Update on Mars: Clues about the Early Solar System

With the widening exploration of the solar system, geology is becoming a science of many more planets than the earth. For several years the term "lunar science" could adequately encompass extraterrestrial geology. But since the spacecraft Mariner 9 produced thousands of detailed pictures of Mars in 1971 and 1972, scientists have new information on a full-sized planet to consider [*Science* **179**, 463 (1973)]. At a recent international colloquium (*1*) in Pasadena, California, most of the scientists who have studied Mars, as well as many lunar and earth scientists, discussed what is now known about Mars and tried to formulate the outstanding questions, as well as the best ways to answer them.

Mariner 9 has shown that many features on Mars are strikingly different from features on the earth. The volcanic structure, Nix Olympica, is far larger than any similar feature found on the earth—almost 500 km across at the base. The great canyon, Coprates, stretches about one-sixth of the way around the Martian equator. Hugh polar caps advance and retreat by as much as 35° latitude every season. Extremely violent dust storms occur on Mars, but its atmosphere is much thinner than the earth's. Dry channels are frequently found in the equatorial regions of Mars, yet there is no evidence of any fluid on the surface now. Extensive systems of faults indicate tensions in the planet's crust, but Mars does not seem to have tectonic activity like the earth.

In spite of the differences between Mars and the earth, it is becoming increasingly clear that a common framework of ideas is useful to describe the two planets, as well as the moon. All three seem to have been formed at the same time, more than 4 billion years ago, and to have undergone considerable geological activity, which might be understood in terms of the thickness of their lithospheres. The moon appears to have a very thick lithosphere, 300 to 1000 km deep, and therefore no tectonic activity. The plates in the earth's lithosphere are about 50 km thick, so they can be easily heated and moved by forces underneath.

At the recent colloquium, several speakers suggested that the activity of Mars is intermediate between that of the earth and the moon, and that Mars has a lithosphere about 200 km thick. In the Tharsis region, delineated by a ridge of three volcanoes, there is a fracture system which is characteristic of uplift or doming of the lithosphere, according to Michael Carr, of the United States Geological Survey (USGS) in Menlo Park, California. But if the lithosphere were spreading in the Tharsis region, it would have to undergo subduction at some other place on the planet, in effect burying itself there. There is no evidence of subduction, so apparently no plate movement is taking place. But evidence of less dramatic activity is abundant. Areas of fretted terrain, which are examples of tectonic fractures, are quite prevalent.

While geological activity varies immensely among planets and planetesimals with different sizes and compositions, the record of crater formation on Mars and the moon seems to suggest that many planets share the same history of bombardment by interplanetary debris. One of the most exciting developments of the recent colloquium was that two researchers, who had previously made different estimates of the cratering history of Mars, now seem to agree that the Martian cratering history is almost identical to that of the moon. Cratering records are compiled by counting the number of craters of a given size on parts of the surface with different ages. Ages on the moon have been precisely determined from samples retrieved by Apollo missions, and a curve that indicates extremely heavy bombardment of the moon about 4 billion years ago is well established (Fig. 1). No samples are available from Mars, but by assuming that the geological evolution of Mars has been fairly uniform, a cratering history for Mars can be derived. The curve for Mars indicated in Fig. 1 was calculated by Laurence Soderblom, at USGS in Flagstaff, Arizona, from counts of craters 4 to 10 km in diameter in various regions indicated. William Hartmann, of Science Applications Inc. in Tucson, Arizona, has derived a similar curve, but, because he estimates the history of erosion on Mars differently from Soderblom, Hartmann calculates somewhat higher cratering rates in the early part of the history.

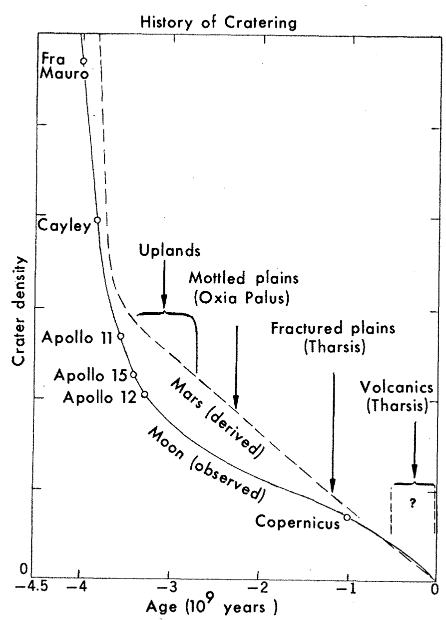

Fig. 1. The number of 4- to 10-km craters per unit area versus the age of the cratered surfaces. Both bodies appear to have been heavily cratered 4 billion years ago, perhaps from the same source of debris.

The idea that Mars and the moon have similar flux histories appears to be novel and may unify a great deal of information about the early history of the solar system. As recently as 6 months ago, many investigators thought that the causes of cratering on Mars and the moon were quite different. But at the Pasadena colloquium it was suggested that the source of cratering debris was material in the asteroid belt that was ejected by perturbations from Jupiter, and the idea appeared to be rapidly accepted. The time required for the cratering rate on Mars to decrease by one-half, during the period of heavy bombardment, agrees well with estimate of the time required for Jupiter to sweep out half the material believed to have once filled the asteroid belt, and also agrees with the data from the moon. The specific rates of cratering need not be identical, since Mars is closer to the asteroid belt, but the ages of heavy bombardment should be the same for both Mars and the moon, as Fig. 1 indicates. (Whereas Mars was once thought to have a very high cratering rate even in recent times, with the result that many features were thought to be quite young, the theory of the "Jovian generator" suggests that the cratering rate on Mars is much lower, probably not more than twice the rate on the moon.) Eugene Shoemaker, of California Institute of Technology and USGS, who proposed the idea that Jupiter once sprayed a great flux of material across the solar system, pointed out that the same steep cratering curve found on Mars and the moon should be found on Mercury.

Whether the cratering on Mercury is similar to that on Mars and the moon should be known soon, because a Mariner spacecraft will fly by Mercury in March. On the other hand, the Galilean satellites of Jupiter, which are outside the asteroid belt, should have a very different cratering history, according to Soderblom. In 1977, two Mariner Jupiter-Saturn missions should photograph the Galilean satellites.

Apart from the growing consensus on a cratering history, the Mars colloquium was characterized by articulate and enthusiastic debate about past and present conditions of the planet. The major unanswered question, of course, is whether there was ever any liquid—particularly water—on the Martian surface. It seemed that those who hoped to find life were biased toward water, while those who didn't, were not. The principal benefit of the colloquium was probably that all the critical questions about Mars were raised and expressed clearly for a large audience of scientists. As Bruce Murray of Caltech repeatedly suggested, there are probably not enough hypotheses proposed yet to explain all the features of Mars, and the procedure of selecting the least unsatisfactory hypothesis inevitably leads to the wrong answer. Four major puzzles about Mars seem to be the history of the crust, the channels, the polar caps, and the volcanic activity of the planet.

Even from a quick look at the map of Mars, it is clear that one half of the planet is almost completely different from the other half. Although the equator is not the exact dividing line, the hemisphere that approximately corresponds to the northern hemisphere is only slightly cratered, while the southern hemisphere is very heavily cratered. The fact that Mars is apparently a bimodal planet, with two halves that have had completely different histories, is perhaps the greatest puzzle of all, suggests Harold Masursky, of USGS, Flagstaff. He thinks that there was an early episode on Mars when the lightweight crust was removed from half the planet and piled on the other half. What mechanism could do this is an extremely interesting question intrinsic to Mars. But Masursky suggests that the problem may be even more interesting because the history of the earth's surface has been traced back to the one big continent, Gondwanaland, and he points out that nobody tries to imagine what the earth looked like before that epoch. So Masursky suggests that, before the onset of the latest episode of continental drift on earth, perhaps Gondwanaland looked like Mars does now.

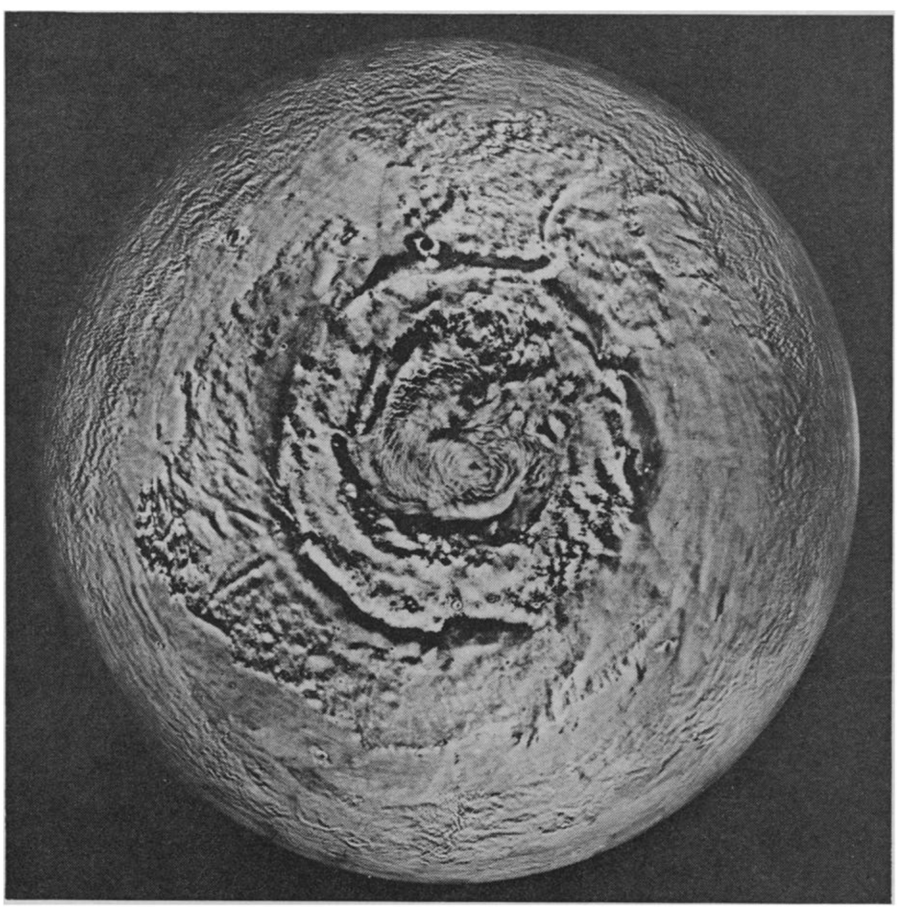

Fig. 2. The north pole of Mars, as observed by the spacecraft Mariner 9. Layered terrain can be seen at the pole. The collar around the pole is cloud cover. [Source: Jet Propulsion Laboratory]

The channels on Mars have been heralded as evidence for aqueous fluids, and indeed many scientists think they were formed by running water—either condensing from the atmosphere or melting on the surface. But neither water nor carbon dioxide, the two principal gases of the atmosphere, could be stable as liquids under the present Martian conditions. Between 5 and 50 times the current atmospheric pressure is required for water to have a liquid phase, and far more pressure is required for liquid carbon dioxide. Liquid water clearly seems the more likely agent for fluvial processes. But if the channels were cut by water, the atmosphere must have changed drastically, and, furthermore, one must ask where did water come from and where did it go?

Water could be stored as surface ice in the north polar cap, as subsurface ice or permafrost, as gas adsorbed to particles of finely ground material called the regolith, which covers much of the Martian surface or even in certain clays, which are possibly found on Mars. Evidence for polar ice, permafrost, and water in clays is somewhat sketchy. Infrared observations from the earth suggest that the regolith may contain 1 percent water, but no one knows how deep the broken soil extends. If the channels could be formed without running water, one argument for a large deposit of water is eliminated, and if some form of life were not expected on Mars, another reason to hope for water would disappear. But two more reasons to expect water remain. Several theorists think that Mars must have had a high concentration of volatile substances when it was formed, and that those volatiles—water among them—would not have escaped. Robert Sharp, of Caltech, thinks that some liquid is necessary over part of the history of Mars to account for the erosion of the surface and features such as etched pits, presumably caused by sapping of ground ice.

Although the majority of investigators seem to favor channels formed by water, others consider the recent symposium valuable because different channel formation processes were discussed. "At least we got the discussion off dead center," said one scientist. Stanley Schumm, of Colorado State University, Fort Collins, suggests that many of the channels, possibly even the braided channels, could have been formed from tectonic fractures that were modified. Erosion by blowing sand and dust is one possible modifying process. Schumm, who specializes in fluvial geomorphology, thinks that none of the channel patterns were necessarily produced by water, although they could be fluvial. Carr proposes that some Martian channels, especially the smaller sinuous channels, were caused by lava flow, but not the larger channels.

Next to the channels, the features of Mars that seem to arouse the most contention are the polar caps. Since the major constituent of the atmosphere, carbon dioxide (CO_2), can freeze onto the polar caps, which are at the temperature of 145°K, the atmosphere and the polar caps are closely coupled. The seasonal variation of CO_2 in the atmosphere seemed small, however, so Robert Leighton, of Caltech, and Murray have proposed that, in addition to the CO_2 caps that obviously advance and retreat each season, there is also a permanent CO_2 cap which acts as a buffer to moderate the atmospheric CO_2 variations. But there are problems with a permanent CO_2 cap. The water vapor in the atmosphere also varies seasonally, and Andrew Ingersoll, of Caltech, thinks that these pressure variations cannot be reconciled with the existence of a permanent CO_2 cold-trap.

The poles could also be the sites of permanent deposits of water ice. Infrared radiometry can distinguish water and CO_2 ices, but the north polar cap was covered with a cloud system, called a hood, when Mariner 9 observed it (Fig. 2), and observations of the south polar cap were severely limited because of the low inclination of the spacecraft's orbit.

Most of those at the conference seemed to agree that the polar regions are likely to be the key to understanding Mars. Besides changing ice caps, the poles have peculiar layered terrain, looking something like stacked poker chips, that almost everyone suspects were laid down during geological periods of alternating climates. The north polar region has the larger cap, and also a more pronounced topography. According to Conway Leovy, of the University of Washington, Seattle, perhaps the question of the existence of a permanent CO_2 cap can be answered by studying the rate at which CO_2 is deposited in the seasonal cap at the north pole of Mars. The layered terrain is particularly interesting because it may establish the dates of climatic variations, such as ice ages on Mars. If variations in solar activity have controlled the glacial ages of Mars, the layered terrain may provide a clue to the intermittent occurrence of glacial ages on earth.

As a result of the conference, planners for the Viking mission have decided to observe the north polar cap, which will be free of clouds when Viking arrives in 1976, from a high inclination orbit. The infrared radiometer on the 1976 Viking will have a small enough field of view to analyze the polar ice without any contribution from nearby soil, and it will also have two high-resolution cameras capable of convergent stereographic mapping that should be able to determine the thickness of the ice and the heights of the layered terrain.

A final puzzle, besides bimodality, channels, and polar caps, is the variety of volcanic features that are observed. When the great shield volcano, Nix Olympica, was observed in a sparsely cratered area, the theory was proposed that volcanism was very young and Mars had just "turned on." Indeed, Nix Olympica is recent, probably not more than 100 million years old, but recently close study has shown that there is also evidence of volcanism more than 2 billion years old. In addition to the shield volcanoes, there are complex volcanic centers, which may be similar to the sort of silicic volcanism on earth that produces large amounts of hot water as well as lava. On Mars, such volcanic centers are found in Alba, Hesperia, and north of Hellas, and are spread widely in Martian time, according to Masursky. Volcanism is generally assumed to have produced the Martian atmosphere, and Masursky stresses that the correlation between the ages of volcanism and the ages of channels, some of which appear to be 2 billion years old, indicates that atmosphere appeared early in Martian history and interacted with the surface for at least half of Martian time. As a limitation on atmospheric activity, Murray emphasizes that if water erosion had been active throughout much of Martian history all the ancient cratered terrain would be gone. But the idea that the atmosphere acted episodically rather than continuously would seem to circumvent this constraint, says Masursky. The atmosphere of Mars seems directly and intricately related to so many phenomena that it will probably be extremely difficult to develop a consistent atmospheric history. But the idea that Mars just turned on seems to have been laid to rest.

The detailed questions raised by the data from Mariner 9 almost all require more physical data about the planet. In a summary of the meeting, Richard Goody, of Harvard University, Cambridge, Massachusetts, suggested some further tests. Samples of surface materials are needed to learn compositions and ages of different terrain. Seismographic measurements should indicate the thickness of the lithosphere. Heat sensors on the surface could tell something about the forces interacting with the lithosphere from below. Measurements of such things as the ratio of argon to xenon in the atmosphere could indicate whether or not the origin of the atmosphere is really volcanism. Electromagnetic sounding could possibly detect ground ice.

Within the U.S. space program, most of these measurements will have to be made some time in the future. Viking is much more heavily instrumented for finding evidence of life than atmospheric or geological data. The two sites chosen for the Viking landers in 1976 are the mouth of a large channel, Chryse, and the region of highest water vapor, Cydonia. But Soviet scientists, who were unable to attend the recent colloquium, do not expect evidence of life on Mars. Four Soviet spacecraft, presumably two orbiters and two landers, are en route to Mars now. They are expected to have sophisticated instruments for analyzing the atmosphere and the surface of the planet, and the first will arrive in early February.

—WILLIAM D. METZ

Notes

1. The International Colloquium on Mars was sponsored by the campus and the Jet Propulsion Laboratory of the California Institute of Technology, 28 November to 1 December 1973. Short summaries of the colloquium will be available from Bruce C. Murray, at the Space Photography Laboratory, and A. Bruce Whitehead, at the Jet Propulsion Laboratory, of California Institute of Technology, Pasadena.