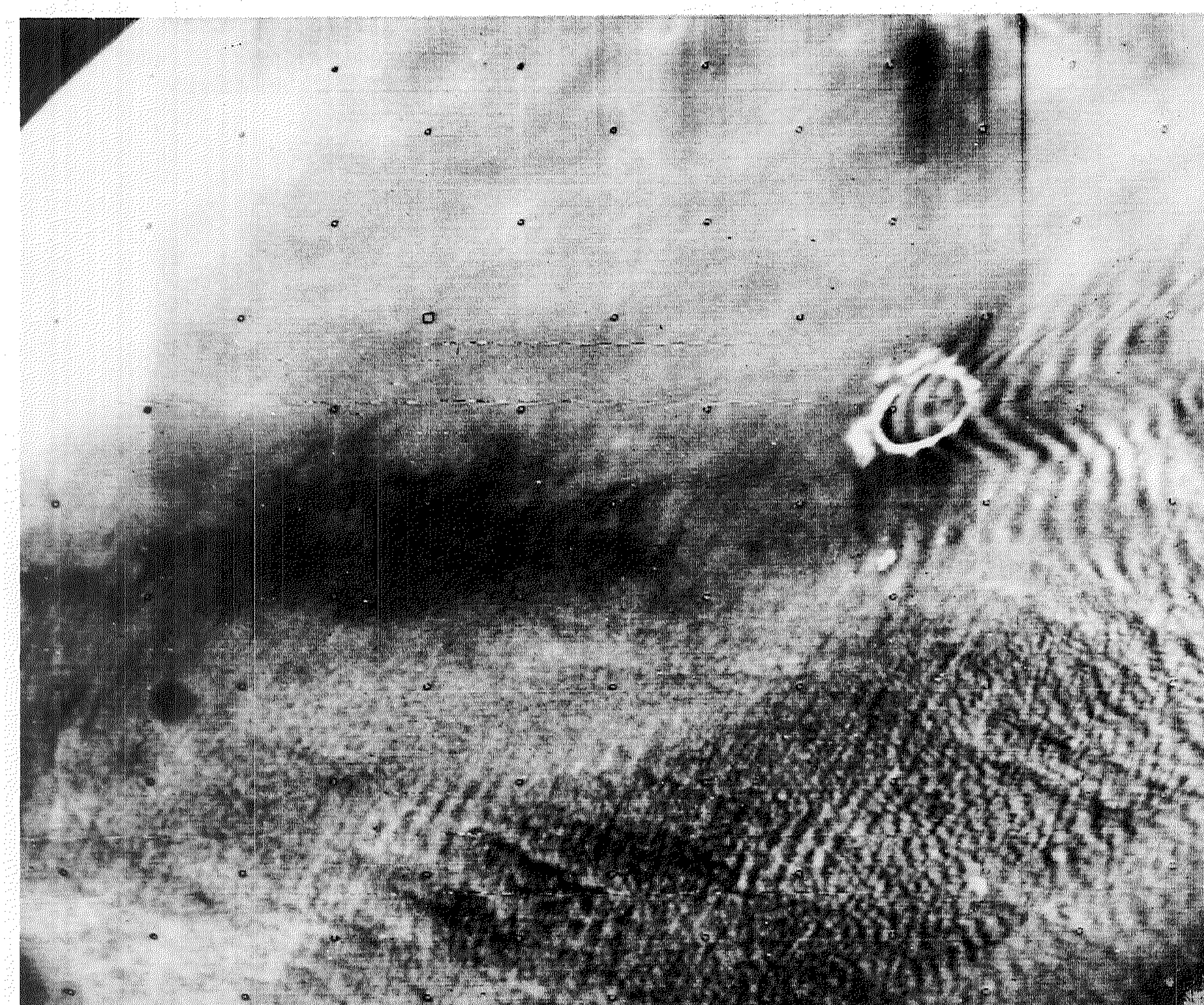
(Continued on page 135)



Development of cloud masses and lee wave clouds in northern latitudes, near 145°, +45°, February 11 to 14, 1972. The horizontal line is 45° N latitude. Circles indicate a fixed crater associated with a lee wave cloud on February 13 and 14. Details of cloud development near dark marking (arrow, February 11) are shown in illustration at right.

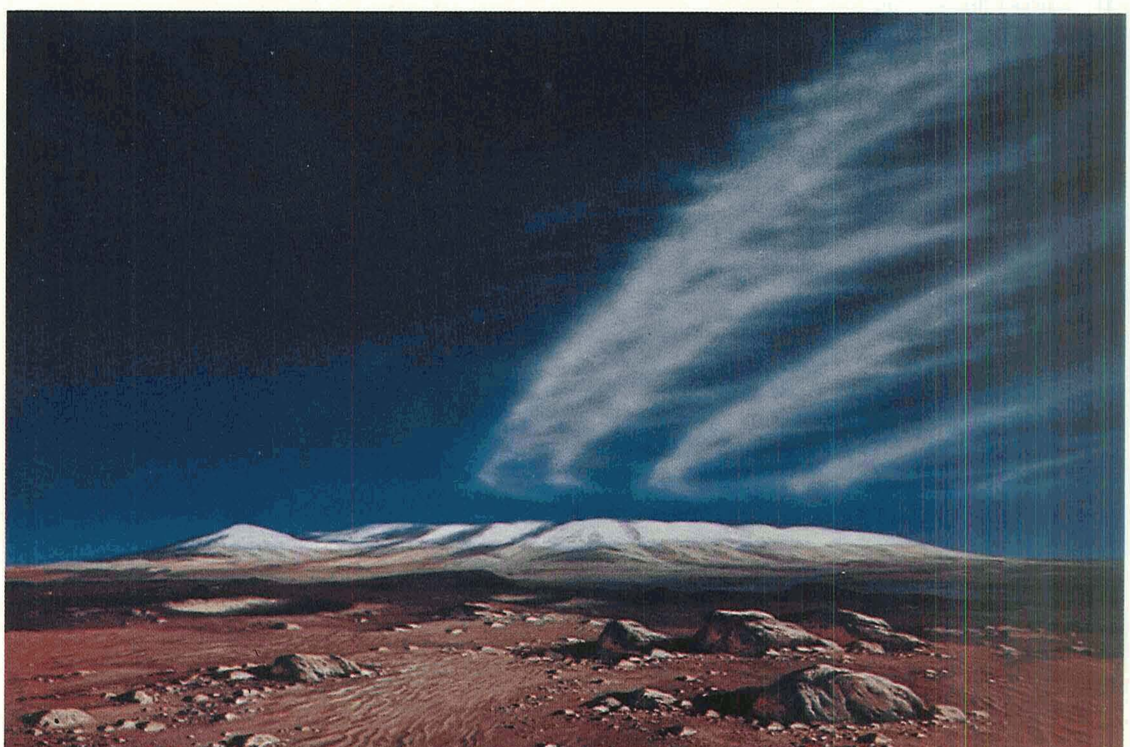


Cloud development near a dark region in Euxinus Lacus, near 158°, +38°. The arrow marks a fixed surface feature. These photographs were made on February 9, 12, and March 2. (P–12945)

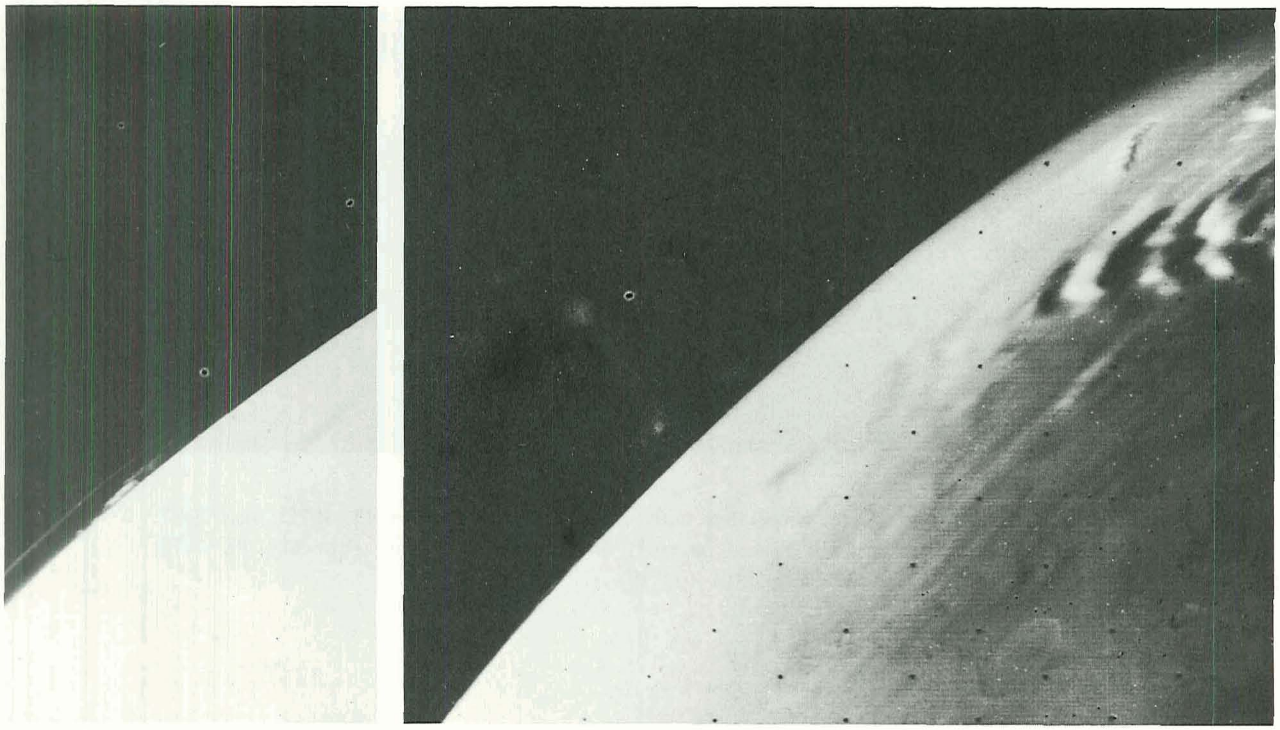


Scattered clouds and prominent lee wave cloud near a bright-rimmed (possibly the result of frost patches) crater at 72°, +55°. Wave spacing is about 30 kilometers. The long axis of frame covers about 900 kilometers. This photograph was made February 9, 1972; the prominent crater was free of wave clouds in photographs on February 27. (4208–90)

Details of wave cloud associated with a double-ring crater about 218 kilometers in diameter, near 327°, +52°. Waves are roughly 30 kilometers apart. (1649–125842)



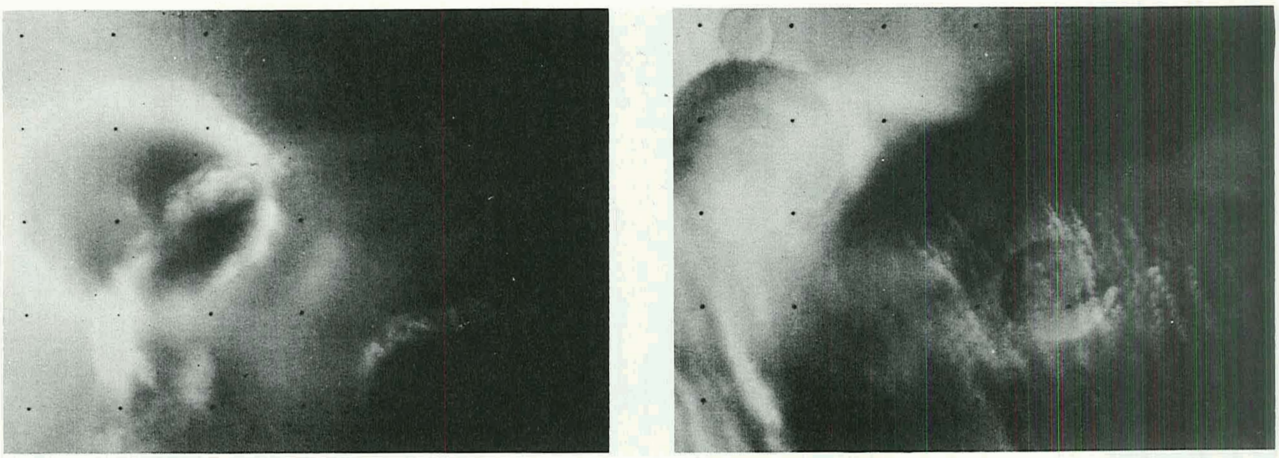
Artist's conception of a lee wave cloud formed over a frost-rimmed crater seen from the Martian surface in the polar latitudes. (Painting by Ludek Pesek, © 1973, National Geographic Society)



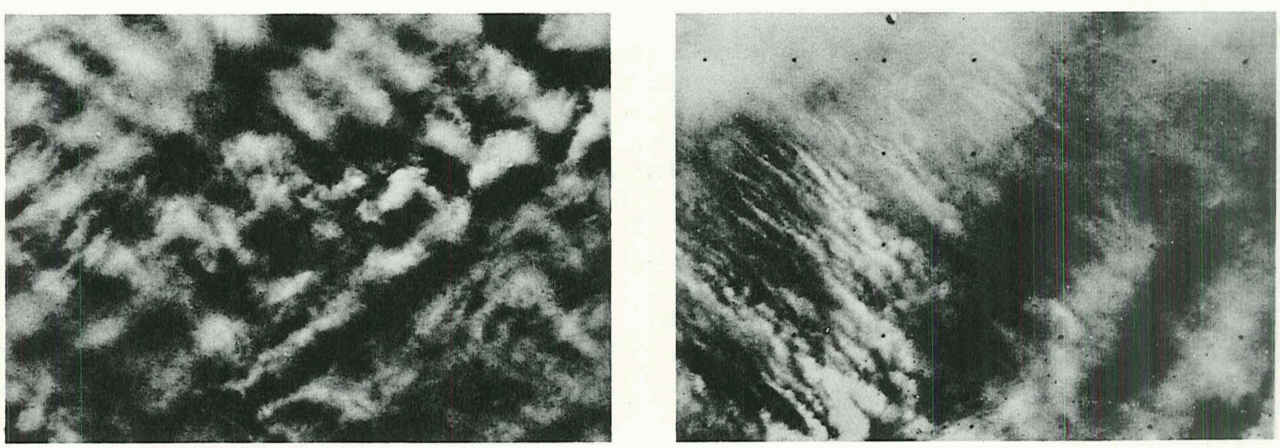
Two views of lee wave clouds over the Martian region of Tempe. Left view shows the clouds as billowy structures in profile on the horizon. The greatest heights are 30 kilometers; there is a thin dust layer at about 45 kilometers. Right view shows the wave clouds from above (upper right), where shadows suggest that they have a typical height of about 20 kilometers. (P–12795)

may well limit the rate at which carbon dioxide can freeze out onto the surface polar cap, and the moisture transfer rate may determine how much water is frozen out into the caps as they grow.

Not all of the condensation clouds observed were easily interpretable in terms of familiar terrestrial processes. As the northern summer progressed, a different type of cloud was seen to develop each afternoon over the west slopes of Olympus Mons and the three great calderas of the Tharsis dome. Clouds have often been seen in this region by astronomers, but the reason for their regular seasonal and diurnal occurrence remains a mystery. Infrared data showed the clouds to be made of ice crystals, and their seasonal appearance may coincide with the period when the water vapor released from the northern polar



Telephoto views of clouds associated with craters. *Left*: February 11, 1972; near 347°, +63°, showing crater with rim apparently frost covered. *Right:* February 19, 1972; near 270°, +60°. (7063–160935, 1431–193240)



Telephoto views of cumuluslike clouds. In right view, filamentary streamers are a few kilometers apart. Both views were made February 28, 1972; photographs have similar scales. *Left:* near 177°, +54°. *Right:* near 178°, +60°. (1391–231015, 1391–232557) cap reaches its maximum concentration in the atmosphere. The diurnal recurrence may be due to the daily heating and rising of this moist air up the slopes of the volcanoes. As previously mentioned, there may also be more water vapor in the atmosphere near the calderas than elsewhere.

Even more puzzling were some of the clouds observed near the retreating north polar cap during the summer. These long clouds, seen streaming off the cap toward the southwest, may have been due to water vapor subliming from the cap and recondensing in the atmosphere. They were quite unlike anything known in Earth's atmosphere.

At the turn of the century, when Lowell was writing, it was imagined that the Martian atmosphere might be like Earth's, which has a surface pressure of 1000 millibars. In 1909, Flammarion's book contained reasoning by the British astronomer Maunder leading to an estimated Martian surface pressure of 140 millibars. By the 1950's a number of techniques converged on a value around 85 millibars for the Martian surface pressure. As late as 1962, E. C. Slipher was able to comment that "numerical values reported for the surface pressure of Mars are remarkably concordant in spite of the many doubtful assumptions introduced." Slipher proposed a "most probable value" of 83 to 89 millibars, based on the various published results. At about the time of the Mariner 4 flight, new ground-based spectra lowered the estimated value to about 15 to 25 millibars. Within months, data from the Mariner 4 occultation experiment lowered the value still further to about 5 to 8 millibars. This value, less than 1 percent of Earth's surface pressure, has been confirmed by subsequent Mariner experiments and ground-based techniques. It means that the surface air density on Mars is equal to that at an altitude of 100 000 feet or more above Earth, an altitude three times that of most commercial jet flights. Thus Mars has been found to have an atmosphere much more rarefied than that assumed by early advocates of life on the planet.

Mariner 9, using data from the radio-occultation experiment and the two spectrometers on board the spacecraft, was able to accurately measure the surface pressure over most of the planet. The occultation experiment obtained 262 data points scattered over the entire surface, each of which provided an accurate pressure at that point. These pressures ranged in value from 2.8 millibars in the Cloritas and Tharsis areas to 10.3 millibars in the region of the north polar cap. It was then possible to normalize the spectrometer data to these points, resulting in a reasonably accurate surface pressure map covering most of the planet. The combined data indicated that some very low areas, such as the floor of Hellas or the bottom of the Vallis Marineris, may have pressures as high as 12 millibars or more. Recalling that the triple-point pressure above which liquid water can exist is 6.1 millibars, it appears there are many areas on Mars low enough to sustain liquid water provided it becomes available under temperature conditions high enough to prevent freezing.

The determination of the topographic shape of Mars, both from atmospheric and other information, raises the possibility of determining information about the internal structure of the planet. This information will be considered in the next chapter.

CHAPTER XI

The Shape and Global Geology of Mars

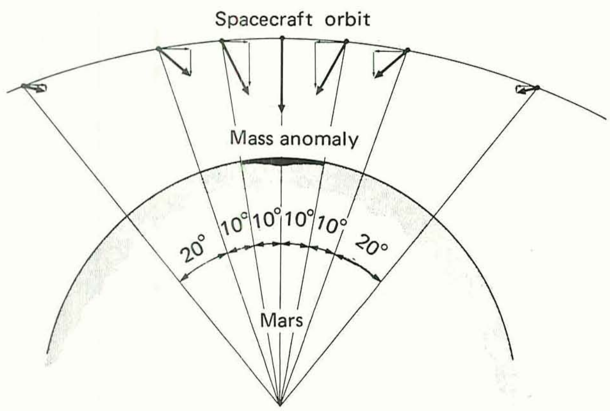
The planet Mars holds out the best possibility of testing the hypothesis that the inner planets can be regarded as having similar compositions, since it possesses satellites and therefore more can be known of its internal mass-distribution than is the case for either Venus or Mercury. Even so, it appears that neither the radius nor mass of Mars has yet been determined with the [needed] accuracy. . . .

—R. A. LYTTLETON, 1963

The previous chapters have discussed the conditions on and near the surface of Mars, both now and in the past. However, Mariner 9 discoveries were not restricted to the surface; they reflected on both the interior and external environment of Mars. For example, the motions of the spacecraft directly indicate the form of the gravitational field around the planet, which is in turn shaped by the mass distribution inside Mars. A topographic bulge on one side of Mars or a concentration of dense material under the surface in one area would distort the gravity field and alter the spacecraft's motion as it passed over that area. Discovery of such motions would imply geologic anomalies that might be seen in the surface structure revealed by photographs. Thus Mariner 9 data on the gravity field, the topography, and the surface geologic units all have a complex relationship.

For many years it has been suspected that Mars is not precisely spherical in shape but rather flattened at the poles like Earth. Direct optical measurements of the shape of the disk have been attempted by astronomers over the past 100 years. These attempts ran into several problems, such as the fuzziness of the image and different results with red and blue light, due to their different sensitivities to the Martian atmosphere. Nonetheless, positive results were obtained: the equatorial radius was found to be about 36 kilometers greater than the radius at the poles. This flattening, or oblateness, is usually expressed in terms of the ratio $(r_e - r_p) / r_e$, where r_e is the equatorial radius and r_p the radius at the pole. For Mars it was found to be approximately 0.011.

Unfortunately, two serious problems with this result were apparent at once: it was well above the theoretical limit for flattening if Mars were a homogeneous planet and it was also twice that obtained from an independent measurement, known as dynamic flattening. Whereas optical flattening is associated with the visual or geometric shape of a planet, dynamic flattening is a calculated value determined from the gravitational field; it is a measure of the total mass distribution within the planet. If a planet has a natural satellite in a closed orbit, the effect of a nonspherical gravitational field on the orbital movement of this satellite will allow a determination of the dynamic flattening. Both of Mars' moons are close to the planet, and calculations based on studies of their orbital motions resulted in a value of 0.0052 for the dynamic flattening; these discrepant results led to some controversy. However, H. C. Urey pointed out in 1950 that the two observations could be brought into accord if there were a ring of high mountainous terrain in the equatorial



Schematic diagram showing gravitational effects of a surface mass anomaly on the motion of the spacecraft orbiting Mars.

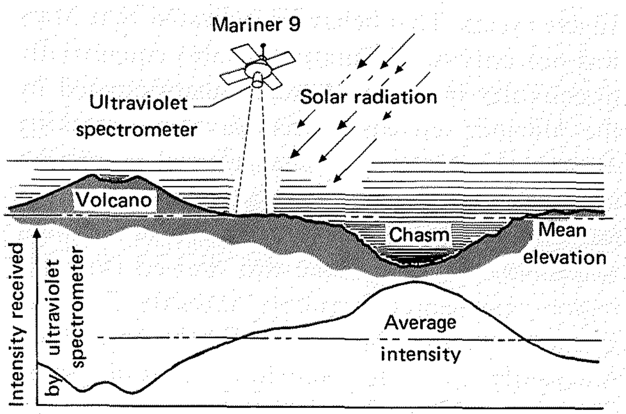
zone, isostatically compensated by a layer of less dense material beneath the mountains. Such high terrain could be responsible for the optically observed oblateness without affecting the validity of the dynamic flattening measurements.

Data from the Mariner 9 radio-occultation experiment determined that the equatorial radius was about 19 kilometers greater than the polar radius, and the photographs indicated low-latitude uplifted volcanic domes in Tharsis and Elysium. At the same time, the Mariner 9 celestial mechanics data verified the value for dynamic flattening derived from the motion of the Martian satellites. Data from both of these experiments also indicated quite early in the mission that the shape of Mars was much more complex than anyone had anticipated.

After the first orbital trim of Mariner 9, tracking data revealed that its orbital period was not constant but was oscillating sinusoidally in 18-day cycles. This behavior indicated that Mars was not only meridionally but also equatorially noncircular in shape—a result unanticipated by the Mariner scientists. Analysis of the tracking data by the occultation and celestial mechanics teams showed that the long axis of the equator ran through the Tharsis region, site of the high volcanoes. Tracking data also showed that this region represented a gravity anomaly 17 times greater than any observed on Earth. Apparently the slowly acting tectonic forces that shattered the crust and produced the volcanism in the Tharsis area also contributed to an irregularly shaped planet. Thus, in geometric terms, the shape of Mars is somewhat better defined by a triaxial ellipsoid than the oblate spheroid representative of Earth's shape.

Analysis of several different measurements of the shape of Mars, such as ultraviolet spectroscopy altimetry and radar data, gives values for the radius of Mars through three axes. March 1973 averages are as follows: the longest equatorial axis (105° longitude), 3396 kilometers; the equatorial axis at right angles to the longest equatorial axis, 3394 kilometers; and the polar axis, 3376 kilometers. It will be noted that the longest equatorial axis lies on a line through the longitudes of Syrtis Major and the highly elevated Tharsis region.

The Mariner 9 occultation data revealed still another anomaly in the shape of the planet: averaging over large regions the northern polar area was found to be lower (closer to the Martian center of mass) than the southern polar area by an average of about 3.4 kilometers. However, some investigators suggested that the surfaces of the northern and southern polar layered

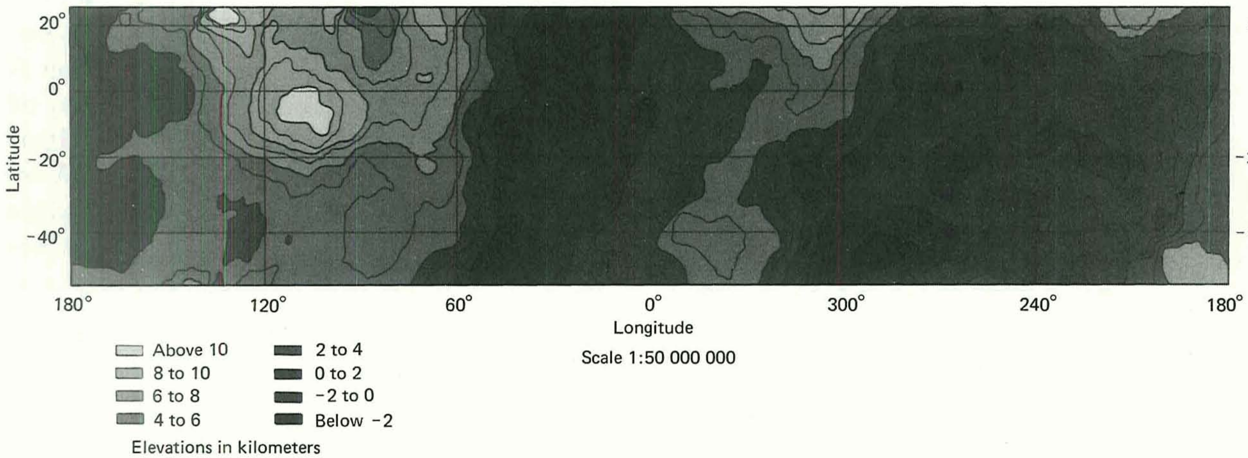


Schematic illustration showing correlation between Martian relief and light intensity received by ultraviolet spectroscopy experiment, which measures ultraviolet light scattered by the Martian atmosphere.

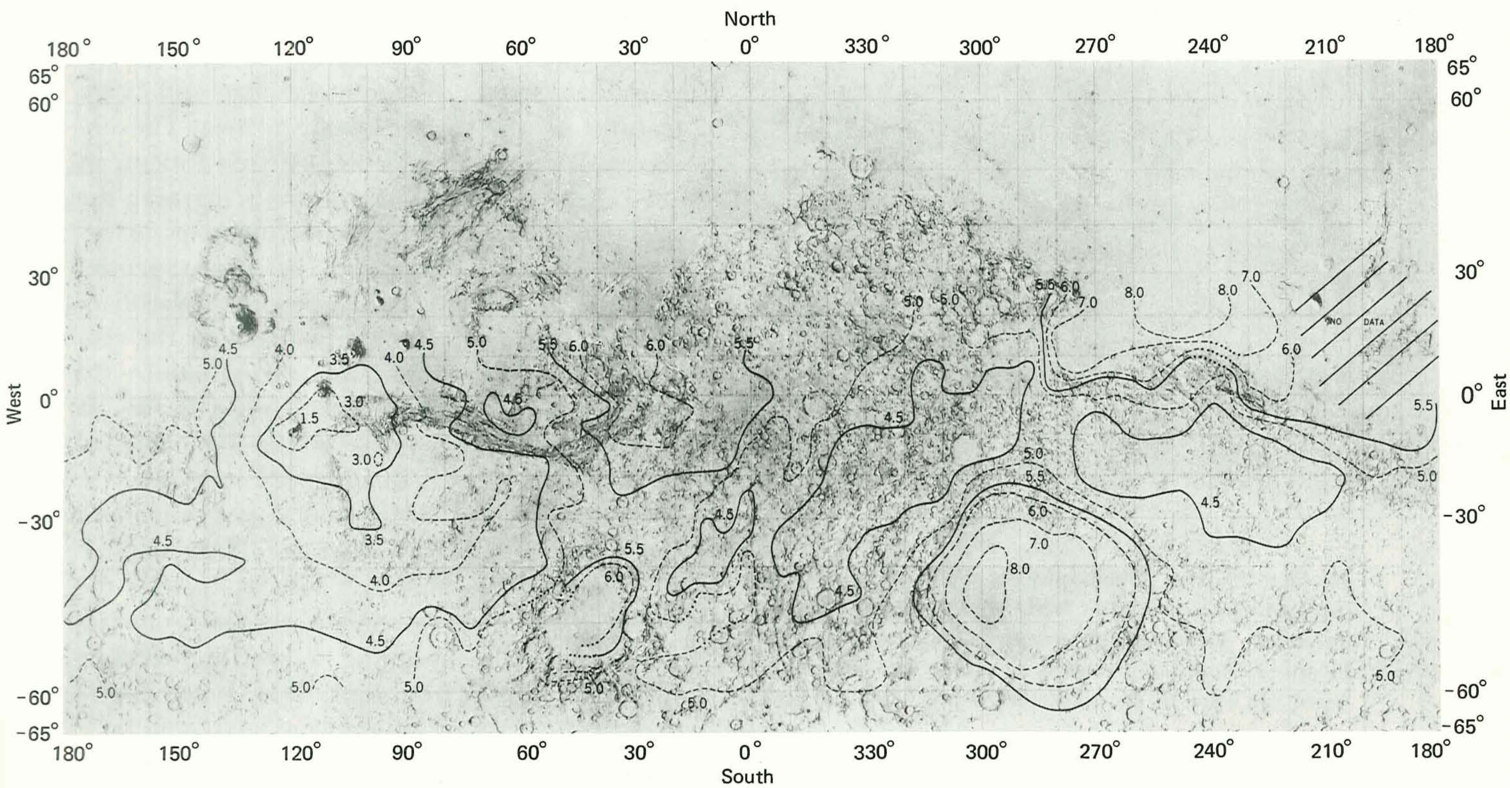
deposits were at about the same altitude, indicating that the layered deposits were considerably thicker at the northern pole. The additional burden represented by this increased thickness is consistent with the hypothesis, mentioned in an earlier chapter, that regional tectonic readjustment may have occurred in the north after the laminated deposits formed, accommodating their weight. Data on the absolute altitudes in layered terrain are relatively poor and this problem will bear further study.

As described earlier, both infrared and ultraviolet spectral instruments aboard Mariner 9 gathered data concerning the Martian surface pressure, which can be converted to topographical information by use of barometric equations with suitable corrections. These data tie together the widely spaced but more geometrically direct occultation measurements of topography and add a striking third dimension to the Martian map. To obtain such data, the infrared spectrometer made use of the absorption properties of carbon dioxide, the principal constituent in Mars' atmosphere. By monitoring the strength of CO_2 absorption features, infrared interferometer spectrometer analysts were able to measure the changes in total carbon dioxide density and convert them to altitude differences correlated with topographical features in the instrument's field of view. This method was limited to some extent by its sensitivity to atmospheric temperature, requiring careful and detailed analysis of each spectrum. The ultraviolet spectroscopy technique was somewhat easier, being based on scattering properties of the atmosphere, which are temperature independent. Molecules in the Martian atmosphere cause Rayleigh scattering, a strong effect at ultraviolet wavelengths. Measurements of the amount of Rayleigh scattering at ultraviolet wavelengths indicate the amount of atmospheric gas in the line of sight, and hence the elevation of the ground, in terms of a reference level. By choosing a narrow-wavelength region in the ultraviolet portion of the spectrum that was free of any absorption or emission features, ultraviolet spectroscopy analysts were able to correlate the measured intensities with the topography as viewed by the television cameras.

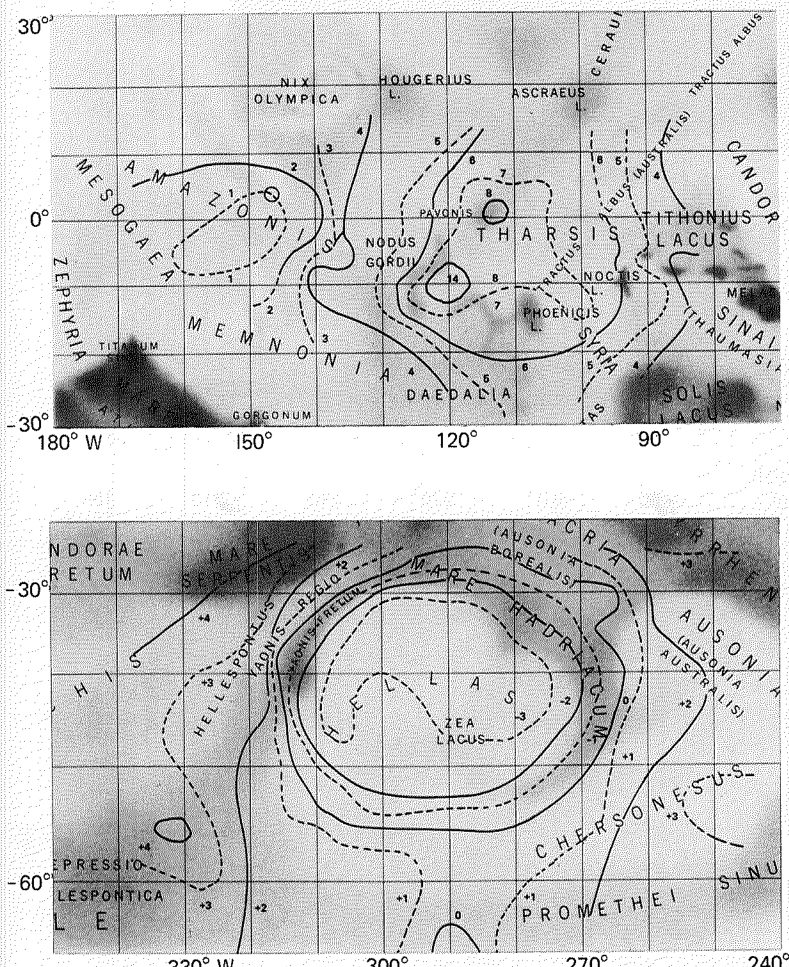
Additional topographical information was obtained from the Mariner 9 data by the use of stereoscopic techniques. Obtaining stereoscopic coverage of the Martian surface was not a specific objective of the Mariner 9 mission, but during the great dust storm many pictures were taken from different viewing angles of the few



Martian topography determined by the ultraviolet spectroscopy experiment showing the high Tharsis volcanic area (left) and depressed Hellas basin (lower right) as prominent features. (University of Colorado)



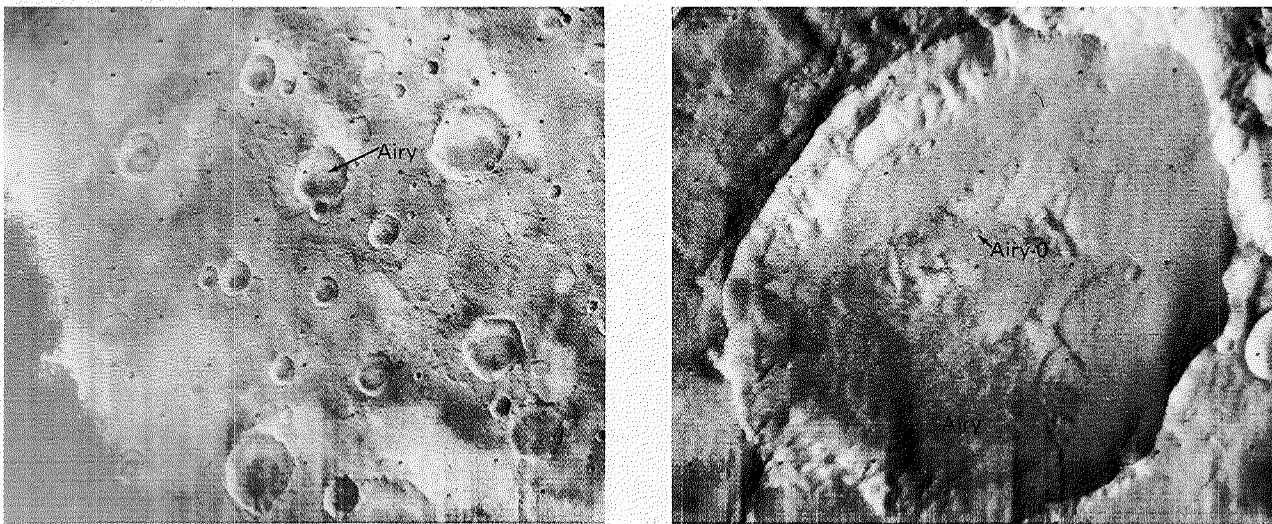
Martian topography, as revealed by pressure contours (numbers indicate millibars of atmospheric pressure), based on infrared spectrometer results. Highest pressures, exceeding 8 millibars, occur in the floor of the Hellas basin and near the Moeris Lacus basin. Low pressures occur on the Tharsis volcanic dome.



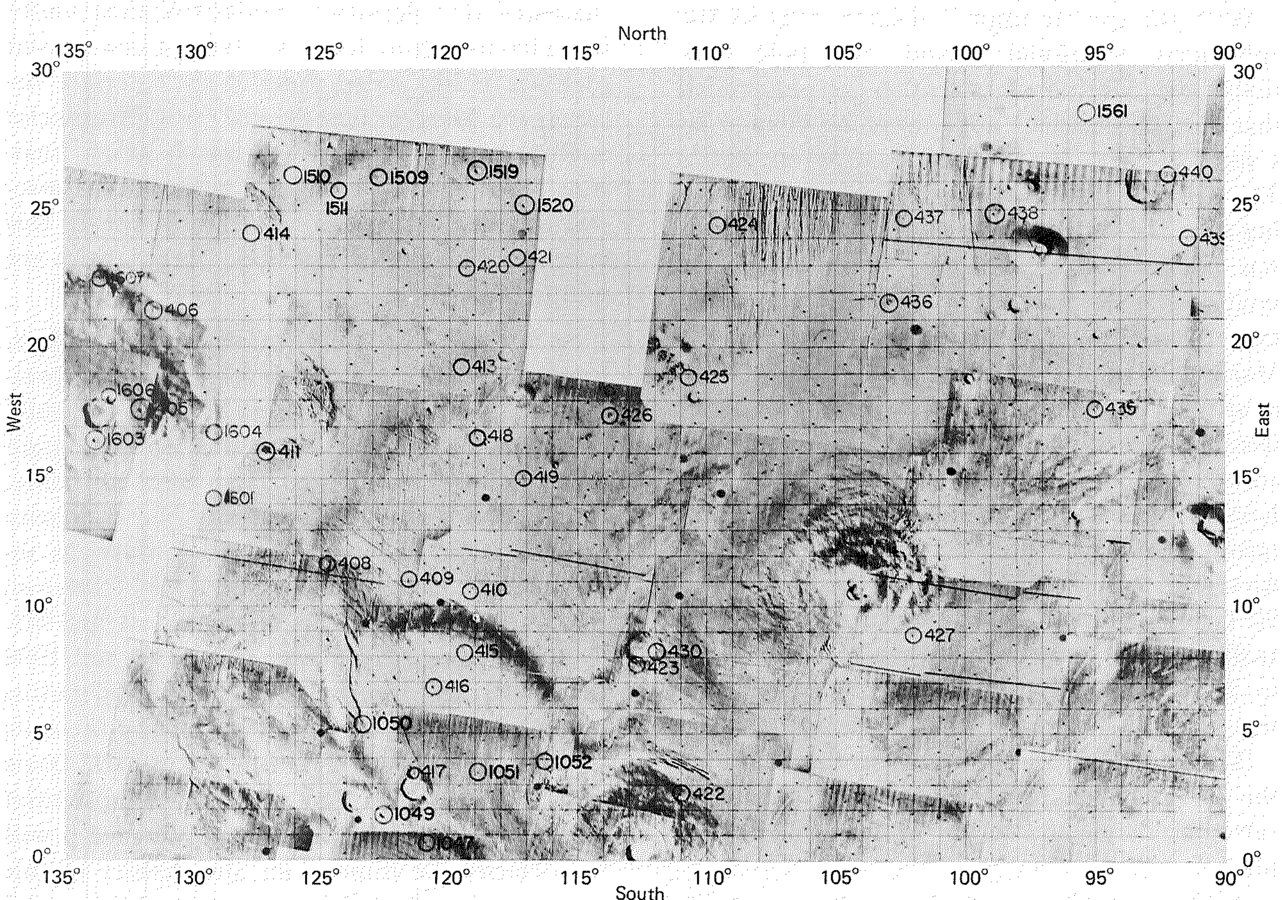
Detailed Martian topography in the highest (Tharsis, *top*) and lowest (Hellas basin, *bottom*) areas showing estimated elevation contours in kilometers, referenced to the 6.1-millibar pressure level in the atmosphere, based on infrared spectrometer results.

surface features that were relatively unobscured, such as the huge volcanoes and the south polar cap. Using computer techniques, the Mariner 9 scientists were able to rectify and scale many of these images into satisfactory stereopairs from which relief information could be obtained by photogrammetry. In spite of less-than-ideal pairs of images, there was reasonable agreement between the altitudes thus obtained and the measurements made by the spectrometers. For example, after refinement all methods converged on a height of Olympus Mons in excess of 20 kilometers.

Having mapped and measured the shape and topography of Mars with a resolution at least 20 times better than obtained by the best Earth-based photographs, there remained the task for the Mariner 9 scientists to make a commensurate improvement in the definition of the Martian coordinate system used to make maps and locate features on the surface of the planet. The observers Beer and Mädler in 1840 and Proctor in 1867 chose a certain dark feature as marking the prime meridian on their pioneering maps. Schiaparelli retained this choice in his influential map of 1877, and he named it "Meridiani Sinus." This longitude line, defined by the center of Sinus Meridiani, was equivalent to the Greenwich Observatory meridian on Earth. As improvements were made in the ephemeris of Mars, which defines the planet's motions, this definition became harder to maintain. Errors in the rotational period necessitated frequent adjustments in the ephemeris. Finally, in 1909 the decision was made to redefine the prime meridian of Mars by assigning a central meridian longitude as seen from Earth at a chosen epoch,



The newly defined position of the Martian prime meridian of longitude, passing through the crater Airy-0, named after the astronomer who defined the prime meridian of Earth.



Scale 1:5 000 000 at 0° latitude

Examples of points identified for use in the control net defining Martian latitude and longitude. These points (circles) are mostly small craters in the Tharsis volcanic region.

adopting the best known rotation period, and predicting the central meridian's longitude at each future instant of time. Thus the prime meridian was defined by the ephemeris itself rather than a fixed surface feature and allowed to drift as necessary to compensate for errors in the rotational period of the planet.

With the greatly improved knowledge of the ephemeris, rotational period, and pole positions, the Mariner 9 scientists recommended that the 0° meridian once more be defined by a fixed topographic feature, just as on Earth. The center of a small, nearly circular crater lying near the center of the Sinus Meridiani area was chosen as the Martian Greenwich. The small crater chosen lies within a larger crater easily seen on wide-angle pictures taken by both Mariners 6 and 9. Thus the known areographic relationship between the progressively larger terrain features allows the prime meridian to be accurately located at any resolution, including Earth-based resolution. The Mariner 9 scientists recommended that the larger crater be named Airy and the small crater Airy-0 in honor of Sir George Biddell Airy, who, during his tenure as director of Greenwich Observatory from 1835 to 1881, installed the transit instrument that was used to define the 0° meridian on Earth.

Thus Mariner 9 not only refined our data on the geometric shape of Mars but also laid the cartographic groundwork for future maps of the planet.

Analysis of Mariner 9 data will also clarify the significance of the shape of Mars. For example the motions of the spacecraft revealed irregularities in the gravitational field that indicated irregularities in the internal structure of the planet. Comparison of the gravity measurements to the geometric shape revealed whether the assumed masses of the Tharsis dome and other bulges were sufficient to account for their large positive-gravity anomalies, or whether additional mass or density concentrations were needed. Preliminary analysis of the gravity data suggested that density irregularities exist under the Tharsis region and that perhaps new crustal rock was being added there at the interface between the Martian mantle and crust. No precise analogs have been found to match lunar "mascons," the broad, flat mass concentrations associated with the lava plains of the Moon; in this sense the Martian crustal mass irregularities are uniquely Martian.

As for the deep interior structure of Mars, it was realized some decades ago that the presence of an internal iron core—like that surmised for Earth—could be tested if sufficiently accurate mass, radius, and related data were available. Such a test would help indicate the similarity or differences between Earth and Mars. As indicated by the quotation from R. A. Lyttleton, this problem was still in doubt as late as 1963. Data from the early Mariners in 1965 and 1969 increased the precision of the mass and radius determinations. As a result, studies by theorists such as D. Anderson, A. Binder, and D. Davis have indicated that Mars does have a substantial dense core. The new data from Mariner 9 will help clarify the dimensions and density of this core and thus shed light on its composition and evolutionary significance. Assumptions have been made in the past about the melting of planetary interiors and the resulting concentration of iron in their centers, but recent studies of the Moon as well as Mars have raised questions about the sequence of temperature changes and chemical differentiation. These questions are now open, but it is widely believed that comparative data on Martian and other cases may produce a new understanding of the structural evolution of planets.

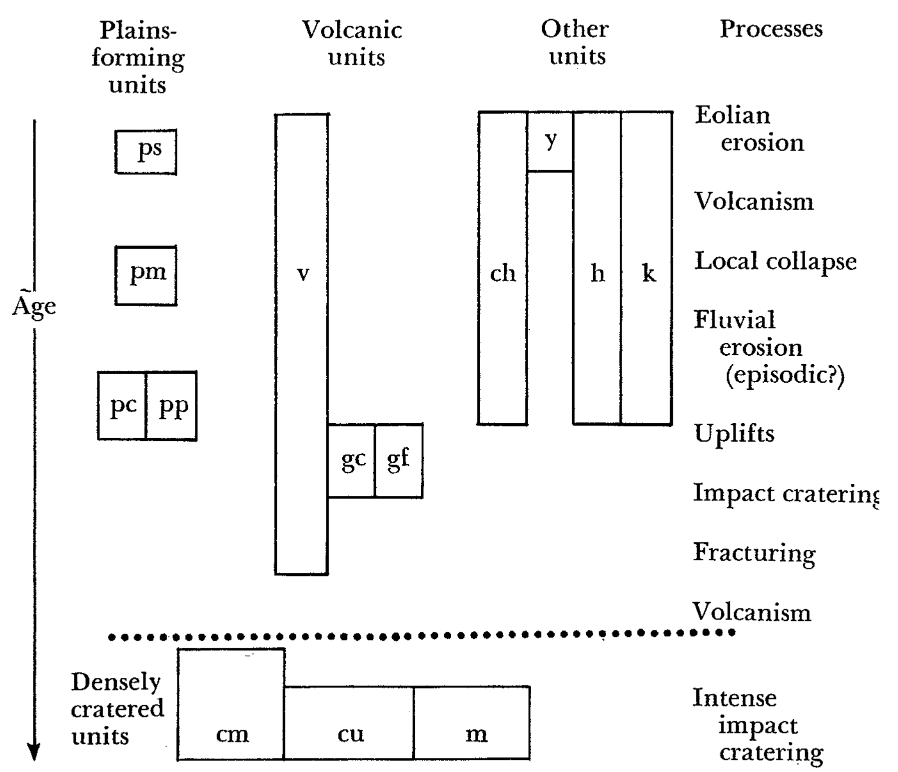
Mariner 9 mapping of shape and gravity irregularities of Mars led to better interpretation of the surface geology than could have been possible from the pictures alone. For example, the knowledge that Tharsis and Elysium are elevated and the measurement of the depths of the Vallis Marineris or the Hellas basin help to sort out physical and structural characteristics of these terrain units from superficial characteristics such as dark veneers of dust. After review and synthesis of the photographs and other data, Mariner 9 geologists have named 4 broad categories of units and 14 types of specific geological units.

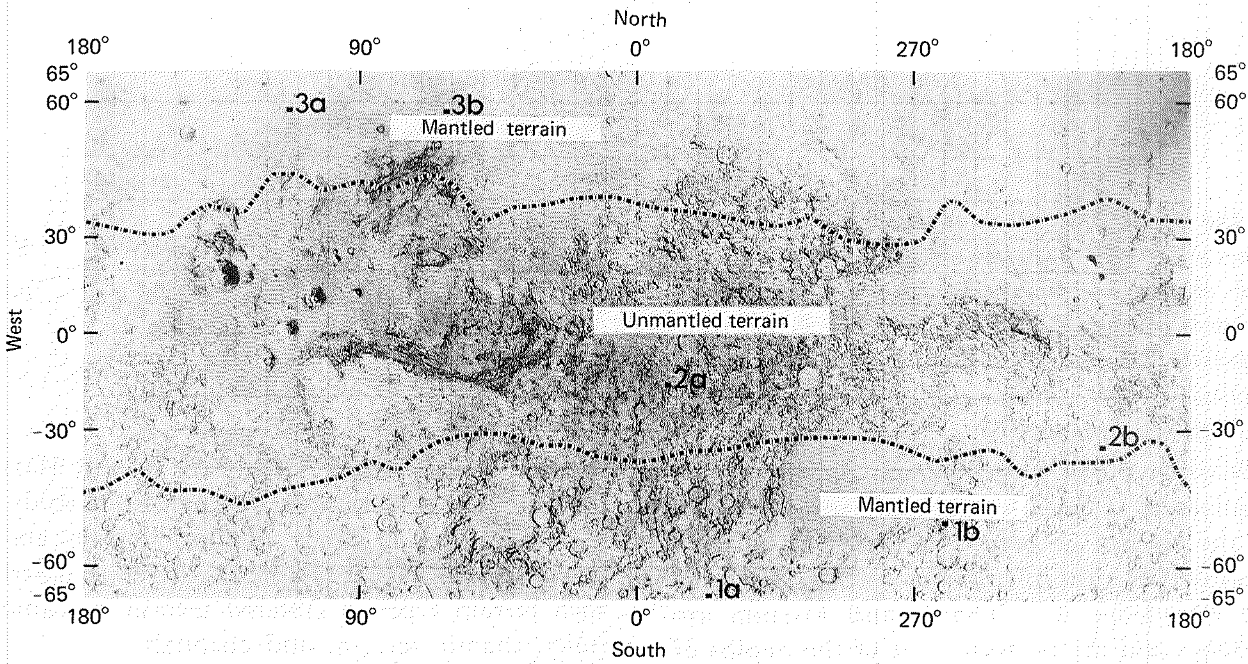
Unit	*Map abbreviation*
(1) Densely cratered:	
(*a*) Cratered deposits, undivided (ancient surface)	cu
(*b*) Cratered deposits, mantled (ancient areas with younger deposits)	cm
(*c*) Mountainous deposits (rims of large basins)	m
(2) Plains-forming materials (generally volcanic and eolian):	
(*a*) Heavily cratered plains material (old lava plains)	pc
(*b*) Moderately cratered plains material (Tharsis and Elysium lavas)	pm
(*c*) Sparsely cratered plains materials (very young Tharsis and other lavas)	ps
(*d*) Mottled cratered plains materials (polar plains with eolian deposits)	pp
(3) Volcanic (excluding plains-forming units):	
(*a*) Volcanic materials (shield volcanoes, domes, etc.)	v
(*b*) Grooved terrain materials, coarse (near Nix Olympica, fractured?)	gc
(*c*) Grooved terrain materials, fine (from Nix Olympica)	gf
(4) Other:	
(*a*) Channel deposits (riverbedlike deposits)	ch
(*b*) Channel deposits (floor of Vallis Marineris, for example)	y
(*c*) Chaotic deposits (low, collapsed (?) units)	h
(*d*) Knobby deposits ("fretted" terrain, isolated hills)	k

These units are used to divide the map of Mars into geologic provinces for more detailed study. They represent a finer subdivision than employed in the earlier chapters, where we noted such terrain types as cratered terrain, volcanic units, chaotic terrain, and channels.

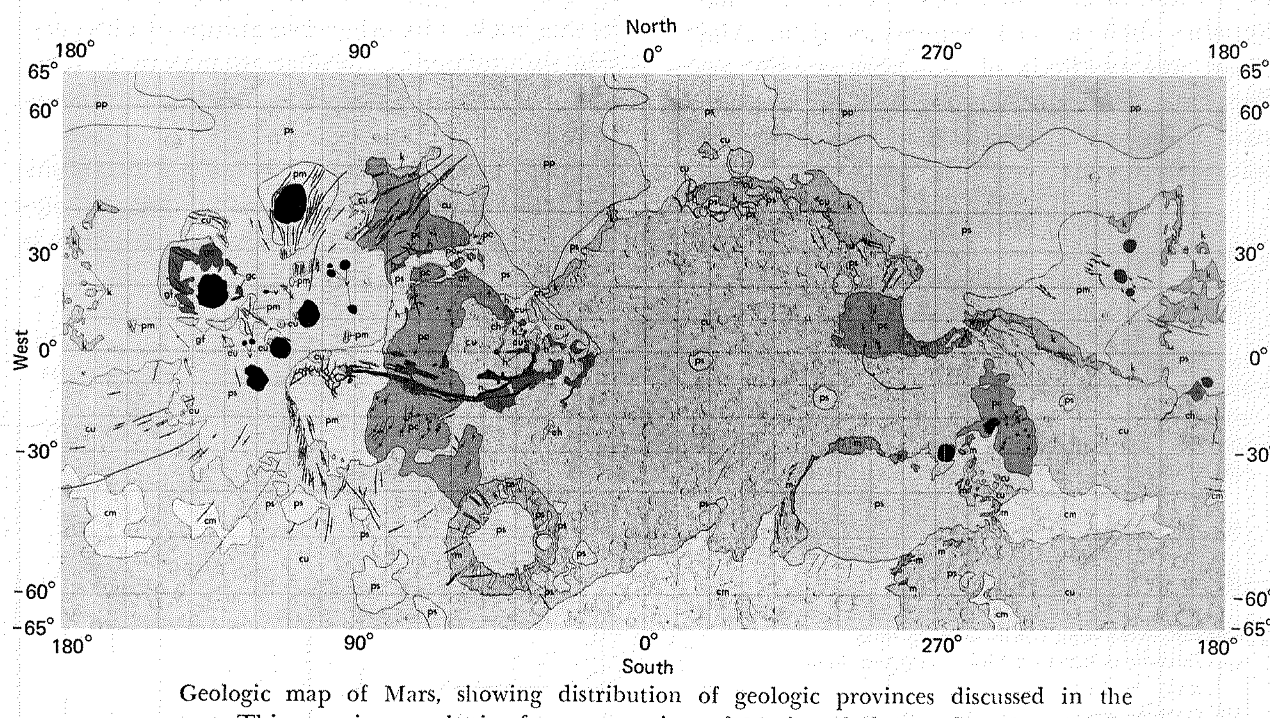
The densely cratered and plains-forming units can be thought of as characterizing the two dissimilar hemispheres of Mars, mentioned earlier in this book. The other two groups of units contain the isolated, somewhat anomalous features, such as large volcanoes, channels, and chaotic terrain.

These units can be arranged in a stratigraphic age sequence based on estimated relative ages and related to Martian processes, as shown in the following diagram:

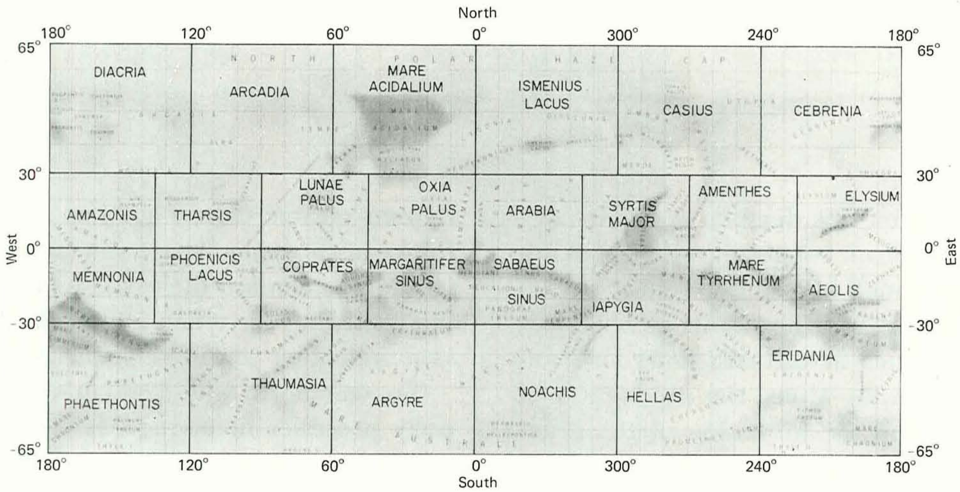




Example of simplified mapping of geologic units (mantled versus unmantled terrain) on the airbrush map of Martian structural features. Mantled units occur at high latitudes and probably result from transport of dust to polar regions.

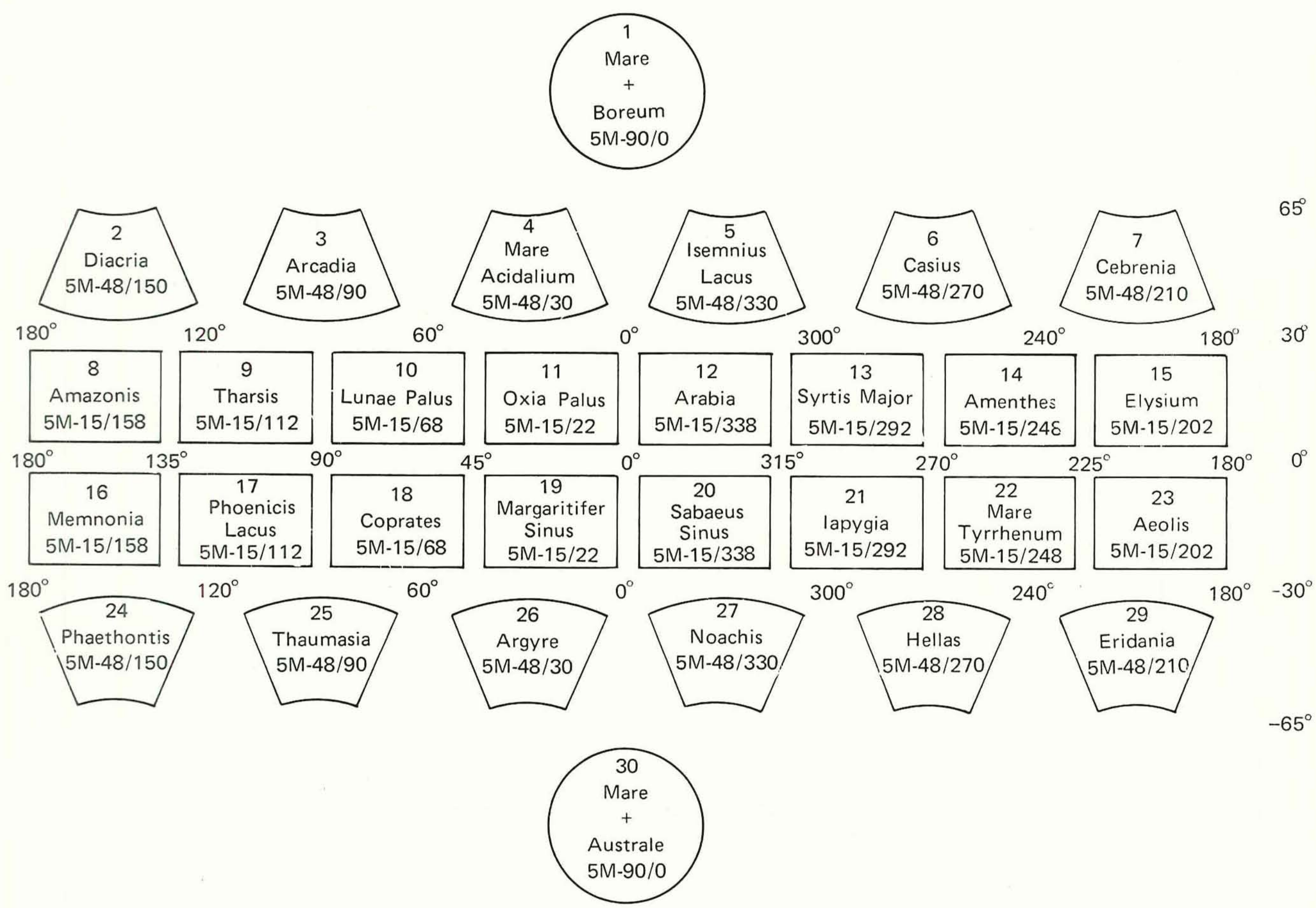


Geologic map of Mars, showing distribution of geologic provinces discussed in the text. This map is a synthesis of a great variety of Mariner 9 data and analyses. (U.S. Geological Survey)



Proposed division of Mars into "quadrangles" for detailed mapping program, superimposed on map of classic features.

Numbering and shapes of quadrangles proposed for mapping program to produce maps at a scale of 1:5 000 000.



The story told by this diagram is the history of Mars, sketched in rough outline. Looking at the present planet we see the results of the current dust storms and the results of relatively recent processes such as the lava flows and volcanism near Olympus Mons, the production of chaotic terrain, and the formation of the channels at a time when more water may have been available. At an earlier time, fracturing must have occurred, as well as early volcanism, that gave rise to the major canyons, fault patterns, and lava plains. Throughout this period and stretching back to the earliest eras, meteorite impacts created craters as Mars swept up debris from interplanetary space. The most densely cratered units contain the earliest surviving record, but even they have ben altered by Martian erosion and other localized disturbances.

To search for the least-altered evidence of early processes involving Mars, we need to escape from the influence of the Martian atmosphere and internal evolutionary processes. Fortunately, nature has provided two small satellites above the Martian atmosphere, and these may contain clues to very ancient events, as described in the next chapter.

CHAPTER XII

Phobos and Deimos

[The astronomers of Laputa] have . . . discovered two lesser stars, or satellites, which revolve about Mars, whereof the innermost is distant from the center of the primary planet exactly three of his diameters and the outermost five . . .

—Dean Swift, 1720, in *Gulliver's Travels*

. . . [five German mariners setting forth] to find out whether it is true that on July 10 of this year [1744] the planet Mars appeared with a satellite or moon for the first time since the world has been in existence.

—Eberhard Christian Kindermann, 1744, in *Die Geschwinde Reise auf dem Lufft-Schiff nach obern Welt,* quoted by Marjorie Nicolson

. . . our travelers crossed a space of about a hundred million leagues and reached the planet Mars. They saw two moons which wait on this planet, and which have escaped the gaze of astronomers. I know well that l'abbé Castrel wrote against the existence of these two moons; but I agree with those who reason from analogy. These good philosophers know how difficult it would be for Mars, which is so far from the Sun, to get on with less than two moons.

—Voltaire, 1750, in *Micromégas*

. . . at half past two o'clock [August 11, 1877] I found a faint object on the following side and a little north of the planet, which afterward proved to be the outer satellite. I had hardly time to secure an observation of its position when fog from the Potomac River stopped the work.

—Asaph Hall, 1877, on the discovery of the Martian satellites

After years of searching by various astronomers Asaph Hall finally discovered satellites near Mars at the Naval Observatory in Washington in 1877. There were two of them and they were small bodies, too faint to be seen by such earlier astronomers as Herschel, who had searched for satellites as early as 1783. Careful reading of the quotations above reveal the curious fact that literary writers were alluding to the two moons of Mars 150 years before they were discovered. This coincidence, which would seem to belong in a book on astrology, can be explained through further historical research. Johann Kepler, who discovered the laws of planetary motion about 1610, was something of a believer in numerology or, as he called it, the harmony of the spheres. When the telescopic observations of Galileo revealed that Jupiter, the next planet beyond Mars, had four satellites, Kepler and others speculated about the possibility of Martian satellites. The argument went that, in order out from the Sun, Venus had no moons, Earth had one, Mars was uncertain, and Jupiter had four. Two moons for Mars seemed the proper assumption to fit the mathematical progression.

This speculation was probably read by Swift (who is known to have been familiar with Kepler's laws) and Voltaire, who worked it into their fiction. As for Swift's prediction of the orbital distances being three and five Martian diameters, the correct numbers as discovered by Hall are about 1.4 and 3.5 Mars diameters.

After Hall discovered the satellites, a number of possible names were suggested, but Hall chose a suggestion by Madan, of Eton, England, who noted in Greek mythology and in Homer that the two horses drawing the chariot of the god of war were Phobos (fear) and Deimos (terror).

Knowing the brightness of the Martian satellites, pre-Mariner astronomers could assume various reflectivities for the Martian satellites and thus compute how big they had to be to reflect the observed amount of light. Assumed reflectivities were those of the Moon, meteorites, or terrestrial rocks. These led to early estimates of Phobos' and Deimos' diameters, respectively, of about 49 and 32 kilometers (30 and 20 miles). The two moons were hardly more than floating mountains. Later Earth-based estimates revised the figures to values as low as 16 and 8 kilometers (10 and 5 miles).

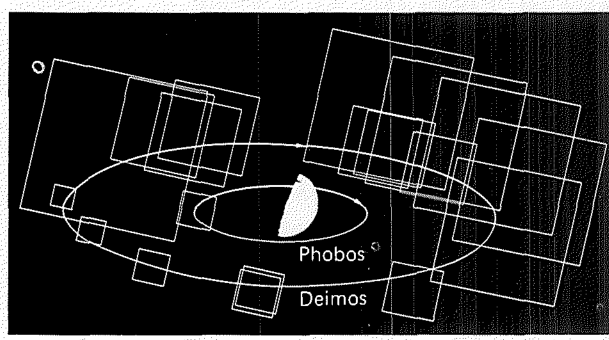
Because these two satellites appear only as faint points of light nearly lost in the glare of nearby Mars, little could be learned about their nature. It was widely assumed that their presence and their unusually small size, unique among the nearby planets, might have something to do with the nearness of Mars to the asteroid belt, which is composed of countless similar objects ranging in size from large asteroids a few hundred kilometers in diameter to many objects smaller than Phobos or Deimos.

In 1969, Mariner 7 obtained a photograph of Mars in which Phobos was silhouetted against the planet. This was the first detection of the disk of Phobos allowing a direct measurement of the size of the satellite. Phobos was found to be irregular in shape with dimensions of about 18 by 22 kilometers and an unusually dark surface. The image was so small and dark that no craters or other surface detail could be seen.

Early in the Mariner 9 mission a similar image of Phobos in silhouette was obtained, but this was of only passing interest when compared to the high-resolution closeup photographs of both Phobos and Deimos that were later to come from the mission. Because of the obscuration of the surface of Mars by the dust storm, a substantial part of the photographic picture budget was applied to the satellites during early weeks of the mission.

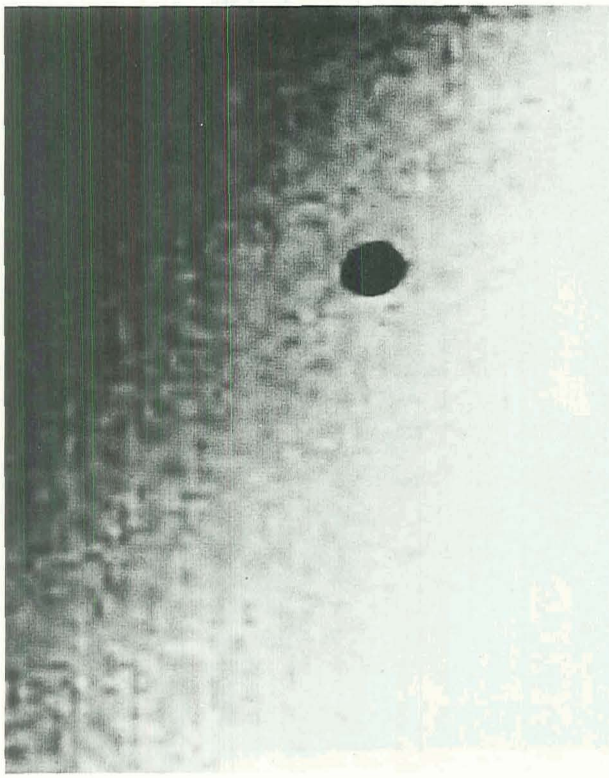
First the satellites had to be reliably located, using the best determinations of their orbits available from Earth-based studies. Searches for the satellites and their eventual acquisition by the telephoto camera resulted in improvements to the earlier knowledge of their orbits. For example, a 600-kilometer (3°) correction was made to the mean longitude of Phobos in its orbit, and the inclination of its orbit was corrected by 0.3°.

Once the satellites were acquired by the telephoto camera, there was much excitement over



Mariner 9's preorbital pictures of the vicinity of Martian satellite orbits. These frames, mapped here against the orbits of Phobos and Deimos, were used to acquire the two satellites and to search for new satellites.

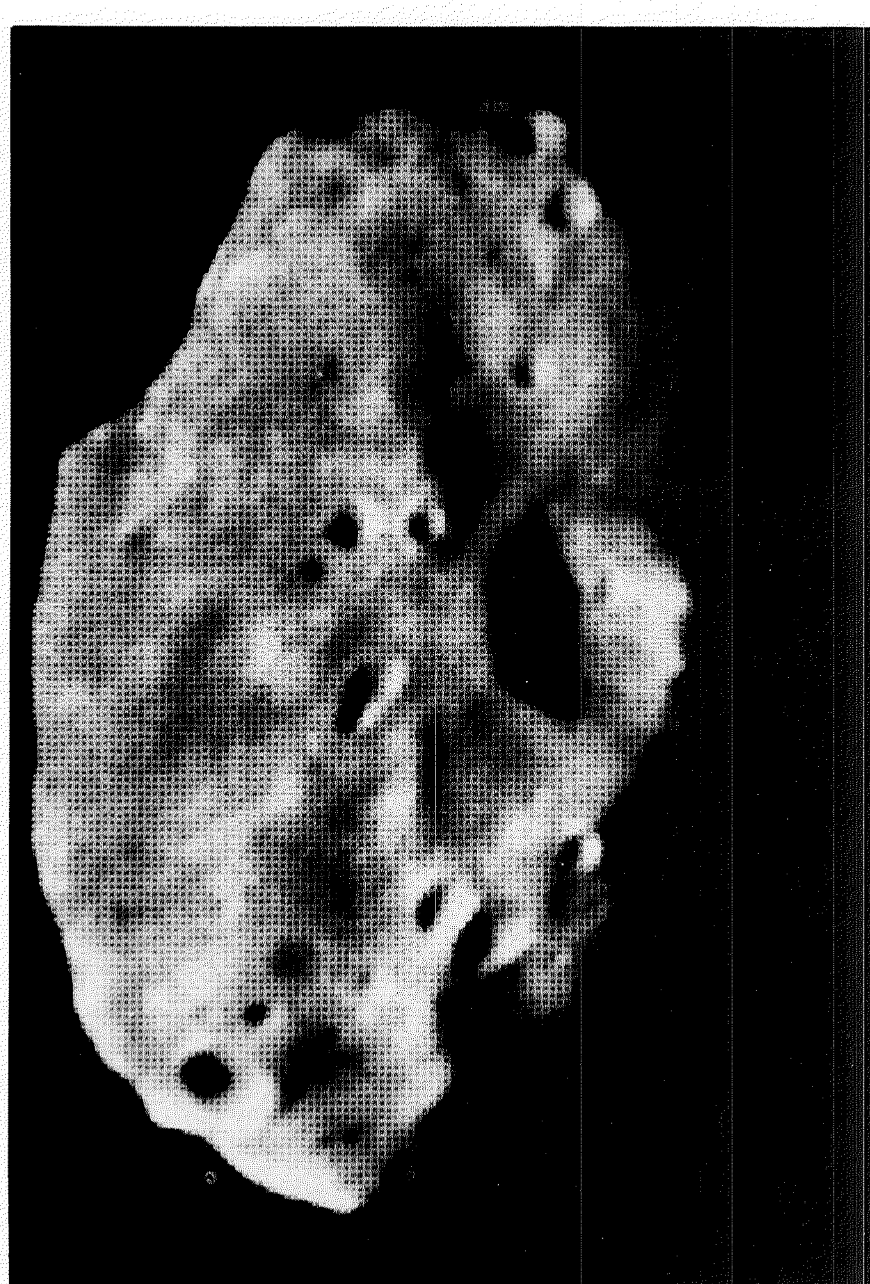
their appearance. Until that moment, no one had known what the surface of an asteroidal-sized body would look like. Would it be polished smooth by countless micrometeorite impacts acting like a sandblasting process? Or would it be pitted with large craters? Would there be a layer of dust, as on the Moon? Or would the dust have been knocked off by impacts, exposing bare rock? Would the surface be coherent or highly fractured? Could it be proven that the satellites were rocky, or could they possibly be metallic (as are iron meteorites) or even loose, sandy agglomerations of particles? Lurking in the back of investigators' minds was a hypothesis advanced a few years ago by the Soviet scientist I. Shklovskii, who reasoned from certain unusual characteristics of Phobos' orbit that it might be an artificial satellite launched by a Martian civilization. (Some of the assumed orbital peculiarities on which this hypothesis had been based had been discounted by the time of the Mariner 9 mission, so the idea was scarcely viable.)



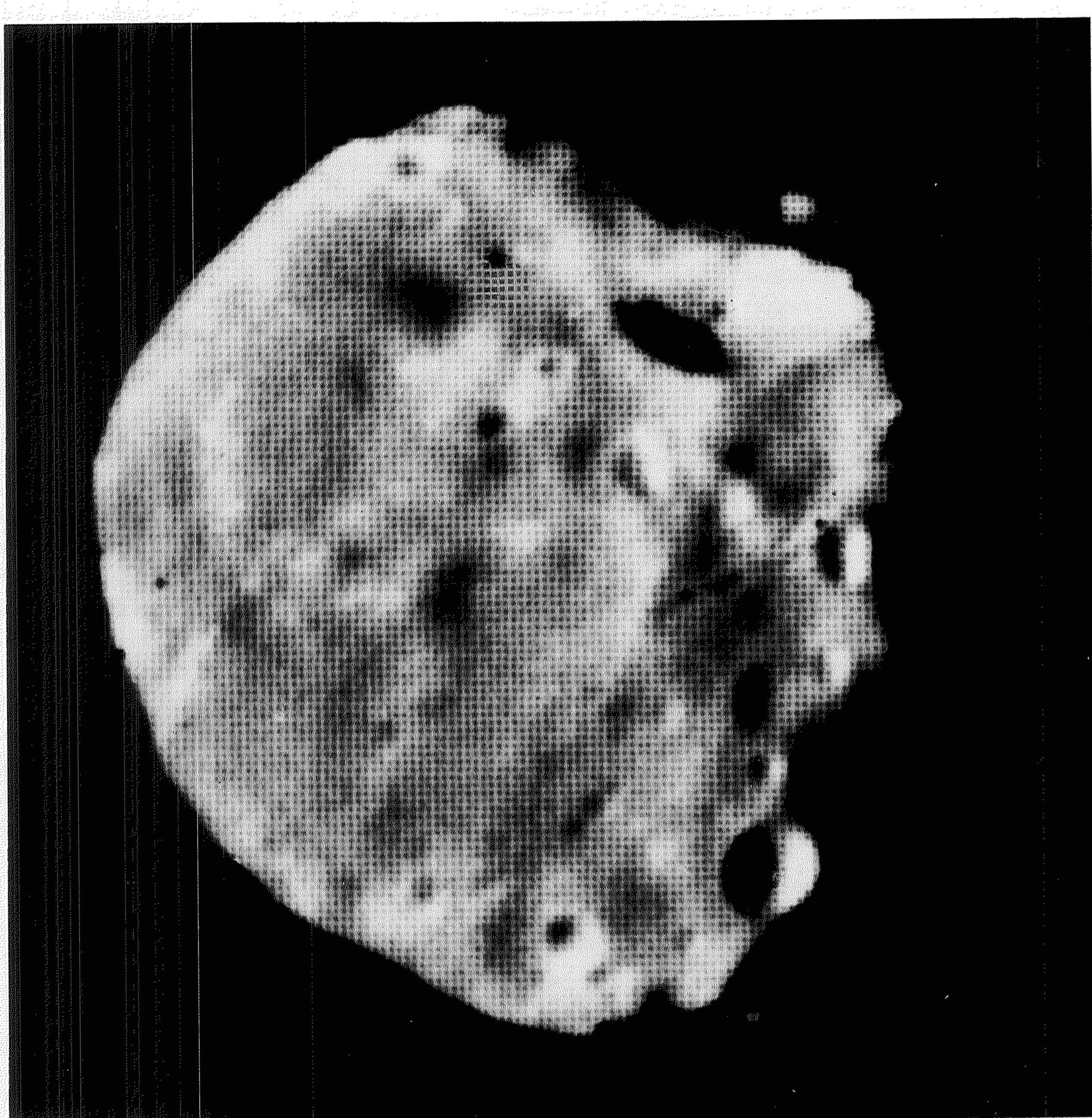
Phobos, silhouetted against Mars, in a preorbital view by Mariner 9 taken about 150 000 kilometers from Phobos. (P–12679)

The first telephoto photographs of Phobos and Deimos revealed them to be heavily cratered bodies with about as many craters per unit area as the most densely cratered parts of the Moon. This discovery, supported by numerical calculations of crater formation rates, indicated that Phobos and Deimos are probably billions of years old and may date back to the formation of Mars.

Phobos was observed by the infrared radiometer on board Mariner 9 as it emerged from the eclipses produced when it passed through the shadow of Mars. Measurements of the temperature as Phobos passed into sunlight indicated the rate of warming of the satellite surfaces and hence allowed an estimate of the amount of insulating dust on the surface. It was found that the satellites have a very thin layer of dust, perhaps millimeters thick. This evidence was supported by University of Arizona astronomer Ben Zellner, who, at about the same time, obtained polarization measures of Deimos with Earth-based telescopes indicating that the surface of Deimos was not bare rock, but had a dust cover.



The first closeup view of Phobos, from 5720 kilometers, showing the satellite's cratered surface. The largest visible crater is about 5 kilometers in diameter. The "notch" in the edge of Phobos, upper left, is the site of a larger crater, about 9 kilometers in diameter. Phase angle (Sun-Phobos-spacecraft), 59°. (83–235921)



Phobos. The largest visible crater is about 5 kilometers in diameter. Somewhat below it, middle right, is an alinement of small craters, which may mark an internal fracture in Phobos. Range, 6460 kilometers; phase angle, 57°. (DAS 4 215 690)

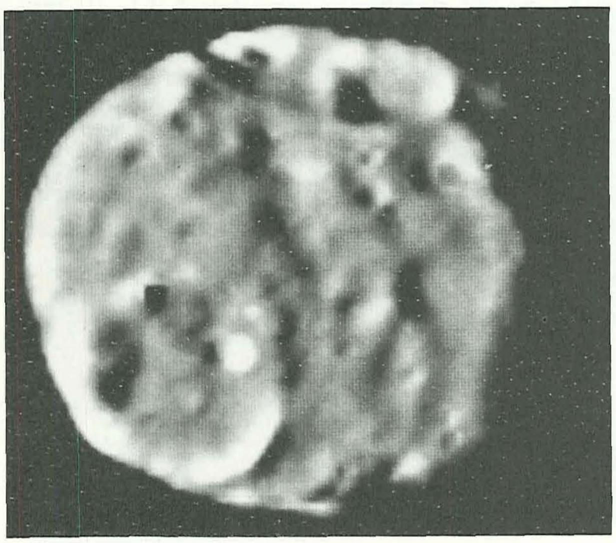
The fact that Phobos and Deimos display discrete impact craters and retain some dust produced during these impacts places interesting and useful constraints on our knowledge of what happens when small interplanetary bodies collide in space. The results cannot be extrapolated directly to asteroids, however, because dust knocked off Phobos and Deimos remains in orbit around Mars and can be swept up by them later, as shown by Berkeley dynamicist Steven Soter.

Measurements of the Mariner 9 pictures have revealed the sizes and shapes of the two satellites. Preliminary measurements show that the satellites can be thought of as roughly potato shaped, with three main axes having the following diameters:

	Phobos	*Deimos*
Longest diameter, kilometers	28	16
Intermediate diameter, kilometers	23	12
Shortest diameter, kilometers	20	10

For each of these measurements, the estimated probable error is about 1 kilometer. Because the shapes are so irregular, another way of expressing the satellite sizes is to give the diameter of a sphere having the same projected area as the average projected area of the satellites. For Phobos the diameter of the equivalent sphere would be 21.8 kilometers; for Deimos, the diameter would be 11.4 kilometers. Thus the two satellites are indeed "flying mountains," about 14 and 8 miles in diameter.

Dynamic studies of elongated satellites by scientists such as Joseph Burns of Cornell University and Steven Soter of the University of California at Berkeley indicated prior to the Mariner 9 mission that they should be alined by tidal forces so that their long axes point toward the primary planet. The same is true for Earth's Moon, which explains the fact that it keeps one face toward Earth at all times. Detailed photography of the surface features of these satellites permitted Mariner 9 scientists to test this prediction and it was found to be correct. Phobos and Deimos keep one side toward Mars at all times. This indicates that no large impact has disrupted the tidal locking or set the moons to spinning within the last 100 million years or so.

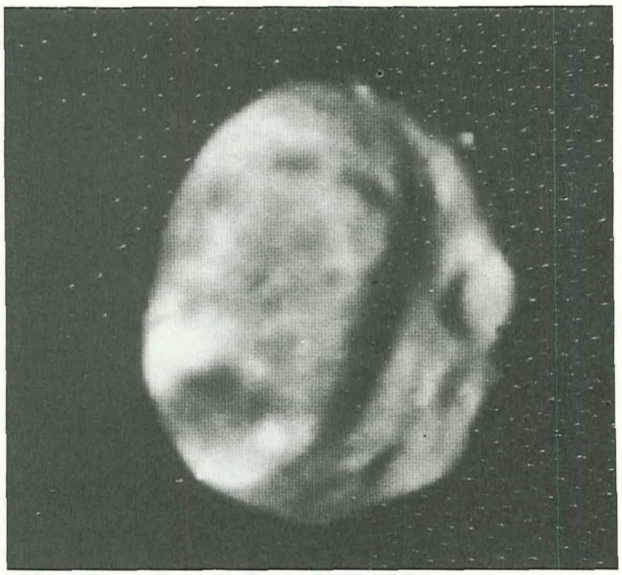


The 8-kilometer crater, largest on Phobos, is prominent in the lower left in this view from 10 400 kilometers; phase angle, 45°. (1581–114434)

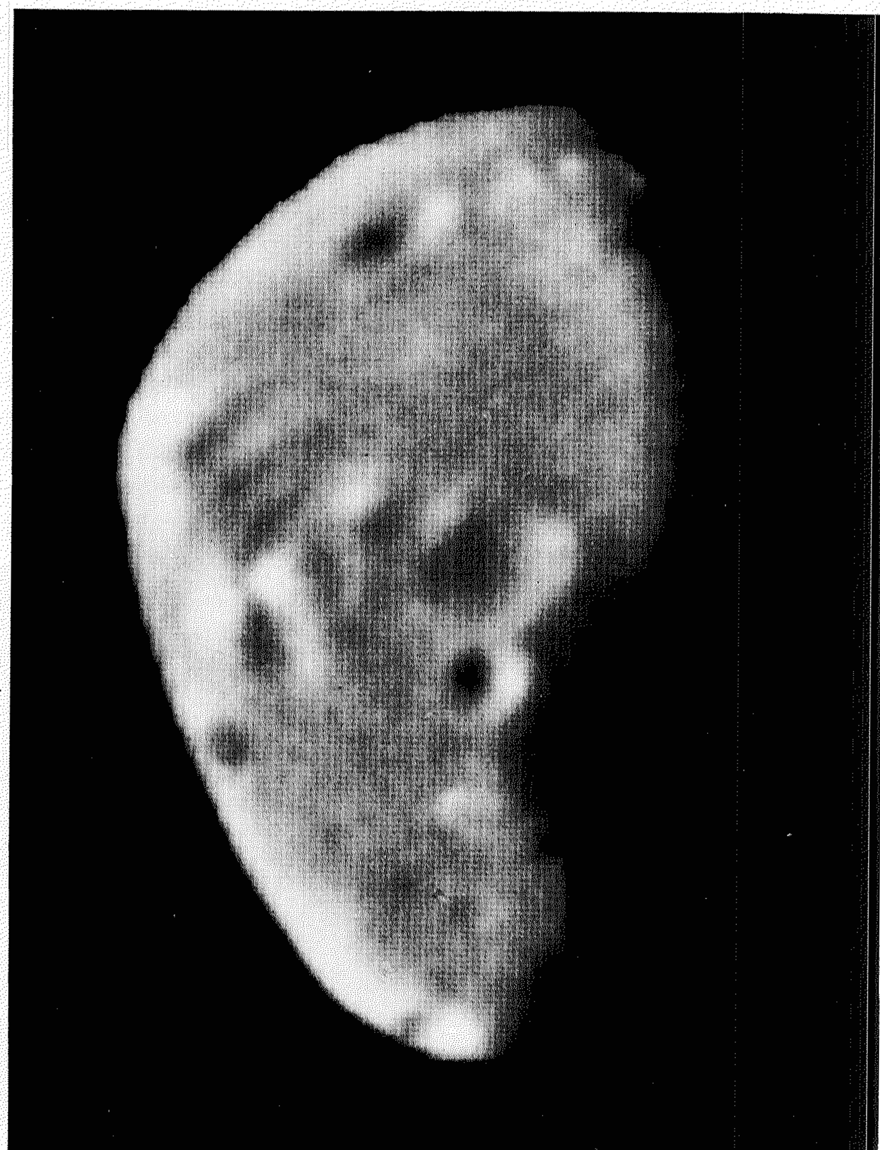
Both Phobos and Deimos have very dark surfaces, as dark as the darker regions of the Moon. This low reflectivity is equivalent to that of dark basaltic lavas or certain types of very primitive meteorites (carbonaceous chondrites) and darker than Mars or such terrestrially familiar rocks as granite.

The fact that Phobos and Deimos have been struck by many crater-forming meteorites leads to the idea that they might be highly fractured internally. The largest clear crater on Phobos is about 8 kilometers in diameter, which approaches the radius of Phobos itself; obviously Phobos could not have sustained a much larger impact without being blown apart. The energy required to form the 8-kilometer crater is believed to be about 10^{25} to 10^{26} ergs, equivalent to 10 000 to 100 000 atomic bombs of the Hiroshima size, or equivalent to perhaps 1000 bombs of megaton size. Mariner scientists have analyzed the effect of this energy dissipation in Phobos and the probability of Phobos' withstanding impacts of still larger size. From these studies it appears that Phobos (and presumably Deimos) must be composed of relatively well-consolidated material; it is believed that this material is probably rock interlaced with fractures caused by the impacts.

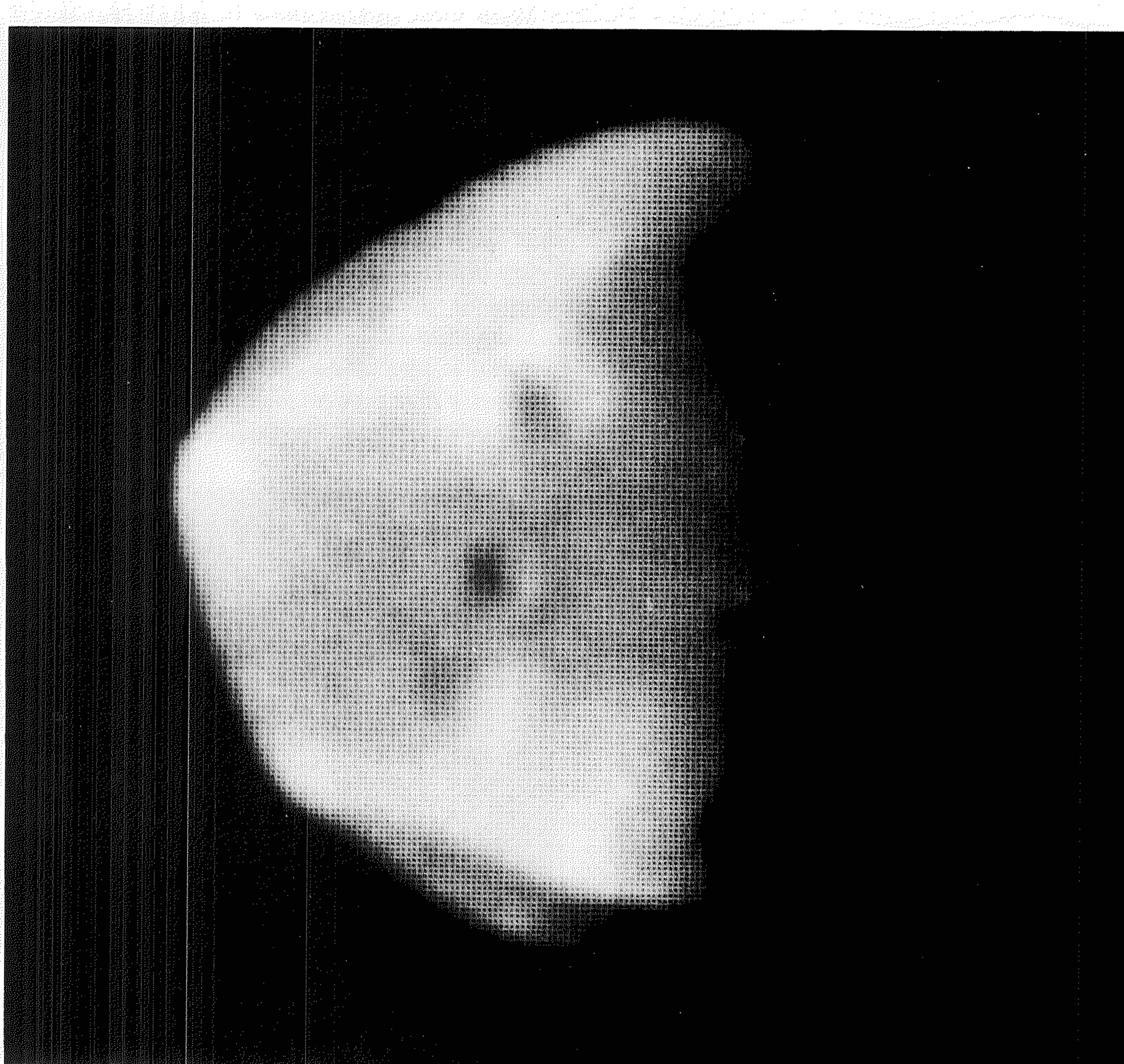
All of these discoveries and conjectures about Phobos and Deimos—perhaps seemingly unrelated—point back to the early history of the solar system, because they all suggest that the satellites have been cratered for a long time and have not been recently captured or disturbed. What, then, is the origin of these two small moons? A direct attack on this question leads to frustrations. For example, the simplest idea, that they are merely captured asteroids, encounters difficulties because of the satellites' orbits. Captured bodies would be expected to have rather "irregular orbits"—i.e., with high eccentricities and/or high inclination to the plane of Mars' equator. Yet Phobos and Deimos have circular orbits lying in the plane of Mars' equator. Dynamicist S. Fred Singer has shown that such orbits might result from tidal forces, but only if the satellites were hundreds of times more massive than Phobos or Deimos. Alternatively, one could invoke a whole swarm of minisatellites that, through collisions, would cause drag forces that might produce such orbits, but then one is faced with the problem of accounting for the present whereabouts of the minisatellites.



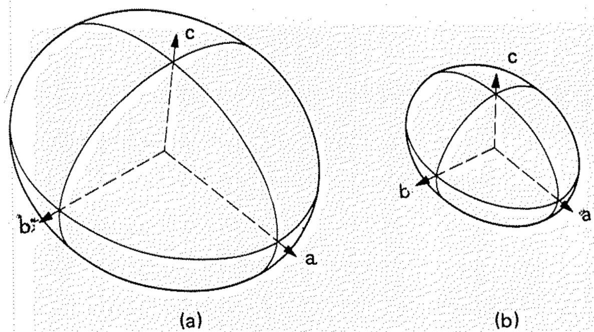
View from a perspective somewhat different from the view on the facing page, showing the lateral valley or scarp on Phobos. Range, 12 500 kilometers; phase angle, 18°. (1570–163600)



The closest available photograph of Deimos, from 5470 kilometers. The phase angle is 65°. Several craters ranging up to about 2 kilometers in diameter can be seen. (1599–201122)



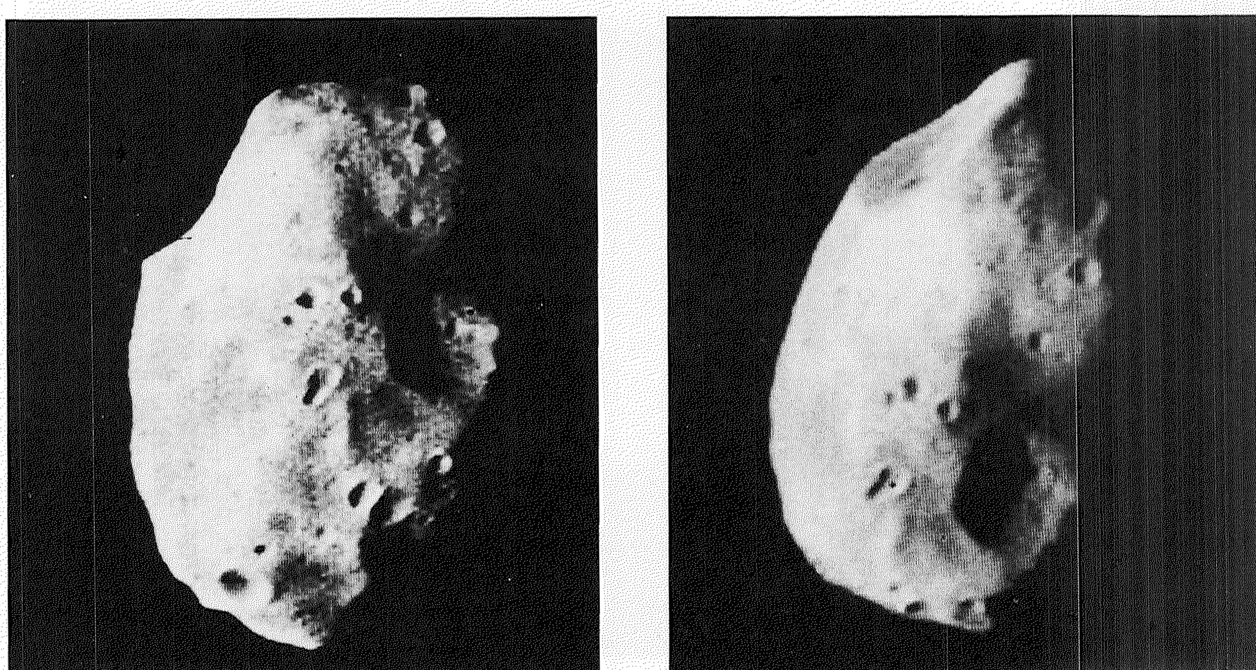
Deimos, seen from 7780 kilometers and with phase angle 73°. Note saddle-shaped valley at bottom edge. (951–220924)



Orientations of Phobos (*a*) and Deimos (*b*) represented as triaxial ellipsoids. (*a* = longest axis, toward Mars; *b* = intermediate axis, in orbit plane; *c* = shortest axis, normal to orbit plane.)

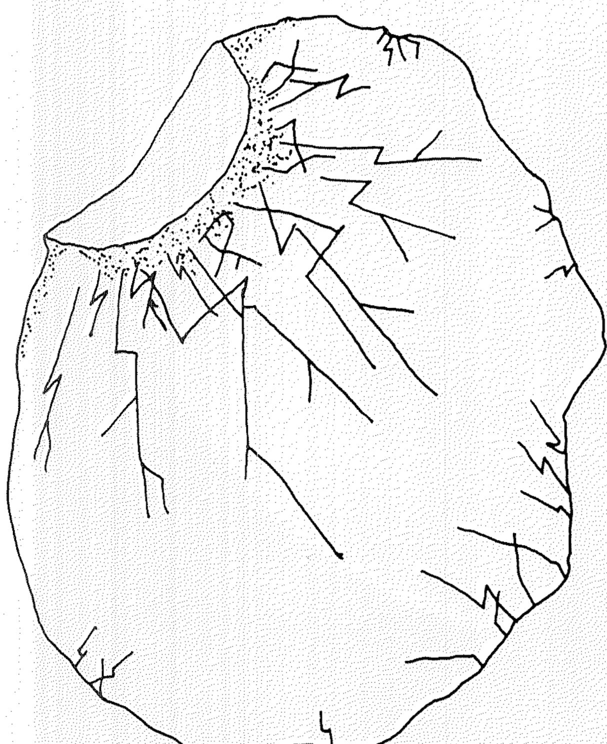
With ideas such as these in mind, Mariner 9 investigators budgeted a number of photographs to search the vicinity of Mars for undiscovered satellites still smaller than Phobos or Deimos. Unfortunately, a thorough survey would have required many more pictures than were available. Nonetheless, combining the new Mariner data with earlier ground-based searches, it appears unlikely that any satellites larger than 1 kilometer in diameter could exist outside the orbit of Phobos.

Another idea about the origin of Phobos and Deimos is that they might have formed in equatorial orbits around Mars using a cloud of finely

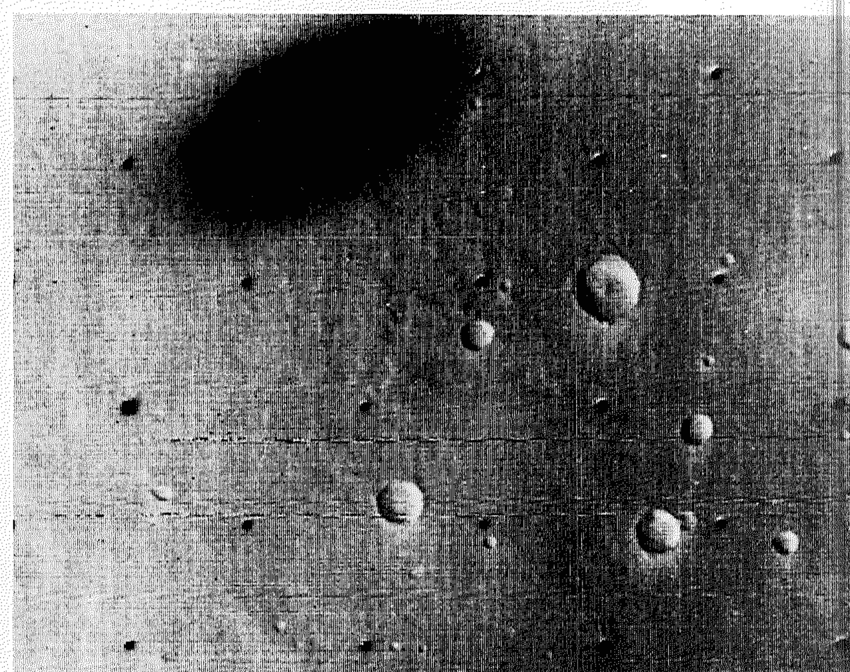


Two views of Phobos from a direction within 20° of Phobos' south pole. The reproducibility between this and other pairs of pictures shows that Phobos is locked in synchronous rotation with Mars, as the Moon is with Earth. (820–00205, 937–103305) dispersed material similar to that which is widely thought to have formed the Moon and many other satellites of the solar system. One unanswered problem in this theory is that if the process was similar to that producing other satellites, why are Phobos and Deimos only a millionth as massive as the supposedly analogous satellites. Another problem is that Phobos and possibly Deimos display valleylike depressions and irregularities of form that would not be expected if they were the direct products of accretion from innumerable tiny bodies. If they are such satellites, they must have been substantially deformed by many impacts subsequent to formation.

Still another idea, favored in a recently published report by Mariner analysts, is that Phobos and Deimos represent fragments of an initially larger satellite. This would be consistent, for example, with their similarity in having unusu-



Hypothetical cross section through the 8-kilometer crater on Phobos, showing fractures beneath the crater and at the antipodal point, based on laboratory experiments with rock samples.



A solar eclipse occurring on Mars. The shadow of Phobos is seen here falling on the Aethiopis region, February 4, 1972. The penumbral shadow measures about 50 by 110 kilometers. An observer inside the shadow would see an annular eclipse, with Phobos passing across, and obscuring part of, the Sun. (P–12868)

Phobos and Mars, showing the cratered satellite, the Martian canyonlands, and the volcano Ascraeus Mons. (Painting by Don Davis, 1972, courtesy of the U.S. Geological Survey and Morrison Planetarium, San Francisco) ally dark surfaces (independently captured asteroids would probably have surfaces of different reflectivity). On the other hand, if the satellite was large enough to produce 22- and 11-kilometer fragments, where is the predictable multitude of smaller fragments that should have formed during its disruption?

The final solution to the intriguing puzzle of Phobos' and Deimos' origin will require careful study of the dynamics of these bodies and of particles interacting with them. In addition to advancing the science of celestial mechanics, such studies will shed new light on the conditions in the primeval solar system.

The problem of the origin of Phobos and Deimos also raises exciting possibilities concerning the future exploration of the solar system. The question of how Earth and other planets formed 4.6 billion years ago has prompted a search for so-called genesis rocks, which could be chemically analyzed to reveal the process of planet formation. No terrestrial rocks date back this far, although a few approach 4 billion years in age. Some meteorites date to this period, but most of them appear to have been chemically altered by heating inside larger parent bodies, and no one is sure in what part of the solar system they originally formed. The search for genesis rocks on the Moon was hampered by similar chemical alterations associated with lunar volcanism, although the Apollo astronauts brought back numerous ancient samples in excess of 4 billion years. Therefore, the existence of two satellites that appear to be very old, the fact that they are closer to Earth than most asteroids, and the demonstrated feasibility of placing spacecraft into orbit around Mars all raise the possibility of eventual collection and return of samples from Phobos and Deimos. Phobos and Deimos, which are comparable in size to the bodies assumed to have formed the planets, might thus become keys to the eventual understanding of the formation of the planets and satellite systems.

CHAPTER XIII

Summary: New Horizons

. . . Mariner 9 has made Mars one of our first orders of business for the next hundred years or so.

—ARTHUR C. CLARKE, ON NATIONAL PUBLIC RADIO, MAY 1973

. . . as you are anxious to know what one looks for in that land, or why one goes there at such great peril, it is that one is moved to do so by the . . . character of human nature [one part of which] is the thirst for knowledge: for in man's nature lies that inclination to explore and see things of which he has before been told, in order to know whether it is as he has been told or not.

—ANONYMOUS, regarding colonization of Greenland and America in *The King's Mirror*, 13th-century Norwegian document

If Mars is empty, . . . we will fill it. But still the voice of Mr. Burroughs calls out on nights when we pace our lawns and eye the Red Planet: "All the evidence is not in! Maybe . . . .

—RAY BRADBURY, commenting on the manuscript of *The New Mars*

During the summer of 1972, Mariner 9 circled Mars on its extended mission, and data were radioed back to Earth for several months at a reduced rate of transmission. Eventually, on Friday, October 27, 1972, the spacecraft ran out of attitude-control gas; therefore, it could not be rotated and stopped on command, nor retain its orientation with respect to the stars, in view of the small perturbing forces. During the final radio contact with Mariner 9 on October 27, it was slowly tumbling with a period of 51 minutes. Such tumbling reduced the solar radiation on the solar panels, and consequently the energy stored in Mariner 9's batteries was depleted on the same day.

At the end of its highly successful 516-day mission, Mariner 9 had performed usefully in orbit around Mars for 349 days, four times the duration of the minimum acceptable 90-day nominal mission. It transmitted 7329 pictures of Mars and its satellites. In terms of the language of information theory, it transmitted 54 billion bits of scientific information, 27 times as much information as transmitted by all three of the preceding Mariner flyby missions combined.

These are indicators of Mariner 9's success as measured against engineering design specifications. Its success is just as dramatic if measured against our knowledge of Mars. Mariner 9 provided a knowledge explosion about the enigmatic planet.

When Mariner 9 was approaching its destination, Mars was no longer the curious Victorian planet pictured by Percival Lowell, H. G. Wells, or Edgar Rice Burroughs, but rather had become in our minds a relatively dry and less interesting place. The craters that had been photographed a few years before suggested a Moon-like Mars; whatever erosive processes were active seemed insufficient to change the surface structure much since the planet formed. Measurements of about 20 micrometers of precipitable water in the atmosphere indicated the planet was too dry to support life, and the photographs of ancient crater fields suggested that there never had been much liquid water on the surface. After three Mariner flights, absence of evidence for folded mountains or major volcanoes again suggested little geologic evolution. In view of the atmosphere and polar caps, there were discussions of whether Mars should be considered more Moon-like or more Earth-like, but these terms were never very clearly defined. Some said that the planet was Mars-like, but such a statement did not allow much in the way of prediction of what would be found there.

Now we can assess the impact of continued exploration. What has been revealed is a new Mars.

With Mariner 9 now in orbit around Mars and its cameras forever shut off, it is appropriate to list some of the discoveries and speculations that the mission has produced, and to show how these have modified our earlier views and will lead on to future exploration. But before proceeding, it is useful to comment on a common misconception raised by reports of new discoveries in many fields. It has become a cliché of science reporting that new questions are raised as fast as old questions are answered. How, then, can a voyage of discovery be worthwhile? The answer lies in the existence of a hierarchy of questions. Ideally, the early questions are first-order questions, and as they are answered, we proceed to finer levels of detail. Later questions are, ideally, more subtle. Before Galileo, Mars could have been considered to be a point of glowing light. After Galileo discovered that it was a globe, there were many questions about its resemblance to Earth. Before the spectroscope, the dark markings could have been thought to be oceans, but afterward, there were questions of how desertlike the planet was. Before Lowell, there could have been a dying civilization, but after sophisticated spectroscopy we learned there was neither enough air or water, and there were questions about whether any degree of life could survive. After Mariners 4, 6, and 7 we knew there were at least some ancient cratered areas, but there were questions about how universally they covered Mars.

Like other areas of human endeavor, science does not progress ideally and sure-footedly, with each footstep falling closer to the truth than the last footprint. There is a bit of shuffling around. We advance by learning which tentative steps are in the wrong direction, as much as by sighting the distant truth. While individual hypotheses may be proven false, we have history's evidence to support the contention that each decade's position is likely to be closer to the truth than that of the previous decade.

The question we have been addressing is, "What is Mars like?" The Mariner experience in general has led to some confirmations and some revisions of earlier ideas, and to the first clear pictures of the surface and the surface conditions. Mariner 9 in particular extended our coverage, discovered a number of hitherto unseen phenomena, and forced us to come to grips with the possible failure of an old idea—the often assumed but rarely stated idea that Mars' present condition resembles its past conditions.

The following lists summarize Mariner 9's accomplishments. Among Mariner 9's space exploration "firsts" are the following:

(1) First orbit of another planet
(2) First complete mapping of another planet
(3) First detailed study of another planet's satellites
(4) First detailed observations of a Martian dust storm

The major discoveries based on Mariner 9 data include the following statements:

(1) The shape of Mars is substantially triaxial.

(2) Mars has a "rough" gravity field, compared to Earth's.

(3) The longest axis and gravity anomalies are associated with a 4-kilometer bulge in the Tharsis region.

(4) The Tharsis region is dominated by shield volcanoes larger than terrestrial examples, with associated lava flows.

(5) A pattern of radial fractures extends over much of the hemisphere centered on Tharsis.

(6) The Tharsis formation is not unique, Elysium being a smaller example with domical topography, volcanoes, and radial fractures.

(7) The hemisphere opposite the Tharsis area is relatively heavily cratered and, in general, displays the oldest surfaces of Mars. Mars thus has a crude hemispheric asymmetry associated with neither the equator nor the meridians.

(8) Craters are a less predominant landform than suggested by Mariners 4, 6, and 7.

(9) An immense canyon lies along stubby "canal" Coprates and extends into the chaotic terrain of Eos; it is part of the Tharsis radial fracture system.

(10) Winding arroyolike channels, often with tributary systems, appear, especially in the equatorial regions.

(11) The arroyolike channels are often associated with chaotic terrain; smaller channels may be associated with volcanoes or other features.

(12) Laminated or stratified terrain units appear in polar regions.

(13) The pattern of classical light and dark markings appears to be in large part associated with deposition of windblown dust by prevailing winds.

(14) At least one dark patch has been clearly resolved into a dune field, and other dunelike formations have been detected.

(15) Streaklike "tails" emanate from some craters and other irregularities because of dust deposition in high winds.

(16) There is no evidence for linear or artificial features corresponding to the "canals" on many classical maps. These features were apparently caused primarily by the presence of complex patterns of dark patches and "tails" just beyond the resolution of Earth-based telescopes.

(17) No direct evidence has yet been found for present-day life on Mars.

(18) The atmospheric surface pressure has been refined from a nominal mean of about 6 millibars to a range from about 3 to 11 millibars, dependent on topography.

(19) Vertical atmospheric temperature profiles during the major dust storm were nearly isothermal in the lower atmosphere.

(20) Daily variations in temperature, humidity, and other "weather" indicators have been

detected and monitored at different latitudes and seasons.

(21) Dust on the Martian surface has a high enough silica content to imply that geochemical differentiation has been important.

(22) Temperature and recession behavior of the polar caps suggest that the seasonal caps are predominantly CO_2, with some H_2O not excluded.

(23) Permanent residual caps exist at both poles; they may be H_2O, CO_2, or mixed deposits.

(24) The white clouds of the W formation and some other white clouds are orographic clouds of H_2O ice crystals.

(25) Polar hazes are mists of condensing CO_2.

(26) Yellow clouds of blowing dust contain particles 1 to 20 micrometers in diameter.

(27) Phobos and Deimos are cratered satellites of natural origin and ancient appearance.

In addition to the factual discoveries listed, Mariner 9 data have led to a number of proposed hypotheses, which are serving as groundwork for continued research. These proposals have come from a variety of scientists in different disciplines. Some of the hypotheses may be refuted and others confirmed by future work. Some hypotheses are incompatible with others. Their range suggests the breadth of the impact of Mariner 9's voyage of discovery. The hypotheses include the following:

(1) Residual ice caps may contain in frozen form most of the water assumed to cause the channels.

(2) Large quantities of frozen water may exist in permafrost layers tens, hundreds, or thousands of meters under the surface. This may sometimes melt and cause ephemeral rivers.

(3) Large quantities of water are probably tied up in surface minerals in the form of water of hydration.

(4) Ice in underground permafrost layers sublimes or melts to cause collapse and erosion; this forms chaotic terrain.

(5) Martian polar layered deposits and arcuate landforms around the poles may be related to periodic variations in the Martian orbit.

(6) Martian polar regions act as a trap for eroded dust, leading to formation of stratified dust and ice layers.

(7) Martian craters and basins such as Hellas act as a repository for dust, leading to formation of relatively featureless plains.

(8) Martian erosion and deposition rates are much lower today than they were a few hundred million years ago.

(9) In the past, Mars had atmospheric pressures as high as 30 to 1000 millibars, during either long eras or short episodes.

(10) At some time (s) in the past the Martian polar caps melted simultaneously, providing a more massive atmosphere.

(11) Gaseous products of Martian volcanism greatly modified or added to the Martian atmosphere.

(12) Martian dust storms are governed primarily by solar radiation input, occur primarily at perihelion. and may involve locally hypersonic winds.

(13) The Sun may be periodically variable in luminosity to such an extent that it periodically changes planetary environments.

(14) Past changes in Earth's environment, such as major ice ages, may be caused by the same solar variations hypothesized to affect

Mars; such changes may have affected Earth's biological evolution, such as the transition from reptile to mammal ascendancy.

(15) The interior of Mars is geologically and seismically active.

(16) Martian crustal fractures and disruptions are signs of incipient plate tectonic activity.

(17) Mars falls between Earth and the Moon in geological activity and evolutionary state.

(18) Martian satellites are relics from the period when the planet itself formed.

(19) The Martian satellites are probably composed of basaltlike fractured rock.

(20) The contrast difference between classical dark and light markings is due mainly to petrological differences in the materials.

(21) The contrast difference between dark and light markings is due mainly to particle size differences in the materials.

(22) Advanced life forms on Mars are unlikely, but primitive life forms cannot be ruled out.

(23) Past conditions on Mars may have been more suited to origin and evolution of life than present conditions.

These wide-ranging hypotheses provide fertile ground for future work of scientists in many disciplines including geology, chemistry, astronomy, meteorology, and biology. Much of the future work will be done in Earth-based laboratories. These programs would include computer calculations of Martian interior and atmosphere conditions, measurements on Mariner 9 photographs, further comparison of data sets from different Mariner 9 instruments, telescopic studies, and continued radar mapping of Martian topography.

In addition to these techniques, new methods of space exploration will be brought to bear on Mars. Orbiting instruments in manned stations such as Skylab or unmanned probes such as the Orbiting Astronomical Observatory have the ability to probe Mars without the effects of Earth's intervening atmosphere, which blurs images and absorbs radiation at certain wavelengths.

Finally, and most direct, will be the future spacecraft sent to the vicinity of Mars. The next announced project is the Viking program. In this program, two launches are planned, each involving a probe similar to Mariner 9 in orbit around Mars, and each in addition to land an instrumented package on the surface of Mars. The Viking launches are planned for 1975 with arrival at Mars planned for summer 1976.

Between the 1971/72 Mariner 9 mission and the scheduled 1975/76 Viking mission, one close approach of Mars occurred in 1973, when another major dust storm was observed. Four Soviet probes were launched toward Mars in 1973, and Western observers were quick to speculate that a repeat of the Soviet Mars 2 and Mars 3 landing missions was planned. It turned out that two of the probes were intended as orbiters, and two as landers. However, a number of malfunctions cut the effectiveness of the program. One lander missed Mars. On March 12, 1974, Mars 6 parachuted into the atmosphere, and transmitted measures of a higher water-vapor content than anticipated. However, radio contact was lost prior to the landing, as was the case with the Mars 2 lander, and no data were returned after contact with Mars. The orbiters produced some photographic coverage. The landing was near 25° W, 24° S.

All three of the spacecraft so far landed on Mars have terminated transmission within minutes before or after landing, raising questions about possible severe wind or dust conditions on the planet. Soviet and American scientists are currently exchanging data on Mars and on unmanned landing sites, and the cooperative program calls for further data exchange. No commitment by any country has been made for manned flights.

The U.S. Viking spacecraft is currently under construction and the scientific programs are being designed by a group of 68 scientists, divided into 13 teams. These teams represent the experiment areas for each of the two missions:

(1) Three mapping experiments from the orbiter vehicle

(2) One atmospheric investigation conducted during entry of the lander

(3) Seven analyses carried out on the surface of Mars

(4) One radio and radar experiment

The surface experiments will include photographic reconnaissance of the immediate landing area, various biological analyses of soil scooped up by a sampler, molecular analyses of soil samples, meteorologic analysis of atmospheric conditions near the lander, seismometry, magnetic studies of the surface material, and physical properties of the surface (for example, soil strength and coherence).

Mariner 9 data are crucial in determining the design of these experiments, planning the conduct of the nominal 90-day Viking missions, and in selecting the Viking landing sites.

In summary, in Mariner 9 we have witnessed a historic voyage of discovery. Whereas the famed voyages of Columbus and the other Renaissance navigators touched only the fringes of the western continents, Mariner 9 has mapped a whole planet in the course of a single year. Mariner 9 has changed Mars from an astronomical object into a place, and has opened not a single frontier but an entire varied globe to future exploration by man.

APPENDIX A

Availability of Mariner 9 Photographs

The National Aeronautics and Space Administration makes available for public use and research copies of data obtained on space missions. These are released through the—

National Space Science Data Center
Code 601
Goddard Space Flight Center
Greenbelt, Md. 20771

Mariner 9 pictures have been identified by several different systems of code numbers. The system used here most frequently refers to a negative roll number assigned by the Jet Propulsion Laboratory, for example 1636-214517. An additional system using the prefix DAS refers to a spacecraft counter, as in DAS 4 215 690.

Mariner 9 television pictures and related data are now available as described in NSSDC Bulletin 73–03, available from the above address. Normally a charge is made to cover the cost of preparation of the requested data, although the Director of NSSDC may waive this charge in some cases for small amounts of data requested for certain scientific or educational purposes.

APPENDIX B

Mariner 9 Television Science Discipline and Task Groups

TEAM LEADERS: H. MASURSKY AND B. SMITH

SCIENCE DISCIPLINE GROUPS

Atmospheric Phenomena

*Leovy, C.
- Briggs, G. (1)
- Shipley, E. (1)
- Smith, B. (1)
- Wildey, R. (2)
- Pollack, J. (3)
- Young, A. (3)

Geodesy/Cartography

*de Vaucouleurs, G.
- Arthur, D. (1)
- Batson, R. (1)
- Borgeson, W. (1)
- Davies, M. (1)
- Leighton, R. (2)
- Young, A. (2)
- Wildey, R. (3)

Geology

*McCauley, J.
- Carr, M. (1)
- Hartmann, W. (1)
- Sharp, R. (1)
- Soderblom, L. (1)
- Wilhelms, D. (1)
- Cutts, J. (2)
- Milton, D. (2)
- Murray, B. (2)
- Sagan, C. (3)

Physics of Polar Phenomena

*Murray, B.
- Leighton, R. (1)
- Lederberg, J. (2)
- Leovy, C. (2)
- Sharp, R. (2)
- Soderblom, L. (2)
- Milton, D. (3)

Satellite Astronomy

*Pollock, J.
- Milton, D. (1)
- Davies, M. (2)
- Hartmann, W. (2)
- Sagan, C. (2)
- Veverka, J. (2)
- Smith, B. (3)
- Young, A. (4)

Variable Surface Features

*Sagan, C.
- Cutts, J. (1)
- Lederberg, J. (1)
- Levinthal, E. (1)
- Veverka, J. (1)
- Wildey, R. (1)
- Young, A. (1)
- Briggs, G. (2)
- Carr, M. (2)
- de Vaucouleurs, G. (2)
- Pollack, J. (2)
- Smith, B. (2)

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*Principal investigator.

Note.—Number in parentheses indicates individual's choice in science discipline groups.

TASK GROUPS

Data Processing and Process Control

*Levinthal, E.
Arthur, D.
Batson, R.
Briggs, G.
Cutts, J.
Davies, M.
Shipley, E.
Smith, B.
Soderblom, L.
Veverka, J.
Wildey, R.
Young, A.

Hardware

*Murray, B.
Borgeson, W.
Cutts, J.
Leighton, R.
Smith, B.
Wildey, R.
Young, A.

Mission Analysis

*Briggs, G.
Borgeson, W.
Davies, M.
Milton, D.
Pollack, J.
Sagan, C.
Smith, B.

Mission Operations

*Smith, B.
Batson, R.
Briggs, G.
Carr, M.
Hartmann, W.
Leovy, C.
McCauley, J.
Murray, B.
Sagan, C.

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*Principal investigator.
Note.—Number in parentheses indicates individual's choice in science discipline groups.

APPENDIX C

Publications Resulting From Mariner 9

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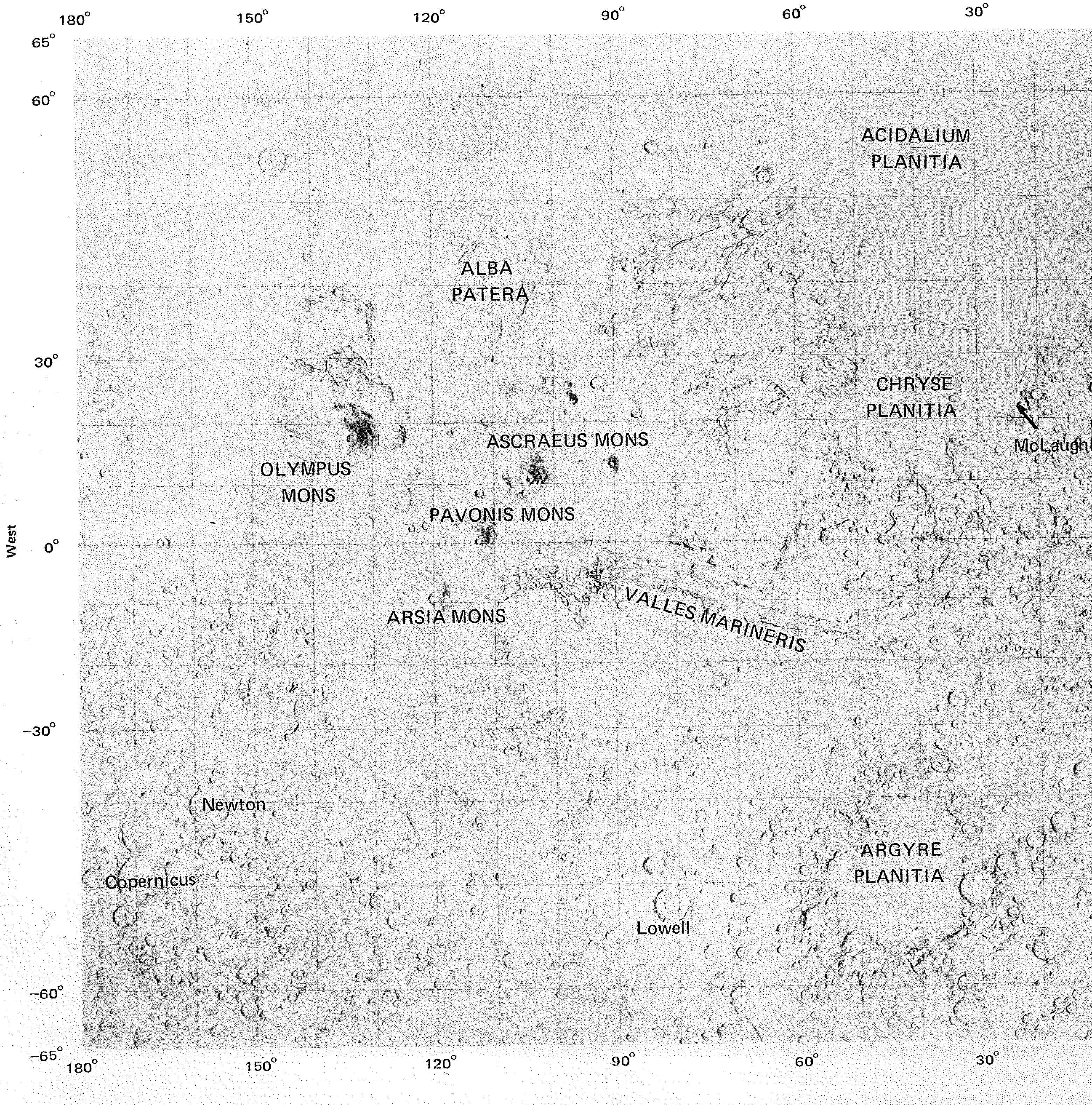

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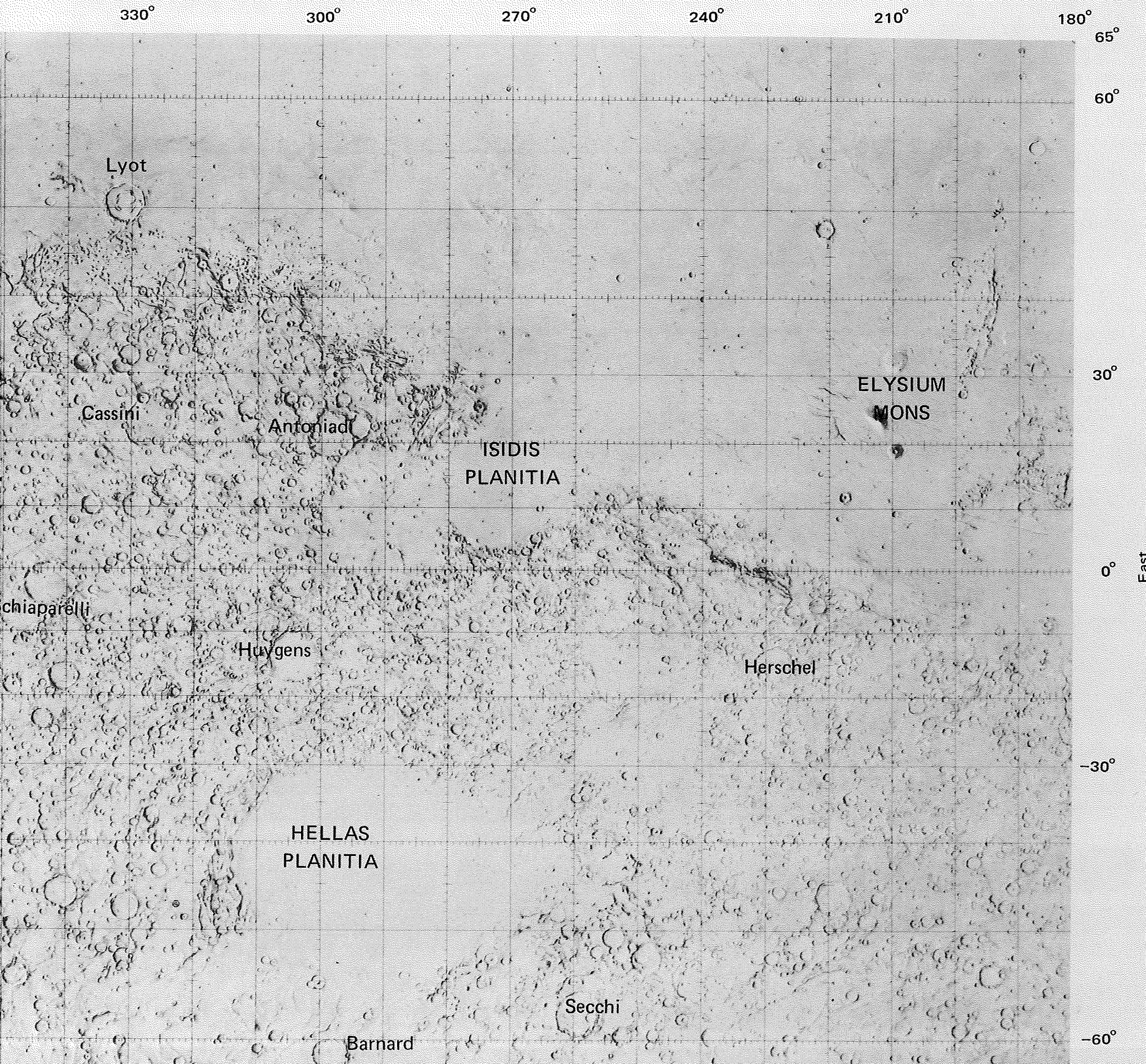
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